HANDBOOK ON ENERGY CONSCIOUS BUILDINGS

Prepared under the interactive R & D project no. 3/4(03)/99-SEC
between
Indian Institute of Technology, Bombay
and
Solar Energy Centre, Ministry of Non-conventional Energy Sources

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Notice:
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Preface

The global energy scenario has undergone a drastic change in the last two decades. Due to ever growing demand and shortage of supply, the cost of fossil fuel (coal, oil and natural gas) is increasing day by day. Increasing consumption has led to environmental pollution resulting in global warming and ozone layer depletion. Consequently, the era of fossil fuel is gradually coming to an end and the attention is focused on the conservation of energy and search for renewable sources of energy, which are environmentally benign.

Buildings are major consumers of energy insofar as their construction, operation and maintenance are concerned. Though this is not very well quantified in India, yet there is ample scope for energy savings. The indoor environments are becoming increasingly important for human comfort and from health point of view. It is estimated that almost 50% of the global energy demand is due to buildings. Thus, the energy conscious architecture has evolved to address these issues. It involves the use of eco-friendly and less energy intensive building materials, incorporation of passive solar principles in building design and operation including daylighting features, integration of renewable energy technologies, conservation of water, waste water recycling, rainfall harvesting and use of energy-efficient appliances in buildings.

In spite of access to a large information base on various features and techniques, and despite pioneering work in this field by architects the world over and in India, the energy conscious design approach is not very widespread. The expertise developed at various Indian institutes has not percolated to architects at large, especially in a form that can directly be implemented in their designs. This book is an effort to orient the thinking of practising architects towards the importance and benefits of energy conscious architecture. The book provides information on basic principles, climatic conditions of India, passive solar approaches, general recommendations, specific guidelines and integration of renewable technologies in buildings. It contains a number of illustrations, working drawings, examples, case studies and references. In addition to practicing architects, it will also be a useful reference book for students of architectural and building scientists. Those who are conversant with the basic aspects of climate and passive solar architecture may skip Chapter 2 and 3 and refer to Chapter 5 for guidelines.

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On a personal basis, we had solicited opinions from a number of experts and professionals. We have sought opinions and suggestions on the "Table of Contents" of the book from Prof. N.K. Bansal, Prof. U.N. Gaitonde, Prof. C.L. Gupta, Prof. R. Hazra, Mr. Anil Misra, Prof. K.R. Rao, Prof. R.L. Sawhney, Prof. M.S. Sodha, Prof. S.P. Sukhatme, Prof. G.N. Tiwari, Mr. Pankaj Agarwal and architects Sabu Francis, Vinod Gupta, Uttam Jain, Sen Kapadia, Prof. S. Kolhatkar, Prof. Rajiv Mishra, Sanjay Mhatre, D.G. Parab and Sanjay Prakash. Some of them attended a discussion meeting to finalise the contents of the book. Besides, a few of them had gone through the draft copy of the book and provided us various suggestions and comments. A book of this kind could not have become meaningful without their feedback. We are grateful to them for their valuable comments.

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CHAPTER 1

INTRODUCTION

Energy is a basic requirement for the existence and development of human life. Primarily, the commercial sources such as fossil fuels (coal, oil and natural gas), hydroelectric power and nuclear power provide the energy needs of a country. The demand for energy is growing at an alarming rate year after year. For example, according to International Energy Agency (IEA), the global consumption of energy has increased from 4606 Mtoe (million ton oil equivalent) in 1973, to 7287 Mtoe in 2003. On the other hand, the fossil fuels are rapidly depleting and the era of fossil fuel is gradually coming to an end. The accelerated demand and the depletion of resources have caused a steep hike in the cost of fossil fuel. Besides, the combustion of fossil fuels has caused air pollution resulting in global warming and ozone layer depletion. In addition, the release of harmful gases into the atmosphere is causing serious problems for living organisms. Similarly, the release of large amounts of waste heat from power plants to water bodies causes water pollution. In case of large hydroelectric power projects, submerging of land — thereby destroying valuable plant life and displacing inhabitants — has become a serious concern. The fear of release of radioactivity into the atmosphere in the event of an accident or from nuclear waste has forced people to reconsider the use of nuclear power. In view of these problems associated with conventional energy sources, the focus is now shifting to conservation of energy, and to the search for renewable sources of energy that are also environmentally benign.

With the increase in standards of living, the consumption of energy in buildings is progressively rising. The boom in building sector is going to create further demands, resulting in greater pressure on the energy supply situation. In this context, the conservation of energy in buildings through appropriate construction, operation and maintenance practices assume prime importance.

The primary function of a building is to provide a comfortable indoor environment. Traditional buildings of earlier times had many built-in architectural features for achieving comfort. Unlike animals and birds that build their shelters intuitively and adapt themselves to environmental changes, man has relied on various resources to build shelters for protection from heat, cold and rain. They are shaped and planned to take maximum advantage of the climate and surroundings. Gradually, as newer materials and techniques of construction developed, vernacular built forms evolved to provide a harmonious balance between buildings, climate and people's lifestyle. A number of passive solar techniques were adopted in vernacular architecture in the various climatic zones. Control of the microclimate around the building was always an important design consideration. While planning a town, care was taken to orient the streets keeping the effects of sun and wind in mind. For example, towns in Gujarat and Rajasthan, which experience a hot and dry climate, had rowhouses with common walls. These were tightly packed along with streets and lanes to minimize exposure to direct sun and hot winds. The front façades were further shaded with well-articulated balconies called "jharokhas". Each house had an open courtyard which acted as an exhaust for warm air and provided enough natural light for the interior of the house.

With technological advancement, people failed to continue the tradition of maintaining harmonious balance between buildings, climate and their lifestyle. Modern architecture has become a "conquest" of nature in the sense that, environmental conditions notwithstanding, a building could be given a sleek, clean and well-proportioned exterior façade, and the interior made as comfortable as required with the help of artificial devices. However, the drawback is that, such buildings consume an enormous amount of energy.

A growing worldwide concern for conservation of energy has reawakened interest in ecologically sustainable materials, processes and sources of energy. With the availability of newer materials and techniques, and with changing demands on built spaces, achieving thermal and visual comfort in buildings has become a design challenge for modern architects, building engineers and scientists. Various analytical methods have been developed using which, the techniques evolved in the past are now scientifically understood, appropriately quantified and improved. These have led to the evolution of *energy conscious building*. Energy conscious building involves the use of eco-friendly and less energy intensive materials, incorporation of passive solar techniques (including day lighting features) and integration of renewable energy technologies. It also includes conservation of water and waste water recycling, rainfall harvesting and the use of energy-efficient appliances in buildings. For example, in a commercial building, the cooling load can be saved by about 26% in a hot and dry climate (like Jodhpur) by adopting appropriate design considerations and operation strategies. Simple design procedures such as orientation, shading, insulation, etc. can be easily incorporated in any building, leading to substantial benefits from the point of view of comfort and energy savings. In some climates, simple techniques alone may not be adequate for achieving ideal comfort conditions. In such cases, advanced features such as wind tower, roof pond, Trombe wall, etc. may be used. Even in conditioned buildings, where mechanical devices are used to create a comfortable environment, the use of passive methods would help reduce the energy consumption. Further, the integration of photovoltaic systems as well as active systems such as hot water or hot air systems would further reduce the consumption of conventional energy.

In spite of access to a large information base and pioneering work in this field, the idea of energy conscious design approach has is not quite caught on. The expertise developed at various institutes in India has not percolated to architects at large, especially in a form that can be directly implemented in their designs. This book endeavours to orient practising architects towards the importance and benefits of energy conscious building.

A brief outline of each chapter of the book is as follows:

Chapter 2 presents basic information regarding climate and its effects on buildings. A description of the characteristics of the different climatic zones of India is given.

The principles of passive solar architecture including simple and advanced techniques are described in detail in *Chapter 3.* Wherever possible, the principles are also accompanied by the details of construction. Additionally, day lighting is described separately as a passive solar technique.

The thermal performance of a conditioned building refers to the estimation of its heating and cooling loads, energy demand, and sizing and selection of HVAC equipment. For a non-conditioned building, it is the calculation of temperature variation inside the building over a specified time, and the estimation of uncomfortable periods. The quantification of these aspects determines the performance of a building design and helps in evolving improved designs for achieving comfortable indoor conditions. *Chapter 4* presents the basic concepts that enable an architect to understand the various aspects of estimation of the thermal performance of a building design.

Chapter 5 provides guidelines on passive techniques for three types of buildings, namely, commercial, industrial and residential buildings. Because the design of passive solar buildings is climatic specific, the guidelines have been structured climate-wise.

The integration of renewable technologies in building design, conservation of water and rain water harvesting are discussed in *Chapter 6.*

Chapter 7 presents a few case studies to illustrate the use of various passive techniques and new building materials.

A technical glossary and a number of appendices containing useful information supplement the main chapters.

CHAPTER - 2

CLIMATE AND BUILDINGS

Contents:

2.1 INTRODUCTION

The weather of a place represents the state of the atmospheric environment over a brief period of time. Integrated weather condition over several years is generally referred to as climate or more specifically, as the 'macro-climate'. An analysis of the climate of a particular region can help in assessing the seasons or periods during which a person may experience comfortable or uncomfortable conditions. It further helps in identifying the climatic elements, as well as their severity, that cause discomfort. The information helps a designer to build a house that filters out adverse climatic effects, while simultaneously allowing those that are beneficial. Discomfort and the corresponding energy demand for mechanical systems can be significantly reduced by judicious control of the climatic effects. The built-form and arrangement of openings of a building can be suitably derived from this analysis. For example, in a place like Mumbai, one feels hot and sweaty owing to intense solar radiation accompanied by high humidity. Here, the building design should be such that (a) it is sufficiently shaded to prevent solar radiation from entering the house and, (b) it is ventilated to reduce discomfort due to high humidity. On the other hand, in a place like Shimla, it is necessary to maintain warmth inside the building due to the predominantly cold climate. Climate thus plays a pivotal role in determining the design and construction of a building.

In this chapter, we will review the various aspects of climate and the methods of its analysis. This includes a brief description of the various climatic factors and climatic zones of India. The design requirements of buildings in different climatic zones are discussed and tabulated. Illustrative examples provide information on how to analyse the climatic conditions of a place.

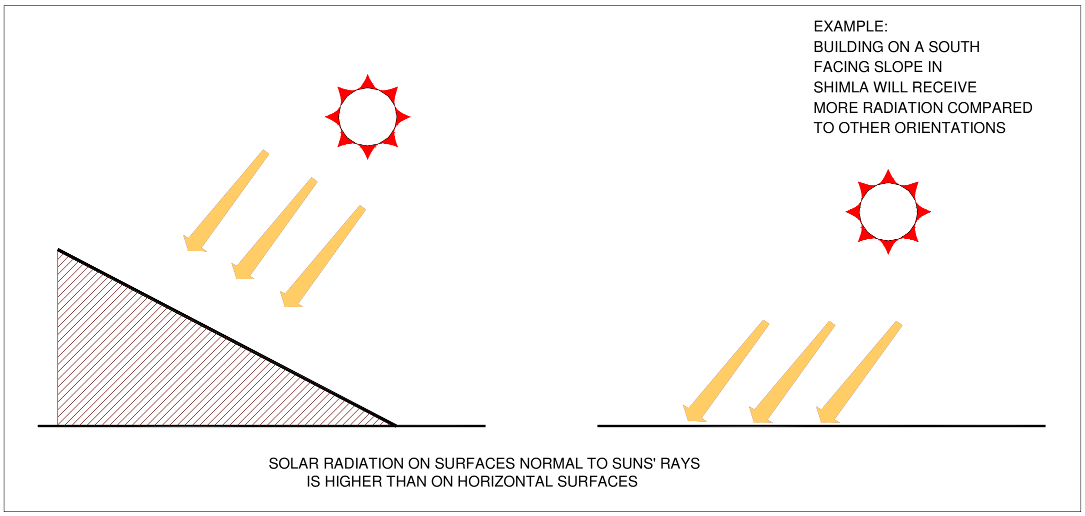
2.2 FACTORS AFFECTING CLIMATE

Both weather and climate are characterised by the certain variables known as climatic factors [1]. They are as follows:

(A) Solar radiation
(B) Ambient temperature
(C) Air humidity
(D) Precipitation
(E) Wind
(F) Sky condition

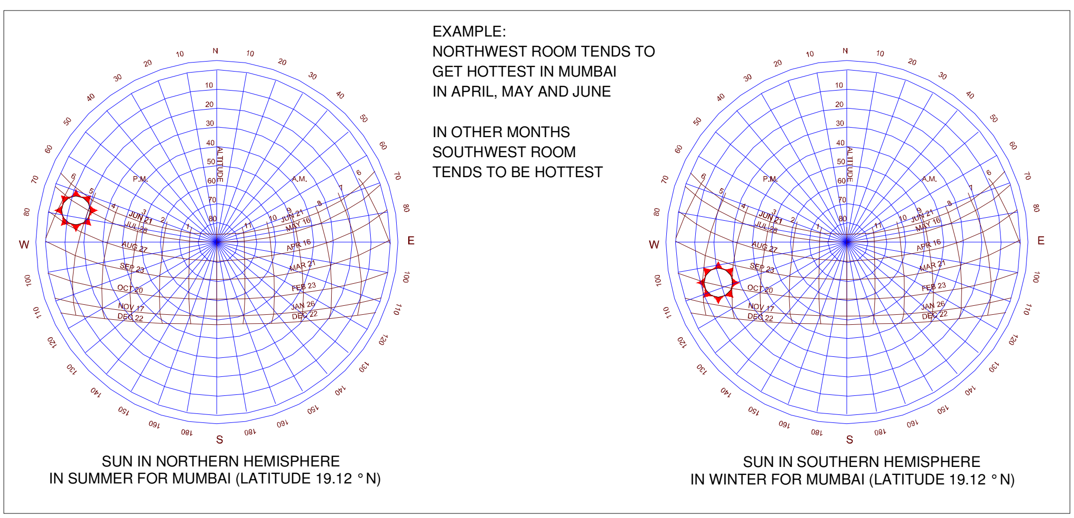
(A) Solar radiation

Solar radiation is the radiant energy received from the sun. It is the intensity of sunrays falling per unit time per unit area and is usually expressed in Watts per square metre (W/m^2). The radiation incident on a surface varies from moment to moment depending on its geographic location (latitude and longitude of the place), orientation, season, time of day and atmospheric conditions (Fig. 2.1). Solar radiation is the most important weather variable that determines whether a place experiences high temperatures or is predominantly cold. The instruments used for measuring of solar radiation are the pyranometer and the pyrheliometer. The duration of sunshine is measured using a sunshine recorder.



EFFECT OF ORIENTATION

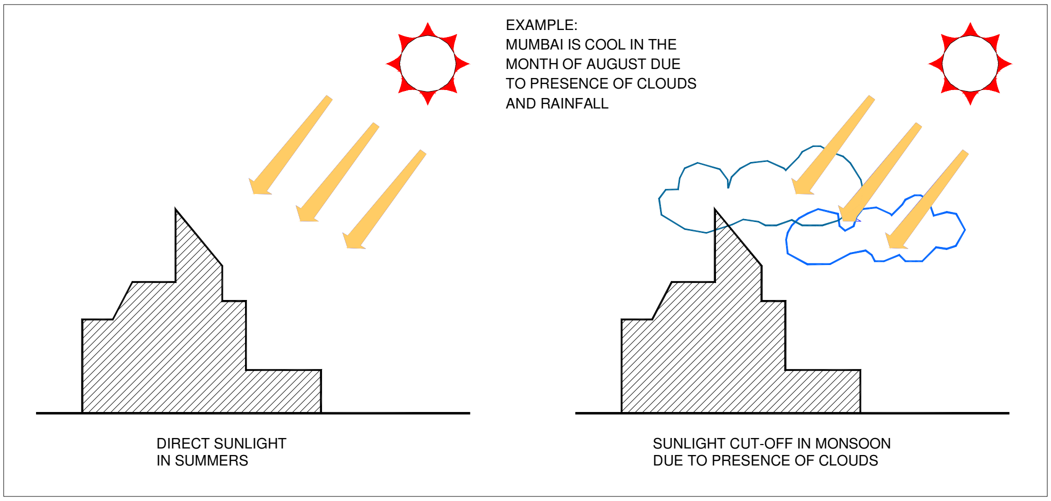
(a)



EFFECT OF SEASON

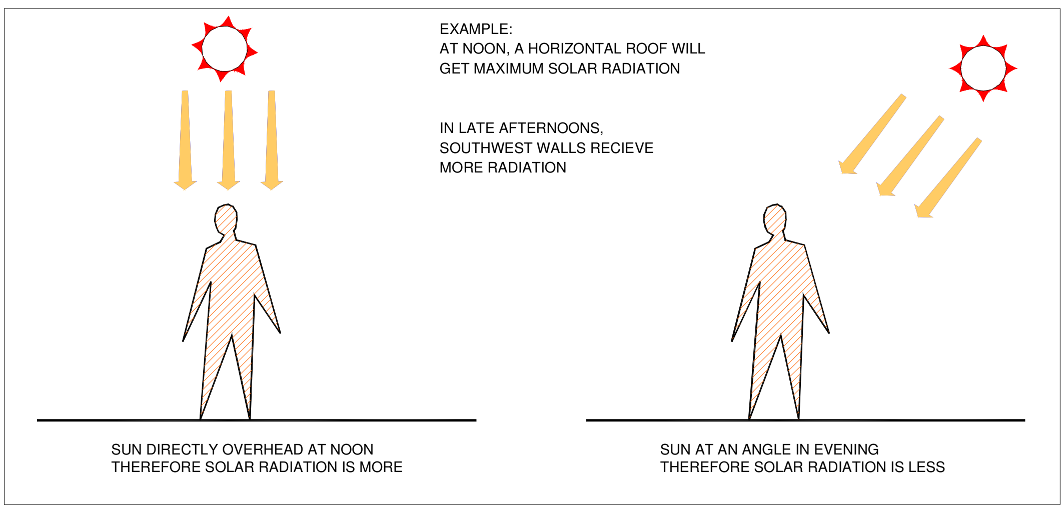
(b)

Fig. 2.1 Factors affecting solar radiation
(a) effect of orientation, (b) effect of season



EFFECT OF SKY COVER

(c)



EFFECT OF TIME

(d)

Fig. 2.1 Factors affecting solar radiation (cont.)
(c) effect of sky cover, (d) effect of time

(B) Ambient temperature

The temperature of air in a shaded (but well ventilated) enclosure is known as the ambient temperature; it is generally expressed in degree Celsius (ºC). Temperature at a given site depends on wind as well as local factors such as shading, presence of water body, sunny condition, etc. When the wind speed is low, local factors strongly influence on temperature of air close to the ground. With higher wind speeds, the temperature of the incoming air is less affected by local factors. The effect of various factors on the ambient temperature is shown in Fig. 2.2. A simple thermometer kept in a Stevenson's screen can measure ambient temperature.

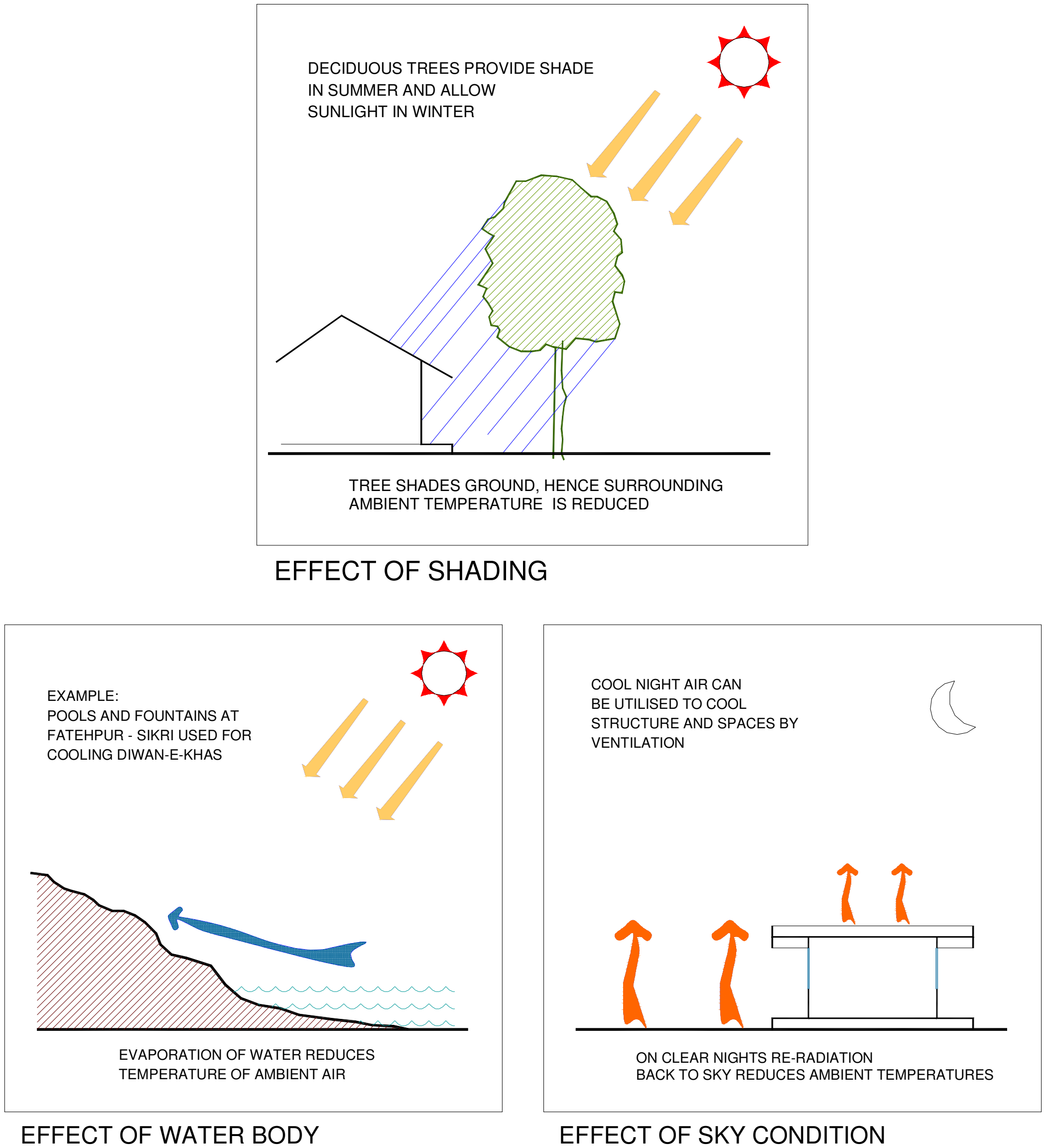


Fig. 2.2 Factors affecting ambient temperature

(C) Air humidity

Air humidity, which represents the amount of moisture present in the air, is usually expressed in terms of 'relative humidity'. Relative humidity is defined as the ratio of the mass of water vapour in a certain volume of moist air at a given temperature, to the mass of water vapour in the same volume of saturated air at the same temperature; it is normally expressed as a percentage. It varies considerably, tending to be the highest close to dawn when the air temperature is at its lowest, and decreasing as the air temperature rises. The decrease in the relative humidity towards midday tends to be the largest in summer. In areas with high humidity levels, the transmission of solar radiation is reduced because of atmospheric absorption and scattering. High humidity reduces evaporation of water and sweat. Consequently, high humidity accompanied by high ambient temperature causes a lot of discomfort. The effects of various combinations of humidity and ambient temperature are presented in Fig. 2.3.

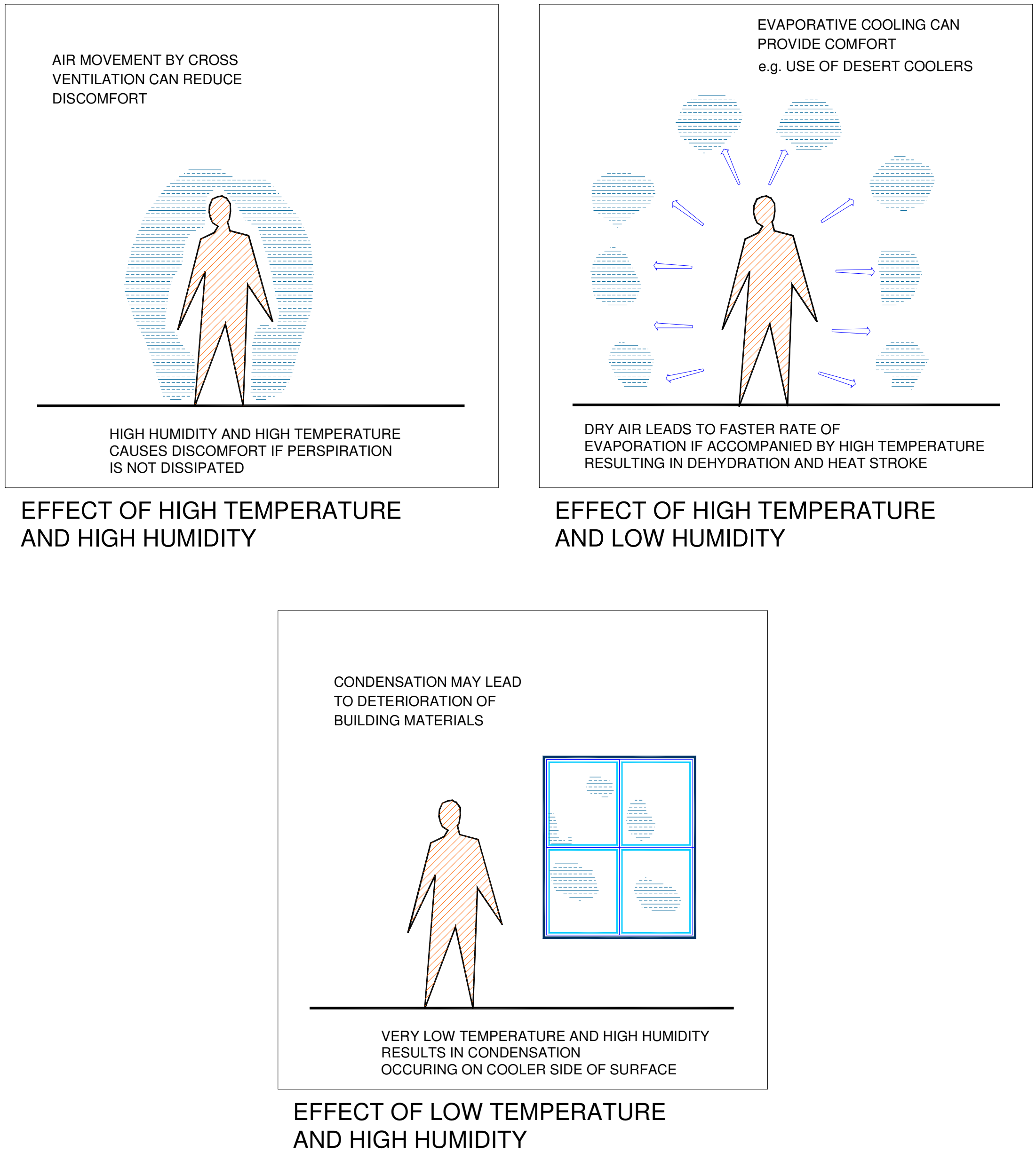


Fig. 2.3 Effects of air humidity

(D) Precipitation

Precipitation includes water in all its forms rain, snow, hail or dew. It is usually measured in millimeters (mm) by using a rain gauge. The effects of precipitation on buildings are illustrated in Fig. 2.4.

(E) Wind

Wind is the movement of air due to a difference in atmospheric pressure, caused by differential heating of land and water mass on the earth's surface by solar radiation and rotation of earth. Wind speed can be measured by an anemometer and is usually expressed in metres per second (m/s). It is a major design consideration for architects because it affects indoor comfort conditions by influencing the convective heat exchanges of a building envelope, as well as causing air infiltration into the building (Fig. 2.5).

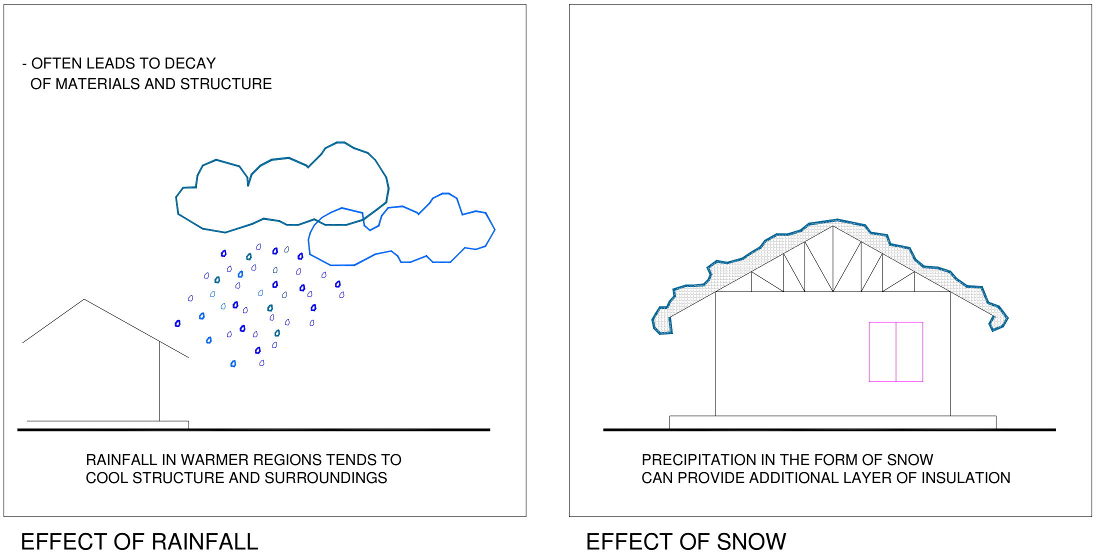


Fig. 2.4 Precipitation

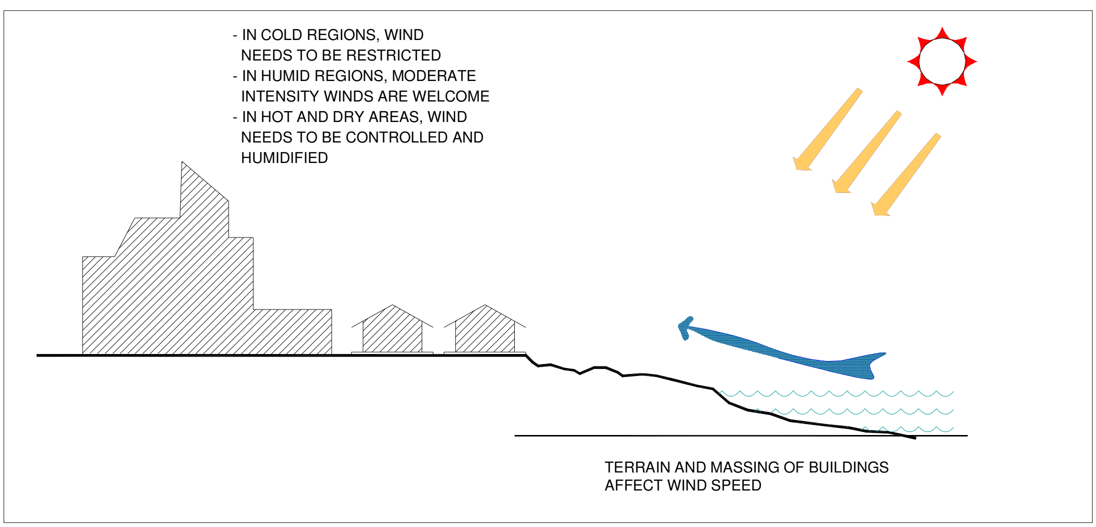


Fig. 2.5 Factors affecting wind

(F) Sky condition

Sky condition generally refers to the extent of cloud cover in the sky or the duration of sunshine. Under clear sky conditions, the intensity of solar radiation increases; whereas it reduces in monsoon due to cloud cover. The re-radiation losses from the external surfaces of buildings increase when facing clear skies than covered skies. This is illustrated in Fig. 2.6. The measurement of sky cover is expressed in oktas. For example, 3 oktas means that 3/8th of the visible sky is covered by clouds.

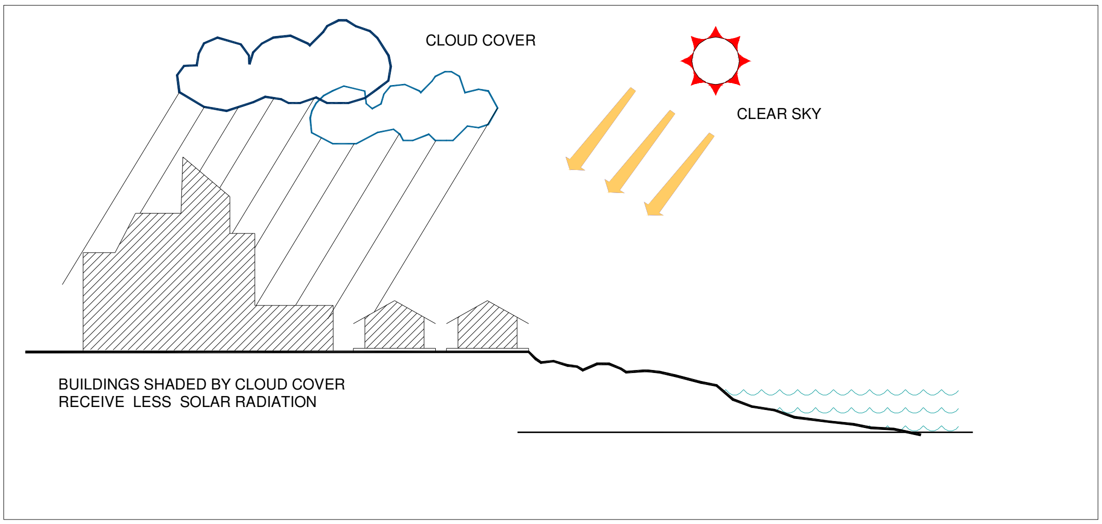


Fig. 2.6 Effect of sky condition

In addition to these factors, a number of natural elements such as hills, valleys, waterbodies, vegetation, etc. affect the climate locally. Buildings, cities and other man-made features also have an impact on the climate. The effects of such features are discussed in the section 2.6 under 'Microclimate'.

2.2.1 Weather Data

The data of all weather variables are recorded at various meteorological stations by the Indian Meteorological Department (IMD), and are also available in a number of books [1-5]. Synthetic data for solar radiation have been generated by ISHRAE [6] as well as Mani and Rangarajan [7]. The distributions of hours of sunshine, global and diffuse solar radiation on an annual basis are presented in Fig. 2.7-2.9 [2]. It can be seen from Fig. 2.7 that Rajasthan, Gujarat, west Madhya Pradesh and north Maharashtra receive more than 3000 to 3200 hours of bright sunshine in a year. Over 2600 to 2800 hours of bright sunshine are available over the rest of the country, except Kerala, the north-eastern states, and Jammu and Kashmir where they are appreciably lower. The corresponding information for different months of the year is also available in the handbook [2]. During monsoon (June – August), a significant decrease in sunshine occurs over the whole country except Jammu and Kashmir where the maximum duration of sunshine occurs in June and July, and minimum in January due to its location. The north-eastern states and south-east peninsula also receive relatively less sunshine during October and November due to the north-east monsoons. As far as the availability of global solar radiation is concerned, more than

2000 kWh/m^2-year are received over Rajasthan and Gujarat, while east Bihar, north West Bengal and the north-eastern states receive less than 1700 kWh/m^2-year (Fig. 2.8). The availability of diffuse solar radiation varies widely in the country (Fig. 2.9). The annual pattern shows a minimum of 740 kWh/m^2-year over Rajasthan increasing eastwards to 840 kWh/m^2-year in the north-eastern states, and south wards to 920 kWh/m^2-year. The monthly availability of global and diffuse solar radiation over entire country is presented in the 'Handbook of solar radiation data for India' by Mani [2].

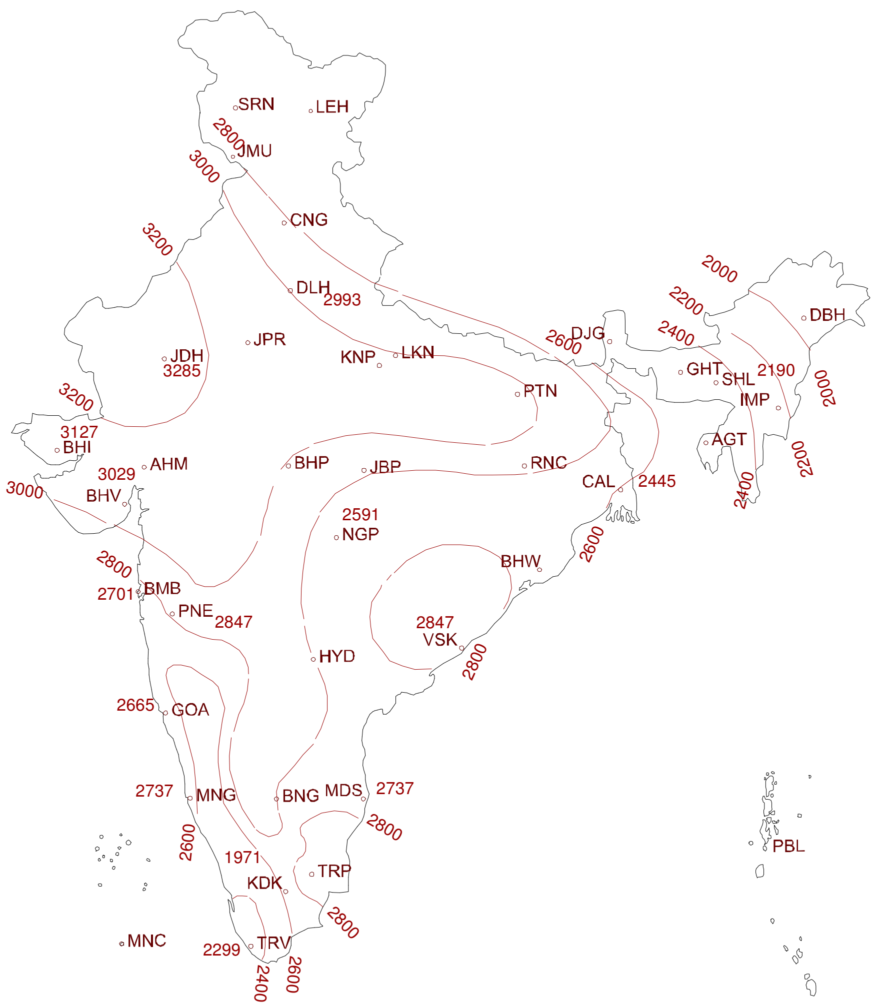


Fig. 2.7 Distribution of annual sunshine hours [2]

The ambient temperature varies across the country. The maps showing the highest maximum and lowest minimum temperature isopleths are shown in Fig. 2.10 and 2.11 [8]. A map showing the average rainfall along with main direction of winds is presented in Fig. 2.12 [8].

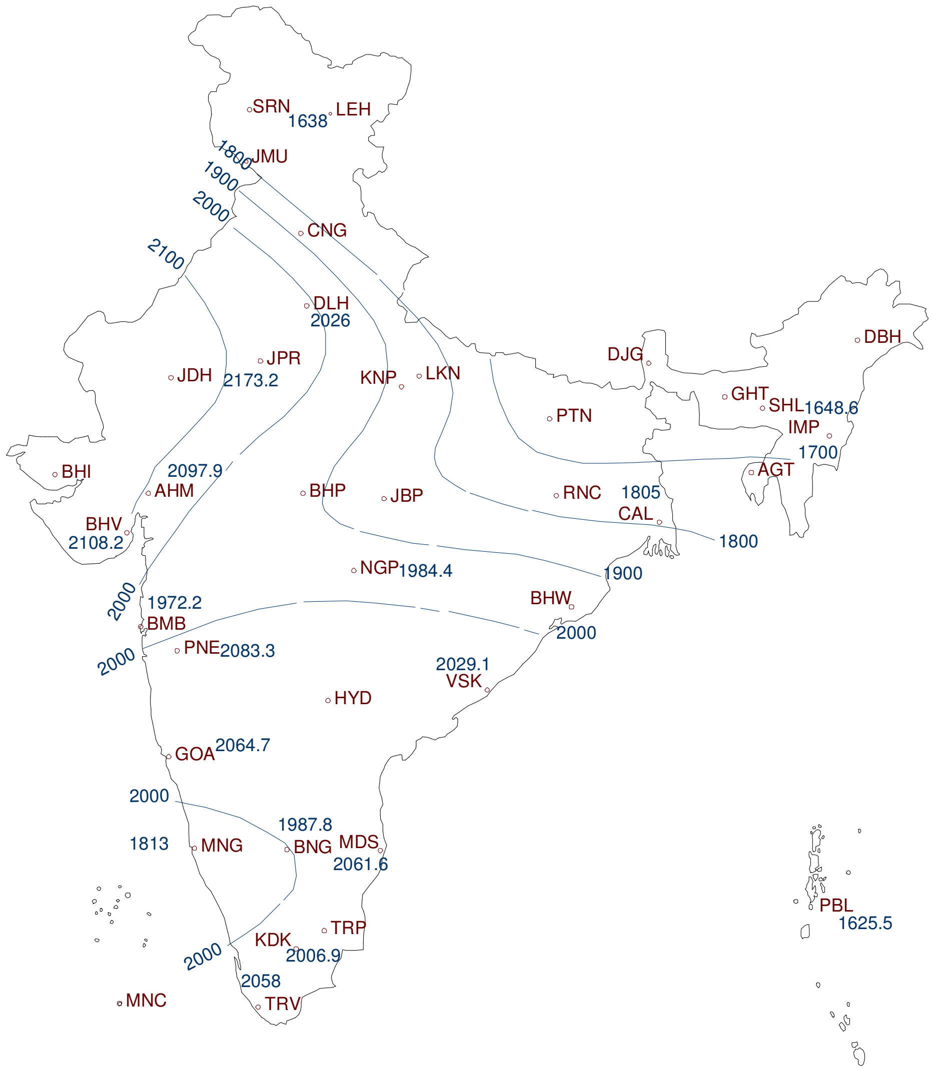


Fig. 2.8 Distribution of annual global solar radiation (kWh/m^2-year) [2]

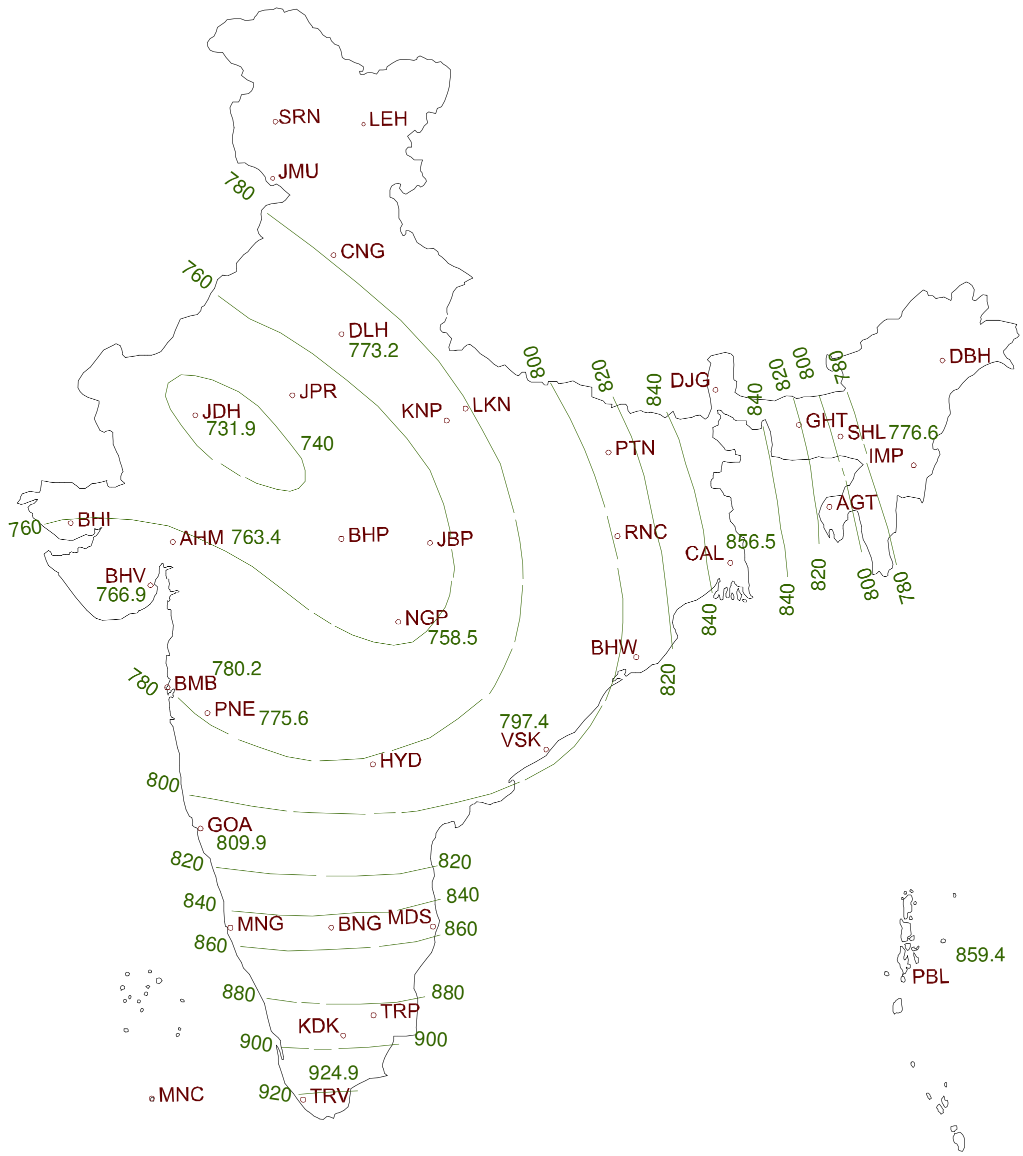


Fig. 2.9 Distribution of annual diffuse solar radiation (kWh/m²-year) [2]

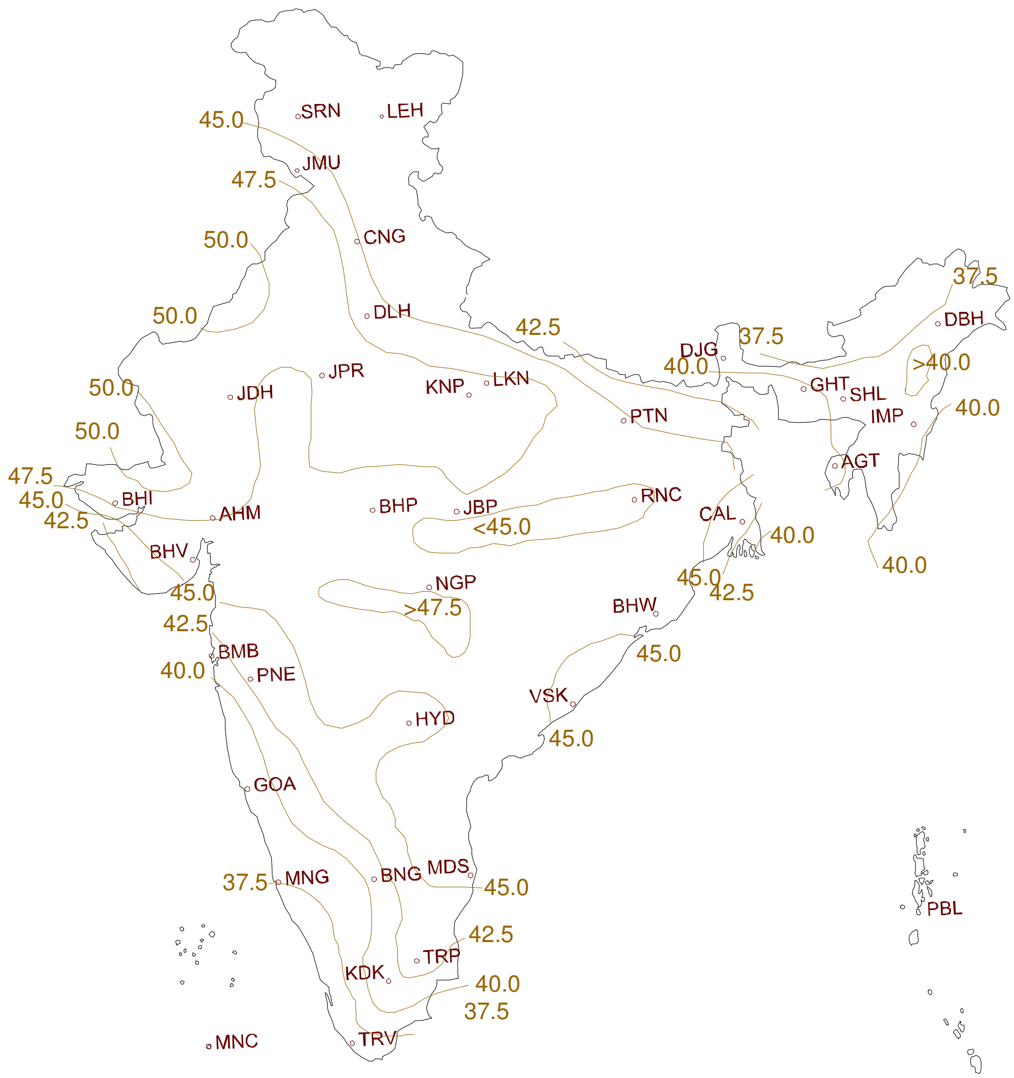


Fig. 2.10 Maximum temperature isopleths [8]

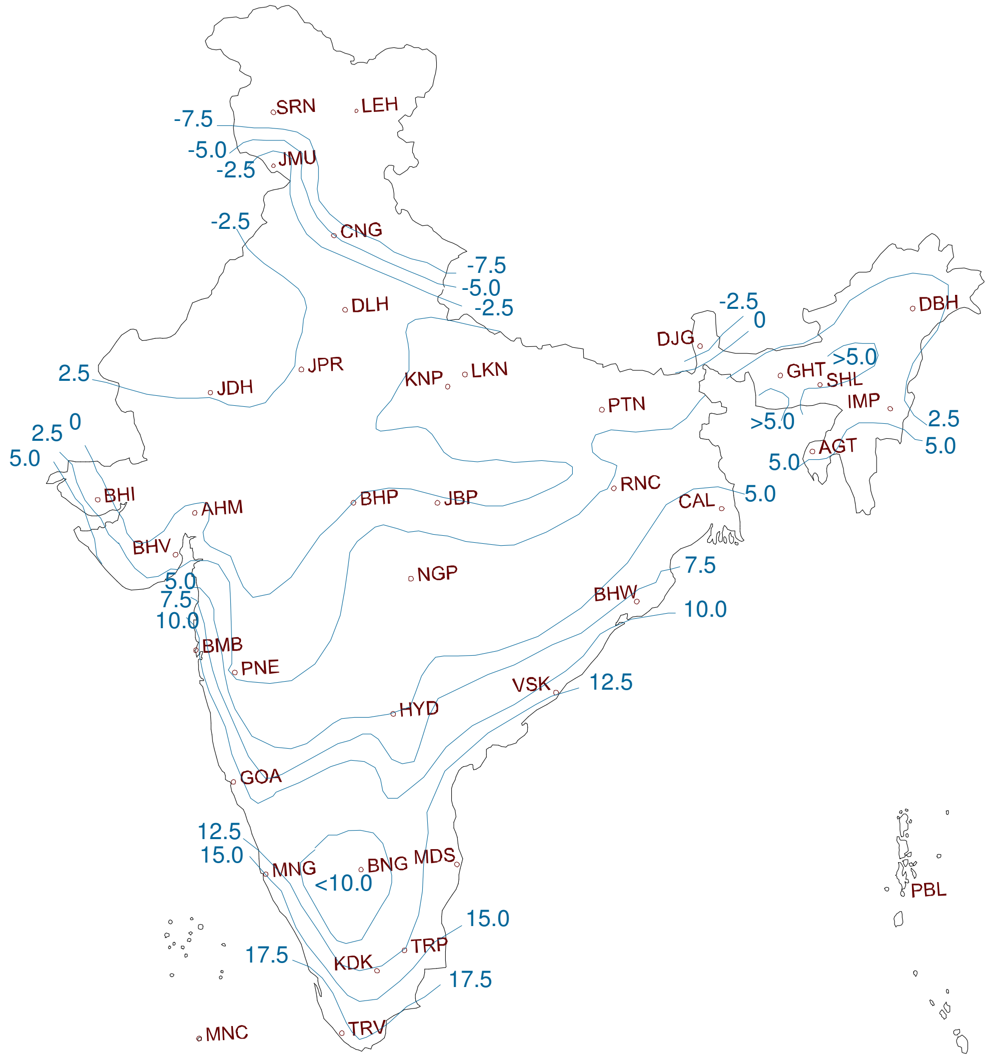


Fig. 2.11 Minimum temperature isopleths [8]

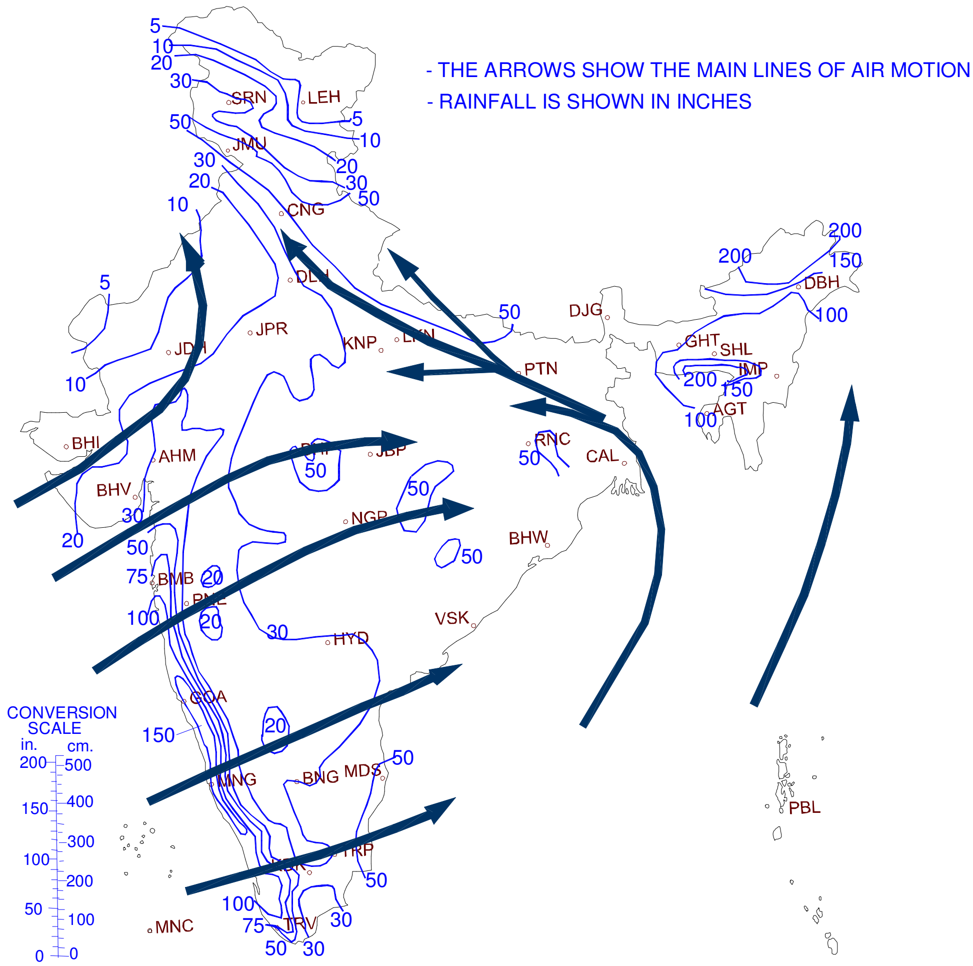


Fig. 2.12 Average rainfall and main wind direction [8]

2.3 CLIMATIC ZONES AND THEIR CHARACTERISTICS

Regions having similar characteristic features of climate are grouped under one climatic zone. Based on the climatic factors discussed in the previous section, the country can be divided into a number of climatic zones. Bansal et al. [1] had carried out detailed studies and reported that India can be divided into six climatic zones, namely, hot and dry, warm and humid, moderate, cold and cloudy, cold and sunny, and composite. The criteria of classification are presented in Table 2.1 and Fig. 2.13(a) shows the climatic zones. A place is assigned to one of the first five climatic zones only when the defined conditions prevail there for more than six months. In cases where none of the defined categories can be identified for six months or longer, the climatic zone is called composite [1]. According to a recent code of Bureau of Indian Standards [9], the country may be divided into five major climatic zones. Table 2.1 presents the criteria of this classification as well; Fig. 2.13(b) shows the corresponding climatic classification map of India. It is seen that the recent classification is not very different from the earlier one except that the cold and cloudy, and cold and sunny have been grouped together as cold climate; the moderate climate is renamed as temperate climate. However, a small variation is noticed as far as the land area of the country corresponding to different zones is concerned (Fig. 2.13(a) and (b)). In this book, we have followed the former classification. It may be mentioned that each climatic zone does not experience the same climate for the whole year. It has a particular season for more than six months and may experience other seasons for the remaining period.

Table 2.1 Classification of Climates

Criteria of Bansal et al. [1]			Criteria of SP 7: 2005 [9]		
Climate	**Mean monthly temperature (°C)**	**Relative humidity (%)**	**Climate**	**Mean monthly maximum temperature(°C)**	**Relative humidity (%)**
Hot and dry	>30	<55	Hot and dry	>30	<55
Warm and humid	>30	>55	Warm and humid	>30 >25	>55 >75
Moderate	25-30	<75	Temperate	25-30	<75
Cold and cloudy	<25	>55	Cold	<25	All values
Cold and sunny	<25	<55			
Composite	This applies, when six months or more do not fall within any of the above categories		Composite	This applies, when six months or more do not fall within any of the above categories	

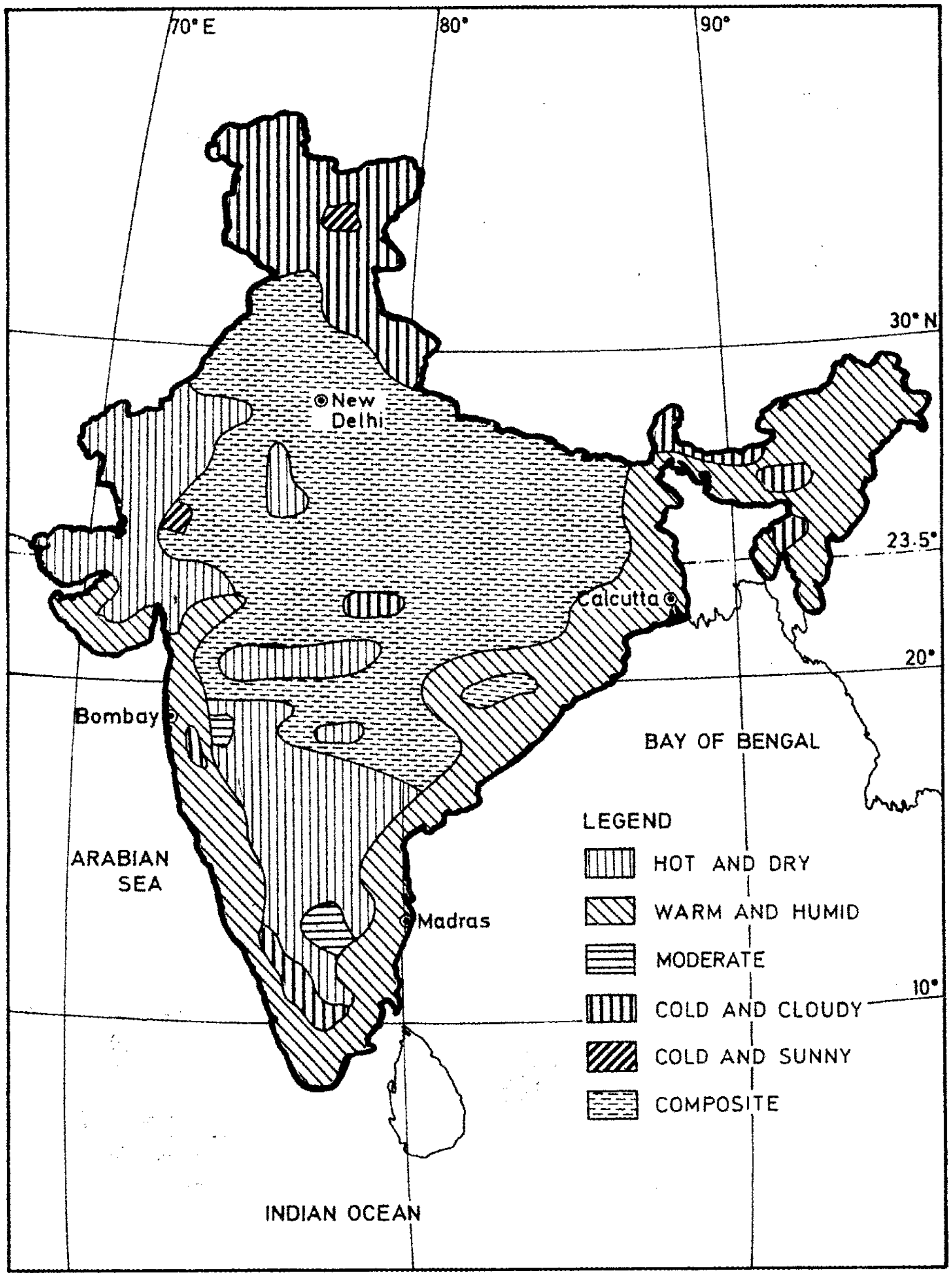


Fig. 2.13a Climatic zones of India [1]

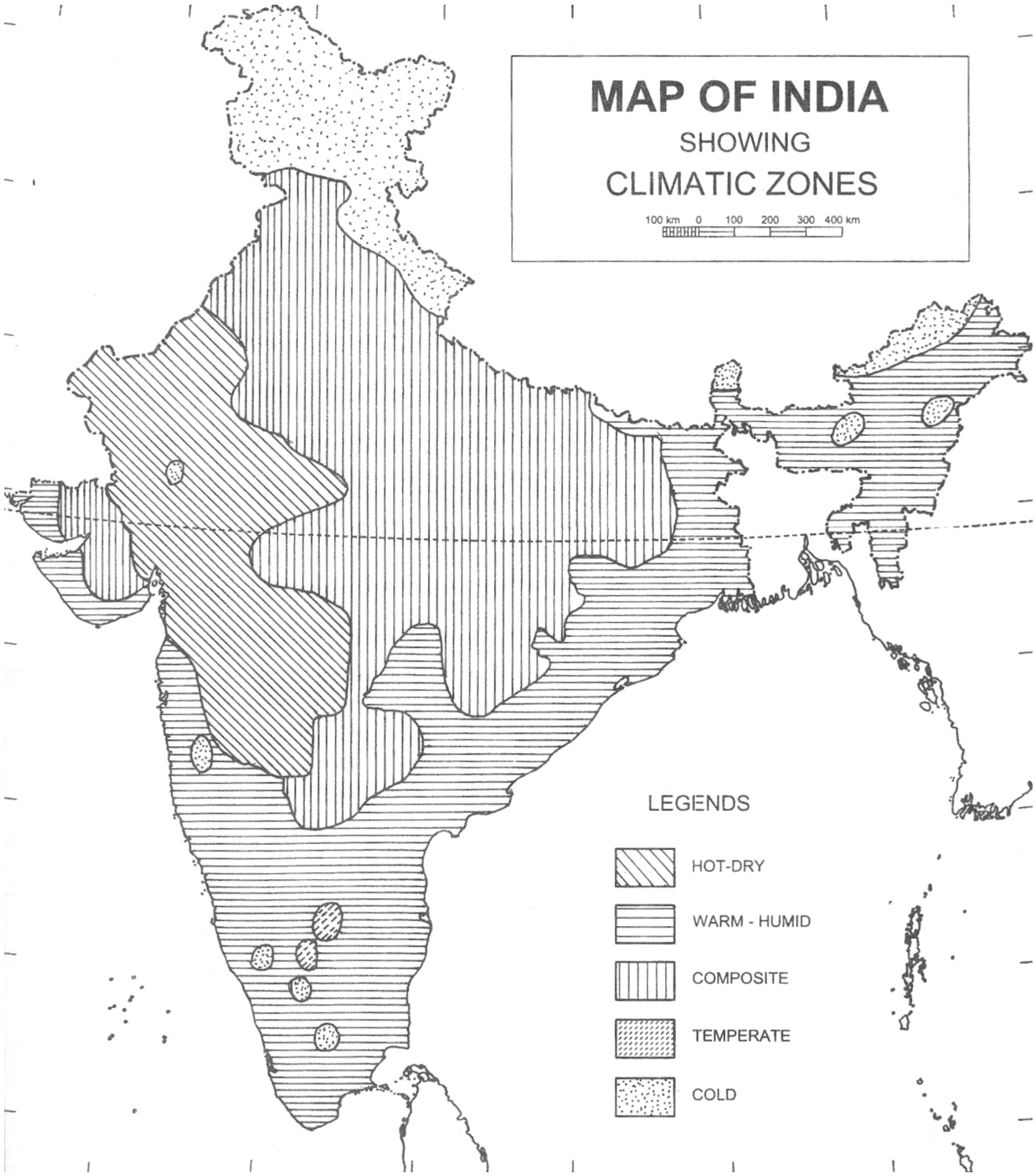


Fig. 2.13b Climatic zones of India [9]

The characteristic features of each climate are described briefly in the following subsections.

2.3.1 Hot and Dry

The hot and dry zone lies in the western and the central part of India; Jaisalmer, Jodhpur and Sholapur are some of the towns that experience this type of climate.

A typical hot and dry region is usually flat with sandy or rocky ground conditions, and sparse vegetation comprising cacti, thorny trees and bushes. There are few sources of water on the surface, and the underground water level is also very low. Due to intense solar radiation (values as high as 800-950 W/m^2), the ground and the surroundings of this region are heated up very quickly during day time. In summer, the maximum ambient temperatures are as high as 40–45 ºC during the day, and 20–30 ºC at night. In winter, the values are between 5 and 25 ºC during the day and 0 to 10 ºC at night. It may be noted that the diurnal variation in temperature is quite high, that is, more than 10 ºC.

The climate is described as dry because the relative humidity is generally very low, ranging from 25 to 40 % due to low vegetation and surface water bodies. Moreover, the hot and dry regions receive less rainfall- the annual precipitation being less than 500 mm.

Hot winds blow during the day in summers and sand storms are also experienced. The night is usually cool and pleasant. A generally clear sky, with high solar radiation causing an uncomfortable glare, is typical of this zone. As the sky is clear at night, the heat absorbed by the ground during the day is quickly dissipated to the atmosphere. Hence, the air is much cooler at night than during the day.

In such a climate, it is imperative to control solar radiation and movement of hot winds. The design criteria should therefore aim at resisting heat gain by providing shading, reducing exposed area, controlling and scheduling ventilation, and increasing thermal capacity. The presence of "water bodies" is desirable as they can help increase the humidity, thereby leading to lower air temperatures. The ground and surrounding objects emit a lot of heat in the afternoons and evenings. As far as possible, this heat should be avoided by appropriate design features.

2.3.2 Warm and Humid

The warm and humid zone covers the coastal parts of the country. Some cities that fall under this zone are Mumbai, Chennai and Kolkata. The high humidity encourages abundant vegetation in these regions.

The diffuse fraction of solar radiation is quite high due to cloud cover, and the radiation can be intense on clear days. The dissipation of the accumulated heat from the earth to the night sky is generally marginal due to the presence of clouds. Hence, the diurnal variation in temperature is quite low. In summer, temperatures can reach as high as 30 – 35 ºC during the day, and 25 – 30 ºC at night. In winter, the maximum temperature is between 25 to 30 ºC during the day and 20 to 25 ºC at night. Although the temperatures are not excessive, the high humidity causes discomfort.

An important characteristic of this region is the relative humidity, which is generally very high, about 70 – 90 % throughout the year. Precipitation is also high, being about 1200 mm per year, or even more. Hence, the provision for quick drainage of water is essential in this zone.

The wind is generally from one or two prevailing directions with speeds ranging from extremely low to very high. Wind is desirable in this climate, as it can cause sensible cooling of the body.

The main design criteria in the warm and humid region are to reduce heat gain by providing shading, and promote heat loss by maximising cross ventilation. Dissipation of humidity is also essential to reduce discomfort.

2.3.3 Moderate

Pune and Bangalore are examples of cities that fall under this climatic zone. Areas having a moderate climate are generally located on hilly or high-plateau regions with fairly abundant vegetation.

The solar radiation in this region is more or less the same throughout the year. Being located at relatively higher elevations, these places experience lower temperatures than hot and dry regions. The temperatures are neither too hot nor too cold. In summers, the temperature reaches 30 – 34 ºC during the day and 17 – 24 ºC at night. In winter, the maximum temperature is between 27 to 33 ºC during the day and 16 to 18 ºC at night.

The relative humidity is low in winters and summers, varying from 20 – 55%, and going upto 55 – 90% during monsoons. The total rainfall usually exceeds 1000 mm per year. Winters are dry in this zone. Winds are generally high during summer. Their speed and direction depend mainly upon the topography. The sky is mostly clear with occasional presence of low, dense clouds during summers.

The design criteria in the moderate zone are to reduce heat gain by providing shading, and to promote heat loss by ventilation.

2.3.4 Composite

The composite zone covers the central part of India. Some cities that experience this type of climate are New Delhi, Kanpur and Allahabad. A variable landscape and seasonal vegetation characterise this zone. The intensity of solar radiation is very high in summer with diffuse radiation amounting to a small fraction of the total. In monsoons, the intensity is low with predominantly diffuse radiation. The maximum daytime temperature in summers is in the range of 32 – 43 ºC, and night time values are from 27 to 32 ºC. In winter, the values are between 10 to 25 ºC during the day and 4 to 10 ºC at night.

The relative humidity is about 20 – 25 % in dry periods and 55 – 95 % in wet periods. The presence of high humidity during monsoon months is one of the reasons why places like New Delhi and Nagpur are grouped under the composite and not hot and dry climate. Precipitation in this zone varies between 500 – 1300 mm per year. This region receives strong winds during monsoons from the south-east and dry cold winds from the north-east. In summer, the winds are hot and dusty. The sky is overcast and dull in the monsoon, clear in winter and frequently hazy in summer.

Generally, composite regions experience higher humidity levels during monsoons than hot and dry zones. Otherwise most of their characteristics are similar to the latter. Thus, the design criteria are more or less the same as for hot and dry climate except that maximising cross ventilation is desirable in the monsoon period.

2.3.5 Cold and Cloudy

Generally, the northern part of India experiences this type of climate. Most cold and cloudy regions are situated at high altitudes. Ootacamund, Shimla, Shillong, Srinagar and Mahabaleshwar are examples of places belonging to this climatic zone. These are generally highland regions having abundant vegetation in summer.

The intensity of solar radiation is low in winter with a high percentage of diffuse radiation. Hence, winters are extremely cold. In summer, the maximum ambient temperature is in the range of 20 – 30 ºC during the day and 17 – 27 ºC at night, making summers quite pleasant. In winter, the values range between 4 and 8 ºC during the day and from -3 to 4 ºC at night, making it quite chilly.

The relative humidity is generally high and ranges from 70 – 80 %. Annual total precipitation is about 1000 mm and is distributed evenly throughout the year. This region experiences cold winds in the winter season. Hence, protection from winds is essential in this type of climate. The sky is overcast for most part of the year except during the brief summer.

Conditions in summer are usually clear and pleasant, but owing to cold winters, the main criteria for design in the cold and cloudy region aim at resisting heat loss by insulation and infiltration, and promoting heat gain by directly admitting and trapping solar radiation within the living space.

2.3.6 Cold and Sunny

The cold and sunny type of climate is experienced in Leh (Ladakh). The region is mountainous, has little vegetation, and is considered to be a cold desert.

The solar radiation is generally intense with a very low percentage of diffuse radiation. In summer, the temperature reaches 17 – 24 ºC during the day and 4 – 11 ºC at night. In winter, the values range from -7 to 8 ºC during the day and -14 to 0 ºC at night. Winters thus, are extremely cold. The relative humidity is consistently low ranging from about 10 – 50 % and precipitation is generally less than 200 mm per year. Winds are occasionally intense. The sky is fairly clear throughout the year with a cloud cover of less than 50%.

As this region experiences cold desert climatic conditions, the design criteria are to resist heat loss by insulation and controlling infiltration. Simultaneously, heat gain needs to be promoted by admitting and trapping solar radiation within the living space.

2.4 IMPLICATIONS OF CLIMATE ON BUILDING DESIGN

The characteristics of each climate differ and accordingly the comfort requirements vary from one climatic zone to another. Before proceeding further, it would be useful to define comfort and the conditions that affect it. According to ASHRAE [10], thermal comfort is, "that condition of mind which expresses satisfaction with the thermal environment". It is also, "the range of climatic conditions within which a majority of the people would not feel discomfort either of heat or cold". Such a zone in still air corresponds to a range of 20 – 30 ºC dry bulb temperature with 30 – 60 % relative humidity. Besides, various climatic elements such as wind speed, vapour pressure and radiation also affect the comfort conditions.

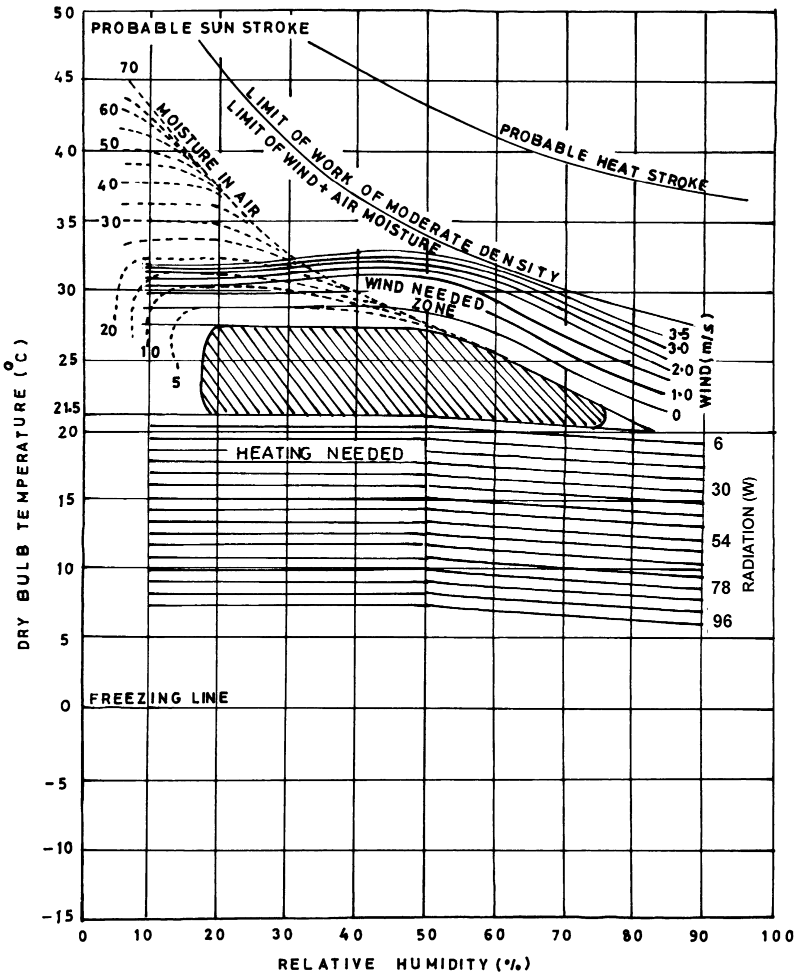


Fig. 2.14 Bio-climatic chart

Figure 2.14 illustrates a 'Comfort Zone' on a bio-climatic chart [11] – a simple tool for analysing the climate of a particular place. It indicates the zones of human comfort based on ambient temperature and humidity, mean radiant temperature, wind speed, solar radiation and evaporative cooling. On the chart, dry bulb temperature is used as the ordinate, and relative humidity as the abscissa. Based on the dry bulb temperature and humidity of a place, one can locate a point on the chart. If it lies within the comfort zone, then the conditions are comfortable. In case it is above the zone, cooling is required; if it is below the zone, heating is needed. If the point is higher than the upper perimeter of the comfort zone, air movement needs to be increased. For conditions when the temperature is high and relative humidity is low, air movement will not help. On the other hand, evaporative cooling is desirable. If the point lies below the lower perimeter of the comfort zone, heating is necessary to counteract low dry-bulb temperature. If the point lies to the left of the comfort zone, either radiant heating or cooling is necessary. Thus, a bio-climatic chart can give ready information about the requirements of comfort at a particular time. Design decisions can be taken accordingly.

Based on the characteristics of climate, the comfort requirements for each climatic zone are presented in Table 2.2. The corresponding physical manifestations are also mentioned in the table.

Table 2.2 Comfort requirements and physical manifestation

1)Hot and Dry Region

OBJECTIVES	PHYSICAL MANIFESTATION
1)Resist heat gain	
• Decrease exposed surface area	Orientation and shape of building
• Increase thermal resistance	Insulation of building envelope
• Increase thermal capacity (Time lag)	Massive structure
• Increase buffer spaces	Air locks/ lobbies/balconies/verandahs
• Decrease air exchange rate (ventilation during day-time)	Weather stripping and scheduling air changes
• Increase shading	External surfaces protected by overhangs, fins and trees
• Increase surface reflectivity	Pale colour, glazed china mosaic tiles etc.
2)Promote heat loss	
• Ventilation of appliances	Provide windows/ exhausts
• Increase air exchange rate (Ventilation during night-time)	Courtyards/ wind towers/ arrangement of openings
• Increase humidity levels	Trees, water ponds, evaporative cooling

2)Warm and Humid Region

OBJECTIVES	PHYSICAL MANIFESTATION
1)Resist heat gain	
• Decrease exposed surface area	Orientation and shape of building
• Increase thermal resistance	Roof insulation and wall insulation. Reflective surface of roof.
• Increase buffer spaces	Balconies and verandahs
• Increase shading	Walls, glass surfaces protected by overhangs, fins and trees
• Increase surface reflectivity	Pale colour, glazed china mosaic tiles, etc.
2)Promote heat loss	
• Ventilation of appliances	Provide windows/ exhausts
• Increase air exchange rate (Ventilation throughout the day)	Ventilated roof construction. Courtyards, wind towers and arrangement of openings
• Decrease humidity levels	Dehumidifiers/ desiccant cooling

3)Moderate Region

OBJECTIVES	PHYSICAL MANIFESTATION
1)Resist heat gain	
• Decrease exposed surface area	Orientation and shape of building
• Increase thermal resistance	Roof insulation and east and west wall insulation
• Increase shading	East and west walls, glass surfaces protected by overhangs, fins and trees
• Increase surface reflectivity	Pale colour, glazed china mosaic tiles, etc.
2)Promote heat loss	
• Ventilation of appliances	Provide windows/ exhausts
• Increase air exchange rate (Ventilation)	Courtyards and arrangement of openings

4)Cold and Cloudy Region (Applies for Cold and Sunny also)

OBJECTIVES	PHYSICAL MANIFESTATION
1)Resist heat loss	
• Decrease exposed surface area	Orientation and shape of building. Use of trees as wind barriers
• Increase thermal resistance	Roof insulation, wall insulation and double glazing
• Increase thermal capacity (Time lag)	Thicker walls
• Increase buffer spaces	Air locks/ Lobbies
• Decrease air exchange rate	Weather stripping
• Increase surface absorptivity	Darker colours
2)Promote heat gain	
• Reduce shading	Walls and glass surfaces
• Utilise heat from appliances	
• Trapping heat	Sun spaces/ green houses/ Trombe walls etc.

5)Composite Region

OBJECTIVES	PHYSICAL MANIFESTATION
1)Resist heat gain in summer and Resist heat loss in winter	
• Decrease exposed surface area	Orientation and shape of building. Use of trees as wind barriers
• Increase thermal resistance	Roof insulation and wall insulation
• Increase thermal capacity (Time lag)	Thicker walls
• Increase buffer spaces	Air locks/ Balconies
• Decrease air exchange rate	Weather stripping
• Increase shading	Walls, glass surfaces protected by overhangs, fins and trees
• Increase surface reflectivity	Pale colour, glazed china mosaic tiles, etc.
2)Promote heat loss in summer/ monsoon	
• Ventilation of appliances	Provide exhausts
• Increase air exchange rate (Ventilation)	Courtyards/ wind towers/ arrangement of openings
• Increase humidity levels in dry summer	Trees and water ponds for evaporative cooling
• Decrease humidity in monsoon	Dehumidifiers/ desiccant cooling

2.5 URBAN CLIMATE

The air temperatures in densely built urban areas are often higher than the temperatures of the surrounding countryside. This is due to rapid urbanisation and industrialisation. The term "urban heat island" refers to increased surface temperatures in some pockets of a city, caused by an ever changing microclimate. The difference between the maximum city temperature (measured at the city centre) and the surrounding countryside is the urban heat-island intensity. An urban heat island study was carried out in Pune, Mumbai, Kolkata, Delhi, Vishakapatnam, Vijayawada, Bhopal and Chennai [12,13]; the heat-island intensities of these cities are presented in Table 2.3. It is seen that, among the cities listed in the table, the heat island intensity is greatest in Pune (about 10 °C) and lowest in Vishakhapatnam (about 0.6°C). In the metropolitan cities of Mumbai, New Delhi, Chennai and Kolkata, the corresponding values are 9.5, 6.0, 4.0 and 4.0^{o}C respectively. Clearly, the values are quite high. The density of the built environment and the extent of tree cover or vegetation primarily affect the heat-island intensity. Pollution and heat due to vehicular traffic, industrialisation and human activities are other contributing factors.

Table 2.3 Heat island intensities in some Indian cities [12,13]

Station	Heat Island Intensity (^{o}C)
New Delhi	6.0
Bhopal	6.5
Kolkata	4.0
Mumbai	9.5
Pune	10.0
Vishakhapatnam	0.6
Vijayawada	2.0
Chennai	4.0

Normally, the central business district (CBD) or the centre of a city experiences higher temperatures than the other parts. This is because the CBD mainly consists of concrete buildings and asphalted roads, which heat up very quickly due to radiation from the sun. Most of this heat is stored and released very slowly, sometimes even upto the night. This phenomenon does not allow the daily minimum temperature to become too low. Though it may be a welcome phenomenon in cold regions during winters, it makes life unbearable for people in the hot regions. Thus, in tropical climates, the provision of sufficient ventilation and spacing between buildings is required to allow the accumulated heat to escape to the atmosphere easily.

Street patterns and urban blocks can be oriented and sized to incorporate concerns of light, sun, and shade according to the dictates of the climate. For example, the densely built areas produce, store and retain more heat than low-density areas. Thus, the temperature differential between urban areas and the surrounding countryside increases as the surrounding areas cool at night. As a result, cooler air from the surrounding countryside flows towards the centre. This kind of circulation is more pronounced on calm summer nights and can be utilised to flush dense areas of heat and pollutants. To achieve cool air movement, a belt of undeveloped and preferably vegetated land at the perimeter of the city, can be provided to serve as a cool air source. Radial street patterns can also be designed for facilitating movement of air from less dense to more dense areas.

A system of linear greenways or boulevards converging towards the city centre will help to maintain the movement of cool air. Provided the soil is adequately moist, a single isolated tree may transpire upto 400 litres of water per day. This transpiration together with the shading of solar radiation, creates a cooler environment around the tree. On a hot summer day, the temperature can drop significantly under trees due to cool breezes produced by convective currents and by shading from direct sunlight. Planted areas can be as much as 5– 8 ^{o}C cooler than built-up areas due to a combination of evapotranspiration, reflection, shading, and storage of cold.

Local wind patterns are created when the warm air over a dense built up area rises, and is replaced by cooler air from vegetated areas. Having many evenly distributed small open spaces will produce a greater cooling effect than a few large parks. Studies suggest that for a city with a population of about one million, 10-20% of the city area should be covered by vegetation for effectively lowering local temperatures. As the vegetation cover in the city increases from 20 to 50%, the minimum air temperature decreases by 3-4 ^{o}C, and the maximum temperature decreases by about 5 ^{o}C [14]. Figure 2.15 illustrates the temperature drop as a function of tree cover in the city of Montreal. Similar findings were reported in another study conducted in Sacramento, Phoenix, USA [14].

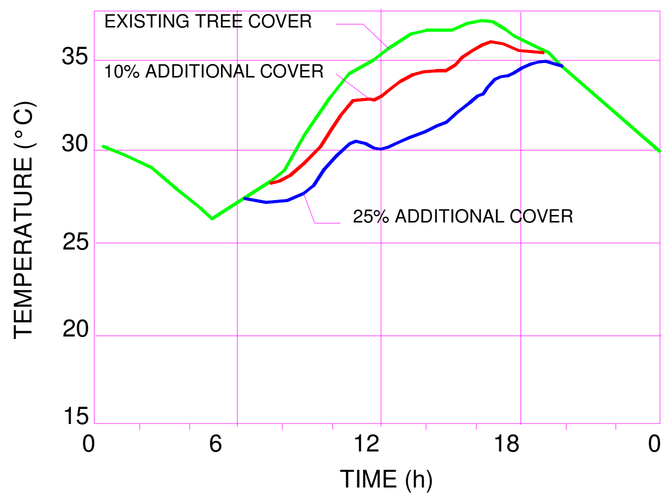


Fig. 2.15 Cooling due to tree cover [14]

The heat released from combustion of fuels and from human activities, adds to the ambient temperature of the city. Air pollution, caused mainly by emissions from vehicles and industries, reduces the longwave radiation back to the sky thereby making the nights are warmer. Global solar radiation during daytime is also reduced due to increased scattering and absorption by polluted air (this can be upto 10-20% in industrial cities). Pollution also affects visibility, rainfall and cloud cover. Effective land use to decongest cities, and the provision of proper vegetation would mitigate the effects of pollution. It is also important to use cleaner fuels and more efficient vehicles.

Meteorological studies and remote sensing by satellites can be used to ascertain drastic changes in the climate, land use and tree cover patterns. Remote sensing can also be used to map hot and cool areas across a city by using GIS tools (Geographical Information System). Such mapping can help to reduce unplanned growth of a city, in preparing a proper land use plan, and to identify future vulnerable areas (those devoid of natural vegetation, parks and water bodies). These measures would certainly help in reducing urban heat island intensity.

2.6 MICROCLIMATE

The conditions for transfer of energy through the building fabric and for determining the thermal response of people are local and site-specific. These conditions are generally grouped under the term of 'microclimate', which includes wind, radiation, temperature, and humidity experienced around a building. A building by its very presence will change the microclimate by causing a bluff obstruction to the wind flow, and by casting shadows on the ground and on other buildings. A designer has to predict this variation and appropriately account for its effect in the design.

The microclimate of a site is affected by the following factors [15,16]:

(A) landform
(B) vegetation
(C) waterbodies
(D) street width and orientation
(E) open spaces and built form

An understanding of these factors greatly helps in the preparation of the site layout plan. For example, in a hot and dry climate, the building needs to be located close to a waterbody. The waterbody helps in increasing the humidity and lowering the temperature by evaporative cooling.

(A) Landform

Landform represents the topography of a site. It may be flat, undulating or sloping. Major landforms affecting a site are mountains, valleys and plains. Depending on the macroclimate and season, some locations within a particular landform experience a better microclimate than others.

In valleys, the hot air (being lighter) rises while cooler air having higher density, settles into the depressions, resulting in a lower temperature at the bottom. Upward currents form on sunny slopes in the morning. By night, the airflow reverses because cold ground surfaces cool the surrounding air, making it heavier and causing it to flow down the valley. Moreover, the wind flow is higher along the direction of the valley than across it due to unrestricted movement. On mountain slopes, the air speed increases as it moves up the windward side, reaching a maximum at the crest and a minimum on the leeward side. The difference in air speed is caused due to the low pressure area developed on the leeward side.

Temperature also varies with elevation. The cooling rate is about 0.8^0C for every 100m of elevation [14]. Air moving down the slope will thus be cooler than the air it replaces lower down, and vice versa. Further, the orientation of the slope also plays a part in determining the amount of solar radiation incident on the site. For example a south-facing slope will get more exposure than a north-facing one in the northern hemisphere. Studies conducted in Mardin, Turkey showed that building groups located on a south facing slope in the city needed approximately 50% less heat to maintain the same indoor temperature as buildings located on the plain land [14].

Careful positioning of a building with respect to landform can thus help in achieving comfort.

(B) Waterbodies

Waterbodies can be in the form of sea, lake, river, pond or fountains. Since water has a relatively high latent heat of vapourisation, it absorbs a large amount of heat from the surrounding air for evaporation. The cooled air can then be introduced in the building. Evaporation of water also raises the humidity level. This is particularly useful in hot and dry climates. Since water has a high specific heat, it provides an ideal medium for storage of heat that can be used for heating purposes.

Large waterbodies tend to reduce the difference between day and night temperatures because they act as heat sinks. Thus, sites near oceans and large lakes have less temperature variation between day and night, as well as between summer and winter as compared to inland sites. Also, the maximum temperature in summer is lower near water than on inland sites.

The wind flow pattern at a site is influenced by the presence of a large waterbody in the following way. Wind flow is generated due to the difference in the heat storing capacity of water and land, and the consequent temperature differentials. During the day, the land heats up faster than the water, causing the air over the land to rise and be replaced by cool air from water. Hence, the breeze blows towards the land from water during the day and in the reverse direction at night. (as land cools more rapidly than water).

Evaporative cooling can help to maintain comfort in buildings in hot and dry climate. This feature was successfully adopted in vernacular architecture. For example, the Deegh palace in Bharatpur is surrounded by a water garden to cool the neighbourhood. Other examples include the Taj Mahal at Agra and the palace at Mandu. The evaporation rate of water in such an open spaces depends on the surface area of the water, the relative humidity of the air, and the water temperature.

(C) Vegetation

Vegetation plays an important role in changing the climate of a city, as seen in section 2.5. It is also effective in controlling the microclimate. Plants, shrubs and trees cool the environment when they absorb radiation for photosynthesis. They are useful in shading a particular part of the structure and ground for reducing the heat gain and reflected radiation. By releasing moisture, they help raise the humidity level. Vegetation also creates different air flow patterns by causing minor pressure differences, and thus can be used to direct or divert the prevailing wind advantage.

Based on the requirement of a climate, an appropriate type of tree can be selected. Planting deciduous trees such as mulberry to shade east and west walls would prove beneficial in hot and dry zones. In summer, they provide shade from intense morning and evening sun, reduce glare, as well as cut off hot breezes. On the other hand, deciduous trees shed their leaves in winter and allow solar radiation to heat the building. The cooling effect of vegetation in hot and dry climates comes predominantly from evaporation, while in hot humid climates the shading effect is more significant.

Trees can be used as windbreaks to protect both buildings and outer areas such as lawns and patios from both hot and cold winds. The velocity reduction behind the windbreak depends on their height, density, cross-sectional shape, width, and length, the first two being the most important factors. When the wind does not blow perpendicular to the windbreak, the sheltered area is decreased. The rate of infiltration in buildings is proportional to the wind pressure. Therefore, it is more important to design windbreaks for maximum wind speed reduction in extreme climates, than to attempt to maximize the distance over which the windbreak is effective.

In cold climates, windbreaks can reduce the heat loss in buildings by reducing wind flow over the buildings, thereby reducing convection and infiltration losses. A single-row of high density trees in the form of a windbreak can reduce infiltration in a residence by about 60% when planted about four tree heights from the building. This corresponds to about 15% reduction in energy costs [14].

Thus, trees can be effectively used to control the microclimate. The data for various trees found in India are presented in Table 2.4 [4, 17].

Table 2.4 Properties of some Indian Trees [17]

S. No	Botanical Name	Common Name English	Height (m)	Spread (m)	Rate of Growth	Root System	Drought Resistance	Foliage
1	Eugenia jambolana	Jamun	12.2 to 13.7	9.1 to 10.7	Medium	Medium	Medium	BLE
2	Azadiracta indica	Margosa	13.7 to 15.2	10.7 to 12.2	Fast	Medium	Good	BLE
3	Mimusops elengi	Bulletwood tree	12.2 to 13.7	10.7 to 12.2	Slow	Large	Good	BLE
4	Peltrophorum ferrigeum	Copper pod tree	13.7 to 15.2	10.7 to 12.2	Fast	Small	Good	BLE
5	Tamarindus indica	Tamarind	10.7 to 12.2	9.1 to 10.7	Slow	Medium	Medium	BLE
6	Pithecellobium dulce	Goras	12.2 to 13.7	9.1 to 10.7	Slow	Large	Medium	BLE
7	Samanea saman	Raintree	10.7 to 12.2	9.1 to 10.7	Fast	Medium	Medium	BLE
8	Bauhinia variegata	Variegated bauhinia	6.1 to 9.1	7.6 to 9.1	Fast	Small	Medium	D
9	Cassia fistula	Indian laburnum	7.6 to 10.7	6.1 to 9.1	Fast	Small	Very Good	D
10	Cassia javanica	Pink cassia	7.6 to 9.1	9.1 to 10.7	Medium	Medium	Good	D
11	Cordia sebestena	Cordia	4.6 to 6.1	4.6 to 5.5	Medium	Small	Good	D
12	Delonix regia	Royal poincana	7.6 to 9.1	7.6 to 8.5	Fast	Large	Medium	E
13	Erythrina indica	Indian coral tree	7.6 to 9.1	4.6 to 6.1	Fast	Small	Good	D
14	Gliricidia maculata	Madra tree	6.1 to 7.6	4.6 to 6.1	Fast	Small	Poor	BLE
15	Largerstroemia spriosa	Pride of India	7.6 to 9.1	6.1 to 7.6	Fast	Medium	Very good	BLE
16	Morus indica	Mulberry	9.1 to 10.7	7.6 to 8.5	Medium	Medium	Medium	D
17	Plumeria alba	White frangipani	4.6 to 6.1	4.6 to 5.5	Fast	Small	Medium	D
18	Pogamia glabra	Pongam	4.6 to 6.1	4.6 to 6.1	Fast	Small	Medium	D
19	Psidium guyava	Guava	6.1 to 7.6	5.5 to 6.1	Fast	Medium	Medium	BLE
20	Mornga oleifera	Drumstick tree	9.1 to 10.7	7.6 to 9.1	Fast	Small	Medium	BLE
21	Pustrajiva roxburghil	Lucky bean tree	7.6 to 9.1	4.6 to 6.1	Slow	Small	Medium	BLE
22	Tecoma undulata	Wary leaved tecoma	6.1 to 7.6	4.6 to 5.5	Fast	Small	Very good	BLE
23	Thespesia populnea	Portia tree	7.6 to 9.1	7.6 to 9.1	Fast	Small	Medium	BLE
24	Thevital peruviana	Yellow oleander	4.6 to 5.5	3.0 to 4.6	Fast	Small	Medium	D
25	Nesium oleander	Oleander	4.6 to 5.5	3.0 to 4.6	Fast	Medium	Good	D
26	Zapota	Zapota	6.1 to 7.6	7.6 to 9.1	Fast	Medium	Good	BLE

BLE = Broad Leaf Evergreen, D = Deciduous, E = Evergreen

(D) Street width and orientation

The amount of direct radiation received by a building and the street in an urban area is determined by the street width and its orientation. The buildings on one side of the street tend to cast a shadow on the street on the opposite building, by blocking the sun's radiation. Thus the width of the street can be relatively narrow or wide depending upon whether the solar radiation is desirable or not. For instance in Jaisalmer (hot and dry climate), most of the streets are narrow with buildings shading each other to reduce the solar radiation, and consequently the street temperature and heat gain of buildings [18]. Figure 2.16 shows the street temperatures in summer and winter in Jaisalmer as compared to temperatures recorded at the meteorological station. It is seen that street temperatures can be upto 2.5^{o}C lower than the ambient air temperatures due to mutual shading of buildings. At high latitudes in the northern hemisphere, the solar radiation is predominantly from the south, hence wider east-west streets give better winter solar access.

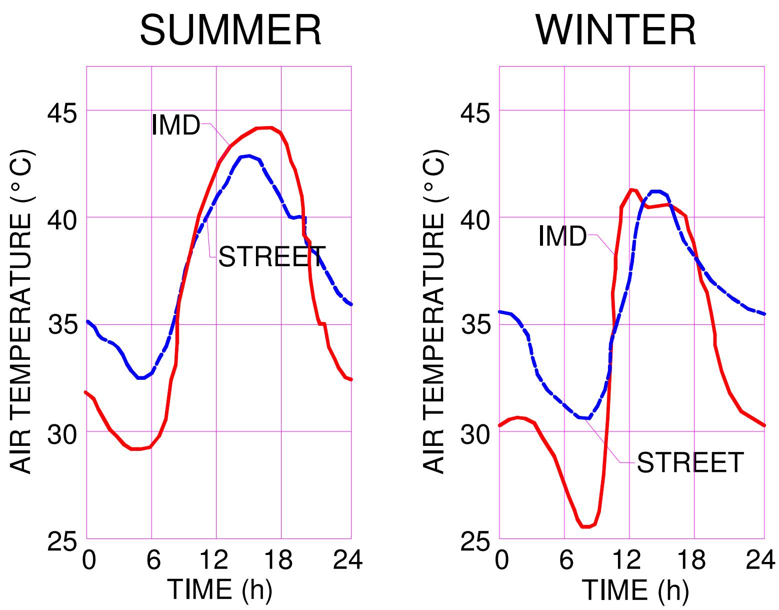


Fig. 2.16 Street temperatures in Jaisalmer [18]
(a) Summer, (b) Winter

The orientation of the street is also useful for controlling airflow. Air movement in streets can be either an asset or a liability, depending on season and climate. The streets can be oriented parallel to prevailing wind direction for free airflow in warm climates. Smaller streets or pedestrian walkways may have number of turns (zigzags) to modulate wind speed. Wind is desirable in streets of hot climates to cool people and remove excess heat from the streets. It can also help in cross ventilation of buildings. This is important in humid climates, and at night in arid climates. In cold regions, wind increases heat losses of buildings due to infiltration. For restricting or avoiding wind in cold regions, the streets may be oriented at an angle or normal to the prevailing wind direction. For regular organisations of buildings in an urban area, tall buildings on narrow streets yield the most wind protection, while shorter buildings on wider streets promote more air movement. When major streets are parallel to winds, the primary factors affecting the wind velocity are the width of streets and the frontal area (height and width) of windward building faces.

(E) Open spaces and built form

The form of a building and the open spaces in its neighbourhood affect the radiation falling on the building's surface and the airflow in and around it. Open spaces such as courtyards can be designed such that solar radiation incident on them during daytime can be reflected on to building façades for augmenting solar heat. This is desirable in cold climates, and it is possible if the surface finish of the courtyard is reflective in nature. Inside a courtyard, wind conditions are primarily dependent on the proportion between building height and courtyard width in the section along the wind flow line. Courtyards can also be designed to act as heat sinks. Grass and other vegetation in a courtyard can provide cooling due to evaporation and shading. Water sprayed on the courtyards would cause cooling effect due to evaporation. Consequently, the air temperature in the courtyard can be much lower compared to street or outdoor air temperatures in a hot and dry climate. Figure 2.17 presents the measured temperature at Jaisalmer, showing the maximum of courtyard temperature as 4 ^{o}C less than that of the outdoor air temperature [18].

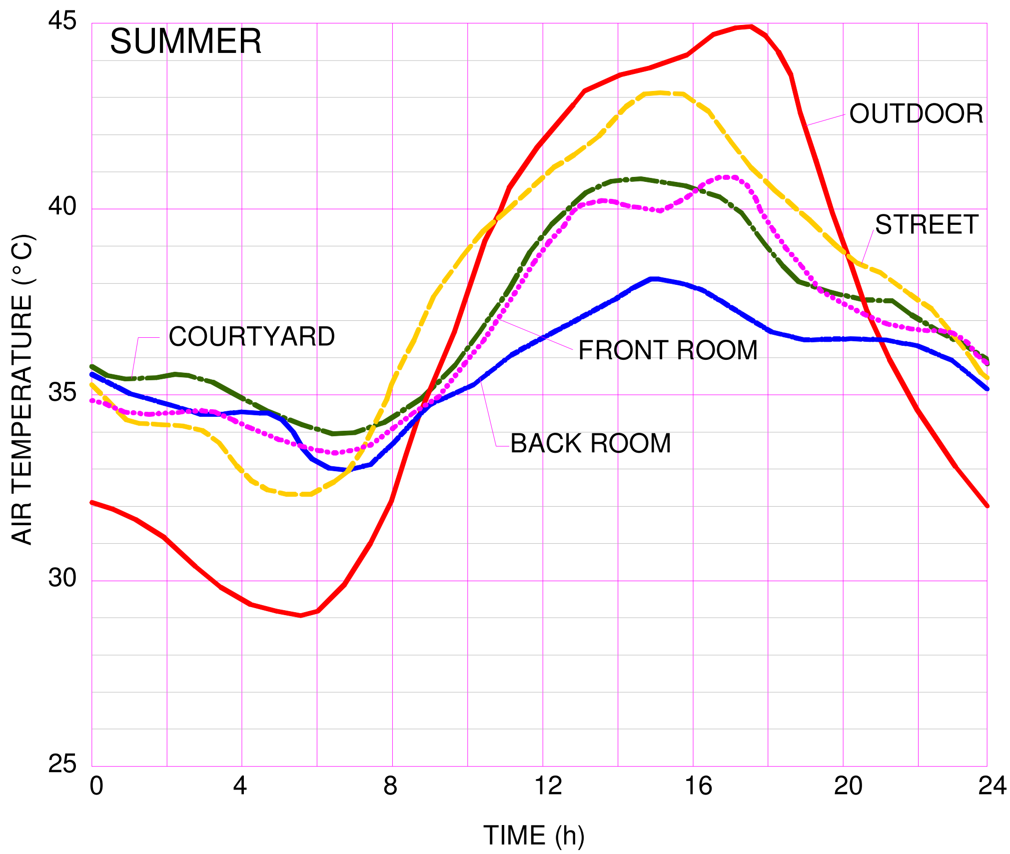


Fig. 2.17 Effect of courtyard [18]

The air in open spaces shaded by surrounding buildings would be cooler and can be used to facilitate proper ventilation and promote heat loss through building envelope. Built forms can be so oriented that buildings cause mutual shading and thus reduce heat gain. For ensuring unobstructed airflow, taller structures can be planned towards the rear side of a building complex. Thus, open spaces and built form can be appropriately used to modulate the microclimate.

2.7 TOOLS FOR ANALYSING WEATHER DATA

The effects of sun, wind and light on a particular site can be analysed in many ways depending on the type of information available for a place. They can be graphical in nature (such as bioclimatic chart [4, 11] and psychrometric chart [11]), or in worksheet format (such as Mahoney table [19]). One could also use computer software such as Climate Consultant [20] or Therm [21]. For example, the effects of temperature and humidity can be plotted on a bioclimatic or psychrometric chart [11] to understand the climate and suggest ways of expanding the comfort zone. Similarly, Mahoney tables facilitate diagnosis of climate and provide design recommendations. The computer software ‘Therm’ evaluates climatic factors and predicts the adaptive comfort index. Climate Consultant, in addition to analyzing weather variables, provides recommendations for building design from the point of view of comfort requirements.

To generate relevant information on the climate of a place, one can use graphical procedures or adopt the measurement route, or resort to computational techniques. The measurement route can be either analysis of the recorded data available from Indian Meteorological Department and other sources (section 2.2), or for conducting on-site measurements. Table 2.5 lists various techniques that can be adopted to generate and analyse climatic factors.

The procedure to be adopted for the analysis of the climate of a place is as follows:

1. Obtain weather data.
2. Find out which months are comfortable (hot or cold), using mean temperature and relative humidity. This also gives an indication of the severity of the climate.
3. Identify the climatic zone to which the city belongs for adopting appropriate strategies to achieve comfort.
4. Establish the positive and negative aspects of climate for a particular season. For example, shading from the sun may be needed during overheated periods. Which are those seasons, and what is the position of the sun in the sky ? During the same period, wind may be required to alleviate discomfort. What are the speed and the direction of the wind during that period ?
5. Adjust the impact of local microclimatic conditions and the urban context in the analysis. For example, in northern hemisphere, larger buildings in the south create shadow zones in the north. Thus the amount of direct solar radiation falling on a smaller building in the north is affected. Also, the presence of a large building, or the orientation of the street can impact the speed and direction of wind.
6. Finalise the zoning of the site. For example, the presence of water bodies on the site may be advantageous in a hot and dry zone. The wind, if allowed to pass over the water body can increase the potential for evaporative cooling. So the building has to be oriented facing the wind.

Table 2.5 Techniques for analysis of climatic factors

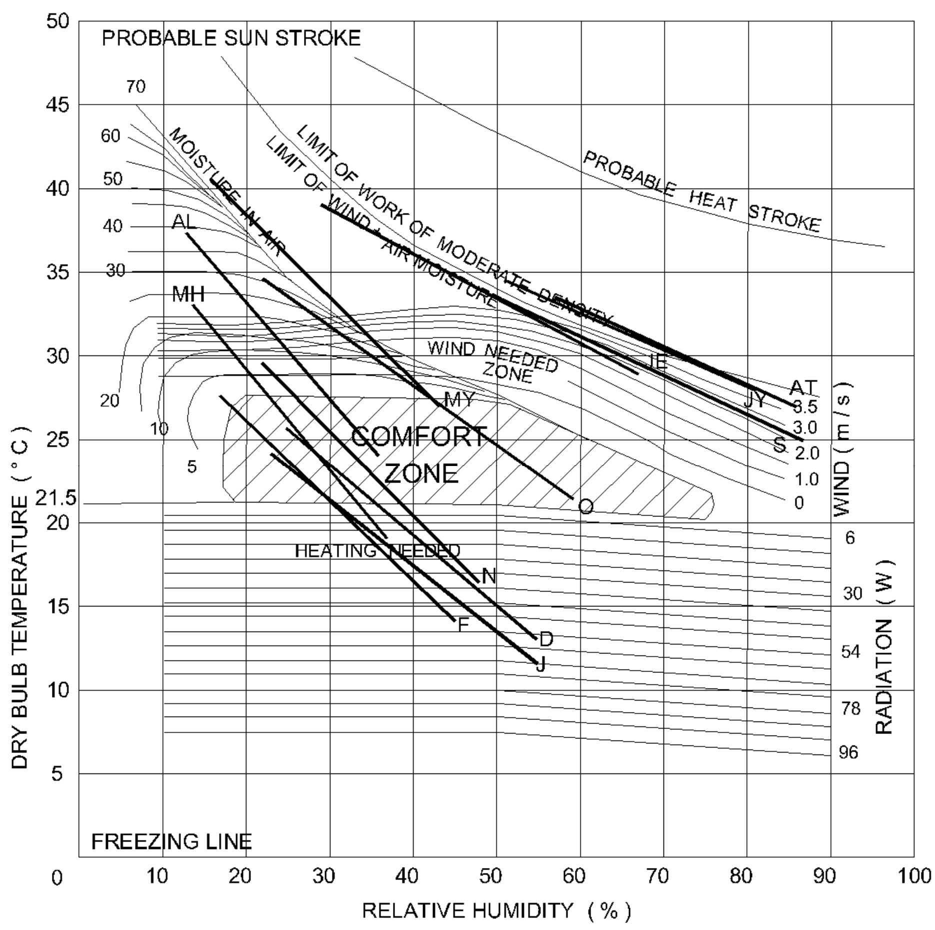
Technique		Solar radiation	Wind	Temperature, humidity, precipitation
Graphical method		Maps for shading analysis [22] Photographic survey [22] Shadow angle protractor [19] Shadow throw angles [3] Solar envelope [14,22] Solar radiation distribution maps [2] Sundial [14] Sundial and scale model [14] Sun path diagrams [3,4,11,14,19]	Wind rose [4] Wind square [14]	Temperature and humidity isopleths on [2,8]
Measurement	Recorded data	Mean, minimum and maximum global, diffuse and direct solar radiation data [1,2,3]	Mean, minimum and maximum with prevailing wind direction data [1,2,3]	Mean, minimum and maximum data [1,2,3].
	Instruments	TNO sunlight meter [14], Pyranometer, Pyrheliometer Sunshine recorder	Anemometer Wind Tunnel Testing	Hygrometer, Thermometer Rain gauge
Software		Solar 2 [23], Suntool [24]	-	-

2.8 ILLUSTRATIVE EXAMPLE

As an illustrative example, the use of bioclimatic charts for analysing the climatic zones of six places, namely Jodhpur (hot and dry), Mumbai (warm and humid), Pune (moderate), New Delhi (composite), Srinagar (cold and cloudy) and Leh (cold and sunny) are discussed in this section.

a) Jodhpur (Latitude: 26.30° N, Longitude: 73.02 ° E, Elevation: 224 MASL)

The climate in Jodhpur is predominantly hot and dry. The months from April to June are very hot with temperatures in excess of 37 ^{o}C during daytime. The chart (Fig. 2.18) shows that the evaporating cooling method is desirable in April and May. Mechanical air-conditioning is required from June to August due to high humidity coupled with high temperatures. September is a relatively cooler month, during which ventilation may be adequate to provide comfort. Nights in October are comfortable, but days are hot and dry. Thus, evaporating cooling is desirable during daytime in this month. Daytime conditions are comfortable during January, February, November and December. Nights are cool in these months.

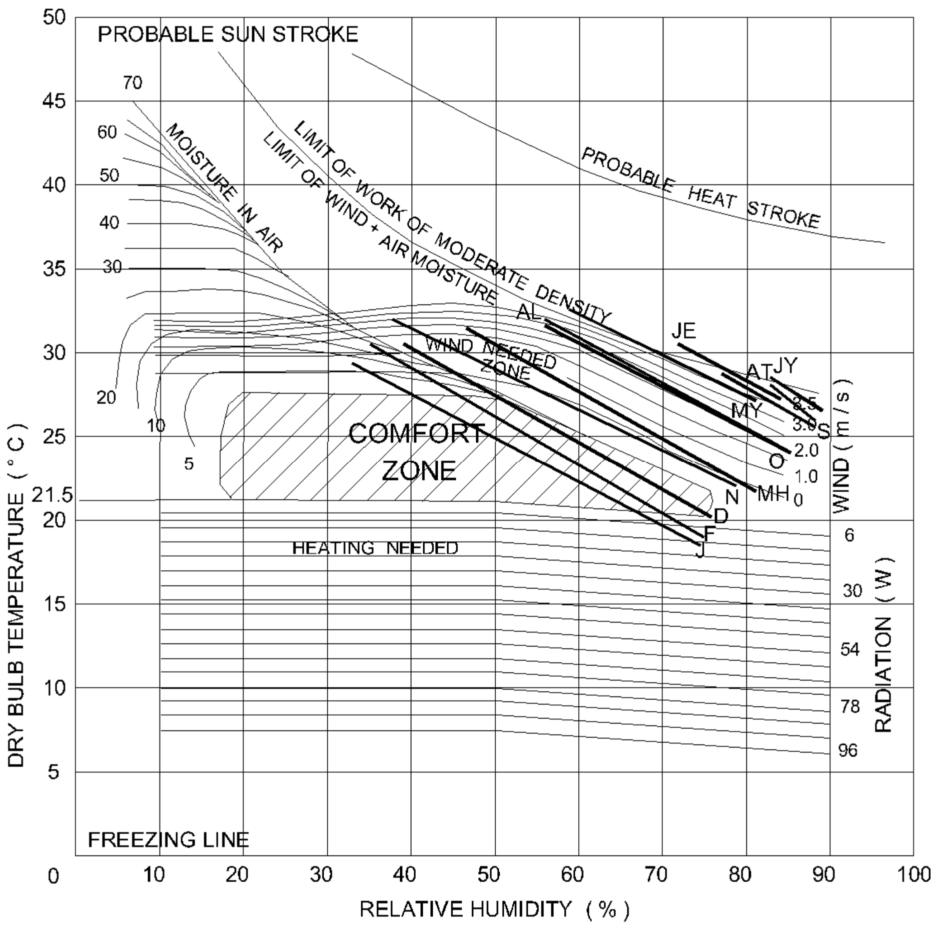


J=January, F=February, MH=March, AL=April, My=May, JE=June, JY=July, AT=August, S=September, O=October, N=November, D=December

Fig. 2.18 Bioclimatic chart of Jodhpur

b) Mumbai (Latitude: 19.12° N, Longitude: 72.85 ° E, Elevation: 14 MASL)

The climate in Mumbai is predominantly warm and humid. Although temperatures are not very high in summer, conditions are uncomfortable due to the high humidity. May is the hottest month with the monthly average daily maximum temperature reaching as high as 32 °C, coupled with a humidity of about 60% during daytime. The chart (Fig. 2.19) shows that mechanical air-conditioning is required from April to October during the day. At nights, wind or fan induced ventilation can provide comfort. In March, only ventilation cooling is needed. The months of January, February, November and December are mostly comfortable.



J=January, F=February, MH=March, AL=April, My=May, JE=June, JY=July, AT=August, S=September, O=October, N=November, D=December

Fig. 2.19 Bioclimatic chart of Mumbai

c) Pune (Latitude: 18.53° N, Longitude: 73.85° E, Elevation: 559 MASL)

The climatic conditions in Pune are mostly warm (Fig. 2.20). The day temperatures are relatively high during March, April and May; the corresponding night temperatures are within comfort level. April is the hottest month with the monthly average daily maximum temperature of 37.4 °C and a corresponding relative humidity of 19%. Evaporative cooling is indicated in these months during daytime. Ventilation can be adopted to achieve comfort at night, as the conditions are relatively cooler. In monsoon months (June to October), ventilation is required to provide comfort throughout the day. Winter months (January, February, November and December) are generally comfortable during the day and cool at night.

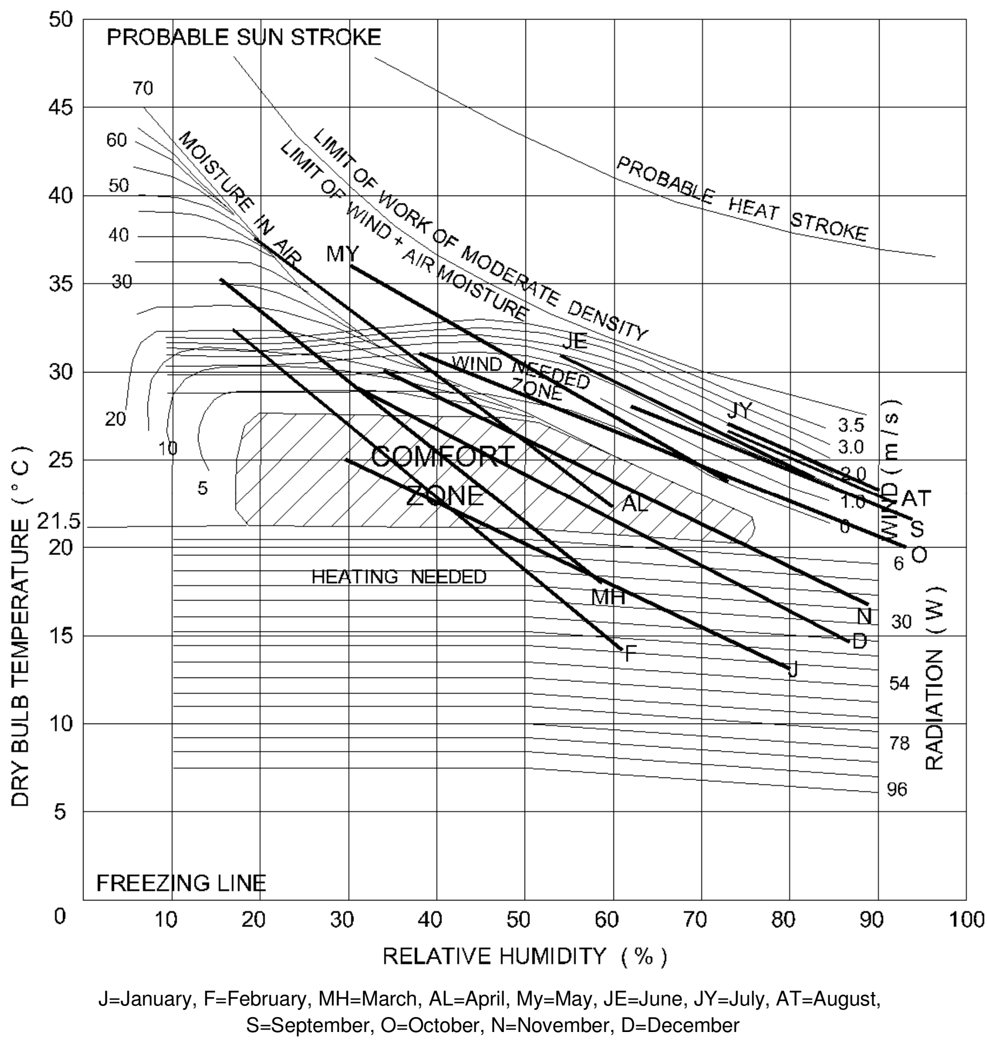
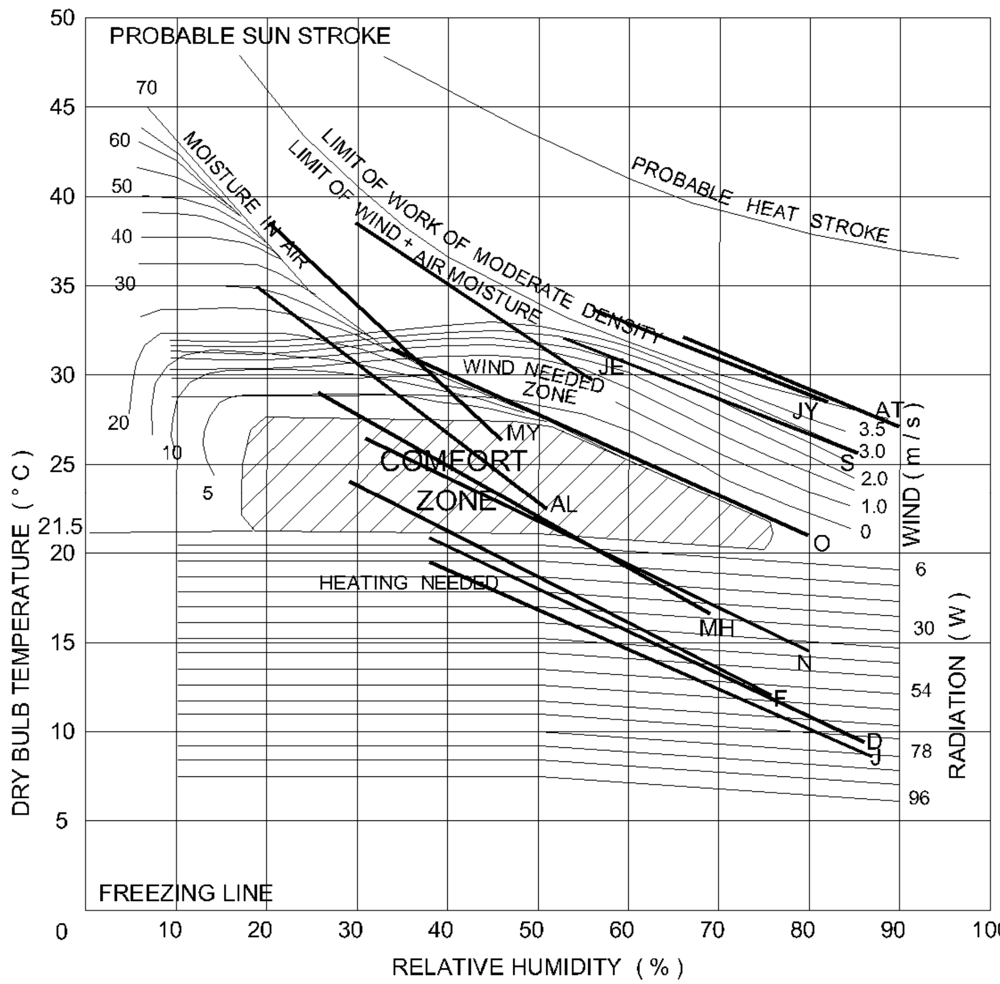


Fig. 2.20 Bioclimatic chart of Pune

d) New Delhi (Latitude:28.58° N, Longitude: 77.20° E, Elevation: 216 MASL)

The climate in New Delhi is predominantly hot. It also has distinct cool and humid seasons. April to June is very hot; May and June are particularly harsh, with maximum daytime temperatures of about 39° C. Evaporating cooling is desirable in April and May (Fig. 2.21). Mechanical air-conditioning is required from June to August due to high humidity coupled with high temperatures. September is warm and humid; air movement in the form of ventilation can help in achieving comfort. In October, days are hot and dry, nights are comfortable. From November to March, the days are pleasant and nights are cool. January is the coolest month.

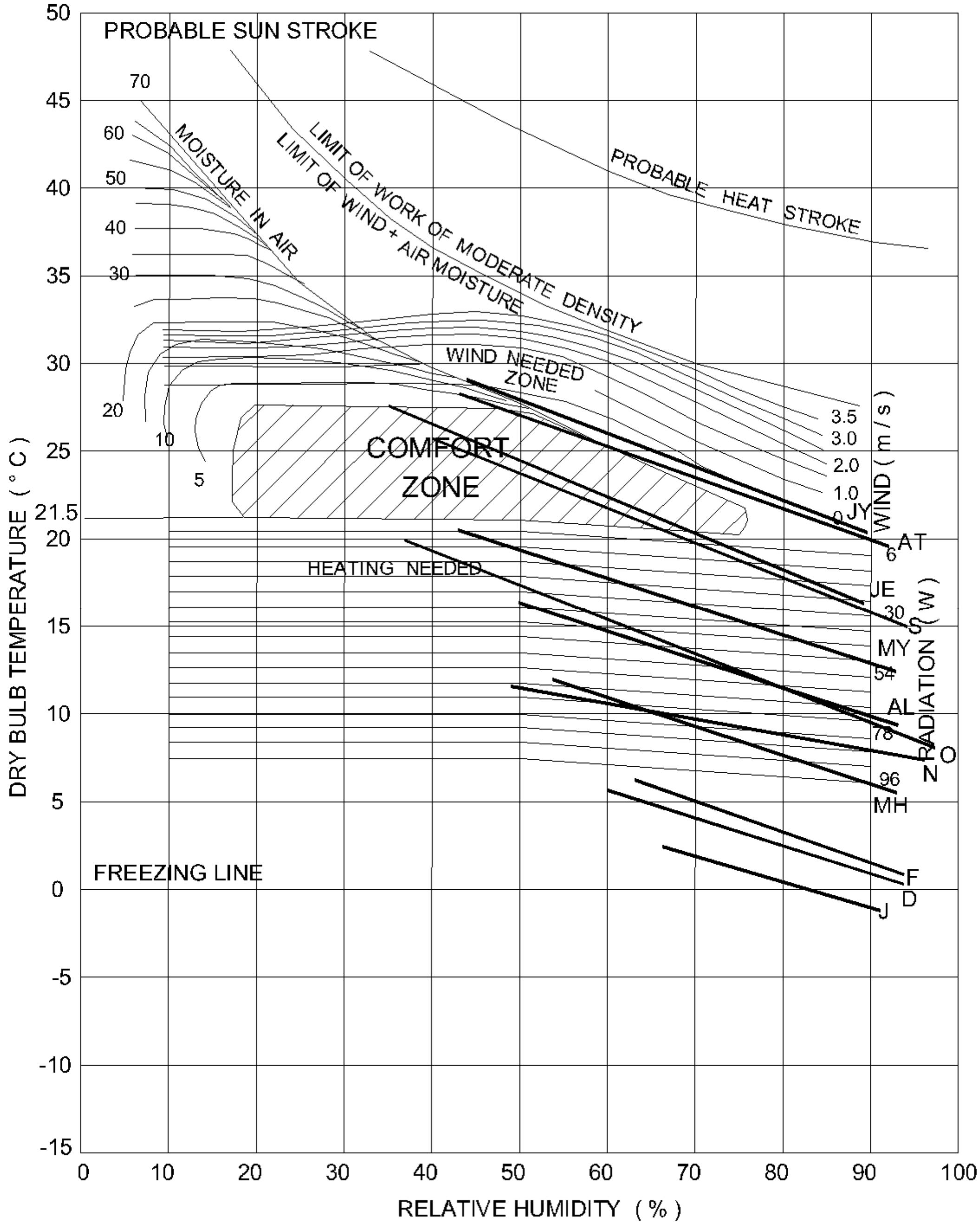


J=January, F=February, MH=March, AL=April, My=May, JE=June, JY=July, AT=August, S=September, O=October, N=November, D=December

Fig. 2.21 Bioclimatic chart of New Delhi

e) Srinagar (Latitude: 34.08° N, Longitude: 74.83° E, Elevation: 1587 MASL)

Figure 2.22 shows that Srinagar is predominantly cool. The months from October to May are uncomfortably cold. The conditions during December, January and February are extremely cold with night temperatures falling below freezing line. Mechanical heating is required during these months. Days are comfortable in June and September; but some heating is required at night. July and August are just above the comfort limit and some cooling may be required. Ventilation should be able to provide comfort during these months. In the months of April, May and October, days can be made comfortable by providing heating through direct solar radiation. The daytime heat can also be trapped for nighttime use by providing adequate thermal mass.

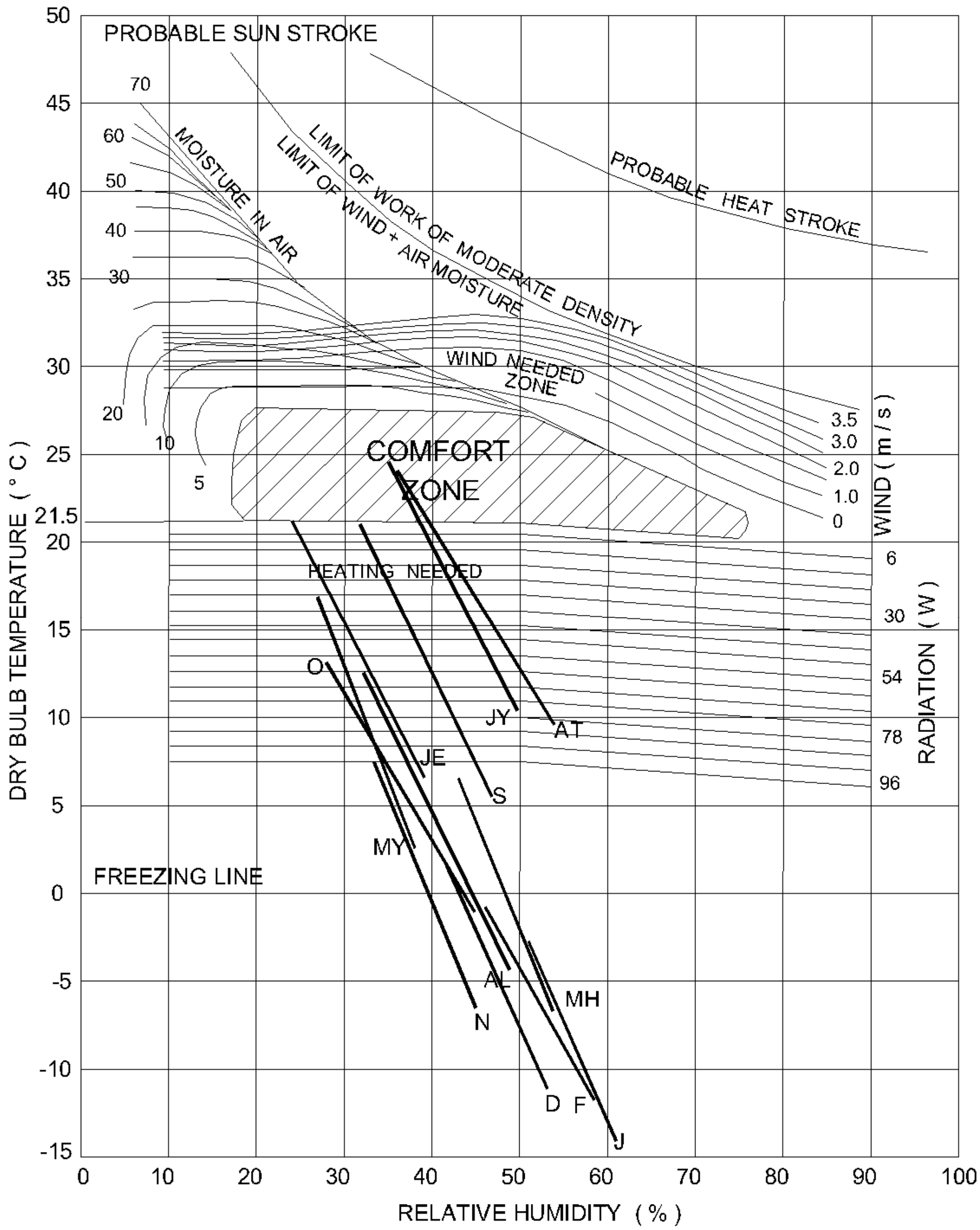


J=January, F=February, MH=March, AL=April, My=May, JE=June, JY=July, AT=August, S=September, O=October, N=November, D=December

Fig. 2.22 Bioclimatic chart of Srinagar

f) Leh (Latitude: 34.15° N, Longitude: 77.57° E, Elevation:3514 MASL)

The chart (Fig. 2.23) shows that Leh is predominantly cold throughout the year. Outside conditions are rarely within the comfort zone except during daytime in the months of July and August. In fact, the months of December, January and February experience sub-zero temperatures almost throughout the day and night.



J=January, F=February, MH=March, AL=April, My=May, JE=June, JY=July, AT=August, S=September, O=October, N=November, D=December

Fig. 2.23 Bioclimatic chart of Leh

Nights are severely cold with temperatures ranging from –14^{o} C in January to –11^{o} C in December. January is the coldest month (minimum and maximum temperatures being –14^{o}C and –3^{o}C respectively). March, April, October and November are less severe. However, the temperatures at night are below freezing point. Therefore, heating is a must in the months from October to April. In other months, the limit of comfort can be extended if adequate radiation from the sun is incident on the interior surfaces of the building. In May and October, additional heating is required at night. The global solar radiation available at this place is quite high; it has more than 300 days of clear sunshine. The radiation can therefore be trapped for use in the building both during day and night, to alleviate discomfort.

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CHAPTER – 3 ~~2~~

PRINCIPLES OF ENERGY CONSCIOUS DESIGN

Contents:

3.1 INTRODUCTION

The energy conscious design approach helps designers and building owners to economically reduce building operating costs, while improving comfort for the building's occupants. The energy consumed by a building depends on its use (whether residential, commercial or industrial), the type of building (air-conditioned or otherwise), the interaction of spaces, and the climate. Architects have to ensure that the design of the built form suits the intended use of the building and the specific needs of the client within the framework of the prevailing climatic conditions. That is, the parameters of architectural design are based on need, context and form, the relationships between which are outlined in Fig. 3.1. Appropriate combinations of these parameters lead to savings of energy required for maintaining healthy and comfortable indoor conditions.

In any building design, one employs simple techniques such as orientation, shading of windows, colour, and vegetation among others, to create comfortable conditions. Such techniques pertain to the *building envelope*. Building envelopes not only provide the thermal divide between the indoor and outdoor environment, but also play an important role in determining how effectively the building can utilise natural lighting, ventilation, and heating and cooling resources. Thus, intelligent configuration and moulding of the built form and its surroundings can considerably minimise the level of discomfort inside a building, and reduce the consumption of energy required to maintain comfortable conditions.

Yet, in extreme climate s, comfortable indoor conditions cannot be completely achieved by limiting oneself to simple techniques. For example, in a city like Ahmadabad where the ambient temperatures can reach up to 42 °C in summer, simple techniques such as orientation, shading, colour of external surfaces and insulation may help to bring down the temperature to around 36 °C [1]. A significant reduction no doubt, but the room temperature is still very much above comfort levels. In such circumstances, additional features need to be considered. One way is to use passive techniques such as wind towers coupled with evaporative cooling to cause further cooling of the interiors.

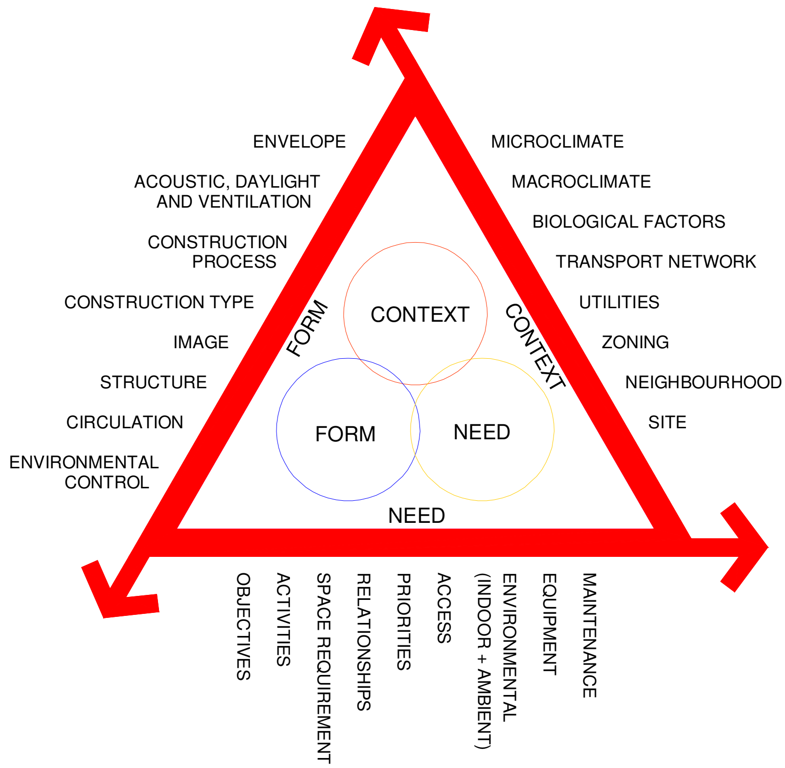


Fig. 3.1 Parameters of architectural design

Passive solar techniques involve methods of collecting, storing, distributing and controlling thermal energy flow by means of natural principles of heat transfer. Passive systems have no separate devices for collecting and storing energy, nor any mechanical means for transporting heat. Instead, they make use of the energy available in the immediate environment and effect energy exchanges through natural processes. However, the term 'natural energy flow' is certainly not synonymous with 'unregulated energy flow'. In fact, the natural flow can be reasonably regulated by controls such as dampers, openable windows, movable insulation or shading devices. Passive systems offer a number of advantages that afford large savings of energy; they are also easy to incorporate into buildings at little or no additional cost. Further, the simplicity of design, operation and maintenance invite interest. Common materials can be used in constructions and the systems subsequently maintained by laypersons. However, as passive systems are dependent on natural forces, it would be incorrect to compare their performance with that of air-conditioning systems. When rooms are required to be maintained at a constant temperature and humidity, it is still advisable to use conventional systems.

This chapter elaborates on both, the simple techniques pertaining to building envelope as well as passive solar techniques. Wherever possible, the principles are accompanied by details of construction. An architect may use the methods described as a starting point for generating customised solutions. Techniques relevant to Indian conditions such as direct gain, Trombe wall, ventilation, evaporative cooling, and earth-air-pipe system are explained in greater detail than others.

The artificial is lighting load on a building can be significantly reduced if its design allows for effective daylighting. Additionally, building materials also play an important role in energy conscious architecture. This chapter also describes daylighting as a passive solar technique, and concludes with a discussion on alternative building materials and their embodied energy aspects.

3.2 BUILDING ENVELOPE

A building interacts with the environment through its external façades such as walls, windows, projections, and roofs, referred to as the building envelope. The envelope acts as a thermal shell, which if thoughtlessly constructed, would result in energy leaks through every component. Hence, each component needs to be properly chosen to ensure an energy efficient building. The choice depends on the site and the primary objective is, therefore, to examine the site conditions. Besides, an ideal orientation of the building at a site and proper building configuration play a significant role in the building's performance.

3.2.1 Site

Of the various factors influencing the building design, site conditions occupy an important position. The environmental conditions experienced on the site are due to the macroclimate as well as the microclimate (discussed in chapter 2). Site-specific conditions such as land form, vegetation, waterbodies, open spaces, etc. (section 2.6) play an important role in building design. Proper analysis of these conditions can enable one to choose a site and make suitable design plans. This would help save energy and also provide a fairly satisfactory indoor environment throughout the year.

3.2.2 Orientation

Appropriate orientation of buildings can provide physically and psychologically comfortable conditions in the building. It can help exclude the undesirable effects of severe weather to a great extent. For example, in cold climates, a building must be oriented to receive maximum solar radiation into the living areas for warmth on one hand, while keeping out the prevailing cold winds on the other. Conversely, in hot regions, solar radiation and hot, dusty winds need to be avoided in summer, while cool winds must be admitted. Thus, appropriate orientation can control the amount of solar radiation and wind entering a building.

The best orientation requires that the building as a whole should receive maximum solar radiation in winter and minimum in summer. To decide on an optimum orientation, it is essential to have an idea of the sun's position on a daily as well as seasonal basis by using tools such as the sun path diagram (Chapter 2, Fig. 2.1 b). It is also necessary to know the intensity of solar radiation on various external surfaces of the building as well as the duration of sunshine. Such information is available in various handbooks (Refer to Chapter 2). Once the orientation is decided, the heat entering a building can be controlled by (1) area and type of glazings, (2) types of walls and roofs, and (3) shading.

As mentioned, wind may be desirable or unwanted, depending on the climate. Hence, it is necessary to study the velocity and direction of the wind on an hourly and monthly basis. This helps one to identify the duration for which the wind may be desirable. Besides, the prevalent wind direction can be identified to plan the orientation of apertures for achieving the desired indoor air motion. It is generally found that a variation of orientation of apertures upto 30° with respect to the prevalent wind direction, does not significantly affect the indoor ventilation (average indoor velocity) of the building [2].

Once orientation is fixed, wind can be controlled by:

- tilting and projecting surfaces to deflect wind
- providing openings of appropriate size
  providing windbreakers to reduce wind speed

To illustrate the effect of orientation, let us consider a rectangular conditioned building having fully glazed wall on one of its long sides. Let us also consider four orientations such as northwest-southeast, north-south, northeast-southwest and east-west of this building with respect to its long axis. The estimated annual cooling load of such a conditioned building in a few Indian cities is shown in Fig. 3.2. It is seen that in warm climates, the maximum load corresponds to the northwest-southeast orientation (the glass curtain wall facing southwest). Hence, such an orientation of the building should be avoided.

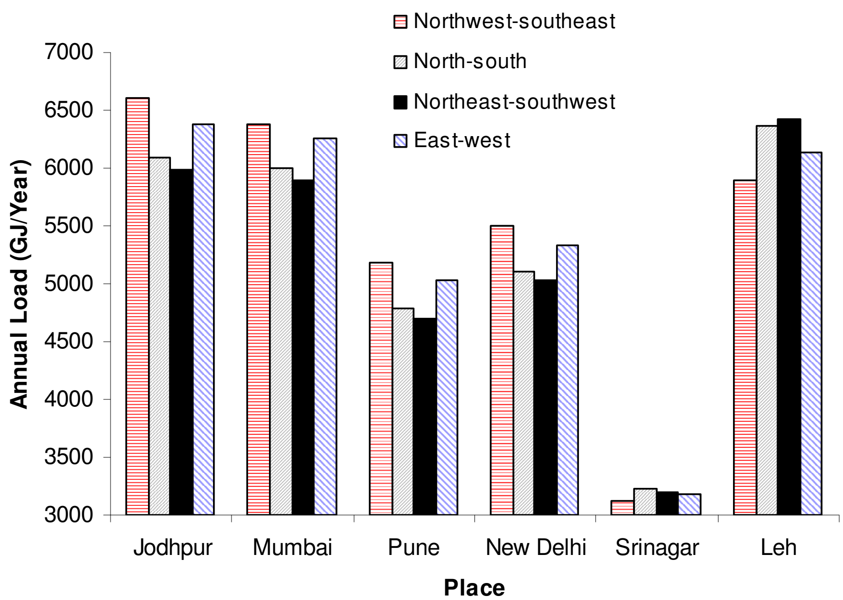


Fig. 3.2 Effect of orientation on the annual load of a conditioned building in various cities

3.2.3 Building configuration

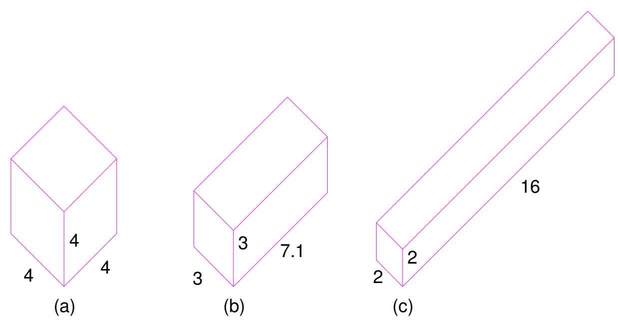
Heat exchange between a building and its surroundings occurs primarily through the 'skin' of the building. Configuring the geometry of the building appropriate to the climate and usage can control the magnitude of the heat flow. For example, in an extremely cold climate, one needs to minimise heat loss from the building to the environment. This can be achieved by:

a) using buffer spaces, e.g., sunspaces and balconies act as sitouts in favourable weather;
b) locating infrequently used spaces such as store rooms and toilets in the directions that face prevailing cold winds;

c) maximising exposure to solar radiation, e.g., major living rooms may be arranged facing the sun to gain heat;
d) locating habitable spaces appropriately, e.g., the most habitable spaces may be kept on leeward side to avoid cold winds. They may be clustered together to reduce exposure to cold.

The heat flow due to radiation and air movement can be controlled by varying the following aspects of the building configuration:

- **surface area to volume ratio (S/V ratio):** The ratio of the surface area to the volume of the building (S/V ratio) determines the magnitude of the heat transfer in and out of the building. The larger the S/V ratio, the greater the heat gain or loss for a given volume of space. Conversely, a smaller S/V ratio will result in the reduction of heat gain/loss. For example, in cold climates it is preferable to have compact house forms with minimum S/V ratio. Figure. 3.3 shows the surface to volume ratios for various building shapes.



SOLID SHAPE	SURFACE AREA 'S'	VOLUME 'V'	SURFACE AREA/ VOLUME RATIO 'S/V'
a	96	64	1.5
b	103.2	64	1.61
c	136	64	2.13

Fig. 3.3 Surface area to volume ratio (S/V ratio) for a few building shapes

- **shape of the building:** Wind when obstructed by a building creates pressure differences, that is, positive pressure on the windward side and negative pressure on the leeward side. Consequently, a new airflow pattern is established around the building. Thus, wind pattern across a building can be modified by shaping it appropriately.
- **buffer spaces:** Buffer spaces such as courtyards, atria, balconies and verandahs provide shadig and catch wind.

- **arrangement of openings:** Appropriate openings connecting high and low pressure areas provide effective ventilation. Solid and glazed surfaces need to be suitably arranged and oriented for receiving or rejecting solar radiation.
- **shading:** Shading of surfaces can be achieved by the self-shading profiles of buildings e.g. H-type or L-type as compared to the simple cube. Shading devices such as chajjas block the solar radiation incident on the exposed surfaces of a building, consequently reducing heat gain. It has been found that in a low-rise residential building in Ahmadabad, shading a window by a simple horizontal chajja of 0.76m depth can lower the maximum room temperature by upto 4.6 ºC [3]. Therefore, the shading of windows can significantly improve the performance of the building. In the case of hot and dry regions, taller structures may be placed towards the south, so as to shade other structures in a cluster. Walls can be shaded by the use of projections, balconies, fins, textured paints and vegetation. Openings can be shaded with appropriately sized chajjas, fins and awnings externally (Fig. 3.4), and/or by using openable shutters and movable covers like curtains and venetian blinds internally. Translucent materials like heat absorbing or heat reflecting glass, plastics, painted glass, etc. can also be used for reducing solar heat gains through glasses. The effectiveness of these shading devices are evaluated in terms of shade factors (defined as the ratio of the solar heat gain from the fenestration under consideration, to the solar heat gain through a 3 mm plain glass sheet). Table 3.1 presents the measured values of shade factors for various types of shading devices; the corresponding U-values are also mentioned [4,5].

Table 3.1 Transmittance and shade factors of different shading devices [5]

Name of the Shading Device	Transmittance (W/m^2-K)	Shade Factor
Plain glass sheet (3.0 mm thick)	5.23	1.00
Plain glass + wire mesh outside	5.00	0.65
Painted glass		
(i) White paint	5.22	0.35
(ii) Yellow paint	5.22	0.37
(iii) Green paint	5.22	0.40
Heat absorbing glass	4.65	0.45
Plain glass sheet + Venetian blind inside		
(i) Light colour	3.72	0.35
(ii) Dark colour	3.72	0.40
Plain glass sheet		
(i) 100 percent shaded	5.23	0.14
(ii) 75 percent shaded	5.23	0.34
(iii) 60 percent shaded	5.23	0.56

As the roof of a building receives the maximum radiation, shading it with movable canvas covers, plant cover (pergola) or a roof garden can reduce heat gain.

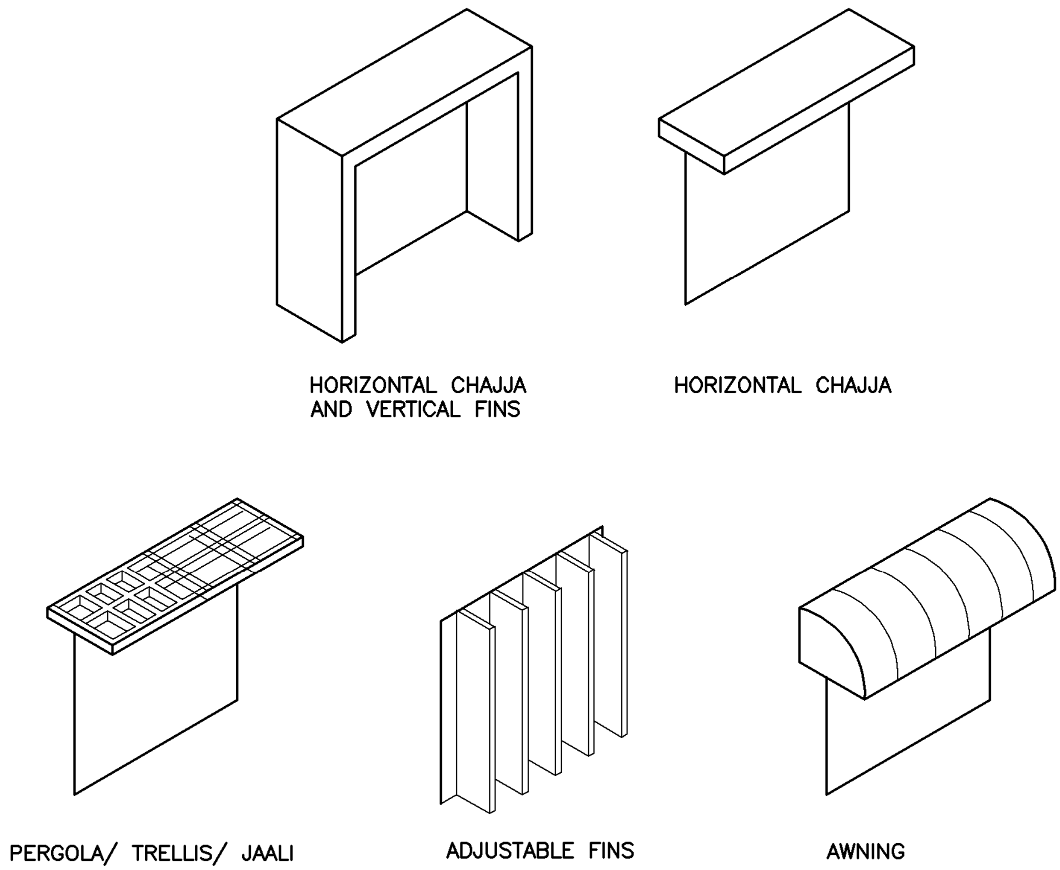
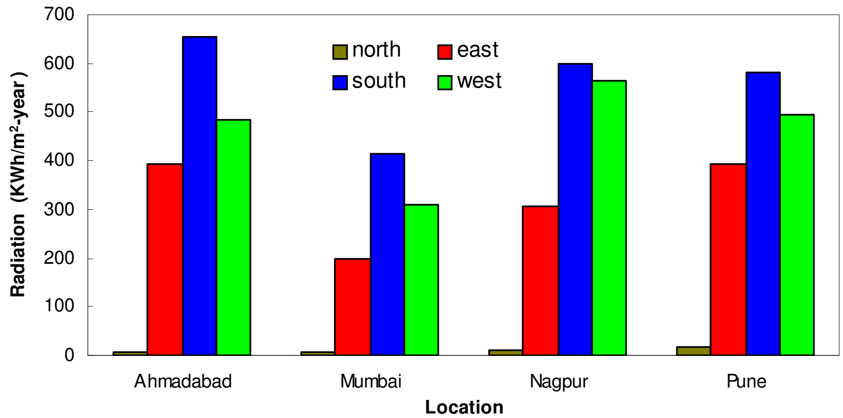
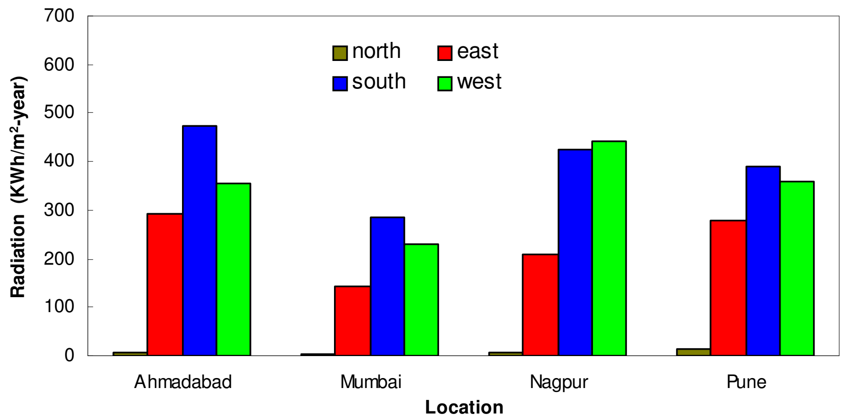


Fig. 3.4 Types of shading devices

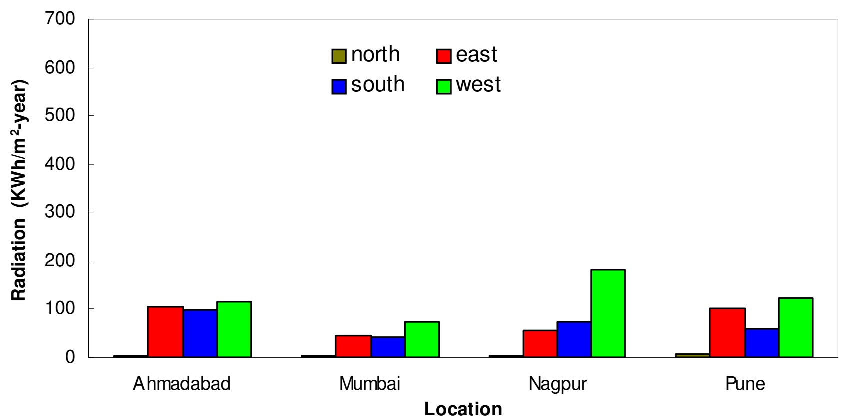
The reduction in yearly beam radiation incident on a typical window of size 1.2m X 1.2m having different external shading devices (horizontal and vertical) in some cities of India is presented in Fig. 3.5 [3]. The figure shows that providing a horizontal chajja can reduce the incident beam radiation falling on the window in various orientations considerably. The shading can be further enhanced by providing vertical fins. The results for various shading devices (horizontal chajjas and vertical fins) on windows of different sizes and in various orientations is given in Appendix III.1 [3].



(a) Unshaded window (1.2m x 1.2 m)



(b) Window shaded by 0.6 m chajja with 0.15 m extension (1.2m x 1.2 m)



(c) Window shaded by 0.6 m chajja and full fins (1.2m x 1.2 m)

Fig. 3.5 Reduction in yearly beam radiation incident on windows due to shading [3]

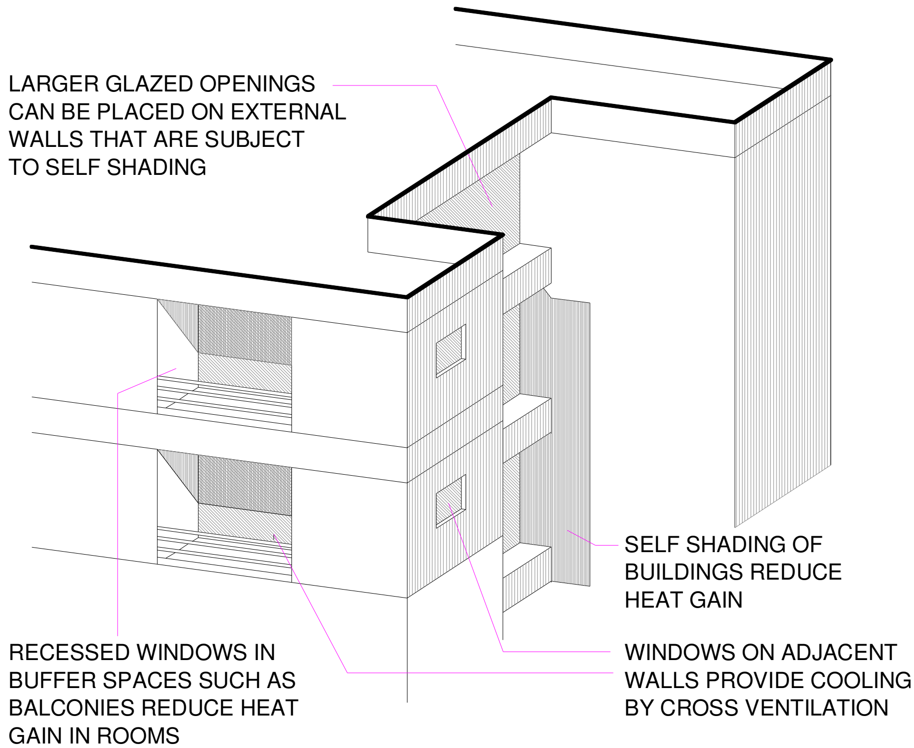


Fig. 3.6 Aspects of building configuration that can reduce heat gains in a hot climate

The physical manifestation of some of the concepts on building configuration that can reduce heat gain in a hot climate is depicted in Fig 3.6.

3.2.4 Building components

The nature of a building envelope determines the amount of radiation and wind that will enter the building. It consists of the following elements:

(A) Roof
(B) Walls
(C) Ground-based floor
(D) Fenestrations
(E) External colour and texture

The heat flow through these elements is characterised by their resistance, thermal capacity, absorption, transmission and emission. The materials for these components have to be chosen carefully depending on specific requirements. The thermophysical parameters of materials that must be considered are specific heat, density and thermal conductivity. While the product of the first two determines the energy storage capacity of a material, the third characterises the energy-flow behaviour. These three parameters together define the time lag (or phase shift) and decrement factor. The former refers to the time delay of heat flow whereas the latter signifies the reduction in the amplitude of heat waves. Thus, depending on the climatic requirements, one would look for materials that would provide the desired thermal storage, time delay and amplitude decrement.

Colour and texture define surface characteristics such as emissivity, reflectivity, absorptivity and roughness. These are vital for heat flow and light distribution. For example, if the roof of a building is painted white, then the transmission of heat can be reduced by upto 80% as compared to a dark colour.

Generally, the building components can be categorised into opaque and transparent elements. For example, a brick wall is an opaque element whereas a glazed window is a transparent element. Transparent elements allow direct solar radiation into the living spaces. Furthermore, an element may also be openable (e.g. skylight, window, door, etc), thereby allowing for air exchanges between the building and its surroundings.

Heat loss or gain from various building components may be reduced by insulating them appropriately. Walls, floors and roofs can be insulated by materials such as polyurethane foam (PUF), or thermocol, either externally or internally. Another mode of insulation is by incorporating an air cavity in the external building envelope. In cavity walls, the air gap inhibits the transmission of the heat into or out of the building as air acts as a bad conductor of heat. A brief description of various types of insulation is provided in Appendix III.2 [6]. Variations can be achieved by using different insulation materials, adjusting their thickness, and using them in different locations (internal or external). In cavity walls, the property of the air gap can be varied by opting for a ventilated or unventilated air cavity, and adjusting its thickness. It may be noted that water absorption adversely affects the performance of insulation materials.

The heat gain or loss through individual elements depends on whether the building is single storeyed or multi-storeyed. For example, in a typical single storeyed building, maximum heat gain occurs through the roof, whereas in a multi-storeyed building it is through the walls and windows. The heat gain through various building elements on the cooling load of a ground + 4 storeyed residential building for some cities of India is given in Table 3.2 [1]. It is seen that the maximum cooling load on an annual basis, is due to windows (52.9%-64.7%). The next to highest cooling load is due to conduction through walls (26.5%-36.4%). The cooling loads through the roof and ground are not significant as compared to walls and windows. Windows and walls together account for more than 80% of the cooling load in all cities. Thus, the control of solar gains through windows and conduction through walls should be an important consideration for reducing the cooling loads.

Table 3.2 Heat gain through various building components [1]

Building component	Ahmadabad (223.037 MWh)		Mumbai (201.892 MWh)		Nagpur (198.756 MWh)		Pune (137.764 MWh)	
	Cooling load (MWh)	Percentage of annual cooling load	Cooling load (MWh)	Percentage of annual cooling load	Cooling load (MWh)	Percentage of annual cooling load	Cooling load (MWh)	Percentage of annual cooling load
Walls	81.141	36.4	66.532	33.0	71.151	35.8	36.487	26.5
Roof	18.996	8.5	15.148	7.5	17.845	9.0	12.288	8.9
Ground	4.957	2.2	4.557	2.3	3.000	1.5	-0.129	-0.1
Window (Conduction + Direct Solar)	117.941 (28.563 + 89.378)	52.9 (12.8 + 40.1)	115.654 (17.405 + 98.249)	57.3 (8.6 + 48.7)	106.761 (19.608 + 87.153)	53.7 (9.9 + 43.8)	89.119 (6.180 + 82.939)	64.7 (4.5 + 60.2)

The heat gain through each element can be varied by:

- area of the element
- orientation and tilt of the element
- material properties (U-value, time lag, decrement factor, transmissivity, emmissivity, etc)
- finishes
- control of incoming solar radiation

(A) Roof

The roof of a building receives a significant amount of solar radiation. Thus, its design and construction play an important role in modifying the heat flow, daylighting and ventilation. As per Indian Standard I.S. code 3792 – 1978 [4], the maximum value of overall thermal transmittance (U-value) of a roof should not exceed 2.33 W/m^2-K in hot-dry, and warm and humid climates. The code recommends that the heat gain through roofs may be reduced by the following methods:

- Insulating materials may be applied externally or internally to the roofs. In case of external application, the insulating material needs to be protected by waterproofing treatments. For internal application, the insulating material may be fixed by adhesive or by other means on the underside of the roofs. A false ceiling of insulation material may be provided below the roofs with air gaps in between. Shining and reflecting material (e.g. glazed china mosaic) may be laid on top of the roof.
- Roofs may be flooded with water in the form of sprays or in other ways. Loss due to evaporation may be compensated by make-up arrangement.
- Movable covers of suitable heat insulating material, if practicable, may be considered.
- White washing of the roof can be done before the onset of each summer.

The second and fourth recommendations would be fully effective if the surfaces are kept clean, without accumulation of dust. The recommended thickness of some insulating materials for roofs is given in Table 3.3. Figure 3.7 [6] shows the reduction of ceiling surface temperature due to some of the above techniques for a flat roof in a hot and dry climate on two consecutive summer days. It is seen that the ceiling surface temperature can be reduced by about 10^0C.

A massive roof composed of material such as reinforced cement concrete (RCC) tends to delay the transmission of heat into the interior when compared to lighter roofs such as asbestos cement sheet roofing. Sometimes, the roof is also covered by inverted earthen pots with a layer of earth over them. The earth and the air inside the pots provide good insulation for resisting heat gain. A doubly pitched or curved roof provides a larger surface area for heat loss compared to a flat roof. Thus, both the shape as well as the material have an effect on the performance of the roof.

Table 3.3 Recommended thicknesses of a few insulating materials for roofs [5]

S. No.	Name and Type of Insulating Material	Density Range (kg/m^3)		Maximum Thermal Conductivity Value (W/m-K)	Optimum Thickness (m)			
		Minimum	Maximum		Flat Roof		Sloped Roof	
					NC	C	NC	C
1	Cellular concrete	320	350	0.081	0.05	0.075	-	0.10
2	Coconut pitch concrete	500	600	0.087	0.05	0.075	-	0.10
3	Light weight bricks	400	450	0.081	0.05	0.075	-	0.10
4	Vermiculite concrete	480	560	0.105	0.05	0.10	-	0.125
5	Wood-wool board	350	450	0.076	0.025	0.05	0.025	0.075
6	Foamtex	150	200	0.046	0.025	0.05	0.025	0.05
7	Thermocol	16	20	0.041	0.025	0.035	0.025	0.05
8	Fibreglass	24	32	0.041	0.025	0.035	0.025	0.05
9	Mineral wool	48	64	0.041	0.025	0.035	0.025	0.05
10	Fibre insulation board	200	250	0.053	0.015	0.025	0.015	0.205

NC: Non-air-conditioned C: Air-conditioned

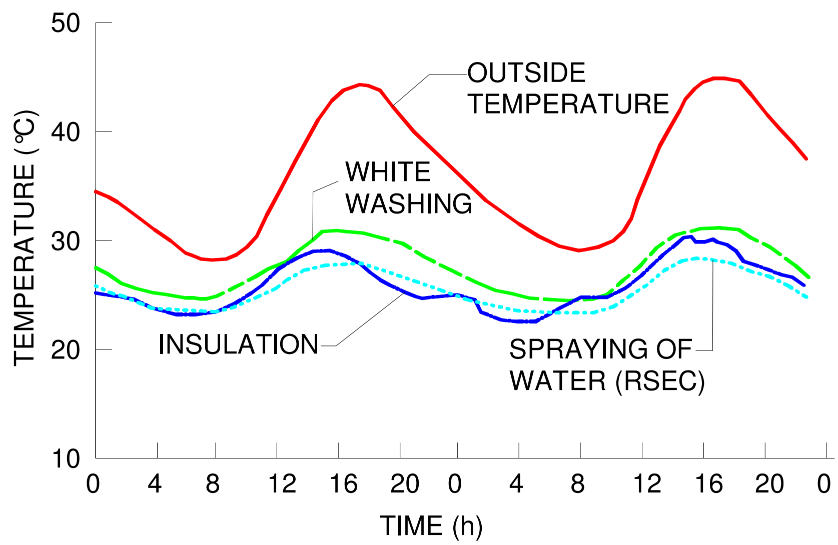


Fig. 3.7 Relative performance of different techniques on a flat roof [5]

The performance indicators such as U-values (thermal transmittance), damping, thermal performance index and thermal time constant of commonly used flat and sloped roofs have been discussed in SP:41 (S&T):1987 [5].

The roof can also be used advantageously for effective ventilation and daylighting by incorporating vents and skylights respectively.

(B) Walls

Walls constitute a major part of the building envelope and receive a large amount of direct radiation. Depending on whether the need is for heating or cooling, the thickness and material of the wall can be varied to control heat gain. The resistance to heat flow through the exposed walls may be increased in the following ways:

- The thickness of the wall may be increased
- Cavity wall construction may be adopted.
- The wall maybe constructed out of suitable heat insulating material, provided structural requirements are met.
- Heat insulating material may be fixed on the inside or outside of the exposed wall. In the case of external application, overall water proofing is essential.
- Light coloured whitewash or distemper may be applied on the exposed side of the wall.

The performance indicators, such as U-values (thermal transmittance), thermal damping, thermal performance index and thermal time constant of some typical wall constructions have been discussed in SP:41 (S&T):1987 [5]. The I.S. code 3972-1978 [4] specifies that the U-values of exposed walls should not exceed 2.56 W/m^2-K in hot and dry, and hot and humid regions. In warm and humid regions, they should not exceed 2.91 W/m^2-K.

(C) Ground-based Floors

Heat is transferred by conduction from the building to the ground through the floor which is in contact with the ground. The transfer of heat between the building and the ground occurs primarily via the perimeter of the building, and to a lesser extent through the central portion of the floor. In warmer climates, this heat loss is desirable from the point of view of comfort. On the other hand, in cold climates, heat loss through the ground needs to be minimised and hence insulation may be provided. The effectiveness of insulation under a floor will depend on factors such as the moisture content and temperatures of the ground. If the moisture content is high or the temperature is low, the tendency for heat to be lost through the floor to the ground will increase. In these instances, insulation (typically of U-value = 0.09 W/m^2-K) of thickness of 50mm and depth of 600mm should be provided along the entire perimeter of the slab. To improve performance, the entire slab should be insulated. Foundation insulation using foam board on the inside face of the foundation wall may also be provided. This protects both during construction and during the life of the building.

(D) Fenestration (openings)

Fenestration is provided for the purposes of heat gain, daylighting and ventilation. Their pattern and configuration form an important aspect of building design. Appropriate design of openings and shading devices help to keep out sun and wind or allow them into the building. Ventilation lets in the fresh air and exhausts hot room air, resulting in cooling.

While planning the position of a window, it must be remembered that the tendency of hot air is to rise. Openings at higher levels would naturally aid in venting the hot air out. The size, shape and orientation of the opening affect the speed and flow of air inside the building. For example, openings on opposite walls relieve high pressure on the windward side, permitting good cross-ventilation of the interior space. Also, a small inlet and large outlet increases the velocity and distribution of airflow through the room. The percentage changes in wind speed in a room due to various window locations and orientations are presented in Fig.

3.8 [5]. A negative sign indicates that the wind speed has decreased and a positive sign indicates an increase.

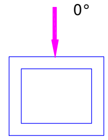
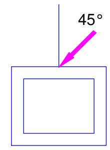
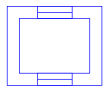
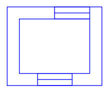
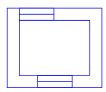
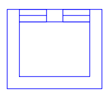
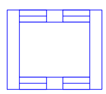
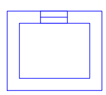
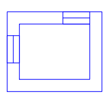
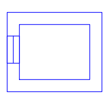
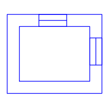
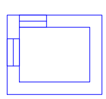
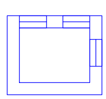
LOCATION OF WINDOWS	PERCENTAGE CHANGE IN VELOCITY OF AIR AS A FUNCTION OF ORIENTATION OF WIND (%)	
	0° 	45° 
	0	0
	-10	+40
	-10	-15
	-15	0
	-15	0
	0	0
	-10	+40
	-10	-15
	0	-60
	-20	-10
	-20	-60

Fig. 3.8 Effect of window location on indoor air motion [5]

Windows are usually glazed, that is, provided with glass. Generally, glass is transparent to solar radiation but opaque to long wave radiation. This characteristic can be used to heat a building interior by promoting heat gain. This is desirable in winter, but may cause overheating in summer. For reducing solar gain during summer, the window size should be kept minimum in the hot and dry regions. For example, in a city like Ahmadabad, the number of uncomfortable hours in a year can be reduced by as much as 35% if glazing is taken as 10 % of the floor area instead of, say, 20%. Thus, though natural light is introduced into the building through glazed openings, skylights, lightshelves, or clerestories, the amount of light and glare that enters needs to be controlled. This can be achieved by providing openable shutters and movable covers like curtains or venetian blinds (section 3.2.3). Besides, tinted glazing or glazing with surface coatings can be used to control solar transmission, absorption and reflection. For example, the direct transmission of solar radiation through a 6mm thick absorbing glass can be reduced by about 45% (Fig. 3.9). Reflective glass is usually made by coating the glass with a layer of reflective material or low emittance layer. Reflectivity could vary depending on whether the coating is on the outer or inner face of the glass (Fig. 3.10). Glazing of these types can reduce heat gain without obstructing viewing. They are usually used for windows which cannot be shaded externally.

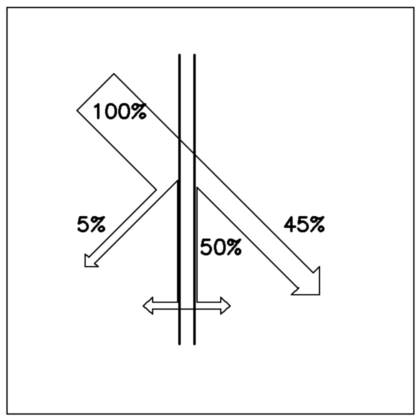


Fig. 3.9 Transmission properties of absorbing glass (6 mm thick)

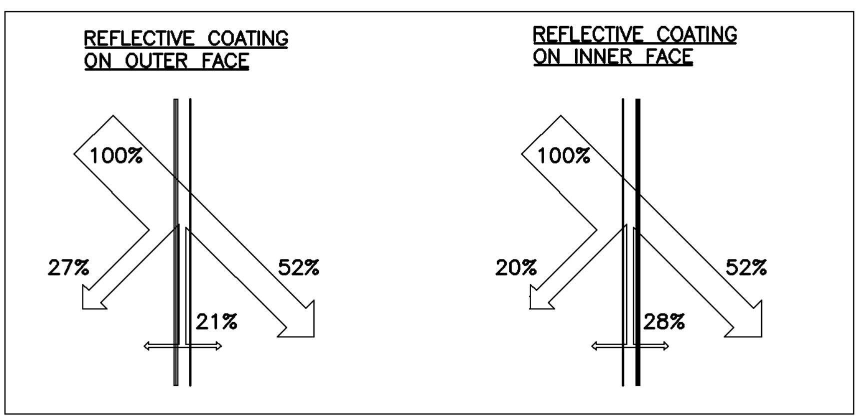


Fig. 3.10 Transmission properties of reflecting glass (6 mm thick)

I.S. Standard 3792-1978 [4] recommends that in the hot and arid, hot and humid, warm and humid and cold zones, no exposed window should have a shade factor of more than 0.5 and a transmittance (U-value) of more than 6.51 W/m^2-K for unconditioned buildings; for conditioned buildings, the corresponding values are 0.4 and 3.8 W/m^2-K respectively.

The thermal transmittance (U-values) of some doors and windows are given in Fig. 3.11 [5]. For heat insulation of exposed windows and doors, suitable methods should be adopted to reduce both solar heat and heat transmission

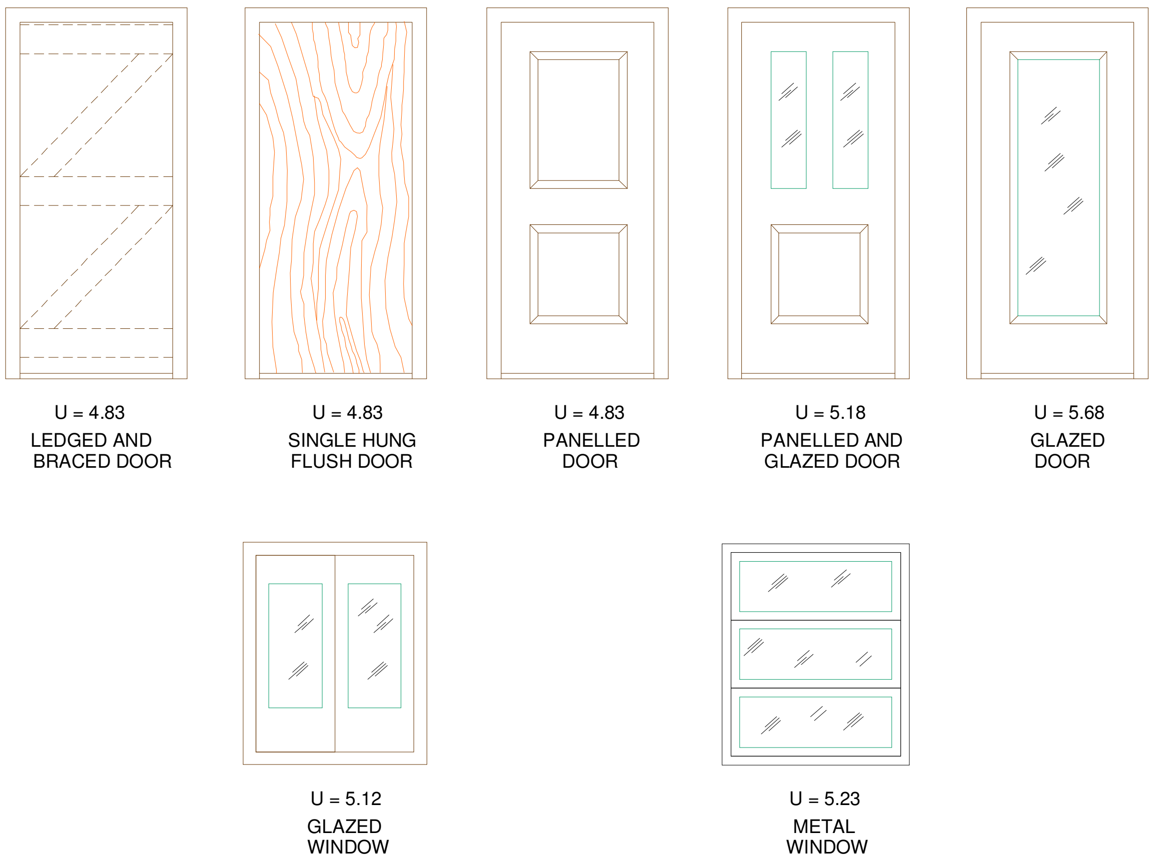


Fig. 3.11 Thermal transmittance of doors and windows [5]

This can be achieved by the following means:

- external shading such as louvered shutters, and sun breakers such as chajjas
- internal shading such as curtains and venetian blinds
- use of heat resistant glasses/ films
- use of double or triple glasses with air space in between (glasses are held apart by spacer bars and a desiccant is used to remove moisture)

Information regarding various types of glazing and their properties is given in Appendix III.3. Under the initiatives of the International Energy Agency (Task 18), a large number of institutes and research organisations are developing advanced glazing materials. The target is to develop the scientific, engineering and architectural basis necessary to support the appropriate use of advance glazing in buildings and other solar applications. Modern research has brought about significant developments in advanced glazing systems, in the form of new glazing types and window system encapsulations. There are many approaches to advanced glazing system design. These include smart windows, evacuated glazings, transparent insulation materials, monolithic and granular aerogels, low-emittance coatings, angular selective transmittance coatings, holographic and prismatic materials, and thermochromic and liquid crystal devices [7,8]. Commercial systems now exist for a few cases and are being developed for the remaining ones. A basic explanation of energy-efficient glazing has recently been reported by Bandyopadhyay [9]. A few of the advanced glazing systems are discussed briefly.

(i) Spectrally selective glazing

Spectrally selective glazing permits some portions of the solar spectrum to enter through it while blocking others. The glazing admits as much daylight as possible while preventing transmission of as much solar heat as possible. Consequently, such glazing when used in windows significantly reduces building energy consumption and peak demand; the capacity of the building's cooling system might also be downsized because of reduced peak loads. The spectral selectivity is achieved by a microscopically thin, low-emissivity (low-E) coating on the glass, or on a film applied to the glass, or suspended within the insulating glass unit.

Spectrally selective glazings can be combined with other absorbing and reflecting glazings to provide a whole range of sun control performance. They can be used in windows, skylights, glass doors, and atria of commercial and residential buildings. It may be noted that these glazings may not provide glare control even if solar gain is reduced.

Spectrally selective glazings offer a number of advantages such as:

- They are more transparent than tinted glazing, enabling occupants to have an unimpeded view and a sense of connection to the outdoors.
- They offer better night views than reflective and dark tinted glazings.
- From the exterior, the appearance of spectrally selective glazing is clear, and not mirrored or heavily tinted.

(ii) Angular selective solar control

From the point of view of daylighting of a building, the objective is to block or reflect direct sun light and admit diffuse light. Angular selective façades provide such control based on the sun's angle of incidence on the façade. These have high transmittance at low angles of incidence and much lower transmittance at slightly higher angles of incidence compared to normal glazing. Consequently, the solar radiation gets transmitted to the building interior during winter (due to lower elevation of the sun) and is prevented from entering the building when the sun has slightly higher elevations.

Variations on this theme include between-pane louvers, or blinds with a mirrored upper surface; these can be used in the clerestory portion of the window wall. In case of exterior glass lamellas (louvers), the upper surface can be treated with a reflective coating. These systems fully or partially block direct sun and redirect sunlight to the interior ceiling plane, given seasonal adjustments. Conventional louvered or venetian blind systems enable users or an automated control system to tailor the adjusted angle of blockage according to solar position, daylight availability, glare, or other criteria.

Frit is the most common angle-selective coating. It consists of a ceramic coating, either translucent or opaque, which is screen printed in small patterns on a glass surface. The pattern used controls the light based on its angle of incidence. The colour of frit controls reflection or absorption, the view and/or visual privacy. Visual transparency can also be controlled by applying frit to both sides of the glass to make it appear transparent in some angles and opaque in others. Angle-selective materials can be thought of as a series of fins or overhangs within a piece of glass, which filter or block light.

(iii) Smart windows

Smart windows are characterised by their ability to vary the visible light as well as solar radiation. This is achieved by incorporating a chromogenic material in the window. Generally, this is done in the form of a thin film having photochromic, thermochromic or electrochromic properties. As the terms suggest, these devices are activated by light, heat and electricity respectively.

Electrochromic windows

An electrochromic window is a thin, multi-layer assembly sandwiched between traditional pieces of glass. The outer two layers of the assembly are transparent electronic conductors. The next one is a counter-electrode layer and an electrochromic layer, with an ion conductor layer in between. When a low voltage is applied across the conductors, the ions move from the counter-electrode to the electrochromic layer. This causes the assembly to change color. When the voltage is reversed, the ions move from the electrochromic layer back to the counter-electrode layer; this restores the device to its previous clear state. The windows operate on a very low voltage -- one to three volts -- and use energy only to change their condition, and not to maintain any particular state. The glass may be programmed to absorb only part of the light spectrum.

Thermochromic windows

Thermochromic windows alter their properties due to heat. In response to changes in the ambient temperature, clear thermochromic glazings become diffused. Among the thermochromic technologies, gel-based coatings seem to be the most promising. In addition to automatically changing from clear to diffuse in response to heat, the glazings also turn white and reflective, thereby reducing the transmission of solar heat. This property can reduce air conditioning costs significantly when the outside is quite hot. As one cannot see through the window once it loses its transparency, this glazing is probably better suited for skylights rather than view windows.

Photochromic windows

Photochromic windows respond to changes in light, much like sunglasses that darken when one moves from a dim light to a bright one. They work well to reduce glare, but don't control heat gain. This is because the amount of light that strikes a window does not necessarily correspond to the amount of solar heat a window absorbs. Photochromic windows are still in the development stage and are yet to be tested successfully on a large-scale and commercial level.

Smart windows hold promise for reducing energy demands and cutting air conditioning and heating loads in the future. They offer the next major step in windows that are increasingly sophisticated and energy efficient.

(E) External colour and texture

The nature of the external surface finish determines the amount of heat absorbed or reflected by it. A smooth and light-coloured surface reflects more heat and light; a rough textured surface causes self-shading and increases the area for re-radiation. White or lighter shades have higher solar reflectivity and therefore are ideally used for reducing heat gain in warmer climates. Moreover, a heavy texture on these light-coloured surfaces helps to reduce the glare. Dark colours absorb more radiation, which increases heat gain through the surface, and can thus be used in cooler regions. An example of the effect of the colour of external surfaces in the four cities of Ahmadabad, Mumbai, Nagpur and Pune is given in Table 3.4 and 3.5 [3]. It is seen that in all cities, a white painted surface outperforms all other colours in terms of lowering room temperatures.

Table 3.4 Effect of colour of external surfaces on room temperatures in different climatic zones [3]

Colour (Absorptivity, Emissivity)	Ahmadabad (Hot and Dry)					Mumbai (Warm and Humid)				
	Yearly min (˚C)	Yearly max (˚C)	Yearly avg (˚C)	H_{25}^{Y} (h)	H_{30}^{Y} (h)	Yearly min (˚C)	Yearly max (˚C)	Yearly avg (˚C)	H_{25}^{Y} (h)	H_{30}^{Y} (h)
White painted surface (0.3, 0.9)	20.6	42.2	29.7	7140	3908	24.5	34.6	29.6	8605	3350
White-washed surface (0.4,0.9)	20.8	42.5	30.0	7319	4123	24.8	34.9	29.8	8667	3654
Dark grey surface (0.9,0.9)	21.9	44.0	31.1	7830	5599	26.0	36.1	30.9	8760	5535
Cream surface (0.4,0.9)	21.2	43.0	30.4	7498	4739	25.3	35.3	30.2	8760	4320
Red surface (0.6, 0.9)	21.2	43.1	30.4	7498	4739	25.2	35.4	30.2	8760	4412

H_{25}^{Y} : Number of hours for which room temperatures exceed 25 ºC in a year

H_{30}^{Y} : Number of hours for which room temperatures exceed 30 ºC in a year

min : minimum; max : maximum; avg : average

Table 3.5 Effect of colour of external surfaces on room temperatures in different climatic zones [3]

Colour (Absorptivity, Emissivity)	Nagpur (Composite)					Pune (Moderate)				
	Yearly min (˚C)	Yearly max (˚C)	Yearly avg (˚C)	H_{25}^{Y} (h)	H_{30}^{Y} (h)	Yearly min (˚C)	Yearly max (˚C)	Yearly avg (˚C)	H_{25}^{Y} (h)	H_{30}^{Y} (h)
White painted surface (0.3, 0.9)	20.4	40.1	29.2	7067	2957	22.0	34.4	27.4	7078	1926
White-washed surface (0.4,0.9)	20.7	40.3	29.5	7220	3139	22.3	34.7	27.7	7319	1957
Dark grey surface (0.9,0.9)	22.2	41.7	30.9	7923	4408	23.7	35.9	28.8	8171	2682
Cream surface (0.4,0.9)	21.4	40.9	30.1	7494	3715	23.0	35.2	28.2	7894	2172
Red surface (0.6, 0.9)	21.3	40.9	30.1	7494	3687	22.9	35.2	28.1	7864	2140

3.3 PASSIVE HEATING

3.3.1 Direct Gain

Direct gain is a passive heating technique that is generally used in cold climates. It is the simplest approach and is therefore widely used. In this technique, sunlight is admitted into the living spaces directly through openings or glazed windows. The sunlight heats the walls and floors, which then store and transmit the heat to the indoor environment. The main requirements of a direct gain system are large glazed windows to receive maximum solar radiation and thermal storage mass.

During the day, the affected part of the house tends to get very hot, and hence, thermal storage mass is provided in the form of bare massive walls or floors to absorb and store heat. This also prevents overheating of the room. The stored heat is released at night when it is needed most for space heating. Carpets and curtains should not be used to cover floors and walls used as storage mass because they impede the heat flow rate. Suitable overhangs for shading and openable windows for ventilation must be provided to avoid overheating in the summer. Thus a direct gain system has the following components: (a) glazing – to transmit and trap the incoming solar radiation, (b) thermal mass – to store heat for night-time use, (c) insulation – to reduce losses at night, (d) ventilation – for summer time cooling, and (e) shading – to reduce overheating in summer. A schematic diagram showing the components of direct gain system is given in Fig. 3.12. Reflectors may be provided outside windows to increase the efficiency of the direct gain system. Clerestories and skylights may also be used to gain heat. For example, clerestories used as a direct gain system in a restaurant in New Mexico, USA can maintain an indoor temperature of about 15^{o}C as compared to an outside temperature of –1.0^{o}C [10].

Direct gain is the most common, simple, cheap and effective heating approach. However, overheating, glare and degradation of building materials due to ultraviolet radiation are some of its disadvantages.

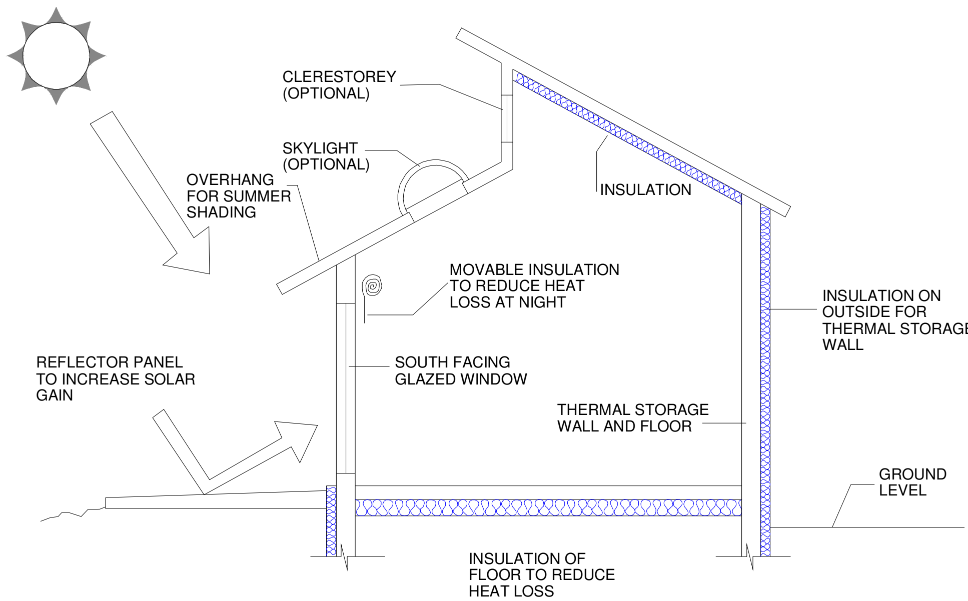


Fig. 3.12 Components of a direct gain system

Components:

Glazed windows

The principal function of a glazed window in a direct gain approach is to admit and trap solar energy so that it can be absorbed and stored by elements within the space. In winter, the sun's altitude is low and its movement is in the southern part of the sky in northern hemisphere. Hence, the window must face south in the northern hemisphere as it receives maximum solar radiation in this direction. Large expanses of south-facing windows used for heating in direct gain applications can, if properly designed, gain significantly more energy than they lose. The orientation of the window may vary by upto 20% east or west of the south without significantly affecting the thermal performance. A slight east-of-south orientation may be desirable to allow the sun to penetrate the living space in the mornings.

Table 3.6 Effect of window-types in cold climates

Place	Annual load (GJ/year)	
	Single clear glass	Double clear glass
Srinagar	212.0	172.0
Leh	416.0	329.0

Table 3.6 presents the effect of window-types for a conditioned residential bungalow in for Srinagar and Leh which represent (i) cold and cloudy, and (ii) cold and dry climates respectively. It is seen that a significant reduction in heat loss can be achieved by using double glazing. Triple glazing may be provided in places that experience severe winters.

Figure 3.13 shows an example of a wooden-framed, double glazed and double rebated window. The extra rebate is provided to reduce infiltration.

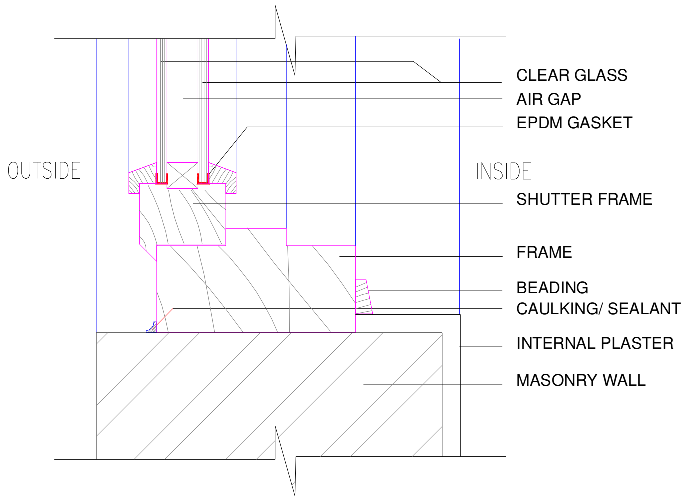


Fig. 3.13 Details of a double glazed window

Thermal Storage Mass

In direct gain systems, solar energy can be stored in the floor, walls, ceiling, and/or furnishings of the living space if these components have sufficient capacity to absorb and store heat for use at night. Materials such as concrete, brick and water have this capability and can be used effectively in direct gain applications. Also used, are phase change materials (PCM) such as salt or wax that store thermal energy when they melt and release heat when they solidify [11].

Care should be taken to ensure a balanced distribution of mass throughout the living space. In general, a thin material spread over a larger area will perform better than thick material concentrated in one part of the space.

Generally, for every square metre of south-facing glazing area, 30 percent of storage area should be provided to receive direct sunlight. The thickness of the storage floor material should be 50 to 150 mm, and that of walls should be 50 to 100 mm [12]. The masonry units used should be solid with full mortar bedding. Storage mass exposed to direct sunlight should be dark in colour to absorb more heat. It is generally more thermally efficient to provide thicker rather than thinner storage mass. However, there is an optimum thickness. For example, in case of the floor being used as the storage mass, the storage effect increases as its thickness increases. For a thickness beyond 100mm, the rate of increase in the storage effect is not significant. In fact, the performance decreases for thicknesses greater than 200mm.

Variations and Controls:

Thermal storage materials can be concrete, bricks, stone or water in containers. The thermal mass is typically located in the external walls, internal walls or floors that receive direct sun. Direct gain can be admitted through various forms of openings like clerestories, skylights, greenhouses or glass curtain walls. The colour of internal surfaces also plays an important role in absorbing radiation, and distributing of daylight. Darker colours absorb more heat than lighter colours as pointed out earlier. As far as the distribution of light is concerned, lighter shades are preferred indoors. Thus, the storage surfaces should be of medium-dark colour, whereas lightweight materials should have light colours to reflect sunlight on the masonry walls or floors. Reflectors may be provided outside the windows, clerestories and skylights to increase the efficiency of the direct gain system.

Reflectors can be placed horizontally above or below a window. In cases where physical obstructions (e.g. trees or other buildings) on or around the building site shade the window, the provision of reflectors can often increase solar collection by about 30-40%. They are usually panels coated on one side with a material of high reflectance. When the windows extend all the way to the ground (e.g. french window or patio door), the reflectors are simply laid on the ground in front of them. They should be placed so that they slope slightly away from the window to increase the amount of reflected sunlight and to facilitate drainage (5% is recommended). The size of the reflector panel should be of the same width as the window, and roughly 1 to 2 times the height. To be economically and aesthetically justifiable, they should also be insulated so that they can serve as movable insulation when not in the reflecting mode. It should be noted that reflecting panels may cause glare and/ or overheating problems within the direct gain living spaces. Light-coloured exterior landscape elements such as patios or terraces, can also serve as reflectors. They will not perform as efficiently as panels with high reflectance, but they will reduce the possibility of glare and overheating.

While windows can admit and trap a great deal of solar energy during clear sunny days, they can also lose a great deal of heat during prolonged overcast periods and at night. Providing some form of movable insulation can result in a significant increase in overall thermal performance. In severe climates, windows may be net energy losers if movable insulation is not provided. There are two basic types of movable insulation: those applied to the outer face of the collector, and those applied on the inside. Both can effectively reduce heat loss during the heating season (winter) and when used like shades, at preventing excessive heat gain during the cooling season (summer). These devices can be hand operated or motor driven. Care must be taken to ensure a very tight seal between the insulation and the collector to avoid heat loss around the edges of the insulation.

To avoid excessive heat gain in the cooling season and to increase overall system performance, some provision should be made for shading the windows. Common external shading devices are overhangs (fixed or adjustable), trellises, awnings, louvers (horizontal or vertical, fixed or adjustable), and wing walls. Interior shading devices, while often not as thermally effective as exterior units, are generally easier to operate and maintain. Common interior shading devices include roller shades, blinds, drapes, and movable panels. For optimum overall performance of the system, these shading elements should also be designed to provide insulation during the day in the cooling season and at night in the heating season. Exhausts and vents can be employed to cool the interior spaces through ventilation when the temperature rises beyond the comfort level.

Heat losses can also be controlled by providing insulation on the storage mass. Direct gain storage walls and floors that are exposed to the outside should be insulated on their exterior surfaces. Insulating the interior surface of a storage wall effectively nullifies any thermal storage capability of the wall, because it prevents solar energy from being absorbed by the wall. Therefore, insulation should be placed on the outside of any exterior wall, above and below the plinth that is used for thermal storage. Similarly, floors should also be insulated on the outside.

Remarks and Practical Considerations:

A direct gain system causes large temperature swings (typically 10 ℃) because of large variations in the input of solar energy to the room. Joint reinforcement should therefore be provided to control cracking caused by thermal movement and shrinkage. Expansion joints should be provided at the connection between floors and masonry walls to prevent cracking. Insulation must be protected wherever it is exposed. Cement plaster over chicken mesh or wire lath or other methods may be employed. Where damp-proofing is used, it should be allowed to completely cure before applying insulation. Care must be taken to ensure a tight fit between any insulation and the glass to reduce heat loss at the edges. Continuous sill sealer is recommended to provide protection against infiltration. In cooler climates, continuous insulation should be used under the slab which is used as storage mass, and a vapour barrier should be placed directly under the slab.

Example:

The Himurja office building located in Shimla, Himachal Pradesh employs the direct gain technique for heating in a cold and cloudy climate. Inside temperatures of 18 to 28 °C compared to outside air temperatures of 9 to 15 °C in January have been recorded. The building does not require any auxiliary heating during winters [13].

3.3.2 Indirect Gain

3.3.2.1 Thermal storage wall

Thermal storage wall systems are designed primarily for space heating purposes. In this approach, a wall is placed between the living space and the glazing such that it receives maximum solar radiation (generally the southern face of the building in the northern hemisphere). This prevents solar radiation from directly entering the living space; instead, the collection, absorption, storage and control of solar energy occur outside it. The glazing reduces heat loss to the ambient. Windows can also be integrated into the thermal storage wall to provide light, view and some direct gain heating. Movable insulation can be applied outside the glazing façades or in the airspace between the glazing and the storage wall to reduce heat loss at night. Shading and reflecting devices are typically placed on the exterior.

Different types of storage walls are discussed in this section.

(a) Trombe wall

A Trombe wall is a thermal storage wall made of materials having high heat storage capacity such as concrete, bricks or composites of bricks, block and sand. A typical Trombe wall is illustrated in Fig 3.14. The external surface of the wall is painted black to increase its absorptivity and is placed directly behind the glazing with an air gap in between. Solar radiation is absorbed by the blackened surface and is stored as sensible heat in the wall. In an unvented wall, the stored heat slowly migrates to the interior, where it heats the adjacent living space. If properly designed, the wall can provide adequate heat to the living space throughout the night. Some of the heat generated in the air space between the glazing and the storage wall is lost back to the outside through the glass. The hotter the air in the airspace, the greater is the heat loss. This heat loss can be reduced by venting the storage wall at the top and bottom. Such units are called as ‘vented Trombe walls’. The air, in the space between the glazing and the wall gets warmed up and enters the living room through the upper vents. Cool room air takes its place through the lower vents, thus establishing a natural circulation pattern (thermocirculation) that needs no mechanical means for moving the air.

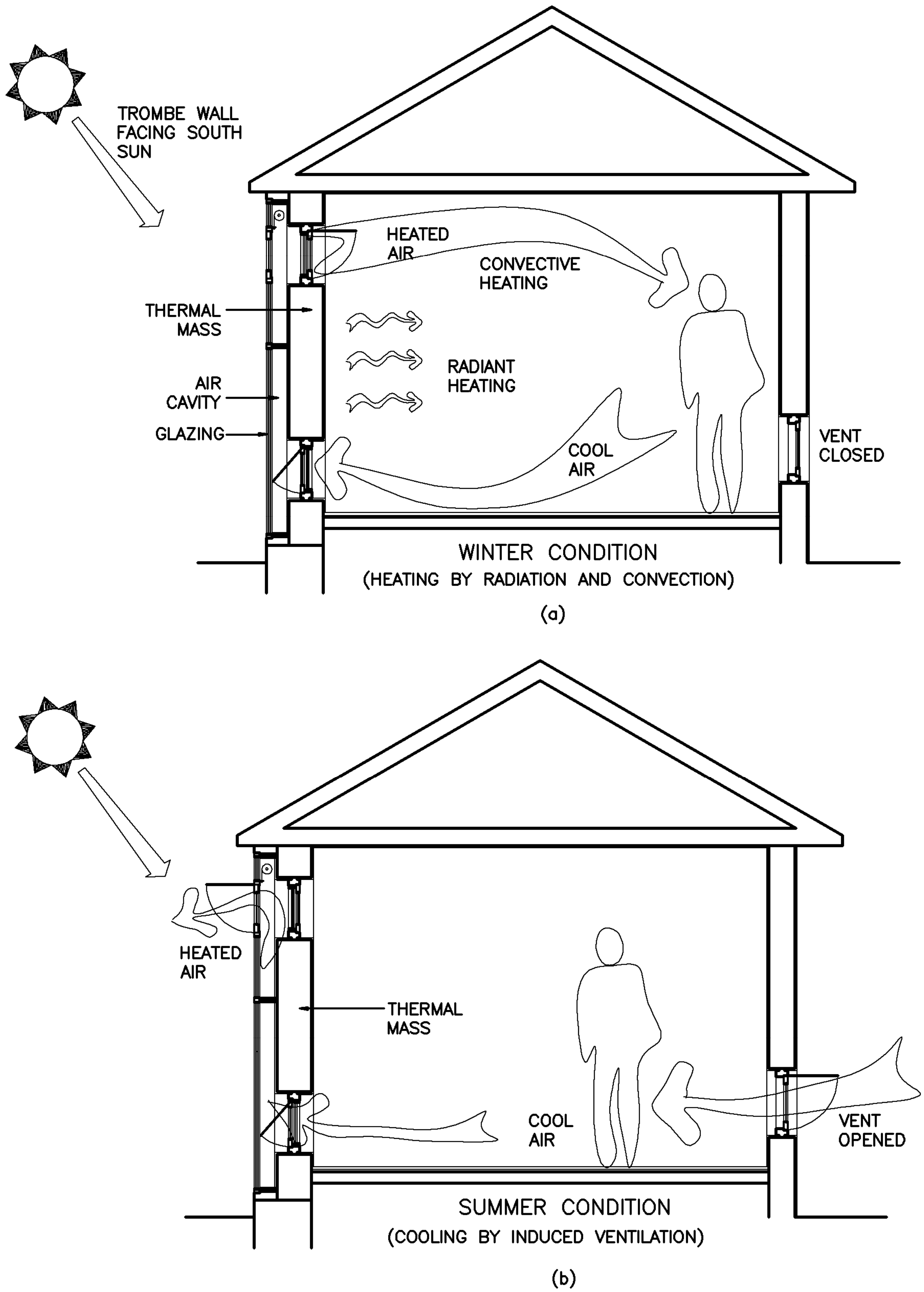


Fig. 3.14 Working principle of a Trombe wall

A part of the absorbed heat is conducted through the wall and is transferred to the living space by convection and radiation. This process is illustrated in Fig. 3.14a. Thus, vented Trombe walls are suitable for buildings having daytime use, such as offices and shops. Care should be taken to ensure that the circulation pattern does not reverse itself at night. This is because temperatures in the airspace drop at night leading to warm air from the living space flowing into the airspace. This warm air then pushes the cooler air in the airspace into the living room. Thus, the heat may actually be lost from the living space to the environment by the Trombe wall. To prevent such reverse circulation, simple backdraft dampers or openable louvers need to be provided on the upper vents.

In a vented system, due to circulation of hot air, the amount of heat available for storage by the Trombe wall is reduced. An unvented system does not lose heat in this way and thus has the advantage of storing a greater percentage of the solar energy available to it than does a vented wall. This stored heat is, however, not readily available for immediate use, instead, it is transferred slowly into the living area. Hence, un-vented Trombe walls are provided for residences, which require heating mainly during the night. Furthermore, in cold climates where daytime as well as night-time heating requirements are high, it is desirable to provide a certain amount of heat directly to the living space. In such situations, a vented wall may be provided. In more moderate climates where daytime heating is not as important as night-time heating, an unvented system may be preferable. The thickness and thermal properties of the wall materials determine the time lag of the heat travelling from the outside surface of the unvented wall to the interiors. This may vary from several hours to an entire day.

A Trombe wall offers several advantages. Glare, and the problem of ultraviolet degradation of materials is eliminated as compared to the direct gain system. The time lag due to the storage wall ensures that heat is available at night when it is needed most. Besides, one is able to provide sufficient storage mass in a relatively small area. However, a storage wall can block view and daylight. It is desirable to provide movable insulation between the glazing and storage wall; otherwise, the stored heat can be lost to the ambient at a very high rate at night due to the difference in temperature between the ambient and the storage wall. It is noteworthy that in buildings with thermal storage walls, the indoor temperature can be maintained at about 15^{o}C when the corresponding outside temperature may be as low as –11^{o}C [10].

During summer months, when the sun's altitude is high, an overhang is required to cut off direct sunshine. The Trombe wall can provide induced ventilation for summer cooling of the space as shown in Fig. 3.14b. Here, the heated air in the collector space flows out through exhaust vents at the top of the outer glazing, and air from outside enters the space through openings on the cooler side to replace the hot air. This continuous air movement cools the living space.

A section of the Trombe wall is shown in Fig. 3.15 giving various construction details. It consists of a number of components such as, (a) glazed walls – to transmit the incoming solar radiation, (b) thermal mass – to store heat for night-time use, (c) air space for trapping heat, and in case of vented wall, to transfer heat by convection, (d) movable insulation in air space– to reduce losses at night, (e) vents in glazed walls and storage walls – for circulating hot air, and in summer for exhausting heat, and (f) shading – to reduce overheating in summer. Reflectors may be provided outside the glazing to increase the efficiency of the Trombe wall system. Generally, the thickness of the storage wall is between 200–450 mm, the air gap between the wall and the glazing is 50–150 mm, and the total area of each row of vents is about 1% of the storage wall area [10,12].

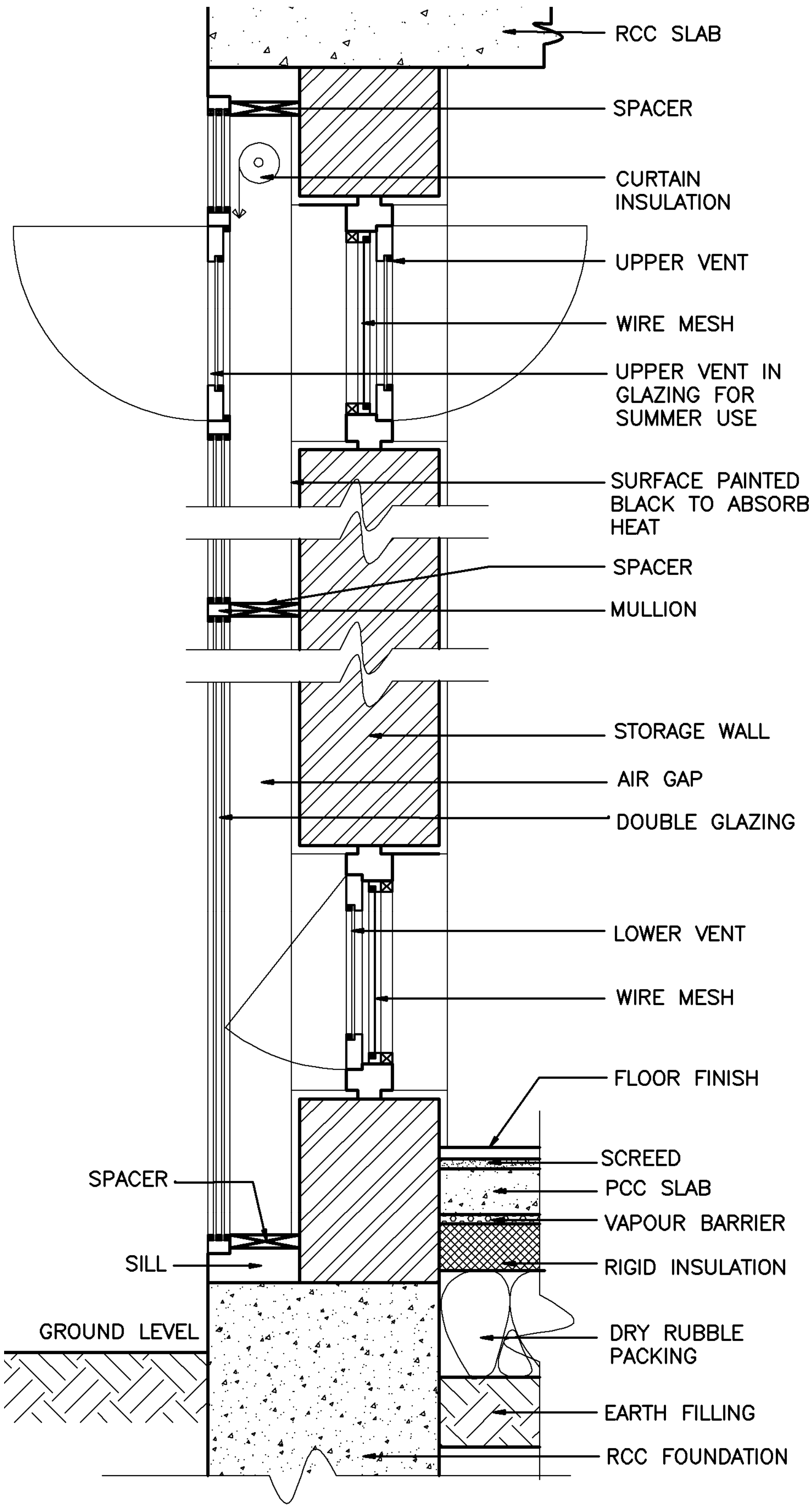


Fig. 3.15 Details of a Trombe wall

Components:
Glazing

The principal function of the glazing in a Trombe wall is to admit and trap solar energy so that it can be absorbed and stored by the thermal storage wall. The Trombe wall must face south in the northern hemisphere to receive maximum solar radiation. A small variation in the orientation of the wall (east or west of the south) does not significantly affect the thermal performance. Using double glazing reduces heat loss compared to a single glazing. If metal framed glazing is used, it should be separated from the wall either by a space or a wood block, to avoid conductive heat losses from the wall through the metal to the outside. Seasoned wood may be used in place of metal. Paints applied on the frames should be able to withstand high temperatures which may go upto 60 °C. The frames should allow for significant expansion (minimum 12mm), particularly in unvented walls. Caulking and sealants must be able to accommodate such movement. The glazing material itself can be glass, fibreglass, acrylic or polycarbonate. and should be able to withstand high temperatures. Vents may be provided in the glazing panels for summer-time exhaust of hot air from the cavity to the ambient. The surface area of the glazing should be equal that of the storage wall.

Thermal Storage Mass

The effect of a thermal storage wall is largely determined by the wall's thickness, type of material and the colour of the external surface. Materials with high thermal capacity (concrete, brick, and water) and phase change materials (PCM) can be used effectively in Trombe walls. The recommended thickness for different materials is given in Table 3.7 [10]. The table also shows the effect of the wall thickness on the daily fluctuation of indoor air temperature. Generally, it is seen that the thicker the wall, the better is its performance. The values given in the table are for clear winter days, and correspond to a wall with its external surface painted dark and having double glazing.

Table3.7 Recommended thickness for various thermal storage walls and their effect on indoor temperatures [10]

Material	Thermal conductivity (W/m-K)	Recommended thickness (m)	Approximate indoor temperature fluctuation[1] as a function of wall thickness (°C)				
			0.2m	0.3m	0.4m	0.5m	0.6m
Adobe	0.519	0.20 to 0.30	10.0	3.9	3.9	4.4	-
Brick (common)	0.727	0.25 to 0.35	13.3	6.1	3.9	-	-
Concrete (dense)	1.731	0.30 to 0.45	15.6	8.9	5.6	3.3	2.8
Brick (magnesium additive[2])	3.462	0.40 to 0.60	19.4	13.3	9.4	6.6	5.0
Water[3]	0.575 (at 10°C)	0.15 or more	10.0	7.2	6.1	5.6	5.0

1. Assuming a double glazed wall. Values are given for clear winter days.
2. Magnesium is added to give bricks a dark colour and also increase thermal conductivity.
3. If water is used in tubes or other circular containers, use at least 0.23 m diameter tubes or 0.15 m^3 of water for every 1 m^2 of glazing.

Storage mass exposed to direct sunlight should have dark colour to absorb solar radiation. To improve performance, selective coatings can also be applied on the exposed surface of storage walls. These coatings have high absorptivity for incoming solar radiation and low emissivity for re-radiation. The interior surface of the wall may be painted or left untreated. The area of the vents for thermocirculation should be about 2% of the wall area, divided evenly between upper and lower vents.

Variations and controls:

The distribution of heat into the living space can be almost immediate or delayed depending on air circulation. Furthermore, the delay can be varied depending on the thickness of the wall, and the time-lag property of the wall materials. If the vents are provided with dampers, the air flow can be controlled.

Shading, reflector panels and insulation controls are more or less the same as those for direct gain systems. Overheating during summer may be prevented by using fixed exterior shades or movable curtains within the air space. For optimum performance, these curtains or shading devices should also be designed to provide insulation during the day in the cooling season, and at night in the heating season.

Another variation is due to wall materials. In addition to conventional building materials, Phase change materials (PCM) can be used as storage materials for thermal storage wall, because they have a greater ability to store and release heat during phase changes. Also, for a given amount of heat storage, PCMs require less space than any sensible storage and are much lighter in weight. They are therefore, convenient for use in retrofit of buildings.

Commonly used PCMs are hydrated salts and hydrocarbons. Of the hydrocarbons, paraffin wax has been very popular in building applications. Also used are, (a) a mixture of stearic acid, paraffin (80%) and mineral oil, and (b) sodium decahydrate. While hydrated salts are inexpensive and can store more heat than a hydrocarbon, their properties degrade with prolonged use; they are also corrosive. On the other hand, hydrocarbons are flammable and require careful handling.

Remarks and Practical Considerations:

The Trombe wall due to its complex construction and weight, may require special foundations and footings. The availability of daylight and view to the exterior are affected by the presence of a Trombe wall, and therefore must be taken care of by other design features. The temperatures in the air space can be quite high. Joint reinforcement should therefore be provided to control cracking caused by thermal movement and shrinkage. Creaking can be prevented by providing expansion joints at the connection between concrete or masonry floors, and the storage walls. Sealants and caulking should also be of high quality to avoid degradation due to high temperatures. Continuous sill sealer is recommended to provide protection against infiltration. Periodic maintenance is required to check whether sealants have cracked. Joints also need to be inspected; otherwise the performance of the Trombe wall may be affected due to infiltration of cold ambient air. The accumulation of dust on the glass and on the dark absorbing surface would deteriorate the performance. Hence, provision for cleaning the glass and wall needs to be made. This has been done in the HP state Co-operative Bank in Shimla, which has incorporated the Tombe wall as a passive heating systems in the building.

Example:

Trombe walls have been successfully used in the cold regions of Leh. In case of LEDeG (Ladakh Ecological Development Group) Hostel at Leh, the temperatures inside the bedrooms have been recorded to be above 8 °C corresponding to outside temperatures of –17 °C [13].

(b) Water wall

Water walls are based on the same principle as that of the Trombe wall, except that they employ water as the thermal storage material. Water walls can store more heat than concrete walls because of the higher specific heat. A water wall is a thermal storage wall made up of drums of water stacked up behind glazing. It is painted black externally to increase the absorption of radiation. The internal surface can be painted with any other colour and can be in contact with the interior space directly, or separated by a thin concrete wall or insulating layer. A view of the same is shown in Fig. 3.16. As the storage in the water wall is a convective body of mass, heat transfer is very rapid compared to a masonry wall. Table 3.8 gives the typical wall area required for maintaining the living space temperatures between 18 and 24°C for different ambient conditions on a clear day (solar radiation > 4 kWh/m^2-day) [11].

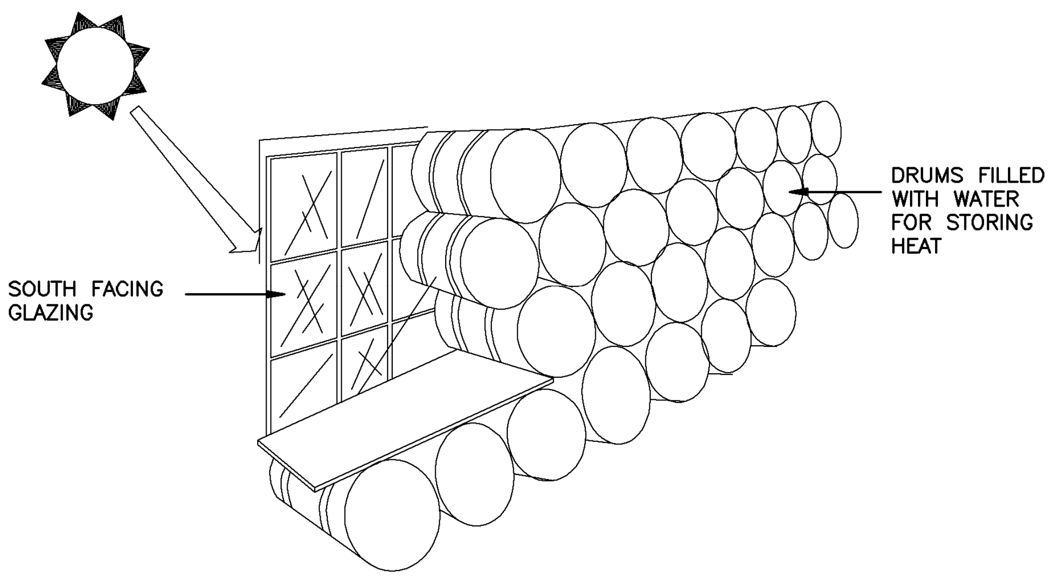


Fig. 3.16 Water wall

Table 3.8 Sizing a water wall for different climatic conditions (Calculated for a mean U-value of 1.9 to 2.1 W/m^2-K for a room) [10,11]

Average winter outdoor temperature (°C)	Area of wall needed for each square metre of floor area (m^2)
-4.0	0.70
-1.0	0.55
2.0	0.45
5.0	0.35

Variations and controls:

A large storage volume provides longer and greater storage capacity, while smaller units enable faster distribution. In order to fix the quantity of water, the thumb rule is usually taken as 150 litres of water per square metre of south oriented water wall. A variety of containers like tin cans, bottles, tubes, bins, barrels, drums, etc., provide different heat-exchange surfaces to the storage mass ratio. Care should be taken to ensure that steel and metal containers are lined with corrosion resistant materials. Also, the water should be treated with algae retardant chemicals. Troughs should be provided as a precaution against leakage of water from containers or from condensation.

Heat transfer through a water wall is much faster than through a Trombe wall. So a control on the distribution of heat is needed, if it (heat) is not immediately necessary for the building. This can be effected by using a thin concrete layer or insulating layer, or by providing air circulation through vents. Buildings like schools or government offices which work during the day, benefit from the rapid heat transfer in water walls. To reduce heat losses, the glazing of the water wall is usually covered with insulation at night. Overheating during summer may be prevented by using movable overhangs.

(c) Transwall

Transwall is a thermal storage wall that is semitransparent in nature. It partly absorbs and partly transmits the solar radiation. The transmitted radiation causes direct heating and illumination of the living space. The absorbed heat is transferred to the living space at a later time. Heat loss through the glazing is low, as much of the heat is deposited at the centre of the transwall ensuring that its exterior surface does not become too hot. Thus, the system combines the attractive features of both direct gain and Trombe wall systems.

A transwall has three main components:

- Container made of parallel glass walls set in metal frame.
- Thermal storage liquid, which is generally water.
- A partially absorbing plate set at the centre of the transwall, parallel to the glass walls.

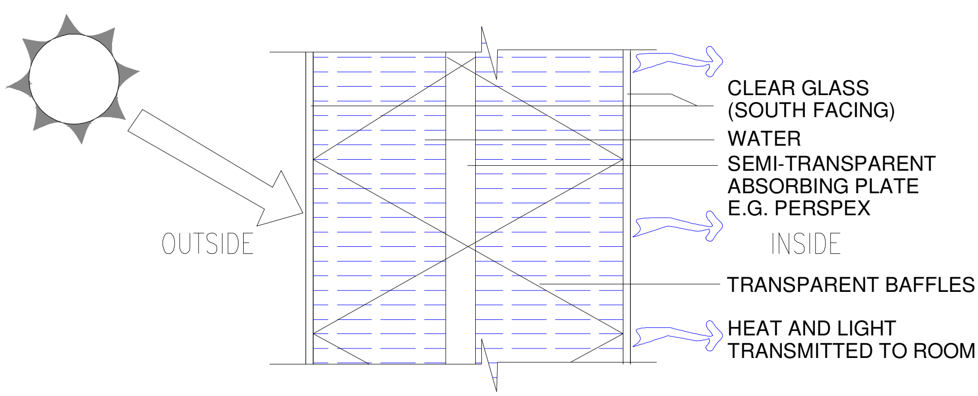


Fig. 3.17 Typical section of a transwall

Figure 3.17 illustrates the typical section of a Transwall. It is installed on the south side of the building (in the northern hemisphere), located directly behind double glazing. To prevent the growth of micro-organisms in the storage, an inhibiting agent may be added.

Variations and controls:

The dimensions of the storage module are dictated by the hydrostatic pressure exerted by the liquid. Also important, are the considerations of transportation, the method of installation, the ways of filling and draining the module, and attachment of the modules to each other and integration with the building.

As the storage is a convective body of water, the transfer of heat is rapid. This can be regulated by providing baffles and adding a gelling compound. Baffles are transparent plates which connect the module walls with the absorbing plate and prevent water movement. The gelling compound increases the general flow resistance.

3.3.2.2 Roof top collectors

There are a few interesting examples of passive heating systems that can be incorporated as part of the roof. Thermosyphon air panels and roof radiation traps are examples of such systems. A brief description of each is given in this section.

(A) Thermosyphon air panels

A thermosyphon air panel is essentially an absorbing surface, with minimum thermal inertia on the south face (in northern hemisphere) of the building and a glazing over it, thus forming a solar air heater. It absorbs incident solar radiation and heats up the air in the absorber-glazing space. A well-insulated collector limits the heat loss to the outside. The hot air forces itself into the living space through the vents, and warms it up. Cooler air takes its place and the cycle is repeated. In addition to heating the space, heat can also be stored for later use by passing the hot air through a storage mass. Figure 3.18 and 3.19 illustrate the working principle and detail section of this type of collector respectively.

The storage is generally the inner structure of the building like an internal wall and/or a concrete ceiling which is not exposed to the outside, thereby minimising the heat loss to the outside. Besides, during the evening and night hours, the well-insulated collector serves as a thermal buffer between the house and the external atmosphere, and eliminates the need for movable insulation.

Dampers and ducts can be used to control the air-flow either to the storage unit or directly into the living space. The thermal storage may be suitably designed to realise a desired time lag for the distribution of heat to the living space.

In summer, when relief from high temperatures is required, the system can be modified to act as a ventilation device. In this case, the hot air is not allowed to enter the room. On the other hand, the room air enters the collector, gets heated up and is vented out at the top. This creates a low pressure in the room, leading to cooler air being sucked into the room from windows. This process continues throughout the day and is known as induced ventilation. Such a system is shown in Fig. 3.20.

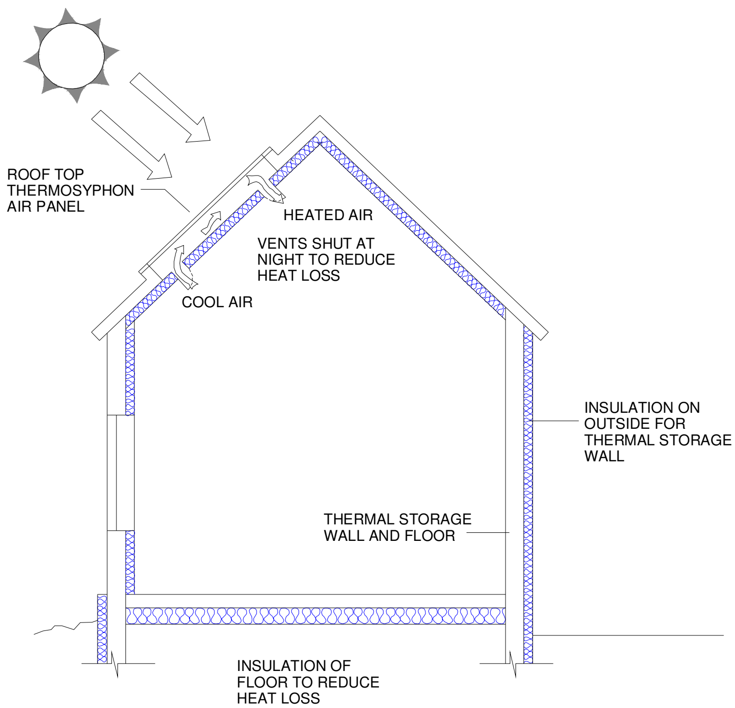


Fig. 3.18 Thermosyphon air panel: working principle

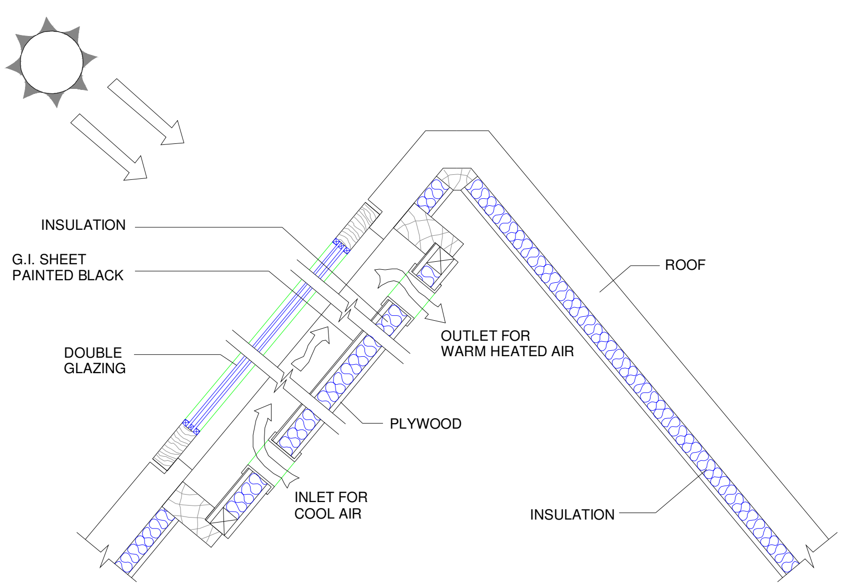


Fig. 3.19 Details of a thermosyphon air panel

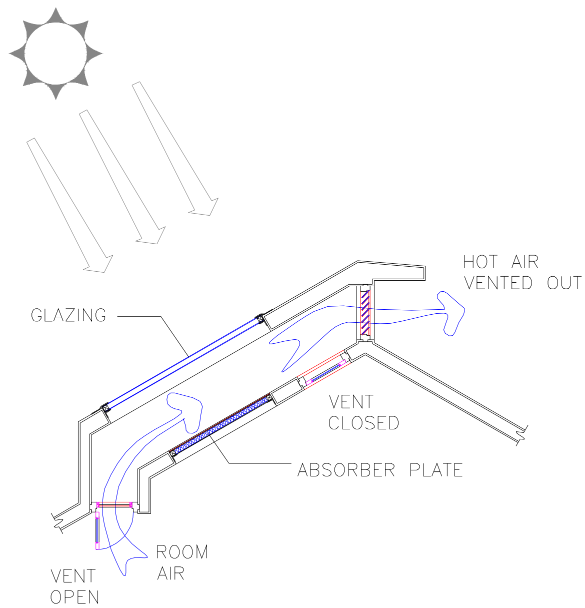


Fig. 3.20 Variation of thermosyphon air panel for summer cooling

(b) Roof Radiation Trap

A roof radiation trap can be used for winter heating and summer cooling. In this technique, the incident solar radiation is trapped and is used for heating the air inside the trap. Some amount of energy is also absorbed by the roof and is conducted through it to be radiated into the living space.

In the northern hemisphere, the trap consists of an inclined south-facing glazing and a north sloping insulated surface on the roof. The latter projects over the glazing to shade it during the summer. Between the roof and the insulation, an air-pocket is formed which is heated by solar radiation. A shutter is used to cover the glazing when desired. Figure 3.21 shows the schematic sketch of a roof radiation trap. A roof can have one or several such units.

In winter (Fig. 3.21a), solar radiation penetrates the glazing and is absorbed by the black roof surface designed to minimise heat loss to the ambient. Further, a movable insulation reduces heat loss through the glazed plane during nights. Part of the absorbed energy is conducted and radiated into the living area through the roof, while the rest is transferred to the air-pocket. This hot air can be drawn to a thermal storage unit (rockbed / water mass) to be used on cold nights or cloudy days.

The system can also be used for summer cooling. The insulating plane is covered with a white metal sheet to increase its emissivity. On summer nights, the sheet gets cooled by nocturnal radiation exchanges and in turn, cools the air blown under it (Fig. 3.21b). This coolness is stored in the storage unit and used for cooling the living space during daytime.

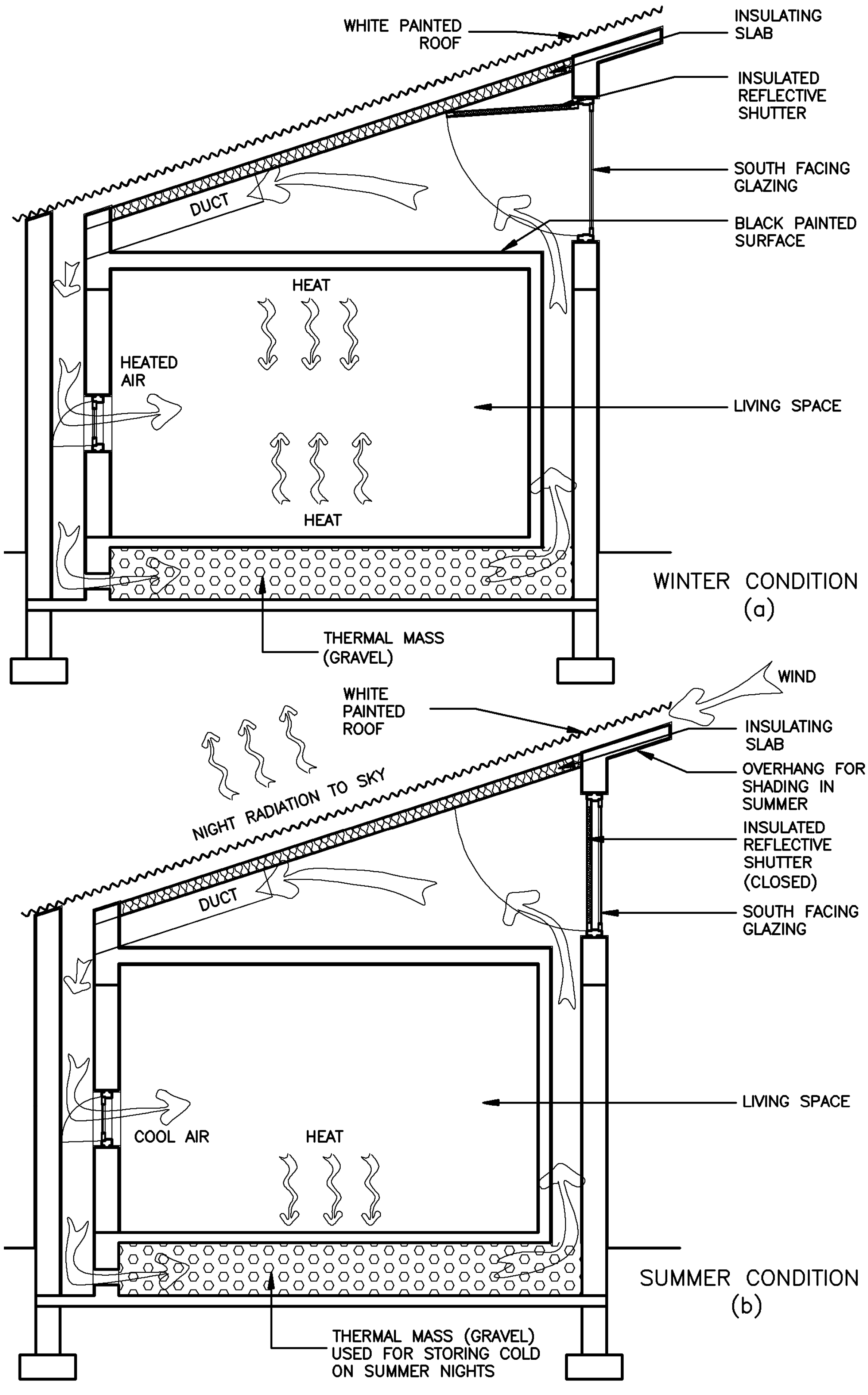


Fig. 3.21 Working principle of a roof radiation trap

The type of roof material and its thickness determine the pattern of heat flow into the living space. A hinged insulating panel inside the radiation trap can help to control the division of heat flow between conduction through roof and convection to storage through air. External insulation can be used to keep summer radiation out and prevent heat loss on winter nights.

3.3.3 Isolated Gain

In isolated gain systems, the solar radiation collection and storage are thermally isolated from the living spaces of the building. This allows in a greater flexibility in the design and operation of the passive concept. The most common example of isolated gain is the natural convective loop. In this system, solar radiation is absorbed to heat air or water. The warm air or water rises and passes through the storage, transferring its heat. The cooler air falls onto the absorber to get heated up again. Thus, a 'thermosiphoning heat flow' occurs as shown in Fig 3.22.

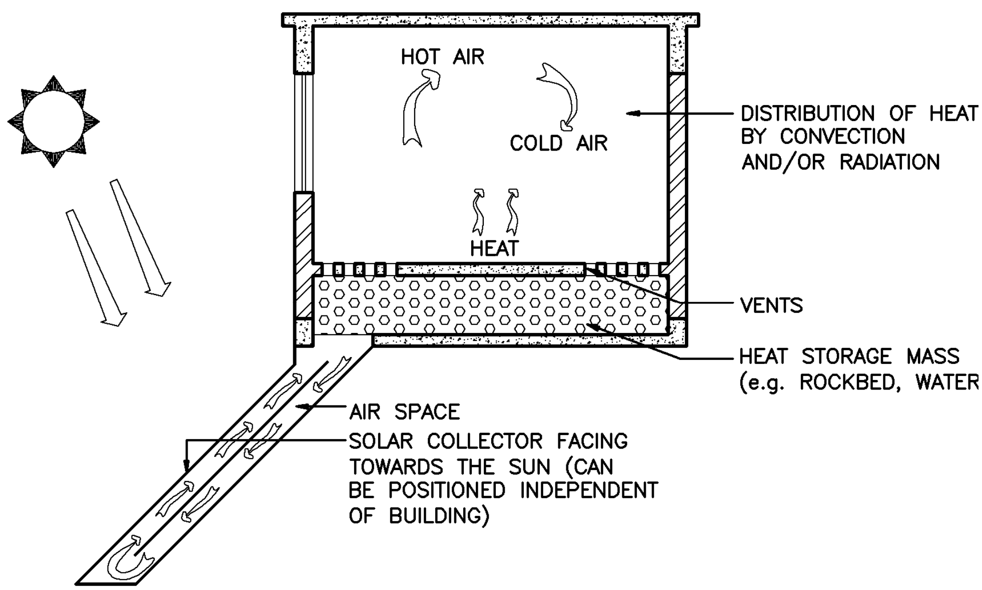


Fig. 3.22 Isolated gain

The basic requirements for this system are:

- a collector, which absorbs the solar radiation to heat the fluid
- a storage mass, which absorbs the heat from the fluid, to be stored for distribution into the living space
- a mechanism to distribute the heat stored in the storage mass

Variations and controls :

The collector can be located at any suitable place and oriented independently of the building for maximum solar gain. Thus the building design can be flexible. The slope of the collector is generally equal to the latitude of the place. Its area may range from 20 to 40 % of the floor area of the living space to be heated. The collector consists of an absorber (usually a corrugated metal plate with a black paint that can withstand temperatures upto 120^{o} C) and glazing. Single glazing is the norm except in severely cold climates where more than one is required to be used. The gap between the glazing and the absorber should be about 5 – 6% of the absorber length.

Variations in the storage materials can be achieved by using different types of materials as well as by varying their location (for example, below the floors and windows or in the wall). The method of distribution of heat from the storage can be either by radiation or convection, or it can also be directly from the collector. If water is used as the working fluid, the hot water can be run through pipes installed in the floor slab, where heat is stored and radiated into the living space. This can be supplemented by a boiler, or fired by wood/gas during extended overcast seasons for maintaining comfort conditions.

If the contact area between the collector space and the storage is not large, then the link between the two can be blocked or disconnected easily to control the performance of the system. It follows that the larger the area of contact, the greater and quicker the heat transfer. Therefore performance control can be exercised by designing the area of contact between the collector space and storage to meet specific heating demands.

3.3.4 Solarium (Attached Green House / Sunspace)

Sunspaces are essentially used for passive heating in cold climates. This approach integrates the direct gain and thermal storage concepts. Solar radiation admitted directly into the sunspace heats up the air, which, by convection and conduction through the mass wall reaches the living space (as shown in Fig 3.23). A solarium essentially consists of a sunspace or a green house constructed on the south side (in the northern hemisphere) of the building with a thick mass wall linking the two. The sunspace can be used as a sit-out during day as it allows solar radiation but keeps out the surrounding cool air. At night, it acts as a buffer space.

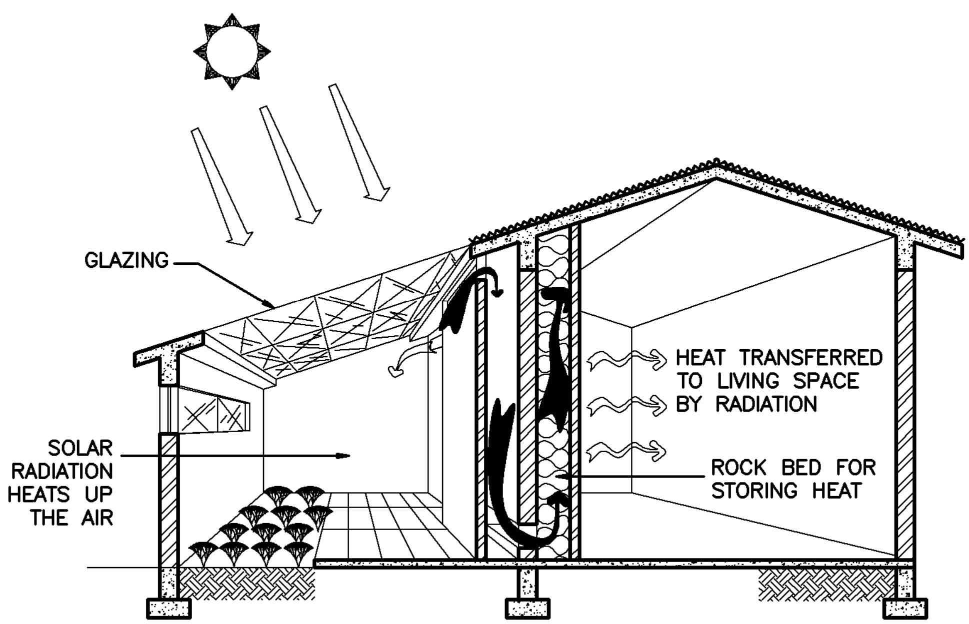


Fig. 3.23 Working principle of a solarium

The basic requirements of this type of building are:

- a glazed south facing collector space attached, yet distinct from the building
- thermal storage link between the collector and living space for heat transfer

Variations and controls:

The location of the sunspace depends on the building design and orientation of the sun. The area of contact between the sunspace and the living space determines the size of the former.

The thermal mass must be located where winter radiation can reach it. Floors, walls, benches, rock bed or covered pools of water can be used to store heat. Glazing should preferably be sloped by about 45^o in overcast and 60^o in clear and sunny areas. The storage walls are generally 200 – 450 mm thick. If a rockbed storage is used, then the typical size is 0.75 – 1.25 m^3 per square metre of the glazed area. Ideally, it should cover the entire floor, the typical rock size being about 5 –7.5 cm in diameter [12].

The temperature inside the sunspace must be controlled depending on its usage. Shading to prevent overheating in summer, and movable insulation and shutters to prevent heat loss in winter can be provided.

If the sunspaces are used for plantation or as a green house, humidity control must be incorporated to prevent mould from growing on the storage mass or other materials kept inside.

General remarks: The manner of arrangement of the passive components, namely. glazing, insulation, collector, storage and the living space to be heated or cooled, differentiates one passive system from the other. The variations and controls that each type offers have been indicated. Further possibilities within each class are created by using different types of heat storage materials. Sometimes passive systems also use small fans for direct control over convective heat distribution. These may be referred to as 'hybrid' systems.

The various passive concepts outlined so far essentially represent passive heating systems wherein attention is given to efficient collection of solar energy. Movable insulating curtains are provided to prevent unwanted heat loss to the environment at nights as well as on overcast winter days. However, as indicated, some of them could also be used for passive cooling purposes by changing the mode of operation. But there are certain concepts which are used exclusively for passive cooling. These are outlined in the next section.

3.4 PASSIVE COOLING

The cooling of buildings by using passive methods has evoked great interest. The underlying principle of passive cooling is to prevent heat from (or at least reduce heat flux) entering the building, or remove heat once it has entered. In this section, we discuss the principles governing each of the concepts used for passive cooling of buildings. The various concepts discussed are ventilation cooling, evaporative cooling, nocturnal radiation cooling, desiccant cooling and earth coupling. The applicability of these concepts depends greatly upon the climatic conditions prevailing in a particular place.

3.4.1 Ventilation Cooling

Ventilation is generally defined as the replacement of stale air by fresh air. It also provides cooling by air movement. Hence, it would be appropriate to define the term ventilation as the supply of outside air to the interior for air motion and replacement of vitiated air. An indoor air speed of 1.5 – 2.0 m/s can cause comfort in warm and humid regions where the outdoor maximum air temperature does not exceed 28 – 32^{o}C [14]. The scheduling of natural ventilation in arid climates (allowing only night-time ventilation) can reduce the maximum indoor temperature by about 5 – 8^{o}C compared to that of the outdoor.

Providing proper ventilation in buildings calls for due consideration in the design phase of buildings. A faulty design resulting in inadequate ventilation will result in higher energy consumption in the building for creating comfortable indoor conditions. Therefore, the ventilation requirements of different seasons, for different types of occupancies should be determined first. A ventilation system should then be suitably designed to meet the required performance standards.

There are many ways in which ventilation can improve comfort. For example, opening the windows to let the wind in, and thus providing a higher indoor air speed, makes people inside a building feel cooler. This approach is termed as comfort ventilation. In hot environments, evaporation is the most important process of heat loss from the human body for achieving thermal comfort. As the air around the body becomes nearly saturated due to humidity, it becomes more difficult to evaporate perspiration and a sense of discomfort is felt. A combination of high humidity and high temperature proves very oppressive. In such circumstances, even a slight movement of air near the body gives relief. It would, therefore, be desirable to consider a rate of ventilation which may produce necessary air movement. If natural ventilation is insufficient, the air movement may be augmented by rotating fans inside the building.

The air movement indoors is mainly due to stack effect (stratification of temperature) and wind pressure. Manipulating these two effects can considerably improve the ventilation. For example, a solar chimney works mainly on the stack effect. The solar chimney is used to exhaust hot air from the building at a quick rate, thus improving the cooling potential of incoming air from other openings. Similarly, wind towers use wind pressure for cooling. The wind is captured at the top of the terrace and is diverted to the indoors using wind towers. Windows can also be arranged to take advantage of stack effect and wind pressure.

An indirect way of cooling is to ventilate the building only at night to cool the interior mass of the building. During the following day, the cooled mass reduces the rate of indoor temperature rise and thus provides a cooling effect. This strategy is termed as nocturnal ventilative cooling.

This section provides more details about cross ventilation, wind towers, and nocturnal ventilation.

3.4.1.1 Cross ventilation

Requirements for air motion in the early summer and late post-monsoon periods are usually small. These can be easily met by providing adequate cross ventilation through rooms. When a building is cross ventilated during the day, the temperature of the indoor air and surfaces closely follow the ambient temperature. Therefore ventilation in daytime should be considered only when indoor comfort can be experienced at the outdoor air temperature (with acceptable indoor speed).

The indoor wind speed varies due to factors such as the area and location of windows in the room, direction of incident wind, weather shades such as louvers, chajjas, verandahs, etc., and the type of interconnection between different rooms of a building. For example, the available wind velocity in a room with a single window on the windward side is about 10% of the outdoor velocity at points upto a distance of one-sixth of room width from the window. Beyond this, the velocity decreases rapidly and hardly any air movement is produced in the leeward end of the room. Therefore, it is better to provide two windows on adjacent or opposite walls to improve ventilation. The window area and the direction of wind affect the performance of this cross ventilation. Figure 3.24 [5] shows how the window area affects the average indoor air velocity. The plot corresponds to the case where there are two windows of identical size on opposite walls; the wind direction is perpendicular or normal to the window. For example, for windows that are 20 percent of floor area, the average indoor wind velocity is about 25 percent of outdoor velocity.

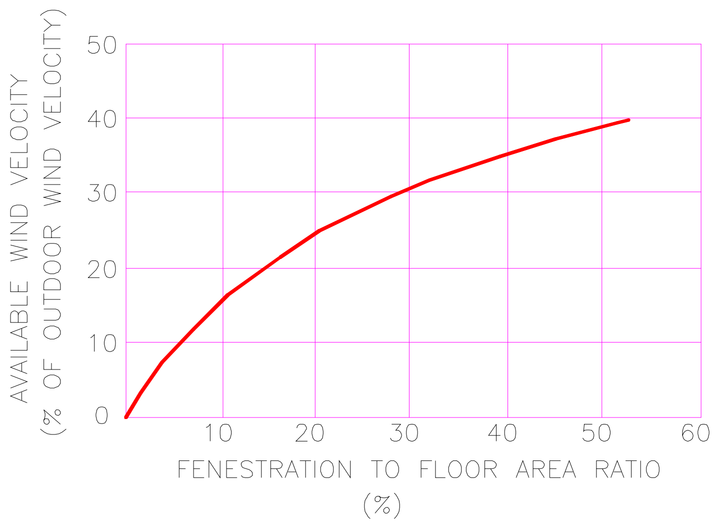


Fig. 3.24 Effect of window area on indoor air speed

3.4.1.2 Wind tower

Wind tower is generally used in hot and dry climates for cooling purposes. The tower is meant to "catch" the wind at higher elevations and direct it into the living space. The air flow passages in the tower may have equal or different areas. The tower may have only one opening facing the wind, if wind is predominantly in one direction, or may have openings in all directions in locations with variable wind directions. Such systems have been used for centuries in West Asian countries for natural ventilation and passive cooling [15,16]. A pre-requisite for using a wind tower is that the site should experience winds with a fairly good and consistent speed. A wind tower operates in various ways according to the time of day and the presence or absence of wind. The cardinal principle of its operation lies in changing the temperature and thereby the density of the air in and around the tower. The difference in density creates a draft, pulling air either upwards or downwards through the tower, shown schematically in Fig. 3.25. The detail section of a wind tower is given in Fig. 3.26.

Working: Night

The tower area is so designed that the top part provides large heat storage capacity, and also has a large surface area for heat transfer. The tower walls and the internal walls of the air-flow passages absorb heat during the day and release it at night, warming the cool night air in the tower. Warm air moves up creating an upward draft and is exhausted through the openings. The pressure difference thus created pulls the cool night air through the doors and windows into the building. In the absence of wind, the tower acts as a chimney. The nocturnal radiation through the roof and the external walls brings about further cooling.

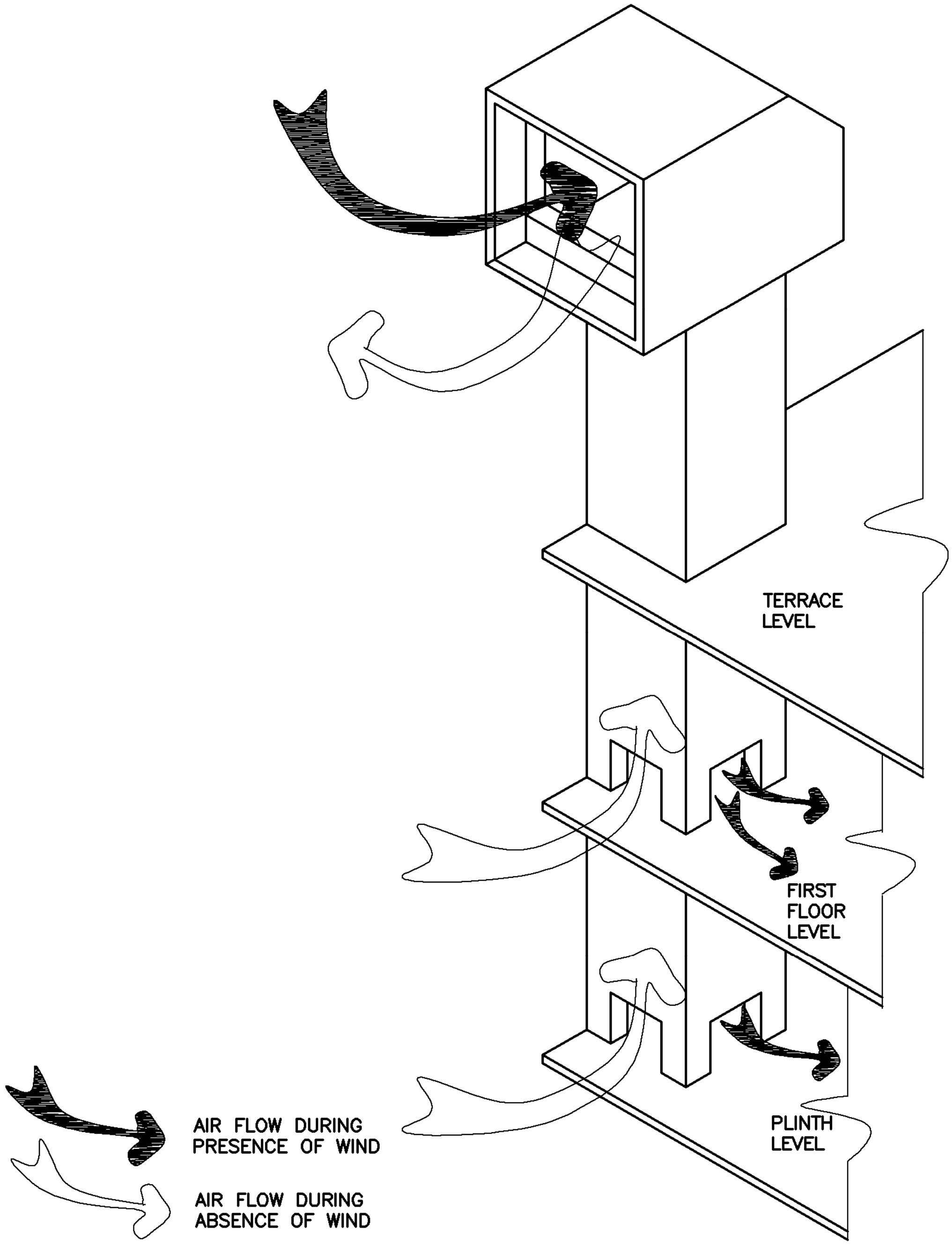


Fig. 3.25 Working principle of a wind tower

In the presence of wind, the cool night air enters the tower and forces itself down into the structure. Though it is warmed slightly during the process, sufficient cooling can be achieved due to forced circulation. Again, cooling due to nocturnal radiation adds to this process.

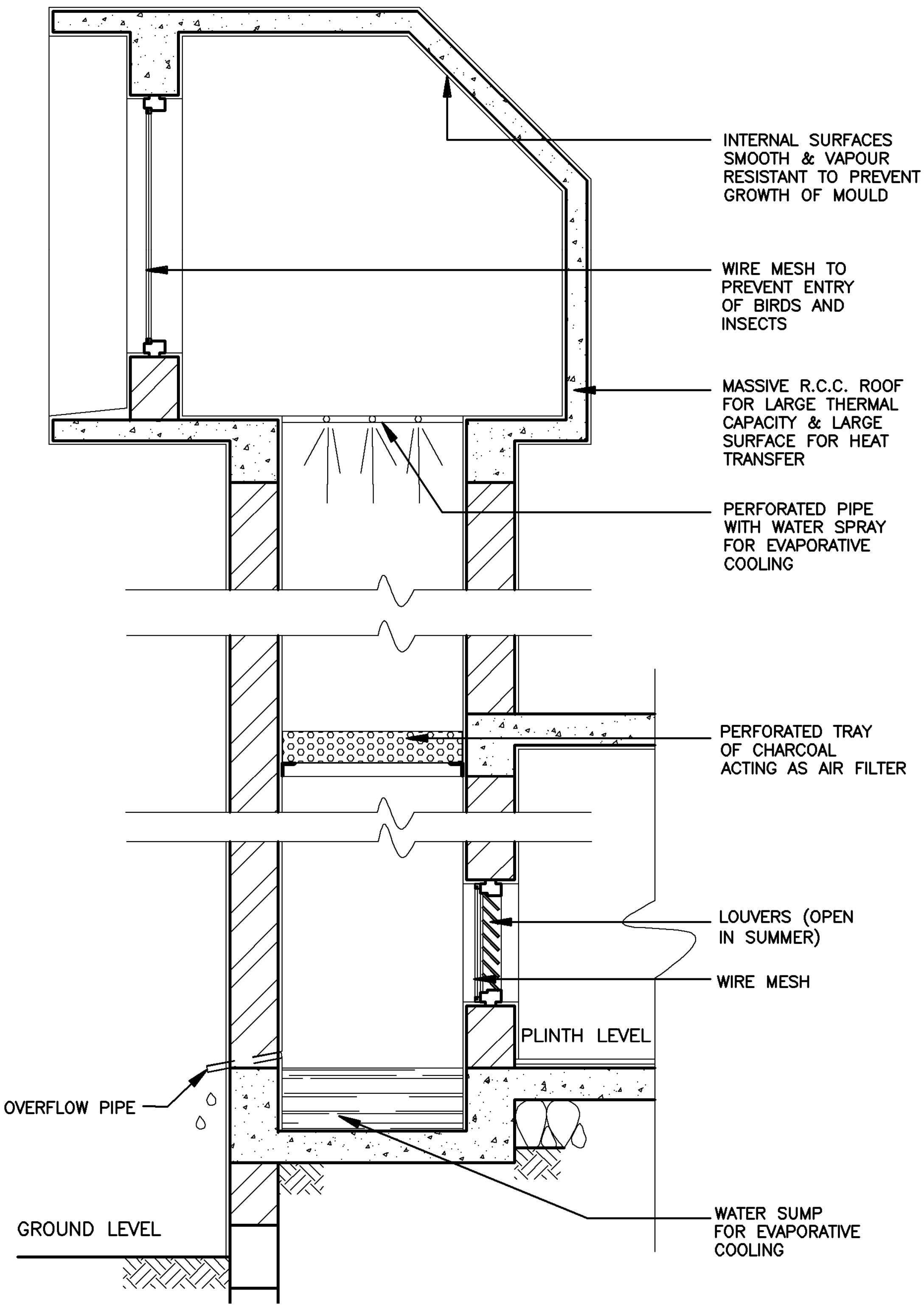


Fig. 3.26 Detail of a wind tower

Working : Day

The hot ambient air coming in contact with the cool upper part of the tower gets cooled. It becomes cold and dense, and sinks through the tower and into the living spaces, replacing the hot air. In the presence of wind, the air is cooled more effectively and flows faster down the tower and into the living area. It must be noted that the temperature of the tower soon reaches that of the ambient air and hence, in the absence of wind, the downward flow ceases, the tower then begins to act like a chimney. The operation of the tower depends greatly on the ambient fluctuations like the wind velocity, air temperature changes, etc.

Variations and controls:

Variations in wind tower design can be achieved by altering tower heights, cross section of the air passages, locations and number of openings, and the location of the wind tower with respect to the living space to be cooled. The variations are aimed at providing the desired air-flow rates, heat transfer area and storage capacity. Air flow through different parts of the buildings can be controlled by the doors and windows.

Due to small storage capacity, the sensible cooling may stop after several hours of operation on hot summer days. In order to improve the efficiency of its operation, evaporative cooling may be introduced. The air flowing down the tower is first sensibly cooled, and then further cooled evaporatively. This can be achieved by providing a shower/spray or dripping of water at top of tower, or a fountain at the bottom. The reduction in the temperature of air can be as much as 10 – 15^{o} C in arid climates [14].

Wind towers can easily be incorporated in low-rise buildings. It may be noted that wind towers may need to be shut off when cooling is not required, and hence, such provisions may be included in the design. Due consideration must also be given to prevent the entry of dust, birds and insects.

3.4.1.3 Induced Ventilation

Passive cooling by induced ventilation can be very effective in hot and humid climates as well as hot and dry climates. This method involves the heating of air in a restricted area through solar radiation, thus creating a temperature difference and causing air movements. The draft causes hot air to rise and escape to the ambient, drawing in cooler air and thereby causing cooling. In effect, a solar chimney is created to cause continuous air circulation. Figure 3.27 illustrates the principle of induced ventilation and some of its variations.

Variations and controls:

Arrangements may be made to draw air from the coolest part of the structure as replacement, to set up a continuous circulation and cool the living spaces. Curved roofs and vents are used in combination for passive cooling of air in hot and dry climates, where dusty winds make wind towers impracticable. The system works on the principle of cooling by induced ventilation, caused by pressure differences. This principle is illustrated in Fig. 3.28. Wind flowing over a curved surface creates a pressure difference across it. If vents are provided on the surface, air is sucked out of the structure through the openings. Therefore, the hot internal air forces its way out through the vents inducing air-circulation. Air vents are usually placed above living rooms.

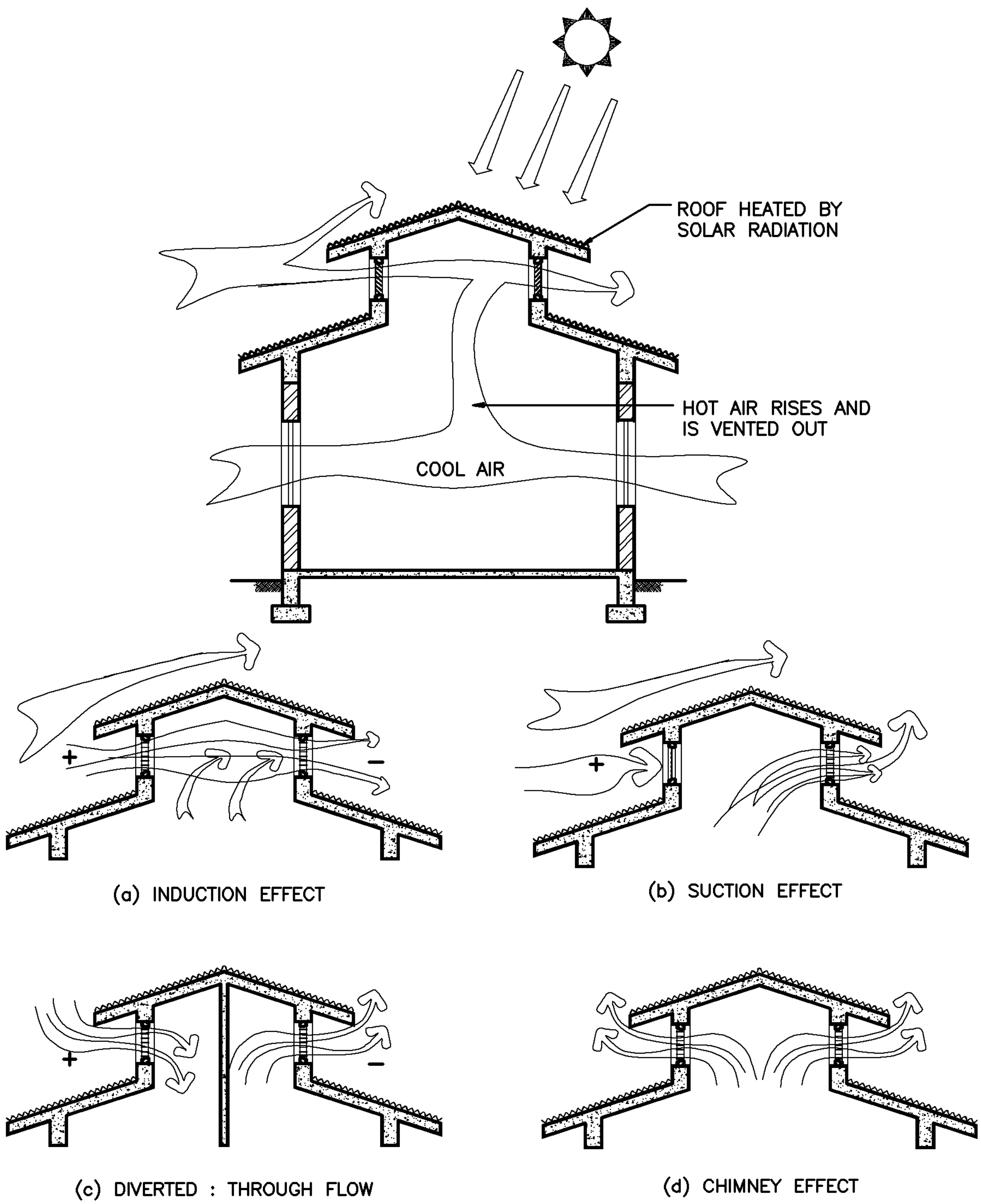


Fig. 3.27 Induced ventilation: principle and variations

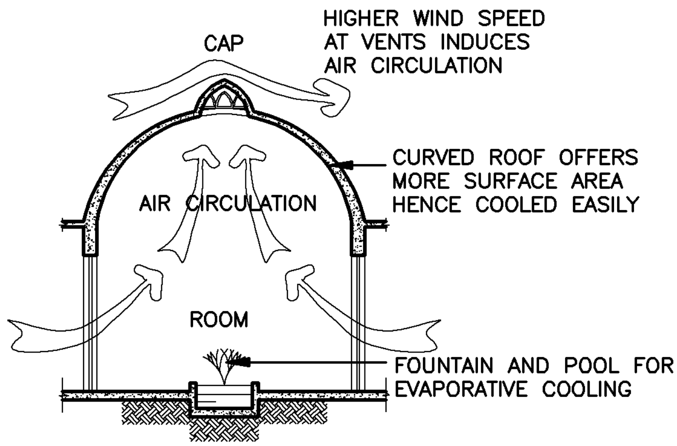


Fig. 3.28 Section showing induced ventilation through curved roof and air vents

The cooling effect can be enhanced by providing evaporative cooling. A pool of water is usually kept on the floor directly below the vents so that the air flowing into the room gets cooled, in turn cooling the living space. The air vents are usually provided with protective caps which help to direct the winds across them.

3.4.1.4 Nocturnal Cooling

Buildings may be cooled indirectly by ventilating at night, if the ambient air is cooler than the room air. This cools the interior mass of the building and on the following day, the cooled mass reduces the rate of indoor temperature rise and thus provides a cooling effect. This strategy is termed as nocturnal ventilative cooling.

Because buildings are usually occupied during the day, nocturnal ventilative cooling can be effective only to the extent that it can lower indoor temperatures the following day. It is particularly important that the indoor maximum temperature the next day be lowered. Such lower indoor temperatures can be achieved only if the building is kept closed and unventilated during the daytime hours. In this respect, daytime comfort ventilation and nocturnal cooling are mutually exclusive. At any given place on any given day, one or the other should be considered as the best approach to provide daytime comfort.

There are several design options to provide the thermal mass that will serve as the nocturnal cold storage:

- structural mass of the building such as walls, partitions, floors, etc., cooled by whole space ventilation
- embedded air spaces (passages) within floors, ceilings and/ or walls through which outdoor air is circulated
- specialised storage such as a rock bed or a water tank with embedded air tubes, cooled at night by outdoor air

The applicability of nocturnal ventilation cooling is limited to a certain range of conditions. Limitations on applicability are posed on the one hand by climatic conditions, and on the other by the comfort and functional needs of occupants. These limitations particularly affect the decision to leave windows open throughout the night to obtain effective nocturnal ventilation cooling.

3.4.2 Evaporative cooling

Evaporative cooling is a passive cooling technique in which outdoor air is cooled by evaporating water before it is introduced in the building. Its physical principle lies in the fact that the sensible heat of air is used to evaporate water, thus cooling the air, which in turn cools the living space in the building. Evaporation occurs at the water-air interface. An increase in the proportion of the contact area between water and air enhances the rate of evaporation and thereby the potential for cooling. The presence of a waterbody such as a pond, lake or sea near the building, or a fountain in the courtyard can provide a cooling effect. Cisterns or wetted surfaces can also be placed in the incoming ventilation stream. Such direct systems typically use little or no auxiliary power, are simple and can avoid the need for large surfaces of water and movement of large volumes of air. They are, therefore, particularly suited to hot and dry regions.

The airflow in these systems can be induced mechanically or passively – for example, evaporative cooling towers that humidify the ambient air can be used. This is direct evaporative cooling. The main disadvantage of direct systems is in the increased moisture content of the ventilation air supplied to the indoor spaces. High evaporation may result in discomfort due to high humidity. However, passive evaporative cooling can also be indirect – the roof can be cooled with a pond, wetted pads or spray, and the ceiling transformed into a cooling element that cools the space below by convection and radiation without raising the indoor humidity [14].

The efficiency of the evaporation process depends on the temperatures of the air and water, the vapour content of the air, and the rate of airflow past the water surface. The provision of shading and the supply of cool, dry air will enhance evaporation. A comprehensive discussion on evaporation has been reported by Bansal et al. [11]. The most commonly used evaporative cooling system in north India is the desert cooler consisting of water, evaporative pads, a fan and a pump. It is a hybrid type of direct evaporative cooling system [17].

Watt [18] has proposed the following guidelines for using evaporative cooling:

- Direct evaporative coolers should have an average saturation efficiency of 70% or more, and the cooled air should enter the indoor space without any additional heat gain.
- The maximum indoor air velocity induced by the cooled air must be 1 m/s.
- The room temperature should be reduced by at least 3°C before the cool air is discharged out of the room.
- The temperature of the cooled space should be about 4 °C below the outdoor dry bulb temperature. This is necessary to counteract the incoming radiant heat.

On a psychrometric chart, evaporation is characterised by a displacement along a constant wet bulb line, AB in Fig. 3.29 [19]. When the decrease in the dry bulb temperature is accompanied by an increase in the moisture content of the air, the process is commonly referred to as 'direct evaporative cooling'. The passive downdraft evaporative cooling system is an example of this process. When the evaporation of water takes place on a surface, or inside a tube, resulting in a decrease of surface temperatures, it is possible to cool air adjacent to these surfaces without increasing its moisture content. In this case, the process is referred to as 'indirect evaporative cooling' and is characterised by a displacement along a constant moisture content line CD shown in Fig. 3.29. An example of this is the roof surface evaporative cooling system. These techniques are discussed in detail in the following sections.

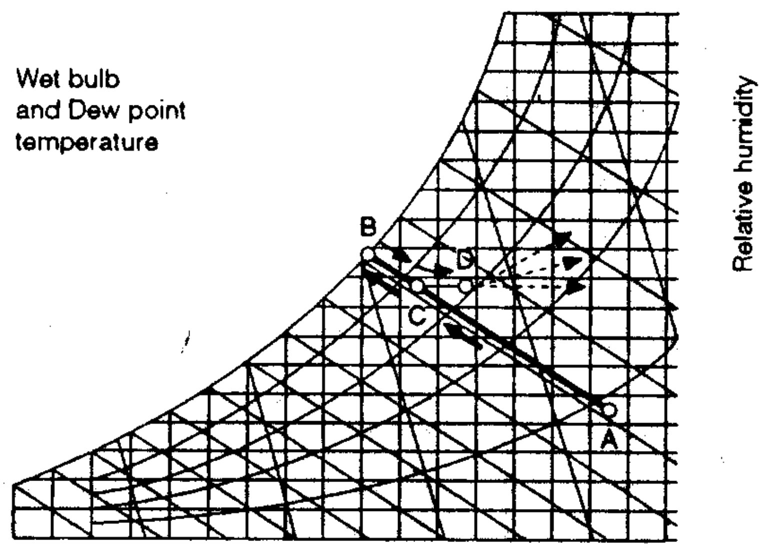


Fig. 3.29 Psychometric chart showing evaporative cooling

3.4.2.1 Passive Downdraft Evaporative Cooling (PDEC)

Evaporative cooling was extensively used in the vernacular architecture of Pakistan, Iran, Turkey and Egypt. Wind catchers called 'malqafs' captured wind and directed it over porous water pots, thus cooling the air as a result of latent heat of vaporisation. This system maintained a balance between two important parameters of passive cooling – thermal performance and ventilation effectiveness.

Contemporary passive downdraft evaporative cooling systems consist of a downdraft tower with wetted cellulose pads at the top of the tower. Water is distributed on the top of the pads, collected at the bottom into a sump and recirculated by a pump. Certain designs exclude the re-circulation pump and use the pressure in the supply water line to periodically surge water over the pads, eliminating the requirement for any electrical energy input. In some designs, water is sprayed using micronisers or nozzles in place of pads, in others, water is made to drip. Thus, the towers are equipped with evaporative cooling devices at the top to provide cool air by gravity flow. These towers are often described as reverse chimneys. While the column of warm air rises in a chimney, in this case the column of cool air falls. The air flow rate depends on the efficiency of the evaporative cooling device, tower height and cross section, as well as the resistance to air flow in the cooling device, tower and structure (if any) into which it discharges. [20]

This system depends on two basic factors that determine its effectiveness: (1) amount of cooling of the ambient air achieved, and (2) the rate at which this conditioned ambient air replaces the stale air within the building. The former can be easily achieved by increased air-water contact zone. This factor usually dictates the height of the tower and in turn, influences the massing of the building design. The second factor, however, requires a complex interplay of different variables to achieve an effective performance. These variables dictate the configuration of the tower termination, the positioning of multiple towers within the building, the circulation pattern within the building, and even the configuration of openings between adjacent spaces served by these towers [14].

The temperature of the incoming ambient air drops while crossing the pads. Therefore, the height of the tower and the area of the wetted pads are not expected to have any appreciable effect on the temperature of the air in the tower in a given combination of ambient dry and wet bulb temperatures. However, these two system design factors affect the airflow rate, and hence the total cooling effect generated by the system [14].

Performance Analysis

PDEC systems have been used with various types of cooling devices such as, spray devices (pressure and ultrasonic nozzles), aspen fibre pads, corrugated cellulose pads, etc. The performance analysis would thus vary depending on the evaporating cooling facilities provided in the tower. Aspen pads cause a high pressure drop relative to sprays and corrugated media, but they are low in cost. Spray devices may require efficient mist eliminators for removing fine droplets from the air because mist impedes air flow [20].

Givoni [21] has proposed a semiempirical model to estimate exit air temperature and flow rate of a PDEC tower. The tower uses vertical wetted cellulose pads called CELdek. Water is distributed at the top of the pads, collected at the bottom into a sump, and is re-circulated using a pump.

The exit air temperature (T_{exit}) is given by

$$T_{exit} = T_{db} - 0.87(T_{db} - T_{wb}) - 0.4 + 0.3 * \upsilon_w \tag{3.1}$$

where T_{db} = dry bulb temperature of ambient air (^{0}C)

T_{wb} = wet bulb temperature of ambient air (^{0}C)

υ_w = wind speed (m/s)

The flow rate of air can be estimated from

$$\dot{m}_{air} = 0.03 A_{wpad} * \sqrt{H * (T_{db} - T_{wb})} \tag{3.2}$$

and exit air speed is given by

$$\upsilon_{air} = \dot{m}_{air} / A_{tower} \tag{3.3}$$

where,

$\dot{m}_{air}$ = tower's air flow rate (m^3/s)

A_{wpad} = area of the wetted pads (m^2)

H = height of the tower (m)

A_{tower} = cross sectional area of the tower (m^2)

These equations can be applied mainly as a tool in the initial design stages [21].

Givoni [22] has developed performance equations for the "shower" tower. It consists of an open shaft with showers at the top and collecting "pond" at the bottom. The water collected at the bottom of the pond is recirculated by a small pump. When drops of water are sprayed vertically downward from the top of the shaft, they entrain a volume of air which flows down the shaft with falling water. The air thus gets cooled and can be used for cooling of a building. The shaft should be installed adjacent to an opening of the building and kept open to the outdoor air. The system can use even brackish or sea water since evaporation takes place in the free air stream.

The exit air temperature is given by

$$T_{exit} = T_{db} - 0.9 * (T_{db} - T_{wb}) * \left[1 - e^{-1.5*H}\right] * \left[1 - e^{-0.15 \dot{m}_{water}}\right] \qquad (3.4)$$

$\dot{m}_{water}$ = water flow rate (litres/minute)

The flow rate of air is given by

$$\dot{m}_{air} = 7\, \dot{m}_{water} \sqrt{H} / 600 \qquad (3.5)$$

These relations are valid for a particular type of shower. Givoni [22] has compared the performance of the "shower" tower under the three different climatic conditions, namely, Riyadh (Saudi Arabia), Los Angeles (USA) and Yokohama (Japan). He has demonstrated that the system can provide effective cooling in all these climates and the relations are validated through measurements.

Example:

Passive downdraft evaporative cooling tower has been used successfully at the Torrent Research Centre in Ahmadabad. The inside temperatures of 29 –30 °C were recorded when the outside temperatures were 43 – 44 °C. Six to nine air changes per hour were achieved on different floors [13].

3.4.2.2 Roof Surface Evaporative Cooling (RSEC)

In a tropical country like India, the solar radiation incident on roofs is very high in summer, leading to overheating of rooms below them. Roof surfaces can be effectively and inexpensively cooled by spraying water over suitable water-retentive materials (e.g., gunny bags) spread over the roof surface. As the water evaporates, it draws most of the required latent heat from the surface, thus lowering its temperature and reducing heat gain. Besides, evaporation also cools the air above the roof. The cool air slides down and enters the living space through infiltration and ventilation, providing additional cooling. This is an example of the passive indirect evaporative cooling technique.

A critical factor determining the performance of a RSEC system is the sustained wetness of the roof surface. The surfaces may be sprayed intermittently, as it is only necessary to keep them moist. Evaporation of the water from a roof pond (a large mass of water stored on the roof) can also be used for reducing the cooling load in summer. However, to use this cooling technique, the roof has to be made structurally strong and waterproof. Comparatively, cooling by sprinkling water is more advantageous as it provides a larger surface area for evaporation without the need for any storage.

For installing a roof surface evaporative cooling system, the following points need to be taken note of:

1) Suitable waterproofing treatment of the roof should be done.
2) The roof must be covered with water absorptive and retentive materials such as gunny bags,
   brick ballast, sintered fly-ash, coconut husk or coir matting. On account of their porosity, these materials when wet, behave like a free water surface for evaporation. The durability of such materials is rather good, but they have to be treated for fire safety.
3) During peak summer, the quantity of water needed is approximately 10 kg/ day/ m^2 of roof area.
4) The roof must be kept wet throughout the day using a water sprayer. The sprayer can be manually operated or controlled by an automatic moisture-sensing device. The sprayer usually works at low water pressure which can be achieved either by a water head of the storage tank on the roof, or by a small water pump.

Performance Analysis

The effectiveness of RSEC depends on:

- ambient air temperature and humidity
- intensity of solar radiation
- wetness of the roof surface
- roof type

The effect of evaporation increases when the air humidity is low and the air temperature as well as the intensity of solar radiation falling on the roof surface are high. A uniform and constant wetting of the roof surface is essential for continuous evaporation. It should be noted that the roof needs to be adequately treated with water proofing material.

The evaporation of water causes cooling of the roof surface. This sets up a temperature gradient between the inside air and outside roof surface, resulting in loss of heat from the inside to outside. Thus, heat transfer through the roof is the dominant aspect in the overall performance of RSEC. Higher the rate of heat transfer, more effective is the RSEC. Consequently the RSEC system is most effective when the roof has a high thermal transmittance (U).

The equivalent temperature of the outer surface of the roof in the presence of RSEC can be calculated from [23]:

$$\theta_{eff} = \left[\alpha I_g + \left(h_0 + 0.13 h_c \gamma R_1\right) T_a - 0.013 h_c R_2 (1-\gamma) - \in \Delta R\right] / \left[h_o + 0.13 h_c R_1\right] \tag{3.6}$$

where

$\alpha =$ absorptivity of the roof surface

$I_g =$ global solar radiation on the roof surface (W/m^2)

$h_o =$ total heat transfer coefficient from roof's surface (W/m^2-K)
$h_c =$ convective heat transfer coefficient from roof's surface (W/m^2-K)
$\gamma =$ relative humidity of air
$\in =$ emittance of the roof surface
$\Delta R =$ net exchange of long wavelength radiation between the roof surface and the sky (W/m^2)
R_1 & R_2 = coefficients of correlation between saturation vapour pressure and temperature (R_1 is in Pa/^{o}C and R_2 is in Pa)
$T_a =$ ambient temperature (^{o}C)

Kumar and Purohit [23] have investigated the performance of RSEC for various roof types under different climatic conditions. The basis of comparison for unconditioned buildings is the discomfort degree hours (DDH), defined as:

$$DDH = \sum_{month} \sum_{day} (T_R - T_C)^+ \qquad (3.7)$$

where T_R and T_C refer to the indoor air and set point temperatures respectively; the + superscript means that only positive values are to be considered. In case of conditioned buildings, the authors have used the monthly cooling load for establishing the effectiveness of the RSEC system. Table 3.9 presents the percentage reduction of DDH by employing RSEC for a few roof types under New Delhi climatic conditions, and for a set point of 27^{0}C for non-conditioned buildings. The table also presents the percentage reduction of the cooling load for the month of May for conditioned buildings under similar conditions. It is seen that the lower the U value of the roof, the lesser is the effect of the RSEC system.

Table 3.9 Percentage reduction of yearly DDH due to roof surface evaporative cooling [23]

Roof Type	U (W/m^2-K)	DDH reduction (%)	Monthly cooling load reduction (%)
RCC	4.29	55.0	52.2
RCC- mud phuska-tile	2.60	38.2	37.1
Insulation- RCC	1.10	19.2	18.9
RCC- lime concrete	2.76	39.9	38.7

DDH: Discomfort degree hours

Example:

A wet gunny bag system was installed at the Bharat Heavy Electricals Limited factory at Haridwar during the summer of 1979. The building over which the cooling system was tried, is a four-storeyed engineering building which has a large number of offices and rooms. A monitoring of the performance showed that a reduction of 17 °C and 8 °C was observed in the peak value of ceiling temperature and indoor air temperature respectively [17].

3.4.2.3 Direct Evaporative Cooling using Drip-type (Desert) Coolers

Desert coolers are very popular in the northern parts of India. They can cool large volumes of outside air through evaporation of water. This air is delivered to the indoors where it absorbs heat from walls, ceilings, furnishings and the occupants. The warm air is finally discharged to the outdoors. Fresh outside air should be used rather than employing recirculation because, in the latter case, the wet bulb temperature continues to increase, resulting in unsatisfactory conditions. The cooler consists of a wetting pad, a water circulating pump, a fan, and a cabinet to hold these components. The water pump lifts the sump water up to a distributing system, from which it runs down through the pads and back into the sump. The wetting pad − usually made of aspen wood fibres − is fixed to the three sides of the coolers' walls in such a way that only air enters through the pads. A propeller-type fan or a centrifugal blower is used above the base of the cooler. The choice of the evaporating pad is a critical factor in determining the performance. The coolers are usually designed for a face velocity of 1 to 1.5 m/s with a pressure drop of about 30 N/m^2. In addition to providing cooling of the incoming air, the pads also act as air filters preventing the entry of particles having a size greater than 10 micrometers. The pads are chemically treated to prevent the growth of bacteria, fungi and other micro-organisms. When the cooler is used only for ventilating purposes, supplementary fibre glass filters are also used. It must be noted that the material used in the construction of the pump, sump, water-distribution system, and casing should necessarily be corrosion resistant.

3.4.3 Nocturnal Radiation Cooling

Nocturnal radiation cooling refers to cooling by exposure of any element of the external envelope of the building to a cool night sky. Warm objects directly exposed to the sky radiate their heat out to it at night. Heat loss occurs by emission of long wavelength radiation, and hence surfaces should ideally have high emissivity. The presence of clouds at night limit the amount of heat that can be radiated to the outer space, but on a clear night, the effective sky temperature can be significantly lower than the ambient air temperature. The heat accumulated during the day is lost by radiation to the cool night air, thereby cooling the envelope. The envelope thus acts as cold storage during the day, drawing the heat away from the living space. The method works efficiently in arid climates, where ambient temperatures in the night are significantly lower than the day temperatures. Nocturnal radiation cooling works without consuming any water, unlike evaporative cooling systems. Its operation is illustrated in Fig 3.30.

The roof, being the part exposed to the sky, is the most effective long wave radiator. The rate of heat exchange depends on the temperature difference between the emitting surface and the surrounding atmosphere. Regions with large diurnal temperature variations will have higher nocturnal radiation cooling. Vapour pressure and the presence of clouds in the sky also affect the heat exchange.

For effective radiant cooling, the thermal link between the emitting surface and the living space has to be good. Otherwise, the cooling resulting from radiation exchange will only serve to cool the ambient air, rather than the living space. The roof pond is an example of the concept of nocturnal radiation cooling . In this system, a mass of water is stored on the roof of the building. During summer days, the pond is protected and insulated by an external, movable and reflective insulation. The insulation prevents solar radiation from reaching the water mass and keeps it cool. The cool water then absorbs heat from the rooms below and cools the indoor air. At night, the insulation is removed and the water cools by convection and radiation. The effectiveness of the roof pond may be gauged from the fact that an indoor temperature of 21^{o}C can be maintained when the outside temperature is as high as 35^{o}C [10].

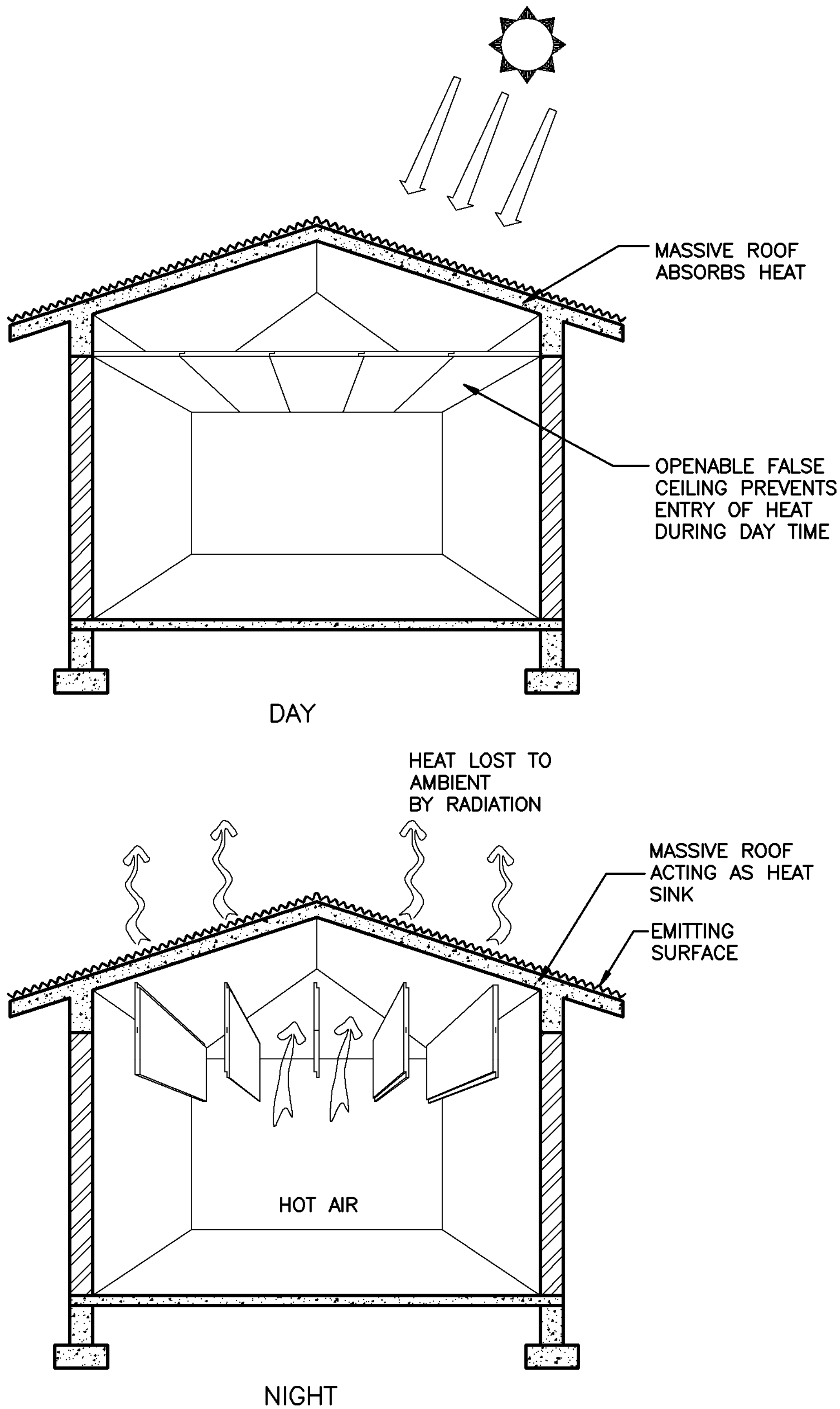


Fig. 3.30 Nocturnal radiation cooling: working principle

In winter, the panel positions are reversed. During the day, the insulation is removed so that heat is absorbed by water for heating the interior. At night, the insulation cover reduces the heat loss. The effectiveness of the roof pond in winter is no less than that in summer: the indoor temperature can be maintained at about 21ºC while the outside is as low as –1.1ºC [10]. The principles involved in this technique are schematically represented in Fig 3.31.

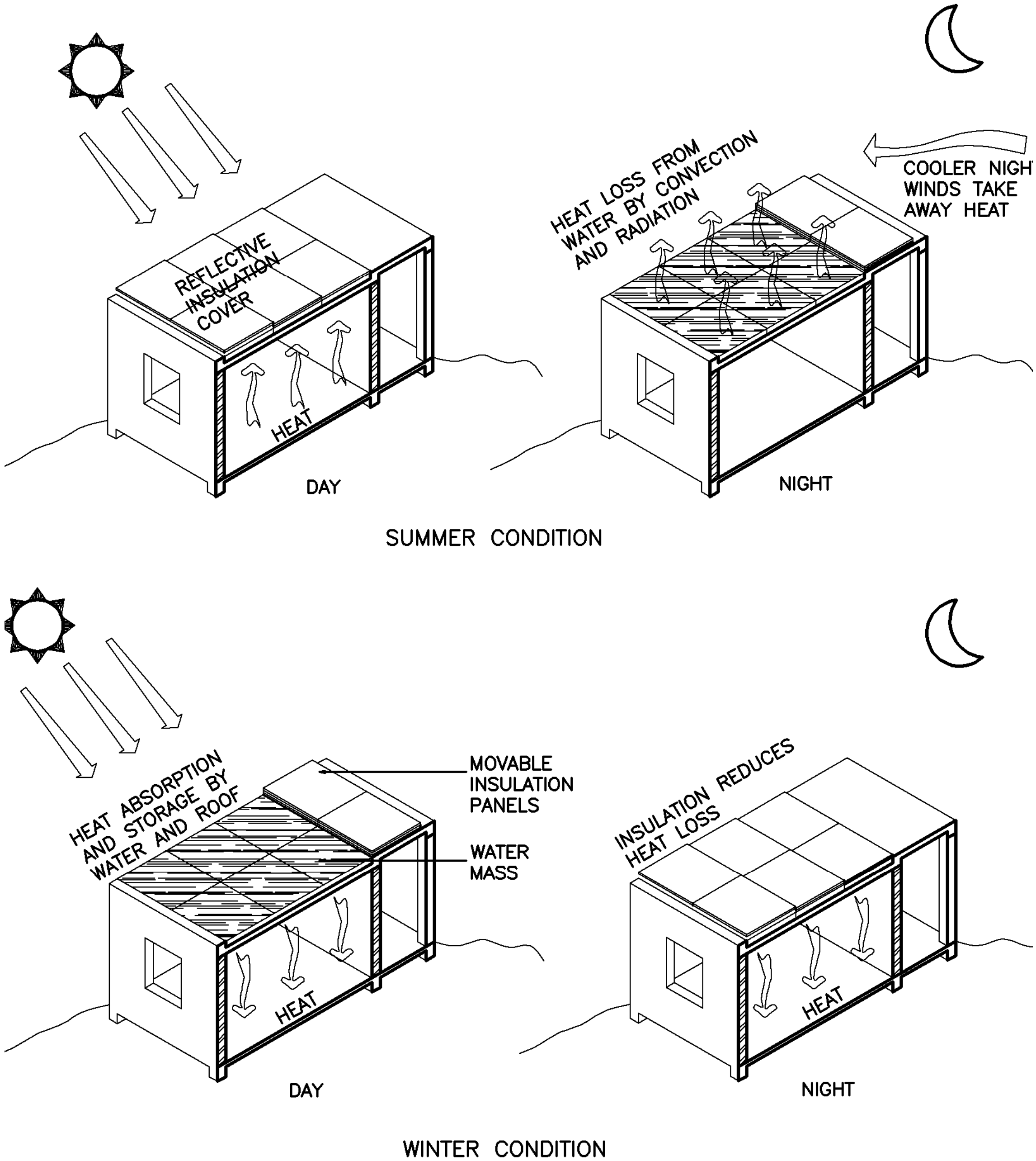


Fig. 3.31 Working principle of a roof pond

Water in transparent bags or in metal / fibreglass tanks is kept on the roof, the depth ranging from 150 to 300 mm. The top of the container/bag must be transparent to solar radiation whereas its bottom (inside surface) should be of a dark colour. If both sides of the container are transparent, then the top surface of the roof needs to be blackened for absorbing solar radiation. A clear top and black bottom helps in minimising temperature stratification in the pond water. Otherwise, hot water at the top would lose its heat to the exterior, and the cold water at the bottom would inhibit the heat transfer to the interior of the building. The movable insulation is usually of 50 mm thick polyurethane foam, reinforced with fibreglass strands and sandwiched between aluminium skins. The water-proofing layer of the roof should not inhibit the heat transfer from the pond to the interior [10]. The details of a roof pond are shown in Fig. 3.32. Radiation is responsible for the thermal interaction between the roof and the living space. Therefore, the ceiling of the room must not be very high, as the intensity of the radiation reduces with height or distance. This technique is effective for one or two storeyed buildings.

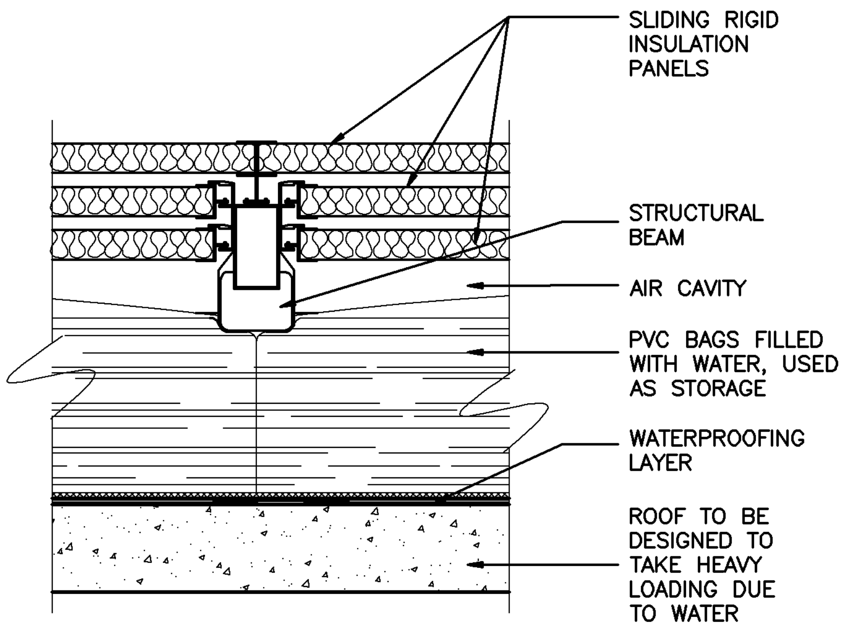


Fig. 3.32 Detail of a roof pond

Variations may be achieved by altering the ratios of heat transfer surfaces to thermal mass. The larger the storage volume, the greater and longer the heat storage. Smaller containers provide greater heat exchange as the surface area increases, resulting in faster distribution. During winter, a transparent cover may be provided over the water bags, leaving a gap. Air is blown through these gaps, forming an insulation cover to reduce heat loss. During summer the gaps are flooded with water and the transparent cover is removed.

Another way of using nocturnal radiation cooling is to expose lightweight radiators to the night sky. Through these radiators, a fluid is circulated which gets cooled. The cooled fluid can be used to cool a thermal storage system at night. The cold storage can be used the following day for space cooling.

Radiative cooling is effective in the hot and dry climate where nights are clear. In the case of humid atmosphere, condensation may occur on the radiating surface due to a decrease in its temperature to below dew point. The condensate transfers the latent heat of vaporisation to the surface, keeping it warm. As a result cooling is not achieved.

3.4.4 Desiccant Cooling

Desiccant cooling is effective in warm and humid climates. Natural cooling of human body through sweating does not occur in highly humid conditions. Therefore, a person's tolerance to high temperature is reduced and it becomes desirable to decrease the humidity level. In the desiccant cooling method, desiccant salts or mechanical dehumidifiers are used to reduce humidity in the atmosphere. Materials having high affinity for water are used for dehumidification. They can be solid like silica gel, alumina gel and activated alumina, or liquids like triethylene glycol. Air from the outside enters the unit containing desiccants and is dried adiabatically before entering the living space. The desiccants are regenerated by solar energy. Sometimes, desiccant cooling is employed in conjunction with evaporative cooling, which adjusts the temperature of air to the required comfort level.

3.4.5 Earth Coupling

This technique is used for both passive cooling as well as heating of buildings, a feat which is made possible by the earth acting as a massive heat sink. The temperature of the earth's surface is controlled by the ambient conditions. However, the daily as well as seasonal variations of the temperature reduce rapidly with increasing depth from the earth's surface. At depths beyond 4 to 5m, both daily and seasonal fluctuations die out and the soil temperature remains almost stable throughout the year. It is equal to the annual average ambient air temperature at that place. The temperature of the soil at depths beyond 4 to 5m can however be modified by suitable treatment of the earth's surface. For increasing the temperature, the earth's surface can be blackened/ glazed, and for decreasing it's value the surface can be shaded, painted white, wetted with water spray or can have thick vegetation. Thus, the underground or partially sunk buildings would provide both cooling (in summer) and heating (in winter) to the living space. Besides, load fluctuations are reduced by the addition of earth mass to the thermal mass of the building. The infiltration of air from outside is reduced, and there is a decrease in noise and storm effects. An earth-sheltered structure has to be heavier and stronger to be able to withstand the load of the earth and the vegetation above. Besides, it should be suitably waterproofed and insulated to avoid ground moisture. For this, a high level of design and supervision in construction is required.

A building may be coupled with the earth by burying it underground or berming. Figure 3.33 shows an example of earth berming. Another possibility of utilising the ground effect is through earth-air pipe systems, and is discussed in the following section.

3.4.5.1 Earth-air pipe system

The earth-air pipe system consists of a pipe of appropriate dimensions buried at a depth of about 4 to 5m in the ground. Ambient air is blown through it by a blower at one end of the pipe. The other end is connected to the building to which it supplies conditioned air. Figure 3.34 shows the schematic of such a system. As explained earlier, the temperature at a depth of about 4 to 5m is very stable and is equal to the annual average ambient temperature. It remains unaffected even if heat is withdrawn from or supplied to the ground, due to its large thermal capacity. The earth-air pipe system takes advantages of this fact. Ambient air flowing through the pipe gets cooled (in summer) or heated up (in winter) before entering the living space of a building. If the pipe is of adequate length (for a given air flow rate), the desired heating or cooling effect can be realised.

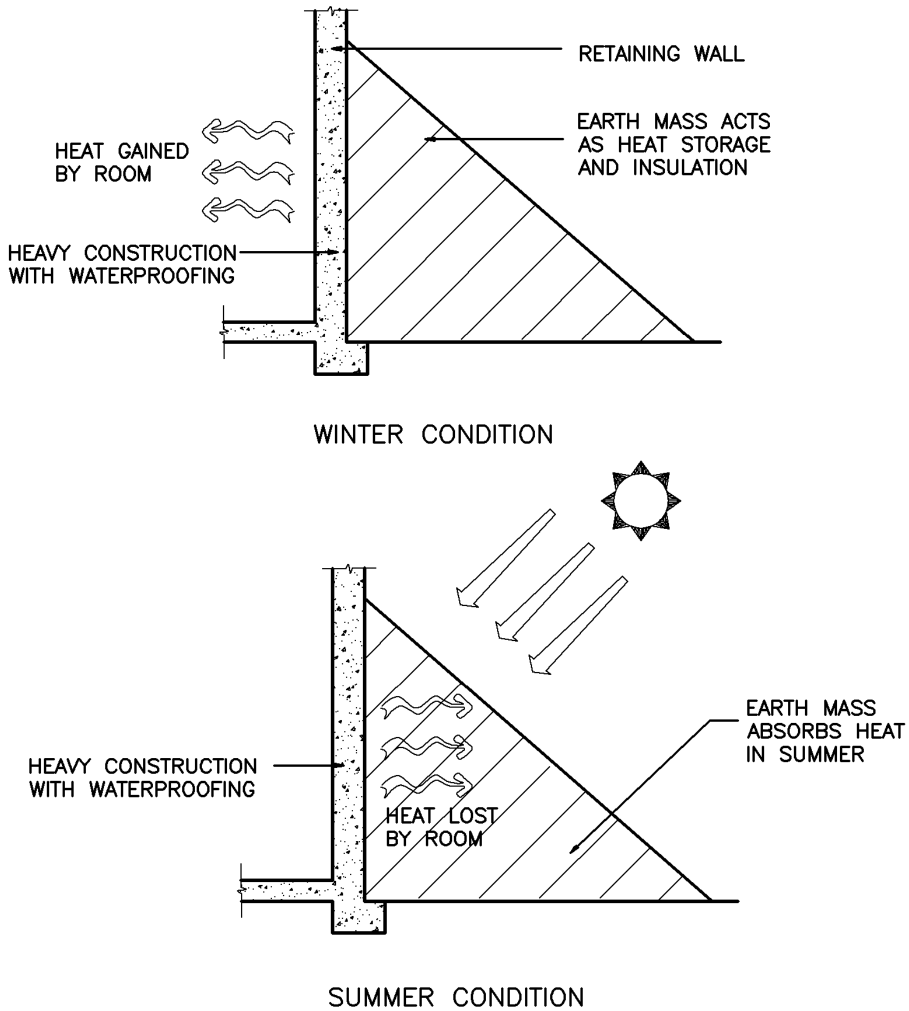


Fig. 3.33 Working principle of earth-berming

To meet the thermal load requirement of the building, one may use more than one pipe buried at the same depth a few metres apart. However, it is possible for the relative humidity of the air from the earth-air pipe system to be higher than the ambient humidity, depending on the soil conditions. If the air fed to living spaces is not reused, the system is called single pass system. The earth-air pipe system can also be used in the re-circulation mode. In that case air from the living space is re-circulated through earth-air pipe and is supplied back to the living space.

By using an earth-air pipe system, energy and peak load requirements for space conditioning of a building can be significantly reduced. This would lead to energy conservation. The use of such systems has gained increasing acceptance during the last few years, and a number of them are being installed in India, China, USA and Europe.

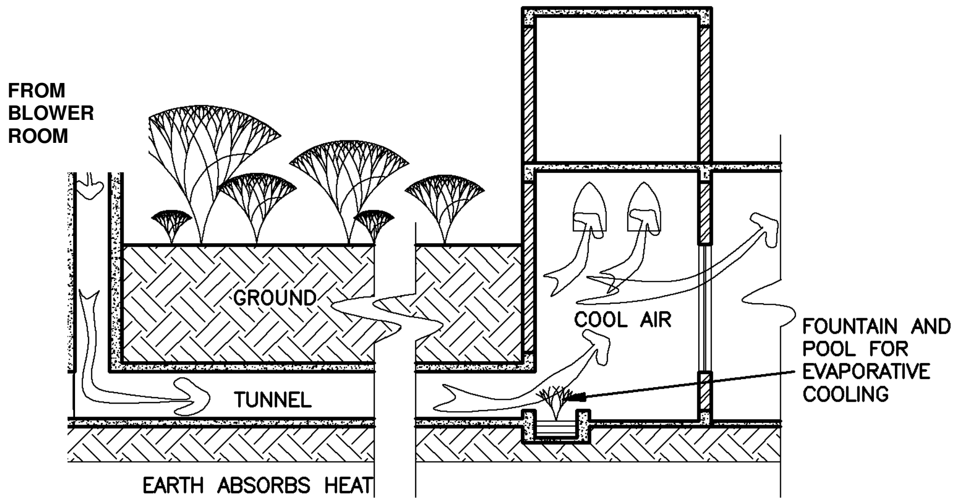


Fig. 3.34 Earth-air pipe system: working principle

Performance Analysis

The performance of the earth-air pipe system depends on the rate of heat transfer between the air and surrounding earth, which in turn is governed by the resistances offered by: (i) the convection between air and inner surface of the pipe, (ii) conduction through the thickness of the pipe wall, and (iii) conduction through the surrounding earth. Thus, the performance of the earth-air pipe system depends on [24,25]:

- system parameters (depth of the pipe from the earth's surface, its length and radius, thermal conductivity of the pipe material, and air speed through the pipe)
- soil parameters surrounding the pipe (thermal conductivity, specific heat, density and moisture content)
- weather conditions (solar radiation, ambient temperature)
- earth's surface conditions (shaded, blackened, white-painted or wetted with water)

The longest resistance to the heat flow is due to the soil surrounding the pipe, and it is the main factor in controlling the rate of cooling/heating of the air in the pipe. Soil having higher thermal conductivity is desirable, and so wet soil is more effective in heat transfer. Resistance to the heat flow due to pipe material is comparatively very less, hence pipe thickness and its material is of little consequence to the process. The configuration (cross section and thickness) and material of the pipe is decided purely on the basis of cost considerations. Thus, a duct made of brick/stone or a concrete pipe will be almost as effective as a copper pipe.

The temperature T_{AL} at the end of a pipe of length L can be written as [24,25]:

$$T_{AL} = T_{EO} + (T_{AO} - T_{EO}) \exp\left(-L/L_p\right) \tag{3.8}$$

where,

$$L_p = \dot{m}_a C_{PA} R_{th}; \; \dot{m}_a = \pi R_{ip}^2 v_A \rho_A$$

$$R_{th} = \frac{1}{2\pi R_{ip} h_i} + \frac{\ln\left(R_{op}/R_{ip}\right)}{2\pi k_p} + \frac{\ln\left[\frac{Z}{R_{op}} + \sqrt{\left(\frac{Z}{R_{op}}\right)^2 - 1}\right]}{2\pi k_g}$$

$$T_{EO} = T_{EM} + (T_{E\max} - T_{EM}) \exp\left(-Z/\xi\right) \cos\left(\frac{2\pi t}{t_y} - Z/\xi\right)$$

$$\xi = \sqrt{t_y k_g / (\pi \rho_g C_{pg})}$$

$$T_{AO} = T_{AM} + (T_{AMax} - T_{AM}) \cos\left(2\pi t'/t_h\right) \tag{3.9}$$

C_{PA} = specific heat of air (J/kg-K)
C_{pg} = specific heat of the soil (J/kg-K)
h_i = connective heat transfer coefficient for the inner surface of the pipe to air (W/m^2-K)
k_g = thermal conductivity of the soil (W/m-K)
k_p = thermal conductivity of pipe material (W/m-K)
R_{ip} = pipe inner radius (m)
R_{op} = pipe outer radius (m)
t = time (zero on the day when $T_{E\max}$ occurs) (s)
t' = time (measured from the time when maximum temperature of the day occurs) (s)
t_h = duration of the day (24 x 3600 s = 86400 s)
t_y = time duration of a year in seconds (365 x 24 x 3600s = 31.5 x 10^6 s)
T_{EM} = annual mean ambient air temperature (^oC)
$T_{E\max}$ = maximum of the daily mean temperature of the year (^oC)
T_{AM} = daily mean ambient air temperature (^oC)
$T_{A\max}$ = maximum temperature of the day (^oC)
v_A = air flow velocity (m/s)
Z = pipe depth (m)
ρ_g = density of the soil (kg/m^3)
ρ_A = air density (kg/m^3)

It is seen that the temperature of the air T_{AL} at the end of the pipe depends on pipe parameters, air parameters and soil parameters.

The hourly cooling potential Q_c (in kWh), and heating potential Q_h (in kWh) can be calculated from the relations:

$$Q_c = \dot{m}_A C_{PA} (T_{AO} - T_{AL}) \quad (3.10)$$

$$Q_h = \dot{m}_A C_{PA} (T_{AL} - T_{AO}) \quad (3.11)$$

The performance of an earth-air pipe system has been estimated for Delhi climate conditions. For the weather data of June (summer) and January (winter), T_{AL} and Q_c are calculated for various soil and systems parameters. The values of air properties and other quantities used in the calculations are:

$\rho_g C_{pg} = 3x10^6$ J/m^3-K , $\rho_A = 1.17$ kg/m^3 , $C_{pA} = 1000$ J/kg-K ; $k_A = 0.0265$ W/m-K;

t = 0 in June and 302400 s in January; T_{Emax} = 34.2°C in June and 13.6°C in January;
T_{AO} = 38.5°C in June and 8.5°C in January; T_{EM} = 24.9°C; Friction factor = 0.08

Table 3.10 presents results for summer conditions in New Delhi. It is seen from the table that T_{AL} decreases as depth of the pipe (Z) increases. The cooling potential also increases. Variations of T_{AL} is significant for low values of Z. After a depth of 5m, it hardly changes. Similarly the effectiveness of the earth-air pipe system improves when the pipe length (L), thermal conductivity of the soil (k_g), as well as that of the pipe (k_p) increase. The performance decreases with increase in pipe radius (R), pipe thickness $(R_{op} - R_{ip})$, and velocity (v_A) of the air in the pipe. While the effects of Z, L, R, v_A and k_g are quite significant, the effects due to k_p and thickness of the pipe are insignificant.

Table 3.11 shows similar effects for winter conditions in New Delhi. The results demonstrate the effect of various parameters from the point of view of designing an earth-air pipe system.

Example:

Earth-air pipe systems have been installed at many places in the country. RETREAT building, Gwalpahari, Gurgaon; Dera Library, Radha Swami Satsang, Beas, Dilwara Bagh; Country House of Reena and Ravi Nath, Wazirpur, Gurgaon[13], etc. use this system to name a few.

Table 3.10 Variation of delivery temperature (T_{AL}) and cooling potential (Q_c) of an earth-air pipe system due to various system parameters for June conditions of New Delhi

Variable	Value	Delivery temperature T_{AL} (^0C)	Cooling potential Q_c (kWh)	Drop in temperature (Inlet - Delivery) (°C)
Depth of pipe Z (m)	1	31.2	0.6	7.3
	3	27.5	0.9	11.0
	5	26.5	1.0	12.0
	7	26.7	1.0	11.8
Length of pipe L (m)	20	31.9	0.5	6.6
	40	28.4	0.8	10.1
	60	26.5	1.0	12.0
	80	25.5	1.1	13.0
Radius of pipe R (m)	R_{ip}.= 0.075; R_{op}= 0.085	24.4	0.3	14.1
	R_{ip}.= 0.150; R_{op}= 0.160	26.3	1.0	12.2
	R_{ip}.= 0.225; R_{op}= 0.250	29.8	2.1	8.7
	R_{ip}.= 0.300; R_{op}= 0.325	32.2	1.0	6.3
	R_{ip}.= 0.150; R_{op}= 0.175	26.5	1.0	12.0
	R_{ip}.= 0.150; R_{op}= 0.190	26.7	1.0	11.8
Air Velocity in pipe V_A (m/s)	1	26.5	1.7	12.0
	3	31.8	1.9	6.7
	5	34.0	2.0	4.5
	7	35.1	1.0	3.4
Conductivity of pipe k_p (W/m K)	0.2	27.3	0.9	11.2
	0.5	26.5	1.0	12.1
	1.0	26.3	1.0	12.2
	1.5	26.2	1.0	12.3
	3.0	26.1	1.0	12.4
Conductivity of soil k_g (W/m K)	0.2	35.8	0.2	2.7
	0.6	31.9	0.5	6.6
	1.0	29.4	0.8	9.1
	1.5	27.5	0.9	11.0
	2.0	26.5	1.0	12.0
	3.0	25.8	1.0	12.7

R_{ip} =Internal diameter of pipe

R_{op}=External diameter of pipe

The inlet air temperature is taken as 38.5 °C (i.e. monthly average maximum air temperature in June)

Table 3.11 Variation of delivery temperature (T_{AL}) and cooling potential (Q_c) of an earth-air pipe system due to various system parameters for January conditions of New Delhi

Variable	Value	Delivery temperature T_{AL} (^0C)	Heating potential Q_c(kWh)	Rise in temperature (Inlet - Delivery) (°C)
Depth of pipe Z (m)	1	18.1	0.8	9.6
	3	21.0	1.0	12.5
	5	22.3	1.1	13.8
	7	22.5	1.2	14.0
Length of pipe L (m)	20	16.2	0.6	7.7
	40	20.2	1.0	11.7
	60	22.3	1.1	13.8
	80	23.5	1.2	15.0
Radius of pipe R (m)	R_{ip}.= 0.075; R_{op}= 0.085	24.7	0.3	16.2
	R_{ip}.= 0.150; R_{op}= 0.160	22.6	1.2	14.1
	R_{ip}.= 0.225; R_{op}= 0.250	18.6	1.9	10.1
	R_{ip}.= 0.300; R_{op}= 0.325	15.8	2.4	7.3
	R_{ip}.= 0.150; R_{op}= 0.175	22.3	1.1	13.8
	R_{ip}.= 0.150; R_{op}= 0.190	22.1	1.1	13.6
Air Velocity in pipe V_A (m/s)	1	22.3	1.1	13.8
	3	16.2	1.9	7.7
	5	13.7	2.2	5.2
	7	12.5	2.3	4.0
Conductivity of pipe k_p (W/m K)	0.2	21.5	1.1	13.0
	0.6	22.4	1.2	13.9
	1.0	22.6	1.2	14.1
	1.5	22.7	1.2	14.2
	3.0	22.8	1.2	14.3
Conductivity of soil k_g (W/m K)	0.2	11.8	0.3	3.3
	0.6	16.4	0.7	7.9
	1.0	19.3	0.9	10.8
	1.5	21.3	1.1	12.8
	3.0	22.9	1.2	14.4

R_{ip} =Internal diameter of pipe
R_{op}=External diameter of pipe
The inlet air temperature is taken as 8.5 °C (i.e. monthly average maximum air temperature in January)

The earth-air pipe system is used to cool about 120 m^2 of floor area in the Dilwara Bagh house. Two rectangular pipes of cross sectional area of 0.6m x 0.8m, and a length of 60m are employed at a depth of 4m. A blower of 3 hp is used to force air into the system, and is housed in a blower room about 67.5m away from the house. It maintains an air velocity of about 6m/s in the pipe, which is made of brick and sand stone. A cross-section of the pipe and a sketch plan of the system are shown in Figs. 3.35 and 3.36. The outlets of the system to the rooms are protected by earth-berms. A cross-section of the same is shown in Fig 3.37.

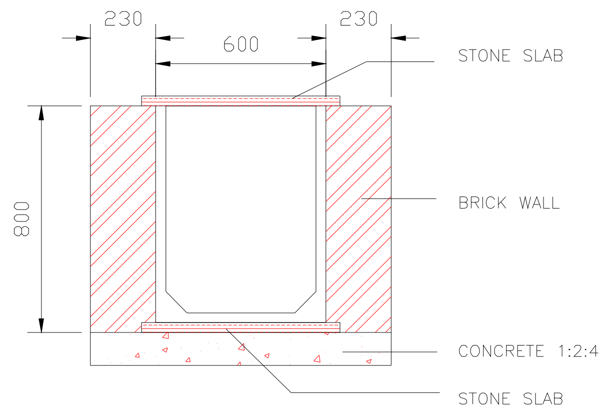


Fig. 3.35 Cross-section of pipe at the Dilwara Bagh House, Gurgaon

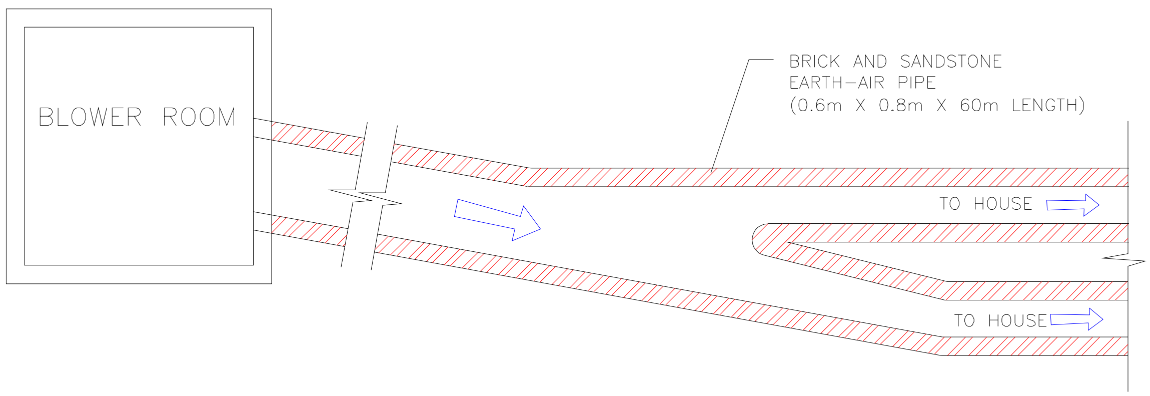


Fig. 3.36 Sketch plan of earth-air pipe system at the Dilwara Bagh House, Gurgaon

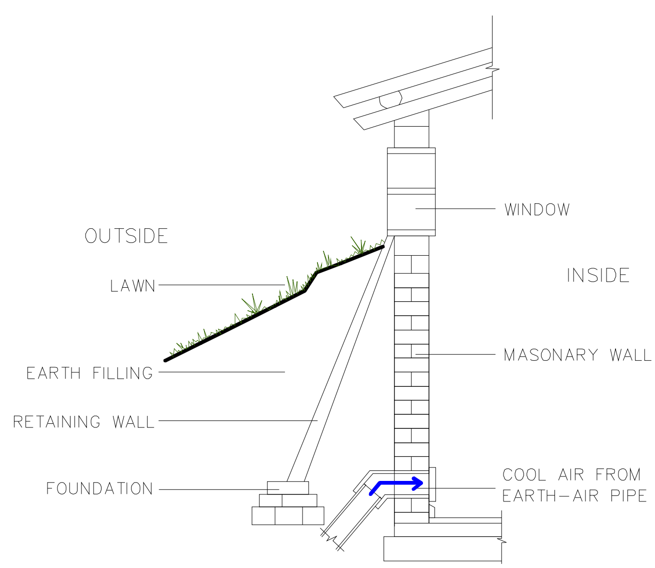
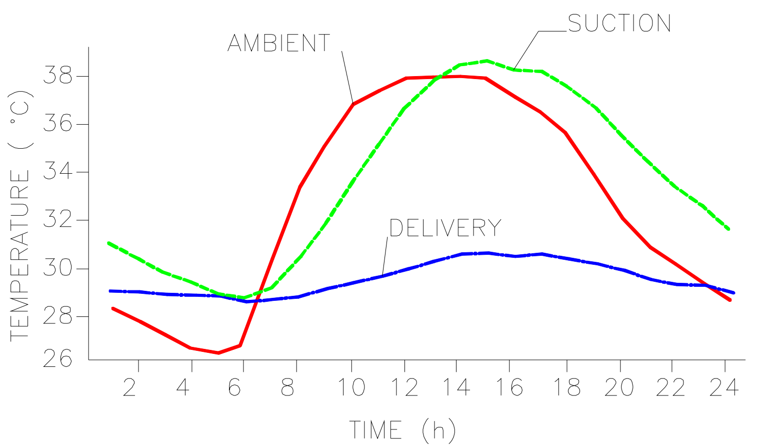
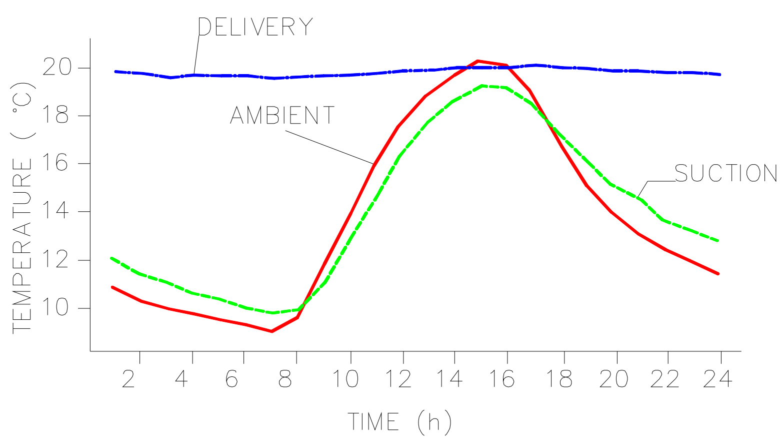


Fig. 3.37 Section showing earth berm at the Dilwara Bagh House, Gurgaon

Extensive post occupancy evaluation studies have been carried out by Thanu et al. [26]. Figure 3.38 shows a typical performance of the system during summer and winter conditions. It is seen that in summer, the exit or delivery temperature is about 29^{0}C when outside can be as high as 38^{0}C. Further, the fluctuation in room temperature is only 2.2^{0}C as compared to 11.8^{0}C for outside air. In winters, the delivery temperature is maintained at about 20^{0}C, when outside air is about 8^{0}C – an increase in temperature by about 12^{0}C. Thus, the earth-air pipe system performs well both in summers as well as in winters. The system provides an average daily cooling potential of 242 kWh (thermal) in a summer month and about 365 kWh in a winter month. As the blower's power is 3 hp (2.2 kW), the coefficient of performance (COP) of the system is 4.5 in summer and 6.8 in winter.



(a) Summer



(b) Winter

Fig. 3.38 Typical performance of the earth-air pipe system

3.5 DAYLIGHTING

Vision is by far the most developed of all our senses and light has been the main prerequisite for sensing things. Light is that part of the electromagnetic radiation which is capable of exciting the retina of the eye to produce visual sensation. It is a vital and invaluable component of human life. Considerable care is therefore essential for creating effective visibility and providing visual satisfaction.

The visible spectrum, to which the human eye is sensitive, is a narrow band of wavelengths between 380 and 780 nm. Buildings must have sufficient lighting in this band. Light has a major effect on the way one perceives spaces and their functions. Sufficient light is required to carry out everyday tasks in homes, offices and factories. The illumination requirements for the comfortable performance of various tasks need to be suitably considered in design. For example, very bright lighting is required in a diamond polishing industry while soft lighting may be sufficient in a bedroom. The required illumination can be provided by daylight through windows and/ or by artificial light in the form of tubelights and lamps. In artificial lighting, the light source is under the user's control in the sense that the illumination level is independent of location, climate or even the construction of the building. On the other hand, daylighting strongly depends on external conditions and its control depends on the way a building is constructed. Very often, one finds numerous tubelights burning in offices, factories and homes during daytime even though there is plenty of sunlight outside. Because of its variability and subtlety, natural light has a more pleasing effect than monotonous artificial lighting. Building components such as windows and skylights, which admit light, enable a visual communication with the outside world. Besides, plentiful daylight also has energy-saving implications. Since most buildings are largely used during the daytime, effective daylighting makes economic sense. Because a good daylighting system involves many elements, it is best to incorporate them in the building design at an early stage. The manner in which daylight enters and distributes itself in a room depends on the size and location of openings, type of glazing, configuration of the room, and reflective properties of walls, ceiling and other surfaces. The intensity of daylight and the daylight factor (explained under 3.5.1) also depend on the height and the location of the opening on a wall; the intensity reduces as the distance from the opening increases.

The pattern of artificial lighting in a building differs from climate to climate. For example, in hot and dry climates, internal shading devices are often used to protect the building from overheating by high solar radiation. This will drastically reduce the daylight entering the room, thereby increasing artificial lighting load. However, in cold and sunny climates shading devices are not required, so there is less need for artificial lighting. Correct daylighting design will reduce not only the energy cost but also the cooling cost, caused by lighting devices.

Under a European research programme, 60 buildings were monitored and documented from the point of view of daylighting. These case studies provide a valuable resource to building designers. Fontoynont [27] presents both quantitative as well as qualitative assessments of a range of daylighting solutions. The designing aspects of daylight systems in buildings have been explained by Baker and Steemers [28] in an accompanying publication.

3.5.1 Basic Principles of Daylighting

The ultimate source of daylight is the sun. By the time sunlight reaches the earth's surface, it has been subjected to atmospheric attenuation, scattering and reflection. The daylight received on the earth's surface is composed of direct light (light directly received from the sun) and diffuse light (light received from all parts of the sky due to atmospheric scattering and reflection). Light reaching a particular point inside a building may consist of, (1) **direct sunlight**, (2) **diffuse light or skylight**, (3) **externally reflected light** (by the ground or other buildings), and (4) **internally reflected light** from walls, ceiling and other internal surfaces [29,30]. This is depicted graphically in Fig. 3.39.

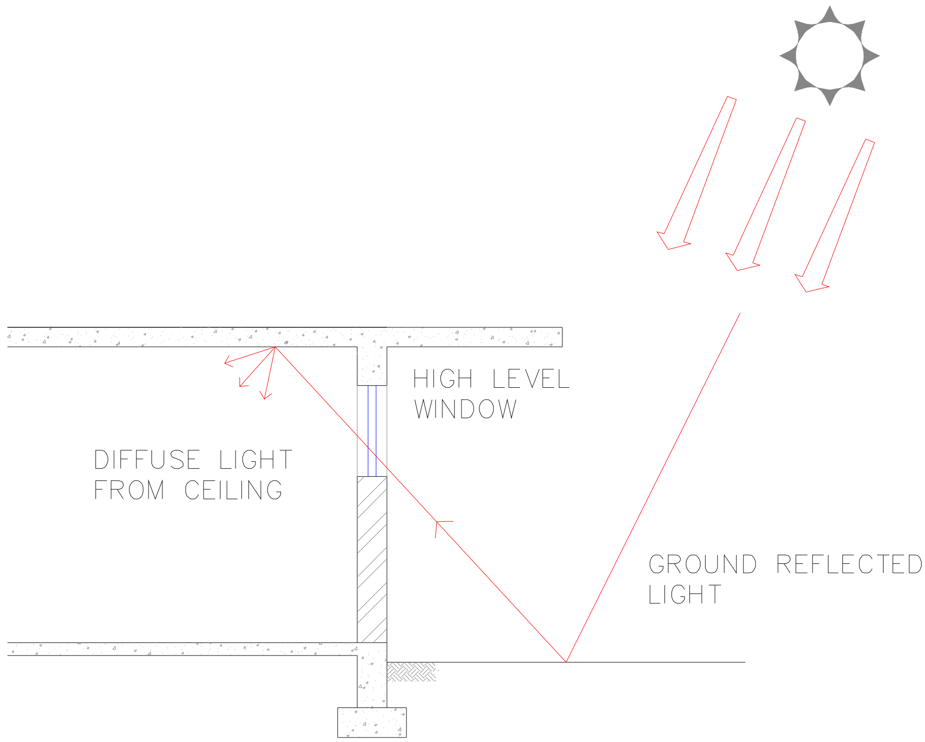


Fig. 3.39 Distribution of daylight

The availability of light within a building depends on its planform, orientation, the location and size of openings, characteristics of glazing, and internal reflections. Because of the variations in outdoor lighting levels, it is difficult (and perhaps meaningless) to calculate interior lighting in photometric illumination terms. However, inside a given building at a given point, the ratio of indoor illumination to the corresponding outdoor illumination can be taken as constant. This constant ratio, expressed in percentage, is the daylight factor (DF), given by:

$$DF = \frac{E_i}{E_o} \times 100 \tag{3.12}$$

where,

E_i = indoor illumination at the point of consideration
E_o = outdoor illumination from unobstructed sky hemisphere

The three components contributing to daylight factor are: (a) sky component (SC), (b) externally reflected component (ERC), and (c) internally reflected component (IRC)

Thus,

$$DF = SC + ERC + IRC \tag{3.13}$$

Each component can be calculated by following standard procedures outlined in the BIS Handbook [5]. The magnitude of each of these components depends on design variables as follows:

Sky component (SC) - The area of sky visible from the point considered and its average altitude angle (luminance of the sky at that angle), window size and position in relation to the point, thickness of window frame, quality of glass and its clearness, and any external obstructions.

Externally reflected component (ERC) - The area of external surfaces visible from the point considered, and the reflectance of these surfaces.

Internally reflected component (IRC) - The size of the room, the ratio of surfaces (wall, roof, etc.) in relation to the window area, and reflectance of indoor surfaces.

Direct sunlight is excluded from the definition of daylight factor as it is not desirable from the perspective of the quality of the light. It creates problems of shadows and severe brightness imbalances that cause glare. Direct sunlight also brings excessive heat in summer. Adequate shading devices are therefore recommended not only for thermal comfort but also for visual comfort.

The outdoor illumination level E_o can be established for a given place by analysing the long-term illumination record. This is taken as 'design sky illumination' value. For India, it is taken as 8,000 lux for clear design sky [5].

For example, if E_i = 300 and E_o = 8000 lux, then,

$$DF = \frac{300}{8000} \times 100 = 3.75$$

(3.14)

Design variables such as window size can be manipulated to achieve this daylight factor. This method will ensure that 90% of the time, the inside illumination level is at the required level or exceeds it. For the remaining 10% of the time, one can rely on human adaptability. Recommended daylight factors for typical building interiors are presented in Table 3.12.

3.5.2 Daylighting Systems

The conventional modes of introducing daylight into the building include windows, clerestories, skylights (Fig. 3.40) and light shelves (Fig. 3.41). They can normally provide adequate daylight in the perimeter of buildings up to 5m of window or skylight. Light shelves are reflective horizontal surfaces that extend from the exterior to the interior of a building. They reflect sunlight onto the ceiling, which in turn reflects into the interior space. They can prevent unwanted direct sunlight, which is a source of glare, from entering the space. Light shelves are intended to modify daylight distribution by reducing the sky component and increasing reflection from the ceiling resulting in a more uniform daylight distribution [27]. Reflective blinds offer good control of glare and solar protection. These also maintain reasonable light levels inside, provided the ceiling is bright. One can use atria and courtyards, or use daylighting optical systems to deliver light to deeper parts of the building. Atria (Fig. 3.42) can help reduce heat losses, but their daylighting efficiency depends on the brightness of their walls and the shading on windows [27]. Daylighting optical systems require a collection system to gather and redirect the available light. This is then transmitted to the point of use inside the building and finally distributed as per the illumination requirement.

Table 3.12 Recommended daylight factors [10]

Building	Area/Activity	Daylight factor (%)
Dwellings	Kitchen	2.5
	Living room	0.625
	Study room	1.9
	Circulation	0.313
Schools	Class room	1.9 – 3.8
	Laboratory	2.5 - 3.8
Offices	General	1.9
	Drawing, typing	3.75
	Enquiry	0.625 – 1.9
Hospitals	General wards	1.25
	Pathology laboratory	2.5 – 3.75
Libraries	Stack room	0.9 – 1.9
	Reading room	1.9 – 3.75
	Counter area	2.5 – 3.75
	Catalogue room	1.9 – 2.5

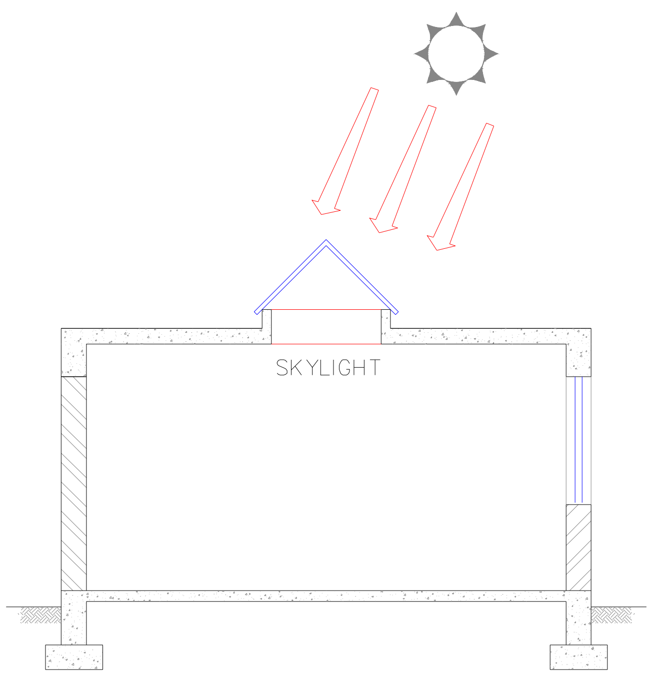


Fig. 3.40 Skylight

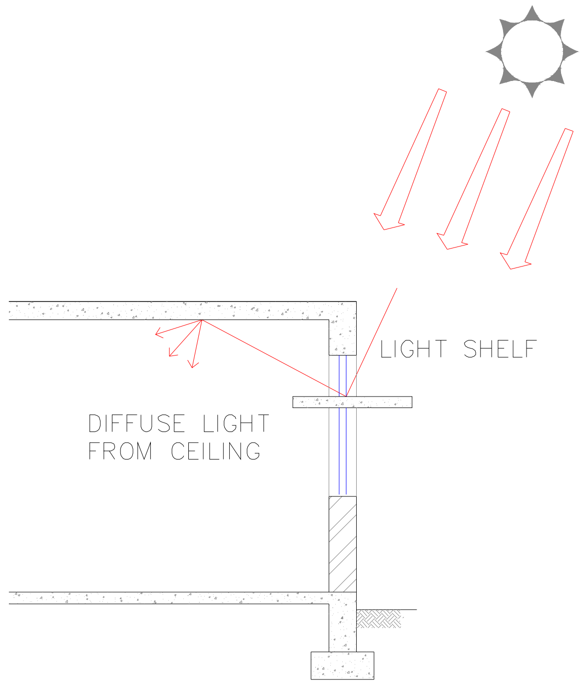


Fig. 3.41 Light shelf

Certain systems capture and distribute light to the interiors using a pipe (Fig. 3.43) or lightwell (Fig. 3.44). These systems usually do not have any moving parts. Aluminium pipes with a clear acrylic dome on top and a translucent acrylic dome at the bottom are installed on the roof and used as sunpipes. The pipes are lined with silver to reduce reflection losses. The translucent dome at the bottom creates diffuse light in the living space. In reflective light guides (Fig. 3.44), mirrors are used inside ducts to guide or direct light coming from the skylights to the interiors. The ducts may open at various levels. The light guides transport light using multiple specular reflection at the reflective inner wall surface. Using highly reflective silvered polyester semi-collimated mirrors, light can be transmitted over 30 m with only small losses.

Mirrors and lenses can be used to augment the availability of daylight. These follow the path of the sun by appropriate tracking mechanisms and direct the light to the desired area using sensors and control systems. Such arrangements can be used to catch the very low-angle light that the sun produces at dawn and dusk, and extend the period of useful daylight by a few hours. Figure 3.45 shows a tracking reflector with a receiver in front for directing daylight deep into the interior in conjunction with lightwells. Additionally, there are systems that can be used to direct light to some fixed points. For example, in the Himawari system (Fig. 3.46), a honeycomb of Fresnel lenses focus the sun’s light onto the ends of quartz-glass optical fibres. The fibres are used to distribute the light deep within the interiors. A six-fibre cable of length of approximately 40 m can provide light which is comparable to the output of a 75-watt incandescent lamp.

Fig. 3.42 Atrium

Fig. 3.43 Light pipe

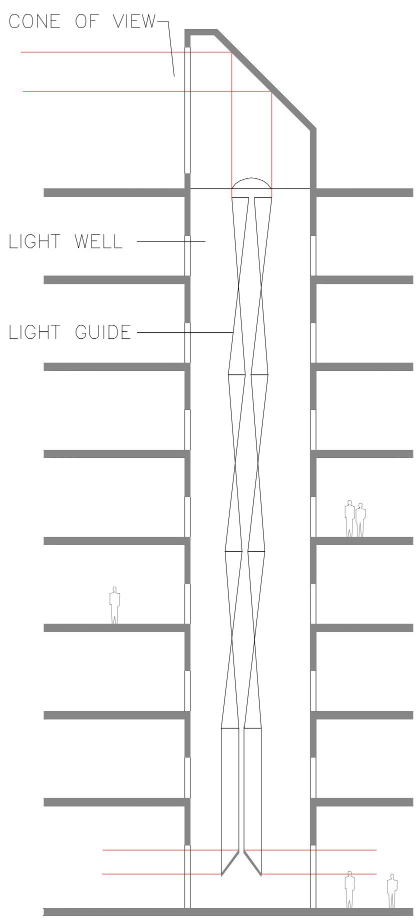


Fig. 3.44 Light well

Fig. 3.45 Sun tracking unit

Fig. 3.46 Himawari system

Laser cut light deflecting panels (LCP) can be used to deflect collimated light at low angles to penetrate the deeper zones. Light deflection results from the inner surfaces within the dielectric material, angled incident light upwards into the interiors due to total internal reflection. LCPs are formed by making laser cuts of about 2mm through a clear acrylic sheet. Each laser cut becomes a narrow mirror internal to the sheet which reflects light incident on the sheet from directions other than normal. The angle of the laser cuts or panels can be varied for different uses:

- It can be used to direct light to the ceiling for deeper penetration. This improves daylighting and reduces glare on working planes.
- When used in skylights, (e.g. pyramidal skylights), or angle selective glazings, the noon time radiation which is directly overhead can be reflected back to the sky so that interiors do not overheat. When the angle of the sun is low (e.g. in winters, mornings and evenings), the light is directed inside.

- They can be used as louvers, which when opened, deflect the direct light back to the sky. This prevents glare and allows breeze to penetrate the building for summer cooling. When closed, they reflect light to the ceiling for deeper penetration of light in winter. Figure 3.47 shows a sketch of the working principles of LCP louvers.

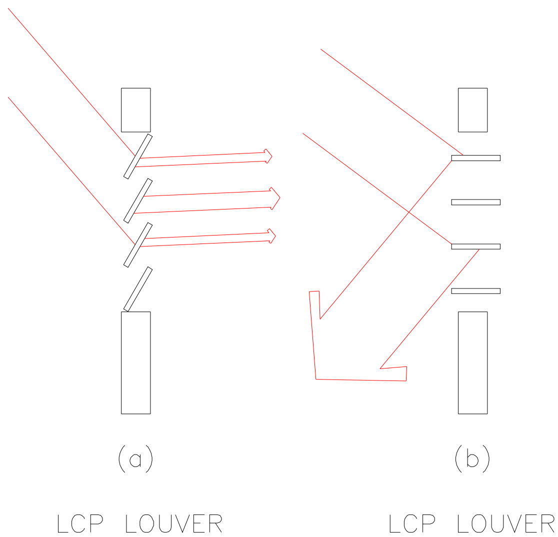


Fig. 3.47 LCP louvers
(a) tilted, (b) open

Refractive devices are devices that can be mounted on a window to redirect sunlight towards the ceiling of a room over a wide range of sun elevations. The basic component of such a device is a single solid section of dielectric with a sloping curved base and a v-shaped trough as the top surface. These are stacked together to form a module. An enclosed air gap is created between two sections. This module can be permanently mounted in a window to redirect sunlight towards the ceiling by total internal reflection. The device is generally placed in the upper parts of windows (i.e. above head height) to reduce possibility of glare and distortion of view. Figure 3.48 shows a sketch of a refracting daylighting device.

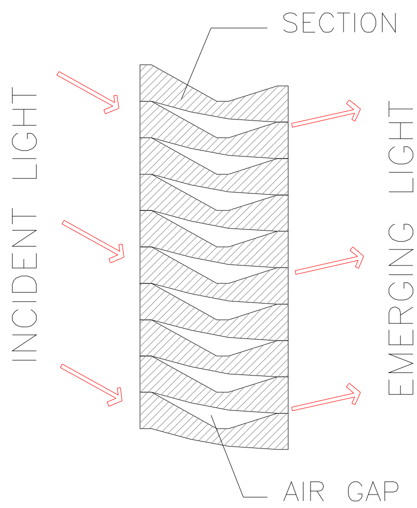


Fig. 3.48 Schematic sketch of a refractive daylighting device

3.6 BUILDING MATERIALS

There are many techniques for improving energy efficiency in buildings, and it is the responsibility of the occupants to operate it in an energy-conserving way. But occupants can operate it only within the range provided by the building's designers. It is ultimately up to the designers to provide the most energy efficient building to owners and occupants. Not only is this a service from an economic standpoint, but it will also prevent the building from becoming impracticable due to high energy costs.

Building materials play a significant role in energy conscious architecture. The rate of heat flow through various components of a building, its time lag and amplitude decrement, as well as the energy storage capability of the building are all governed by the materials used. The choice of materials is therefore crucial from the perspective of the thermal performance of the building. Besides, the materials provide the required structural strength for the building. While the conventional building materials are well known to architects, building scientists and users (Refer to Appendix IV.1), it is desirable to focus on alternative materials to reduce costs and energy consumption. It may be noted that a certain amount of energy is consumed for the very production of the building materials from their basic raw ingredients. This is known as the *embodied energy* of the materials. This aspect has a bearing on the choice of building materials.

3.1.1 Embodied Energy of Building Materials

Energy used in the construction process and particularly in the building materials used should be minimised as a whole. Energy consumed in the procurement, manufacture, processing and recycling of building materials affects the cost of construction. The process of energy analysis consists of three steps: (i) the energy used in the production of raw materials (ii) the energy used in the making of the finished materials, and (iii). the energy used for the machinery and equipment required in the manufacturing process [31]. Sum total of these three is known as energy intensity.

Building materials have been categorised into three types based on their energy intensities. High energy materials are those with energy intensities greater than about 5GJ per tonne of manufactured materials and include items like aluminium, steel, plastics, glass and cement. Medium energy group materials comprise those requiring energy inputs between 0.5 to 5 GJ per tonne of material and include concrete, lime plaster and most types of blocks based on cement, lime, flyash and fireclay bricks and tiles. Low energy group materials include fine and coarse aggregates for construction, pozzolona types of soil and stabilised soil. It is essential to promote low cost, low energy and medium energy materials for energy efficiency in building construction. However, these materials should also be durable, require less maintenance and should be recyclable. It may be noted that materials such as aluminium and steel although being highly energy intensive, can be recycled very cheaply in terms of energy.

A detailed study of the embodied energy of various building materials has been carried out by Development Alternatives, New Delhi [32]. The document provides information for different building materials and components at various levels, namely, manufacturing, processing and fabrication. A designer can obtain information on material description, technology and resources, environmental implications, production statistics, and world status on energy data. The report also presents data on energy that is consumed at the quarrying, production and transportation of raw materials, intermediate materials and finished goods. The embodied energy of various materials is provided in Table 3.13. In addition to conventional materials, the table also includes a few alternative building materials. The primary energy required by weight, volume and/or surface area of the product is listed in the table.

Table 3.13 Energy requirements of different building materials [32]

Material	Density (kg/m^3)	Primary Energy M J thermal		
		Per tonne	Per m^3	Per m^2
Primary Materials				
Coarse Aggregate (25-40mm)	2240	240	538	-
Lime (quick)	640	6220	3968	-
Cement (OPC 33 grade)	1440	6700	9648	-
Steel (semis)	7800	-	-	-
Mini (billets)	-	23000	-	-
ISP (ingots)	32000	-	-	-
PVC (billets)	1500	158000	-	-
Secondary Materials				
Bricks weight (average 2.75 kg)	1800	1286	2235	518
Solid Concrete Blocks (30 x 20x 15) cm	2000	580	1002	209
Hollow Concrete Blocks (20 x 20 x 40) cm	1300	700	910	121
FalG Block (30 x 20 x 15) cm	2000	4400	879	127
Aerated Concrete block (19 x 19 x 39) cm	1278	6400	818	138
Steel Rods (6, 8, 10mm etc.)	7800	28212	-	-
Steel RSJ (standard sizes)	7800	42840	-	-
Steel Cold Rolled Sheets	7800	51642	-	-
Steel Hot Rolled Sheets	7800	34715	-	-
CGI	-	48276	-	302
Ferrocement (1 inch thick)	1687	3669	-	186
Cement Bonded Board (40 mm)	1250	6487	8109	324
MDF (Including raw material energy)(19 mm)	770			472
MDF (excluding raw material energy)(19mm)	770			188
Plywood (6mm thick)	700	-	-	142
Plywood (19mm thick)	700	-	-	312
Flush door (35mm thick)	700	-	-	482
PVC pipe (40 cm diameter)	1500	-	-	-

3.1.2 Alternative Building Materials

This section presents a summary of various alternative building materials and technologies that have been developed to reduce energy consumption as well as cost [31-37].

a) Autoclaved aerated concrete (AAC)

Autoclaved aerated concrete is known more by its patented or trade name such as Siporex, Trustone and Environcrete in various parts of the world. It is a factory-produced light weight precast concrete which is available in a wide variety of shapes and sizes. A typical 200 mm thick AAC wall can be about half the weight of an ordinary hollow-core concrete block. Further, AAC blocks can be bonded by a thin layer of adhesive and thus do not need mortar. AAC blocks are made from a mixture of Portland cement, lime, silica sand or fly ash, water and aluminium powder or paste. When mixed, millions of tiny hydrogen bubbles expand the mix to approximately five times its original volume. AAC can be reinforced and can be easily cut using ordinary carpentry tools. It is a stable, non-polluting, fire resisting, thermally and acoustically insulating, and durable material. However, it needs to be plastered for protection from rain.

b) Fly ash

Fly ash is a by-product of coal in thermal power plants. It consists of organic and inorganic matter that is not fully burnt, and can be recycled for use in a variety of building materials. The properties of fly ash make it suitable for the manufacture of bricks, hollow and solid blocks, cellular concrete, partial replacement of cement, filler material in concrete, wood substitute, and also for use in the manufacture of emulsion paints, building distempers, etc. Using fly ash in building materials can result in a number of advantages. For example, fly ash bricks can replace burnt clay bricks, which require use of fertile agricultural soil. They are dimensionally stable having a smooth finish and fine edges, and are available in a number of sizes. They also have good resistance to weathering and need not be plastered. The bricks can be made in a number of colours using pigments. This material is being tried and tested at Central Building Research Institute, Roorkee. It has been used at IIT Delhi and The Energy Resources Institute, Gwalpahari and shown to have good results [31]. Fly ash is also used to make FaL-G (hydraulic cement). The name FaL-G stands for fly ash (Fa), Lime (L) and Gypsum (G) which are its ingredients. It can be used as an alternative to ordinary Portland cement as a binder, and to burnt clay bricks as a masonry block. It can also be used for road pavements, and in plain concrete in the form of Fal-G concrete.

c) Compressed earth blocks

The manual production of earth blocks by compressing them in small moulds has been practised for centuries. The process has now been mechanised and a variety of presses are used, including mprocessanual and hydraulic . The soil for compressed earth blocks consists of a mixture of pebbles (1.5 parts), sand (5 parts), silt (1.5 parts) and clay (2 parts). About 5 % cement is used to stabilise the earth blocks. Products range from accurately shaped solid, cellular and hollow bricks, to flooring and paving elements. Compressed earth blocks are sun dried and do not need to be burnt. They are also economical, strong, energy saving and simple to manufacture. Soil stabilised hollow and interlocking blocks can provide better thermal insulation than bricks. Mud blocks stabilised with Fal-G are much stronger, absorb less water, and are cheaper than cement stabilised blocks. Development Alternatives, New Delhi [32] and Auroville, Pondicherry have carried out extensive research on this material. A number of buildings at Auroville, Pondicherry have been built using compressed earth blocks.

d) Clay red mud burnt bricks

Clay red mud burnt bricks are produced from alumina red mud or bauxite, an industrial waste of aluminium producing plants, in combination with clay. The brick possesses all the physical properties of normal clay bricks. Incidentally, they also solve the problem of waste disposal and environmental pollution. In addition, they have good architectural value as facing bricks due to their pleasing colour.

e) Lato blocks

Lato blocks are bricks made from lateritic soil and cement or lime. The blocks are moulded under pressure to produce strong and good quality blocks which consume lesser energy than conventional bricks, and hence are cheaper. They are available in various colours ranging from cream to light crimson.

f) Precast hollow concrete blocks

Precast hollow concrete blocks are manufactured using lean cement-concrete mixes and extruded through block making machines of the egg laying or static types. They need lesser cement mortar and enable speedy construction as compared to brick masonry. The cavity in the blocks provide better thermal protection. Further, the blocks may not need external or internal plastering. These can be used as walling blocks or as roofing blocks along with inverted precast tee beams.

g) Bamboo/timber mat based walls

These walls are made up of bamboo mat placed between horizontal and vertical timber/bamboo frames. The plastering is done using mud or cement mortar on either side. These are easy to construct, cost less and are popular in hilly areas as they can be self-assembled. However, these are not load bearing and need a supporting structure. This upgraded traditional technology is a relevant option for walling from the perspective of earthquakes to minimise damage in the event of a collapse

h) Rat trap bond

The rat trap bond is an alternative brick bonding system for English and Flemish bond. It is economical, strong and aesthetically appealing. It can save about 25% of the total number of bricks and about 40% of the mortar cost for a wall. The rat trap bond is simple to build and has better insulation properties.

i) Composite ferrocement system

The system is simple to construct and is made of ferrocement (rich mortar reinforced with chicken mesh and welded wire mesh). These reduce the wall thickness and allow a larger carpet area. Precast ferrocement units in trough shape are integrated with RCC columns. Ferrocement units serve as a permanent skin unit, and as a diagonal strut between columns. Inside cladding can be done with mud blocks or any locally available material. These are ideally suited for seismic areas.

j) Coconut fibre and wooden chips roofing sheets

Coconut fibre and wooden chips or fibre are soaked in water for two hours and after which the water drained off. These are then mixed with cement, laid over a corrugated mould and kept under pressure for 8 to 10 hours. After demoulding, the sheets are cured and dried before use.

k) Cement bonded fibre roofing sheets

These are made from coir waste, coconut pith, wood wool or sisal fibre in combination with cement as binder, for production of corrugated or plain roofing sheets. These sheets use lesser cement than AC sheets and are 50% cheaper than AC/CGI sheets. Besides, they are light weight, fire resistant, water proof and can be used for sloping roof options.

l) Micro concrete roofing tiles

Micro concrete roofing tiles are made of graded cement mortar layer and formed over sloping mould. They are used in pitched roofing systems and are less expensive than ACC/CGI sheets. These tiles are appropriate where fired clay tiles are not available, and timber supporting skeletal system is costlier. The rafter and purlin system cost less when micro concrete roofing tiles are used. Further cost reduction can be made by using ferrocement rafters and purlins.

m) **Stone patti roofing:**
Stone patti roofing is a flat roofing system with sand stone slabs (patties) resting over steel or slender RCC section beams. The slabs are overlaid with terracing for insulation. This type of roofing is appropriate where (sand) stone slabs are available, and is more economical than RCC slabs. In places like the states of Rajasthan, Madhya Pradesh and Andhra Pradesh where large granite stone patties are available, the beams are not needed as the pattis can rest on walls.

n) **Precast brick arch panel system**
In this technique, precast brick arches of size 50cm x 50cm are cast on a platform. The arches are placed side by side over the partially precast joist. The haunches between the arches are filled with cement concrete to have a level surface on the top. Such roofs/floors are 30 percent more economical when compared with conventional RCC.

o) **Filler slabs**
Filler slabs are normal RCC slabs in which bottom half (tension) concrete portions are replaced by filler materials such as bricks, tiles, cellular concrete blocks, etc. Filler materials are so placed as not to compromise structural strength; they replace unwanted and non-functional tension concrete, thus resulting in economy. These are safe, sound and provide aesthetically pleasing pattern for ceilings. An additional advantage of filler slabs is that they do not need plastering.

p) **Particle boards**
Particle boards are made from wood waste, cotton stalk and bagasse, and bonded by resin. They can be used as inserts, and with veneering, they can be used as an alternative to timber in panelling, false ceiling flooring, partitioning and furniture.

Table 3.14 gives the possible savings that could be achieved by using alternative building materials [37].

Table 3.14 Estimated cost savings on using innovative building materials [37]

S. No.	Cost-Effective Technologies	In place of Conventional options	% of Saving
I.	**FOUNDATIONS**		
1.	Pile foundation (under reamed)	Traditional stone/bricks	15
2.	Brick Arch foundations .	Footings	25
II.	**WALLING (SUPER STRUCTURE)**		
1.	230 mm Thick wall in lower floors	330 mm brick walls	5
2.	180 mm Thick wall in bricks	230 mm brick walls	13
3.	115 mm thick recessed walls	230 mm brick walls	20
4.	150/200 mm Stone block masonry'	Random rubble masonry	30-20
5.	Stabilised mud blocks	Burnt brick walls	20
6.	FaL-G Block masonry	Clay brick walls	20
7.	Fly ash brick walls	Gay brick walls	25
8.	Rat trap bond walls .	English/Flemish bond	25
9.	Hollow blocks walls	Solid masonry	20
III.	**ROOFING**		
1.	85 mm thick sloping RCC	110 mm RCC	30
2.	Tiles over RCC rafters	Tiles over timber rafters	25
3.	Brick panel with joists	RCC	20-25
4.	Cuddapah slabs over RCC rafters	CS over timber rafters	20
5.	L-panel sloping roofing	RCC	10
6	RCC planks over RCC joists	RCC	10
7.	Ferrocement shell roofing	RCC	40
8.	Filler slab roofing	RCC	22
9.	Waffle roofing	RCC	15
10.	RCC channel units	RCC	12
11.	Jack arch brick roofing	RCC	15
12.	Funicular shell roofing	RCC	18
13.	Brick funicular shell roofing	RCC	30
14.	Precast blocks over inverted T-beams	RCC	25
15.	Micro-concrete roofing tiles	Clay tile roofing AC sheet roofing	20-15
IV.	**MISCELLANEOUS ITEMS**		
1.	RCC door frames	Timber Frames	30
2.	Frameless doors (only inserts)	Frames and shutters	50
3.	Ferrocement door shutters	Timber shutters (second class timber)	30
4.	RCC window frames	Timber frames	30
5.	RCC jellies	Timber windows/ventilators	50
6.	Precast thin lintels	RCC lintels	25
7.	Precast sunshades	Cast sunshades	30
8.	Ferrocement sun shades-cum-lintel	RCC lintel-cum-sunshades	50
9.	Brick on edge lintels	RCC lintels	50
10.	Corbelling for lintels	RCC lintels	40
11.	Brick arch-for lintels	RCC lintels	30
12.	Precast RCC shelves units	Timber/concrete	20-35
13.	Precast Ferrocement shelves	Timber/concrete	35-45
14.	Ferrocement manhole covers	Casion/concret e	50-40
15.	Ferrocement water tank	Rigid PVC	60

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APPENDIX III.1

EFFECT OF SHADING DEVICES

The heat gain through windows has a major role in controlling the indoor temperatures in case of non-conditioned buildings and heating and cooling load in case of conditioned buildings. It is therefore necessary to examine the effect of various chajja-fin combinations to reduce the heat gain. For this purpose the amount of direct solar radiation incident on windows has been considered as the basis. The effect of size of chajja, fin, gap, extension and windows in the four cardinal directions (i.e. north, east, south and west) has been studied. These terms are defined as follows:

Fin/Chajja depth: Projection outward from the wall,. (When a chajja is assumed to have a depth of say X meters, all the fins are also assumed to have a depth of X meters. The chajja and fin meet at an edge at top)

Fin length : Length measured from the top edge of the window to the bottom of the fin. (Four cases considered are: no fin, fin upto one third of window height measured downwards from top edge of window, fin upto two third of window height measured downwards from top edge of window and fin upto window height measured downwards from top edge of window).

Gap : The distance between the top edge of window and the chajja

Extension : The distance between the left or right fin to the nearest vertical edge of window. In case there is no fin, it is the length by which the chajja extends beyond the width of the window.(Extension is assumed equal on both sides of the window)

Figure III.1 illustrates these terms graphically.

The various cases considered are:

Window size	:	0.6 x 1.2 , 0.6 x 1.8, 1.2 x 1.2, 1.2 x 1.8, 1.8 x 1.2, 1.8 x 1.8 (m^2)
Fin/Chajja depth	:	0.0, 0.3, 0.6, 1.0 (m)
Fin length	:	No fin,
	:	Upto 1/3 of window height measured from top.
	:	Upto 2/3 of window height measured from top.
	:	Equal to the window height.
Gap	:	0.0, 0.15(m)
Extension	:	0.0, 0.15(m)

Windows are given a set back of 0.1 m from the exterior surface of the wall.

Beam radiation incident on the window per unit area (i.e., Beam radiation on window X (Window area - Shaded area) / Window area) is found out for the hours between 9 a.m. to 4 p.m. (IST) for all days of the year. This particular time span has been chosen to avoid the absurd values, which may crop in due to the low magnitudes of the trigonometric functions for hours before 9 a.m. and after 4 p.m. It may be mentioned that the intensities of solar radiation before 9 am and after 4 p.m. are generally small. So the assumption does not lead to significant error. Further, this calculation has been used for relative comparisons. These hourly values are summed up over the year to yield yearly total radiation incident on window.

Yearly beam solar radiation incident on windows for various chajja-fin combinations have been estimated for Mumbai, Pune, Ahmedabad and Nagpur. Table III.1 presents results of such calculations for a window of size 1.2m X 1.2m. Tables show the percentage radiation incident for various chajja-fin combinations as compared to an unshaded window (with no chajja or fin). The radiation falling on an unshaded window (over the year) in each of the directions corresponding to different climates is given at the end of the table. To find out the actual radiation per unit area of window with shading device/s, multiply the radiation on unshaded window with the corresponding number from the table and divide by 100.

$$\text{Radiation falling on window} = \frac{P \times Q}{100} \quad \text{Wh/m}^2\text{ - year} \qquad \text{...(III.1)}$$

$$\text{Total radiation on the window} = \frac{P \times Q \times R}{100} \quad \text{Wh/year} \qquad \text{.........(III.2)}$$

Where : P = Percentage of radiation falling on shaded window.

Q = Radiation on unshaded window

R = Window area (m^2)

The radiation blocked by the shading device is the difference of the radiation on the unshaded window and that on the shaded window. The smaller is the value of P, the better is the performance of window shading device combination. By keeping this fact in mind, one can find out the best window shading device combination for any of the four cities and in any of the four directions.

It is seen that providing a chajja in general reduces the radiation incident on windows. This is as expected. If, however, a gap between the top of the window and chajja is provided, the shading decreases and the percentage of radiation increases. In addition, if fins are provided, the percentage further reduces in general. However, providing an extension leads to a decrease in shading since the fins are moved apart. This leads to an increase in the percentage of radiation incident. But the reverse is the case if a window does not have fins. From these results the relative performance of the shading combinations can be found out. For an example, consider a window with 0.6m chajja, 0.15m extension, zero gap and no fin, the percentage of radiation incident on south window is 72.3% compared to an unshaded window for Ahmedabad climate. But for a window with 1.0m chajja, zero extension, zero gap and full fins, the corresponding number is 14.8%. A graphical representation of such behaviour for all cities corresponding to a few cases has been shown in Fig. III.2. The results for other window sizes are reported in Table III.2.

From Tables III.1 and III.2, the best combination of shading devices can be identified. For an example, for north facing window in Ahmadabad, the percentage of radiation incident is the least (57%) for a chajja depth of 0.3m, full fin length, zero extension and zero gap. Such combinations have been identified for all window sizes corresponding to four cities and are listed in Table III.3. The magnitudes of the radiation incident on such windows are also listed in the table. The numbers in parentheses give the corresponding radiation value for unshaded window. These provide ready reference for comparison of different cases.

Appropriate window sizing and shading combinations in different orientations can be found from the table. For example, it is found that in Ahmadabad, a large window of 1.8 m x 1.8 m in the north shaded by a chajja of depth 0.6m and full fins performs better than a well-shaded smaller window of 0.6 m x 1.2 m (protected by 1.0m chajja and full fins) in the east, west and south. The magnitude of radiation incident on window reduces by more than 3 times. Thus, it may be inferred that larger windows should preferably be located in the north. Conversely, smaller windows should be provided in the other directions and they should be well shaded. It is also seen that out of two windows (width 1.2m, height 1.8m and width 1.8m, height 1.2m), the one with higher height is better since the percentage of radiation incident is lower. This is because of the fact that the shading increases for a window of higher height compared to a wider one, when fins are also provided. A combination of deep chajjas and full-fins of 1.0m depth can significantly reduce the radiation falling on a large window (1.8m X 1.8m); the values are ranging from about 3.5 times in the east to 4.9 times in the south. Hence, chajja and full-fin combinations are very effective in reducing the heat gain through windows.

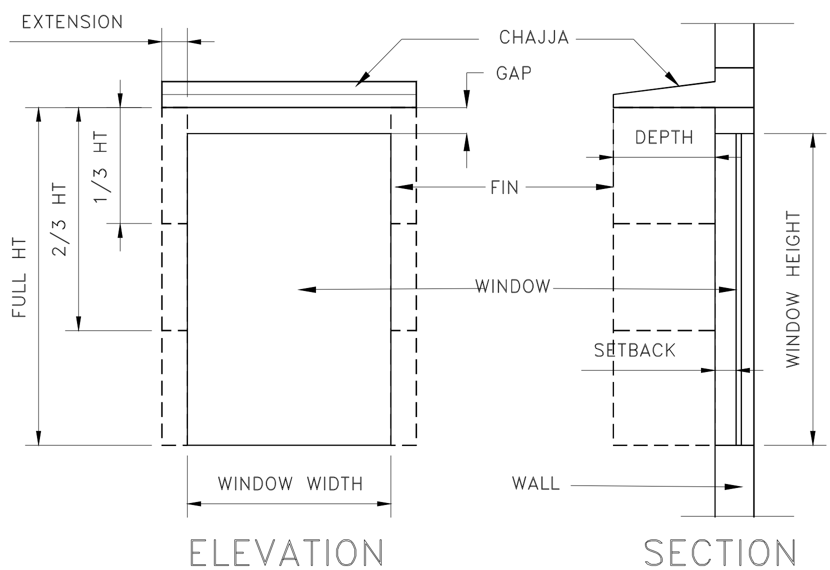

Fig. III.1 Illustrations of chajja depth, fin length, gap and extension

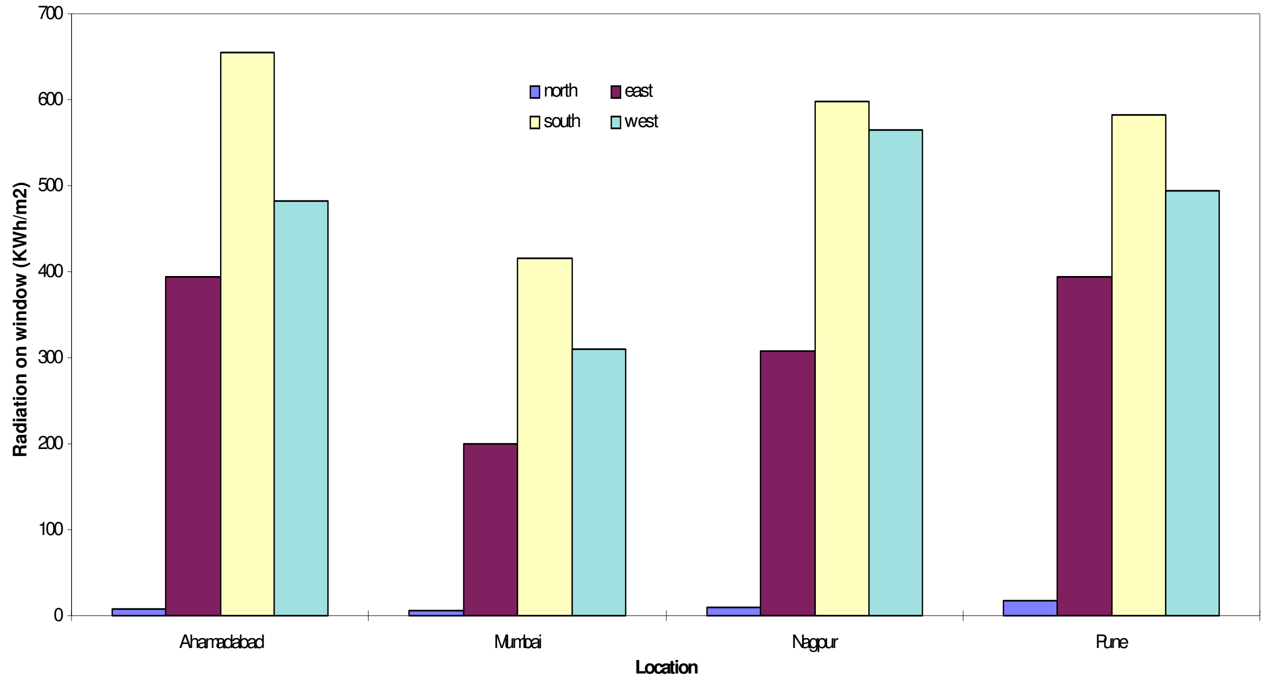

Fig. III.2 (Case 1) Radiation on unshaded 1.2m x 1.2 m window

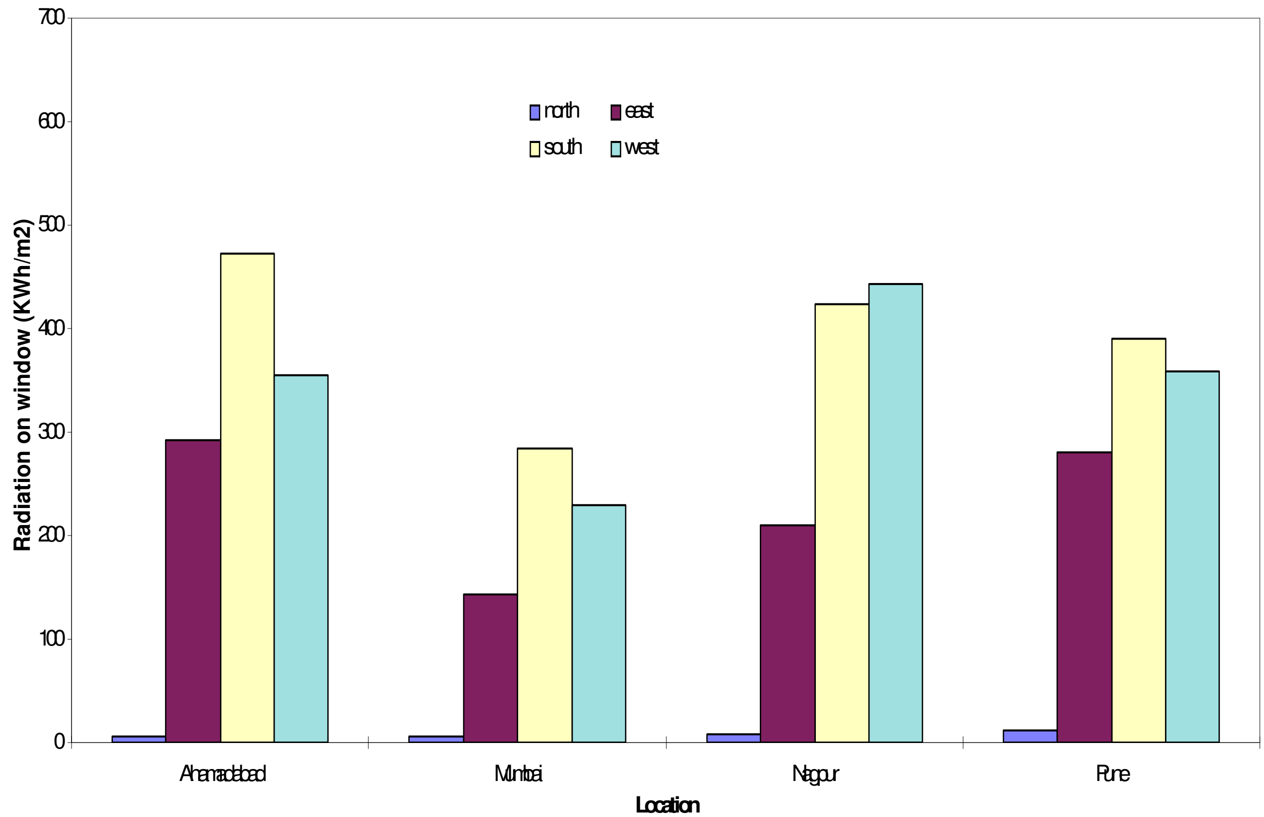

Fig. III.2 (Case 2) Radiation on 1.2m x 1.2 m window shaded by 0.6 m chhajja with 0.15 m extension

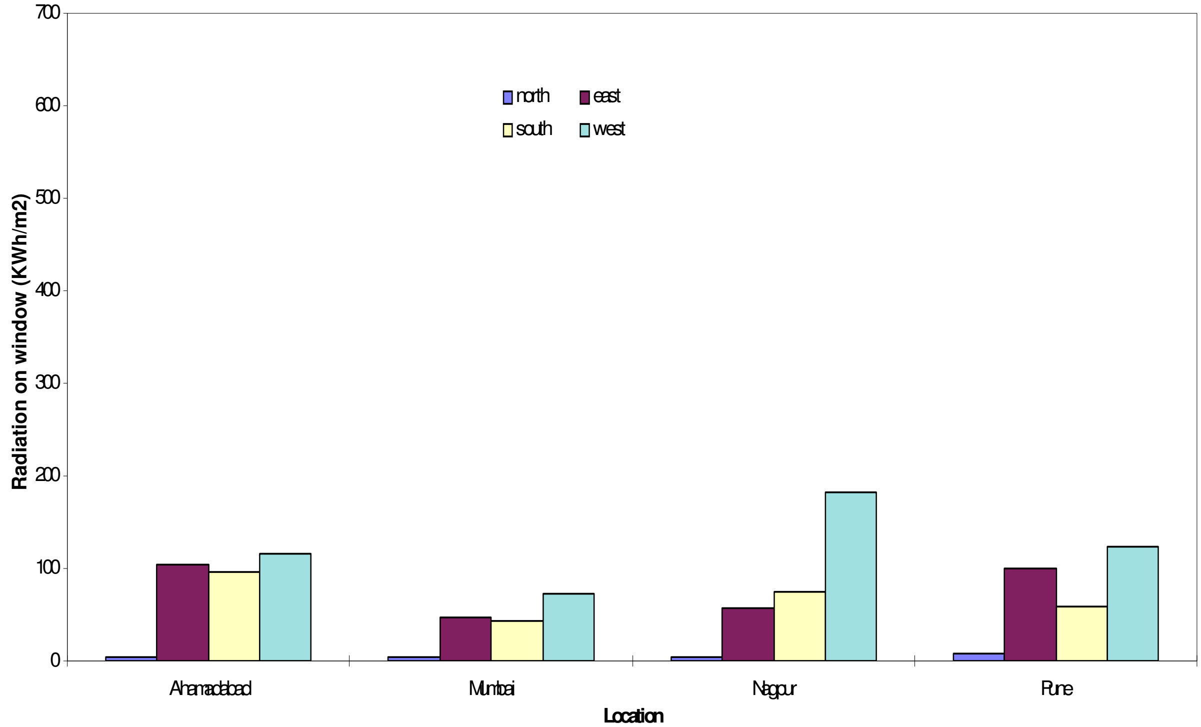

Fig. III.2 (Case 3) Radiation on 1.2m x 1.2 m window shaded by 0.6 m chhajja and full fins

Table III.1 Percentage of beam radiation incident on window (1.2m wide by 1.2m height)

Parameters				Percentage radiation incident (%)															
				Ahmadabad				Mumbai				Nagpur				Pune			
ext	fin	gap	CL	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
0	0	0	0.3	95.30	94.74	95.84	96.35	89.86	94.22	95.88	96.37	91.12	94.81	95.43	95.59	83.18	94.48	94.86	95.92
0	0	0	0.6	95.30	76.97	75.98	76.59	89.86	75.94	72.83	77.54	91.12	71.69	74.62	80.84	83.11	74.04	71.65	75.78
0	0	0	1	95.30	58.64	57.21	55.74	89.86	58.94	52.62	57.73	91.12	50.25	55.81	62.77	83.11	54.15	52.75	54.97
0	0	0.15	0.3	98.79	97.10	98.06	98.47	93.79	96.95	98.20	98.49	96.25	97.72	97.96	97.58	88.90	97.09	97.36	98.13
0	0	0.15	0.6	98.79	85.13	85.43	84.96	93.77	84.27	83.16	85.63	96.25	80.91	84.24	87.80	88.82	82.99	81.80	84.24
0	0	0.15	1	98.79	67.85	65.81	65.30	93.77	68.19	61.90	67.65	96.25	59.19	64.40	71.68	88.82	63.87	61.64	64.89
0	1/3	0	0.3	75.10	91.75	92.01	93.70	75.01	90.59	91.98	93.55	67.34	91.85	91.42	93.19	61.95	91.71	90.73	93.47
0	1/3	0	0.6	75.10	68.93	65.17	68.93	74.82	66.54	61.51	69.20	67.34	63.24	63.35	74.11	61.17	66.66	59.80	68.50
0	1/3	0	1	75.10	45.81	40.46	43.14	74.82	44.32	35.24	43.96	67.34	37.09	38.73	51.27	61.17	42.35	35.20	42.94
0	1/3	0.15	0.3	70.59	92.40	91.93	94.24	73.75	91.35	91.99	94.00	63.42	93.01	91.54	93.72	59.93	92.80	90.83	94.21
0	1/3	0.15	0.6	70.59	73.53	69.75	73.90	73.52	70.84	66.85	73.64	63.42	68.85	67.89	77.92	59.00	72.42	64.78	73.74
0	1/3	0.15	1	70.59	49.93	42.32	47.72	73.52	47.96	37.74	48.54	63.42	41.04	40.43	55.47	59.00	47.54	37.27	48.17
0	2/3	0	0.3	59.20	87.52	86.22	89.65	64.55	85.73	86.09	89.30	48.19	87.44	85.33	89.52	45.92	87.89	84.62	89.73
0	2/3	0	0.6	59.20	60.26	53.05	60.55	64.31	56.81	49.09	60.21	48.19	54.43	50.70	66.30	44.98	58.92	46.94	60.58
0	2/3	0	1	59.20	33.70	24.29	31.24	64.31	31.14	19.21	31.25	48.19	25.39	22.28	39.88	44.98	31.65	19.06	31.77
0	2/3	0.15	0.3	60.83	88.44	86.40	90.34	66.82	86.81	86.28	89.93	50.19	88.84	85.69	90.23	49.01	89.17	84.95	90.61
0	2/3	0.15	0.6	60.83	65.69	58.55	66.23	66.58	62.13	55.41	65.42	50.19	60.93	56.17	70.72	48.07	65.44	53.01	66.49
0	2/3	0.15	1	60.83	39.43	28.26	37.34	66.58	36.68	24.06	37.51	50.19	31.09	26.19	45.35	48.07	38.33	23.50	38.45
0	full	0	0.3	56.99	84.03	81.25	86.15	62.24	81.79	80.89	85.66	43.56	83.86	80.01	86.35	42.09	84.71	79.34	86.47
0	full	0	0.6	56.99	54.11	44.39	54.47	62.01	50.16	40.55	53.75	43.56	48.52	41.59	60.38	41.16	53.54	38.29	54.82

Continued ....

Table III.1 Percentage of beam radiation incident on window (1.2m wide by 1.2m height) Continued from previous page

Parameters				Percentage radiation incident (%)															
				Ahmadabad				Mumbai				Nagpur				Pune			
ext	fin	gap	CL	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
0	full	0	1	56.99	26.28	14.76	23.94	62.01	23.36	10.18	23.62	43.56	18.77	12.45	32.33	41.16	25.31	9.98	24.95
0	full	0.15	0.3	60.48	85.70	82.54	87.60	66.16	83.81	82.36	87.09	48.68	86.14	81.54	87.64	47.81	86.74	80.98	88.03
0	full	0.15	0.6	60.48	61.39	52.83	62.03	65.93	57.62	49.99	61.00	48.68	57.04	50.13	66.36	46.88	61.77	47.54	62.50
0	full	0.15	1	60.48	34.61	22.34	32.68	65.93	31.72	18.57	32.70	48.68	27.01	19.97	40.23	46.88	34.31	17.98	34.10
0.15	0	0	0.3	89.89	94.06	95.22	95.89	84.52	93.35	95.28	95.85	83.96	94.20	94.76	95.07	75.66	93.82	94.09	95.42
0.15	0	0	0.6	89.89	74.01	72.28	73.69	84.32	72.27	68.65	74.39	83.86	68.10	70.81	78.49	75.01	70.84	67.14	72.78
0.15	0	0	1	89.89	52.70	49.76	49.69	84.32	52.02	44.33	51.10	83.86	43.20	48.38	57.58	75.01	47.79	44.28	48.66
0.15	0	0.15	0.3	95.55	96.66	97.73	98.25	89.36	96.41	97.89	98.22	91.13	97.42	97.61	97.24	82.69	96.69	96.89	97.87
0.15	0	0.15	0.6	95.55	83.03	82.97	82.86	89.15	81.61	80.37	83.32	91.04	78.20	81.72	86.14	81.98	80.67	78.69	82.06
0.15	0	0.15	1	95.55	62.90	59.49	60.30	89.15	62.34	54.81	62.18	91.04	53.06	58.13	67.43	81.98	58.44	54.32	59.61
0.15	1/3	0	0.3	67.77	92.61	93.23	94.78	70.69	91.53	93.40	94.76	60.32	92.87	92.64	94.10	56.76	92.60	91.93	94.52
0.15	1/3	0	0.6	67.77	68.21	63.84	68.25	69.65	65.35	59.86	68.50	59.27	61.88	61.73	73.92	53.38	65.85	57.85	67.89
0.15	1/3	0	1	67.77	42.29	35.06	39.48	69.65	39.99	29.03	40.02	59.27	32.46	32.98	48.50	53.38	38.70	28.66	39.37
0.15	1/3	0.15	0.3	67.55	94.71	94.86	96.70	71.96	93.99	95.18	96.73	60.41	95.57	94.56	95.92	58.29	95.07	93.80	96.65
0.15	1/3	0.15	0.6	67.55	75.17	71.28	75.46	70.85	72.30	68.26	75.37	59.23	69.87	69.18	79.86	54.68	73.97	65.92	75.45
0.15	1/3	0.15	1	67.55	49.04	39.58	46.66	70.85	46.42	34.26	47.44	59.23	38.92	37.31	55.23	54.68	46.43	33.37	47.26
0.15	2/3	0	0.3	57.47	91.46	91.13	93.72	63.89	90.15	91.33	93.79	46.72	91.60	90.36	93.29	46.13	91.67	89.60	93.76
0.15	2/3	0	0.6	57.47	63.36	55.96	63.61	62.79	59.81	51.76	63.57	45.54	56.89	53.29	69.85	42.57	61.86	49.41	63.81
0.15	2/3	0	1	57.47	34.31	22.87	31.53	62.79	31.17	16.98	31.59	45.54	24.80	20.36	41.14	42.57	32.04	16.46	32.31
0.15	2/3	0.15	0.3	62.65	93.75	92.98	95.75	68.03	92.84	93.23	95.88	52.21	94.47	92.45	95.25	51.89	94.28	91.62	95.98
0.15	2/3	0.15	0.6	62.65	71.05	64.29	71.44	66.92	67.65	61.06	71.11	51.04	65.64	61.61	76.31	48.28	70.61	58.46	71.91

Continued ....

Table III.1 Percentage of beam radiation incident on window (1.2m wide by 1.2m height) **Continued from previous page**

Parameters				Percentage radiation incident (%)															
				Ahmadabad				Mumbai				Nagpur				Pune			
ext	fin	gap	CL	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
0.15	2/3	0.15	1	62.65	42.48	29.51	40.08	66.92	39.34	24.60	40.51	51.04	32.81	26.89	48.99	48.28	41.06	23.60	41.45
0.15	full	0	0.3	56.99	90.86	89.66	93.09	63.11	89.46	89.77	93.28	44.74	90.96	88.63	92.86	44.72	91.21	87.88	93.35
0.15	full	0	0.6	56.99	60.67	51.23	60.91	62.01	56.94	47.15	60.81	43.56	54.34	48.06	67.36	41.16	59.78	44.67	61.47
0.15	full	0	1	56.99	30.43	17.21	27.64	62.01	27.22	11.85	27.68	43.56	21.58	14.27	37.12	41.16	29.08	11.26	28.97
0.15	full	0.15	0.3	62.63	93.44	92.00	95.41	67.95	92.50	92.23	95.64	51.91	94.16	91.27	95.01	51.75	94.07	90.54	95.78
0.15	full	0.15	0.6	62.63	69.54	61.68	69.94	66.85	66.14	58.69	69.63	50.73	64.36	58.67	74.80	48.13	69.52	56.03	70.64
0.15	full	0.15	1	62.63	40.47	26.70	38.12	66.85	37.40	22.16	38.65	50.73	31.35	23.73	46.74	48.13	39.64	21.12	39.83

Radiation on unshaded window (1.2m wide by 1.2m height)

	North (Wh/m^2-year)	East (Wh/m^2-year)	South (Wh/m^2-year)	West (Wh/m^2-year)
Ahmadabad	7219	394074	654682	482717
Mumbai	5865	199200	414788	308871
Nagpur	9537	307567	598595	564900
Pune	16700	394949	581880	494051

Table III.2(A) Percentage of beam radiation incident on window (0.6m wide by 1.2m height)

Parameters				Percentage radiation incident (%)															
				Ahmadabad				Mumbai				Nagpur				Pune			
ext	fin	gap	CL	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
0	0	0	0.3	100.00	96.07	97.04	97.32	99.78	96.05	97.08	97.55	100.00	96.07	96.75	96.68	98.64	95.82	96.36	96.98
0	0	0	0.6	100.00	82.67	82.89	82.16	99.78	83.63	80.76	84.18	100.00	78.45	81.73	85.55	98.64	80.17	80.00	81.55
0	0	0	1	100.00	69.87	71.36	67.32	99.78	73.35	68.57	71.65	100.00	63.38	70.07	72.91	98.64	66.20	68.63	67.26
0	0	0.15	0.3	100.00	97.91	98.72	98.93	99.90	98.03	98.82	99.08	100.00	98.25	98.66	98.27	99.23	97.89	98.27	98.74
0	0	0.15	0.6	100.00	89.07	90.10	89.00	99.90	89.81	88.42	90.55	100.00	85.97	89.02	91.15	99.23	87.46	87.53	88.56
0	0	0.15	1	100.00	76.87	77.87	74.44	99.90	80.08	75.52	78.94	100.00	70.18	76.59	79.81	99.23	73.95	75.31	75.01
0	1/3	0	0.3	98.15	90.87	90.10	92.41	94.10	89.76	89.81	92.05	93.98	90.44	89.54	92.27	86.59	90.91	88.59	92.15
0	1/3	0	0.6	98.15	69.75	66.39	69.42	94.10	68.20	63.34	69.80	93.98	64.77	65.02	73.81	86.59	67.49	62.36	68.79
0	1/3	0	1	98.15	51.86	50.28	49.40	94.10	52.57	46.75	51.46	93.98	45.10	49.15	55.63	86.59	48.55	46.87	48.96
0	1/3	0.15	0.3	96.14	89.42	87.30	90.83	90.01	87.91	86.91	90.06	88.44	89.16	86.75	90.96	79.43	89.98	85.66	90.87
0	1/3	0.15	0.6	96.14	69.75	65.45	69.95	90.01	66.94	62.55	69.20	88.44	65.80	63.94	73.41	79.43	68.77	61.41	69.68
0	1/3	0.15	1	96.14	50.71	47.22	48.49	90.01	50.03	44.04	49.82	88.44	43.93	46.08	54.57	79.43	48.63	43.94	48.73
0	2/3	0	0.3	92.89	82.46	78.60	84.19	84.19	79.97	77.85	83.02	79.99	81.59	77.47	84.85	67.90	83.23	76.16	84.33
0	2/3	0	0.6	92.89	53.58	45.74	53.40	84.19	49.42	41.92	52.08	79.99	48.34	43.85	58.62	67.90	52.33	40.91	53.23
0	2/3	0	1	92.89	31.56	26.75	29.37	84.19	29.45	23.21	29.15	79.99	25.41	25.59	35.68	67.90	29.53	23.50	29.06
0	2/3	0.15	0.3	90.93	81.24	76.08	82.82	81.61	78.43	75.20	81.30	75.33	80.62	74.96	83.76	63.51	82.55	73.56	83.30
0	2/3	0.15	0.6	90.93	54.37	45.79	54.68	81.61	49.23	42.27	52.38	75.33	50.31	43.86	58.90	63.51	54.50	41.21	54.94
0	2/3	0.15	1	90.93	31.85	25.78	29.91	81.61	28.65	22.77	29.17	75.33	25.95	24.68	35.87	63.51	31.20	22.86	30.38
0	full	0	0.3	89.94	75.03	68.07	76.86	79.95	71.58	66.83	75.10	71.54	74.08	66.35	78.19	59.45	76.63	64.91	77.51
0	full	0	0.6	89.94	40.69	29.38	40.51	79.95	35.25	25.62	38.27	71.54	36.10	27.29	46.16	59.45	40.92	24.78	41.18

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Table III.2(A) Percentage of beam radiation incident on window (0.6m wide by 1.2m height) **Continued from previous page**

Parameters				Percentage radiation incident (%)															
				Ahmadabad				Mumbai				Nagpur				Pune			
ext	fin	gap	CL	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
0	full	0	1	89.94	16.68	10.05	14.78	79.95	13.28	6.82	13.45	71.54	12.14	8.87	20.50	59.45	16.54	7.28	15.21
0	full	0.15	0.3	89.94	75.42	67.73	77.02	80.06	72.04	66.66	75.08	71.54	75.01	66.11	78.32	60.04	77.49	64.94	77.92
0	full	0.15	0.6	89.94	45.22	34.39	45.55	80.06	39.57	31.28	42.80	71.54	42.23	32.26	49.69	60.04	46.71	30.37	46.57
0	full	0.15	1	89.94	21.80	14.36	20.10	80.06	18.14	11.78	18.90	71.54	17.54	13.08	25.30	60.04	22.80	12.02	21.34
0.15	0	0	0.3	100.00	95.07	96.05	96.60	98.91	94.72	96.06	96.68	99.98	95.09	95.64	95.86	95.61	94.79	95.10	96.16
0.15	0	0	0.6	100.00	77.92	76.54	77.37	98.91	77.68	73.50	78.67	99.98	72.56	75.21	81.48	95.61	74.71	72.39	76.29
0.15	0	0	1	100.00	60.73	59.63	57.83	98.91	62.91	55.54	60.92	99.98	52.34	58.48	64.36	95.61	55.76	55.62	56.66
0.15	0	0.15	0.3	100.00	97.36	98.24	98.67	99.44	97.33	98.35	98.74	100.00	97.89	98.15	97.82	97.29	97.34	97.55	98.37
0.15	0	0.15	0.6	100.00	86.15	86.13	85.93	99.44	86.09	83.80	87.06	100.00	82.07	84.98	88.62	97.29	83.93	82.48	85.14
0.15	0	0.15	1	100.00	70.01	68.27	67.25	99.44	72.33	64.80	70.97	100.00	61.33	67.20	73.45	97.29	65.81	64.44	66.84
0.15	1/3	0	0.3	96.37	92.77	92.65	94.58	89.48	91.87	92.59	94.52	89.04	92.39	91.92	94.17	77.99	92.84	91.25	94.45
0.15	1/3	0	0.6	96.37	68.23	62.80	67.67	89.48	65.64	58.64	67.93	89.04	61.99	60.79	73.33	77.99	65.89	57.31	67.44
0.15	1/3	0	1	96.37	44.79	39.77	41.56	89.48	43.41	34.92	42.23	89.04	35.85	38.07	49.53	77.99	40.85	35.09	40.75
0.15	1/3	0.15	0.3	94.35	94.13	93.22	95.81	86.61	93.36	93.24	95.72	83.73	94.07	92.63	95.47	73.02	94.63	91.90	95.97
0.15	1/3	0.15	0.6	94.35	72.66	66.80	72.44	86.61	69.45	63.04	72.21	83.73	67.50	64.70	77.22	73.02	71.76	61.43	72.91
0.15	1/3	0.15	1	94.35	48.13	40.92	44.99	86.61	45.69	36.66	45.50	83.73	38.95	39.11	53.00	73.02	45.52	36.44	45.19
0.15	2/3	0	0.3	91.19	90.48	88.61	92.44	81.70	89.17	88.42	92.36	76.09	89.63	87.42	92.57	63.39	91.00	86.69	92.77
0.15	2/3	0	0.6	91.19	58.85	48.87	58.23	81.70	54.50	43.95	57.86	76.09	52.18	46.21	65.30	63.39	57.81	42.50	59.19
0.15	2/3	0	1	91.19	30.30	21.87	26.89	81.70	26.27	17.15	25.86	76.09	21.74	19.91	35.76	63.39	28.03	17.43	26.95
0.15	2/3	0.15	0.3	90.01	92.05	89.45	93.86	80.62	91.00	89.25	93.79	72.42	91.65	88.37	94.07	61.60	93.03	87.56	94.49
0.15	2/3	0.15	0.6	90.01	64.21	53.97	63.86	80.62	59.76	49.61	63.25	72.42	58.88	51.26	69.95	61.60	64.74	47.94	65.59

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Table III.2(A) Percentage of beam radiation incident on window (0.6m wide by 1.2m height) **Continued from previous page**

Parameters				Percentage radiation incident (%)															
				Ahmadabad				Mumbai				Nagpur				Pune			
ext	fin	gap	CL	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
0.15	2/3	0.15	1	90.01	35.34	25.50	32.00	80.62	31.05	21.58	31.37	72.42	26.95	23.57	40.73	61.60	34.67	21.43	33.33
0.15	full	0	0.3	89.94	89.08	85.51	91.16	79.95	87.74	85.07	91.16	71.54	88.19	83.79	91.67	59.45	90.03	83.08	91.86
0.15	full	0	0.6	89.94	53.08	39.49	52.29	79.95	48.44	34.77	51.94	71.54	46.89	36.44	60.09	59.45	53.40	33.27	54.34
0.15	full	0	1	89.94	22.11	11.92	18.65	79.95	17.77	7.77	17.59	71.54	15.09	9.74	27.45	59.45	21.82	8.02	19.99
0.15	full	0.15	0.3	89.94	91.31	87.35	93.18	80.47	90.31	87.05	93.19	71.54	90.95	85.83	93.60	61.13	92.56	85.22	94.04
0.15	full	0.15	0.6	89.94	60.96	48.57	60.52	80.47	56.59	44.67	60.09	71.54	56.24	45.53	66.79	61.13	62.44	42.97	62.98
0.15	full	0.15	1	89.94	31.03	20.04	27.75	80.47	26.92	16.64	27.40	71.54	23.92	17.80	36.06	61.13	31.68	16.46	29.96

Radiation on unshaded window (0.6 m wide by 1.2 m height)

	North (Wh/m^2-year)	East (Wh/m^2-year)	South (Wh/m^2-year)	West (Wh/m^2-year)
Ahmadabad	4575	369392	599872	456362
Mumbai	4549	184624	381757	290797
Nagpur	5808	287657	547393	534582
Pune	11562	372541	529888	467038

Table III.2(B) Percentage of beam radiation incident on window (0.6m wide by 1.8m height)

Parameters				Percentage radiation incident (%)															
				Ahmadabad				Mumbai				Nagpur				Pune			
ext	fin	gap	CL	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
0	0	0	0.3	99.65	85.77	86.02	86.42	95.87	85.59	85.44	86.76	98.48	84.72	85.77	87.38	88.97	84.78	84.82	85.88
0	0	0	0.6	99.65	73.45	74.12	72.55	95.87	74.25	72.96	74.21	98.48	69.43	73.66	75.68	88.97	71.20	72.53	71.96
0	0	0	1	99.65	63.84	66.03	62.40	95.87	66.43	64.34	65.71	98.48	58.88	65.31	66.15	88.97	60.81	64.35	62.04
0	0	0.15	0.3	100.00	93.56	94.00	94.41	98.03	93.36	93.55	94.70	100.00	93.01	93.74	94.94	93.00	92.80	92.90	93.89
0	0	0.15	0.6	100.00	81.49	82.01	80.69	98.03	82.29	80.93	82.38	100.00	77.43	81.44	83.64	93.00	79.40	80.43	80.22
0	0	0.15	1	100.00	71.29	73.59	70.17	98.03	73.95	71.94	73.50	100.00	66.68	72.84	73.60	93.00	68.33	71.85	69.76
0	1/3	0	0.3	94.48	77.27	74.59	78.31	83.72	75.65	73.61	77.82	84.58	76.04	73.79	79.87	67.86	77.00	72.42	78.08
0	1/3	0	0.6	94.48	56.77	52.90	56.08	83.72	54.85	50.98	56.00	84.58	52.50	52.03	60.08	67.86	55.38	50.32	55.88
0	1/3	0	1	94.48	42.08	40.20	40.86	83.72	41.78	37.88	41.84	84.58	37.39	39.41	44.99	67.86	40.11	37.90	40.55
0	1/3	0.15	0.3	93.48	82.94	79.70	84.25	83.24	80.96	78.75	83.51	82.59	82.12	78.74	85.55	67.46	83.09	77.41	84.14
0	1/3	0.15	0.6	93.48	60.66	55.51	60.13	83.24	58.08	53.50	59.65	82.59	56.31	54.41	64.14	67.46	59.68	52.73	60.18
0	1/3	0.15	1	93.48	44.19	41.50	43.37	83.24	43.26	39.09	43.80	82.59	39.98	40.65	47.23	67.46	42.61	39.05	43.04
0	2/3	0	0.3	89.20	69.04	63.36	70.28	74.68	66.09	61.93	69.01	71.12	67.44	62.00	72.56	52.31	69.52	60.33	70.47
0	2/3	0	0.6	89.20	40.97	32.78	40.45	74.68	36.59	30.16	38.73	71.12	36.56	31.44	45.15	52.31	40.65	29.54	40.75
0	2/3	0	1	89.20	22.28	17.35	21.33	74.68	19.34	14.97	20.13	71.12	18.30	16.53	25.41	52.31	21.65	15.20	21.21
0	2/3	0.15	0.3	88.55	74.99	68.79	76.47	75.53	71.80	67.38	75.02	70.13	73.88	67.27	78.50	54.07	75.92	65.69	76.82
0	2/3	0.15	0.6	88.55	45.76	36.55	45.34	75.53	41.07	34.04	43.42	70.13	41.45	35.05	49.99	54.07	45.98	33.40	46.00
0	2/3	0.15	1	88.55	25.94	20.74	25.40	75.53	22.75	18.47	23.92	70.13	22.71	19.89	29.02	54.07	25.88	18.66	25.41
0	full	0	0.3	88.14	64.53	57.05	65.83	73.21	61.17	55.49	64.24	67.83	63.14	55.30	68.32	49.51	65.62	53.85	66.35
0	full	0	0.6	88.14	33.83	23.94	33.35	73.21	29.03	21.60	31.25	67.83	30.21	22.44	37.94	49.51	34.56	21.12	34.23

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Table III.2(B) Percentage of beam radiation incident on window (0.6m wide by 1.8m height) **Continued from previous page**

Parameters				Percentage radiation incident (%)															
				Ahmadabad				Mumbai				Nagpur				Pune			
ext	fin	gap	CL	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
0	Full	0	1	88.14	14.35	8.46	13.61	73.21	11.01	6.41	11.98	67.83	11.63	7.52	17.05	49.51	14.99	6.79	14.06
0	Full	0.15	0.3	88.44	72.32	65.03	73.81	75.36	68.94	63.61	72.18	69.35	71.43	63.27	75.88	53.54	73.63	61.94	74.36
0	Full	0.15	0.6	88.44	41.87	31.83	41.49	75.36	37.07	29.58	39.41	69.35	38.22	30.21	45.90	53.54	42.75	29.02	42.49
0	full	0.15	1	88.44	21.80	16.03	21.38	75.36	18.54	14.01	19.78	69.35	19.43	15.05	24.51	53.54	22.52	14.29	21.78
0.15	0	0	0.3	98.49	83.79	83.61	84.66	91.23	83.10	82.87	84.75	95.17	82.70	83.24	85.75	80.56	82.79	82.01	84.07
0.15	0	0	0.6	98.49	68.07	67.15	67.10	91.23	67.77	65.50	68.06	95.17	63.18	66.67	70.81	80.56	65.52	64.84	66.27
0.15	0	0	1	98.49	55.14	55.30	53.66	91.23	56.60	52.82	55.98	95.17	49.10	54.70	57.84	80.56	51.46	52.76	52.62
0.15	0	0.15	0.3	99.78	92.18	92.41	93.23	94.21	91.54	91.86	93.34	98.66	91.58	92.09	93.88	85.85	91.31	90.96	92.62
0.15	0	0.15	0.6	99.78	76.76	75.82	75.90	94.21	76.54	74.29	76.95	98.66	71.73	75.26	79.43	85.85	74.28	73.53	75.15
0.15	0	0.15	1	99.78	63.05	63.50	61.96	94.21	64.65	61.06	64.36	98.66	57.34	62.94	65.76	85.85	59.34	60.86	60.79
0.15	1/3	0	0.3	93.29	81.20	79.41	82.42	80.82	80.01	78.54	82.42	81.36	79.81	78.48	83.89	62.83	80.68	77.21	82.22
0.15	1/3	0	0.6	93.29	57.83	52.37	56.81	80.82	55.37	49.81	56.88	81.36	52.27	50.99	62.01	62.83	56.44	48.85	57.07
0.15	1/3	0	1	93.29	38.71	34.30	37.01	80.82	36.82	31.18	37.01	81.36	32.35	32.97	42.31	62.83	36.35	31.16	36.48
0.15	1/3	0.15	0.3	93.26	88.97	87.16	90.44	81.45	87.72	86.46	90.43	81.49	87.98	86.16	91.57	64.02	88.71	84.99	90.32
0.15	1/3	0.15	0.6	93.26	64.04	57.40	63.13	81.45	61.13	54.76	63.07	81.49	58.22	55.74	68.47	64.02	63.01	53.66	63.73
0.15	1/3	0.15	1	93.26	42.68	37.53	41.32	81.45	40.18	34.37	40.89	81.49	36.67	36.06	46.51	64.02	40.66	34.25	40.85
0.15	2/3	0	0.3	88.35	78.97	75.49	80.36	73.53	77.41	74.45	80.33	69.09	77.18	74.08	82.33	50.21	78.92	72.77	80.60
0.15	2/3	0	0.6	88.35	48.74	38.86	47.66	73.53	44.66	35.60	47.14	69.09	42.86	36.82	54.16	50.21	48.68	34.56	49.10
0.15	2/3	0	1	88.35	24.66	17.03	22.77	73.53	20.37	13.99	21.21	69.09	18.78	15.36	28.89	50.21	24.04	14.11	23.19
0.15	2/3	0.15	0.3	89.42	86.98	83.50	88.59	76.22	85.46	82.60	88.60	71.31	85.70	82.02	90.22	54.80	87.18	80.81	88.91
0.15	2/3	0.15	0.6	89.42	55.94	45.07	54.92	76.22	51.85	41.95	54.50	71.31	50.04	42.86	61.43	54.80	56.29	40.81	56.73

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Table III.2(B) Percentage of beam radiation incident on window (0.6m wide by 1.8m height) **Continued from previous page**

Parameters				Percentage radiation incident (%)															
				Ahmadabad				Mumbai				Nagpur				Pune			
ext	fin	gap	CL	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
0.15	2/3	0.15	1	89.42	30.43	22.66	28.88	76.22	26.19	19.78	27.39	71.31	25.27	20.99	34.65	54.80	30.28	19.77	29.51
0.15	full	0	0.3	88.14	78.36	73.87	79.80	73.21	76.82	72.76	79.83	67.83	76.59	72.14	81.94	49.51	78.52	70.96	80.23
0.15	Full	0	0.6	88.14	46.11	34.53	44.95	73.21	42.05	31.54	44.55	67.83	40.66	32.23	51.63	49.51	46.78	30.50	46.97
0.15	full	0	1	88.14	21.10	12.59	19.23	73.21	16.87	9.92	17.81	67.83	16.15	10.70	25.08	49.51	21.51	10.03	20.32
0.15	full	0.15	0.3	89.42	86.74	82.68	88.37	76.22	85.27	81.75	88.41	71.31	85.48	80.99	90.06	54.80	87.05	79.92	88.77
0.15	full	0.15	0.6	89.42	54.81	43.20	53.76	76.22	50.82	40.33	53.43	71.31	49.21	40.81	60.25	54.80	55.53	39.18	55.84
0.15	full	0.15	1	89.42	29.01	20.78	27.53	76.22	24.93	18.16	26.19	71.31	24.39	18.94	33.01	54.80	29.38	18.14	28.49

Radiation on unshaded window (0.6 m wide by 1.8 m height)

	North (Wh/m^2-year)	East (Wh/m^2-year)	South (Wh/m^2-year)	West (Wh/m^2-year)
Ahmadabad	4668	386015	628425	476830
Mumbai	4968	193468	399947	303775
Nagpur	6125	301676	573212	555261
Pune	13883	390659	556658	489083

Table III.2(C) Percentage of beam radiation incident on window (1.2m wide by 1.8m height)

Parameters				Percentage radiation incident (%)															
				Ahmadabad				Mumbai				Nagpur				Pune			
ext	fin	gap	CL	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
0	0	0	0.3	87.74	83.91	84.00	84.80	80.09	83.18	83.37	84.93	81.70	82.97	83.69	85.91	70.26	82.96	82.45	84.30
0	0	0	0.6	87.74	68.12	67.30	67.19	80.09	67.40	65.67	68.03	81.70	63.37	66.75	71.05	70.22	65.78	64.96	66.66
0	0	0	1	87.74	54.35	54.11	52.82	80.09	54.67	51.36	54.51	81.70	48.54	53.26	57.38	70.22	51.02	51.36	52.15
0	0	0.15	0.3	93.26	92.05	92.46	93.11	84.84	91.36	92.03	93.23	88.31	91.57	92.20	93.79	76.52	91.27	91.07	92.59
0	0	0.15	0.6	93.26	76.49	75.60	75.71	84.84	75.81	74.09	76.59	88.31	71.64	74.96	79.31	76.48	74.26	73.26	75.23
0	0	0.15	1	93.26	61.89	61.85	60.76	84.84	62.33	59.13	62.48	88.31	56.43	61.08	64.96	76.48	58.60	58.97	59.94
0	1/3	0	0.3	64.24	79.31	78.07	80.62	62.84	77.74	77.38	80.51	54.75	78.45	77.44	82.00	47.49	78.74	76.12	80.37
0	1/3	0	0.6	64.24	58.25	54.27	57.79	62.67	56.01	52.31	57.81	54.75	53.19	53.17	62.42	46.85	56.76	50.97	57.67
0	1/3	0	1	64.24	39.63	35.12	38.50	62.67	37.87	31.84	38.85	54.75	33.58	33.80	43.90	46.85	37.47	31.58	38.40
0	1/3	0.15	0.3	64.48	86.33	85.05	87.91	64.15	84.63	84.56	87.73	55.71	85.94	84.39	88.92	49.15	86.04	83.19	87.72
0	1/3	0.15	0.6	64.48	64.25	59.39	64.06	63.94	61.74	57.48	63.95	55.71	59.07	58.05	68.59	48.39	63.13	55.90	64.12
0	1/3	0.15	1	64.48	43.73	38.39	43.11	63.94	41.74	35.07	43.22	55.71	38.07	37.04	48.31	48.39	42.00	34.61	43.04
0	2/3	0	0.3	50.20	75.18	72.44	76.67	53.64	73.00	71.63	76.37	38.37	74.19	71.50	78.39	34.54	75.00	70.18	76.72
0	2/3	0	0.6	50.20	49.79	42.52	49.62	53.42	46.56	40.27	49.04	38.37	44.65	40.87	54.76	33.73	49.25	38.56	49.97
0	2/3	0	1	50.20	27.85	19.51	26.94	53.42	25.08	16.33	26.47	38.37	22.21	17.91	32.74	33.73	27.10	16.00	27.54
0	2/3	0.15	0.3	55.30	82.46	79.68	84.14	57.84	80.22	79.03	83.77	43.91	81.91	78.71	85.50	39.96	82.53	77.51	84.23
0	2/3	0.15	0.6	55.30	56.63	48.62	56.63	57.62	53.30	46.51	56.00	43.91	51.43	46.77	61.55	39.15	56.38	44.67	57.10
0	2/3	0.15	1	55.30	33.53	24.85	33.03	57.62	30.78	21.82	32.51	43.91	28.43	23.24	38.41	39.15	33.08	21.33	33.61
0	full	0	0.3	49.77	73.07	69.50	74.58	53.02	70.69	68.67	74.19	37.05	72.13	68.35	76.36	33.54	73.14	67.18	74.76
0	full	0	0.6	49.77	46.44	38.04	46.35	52.81	43.03	36.00	45.59	37.05	41.61	36.14	51.34	32.73	46.38	34.26	46.86

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Table III.2(C) Percentage beam radiation incident on window (1.2m wide by 1.8m height) Continued from previous page

Parameters				Percentage radiation incident (%)															
				Ahmadabad				Mumbai				Nagpur				Pune			
ext	fin	Gap	CL	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
0	full	0	1	49.77	24.03	14.81	23.24	52.81	21.15	11.96	22.64	37.05	18.96	12.97	28.67	32.73	23.91	11.61	24.09
0	full	0.15	0.3	55.27	81.21	77.97	82.89	57.75	78.88	77.33	82.49	43.67	80.73	76.86	84.24	39.80	81.44	75.79	83.05
0	full	0.15	0.6	55.27	54.81	46.33	54.87	57.53	51.43	44.42	54.16	43.67	49.87	44.35	59.60	38.99	54.86	42.56	55.43
0	full	0.15	1	55.27	31.57	22.55	31.18	57.53	28.81	19.73	30.61	43.67	26.85	20.79	36.24	38.99	31.48	19.22	31.88
0.15	0	0	0.3	81.55	82.79	82.75	83.89	74.24	81.81	82.10	83.92	74.34	81.84	82.39	85.04	62.68	81.87	80.97	83.35
0.15	0	0	0.6	81.55	65.04	63.46	64.18	74.11	63.70	61.67	64.71	74.29	59.76	62.88	68.41	62.25	62.62	60.67	63.58
0.15	0	0	1	81.55	49.03	47.63	47.59	74.11	48.50	44.42	48.78	74.29	42.53	46.78	52.60	62.25	45.47	44.21	46.68
0.15	0	0.15	0.3	87.78	91.21	91.59	92.45	78.91	90.29	91.15	92.50	81.42	90.74	91.31	93.19	68.97	90.41	90.00	91.90
0.15	0	0.15	0.6	87.78	73.69	72.10	72.98	78.78	72.41	70.42	73.58	81.37	68.28	71.42	76.97	68.47	71.34	69.32	72.43
0.15	0	0.15	1	87.78	56.73	55.59	55.70	78.78	56.34	52.39	56.93	81.37	50.60	54.84	60.36	68.47	53.15	52.01	54.62
0.15	1/3	0	0.3	59.40	81.18	80.38	82.62	60.16	79.79	79.80	82.70	50.39	80.37	79.78	83.94	45.02	80.50	78.32	82.34
0.15	1/3	0	0.6	59.40	58.88	54.52	58.37	59.15	56.40	52.49	58.45	49.54	53.20	53.20	63.42	42.09	57.35	50.95	58.39
0.15	1/3	0	1	59.40	38.12	32.36	37.01	59.15	35.78	28.59	37.23	49.54	31.31	30.72	42.93	42.09	35.87	28.02	36.99
0.15	1/3	0.15	0.3	61.23	89.25	88.64	90.89	62.26	87.85	88.30	91.00	52.88	88.94	88.08	91.86	47.81	88.76	86.73	90.67
0.15	1/3	0.15	0.6	61.23	66.13	61.02	65.85	61.18	63.49	59.05	65.92	51.83	60.29	59.45	70.82	44.51	64.90	57.30	66.07
0.15	1/3	0.15	1	61.23	43.43	36.81	42.76	61.18	40.93	32.99	42.86	51.83	36.99	35.10	48.54	44.51	41.53	32.19	42.82
0.15	2/3	0	0.3	49.81	80.04	78.34	81.60	54.03	78.43	77.77	81.76	38.51	79.16	77.54	83.15	36.23	79.59	76.05	81.59
0.15	2/3	0	0.6	49.81	54.16	46.90	53.84	52.90	51.02	44.65	53.65	37.44	48.37	45.00	59.43	32.94	53.47	42.81	54.41
0.15	2/3	0	1	49.81	30.35	20.64	29.28	52.90	27.23	16.98	29.02	37.44	23.85	18.53	35.73	32.94	29.42	16.29	30.13
0.15	2/3	0.15	0.3	56.01	88.30	86.80	89.99	58.60	86.73	86.43	90.20	45.22	87.90	86.02	91.19	42.31	88.01	84.65	90.04
0.15	2/3	0.15	0.6	56.01	62.12	54.30	61.95	57.48	58.98	52.19	61.81	44.14	56.23	52.18	67.35	38.94	61.65	50.21	62.65

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Table III.2(C) Percentage beam radiation incident on window (1.2m wide by 1.8m height) **Continued from previous page**

Parameters				Percentage radiation incident (%)															
				Ahmadabad				Mumbai				Nagpur				Pune			
ext	fin	gap	CL	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
0.15	2/3	0.15	1	56.01	37.05	27.13	36.36	57.48	34.03	23.64	36.14	44.14	31.08	25.02	42.45	38.94	36.32	22.76	37.19
0.15	full	0	0.3	49.77	79.79	77.58	81.32	53.94	78.14	77.00	81.56	38.12	78.90	76.64	82.96	36.01	79.41	75.21	81.42
0.15	full	0	0.6	49.77	52.94	44.78	52.63	52.81	49.78	42.68	52.44	37.05	47.31	42.62	58.23	32.73	52.57	40.80	53.38
0.15	full	0	1	49.77	28.68	18.27	27.63	52.81	25.60	14.91	27.43	37.05	22.59	15.91	33.90	32.73	28.21	14.19	28.75
0.15	full	0.15	0.3	56.01	88.21	86.42	89.87	58.60	86.63	86.05	90.13	45.22	87.80	85.55	91.11	42.31	87.95	84.24	89.98
0.15	full	0.15	0.6	56.01	61.60	53.41	61.43	57.47	58.49	51.44	61.31	44.14	55.83	51.17	66.78	38.94	61.29	49.44	62.22
0.15	full	0.15	1	56.01	36.39	26.23	35.74	57.47	33.44	22.88	35.58	44.14	30.66	23.97	41.66	38.94	35.90	21.99	36.69

Radiation on unshaded window (1.2 m wide by 1.8 m height)

	North (Wh/m^2-year)	East (Wh/m^2-year)	South (Wh/m^2-year)	West (Wh/m^2-year)
Ahmadabad	8267	412960	687407	505548
Mumbai	6886	209569	435137	323395
Nagpur	11214	323366	627902	587495
Pune	21002	415438	612513	518350

Table III.2(D) Percentage of beam radiation on window (1.8m wide by 1.2m height)

Parameters				Percentage radiation incident (%)															
				Ahmadabad				Mumbai				Nagpur				Pune			
ext	fin	gap	CL	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
0	0	0	0.3	79.18	94.01	95.20	95.88	79.97	93.24	95.34	95.84	76.05	94.26	94.75	95.09	71.26	93.78	94.16	95.42
0	0	0	0.6	78.53	74.23	72.64	74.11	77.27	72.39	69.31	74.72	73.21	68.41	71.21	78.76	66.39	71.32	67.70	73.31
0	0	0	1	78.53	52.72	49.41	50.14	77.27	51.53	44.21	51.30	73.21	43.39	47.92	57.84	66.39	48.38	43.95	49.34
0	0	0.15	0.3	85.51	96.52	97.65	98.16	84.72	96.18	97.85	98.11	83.03	97.39	97.50	97.18	77.96	96.56	96.86	97.78
0	0	0.15	0.6	84.84	82.82	82.88	82.82	81.60	81.19	80.55	83.15	79.94	77.99	81.68	86.02	72.66	80.66	78.80	82.12
0	0	0.15	1	84.84	62.28	58.68	60.18	81.60	60.94	54.15	61.63	79.94	52.65	57.25	67.13	72.66	58.24	53.49	59.61
0	1/3	0	0.3	62.58	91.99	92.56	94.16	69.72	90.87	92.83	94.03	59.21	92.22	92.09	93.50	57.50	91.95	91.36	93.79
0	1/3	0	0.6	61.20	68.91	65.22	69.02	65.55	66.21	61.58	69.31	52.92	62.82	63.43	74.24	49.42	66.46	59.63	68.63
0	1/3	0	1	61.20	44.08	37.14	41.60	65.55	41.89	31.53	42.26	52.92	34.53	35.23	50.18	49.42	40.63	31.00	41.44
0	1/3	0.15	0.3	64.06	93.36	93.50	95.39	71.21	92.53	93.84	95.24	60.43	94.18	93.28	94.63	59.41	93.74	92.47	95.19
0	1/3	0.15	0.6	62.66	75.14	72.21	75.46	66.60	72.37	69.49	75.37	53.82	70.06	70.45	79.41	50.80	73.71	67.31	75.38
0	1/3	0.15	1	62.66	50.29	41.68	48.31	66.60	47.66	36.67	49.11	53.82	40.51	39.63	56.39	50.80	47.55	35.69	48.67
0	2/3	0	0.3	53.06	89.13	88.77	91.50	63.18	87.70	89.01	91.30	47.44	89.27	88.15	91.06	47.55	89.46	87.31	91.36
0	2/3	0	0.6	51.67	63.15	57.24	63.46	58.97	59.87	53.35	63.47	41.09	57.10	54.94	69.04	39.36	61.38	51.23	63.57
0	2/3	0	1	51.67	36.08	25.99	33.67	58.97	33.31	20.38	33.99	41.09	26.86	23.59	42.72	39.36	33.70	19.79	34.21
0	2/3	0.15	0.3	58.28	90.67	89.89	92.84	66.91	89.56	90.14	92.61	52.53	91.40	89.50	92.31	52.62	91.40	88.58	92.87
0	2/3	0.15	0.6	56.89	69.93	64.92	70.38	62.31	66.71	61.95	70.03	45.92	64.90	62.68	74.61	44.00	69.13	59.69	70.74
0	2/3	0.15	1	56.89	43.35	32.21	41.41	62.31	40.31	27.39	41.92	45.92	34.01	29.71	49.78	44.00	41.60	26.40	42.39
0	full	0	0.3	51.71	86.75	85.51	89.19	61.83	85.11	85.62	88.97	44.62	86.90	84.69	88.95	45.10	87.42	83.81	89.27
0	full	0	0.6	50.34	59.06	51.64	59.39	57.63	55.53	47.73	59.25	38.27	53.24	48.97	65.08	36.90	57.84	45.64	59.88

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Table III.2(D) Percentage of beam radiation on window (1.8m wide by 1.2m height) Continued from previous page

Parameters				Percentage radiation incident (%)															
				Ahmadabad				Mumbai				Nagpur				Pune			
ext	fin	gap	CL	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
0	full	0	1	50.34	31.15	19.79	28.79	57.63	28.24	14.43	29.00	38.27	22.56	17.00	37.77	36.90	29.57	13.86	29.82
0	full	0.15	0.3	58.05	88.80	87.36	91.01	66.56	87.59	87.54	90.78	51.61	89.64	86.80	90.57	51.81	89.83	85.94	91.24
0	Full	0.15	0.6	56.65	67.04	61.23	67.55	61.93	63.76	58.36	67.13	45.00	62.38	58.73	71.68	43.18	66.72	56.14	68.20
0	full	0.15	1	56.65	40.11	28.41	38.28	61.93	37.08	23.76	38.78	45.00	31.38	25.61	46.40	43.18	38.97	22.81	39.60
0.15	0	0	0.3	73.70	93.55	94.77	95.58	76.45	92.65	94.94	95.49	71.08	93.86	94.29	94.74	66.48	93.34	93.65	95.09
0.15	0	0	0.6	72.47	72.27	70.14	72.18	72.56	69.95	66.50	72.62	66.36	65.99	68.65	77.13	59.60	69.22	64.70	71.33
0.15	0	0	1	72.47	48.63	44.22	46.03	72.56	46.88	38.45	46.87	66.36	38.60	42.73	54.24	59.60	44.13	38.12	45.12
0.15	0	0.15	0.3	80.64	96.22	97.41	97.99	81.78	95.80	97.64	97.92	78.91	97.19	97.24	96.95	73.99	96.28	96.54	97.60
0.15	0	0.15	0.6	79.06	81.39	81.17	81.40	77.00	79.38	78.64	81.60	73.73	76.14	79.94	84.84	66.02	79.13	76.68	80.68
0.15	0	0.15	1	79.06	58.80	54.18	56.69	77.00	56.88	49.13	57.90	73.73	48.40	52.75	64.13	66.02	54.54	48.36	56.04
0.15	1/3	0	0.3	58.66	92.53	93.41	94.86	67.76	91.48	93.67	94.73	56.42	92.97	92.82	94.08	54.47	92.56	92.22	94.48
0.15	1/3	0	0.6	56.76	68.40	64.41	68.52	62.27	65.48	60.47	68.91	47.69	62.04	62.48	74.18	44.57	65.90	58.33	68.20
0.15	1/3	0	1	56.76	41.63	33.80	39.19	62.27	38.93	27.57	39.64	47.69	31.58	31.65	48.31	44.57	38.20	27.02	39.08
0.15	1/3	0.15	0.3	62.14	94.84	95.50	97.01	70.86	94.25	95.83	96.89	60.06	95.95	95.15	96.06	58.55	95.25	94.52	96.78
0.15	1/3	0.15	0.6	59.88	76.13	73.31	76.43	64.47	73.38	70.40	76.61	50.77	70.87	71.43	80.79	47.46	74.68	68.00	76.45
0.15	1/3	0.15	1	59.88	49.49	40.20	47.57	64.47	46.37	34.64	48.30	50.77	39.17	37.85	56.16	47.46	46.70	33.59	48.02
0.15	2/3	0	0.3	52.57	91.70	92.09	94.21	63.56	90.61	92.32	94.06	48.29	92.13	91.29	93.52	47.85	91.97	90.73	93.97
0.15	2/3	0	0.6	50.68	65.13	59.29	65.38	58.06	61.94	55.12	65.85	39.47	58.91	56.85	71.55	37.85	63.28	52.77	65.59
0.15	2/3	0	1	50.68	36.31	25.61	33.91	58.06	33.13	19.41	34.18	39.47	26.61	22.84	43.53	37.85	33.87	18.77	34.55
0.15	2/3	0.15	0.3	59.20	94.13	94.32	96.43	68.50	93.52	94.56	96.30	55.12	95.23	93.75	95.59	54.53	94.75	93.11	96.33
0.15	2/3	0.15	0.6	56.95	73.34	68.81	73.70	62.11	70.43	65.68	73.95	45.83	68.23	66.44	78.49	43.44	72.48	63.12	74.18

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Table III.2(D) Percentage of beam radiation incident on window (1.8m wide by 1.2m height) **Continued from previous page**

Parameters				Percentage radiation incident (%)															
				Ahmadabad				Mumbai				Nagpur				Pune			
ext	fin	gap	CL	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
0.15	2/3	0.15	1	56.95	45.12	33.58	43.21	62.11	41.71	28.22	43.82	45.83	35.23	30.68	52.11	43.44	43.22	27.10	44.31
0.15	full	0	0.3	52.23	91.24	91.20	93.84	63.15	90.19	91.32	93.70	47.10	91.71	90.15	93.22	46.90	91.67	89.60	93.71
0.15	full	0	0.6	50.34	63.31	56.27	63.54	57.63	60.16	52.10	64.11	38.27	57.34	53.42	69.94	36.90	61.91	49.67	64.10
0.15	full	0	1	50.34	33.73	21.97	31.34	57.63	30.55	16.06	31.68	38.27	24.57	18.79	40.92	36.90	31.95	15.36	32.45
0.15	full	0.15	0.3	59.18	93.89	93.75	96.25	68.47	93.32	93.92	96.13	54.92	95.03	92.97	95.42	54.41	94.61	92.40	96.21
0.15	full	0.15	0.6	56.93	72.32	67.15	72.67	62.07	69.50	64.13	73.03	45.63	67.45	64.50	77.51	43.32	71.77	61.53	73.40
0.15	full	0.15	1	56.93	43.78	31.79	41.90	62.07	40.47	26.62	42.64	45.63	34.32	28.60	50.65	43.32	42.30	25.47	43.31

Radiation on unshaded window (1.8 m wide by 1.2 m height)

	North (Wh/m^2-year)	East (Wh/m^2-year)	South (Wh/m^2-year)	West (Wh/m^2-year)
Ahmadabad	8174	403527	672479	493711
Mumbai	6311	203988	427617	315284
Nagpur	10857	313416	616668	575200
Pune	18625	402145	599192	501918

Table III.2(E) Percentage of beam radiation incident on window (1.8m wide by 1.8m height)

Parameters				Percentage radiation incident (%)															
				Ahmadabad				Mumbai				Nagpur				Pune			
ext	fin	gap	CL	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
0	0	0	0.3	72.95	83.09	83.16	84.20	70.48	82.05	82.63	84.22	67.99	82.18	82.85	85.32	60.22	82.11	81.47	83.62
0	0	0	0.6	72.48	65.71	64.21	64.99	68.65	64.24	62.71	65.45	66.20	60.44	63.70	69.07	57.29	63.36	61.62	64.41
0	0	0	1	72.48	49.52	47.82	48.30	68.65	48.45	44.82	49.21	66.20	43.05	46.94	53.22	57.29	46.12	44.45	47.41
0	0	0.15	0.3	79.27	91.30	91.77	92.57	75.00	90.32	91.42	92.61	74.71	90.89	91.52	93.31	66.37	90.50	90.24	92.03
0	0	0.15	0.6	78.79	74.09	72.58	73.57	73.11	72.64	71.18	74.10	72.90	68.73	71.95	77.38	63.12	71.85	69.99	73.05
0	0	0.15	1	78.79	56.93	55.46	56.14	73.11	55.92	52.45	57.04	72.90	50.82	54.66	60.70	63.12	53.56	51.92	55.12
0	1/3	0	0.3	52.96	79.92	79.15	81.42	58.33	78.47	78.68	81.35	48.41	79.12	78.68	82.72	44.59	79.34	77.17	81.06
0	1/3	0	0.6	51.09	59.00	55.35	58.64	53.88	56.66	53.56	58.78	42.54	53.64	54.33	63.22	37.33	57.40	52.09	58.63
0	1/3	0	1	51.09	39.28	34.01	38.38	53.88	37.10	30.60	38.77	42.54	32.81	32.54	44.06	37.33	37.06	29.94	38.30
0	1/3	0.15	0.3	55.90	87.38	86.78	89.11	60.69	85.90	86.50	89.05	51.46	87.08	86.32	90.06	47.89	87.07	84.91	88.85
0	1/3	0.15	0.6	54.03	65.83	61.58	65.73	56.11	63.32	59.84	65.85	45.31	60.38	60.33	70.14	40.11	64.51	58.21	65.92
0	1/3	0.15	1	54.03	44.42	38.47	43.99	56.11	42.10	34.98	44.27	45.31	38.35	36.95	49.47	40.11	42.51	34.12	43.96
0	2/3	0	0.3	44.59	77.13	75.45	78.83	52.69	75.38	74.95	78.69	38.43	76.28	74.82	80.32	36.70	76.92	73.24	78.70
0	2/3	0	0.6	42.70	53.40	47.60	53.23	48.16	50.51	45.57	53.09	32.29	48.10	46.09	58.12	29.21	52.48	43.96	53.71
0	2/3	0	1	42.70	31.50	23.23	30.68	48.16	28.78	19.81	30.73	32.29	25.37	21.28	36.76	29.21	30.33	19.12	31.28
0	2/3	0.15	0.3	50.65	84.76	83.26	86.63	56.89	83.02	82.91	86.51	44.51	84.40	82.65	87.78	42.32	84.81	81.16	86.60
0	2/3	0.15	0.6	48.77	60.77	54.55	60.80	52.30	57.83	52.61	60.68	38.36	55.42	52.84	65.44	34.52	60.08	50.92	61.43
0	2/3	0.15	1	48.77	37.67	29.32	37.28	52.30	34.98	25.96	37.29	38.36	32.06	27.34	43.00	34.52	36.74	25.11	37.86
0	full	0	0.3	44.32	75.68	73.53	77.43	52.36	73.88	72.99	77.29	37.65	74.93	72.78	78.96	36.06	75.72	71.25	77.46
0	full	0	0.6	42.44	51.15	44.71	51.02	47.83	48.21	42.74	50.84	31.52	46.12	43.00	55.83	28.57	50.60	41.17	51.74

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Table III.2(E) Percentage of beam radiation incident on window (1.8m wide by 1.8m height) **Continued from previous page**

Parameters				Percentage radiation incident (%)															
				Ahmadabad				Mumbai				Nagpur				Pune			
ext	fin	gap	CL	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
0	full	0	1	50.34	31.15	19.79	28.79	57.63	28.24	14.43	29.00	38.27	22.56	17.00	37.77	36.90	29.57	13.86	29.82
0	full	0.15	0.3	58.05	88.80	87.36	91.01	66.56	87.59	87.54	90.78	51.61	89.64	86.80	90.57	51.81	89.83	85.94	91.24
0	full	0.15	0.6	56.65	67.04	61.23	67.55	61.93	63.76	58.36	67.13	45.00	62.38	58.73	71.68	43.18	66.72	56.14	68.20
0	full	0.15	1	56.65	40.11	28.41	38.28	61.93	37.08	23.76	38.78	45.00	31.38	25.61	46.40	43.18	38.97	22.81	39.60
0.15	0	0	0.3	73.70	93.55	94.77	95.58	76.45	92.65	94.94	95.49	71.08	93.86	94.29	94.74	66.48	93.34	93.65	95.09
0.15	0	0	0.6	72.47	72.27	70.14	72.18	72.56	69.95	66.50	72.62	66.36	65.99	68.65	77.13	59.60	69.22	64.70	71.33
0.15	0	0	1	72.47	48.63	44.22	46.03	72.56	46.88	38.45	46.87	66.36	38.60	42.73	54.24	59.60	44.13	38.12	45.12
0.15	0	0.15	0.3	80.64	96.22	97.41	97.99	81.78	95.80	97.64	97.92	78.91	97.19	97.24	96.95	73.99	96.28	96.54	97.60
0.15	0	0.15	0.6	79.06	81.39	81.17	81.40	77.00	79.38	78.64	81.60	73.73	76.14	79.94	84.84	66.02	79.13	76.68	80.68
0.15	0	0.15	1	79.06	58.80	54.18	56.69	77.00	56.88	49.13	57.90	73.73	48.40	52.75	64.13	66.02	54.54	48.36	56.04
0.15	1/3	0	0.3	58.66	92.53	93.41	94.86	67.76	91.48	93.67	94.73	56.42	92.97	92.82	94.08	54.47	92.56	92.22	94.48
0.15	1/3	0	0.6	56.76	68.40	64.41	68.52	62.27	65.48	60.47	68.91	47.69	62.04	62.48	74.18	44.57	65.90	58.33	68.20
0.15	1/3	0	1	56.76	41.63	33.80	39.19	62.27	38.93	27.57	39.64	47.69	31.58	31.65	48.31	44.57	38.20	27.02	39.08
0.15	1/3	0.15	0.3	62.14	94.84	95.50	97.01	70.86	94.25	95.83	96.89	60.06	95.95	95.15	96.06	58.55	95.25	94.52	96.78
0.15	1/3	0.15	0.6	59.88	76.13	73.31	76.43	64.47	73.38	70.40	76.61	50.77	70.87	71.43	80.79	47.46	74.68	68.00	76.45
0.15	1/3	0.15	1	59.88	49.49	40.20	47.57	64.47	46.37	34.64	48.30	50.77	39.17	37.85	56.16	47.46	46.70	33.59	48.02
0.15	2/3	0	0.3	52.57	91.70	92.09	94.21	63.56	90.61	92.32	94.06	48.29	92.13	91.29	93.52	47.85	91.97	90.73	93.97
0.15	2/3	0	0.6	50.68	65.13	59.29	65.38	58.06	61.94	55.12	65.85	39.47	58.91	56.85	71.55	37.85	63.28	52.77	65.59
0.15	2/3	0	1	50.68	36.31	25.61	33.91	58.06	33.13	19.41	34.18	39.47	26.61	22.84	43.53	37.85	33.87	18.77	34.55
0.15	2/3	0.15	0.3	59.20	94.13	94.32	96.43	68.50	93.52	94.56	96.30	55.12	95.23	93.75	95.59	54.53	94.75	93.11	96.33
0.15	2/3	0.15	0.6	56.95	73.34	68.81	73.70	62.11	70.43	65.68	73.95	45.83	68.23	66.44	78.49	43.44	72.48	63.12	74.18

Continued ....

Table III.2(E) Percentage of beam radiation incident on window (1.8m wide by 1.8m height) **Continued from previous page**

Parameters				Percentage radiation incident (%)															
				Ahmadabad				Mumbai				Nagpur				Pune			
ext	fin	gap	CL	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
0.15	2/3	0.15	1	48.83	39.89	31.36	39.54	52.11	36.87	27.65	39.60	38.21	33.88	29.08	45.69	34.33	38.76	26.65	40.16
0.15	Full	0	0.3	45.32	80.11	78.99	81.96	53.79	78.77	78.37	81.89	40.07	79.48	78.03	83.31	37.73	79.81	76.69	81.73
0.15	Full	0	0.6	42.44	55.41	49.25	55.13	47.83	52.79	47.20	55.55	31.52	50.09	47.45	60.61	28.57	54.61	45.37	55.88
0.15	full	0	1	42.44	31.95	23.05	31.18	47.83	28.99	19.41	31.35	31.52	25.80	20.51	37.59	28.57	31.02	18.61	32.12
0.15	full	0.15	0.3	51.82	88.52	87.84	90.51	58.18	87.23	87.43	90.45	46.98	88.37	86.97	91.47	43.91	88.34	85.72	90.29
0.15	full	0.15	0.6	48.83	63.98	57.83	63.91	52.11	61.35	55.90	64.38	38.21	58.52	55.93	69.11	34.33	63.23	53.96	64.68
0.15	full	0.15	1	48.83	39.45	30.79	39.13	52.11	36.50	27.16	39.25	38.21	33.62	28.39	45.17	34.33	38.49	26.15	39.86

Radiation on unshaded window (1.8 m wide by 1.8 m height)

	North (Wh/m^2-year)	East (Wh/m^2-year)	South (Wh/m^2-year)	West (Wh/m^2-year)
Ahmadabad	9694	423229	706689	517515
Mumbai	7603	214886	448880	330390
Nagpur	13182	329996	647446	598446
Pune	24055	423475	631509	527060

Table III.3 Best combinations of windows and shading devices and corresponding beam radiation incident on window

Orien-tation	Combination					Radiation on window (kWh/year)			
	Size (w X h)	Ext (m)	Gap (m)	CL (m)	fin-ht	Ahmadabad	Mumbai	Nagpur	Pune
North	0.6X1.2	0.0	0.0	0.3	full	3(3)	3(3)	3(4)	5(8)
	0.6X1.8	0.0	0.0	0.3	full	4(5)	4(5)	4(7)	7(15)
	1.2X1.2	0.0	0.0	*	full	6(10)	5(8)	6(14)	10(24)
	1.2X1.8	0.0	0.0	*	full	9(18)	8(15)	9(24)	15(45)
	1.8X1.2	0.0	0.0	0.6	full	9(18)	8(14)	9(23)	15(40)
	1.8X1.8	0.0	0.0	0.6	full	13(31)	12(25)	13(43)	22(78)
East	0.6X1.2	0.0	0.0	1.0	full	44(266)	18(133)	25(207)	44(268)
	0.6X1.8	0.0	0.0	1.0	full	60(417)	23(209)	38(326)	63(422)
	1.2X1.2	0.0	0.0	1.0	full	149(567)	67(287)	83(443)	144(569)
	1.2X1.8	0.0	0.0	1.0	full	214(892)	96(453)	132(698)	215(897)
	1.8X1.2	0.0	0.0	1.0	full	272(872)	124(441)	153(677)	257(869)
	1.8X1.8	0.0	0.0	1.0	full	397(1371)	183(696)	249(1069)	388(1372)
South	0.6X1.2	0.0	0.0	1.0	full	43(432)	19(275)	35(394)	28(382)
	0.6X1.8	0.0	0.0	1.0	full	57(679)	28(432)	47(619)	41(601)
	1.2X1.2	0.0	0.0	1.0	full	139(943)	61(597)	107(862)	84(838)
	1.2X1.8	0.0	0.0	1.0	full	220(1485)	112(940)	176(1356)	154(1323)
	1.8X1.2	0.0	0.0	1.0	full	287(1453)	133(924)	226(1332)	179(1294)
	1.8X1.8	0.0	0.0	1.0	full	463(2290)	246(1454)	378(2098)	333(2046)
West	0.6X1.2	0.0	0.0	1.0	full	49(329)	28(209)	79(385)	51(336)
	0.6X1.8	0.0	0.0	1.0	full	70(515)	39(328)	102(600)	74(528)
	1.2X1.2	0.0	0.0	1.0	full	166(695)	105(445)	263(813)	178(711)
	1.2X1.8	0.0	0.0	1.0	full	254(1092)	158(699)	364(1269)	270(1120)
	1.8X1.2	0.0	0.0	1.0	full	307(1066)	197(681)	469(1242)	323(1084)
	1.8X1.8	0.0	0.0	1.0	full	473 (1677)	302 (1070)	661 (1939)	496 (1708)

* 0.3 for Mumbai and Pune; 0.6 for Ahmadabad and Nagpur

w : Width in meters h :Height in meters

The numbers in parentheses show the corresponding radiation values on an unshaded window.

APPENDIX III.2

TYPES OF INSULATION

The building envelope is a device through which heat exchange between the internal and external environments is controlled. The various modes of operation of an envelope are: (1) admit heat gain, (2) exclude heat gain, (3) containing heat gain, or (4) dissipating excess internal heat. The opaque portions of the envelope, once designed, are generally considered fixed controls. The dynamic elements of the envelope include openable windows, shading devices and insulating shutters.

The effect of insulation is to reduce heat gain and heat loss. The more insulation in a buildings exterior envelope, the less heat transferred into or out of the building due to temperature difference between the interior and exterior. Insulation also controls the interior mean radiant temperature (MRT) by isolating the interior surfaces from the influence of the exterior conditions, and also reduces drafts produced by temperature differences between walls and air.

Insulation along with infiltration control is important for reducing heating and cooling loads in skin-load-dominated buildings such as residences (internal load dominated buildings are typically offices). Increased insulation levels in internally load-dominated buildings, may cause an increase in energy usage for cooling when the outside is cooler than the inside, unless natural ventilation or an economiser cycle on the HVAC system is available.

Types:

Insulation is made from a variety of materials and in several forms. The forms generally fall into the following categories: (1) rigid or semirigid blocks or boards, (2) boards with impact- or weather-resistant surfaces, which are employed on building exteriors or below grade, (3) blankets, felts, or sheets, which are either mechanically attached to vertical surfaces or laid flat on horizontal ones, (4) loose-fill, which is poured or blown into cavities or onto flat surfaces such as above ceilings, (5) foams and dry spray-on types; which can be pneumatically applied in a variety of ways. When specifying insulation, both performance and any complications arising from the thickness required must be considered.

Rigid

In the first category are polystyrene, polyurethane (PUF), and polyisocyanurate. Polystyrene comes in the form of “beadboard” so called because it is manufactured from small Styrofoam beads which are puffed up and fused together into slabs (also called as thermocole) – and extruded polystyrene. The latter has the advantage of some compressive strength, which makes it suitable for insulating beneath heavy objects. High-density beadboard also has a high compressive strength (generally found as packing material in the cartons for electrical appliances such as televisions and refrigerators).

Both burn readily and give off a dense black smoke. Polyurethane (PUF) and polyisocyanurate are harder to ignite but give off cyanide fumes in a fire. In case of fire, these are hazardous, hence they are generally not exposed on interior surfaces but covered with a fireproof wall or plaster or sheetrock.

The most common way of insulating masonry walls is to affix rigid sheets of insulation to the wall surfaces, and covering them with a protective material. For a given thickness, the most effective insulation material is polyurethane foam. 25 mm of urethane is equivalent to about 50 mm of fibreglass. The rigid sheets are available in 12mm to 50 mm thickness.

Blanket

This type of insulation is most commonly used in standard cavity walls, where the depth of the stud determines the amount of insulation that can be placed in the wall. The material usually consists of glass fibre or mineral wool. It is manufactured in standard widths of 400mm – 600m and is generally 75 to 175 mm thick. It comes in long rolls or batts of specific length. It is available with reflective foil or a vapour barrier on one side. One advantage of fibreglass is that it is highly fire resistant. Its drawbacks are that it loses its effectiveness when wet, and that it is not self-supporting in its normal form.

Loose fill

Loose fill insulations that are commercially available include cellulose, vermiculite, and blown in fibreglass. Sawdust, wood shavings, and shredded bark can also be used. These materials are principally used in existing walls that were not insulated during construction. They are also commonly added between ceiling joists in unheated attics. Vermiculite and perlite are mixed with concrete aggregates to reduce heat loss.

Foam-in-situ

Foams such as polyurethane are also available in liquid form with a catalyst for on-the-job foaming. The liquid may be poured into forms or sprayed on with special equipment. In the hands of a skilled applicator, this material can be rendered into almost any sculptural form and will provide considerable structural support. It is applicable to odd-shaped structures, but needs a weather-protective membrane.

Superinsulation

Superinsulation is the application of abnormal amounts of insulation in order to eliminate all need for mechanical space heating. Due to reduction in heat gains and losses due to conduction and air tightness of buildings, the internal and solar heat gains become the primary source of heat. The savings on heating equipment and distribution systems may equal or outweigh the additional costs of extra insulation, extra thermal mass, and insulative window treatments. Since insulation is required at all external surfaces, it can add significantly to the construction cost. Therefore, the desirable amount of insulation must be carefully considered. It is also important to consider overheating in mild winters and summer. The building must be ventilated during such periods. Fresh air due to ventilation also reduces risk of diseases and foul odours.

APPENDIX III.3

TYPES OF GLAZINGS

Material		Thermal Expansion	Ease of Handling	Weatherability	Estimated Lifetime (years)	Solar Transmissivity (-)	Infrared Transmissivity (-)
Glass	Single Glazed Float Glass	0.47	P	E	25+	0.91	0.01
	Double Glazed Float Glass	0.47	P	E	25+	0.77-0.85	
Acrylic	Flexiglas (Rhom& Haas)	4.10	E	E	10-20	0.90	0.02
	Lucite (Du Pont)	3.90	E	E	10-20	0.92	0.02
	Exolite (CY/RO)	4.00	E	E	10-20	0.83	0.02
Polycarbo-nate	Lexan (G.E.)	3.75	E	F	15-17	0.81-0.89	0.02
	Tuffack Twinwall (Rhom & Haas)	3.30	E	F	5-7	0.77	
	Cyrolon SDP (CY/RO)	4.00	E	F		0.74	
Fibreglass reinforced polyester	Lascolite (Lasco Industries)	1.60	VG	G	10-20	0.86	
	Filon w/Tedlar (Vistron Corp.)	2.30	VG	G	10-20	0.86	
	Sunlite Premium II (Kalwall)	1.36	E	G	20	0.87	0.02
Polyester film	Mylar Type W (Du Pont)	1.50	F	F	4	0.85	0.16-0.32
	Flexiguard (3M)		F	G	10	0.89	0.095
Polyethyl-ene film	Monsanto 602 (Monsanto)		F	P	1	0.85	0.70
	Teflon (Du Pont)	30.00	P	E	25	0.96	0.57
Polyvinyl fluoride film	Tedlar (Du Pont)	2.80	F	E	10-20	0.95	0.30

P=Poor, F=Fair, G=Good, VG=Very good, E=Excellent

CHAPTER 4

THERMAL PERFORMANCE OF BUILDINGS

Contents

4.1 INTRODUCTION

The thermal performance of a building refers to the process of modeling the energy transfer between a building and its surroundings. For a conditioned building, it estimates the heating and cooling load and hence, the sizing and selection of HVAC equipment can be correctly made. For a non-conditioned building, it calculates temperature variation inside the building over a specified time and helps one to estimate the duration of uncomfortable periods. These quantifications enable one to determine the effectiveness of the design of a building and help in evolving improved designs for realising energy efficient buildings with comfortable indoor conditions. The lack of proper quantification is one of the reasons why passive solar architecture is not popular among architects. Clients would like to know how much energy might be saved, or the temperature reduced to justify any additional expense or design change. Architects too need to know the relative performance of buildings to choose a suitable alternative. Thus, knowledge of the methods of estimating the performance of buildings is essential to the design of passive solar buildings.

In this chapter, we will discuss a simple method for estimating the thermal performance of a building and introduce a few simulation tools used for more accurate calculations.

Various heat exchange processes are possible between a building and the external environment. These are shown in Fig. 4.1. Heat flows by conduction through various building elements such as walls, roof, ceiling, floor, etc. Heat transfer also takes place from different surfaces by convection and radiation. Besides, solar radiation is transmitted through transparent windows and is absorbed by the internal surfaces of the building. There may be evaporation of water resulting in a cooling effect. Heat is also added to the space due to the presence of human occupants and the use of lights and equipments. The interaction between a human body and the indoor environment is shown in Fig. 4.2. Due to metabolic activities, the body continuously produces heat, part of which is used as work, while the rest is dissipated into the environment for maintaining body temperature. The body exchanges heat with its surroundings by convection, radiation, evaporation and conduction. If heat is lost, one feels cool. In case of heat gain from surroundings, one feels hot and begins to perspire. Movement of air affects the rate of perspiration, which in turn affects body comfort.

The thermal performance of a building depends on a large number of factors. They can be summarised as (i) design variables (geometrical dimensions of building elements such as walls, roof and

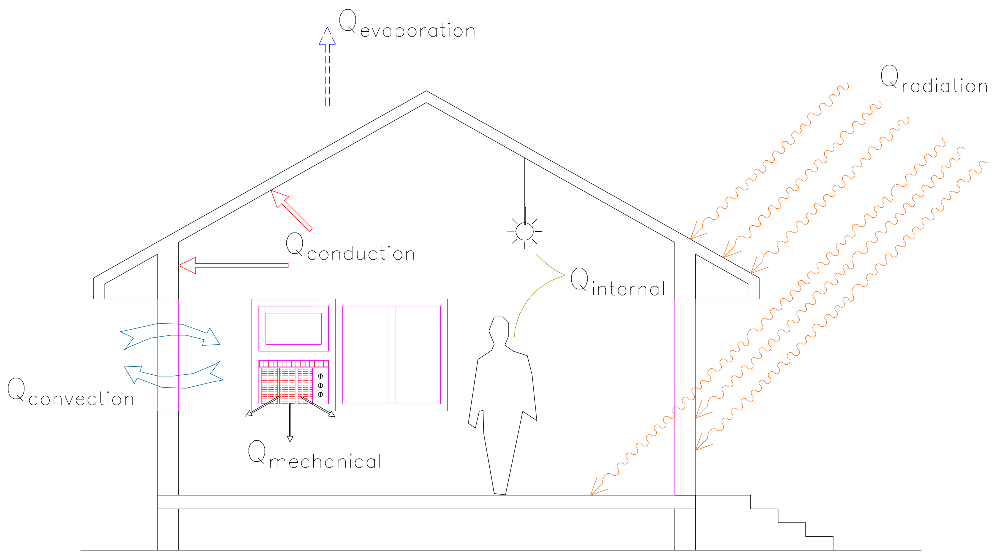

Fig. 4.1 Heat exchange processes between a building and the external environment

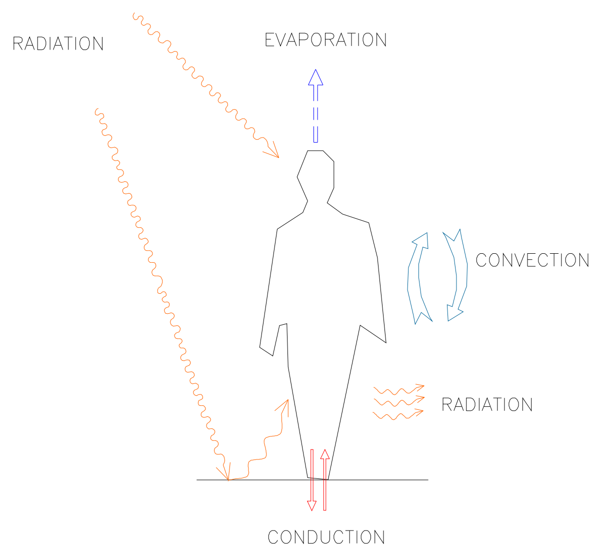

Fig. 4.2 Heat exchange processes between a human body and the indoor environment

windows, orientation, shading devices, etc.); (ii) material properties (density, specific heat, thermal conductivity, transmissivity, etc.); (iii) weather data (solar radiation, ambient temperature, wind speed, humidity, etc.); and (iv) a building's usage data (internal gains due to occupants, lighting and equipment, air exchanges, etc.). A block diagram showing various factors affecting the heat balance of a building is presented in Fig. 4.3. The influence of these factors on the performance of a building can be studied using appropriate analytical tools. Several techniques are available for estimating the performance of buildings. They can be classified under Steady State methods, Dynamic methods and Correlation methods. Some of the techniques are simple and provide information on the average load or temperature, on a monthly or annual basis. Others are complex and require more detailed input information. However, the latter perform a more accurate analysis and provide results on an hourly or daily basis. In this chapter, we discuss a simple method that is easy to understand and amenable to hand calculations.

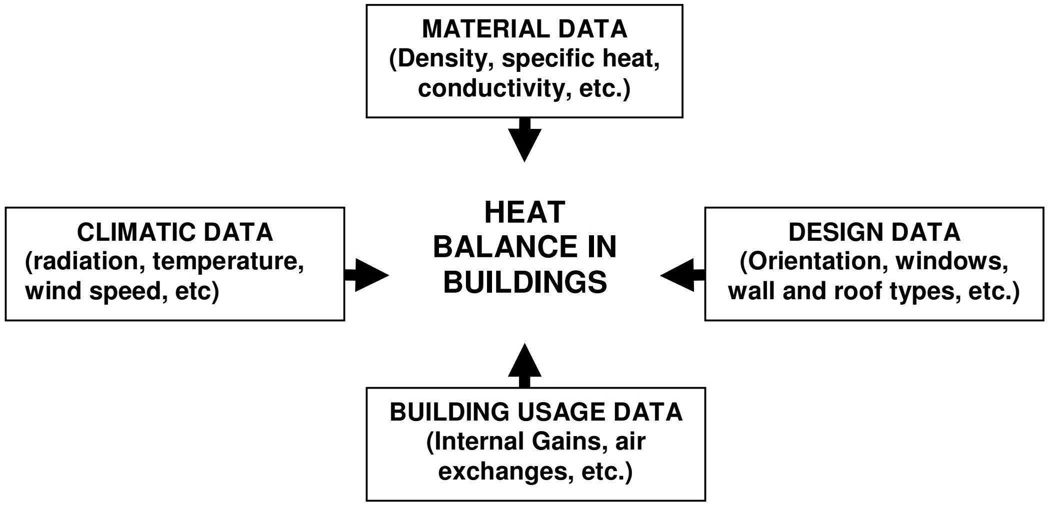

Fig. 4.3 Thermal simulation flow paths of a building

To understand the process of heat conduction, convection and radiation occurring in a building, consider a wall having one surface exposed to solar radiation and the other surface facing a room (Fig. 4.4). Of the total solar radiation incident on the outer surface of the wall, a part of it is reflected to the environment. The remaining part is absorbed by the wall and converted into heat energy. A part of the heat is again lost to the environment through convection and radiation from the wall's outer surface. The remaining part is conducted into the wall; where it is partly stored – thereby raising the wall temperature – while the rest reaches the room's interior surface. The inner surface transfers heat by convection and radiation to the room air, raising its temperature. Heat exchanges like these take place through opaque building elements such as walls and roofs. Additionally, mutual radiation exchanges between the inner surfaces of the building also occur (for example, between walls, or between a wall and roof). Such heat transfer processes affect the indoor temperature of a room and consequently, the thermal comfort experienced by its occupants.

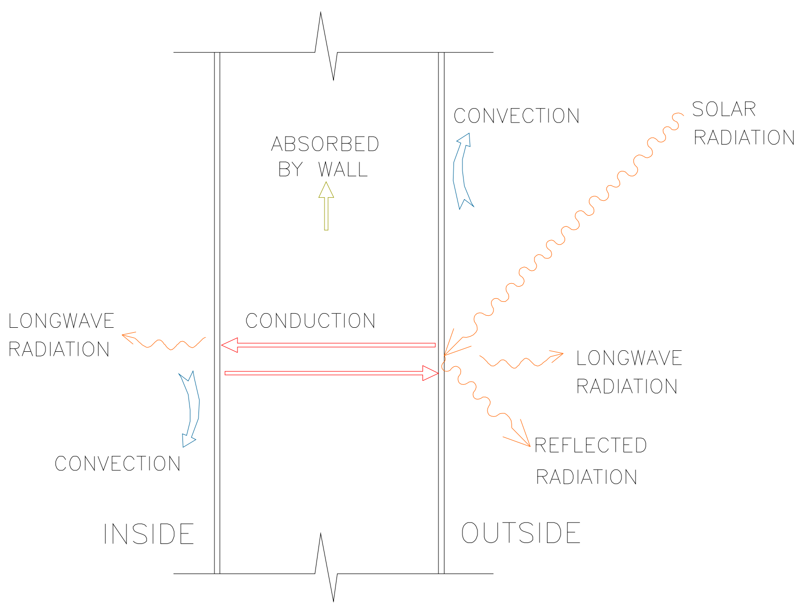

Fig. 4.4 Heat transfer processes occurring in a wall

Thus, a knowledge of the fundamentals of heat transfer and solar radiation would help in understanding the underlying processes that take place in a building and its interaction with the external environment. The reader can refer to the Glossary at the end of this book for definitions of unfamiliar terms. The reader may also like to refer to Koenisberger et al. [1] and Markus and Morris [2] for more information.

4.2 HEAT TRANSFER

In this section, we discuss the basic concepts on conduction, convection, radiation and evaporation.

4.2.1 Conduction

Thermal conduction is the process of heat transfer from one part of a body at a higher temperature to another (or between bodies in direct contact) at a lower temperature. This happens with negligible movement of the molecules in the body, because the heat is transferred from one molecule to another in contact with it. Heat can be conducted through solids, liquids and gases. Some materials conduct more rapidly than others. The basic equation of heat conduction is

$$Q_{conduction} = \frac{k\ A\ (T_h - T_c)}{L} \tag{4.1}$$

where $Q_{conduction}$ = quantity of heat flow (W)

k = thermal conductivity of the material (W/m-K)

A = area (m^2)

L = thickness (m)

T_h = temperature of the hot surface (K)

T_c = temperature of the cold surface (K)

For a given temperature difference, the higher the thermal conductivity of a material of fixed thickness and cross-sectional area, the greater is the quantity of heat transferred. Appendix IV.1 presents the values of thermal conductivity, density and specific heat of some building materials.

4.2.2 Convection

The convection is the transfer of heat from one part of a fluid (gas or liquid) to another part at a lower temperature by mixing of fluid particles. Heat transfer by convection takes place at the surfaces of walls, floors and roofs. Because of the temperature difference between the fluid and the contact surface, there is a density variation in the fluid, resulting in buoyancy. This results in heat exchange between the fluid and the surface and is known as free convection. However, if the motion of the fluid is due to external forces (such as wind), it is known as forced convection. These two processes could occur simultaneously. The rate of heat transfer ($Q_{convection}$) by convection from a surface of area A, can be written as

$$Q_{convection} = h\,A\,(T_s - T_f) \quad (4.2)$$

where, h = heat transfer coefficient (W/m^2-K)

T_s = temperature of the surface (K)

T_f = temperature of the fluid (K)

The numerical value of the heat transfer coefficient depends on the nature of heat flow, velocity of the fluid, physical properties of the fluid, and the surface orientation.

4.2.3 Radiation

Radiation is the heat transfer from a body by virtue of its temperature; it increases as temperature of the body increases. It does not require any material medium for propagation. When two or more bodies at different temperatures exchange heat by radiation, heat will be emitted, absorbed and reflected by each body. The radiation exchange between two large parallel plane surfaces (of equal area A) at uniform temperatures T_1 and T_2 respectively, can be written as

$$Q_{12} = \varepsilon_{eff}\ A\ \sigma\,(T_1^4 - T_2^4) \quad (4.3)$$

with $\varepsilon_{eff} = [\ 1/\ \varepsilon_1 + 1/\varepsilon_2 - 1]^{-1}$

where Q_{12} = net radiative exchange between surfaces (W)

σ = Stefan-Boltzmann constant ($5.67\text{x}10^{-8}$ W/m^2-K^4)

A = area of surface (m^2)

T_1 = temperature of surface 1 (K)

T_2 = temperature of surface 2 (K)

ε_1 and ε_2 = emissivities of surfaces 1 and 2 respectively

In case of buildings, external surfaces such as walls and roofs are always exposed to the atmosphere. So the radiation exchange ($Q_{radiation}$) between the exposed parts of the building and the atmosphere is an important factor and is given by

$$Q_{radiation} = A\,\varepsilon\,\sigma\,(T_s^4 - T_{sky}^4) \quad (4.4)$$

where A = area of the building exposed surface (m^2)

ε = emissivity of the building exposed surface

T_s = temperature of the building exposed surface (K)

T_{sky} = sky temperature (K)

T_{sky} represents the temperature of an equivalent atmosphere. It considers the fact that the atmosphere is not at a uniform temperature, and that the atmosphere radiates only in certain wavelengths. There are many correlations suggested for expressing sky temperature in terms of ambient air temperature.

Equation (4.4) can be written as:

$$\frac{Q_{radiation}}{A} = h_r (T_s - T_a) + \varepsilon \Delta R \qquad (4.5)$$

where T_a = ambient temperature (K)

$$h_r = \varepsilon \sigma (T_s^4 - T_a^4)/(T_s - T_a) \qquad (4.6)$$

h_r is the radiative heat transfer coefficient, and ΔR is the difference between the long wavelength radiation incident on the surface from the sky and the surroundings, and the radiation emitted by a black body at ambient temperature. For horizontal surface, ΔR can be taken as 63 W/m^2 and for a vertical surface, it is zero [3].

For building applications, usually convective and radiative heat transfer coefficients are combined to define surface heat transfer coefficient. Table 4.1 presents values of the surface heat transfer coefficient for a few cases [4].

Table 4.1 Values of surface heat transfer coefficient [4]

Serial No.	Wind Speed	Position of Surface	Direction of Heat Flow	Surface Heat Transfer Coefficient (W/m^2-K)
1.	Still air	Horizontal	Up	9.3
		Sloping 45°	Up	9.1
		Vertical	Horizontal	8.3
		Sloping 45°	Down	7.5
		Horizontal	Down	6.1
2.	Moving air 12 (km/h)	Any position	Any direction	22.7
	Moving air 24 (km/h)	Any position	Any direction	34.1

4.2.4 Evaporation

Evaporation generally refers to the removal of water by vaporisation from aqueous solutions of non-volatile substances. It takes place continuously at all temperatures and increases as the temperature is raised. Increase in the wind speed also causes increased rates of evaporation. The latent heat required for vapourisation is taken up partly from the surroundings and partly from the liquid itself. Evaporation thus causes cooling.

The rate of evaporation depends on:

- the temperature (rate of evaporation increases with increase in temperature)
- the area of the free surface of water (larger the surface exposed, greater is this rate)
- the wind (rate is faster when wind blows than when the air is still)
- the pressure (lower the external pressure, more rapid is the evaporation)

4.3 SOLAR RADIATION

The sun is the only source of heat and light for the entire solar system. It is made up of extremely hot gaseous matter, and gets progressively hotter towards its centre. The heat is generated by various kinds of fusion reactions. The sun is approximately spherical in shape, about 1.39×10^6 km in diameter and its average distance from the earth is 1.496×10^8 km (Fig. 4.5). The solar disc subtends a very small angle of 32' at any point on the earth's surface and hence, the radiation received from the sun directly on the earth's surface can be considered parallel for all practical purposes.

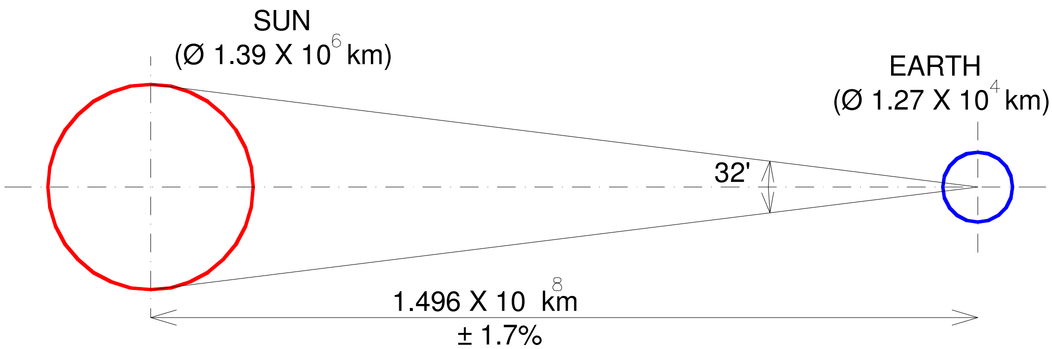

Fig. 4.5 Sun-Earth geometric relationship

The earth is approximately spherical in shape, about 1.27×10^4 km in diameter. It revolves around the sun in an elliptical orbit taking a year to complete one revolution. At the same time, it also rotates about its own axis once every 24 hours. The energy flux received from the sun outside the earth's atmosphere is of nearly constant value and is termed as the Solar Constant (I_{sc}). It is defined as the energy received outside the atmosphere, per second, by a unit surface area normal to the direction of sun's rays at the mean sun-earth distance; its value is accepted as 1367 W/m^2. However, because the earth revolves round the sun in an elliptical orbit with the sun as one of the foci, there is a variation in the extraterrestrial radiation. Hence, the intensity of extraterrestrial radiation on a plane normal to sun's rays on any day is given by:

$$I_{ext} = I_{sc}\left[1.0 + 0.033\cos(360\,n/365)\right] \qquad (4.7)$$

where n is the day of the year and is

$$1 \le n \le 365 \qquad (4.8)$$

Solar radiation is received on the earth's surface after undergoing various mechanisms of attenuation, reflection and scattering in the earth's atmosphere. Consequently, two types of radiation are received at the earth's surface: one that is received from the sun without change of direction, called *beam radiation*, and the other whose direction has been changed by scattering and reflection, called *diffuse radiation*. The sum of these two types is known as total or global radiation.

Usually solar radiation incident on the earth's surface is measured on a horizontal surface. Both global and diffuse radiation are recorded at a number of places in India. In order that the data reflect a true representation of the place, hourly measurements are carried out for a large number of years (typically ten years), and monthly averages of hourly radiation values over a number of years are calculated. Such data are available in various handbooks [e.g., Reference 5].

4.3.1 Radiation on Tilted Surfaces

External surfaces of buildings receiving solar radiation are generally tilted, except for the flat roof, which is a horizontal surface. Consequently, it is required to estimate radiation on such surfaces from the data measured on a horizontal surface.

A tilted surface receives three types of solar radiation, namely beam radiation directly from the sun, diffuse radiation coming from the sky dome, and reflected radiation due to neighbouring buildings and objects. The estimation of the last component is very complicated. However, its contribution is much less compared to the first two sources. Therefore, the reflected component from the surrounding ground surface is generally taken for simple calculations. However, simulation software like DOE2.1E [6] performs a more detailed calculation for accounting the effects of neighbouring buildings and trees.

4.3.1.1 Unshaded surface

For a surface tilted at an angle β and with no shading, hourly incident solar radiation can be estimated as:

$$I_T = I_g r \qquad (4.9)$$

where r is the global radiation tilt factor and is given by [7]

$$r = \left(1 - \frac{I_d}{I_g}\right) r_b + \left(\frac{1+\cos\beta}{2}\right)\frac{I_d}{I_g} + \rho\left(\frac{1-\cos\beta}{2}\right)$$

$$r_b = \frac{\cos\theta}{\cos\theta_z}$$

$$\begin{aligned}\cos\theta &= \sin\phi\,(\sin\delta\cos\beta + \cos\delta\cos\gamma\cos\omega\sin\beta) \\ &\quad + \cos\phi\,(\cos\delta\cos\omega\cos\beta - \sin\delta\cos\gamma\sin\beta) \\ &\quad + \cos\delta\sin\gamma\sin\omega\sin\beta)\end{aligned}$$

$$\cos\theta_z = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega \qquad (4.10)$$

I_g = mean hourly global solar radiation (W/m^2)
I_d = mean hourly diffuse solar radiation (W/m^2)
ρ = reflectivity of the ground surface
ϕ = latitude of a location (degree). By convention, the latitude is measured as positive

for the northern hemisphere.

δ = declination angle (degree). It is defined as the angle made by the line joining the centres of the sun and the earth with its projection on the equatorial plane. It can be calculated from the following relation:

$$\delta(\text{in degrees}) = 23.45 \sin\left[\frac{360}{365}(284 + n)\right] \quad (4.11)$$

n = day of the year

γ = surface azimuth angle (degree). It is the angle made in the horizontal plane between the line due south, and the projection of the normal to the surface on the horizontal plane. By convention, the angle is taken to be positive if the normal is east of south and negative if west of south.

β = slope (degree). It is the angle made by the plane surface with the horizontal.

ω = hour angle (degree). It is the angular measure of time and is equivalent to 15° per hour. It is measured from noon based on local apparent time (LAT), being positive in the morning and negative in the afternoon.

The local apparent time (LAT) can be estimated from Indian Standard Time (IST) using the following equation:

$$\text{LAT} = \text{IST} - 4\,(\text{Reference longitude} - \text{Local longitude}) + \text{ET} \quad (4.12)$$

The second term in the equation becomes positive for any country in the western hemisphere. The reference longitude for India is 82.5^0 E. The Equation of Time (ET) correction is plotted in Fig. 4.6 and it can also be calculated from:

$$\text{ET} = 229.2\,(0.000075 + 0.001868 \cos B - 0.032077 \sin B - 0.014615 \cos 2B - 0.04089 \sin 2B) \quad (413)$$

where B = (n - 1) 360/365 and n is the day of the year.

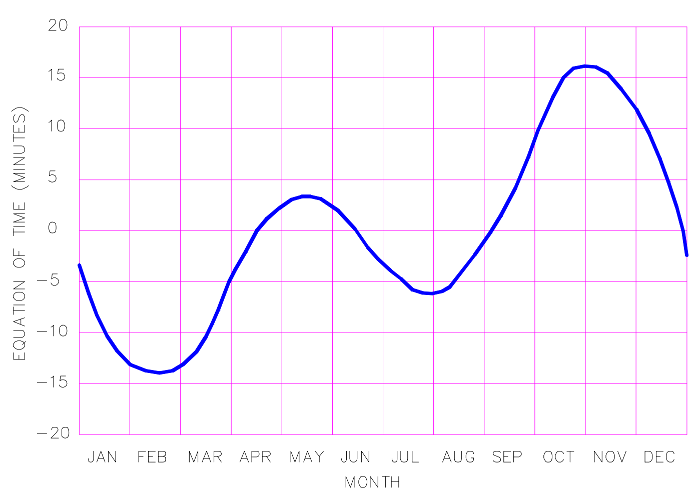

Fig. 4.6 Equation of time correction [4]

Equation (4.9) can be used to calculate hourly radiation on any tilted surface. The values for mean hourly global and diffuse solar radiation on horizontal, and global radiation on vertical surfaces (south, north, east and west) for some Indian cities during the months of May and December are presented in Appendix IV.2. The appendix also lists hourly ambient temperature for these months.

4.3.1.2 Shaded surface

If a surface is shaded, the radiation incident on it gets modified, and depending on the type of shading, its estimation becomes complicated. To illustrate, let us consider the simple case of a horizontal rectangular overhang on a wall (Fig. 4.7). The height and width of the wall are H and W respectively, the depth of the overhang is P.

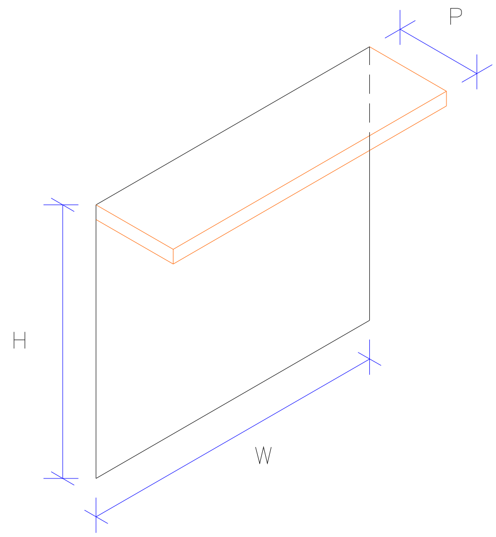

Fig. 4.7 Horizontal rectangular overhang on a wall

Hourly solar radiation on the wall can be written as:

$$I_T = I_g\, r \tag{4.14}$$

where $$r = (1 - \frac{I_d}{I_g})\, r_b\, f_i + \frac{I_d}{I_g} F_{r-s} + 0.5\,\rho \tag{4.15}$$

f_i = fraction of unshaded area
and F_{r-s} = view factor of the wall for radiation from the sky.

f_i is given by

$$f_i = \frac{A_i}{WH} \tag{4.16}$$

A_i is the unshaded area of the wall and is given by

$$A_i \quad = W\ H - A_{shade} \tag{4.17}$$

The shaded area (A_{shade}) of the wall at any time, on any day is given by:

$$A_{shade} \quad = \left[W - 0.5\,P\tan(\gamma_s - \gamma)\right] P\ \tan(90 - \theta_z)\ \sec(\gamma_s - \gamma) \tag{4.18}$$

γ_s = solar azimuth angle (degree). It is the angle made in the horizontal plane between the line due south, and the projection of the sun's rays on the horizontal plane. By convention, the angle is positive if the normal is east of south, and negative if west of south. It is given by:

$$\cos\gamma_s \quad = (\cos\theta_z\ \sin\phi - \sin\delta)/\sin\theta_z\ \cos\phi \tag{4.19}$$

F_{r-s} for a wall of relative width w (= W/H) and relative projection p (= P/H) is presented in Table 4.2 [8].

Table 4.2 Wall radiation view factor for the sky, F_{r-s} [8]

w	F_{r-s} at p=								
	0.10	0.20	0.30	0.40	0.50	0.75	1.00	1.50	2.00
1.0	0.46	0.42	0.40	0.37	0.35	0.32	0.30	0.28	0.27
4.0	0.46	0.41	0.38	0.35	0.32	0.27	0.23	0.19	0.16
25.0	0.45	0.41	0.37	0.34	0.31	0.25	0.21	0.15	0.12

4.4 SIMPLIFIED METHOD FOR PERFORMANCE ESTIMATION

Based on the concepts discussed in previous sections, we can calculate the various heat exchanges (Fig. 4.1) taking place in a building.

4.4.1 Conduction

The rate of heat conduction (Q_{cond}) through any element such as roof, wall or floor under steady state can be written as

$$Q_{cond} = A\ U\ \Delta T \tag{4.20}$$

where,

A = surface area (m^2)

U = thermal transmittance ($W/\ m^2$- K)

ΔT = temperature difference between inside and outside air (K)

It may be noted that the steady state method does not account for the effect of heat capacity of building materials.

U is given by

$$U = \frac{1}{R_T} \tag{4.21}$$

where R_T is the total thermal resistance and is given by

$$R_T = \frac{1}{h_i} + \left(\sum_{j=1}^{m} L_j / k_j \right) + \frac{1}{h_o} \tag{4.22}$$

h_i and h_o respectively, are the inside and outside heat transfer coefficients. L_j is the thickness of the j^{th} layer and k_j is the thermal conductivity of its material.

U indicates the total amount of heat transmitted from outdoor air to indoor air through a given wall or roof per unit area per unit time. The lower the value of U, the higher is the insulating value of the element. Thus, the U-value can be used for comparing the insulating values of various building elements. Examples showing calculation of U-values for a few typical cases are presented in Appendix IV.3.

Equation (4.20) is solved for every external constituent element of the building i.e., each wall, window, door, roof and the floor, and the results are summed up. The heat flow rate through the building envelope by conduction, is the sum of the area and the U-value products of all the elements of the building multiplied by the temperature difference. It is expressed as:

$$Q_c = \sum_{i=1}^{N_c} A_i U_i \Delta T_i \tag{4.23}$$

where,

i = building element

N_c = number of components

If the surface is also exposed to solar radiation then,

$$\Delta T = T_{so} - T_i \tag{4.24}$$

where T_i is the indoor temperature; T_{so} is the sol-air temperature, calculated using the expression:

$$T_{so} = T_o + \frac{\alpha S_T}{h_o} - \frac{\varepsilon \Delta R}{h_o} \tag{4.25}$$

where,

T_o = daily average value of hourly ambient temperature (K)

α = absorptance of the surface for solar radiation

S_T = daily average value of hourly solar radiation incident on the surface (W/m^2)

h_o = outside heat transfer coefficient (W/m^2 -K)

ε = emissivity of the surface

ΔR = difference between the long wavelength radiation incident on the surface from the sky and the surroundings, and the radiation emitted by a black body at ambient temperature

Values of heat transfer coefficient (h_o) at different wind speeds and orientation are presented in Table 4.1. The absorptance values of some common building surfaces are given in Appendix IV.4.

Daily average values of hourly solar radiation can be calculated from the hourly data. As mentioned earlier, measurements of global and diffuse solar radiation are carried out on a horizontal surface. Mean hourly values of such data for various places in India are available in the handbook by Mani [5]. Hourly radiation on a tilted surface can be estimated from these data using Eq. (4.9) for unshaded surfaces or Eq. (4.13) for shaded surfaces.

4.4.2 Ventilation

The heat flow rate due to ventilation of air between the interior of a building and the outside, depends on the rate of air exchange. It is given by:

$$Q_v = \rho \, V_r \, C \, \Delta T \qquad (4.26)$$

where,

ρ = density of air (kg/ m^3)

V_r = ventilation rate (m^3/ s)

C = specific heat of air (J/ kg-K)

ΔT = temperature difference ($T_o - T_i$) (K)

Table 4.3 Recommended air change rates [4]

Space to be ventilated	Air changes per hour
Assembly hall/ Auditorium (smoking)	3-6
Bedrooms / Living rooms (smoking)	3-6
Bathrooms/ Toilets	6-12
Cafes/Restaurants (smoking)	12-15
Cinemas/Theatres (non –smoking)	6-9
Classrooms	3-6
Factories(medium metal work - smoking)	3-6
Garages (smoking)	12-15
Hospital wards (smoking)	3-6
Kitchens (common - smoking)	6-9
Kitchens (Domestic - smoking)	3-6
Laboratories	3-6
Offices (smoking)	3-6

If the number of air changes is known, then

$$V_r = \frac{NV}{3600} \tag{4.27}$$

where,

N = number of air changes per hour

V = volume of the room or space (m^3)

Thus,

$$Q_v = \rho\, C\, \frac{NV}{3600}\, \Delta T \tag{4.28}$$

The minimum standards for ventilation in terms of air changes per hour (N) are presented in Table 4.3.

4.4.3 Solar Heat Gain

The solar gain through transparent elements can be written as:

$$Q_s = \alpha_s \sum_{i=1}^{M} A_i\, S_{gi}\, \tau_i \tag{4.29}$$

where,

α_s = mean absorptivity of the space

A_i = area of the i^{th} transparent element (m^2)

S_{gi} = daily average value of solar radiation (including the effect of shading) on the i^{th} transparent element (W/m^2)

τ_i = transmissivity of the i^{th} transparent element

M = number of transparent elements

4.4.4 Internal Gain

The internal heat gain of a building is estimated as follows:

- The heat generated by occupants is a heat gain for the building; its magnitude depends on the level of activity of a person. Table 4.4 shows the heat output rate of human bodies for various activities [9]. The total rate of energy emission by electric lamps is also taken as internal heat gain. A large part of this energy is emitted as heat (about 95% for ordinary incandescent lamps and 79% for fluorescent lamps) and the remaining part is emitted as light, which when incident on surfaces, is converted into heat. Consequently, the total wattage of all lamps in the building when in use, must be added to the Q_i.

- The heat gain due to appliances (televisions, radios, etc.) should also be added to the Q_i. If an electric motor and the machine driven by it are both located (and operating) in the same space, the total wattage of the motor must be included. If the horse power (hp) of a motor is known, its corresponding wattage can be calculated by multiplying it by 746 (1 hp = 746 W). If the motor alone is in the space considered, and if efficiency is M_{eff}, then energy release into the space is 746 (1-M_{eff}) hp. The load due to common household appliances is listed in Table 4.5 [9].

Table 4.4 Heat production rate in a human body [9]

Activity	Rate of heat production	
	(W)	(W/m^2)
Sleeping	60	35
Resting	80	45
Sitting, Normal office work	100	55
Typing	150	85
Slow walking(3 km/h)	200	110
Fast walking(6 km/h)	250	140
Hard work(filing, cutting, digging, etc.)	more than 300	More than 170

Table 4.5 Wattage of common household appliances [9]

Equipment	Load (W)
Radio	15
Television(black/white)	110
Refrigerator	120
Television(colour)	250
Coffee machine	400
Vacuum cleaner	800
Washing machine	2500
Dishwasher	3050
Water heater	3500

Thus the heat flow rate due to internal heat gain is given by the equation:

$$Q_i = (\text{No. of people} \times \text{heat output rate}) + \text{Rated wattage of lamps} + \text{Appliance load} \quad (4.30)$$

4.4.5 Evaporation

The rate of cooling by evaporation (Q_{ev}) from, say, a roof pond, fountains or human perspiration, can be written as:

$$Q_{ev} = m\,L \quad (4.31)$$

where m is the rate of evaporation (kg/s) and L is the latent heat of evaporation (J/kg-K)

4.4.6 Equipment Gain

If any mechanical heating or cooling equipment is used, the heat flow rate of the equipment is added to the heat gain of the building.

4.5 EXAMPLE

Suppose we have a room that is 5 m long, 4 m wide and 3 m high, as shown in Fig. 4.8. If the room is maintained at 23.3°C by an air-conditioner, how may we calculate the load on the appliance using the steady state approach?

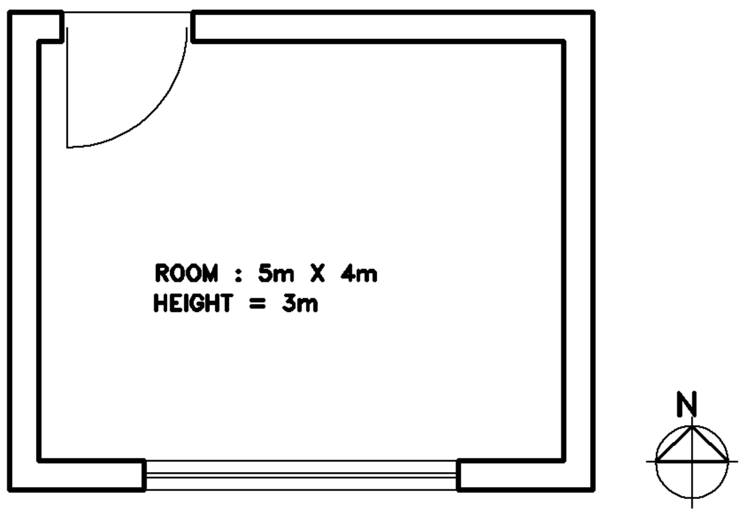

Fig. 4.8 Plan of a single zone room

We have the following data available:

Place: New Delhi
Month: May
Ventilation rate: 2 h^{-1}
Artificial light: Three 100 W bulbs continuously used
Occupants: Four persons (normal office work; 24 hours occupancy)
Window: (1.5m X 3m) on south wall, single glazed
Door: (1.2m X 2m) on north wall
$U_{glazing}$ = 5.77 W/m^2-K
U_{wall} = 3.00 W/m^2-K
U_{roof} = 2.31 W/m^2-K
U_{door} = 3.18 W/m^2-K
Daily average outside temperature in May: 32.7 ºC [Appendix IV.2]
Absorptance of external wall surfaces: 0.6
Outside heat transfer coefficient: 22.7 W/m^2-K
Inside design temperature: 23.3 ºC

Daily average solar radiation on south wall: 111.3 W/m^2
Daily average solar radiation on east wall: 158.2 W/m^2
Daily average solar radiation on north wall: 101.1 W/m^2
Daily average solar radiation on west wall: 155.2 W/m^2
Daily average solar radiation on roof: 303.1 W/m^2
Daily average solar radiation on window: 111.3 W/m^2 (no shading)
Mean absorptivity of the space: 0.6
Transmissivity of window: 0.86
Absorptivity of glazing for solar radiation: 0.06
Absorptivity of wood for solar radiation: 0.0
Density of air: 1.2 kg/m^3
Specific heat of air: 1005 J/ kg-K

Under the steady state approach (which does not account the effect of heat capacity of building materials), the heat balance for room air can be written as

$$Q_{total} = Q_c + Q_s + Q_i + Q_v \qquad (4.32)$$

From Eq. (4.25), with ΔR = 0 for vertical surfaces, the values of sol-air temperatures are:

$$T_{so}^{south} = 32.7 + (0.6 \text{ x } \frac{111.3}{22.7}) = 35.6 \text{ °C}$$

Similarly, $T_{so}^{east} = 36.9$ °C , $T_{so}^{north} = 35.4$ °C , $T_{so}^{west} = 36.8$ °C , $T_{so}^{door} = 32.7$ °C and $T_{so}^{glazing} = 33.0$ °C

For the roof, ΔR = 63 W/ m^2 and hence $T_{so}^{roof} = 38.2$ °C

$$\begin{aligned} Q_c &= 3.00\ (15 - 4.5)\ (35.6 - 23.3) + 3.00 \text{ x } 12\ (36.9 - 23.3) + 3.00\ (15 - 2.4)\ (35.4 - 23.3) \\ &\quad + 3.00 \text{ x } 12\ (36.8 - 23.3) + 3.18 \text{ x } 2.4\ (32.7 - 23.3) + 2.31 \text{ x } 20\ (38.2 - 23.3) \\ &\quad + 5.77 \text{ x } 4.5\ (33.0 - 23.3) \\ &= 2832.4 \text{ W} \end{aligned}$$

Using Eqs. (4.26 – 4.30),
$Q_s = 0.6 \text{ x } 4.5 \text{ x } 111.3 \text{ x } 0.86 = 258.4$ W
$Q_i = 3 \text{ x } 100 + 4 \text{ x } 100 = 700$ W
$Q_v = 1.2 \text{ x } 1005\ (2 \text{ x } 5 \text{ x } 4 \text{ x } 3/3600)\ (32.7 - 23.3) = 377.9$ W

Thus, $Q_m = 2832.4 + 258.4 + 700 + 377.9 = 4168.7 \approx 4.2$ kW

Remarks: Now, the problem facing a designer is to make sense of this quantity. As the total heat gain rate is positive; it represents the total heat entering the building. How does 4.2 kW translate practically? Let us consider it from two angles.

- The COP of a standard window air conditioner of 1.5 tons cooling capacity is about 2.8. So the power required is 1.5 kW (i.e., 4.2 kW/2.8)

- Suppose the machine were to be used for 8 hours a day; then it would consume 12 kWh per day (1.5 kW × 8 hours = 12) or 12 units (One kWh is equivalent to one unit) of electricity supplied by the power company. At a rate of Rs. 4 per unit, expenses would amount to Rs. 48 per day.

4.6 COMPUTER-BASED TOOLS

The above example illustrates the steady state calculation of heat gain or loss for a single zone conditioned building. The method can also be extended to multi-zone or multi-storeyed buildings, but the algebra becomes complicated. Besides, the effects of: (a) variation of outside air temperature and solar radiation with time, (b) shading by neighbouring objects, (c) self shading, and (d) thermal capacity of the building (i.e. the ability of building materials to store heat during daytime and release it back to the environment later) add to the complexity of the calculations. Consequently, one resorts to computer-based tools known as building simulation tools. A number of such tools are now available to do quick and accurate assessment of a building's thermal and daylighting performance. These tools can estimate the performances of different designs of the building for a given environmental condition. From these results, a designer can choose the design that consumes minimum energy. Thermal calculations also help to select appropriate retrofits for existing buildings from the viewpoint of energy conservation. Thus, by integrating the simulation of thermal performance of a building with its architectural design, one can achieve an energy efficient building.

A number of tools are available for simulating the thermal performance of buildings; they address different needs. For example, an architect's office requires a tool that is quick and gets well integrated into the design process. On the other hand an HVAC engineer would look for a tool that would accurately predict the energy a building would consume, for optimum sizing of the air-conditioning systems. A short description of a few simulation tools is provided in Appendix IV.5. The reader may also refer to internet websites (such as http://www.energytoolsdirectory.gov) for more information.

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APPENDIX IV.1

PROPERTIES OF BUILDING MATERIALS [4]

Material	Density (kg/m^3)	Specific heat (kJ/kg-K)	Thermal conductivity (W/m-K)
Burnt brick	1820	0.88	0.811
Mud brick	1731	0.88	0.750
Dense concrete	2410	0.88	1.740
RCC	2288	0.88	1.580
Limestone	2420	0.84	1.800
Slate	2750	0.84	1.720
Reinforced concrete	1920	0.84	1.100
Brick tile	1892	0.88	0.798
Lime concrete	1646	0.88	0.730
Mud phuska	1622	0.88	0.519
Cement mortar	1648	0.92	0.719
Cement plaster	1762	0.84	0.721
Cinder concrete	1406	0.84	0.686
Foam slag concrete	1320	0.88	0.285
Gypsum plaster	1120	0.96	0.512
Cellular concrete	704	1.05	0.188
AC sheet	1520	0.84	0.245
GI sheet	7520	0.50	61.060
Timber	480	1.68	0.072
Plywood	640	1.76	0.174
Glass	2350	0.88	0.814
Sand	2240	0.84	1.740
Expanded polystyrene	34	1.34	0.035
Foam glass	160	0.75	0.055
Foam concrete	704	0.92	0.149
Rock wool (unbonded)	150	0.84	0.043
Mineral wool (unbonded)	73.5	0.92	0.030
Glass wool (unbonded)	189	0.92	0.040
Resin bonded mineral wool	99	1.00	0.036
Resin bonded glass wool	24	1.00	0.036
Asbestos mill board	1397	0.84	0.249
Hard board	979	1.42	0.279
Straw board	310	1.30	0.057
Soft board	249	1.30	0.047
Wall board	262	1.26	0.047
Chip board	432	1.26	0.067
Particle board	750	1.30	0.098
Coconut pith insulation board	520	1.09	0.060
Jute fibre	329	1.09	0.067
Wood wool board (bonded with cement)	674	1.13	0.108
Coir board	97	1.00	0.038
Saw dust	188	1.00	0.051
Rice husk	120	1.00	0.051
Aluminium Composite panels (Alucopan – 150)*	150	0.902	0.060
Face bricks*	2083	1.004	1.30
Polycarbonate sheet*	1350	1.17	0.21
Fly ash brick*	1570	0.8	0.54 to 0.70
Fibre reinforced plastic (FRP) sheet (Durostone standard)*	1850	0.96	0.260

Polyurethane foam (PUF)*	30	1.570	0.026
Polyvinyl chloride sheet*	1350	1.255	0.160
Cork tile*	540	1.00	0.085
Plastic tile*	1050	1.07	0.50
PVC asbestos tile*	2000	1.00	0.85
Gypsum plasterboard*	950	0.82	0.16
Brown cellulose fibres*	37-51	1.35	0.045
Thatch (reed)*	270	1.00	0.09
Thatch (straw)*	240	1.00	0.07
Acoustic tile*	290	1.34	0.058

* compiled from various websites.

APPENDIX - IV.2

GLOBAL SOLAR RADIATION AND AMBIENT TEMPERATURE DATA

(A) Place: Jodhpur (26^o 18'N, 73^o 01'E)

Hour (LAT)	Month: May						Month: December					
	Solar radiation (kW/m^2)					Ambient temperature (^{o}C) [5]	Solar radiation (kW/m^2)					Ambient Temperature (^{o}C) [5]
	Horizontal surface [5]	South surface	East surface	North surface	West surface		Horizontal surface [5]	South surface	East surface	North surface	West surface	
6	0.024	0.012	0.012	0.012	0.012	28.1	0.000	0.000	0.000	0.000	0.000	13.3
7	0.175	0.070	0.332	0.135	0.070	27.1	0.005	0.002	0.002	0.002	0.002	12.9
8	0.393	0.130	0.525	0.188	0.130	29.5	0.110	0.268	0.428	0.033	0.033	12.9
9	0.603	0.176	0.599	0.195	0.176	31.9	0.311	0.487	0.577	0.073	0.073	14.4
10	0.771	0.234	0.568	0.207	0.207	34.0	0.491	0.646	0.553	0.100	0.100	16.5
11	0.892	0.292	0.468	0.226	0.226	36.1	0.613	0.735	0.417	0.118	0.118	19.6
12	0.953	0.321	0.319	0.234	0.234	37.7	0.676	0.779	0.232	0.128	0.128	22.6
13	0.951	0.322	0.236	0.236	0.320	39.1	0.677	0.778	0.129	0.129	0.232	24.4
14	0.884	0.291	0.226	0.226	0.464	40.0	0.613	0.732	0.120	0.120	0.416	25.4
15	0.751	0.236	0.210	0.210	0.550	40.4	0.484	0.632	0.101	0.0101	0.542	25.6
16	0.577	0.177	0.177	0.194	0.562	40.4	0.307	0.481	0.072	0.072	0.570	25.4
17	0.362	0.127	0.127	0.177	0.464	40.3	0.109	0.265	0.033	0.033	0.421	24.8
18	0.157	0.066	0.066	0.118	0.277	39.6	0.005	0.002	0.002	0.002	0.002	22.9
19	0.020	0.011	0.011	0.033	0.070	38.5	0.000	0.000	0.000	0.000	0.000	20.7
20	0.000	0.000	0.000	0.000	0.000	37.1	0.000	0.000	0.000	0.000	0.000	19.5
21	0.000	0.000	0.000	0.000	0.000	35.6	0.000	0.000	0.000	0.000	0.000	18.6
22	0.000	0.000	0.000	0.000	0.000	34.5	0.000	0.000	0.000	0.000	0.000	17.9
23	0.000	0.000	0.000	0.000	0.000	33.6	0.000	0.000	0.000	0.000	0.000	16.4
24	0.000	0.000	0.000	0.000	0.000	32.7	0.000	0.000	0.000	0.000	0.000	16.3
1	0.000	0.000	0.000	0.000	0.000	31.9	0.000	0.000	0.000	0.000	0.000	15.6
2	0.000	0.000	0.000	0.000	0.000	31.1	0.000	0.000	0.000	0.000	0.000	15.1
3	0.000	0.000	0.000	0.000	0.000	30.2	0.000	0.000	0.000	0.000	0.000	14.5
4	0.000	0.000	0.000	0.000	0.000	29.6	0.000	0.000	0.000	0.000	0.000	14.1
5	0.000	0.000	0.000	0.000	0.000	28.9	0.000	0.000	0.000	0.000	0.000	13.7

LAT: Local Apparent Time

GLOBAL SOLAR RADIATION AND AMBIENT TEMPERATURE DATA

(B) Place: New Delhi (28° 35'N, 77° 12'E)

Hour (LAT)	Month: May						Month: December					
	Solar radiation (kW/m^2)					Ambient temperature (°C) [5]	Solar radiation (kW/m^2)					Ambient Temperature (°C) [5]
	Horizontal surface [5]	South surface	East surface	North surface	West surface		Horizontal surface [5]	South surface	East surface	North surface	West surface	
6	0.030	0.017	0.017	0.017	0.017	26.3	0.000	0.000	0.000	0.000	0.000	9.7
7	0.177	0.075	0.300	0.128	0.075	27.1	0.003	0.001	0.002	0.001	0.001	9.5
8	0.383	0.133	0.491	0.178	0.133	29.3	0.085	0.199	0.310	0.031	0.031	9.8
9	0.581	0.180	0.563	0.184	0.180	31.8	0.259	0.407	0.472	0.072	0.072	12.3
10	0.746	0.258	0.545	0.214	0.214	34.1	0.425	0.565	0.477	0.104	0.104	14.9
11	0.865	0.321	0.459	0.238	0.238	35.7	0.543	0.662	0.378	0.126	0.126	17.3
12	0.925	0.354	0.327	0.250	0.250	36.9	0.605	0.710	0.226	0.138	0.138	19.0
13	0.920	0.353	0.251	0.251	0.327	37.7	0.605	0.709	0.139	0.139	0.226	20.1
14	0.844	0.317	0.238	0.238	0.449	38.3	0.538	0.652	0.127	0.127	0.374	20.7
15	0.719	0.256	0.215	0.215	0.522	38.5	0.418	0.552	0.104	0.104	0.466	20.9
16	0.547	0.178	0.178	0.181	0.519	38.7	0.255	0.399	0.072	0.072	0.462	20.7
17	0.352	0.130	0.130	0.168	0.432	38.0	0.086	0.211	0.030	0.030	0.330	19.7
18	0.158	0.069	0.069	0.113	0.252	37.5	0.003	0.002	0.001	0.001	0.001	17.2
19	0.027	0.014	0.014	0.051	0.117	35.9	0.000	0.000	0.000	0.000	0.000	15.9
20	0.000	0.000	0.000	0.000	0.000	34.1	0.000	0.000	0.000	0.000	0.000	14.7
21	0.000	0.000	0.000	0.000	0.000	32.6	0.000	0.000	0.000	0.000	0.000	13.9
22	0.000	0.000	0.000	0.000	0.000	31.5	0.000	0.000	0.000	0.000	0.000	13.2
23	0.000	0.000	0.000	0.000	0.000	30.7	0.000	0.000	0.000	0.000	0.000	12.5
24	0.000	0.000	0.000	0.000	0.000	29.9	0.000	0.000	0.000	0.000	0.000	11.9
1	0.000	0.000	0.000	0.000	0.000	29.1	0.000	0.000	0.000	0.000	0.000	11.5
2	0.000	0.000	0.000	0.000	0.000	28.4	0.000	0.000	0.000	0.000	0.000	11.1
3	0.000	0.000	0.000	0.000	0.000	27.8	0.000	0.000	0.000	0.000	0.000	10.6
4	0.000	0.000	0.000	0.000	0.000	27.2	0.000	0.000	0.000	0.000	0.000	10.3
5	0.000	0.000	0.000	0.000	0.000	26.7	0.000	0.000	0.000	0.000	0.000	10.1

LAT: Local Apparent Time

GLOBAL SOLAR RADIATION AND AMBIENT TEMPERATURE DATA

(C) Place: Mumbai (19° 07'N, 72° 51'E)

Hour (LAT)	Month: May						Month: December					
	Solar radiation (kW/m²)					Ambient temperature (°C) [5]	Solar radiation (kW/m²)					Ambient Temperature (°C) [5]
	Horizontal surface [5]	South surface	East surface	North surface	West surface		Horizontal surface [5]	South surface	East surface	North surface	West surface	
6	0.012	0.006	0.006	0.006	0.006	27.2	0.000	0.000	0.000	0.000	0.000	20.3
7	0.124	0.056	0.212	0.100	0.056	27.5	0.013	0.006	0.006	0.006	0.006	20.1
8	0.294	0.115	0.354	0.166	0.115	28.9	0.142	0.237	0.381	0.045	0.045	21.1
9	0.489	0.166	0.461	0.211	0.166	30.4	0.342	0.425	0.535	0.080	0.080	24.2
10	0.710	0.205	0.518	0.237	0.205	31.2	0.517	0.546	0.511	0.108	0.108	26.4
11	0.864	0.226	0.453	0.238	0.226	31.9	0.647	0.627	0.399	0.129	0.129	28.3
12	0.952	0.238	0.319	0.236	0.236	32.3	0.717	0.669	0.235	0.140	0.140	29.6
13	0.962	0.235	0.233	0.233	0.319	32.4	0.719	0.670	0.141	0.141	0.236	30.3
14	0.899	0.219	0.219	0.232	0.468	32.4	0.652	0.630	0.132	0.132	0.402	30.5
15	0.768	0.195	0.195	0.233	0.571	32.3	0.524	0.551	0.112	0.112	0.516	30.1
16	0.578	0.157	0.157	0.225	0.595	31.9	0.353	0.436	0.084	0.084	0.549	29.5
17	0.360	0.113	0.113	0.198	0.517	31.5	0.155	0.269	0.046	0.046	0.437	28.2
18	0.150	0.058	0.058	0.134	0.328	30.7	0.017	0.007	0.007	0.007	0.007	26.6
19	0.017	0.007	0.007	0.007	0.007	29.9	0.000	0.000	0.000	0.000	0.000	25.6
20	0.000	0.000	0.000	0.000	0.000	29.5	0.000	0.000	0.000	0.000	0.000	25.0
21	0.000	0.000	0.000	0.000	0.000	29.1	0.000	0.000	0.000	0.000	0.000	24.3
22	0.000	0.000	0.000	0.000	0.000	28.9	0.000	0.000	0.000	0.000	0.000	23.5
23	0.000	0.000	0.000	0.000	0.000	28.7	0.000	0.000	0.000	0.000	0.000	22.7
24	0.000	0.000	0.000	0.000	0.000	28.4	0.000	0.000	0.000	0.000	0.000	21.9
1	0.000	0.000	0.000	0.000	0.000	28.2	0.000	0.000	0.000	0.000	0.000	21.4
2	0.000	0.000	0.000	0.000	0.000	28.0	0.000	0.000	0.000	0.000	0.000	21.0
3	0.000	0.000	0.000	0.000	0.000	27.7	0.000	0.000	0.000	0.000	0.000	20.7
4	0.000	0.000	0.000	0.000	0.000	27.5	0.000	0.000	0.000	0.000	0.000	20.5
5	0.000	0.000	0.000	0.000	0.000	27.4	0.000	0.000	0.000	0.000	0.000	20.4

LAT: Local Apparent Time

GLOBAL SOLAR RADIATION AND AMBIENT TEMPERATURE DATA

(D) Place: Pune (18^{o} 32'N, 73^{o} 51'E)

Hour (LAT)	Month: May						Month: December					
	Solar radiation (kW/m^2)					Ambient temperature (^{o}C) [5]	Solar radiation (kW/m^2)					Ambient Temperature (^{o}C) [5]
	Horizontal surface [5]	South surface	East surface	North surface	West surface		Horizontal surface [5]	South surface	East surface	North surface	West surface	
6	0.012	0.007	0.007	0.007	0.007	23.9	0.000	0.000	0.000	0.000	0.000	15.0
7	0.144	0.057	0.305	0.128	0.057	24.2	0.015	0.008	0.008	0.008	0.008	14.6
8	0.364	0.112	0.530	0.203	0.112	26.1	0.148	0.246	0.398	0.045	0.045	15.5
9	0.585	0.156	0.608	0.229	0.156	28.6	0.350	0.423	0.535	0.085	0.085	19.1
10	0.764	0.184	0.572	0.229	0.184	30.5	0.537	0.555	0.524	0.115	0.115	22.2
11	0.890	0.204	0.461	0.223	0.204	32.5	0.673	0.641	0.413	0.135	0.135	24.9
12	0.957	0.213	0.303	0.218	0.213	34.0	0.742	0.681	0.243	0.145	0.145	26.7
13	0.950	0.215	0.215	0.220	0.303	35.3	0.743	0.681	0.146	0.146	0.243	28.0
14	0.858	0.208	0.208	0.226	0.447	35.9	0.667	0.633	0.137	0.137	0.409	28.7
15	0.708	0.182	0.182	0.222	0.525	35.9	0.534	0.550	0.116	0.116	0.519	29.0
16	0.524	0.147	0.147	0.210	0.535	35.4	0.354	0.429	0.085	0.085	0.543	28.8
17	0.327	0.104	0.104	0.183	0.465	34.2	0.154	0.262	0.045	0.045	0.427	27.9
18	0.139	0.054	0.054	0.125	0.302	32.4	0.015	0.006	0.006	0.006	0.006	26.1
19	0.016	0.008	0.008	0.008	0.008	30.7	0.000	0.000	0.000	0.000	0.000	23.7
20	0.000	0.000	0.000	0.000	0.000	29.2	0.000	0.000	0.000	0.000	0.000	22.1
21	0.000	0.000	0.000	0.000	0.000	28.3	0.000	0.000	0.000	0.000	0.000	21.0
22	0.000	0.000	0.000	0.000	0.000	27.5	0.000	0.000	0.000	0.000	0.000	19.9
23	0.000	0.000	0.000	0.000	0.000	26.9	0.000	0.000	0.000	0.000	0.000	19.0
24	0.000	0.000	0.000	0.000	0.000	26.4	0.000	0.000	0.000	0.000	0.000	18.2
1	0.000	0.000	0.000	0.000	0.000	25.8	0.000	0.000	0.000	0.000	0.000	17.6
2	0.000	0.000	0.000	0.000	0.000	25.5	0.000	0.000	0.000	0.000	0.000	16.9
3	0.000	0.000	0.000	0.000	0.000	25.0	0.000	0.000	0.000	0.000	0.000	16.3
4	0.000	0.000	0.000	0.000	0.000	24.6	0.000	0.000	0.000	0.000	0.000	15.8
5	0.000	0.000	0.000	0.000	0.000	24.3	0.000	0.000	0.000	0.000	0.000	15.4

LAT: Local Apparent Time

GLOBAL SOLAR RADIATION AND AMBIENT TEMPERATURE DATA

(E) Place: Srinagar (34° 05'N, 74° 50'E)

Hour (LAT)	Month: May						Month: December					
	Solar radiation (kW/m^2)					Ambient temperature (°C)**	Solar radiation (kW/m^2)					Ambient Temperature (°C)**
	Horizontal surface*	South surface	East surface	North surface	West surface		Horizontal surface*	South surface	East surface	North surface	West surface	
6	0.064	0.034	0.034	0.034	0.034	12.3	0.0	0.0	0.0	0.0	0.0	0.5
7	0.224	0.098	0.337	0.149	0.098	12.8	0.031	0.019	0.019	0.019	0.019	0.4
8	0.413	0.153	0.497	0.178	0.153	14.0	0.108	0.160	0.224	0.058	0.058	0.4
9	0.572	0.223	0.528	0.199	0.199	15.8	0.217	0.283	0.310	0.094	0.094	0.7
10	0.697	0.304	0.499	0.233	0.233	17.0	0.308	0.375	0.314	0.117	0.117	1.8
11	0.793	0.365	0.432	0.257	0.257	18.3	0.365	0.420	0.258	0.132	0.132	2.9
12	0.831	0.393	0.328	0.269	0.269	19.5	0.386	0.430	0.180	0.138	0.138	4.0
13	0.793	0.375	0.257	0.257	0.313	20.2	0.365	0.404	0.132	0.132	0.171	4.8
14	0.697	0.324	0.233	0.233	0.381	20.9	0.308	0.341	0.117	0.117	0.215	5.4
15	0.572	0.254	0.199	0.199	0.406	21.2	0.217	0.232	0.094	0.094	0.199	5.7
16	0.413	0.169	0.153	0.153	0.369	21.2	0.108	0.094	0.058	0.058	0.100	5.5
17	0.224	0.098	0.098	0.108	0.229	21.0	0.031	0.019	0.019	0.019	0.019	5.0
18	0.064	0.034	0.034	0.040	0.064	20.5	0.0	0.0	0.0	0.0	0.0	4.2
19	0.0	0.0	0.0	0.0	0.0	19.4	0.0	0.0	0.0	0.0	0.0	3.5
20	0.0	0.0	0.0	0.0	0.0	18.0	0.0	0.0	0.0	0.0	0.0	2.8
21	0.0	0.0	0.0	0.0	0.0	16.9	0.0	0.0	0.0	0.0	0.0	2.4
22	0.0	0.0	0.0	0.0	0.0	16.1	0.0	0.0	0.0	0.0	0.0	2.0
23	0.0	0.0	0.0	0.0	0.0	15.4	0.0	0.0	0.0	0.0	0.0	1.7
24	0.0	0.0	0.0	0.0	0.0	14.9	0.0	0.0	0.0	0.0	0.0	1.5
1	0.0	0.0	0.0	0.0	0.0	14.2	0.0	0.0	0.0	0.0	0.0	1.1
2	0.0	0.0	0.0	0.0	0.0	13.8	0.0	0.0	0.0	0.0	0.0	1.1
3	0.0	0.0	0.0	0.0	0.0	13.2	0.0	0.0	0.0	0.0	0.0	0.9
4	0.0	0.0	0.0	0.0	0.0	12.9	0.0	0.0	0.0	0.0	0.0	0.7
5	0.0	0.0	0.0	0.0	0.0	12.5	0.0	0.0	0.0	0.0	0.0	0.6

LAT: Local Apparent Time

* based on procedure outlined in Mani and Rangarajan [11]

** based on procedure outlined in Bansal and Minke [12] with minimum and maximum temperature data from Mani and Rangarajan [11]

GLOBAL SOLAR RADIATION AND AMBIENT TEMPERATURE DATA

(F) Place: Leh (34° 09'N, 77° 34'E)

Hour (LAT)	Month: May						Month: December					
	Solar radiation (kW/m^2)					Ambient temperature (°C)**	Solar radiation (kW/m^2)					Ambient Temperature (°C)**
	Horizontal surface*	South surface	East surface	North surface	West surface		Horizontal surface*	South surface	East surface	North surface	West surface	
6	0.076	0.033	0.033	0.033	0.033	2.5	0.0	0.0	0.0	0.0	0.0	-12.4
7	0.266	0.096	0.520	0.185	0.096	3.1	0.036	0.017	0.017	0.017	0.017	-11.7
8	0.491	0.152	0.672	0.189	0.152	4.3	0.141	0.483	0.751	0.056	0.056	-10.3
9	0.681	0.234	0.679	0.198	0.198	6.1	0.284	0.500	0.558	0.093	0.093	-8.4
10	0.829	0.334	0.613	0.231	0.231	8.1	0.405	0.599	0.485	0.117	0.117	-6.1
11	0.943	0.409	0.504	0.256	0.256	10.3	0.480	0.649	0.359	0.133	0.133	-3.6
12	0.989	0.445	0.352	0.268	0.268	12.4	0.507	0.656	0.213	0.139	0.139	-1.2
13	0.943	0.424	0.256	0.256	0.336	14.0	0.480	0.619	0.133	0.133	0.202	0.6
14	0.829	0.363	0.231	0.231	0.444	15.1	0.405	0.535	0.117	0.117	0.300	1.8
15	0.681	0.279	0.198	0.198	0.500	15.5	0.284	0.389	0.093	0.093	0.319	2.2
16	0.491	0.176	0.152	0.152	0.478	15.1	0.141	0.208	0.056	0.056	0.230	1.8
17	0.266	0.096	0.096	0.113	0.328	14.2	0.036	0.083	0.017	0.017	0.125	0.7
18	0.076	0.033	0.033	0.051	0.119	12.7	0.0	0.0	0.0	0.0	0.0	-0.9
19	0.0	0.0	0.0	0.0	0.0	11.0	0.0	0.0	0.0	0.0	0.0	-2.9
20	0.0	0.0	0.0	0.0	0.0	9.2	0.0	0.0	0.0	0.0	0.0	-4.8
21	0.0	0.0	0.0	0.0	0.0	7.8	0.0	0.0	0.0	0.0	0.0	-6.4
22	0.0	0.0	0.0	0.0	0.0	6.5	0.0	0.0	0.0	0.0	0.0	-7.9
23	0.0	0.0	0.0	0.0	0.0	5.4	0.0	0.0	0.0	0.0	0.0	-9.1
24	0.0	0.0	0.0	0.0	0.0	4.6	0.0	0.0	0.0	0.0	0.0	-10.0
1	0.0	0.0	0.0	0.0	0.0	3.9	0.0	0.0	0.0	0.0	0.0	-10.8
2	0.0	0.0	0.0	0.0	0.0	3.3	0.0	0.0	0.0	0.0	0.0	-11.5
3	0.0	0.0	0.0	0.0	0.0	2.7	0.0	0.0	0.0	0.0	0.0	-12.1
4	0.0	0.0	0.0	0.0	0.0	2.3	0.0	0.0	0.0	0.0	0.0	-12.6
5	0.0	0.0	0.0	0.0	0.0	2.2	0.0	0.0	0.0	0.0	0.0	-12.7

LAT: Local Apparent Time

* based on procedure outlined in Mani and Rangarajan [11]

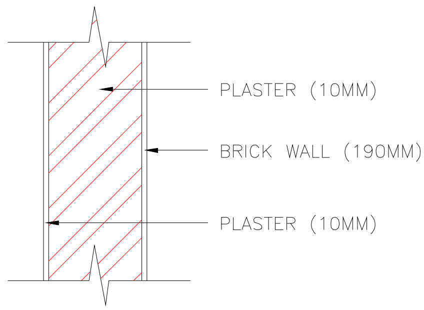
** based on procedure outlined in Bansal and Minke [12] with minimum and maximum temperature data from Mani and Rangarajan [11]

APPENDIX IV.3

EXAMPLES SHOWING ESTIMATION OF U-VALUES

Example 1:

To find U for a 19.00 cm thick brick wall provided with 1.00 cm thick cement plaster on both sides.



$L_1 = 0.01$ m; $k_1 = 0.721$ W/m-K
$L_2 = 0.19$ m; $k_2 = 0.811$ W/m-K
$L_3 = 0.01$ m; $k_3 = 0.721$ W/m-K

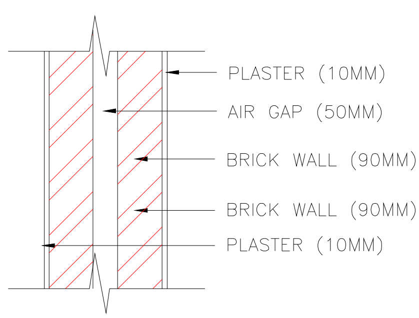
$h_i = 8.3$ W/m^2-K; $h_o = 22.7$ W/m^2-K

$R_T = 1/8.3 + 0.01/0.721 + 0.19/0.811 + 0.01/0.721 + 1/22.7 = 0.4266$

$U = 1/R_T = 1/0.4266 = 2.344$ W/m^2-K

Example 2:

To find U for an outside wall made up of two layers of 9.00 cm brick with a 5.00 cm air gap, plastered with 1.00 cm thick cement plaster on both sides.



Layer 1: $L_1 = 0.01$ m; $k_1 = 0.721$ W/m-K
Layer 2: $L_2 = 0.09$ m; $k_2 = 0.811$ W/m-K

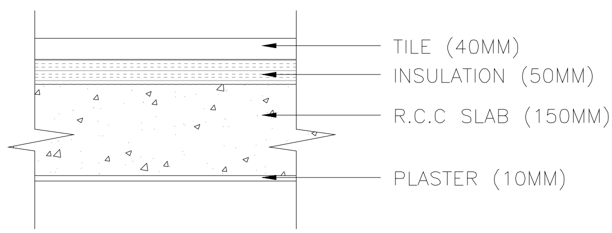
Layer 3: Enclosed air conductance C = 6.22 W/m^2 -K
Layer 4: L_4 = 0.09 m; k_4 = 0.811 W/m-K
Layer 5: L_5 = 0.01 m; k_5 = 0.721 W/m-K

R_T = 1/8.3 + 1/22.7 + 0.01/0.721 + 0.09/0.811 + 1/6.22 + 0.09/0.811+ 0.01/0.721
= 0.5750

U = 1/R_T
= 1.739 W/m^2-K

Example 3:

To find U for a 15.00 cm thick RCC roof slab insulated with 5.00 cm thick expanded polystyrene, and finished with 4.00 cm thick brick tiles on the top, and 1.00 cm thick cement plaster on the bottom.



h_i = 6.1 W/m^2-K; h_o = 22.7 W/m^2-K

Layer 1: L_1 = 0.01 m; k_1 = 0.721 W/m-K
Layer 2: L_2 = 0.15 m; k_2 = 1.580 W/m-K
Layer 3: L_3 = 0.05 m; k_3 = 0.035 W/m-K
Layer 4: L_4 = 0.04 m; k_4 = 0.798 W/m-K

R_T = 1/6.1 + 1/22.7 + 0.01/0.721 + 0.15/1.580 + 0.05/0.035 + 0.04/0.798
= 1.795

U = 1/R_T
= 0.55 W/m^2-K

APPENDIX IV.4

AVERAGE EMISSIVITIES, ABSORPTIVITIES AND REFLECTIVITIES OF SOME BUILDING MATERIALS [4]

Surface	Emmisivity or Absorptivity		Reflectivity (Solar radiation)
	(Low temperature radiation)	(Solar radiation)	
Aluminium, bright	0.05	0.20	0.80
Asbestos cement, new	0.95	0.60	0.40
Asbestos cement, aged	0.95	0.75	0.25
Asphalt pavement	0.95	0.90	0.10
Brass and copper, dull	0.20	0.60	0.40
Brass and copper, polished	0.02	0.30	0.70
Brick, light puff	0.90	0.60	0.40
Brick, red rough	0.90	0.70	0.30
Cement, white portland	0.90	0.40	0.60
Concrete, uncoloured	0.90	0.65	0.35
Marble, white	0.95	0.45	0.55
Paint, Aluminium	0.55	0.50	0.50
Paint, white	0.90	0.30	0.70
Paint, brown, red, green	0.90	0.70	0.30
Paint, black	0.90	0.90	0.10
Paper, white	0.90	0.30	0.70
Slate, dark	0.90	0.90	0.10
Steel, galvanized new	0.25	0.55	0.45
Steel, galvanized weathered	0.25	0.70	0.30
Tiles, red clay	0.90	0.70	0.30
Tiles, uncoloured concrete	0.90	0.65	0.35

APPENDIX IV.5

SIMULATION TOOLS

A brief description of a few simulation tools is presented in this appendix.

1 Therm Version 1.0 (Thermal Evaluation Tool for Buildings) [13]

"Therm" evaluates the thermal performance of a passive or partly air-conditioned building, by calculating the hourly floating inside air temperature. The tool considers the effects of various parameters and variables like building fabric, opening/fenestration type, orientation, natural ventilation, and internal gains through convection and radiation. Effects of passive elements such as Trombe wall, evaporative cooling and roof pond can be analysed using Therm. It is intended as a preliminary tool for the analysis of thermal performance of a building, to help select a suitable building envelope or passive system appropriate for a particular climate and function. Therm incorporates various rating criteria such as comfort fraction, decrement factor, and depression or elevation of mean indoor temperature. The tool is developed using Microsoft Excel and Visual basic and is in a spread sheet format. It is used as a plug-in in MS Excel.

Therm has a facility to update the materials library and the climatic database. A handy tool for calculating the U-value of various building sections is also provided.

2. TADSIM (Tools for Architectural Design and Simulation) [14]

TADSIM has been developed as a computer interface between building design and simulation software. The basic philosophy is to ensure that architects can make use of simulation tools quickly and efficiently. Relevant information on building geometry and associated details are automatically extracted from the design made in the architectural design module (TAD Designer). This information can be passed on to a number of simulation tools namely Dynsim, TRNSYS and DOE2.1E for thermal analysis. Dynsim has been integrated into TADSIM for dynamic simulation of non-conditioned and conditioned multi-storey, multi-zone buildings. It estimates the room temperatures and thermal loads. This tool can be used to quickly analyse the effect of materials, windows, orientation, colour, etc. on the thermal performance of the building. The effect of shading of external surfaces can be approximated by specifying a shade fraction for each window.

TADSIM is also capable of generating input files for TRNSYS and DOE2.1E, if the user wants to use these for simulating the building's thermal performance. Besides, it has a module that advises the user on various aspects of passive solar architecture, called TADSIM adviser. It provides information on climatic design, daylighting, passive solar techniques and material properties. It also contains a glossary. Additionally the data can be updated by the user at a later stage.

3. TRNSYS

TRNSYS is a dynamic simulation tool for estimating the performance of any solar thermal system. For example, it can estimate the performance of a building, a solar photovoltaic system, and solar domestic hot water system. It is one of the most widely used commercially available tool for building simulation. It uses a menu driven interface to provide the building description (building geometry, materials and their properties, scheduling, heating and cooling system, etc.) using the PREBID module. This file can also be edited directly using any text editor (e.g. Notepad, MS Editor), without using PREBID, if one knows the sequence of information needed for the software.

The weather data, simulation run time, output types can be provided by using the IISiBat or PRESIM interface, or manually edited using any text editor. TRNSYS can be used with a general purpose CAD software called SimCAD, to integrate the architectural design and simulation.

The output of a building's thermal performance in terms of temperature and loads, can be obtained both graphically and in text format. Multi-zone, conditioned and non-conditioned buildings can be analysed by using TRNSYS. It can also do quick parametric analyses by using parameter tables. It has a built-in materials library.

4. DOE-2.1E [6]

DOE-2.1E predicts the hourly energy use and energy cost of a building. The inputs required are hourly weather information, building geometric dimensions, and its HVAC description. Designers can determine the choice of building parameters that improve energy efficiency, while maintaining thermal comfort and cost-effectiveness. DOE-2.1E has one subprogram for translation of input (BDL Processor),and four simulation subprograms (LOADS, SYSTEMS, PLANT and ECONOMICS). LOADS, SYSTEMS, PLANT and ECONOMICS are executed in sequence, with the output of LOADS becoming the input of SYSTEMS, and so on. Each of the simulation subprograms also produces printed reports of the results of its calculations. The Building Description Language (BDL) processor reads input data and calculates response factors for the transient heat flow in walls, and weighting factors for the thermal response of building spaces.

The LOADS simulation subprogram calculates the sensible and latent components of the hourly heating or cooling load for each constant temperature space, taking into account weather and building use patterns. The SYSTEMS subprogram calculates the performance of air-side equipment (fans, coils, and ducts); it corrects the constant-temperature loads calculated by the LOADS subprogram by taking into account outside air requirements, hours of equipment operation, equipment control strategies, and thermostat set points. The output of SYSTEMS is air flow and coil loads. PLANTS calculates the behavior of boilers, chillers, cooling towers, storage tanks, etc., in satisfying the secondary systems heating and cooling coil loads. It takes into account the part-load characteristics of the primary equipment, to calculate the fuel and electrical demands of the building. The ECONOMICS subprogram calculates the cost of energy and so, can be used to compare the cost benefits of different building designs, or to calculate savings for retrofits to an existing building.

A number of interfaces have been developed to make the program easy to use.

5. EnergyPlus [16]

EnergyPlus is a modular, structured software tool based on the most popular features and capabilities of BLAST and DOE-2.1E. It is primarily a simulation engine; input and output are simple text files. EnergyPlus grew out of a perceived need to provide an integrated (simultaneous load and systems) simulation for accurate temperature and comfort prediction. Loads calculated (by a heat balance engine) at user-specified time step (15-minute default) are passed to the building system simulation module at the same time step. The EnergyPlus building systems simulation module, with a variable time step (down to 1 minute as needed), calculates the heating and cooling system, and plant and electrical system response. This integrated solution provides more accurate space-temperature prediction, crucial for system and plant sizing, and occupant comfort and health calculations. Integrated simulation also allows users to evaluate realistic system controls, moisture adsorption and desorption in building elements, radiant heating and cooling systems, and interzone air flow.

EnergyPlus has two basic components: a heat and mass balance simulation module, and a building systems simulation module. The heat and mass balance calculations are based on IBLAST – a research version of BLAST with integrated HVAC systems and building loads simulation. The heat balance module manages the surface and air heat balance, and acts as an interface between the heat balance and the building system simulation manager. EnergyPlus inherits three popular windows and daylighting models from DOE-2.1E – fenestration performance based on WINDOW 5 calculations, daylighting using the split-flux interreflection module, and antistrophic sky models. In addition, a new daylighting analysis module named ‘Delight’ has been integrated with EnergyPlus.

6. eQUEST [17]

eQUEST is an easy to use building energy use analysis tool that provides professional-level results with an affordable level of effort. This is accomplished by combining a building creation wizard, an energy efficiency measure (EEM) wizard and a graphical results display module, with an enhanced DOE-2.2-derived building energy use simulation program.

eQUEST features a building creation wizard that guides the user through the process of creating an effective building energy model. This involves following a series of steps that help one to describe the features of the design that would impact energy use such as architectural design, HVAC equipment, building type and size, floor plan layout, construction material, area usage and occupancy, and lightning system. After compiling a building description, eQUEST produces a detailed simulation of the building, as well as an estimate of how much energy the building would use.

Within eQUEST, DOE-2.2 performs an hourly simulation of the building design for a one-year period. It calculates heating or cooling loads for each hour of the year, based on factors such as walls, windows, glass, people, plug loads, and ventilation. DOE-2.2 also simulates the performance of fans, pumps, chillers, boilers, and other energy-consuming devices. During the simulation, DOE-2.2 tabulates the building's projected use for various end uses.

eQUEST offers several graphical formats for viewing simulation results. It allows one to perform multiple simulations and view alternative results in side-by-side graphics. It offers features like: energy cost estimating, daylighting and lighting system control , and automatic implementation of common energy efficiency measures (by selecting preferred measures from a list).

CHAPTER 5

DESIGN GUIDELINES

Contents:

5.1 INTRODUCTION

This chapter presents guidelines for designing buildings for six climatic conditions of India from the perspective of energy conservation. The guidelines are presented in two parts for each climate. The first part provides general recommendations based on various aspects of building design as discussed in Chapters 2 and 3; the second part is more specific, dealing with particular building types, and is based on studies conducted using simulation tools explained in Chapter 4. The actual methodology adopted for developing the specific guidelines is discussed in section 5.3 of this chapter. Three types of buildings have been considered for the purpose: commercial, industrial and residential. The guidelines formulated are based on detailed thermal performance studies (also referred to as simulation studies) using the commercial software, TRNSYS (version 14.2) [1]. In order to establish confidence in the simulation results of TRNSYS, we have validated the predictions of this software in the following way. The room temperatures of different floors of a commercial building located in Mumbai city were measured for a week and then compared with the predictions of TRNSYS. Based on this comparison, the input parameters of the simulation tool were calibrated so that the maximum deviation of the prediction from the actual measurement was less than 5%, and the average deviation (over a 24 hour period) did not exceed 2% [2]. Having calibrated the simulation software predictions, various calculations were carried out to determine the heating and cooling load, and/or room temperatures of buildings. For example, it is important to know how much heat is being lost or gained from the various components of the building envelope (i.e., walls, roof, windows, etc.). What affects the building heating and cooling loads more – the building envelope or the internal gains? Is the top floor more comfortable than the ground or intermediate floors? And so forth. Based on the results, several parameters pertaining to building design and usage have been identified for improving the thermal performance of each building type, along with recommendations for energy conservation measures for the six climatic conditions of India. The cities of Jodhpur, Delhi, Mumbai, Pune, Srinagar and Leh (respectively representing hot and dry, composite, warm and humid, moderate, cold and cloudy, and cold and sunny) have been selected for the investigation. The building plans considered for this purpose are types that are commonly observed; they are briefly described in the following section. However, the recommendations are limited to these particular types of buildings, and may give incorrect results if applied blindly for other cases. The proposed design guidelines are to be used as a starting point for commencing design of other types of buildings. In such cases, we recommend that a simulation tool be used to ascertain the performance for best results

5.2 DESCRIPTION OF BUILDINGS

5.2.1 Commercial building

Commercial buildings use air-conditioning (AC) by mechanical means for providing thermally comfortable indoor conditions. This is mainly aimed at promoting productivity among occupants. However, the process is energy intensive and the running costs are generally very high. The monthly electricity bills of a typical commercial building can run into lakhs of rupees. The options for energy conservation are limited once a building is constructed, especially when aspects of optimal energy use have not been taken into account in building design. Considering that many such buildings are being constructed all over India, there is an urgent need to study their thermal behaviour and explore various means to reduce the AC load. We have analysed an existing commercial building in Mumbai for this purpose. The building has a basement and 8 floors (ground and 7 upper floors). A block plan and section of the building is shown in Fig. 5.1. The typical cross section of the roof, wall and floor are shown in Fig. 5.2. It is a reinforced cement concrete (RCC) framed structure with brick and concrete block infill panel walls. The building is rectangular with its longer axis oriented along the northwest and southeast direction. Most of the southwest, southeast, and northwest façades are glazed. The southwest façade is fully glazed with reflective coating on the glass panels. The circulation spaces such as the lift lobbies and staircases are located on the north side of the building. While most of the spaces are open plan offices, cabins are located on the periphery of the building and are separated from the main office hall by means of glass partitions. Most of the building is generally occupied only during the daytime on weekdays. The ground, second and third floors are occupied for 24 hours throughout the week including Saturdays, Sundays and national holidays. The total built-up area of the building including the circulation and service areas (but excluding the basement) is approximately 7074 m^2. Out of this area, about 5400 m^2 of carpet area is centrally air-conditioned. The first to seventh floors are fully air-conditioned whereas the ground and basement are partly air-conditioned. All floors have an air change rate of one per hour except for the ground floor where it is 5 per hour. A higher air change rate is specified on the ground floor as it is used for loading and unloading of materials, entailing frequent opening of large doors at the two ends of the building. These assumptions are based on the calibration of the simulation software TRNSYS (section 5.1). The upper floors are provided with false ceiling to conceal service ducts and reduce cooling loads. Lighting is provided mostly by fluorescent tube-lights. On a regular weekday, about 560 people occupy the building. The internal load is due to the convective load (gain due to occupants and equipment) and radiative load (lighting). A building automation system has been provided to control the air-conditioning system. The occupancy and the internal gains have been appropriately scheduled for all zones. The heat storage capacities of furnishings and structures in the building have also been considered.

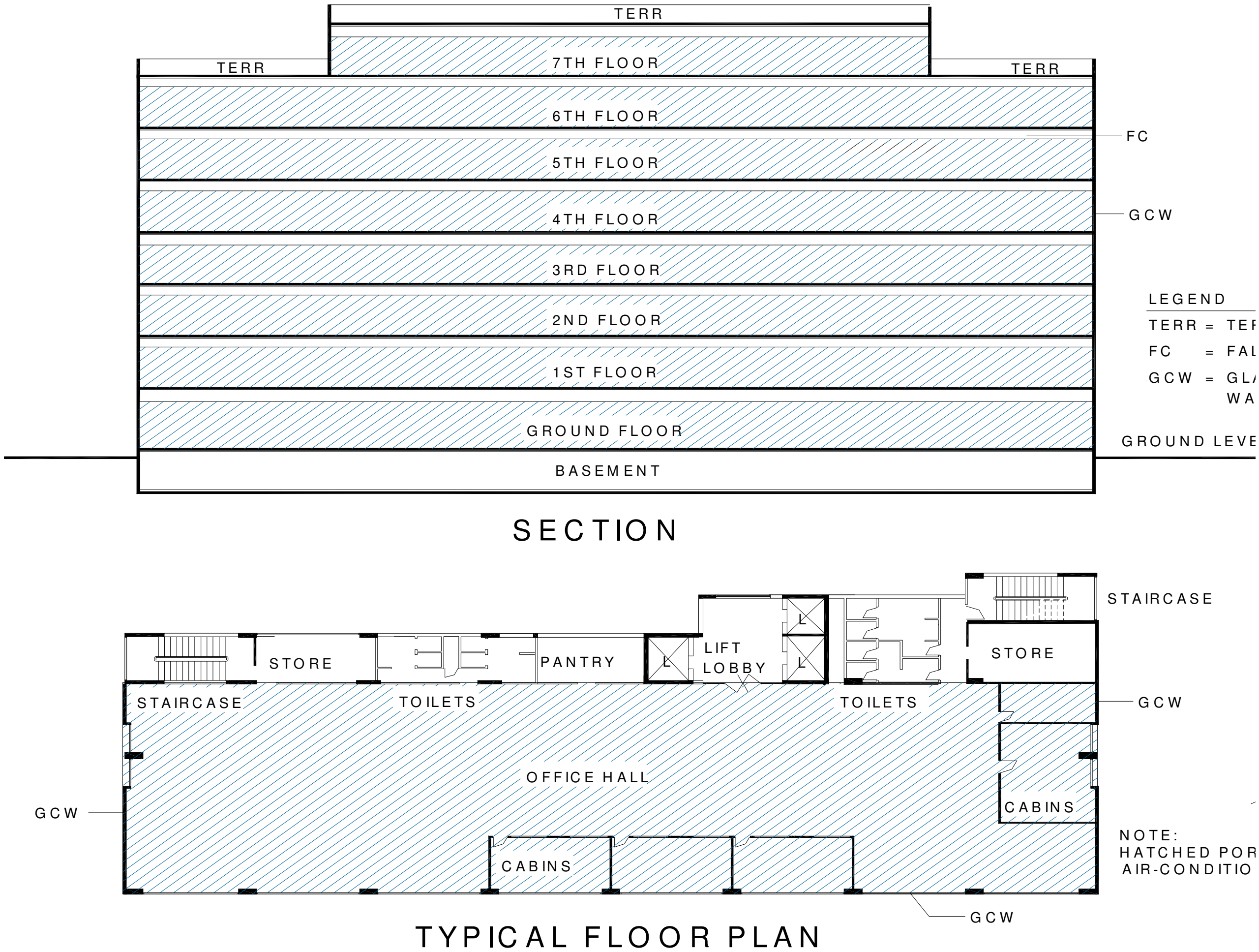


Fig. 5.1 Block plan and section of the commercial building

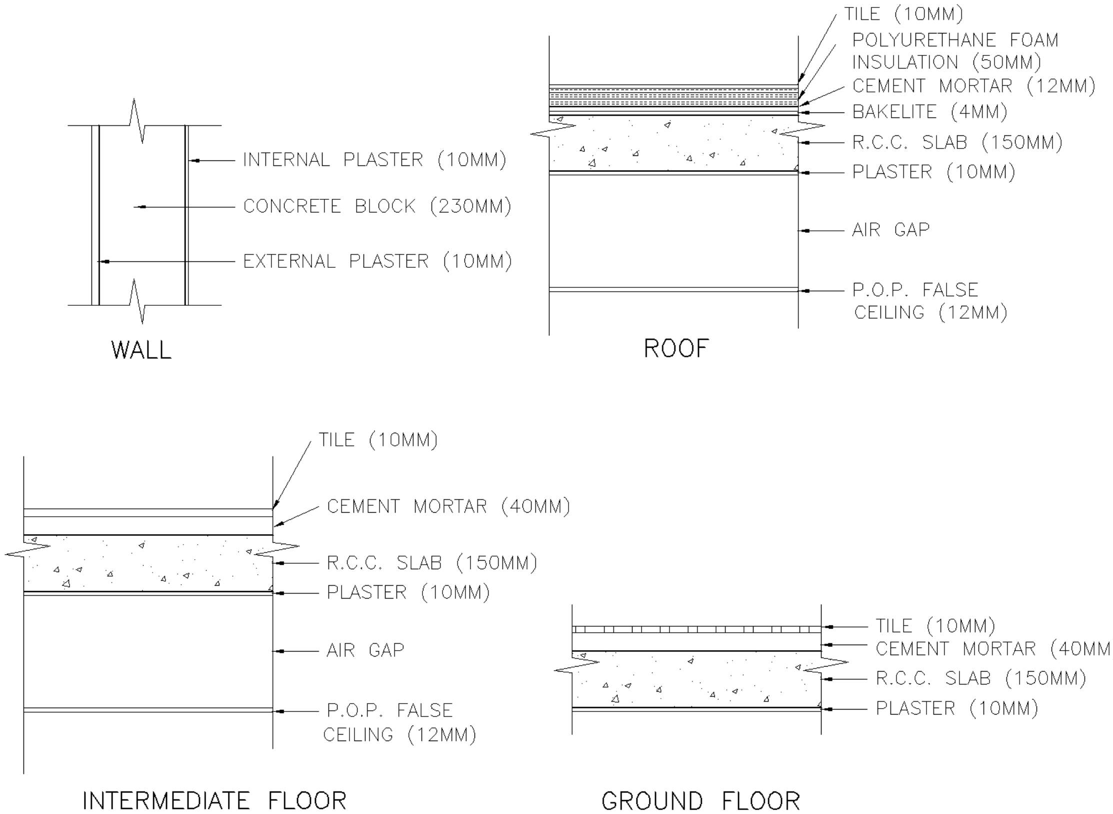
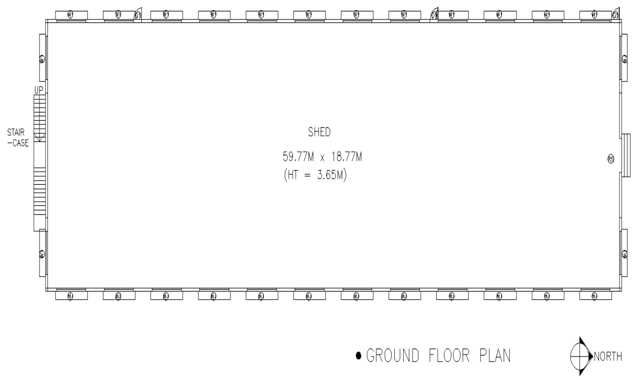


Fig. 5.2 Cross section of typical wall, roof and floor of the commercial building

5.2.2 Industrial Building

An existing industrial building in Daman (Union Territory) has been the subject of study. A block plan of the building is shown in Fig. 5.3. The building is a ground and partly one storeyed structure. It is an RCC framed structure with brick infill panel walls. The cross-sectional details of the roof, wall and floor are shown in Fig. 5.4. Most of the south, east, and west façades are glazed. The building is rectangular, having its longer axis oriented along the north-south direction with most of the windows facing east and west. It consists of a large shed (59.77m X 18.77m) on the ground floor and a smaller store room (9.77m X 18.77m) on the first floor. The height of the shed is 3.65m and that of the store is 3.05m. The flat roof is made of RCC slabs with brick-bat-coba waterproofing on top. The shed houses 24 machines of rated capacity of 7.5 kW each. It is considered that at a time, 50% of the machines are in operation. 45 persons work for six days a week. There are 80 tube lights of 40W each in the shed to provide illumination. The store is considered to be occupied by a single person. Occupancy, equipment and lighting are considered to be ON for 24 hours on each working day. Windows are provided as per factory standards, i.e. 20% of floor area to provide sufficient light and ventilation. The occupancy and the internal gains have been appropriately scheduled for all zones. The heat storage capacities of furnishings and structures in the building have also been considered.



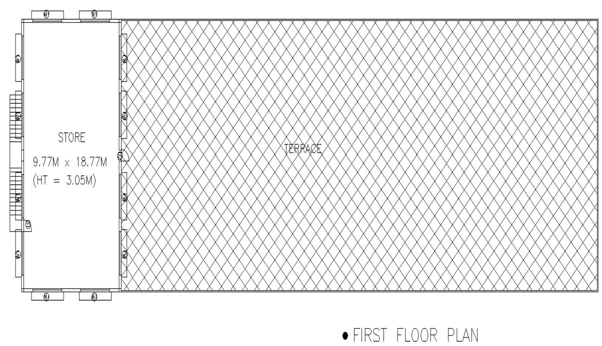


Fig. 5.3 Block plans of the industrial shed

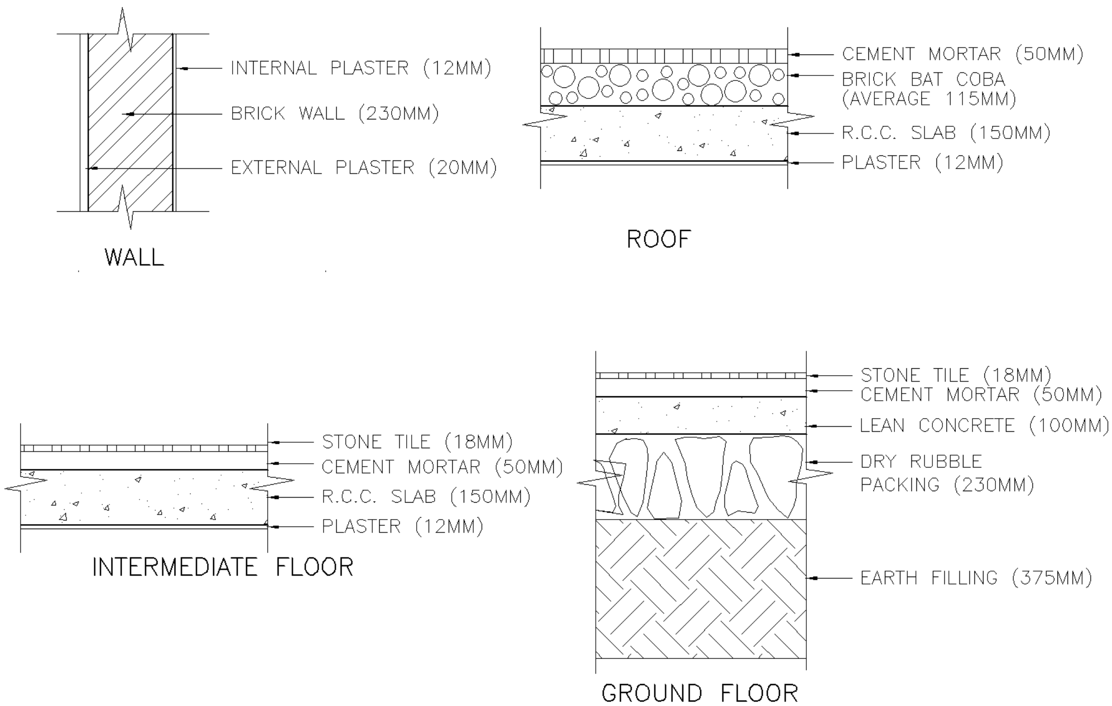


Fig. 5.4 Cross section of typical wall, roof and floor of the industrial building and residential bungalow

5.2.3 Residential Building (Bungalow)

The building considered under this category is a ground and one storeyed structure. It is a single family dwelling commonly referred to as a bungalow. The construction details are similar to those of the industrial building as shown in Fig. 5.4. The block plans of the building are given in Fig. 5.5. The building is an RCC structure with brick infill panel walls. Windows consist of single clear glazed panes and are openable. The total built-up area of the building is about 288 m^2 (145 m^2 on ground and 143 m^2 on the first floor). It is a rectangular structure with its longer axis along the east-west direction. The ground floor consists of a common living and dining hall, which is partly of double height; the kitchen and stores are on the east side, and there is a master bedroom wth attached toilet on the northwest corner. Most of the living-dining area faces south; the dining portion faces north. A circular open-well staircase on the south side connects the ground floor with the first. It is considered to be part of the living-dining area. The first floor consists of four bedrooms with attached toilets. Three bedrooms are located on the northeast, southeast and northwest corners of the building with windows on the adjacent external walls. Thus, there is good potential for cross ventilation in these rooms. The fourth bedroom has only one external wall facing north. There is an open family room on the southwest corner. This space is contiguous with that of the living-dining area on the ground floor as there is free exchange of air. Hence, the living-dining area on ground floor and the

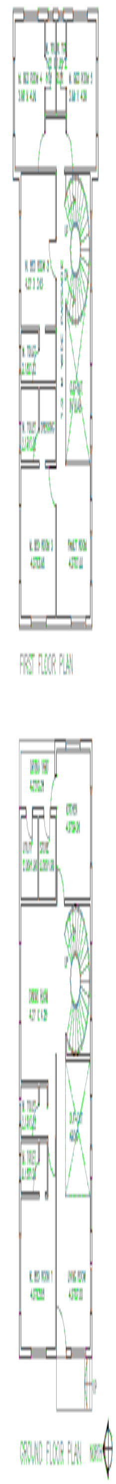


Fig. 5.5 Block plans of the bungalow

family area including circulation areas are considered as a single thermal zone. The bedrooms are assumed to be occupied only at nights on weekdays. On weekends, they are occupied in the afternoon hours as well. Two occupants, a television, a fan and a tubelight are considered for the internal gains of the bedroom whenever it is occupied. The kitchen is occupied by a single person during breakfast, lunch and dinner times. A hotplate, a tubelight and a fan are considered as internal gains when occupied. In addition, a refrigerator is assumed to be working throughout the day. The living room is considered to be occupied by a maximum of 5 persons during mealtimes and for a few hours on weekdays. On weekends, this room is considered to be used for a longer period. The internal gains in this room are due to the occupants, 4 fans, 8 tubelights and a television. The occupancy and the internal gains have been appropriately scheduled for all zones. The heat storage capacities of furnishings and structures in the room have also been considered.

5.3 METHODOLOGY

The performance studies of the buildings were carried out using TRNSYS. The weather data for the calculations have been taken from handbooks [3,4]. The methodology adopted was based on two assumptions, namely, (i) the building is conditioned and (ii) the building is not conditioned. The commercial building has been considered to be conditioned and the industrial building, not conditioned. The residential building has been investigated under both conditions. Comfort requirements are stringent in the conditioned commercial building, hence set points for heating and cooling were taken as 21 and 24°C respectively. For the conditioned bungalow, however, they were relaxed to 20°C for heating and 25°C for cooling. For the ground floor of the commercial building, the corresponding values were 19 and 26°C. This is because the ground floor is used for loading and unloading of materials and hence, the shutters are opened more frequently to ambient conditions. The monthly as well as annual cooling and heating loads for each building type and for each of the six cities mentioned earlier, are presented graphically. The share of loads through various building components is also given. The components are: (i) surfaces: heat transfer from all surfaces to the room air, (ii) air exchanges: the heat transfer caused by air exchanges, and (iii) internal gain: the convective heat gains due to metabolic heat released by occupants and that released by equipment and lights. The percentage-wise heat gains and losses due to the components on a monthly basis are presented graphically for easier interpretation. It may be noted that the percentage values are based on absolute numbers.

In the case of non-conditioned buildings, the room temperatures have been calculated. From these, the yearly minimum, maximum and average temperatures of each room are used for comparison. Additionally, two other performance indicators have been used for comparison. One of them is the percentage of hours in a year that each room is within the comfortable temperature range. This range is based on the monthly adaptive comfort temperature (ACT) of a place [5], which is defined as:

$$ACT = 16.2 + 0.41\, T_m \tag{5.1}$$

where, T_m is the monthly mean ambient dry bulb temperature. For annual percentage, the lower limit of the range is ACT-2.2°C for the coldest month of the place, and the upper limit is ACT+2.2°C for the hottest month of the place.

The other parameter used for comparison of non-conditioned buildings is the comfort fraction i.e. CF, which is defined as [5]:

$$CF = 1 - \text{Discomfort Degree Hours} / 105.6 \quad (5.2)$$

where, discomfort degree hours (DDH) is the sum of the hourly room air temperatures outside the comfort zone defined by ACT ± 2.2 °C.

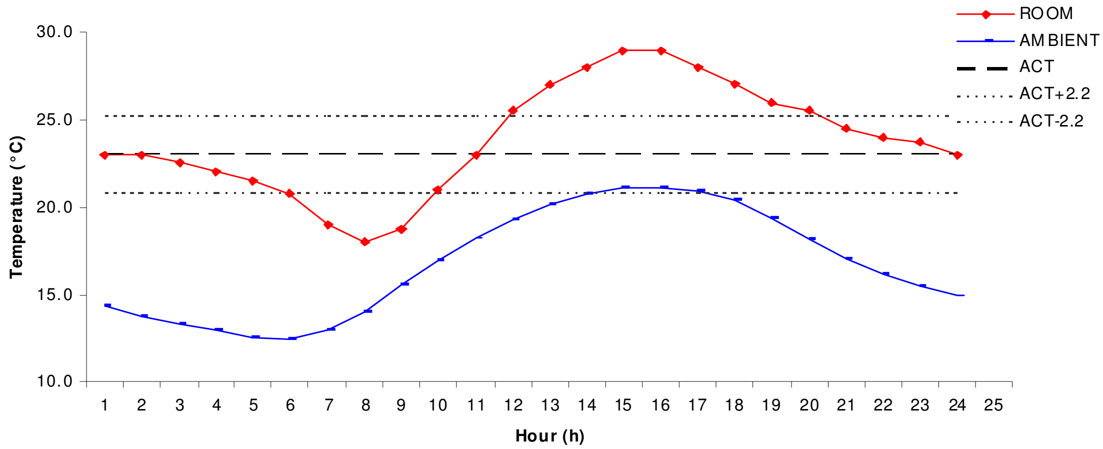
The procedure for calculation of the comfort fraction is explained as follows:

- Calculate monthly ACT from Eq. 5.1 and plot ACT ± 2.2 °C against the hour of the day. The zone defined by ACT ± 2.2 °C is called as comfort zone. (Figure 5.6 shows an example).
- Find out the hourly room air temperature for the average day of the month and plot it in the same figure.
- Find out the deviations (absolute values) of room air temperatures from the comfort zone. (Values are tabulated along the side of the plot in Fig. 5.6 for the example case).
- The sum of these values are the discomfort degree hours.
- Calculate the comfort fraction using Eq. 5.2.

The maximum value of CF is 1, which means quite comfortable. A negative value of CF indicates acute discomfort. On the other hand, a value approaching 1 indicates comfort.

The graphs for hourly variation of room temperatures for a typical day of January and that of May representing winter and summer months respectively, are also presented along with the corresponding ambient temperature and comfort zone. This provides a direct comparison of room conditions vis-à-vis ambient along with the comfort requirements (based on ACT).

Following this methodology, the results have been generated both for conditioned and non-conditioned buildings. Such results have been grouped as "base case studies". The parameters considered for the base case are listed in Table 5.1 for all the three buildings. In order to ascertain the effects of various design and operational parameters on the thermal performance of a building, parametric studies have been carried out. The design parameters include building orientation, window area, window types, shading, roof types, wall-types and colour of external surfaces. The operational parameters include air change rate with its scheduling effect, internal gain and set points (in conditioned building), etc. In the commercial building, the scheduling of air changes has been carried out on all floors except the ground floor. This is because ground floor doors are frequently opened and closed due to user requirements. Hence, controlling air change rates at specific times would be difficult in practice. The effect of window area was investigated only in the case of commercial building; the base case of this building refers to the design where the window height is of full height, extending from ceiling to the floor. The effect of reducing its size to 1.2 m was studied. The window types include plain glass, single reflective coated glass, double glazing, double glazing with one pane of low-emissivity (low-E) glass and double glazing with one pane of reflective coated glass. Shadings of 10, 20 and 50 % of window area for the commercial building and bungalow, and 10 and 20 % for the industrial building were considered. The apartment building has horizontal overhangs on the windows; the effect of the absence of the overhangs (i.e., no-shading) is investigated for this building. The roof types include RCC roof with brick-bat-coba waterproofing, plain RCC roof with bitumen felt



TIME (h)	TEMPERATURE (°C)					DDH
	ROOM	AMBIENT	ACT	ACT+2.2	ACT-2.2	
1	23.0	14.3	23.1	25.3	20.9	0.0
2	23.0	13.8	23.1	25.3	20.9	0.0
3	22.5	13.3	23.1	25.3	20.9	0.0
4	22.0	12.9	23.1	25.3	20.9	0.0
5	21.5	12.6	23.1	25.3	20.9	0.0
6	20.8	12.5	23.1	25.3	20.9	0.1
7	19.0	12.9	23.1	25.3	20.9	1.9
8	18.0	14.1	23.1	25.3	20.9	2.9
9	18.7	15.6	23.1	25.3	20.9	2.2
10	21.0	17.0	23.1	25.3	20.9	0.0
11	23.0	18.2	23.1	25.3	20.9	0.0
12	25.5	19.3	23.1	25.3	20.9	0.2
13	27.0	20.2	23.1	25.3	20.9	1.7
14	28.0	20.8	23.1	25.3	20.9	2.7
15	29.0	21.1	23.1	25.3	20.9	3.7
16	29.0	21.2	23.1	25.3	20.9	3.7
17	28.0	21.0	23.1	25.3	20.9	2.7
18	27.0	20.4	23.1	25.3	20.9	1.8
19	26.0	19.4	23.1	25.3	20.9	0.7
20	25.5	18.2	23.1	25.3	20.9	0.2
21	24.5	17.0	23.1	25.3	20.9	0.0
22	24.0	16.2	23.1	25.3	20.9	0.0
23	23.7	15.5	23.1	25.3	20.9	0.0
24	23.0	14.9	23.1	25.3	20.9	0.0
				SUM DDH =		24.6

Average monthly temperature (Tm)= 16.8 °C

ACT = **23.1** °C
CF = **0.8**

DDH = Discomfort Degree Hours

Fig. 5.6 Example of calculation of Adaptive Comfort Temperature (ACT) and Comfort Fraction (CF)

Table 5.1 Parameters of base case

Parameters		Commercial building	Industrial building	Bungalow
Glazing type		Reflective coated (single pane)	Clear glass (single pane)	Clear glass (single pane)
Roof type		RCC with brick-bat-coba waterproofing	RCC with brick-bat-coba waterproofing	RCC with brick-bat-coba waterproofing
Wall type		Concrete block wall	Brick	Brick
Colour of external surface		White	Brick red	Brick red
Air exchange rate (ach)		5.0 (ground floor) 1.0 (Rest floors)	6.0	Conditioned: 0.5 (Srinagar & Leh) 1.0 (other places) Non-conditioned: 1.5 (Srinagar) 0.5 (Leh) 3.0 (other places)
Building orientation (longer axis)		Northwest-southeast	North-south	East-west
Set point (ºC)	Heating	19 (Ground floor) 21 (Rest floors)	–	20
	Cooling	26 (Ground floor) 24 (Rest floors)	–	25
Shading		No shading	No shading	No shading

waterproofing and RCC roof with polyurethane foam (PUF) insulation. The wall types considered were brick wall, concrete block wall, autoclaved cellular concrete block wall (e.g. Siporex) and brick wall with expanded polystyrene insulation. Four colours, namely, white, cream, brick red (puff shade) and dark grey were considered for the external wall surfaces. Table 5.2 lists various options investigated for different cases. It also lists the variations studied for air change rates, internal gain, orientation and set points. The results of the parametric studies are presented in tabular form for each building type for each of the six cities. The effects of the various parameters are compared vis-à-vis the base case. In the conditioned buildings, the energy saved annually is presented in terms of loads (MJ) and percentage savings (%). A positive value indicates a saving whereas a negative value shows that the base case is better. In non-conditioned buildings, the results are presented in terms of the number of comfortable hours in a year. This is also presented as a percentage improvement over the base case. A positive percentage value means an increase in number of comfortable hours with respect to the base case. A negative value indicates that the number of comfortable hours has reduced.

Based on these predictions, specific recommendations are made for each building type, for each of the six climates vis-à-vis their design and operational parameters. Additionally, this information has been summarised in tabular form at the end of this chapter (under section 5.6) for the reader's convenience and for quick reference. From the study of individual parameters, the best condition is identified and the combined effects of such parameters (excluding building orientation and internal gain) are investigated. This result is termed as the "best case". In addition to design and operational parameters listed in Table 5.2, the roof surface evaporative cooling technique has been evaluated for two building types in warm climates (Jodhpur, Mumbai, Pune and New Delhi). The performance results for these building types (industrial and residential bungalow) are presented in Appendix V.1.

The commercial building investigated has large internal gains, a fact that has a significant bearing on the performance of the building. Therefore, the parametric performance of this building with zero internal gains was also investigated. Appendix V.2 presents the results of such calculations for a composite climate (New Delhi).

5.4 GENERAL RECOMMENDATIONS

The general recommendations based on climatic requirements are discussed in this section. These are applicable to almost all types of building designs.

5.4.1 Hot and Dry Climate

The hot and dry climate is characterised by very high radiation levels and ambient temperatures, accompanied by low relative humidity. Therefore, it is desirable to keep the heat out of the building, and if possible, increase the humidity level. The design objectives accordingly are:

(A) Resist heat gain by:

- Decreasing the exposed surface
- Increasing the thermal resistance
- Increasing the thermal capacity
- Increasing the buffer spaces
- Decreasing the air-exchange rate during daytime
- Increasing the shading

Table 5.2 Parameters investigated

Building type	Design parameters							Operational parameters		
	Glazing type	Wall type	Colour of external surface	Roof type	Building Orientation	Air exchange* (ach)	Shading (% of window area)	Internal gain (% of base case)	Set point (°C)	
									cooling	heating
Commercial**	A	concrete block wall, Autoclaved cellular concrete block wall	White, Dark Grey	RCC with brick-bat-coba waterproofing	Northwest-southeast; East-west; North-south; Northeast-southwest	0.5, 1.0, 2.0, 4.0	0, 10, 20, 50	0, 10, 50	24 25	21 20
Industrial	A	B	C	D	Northwest-southeast; East-west, North-south; Northeast-southwest	3.0, 6.0, 9.0, 12.0	0, 10, 20	20, 40	----	-----
Bungalow (Conditioned)	A	B	C	D	East-west; North-south	0.5, 1.5	0, 10, 20, 50	0, 50	25 26	20 19
Bungalow (Non-conditioned)	A	B	C	D	East-west; North-south	0.5, 1.5, 3.0+, 6.0+, 9.0+	0, 10, 20, 50	0, 50	----	------

A	B	C	D
Single pane clear glass	Brick wall	Brick Red	RCC with brick-bat-coba waterproofing
Single pane reflective coated glass	Brick wall with expanded polystyrene insulation (inner side)	White	RCC with Bitumen felt water proofing
Double pane clear glass	Autoclaved cellular concrete block wall	Cream	RCC with polyurethane foam insulation
Double pane reflective coated glass	Concrete block wall	Dark Grey	
Double pane low-E glass			

***Scheduling of air exchanges are considered for all buildings (promoting air exchanges when ambient air is comfortable compared to room air)**
**** Reduction of window height to 1.2 m in place of fully glazed curtain walls considered as an additional parameter for the commercial building**
+ Not considered for Srinagar and Leh

(B) Promote heat loss by:

- **(a)** Ventilation of appliances
- **(b)** Increasing the air exchange rate during cooler parts of the day or night-time
- **(c)** Evaporative cooling (e.g. roof surface evaporative cooling)
- **(d)** Earth coupling (e.g. earth-air pipe system)

The general recommendations for the climate are summarised as follows:

(1) Site

(a) Landform: Regions in this zone are generally flat, hence the surrounding areas tend to heat up uniformly. In case of an undulating site, constructing on the leeward side of the slope is preferred so that the effect of hot dusty winds is reduced. In case ventilation is assured, then building in a depression is preferable as cool air tends to sink in valleys (Fig. 5.7).

(b) Waterbodies: Waterbodies such as ponds and lakes not only act as heat sinks, but can also be used for evaporative cooling. Hot air blowing over water gets cooled which can then be allowed to enter the building. Fountains and water cascades in the vicinity of a building aid this process (Fig. 5.8 and 5.9).

(c) Street width and orientation: Streets must be narrow so that they cause mutual shading of buildings (Fig. 5.10). They need to be oriented in the north-south direction to block solar radiation.

(d) Open spaces and built form: Open spaces such as courtyards and atria are beneficial as they promote ventilation. In addition, they can be provided with ponds and fountains for evaporative cooling. Courtyards act as heat sinks during the day and radiate the heat back to the ambient at night. The size of the courtyards should be such that the mid-morning and the hot afternoon sun are avoided. Grass can be used as ground cover to absorb solar radiation and aid evaporative cooling (Fig. 5.11). Earth-coupled building (e.g. earth berming) can help lower the temperature and also deflect hot summer winds.

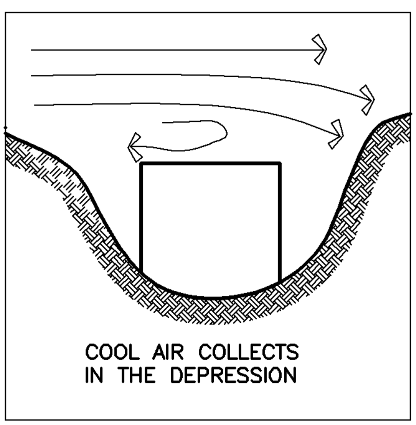


Fig. 5.7

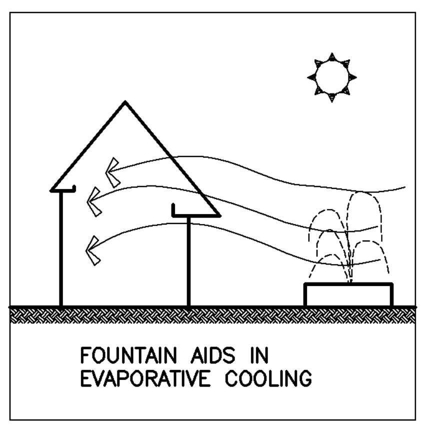
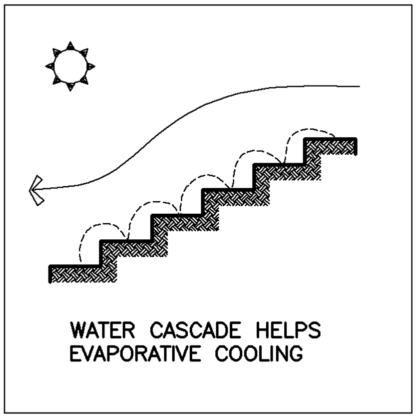


Fig. 5.8



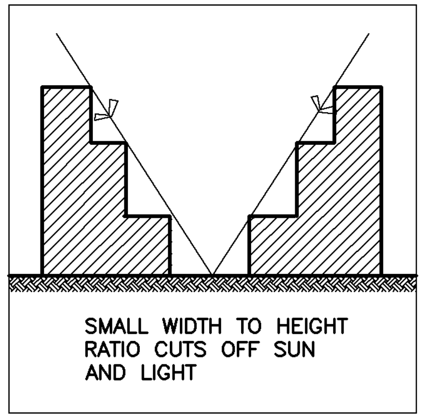
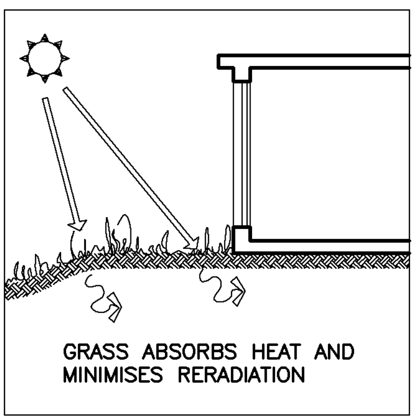


Fig. 5.9 **Fig. 5.10**

(2) Orientation and planform

An east-west orientation (i.e. longer axis along the east-west), (Fig. 5.12) should be preferred. This is due to the fact that south and north facing walls are easier to shade than east and west walls. It may be noted that during summer, it is the north wall which gets significant exposure to solar radiation in most parts of India, leading to very high temperatures in north-west rooms. For example, in Jodhpur, rooms facing north-west can attain a maximum temperature exceeding 38 ºC. Hence, shading of the north wall is imperative. The surface to volume (S/V) ratio should be kept as minimum as possible to reduce heat gains (Fig. 5.13). Cross-ventilation must be ensured at night as ambient temperatures during this period are low.



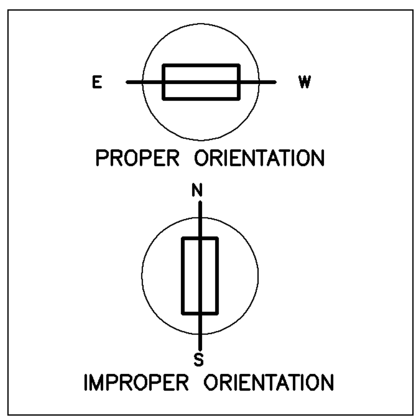


Fig. 5.11 **Fig. 5.12**

(3) Building envelope

(a) Roof: The diurnal range of temperature being large, the ambient night temperatures are about 10 ºC lower than the daytime values and are accompanied by cool breezes. Hence, flat roofs may be considered in this climate as they can be used for sleeping at night in summer as well as for daytime activities in winter. The material of the roof should be massive; a reinforced cement concrete (RCC) slab is preferred to asbestos cement (AC) sheet roof. External insulation in the form of mud phuska with inverted earthen pots is also suitable. A false ceiling in rooms having exposed roofs can help in reducing the discomfort level [6]. Sodha et al. [7] have reported that the provision of roof insulation yields greater lifecycle savings compared to walls in this climate. Evaporative cooling of the roof surface and night-time radiative cooling can also be employed. In case the former is used, it is better to use a roof having high thermal transmittance (a high U-value roof rather than one with lower U-value). The larger the roof area, the better is the cooling effect.

The maximum requirement of water per day for a place like Jodhpur is about 14.0 kg per square metre of roof area cooled. Spraying of water is preferable to an open roof pond system [7]. One may also consider of using a vaulted roof (Fig. 5.14) since it provides a larger surface area for heat loss compared to a flat roof.

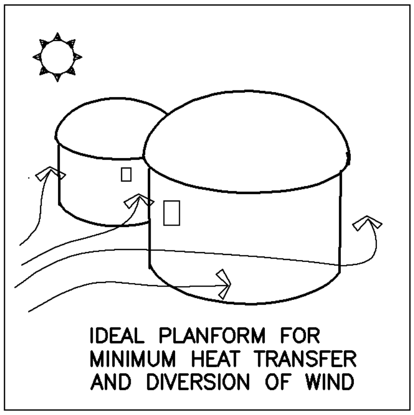


Fig. 5.13

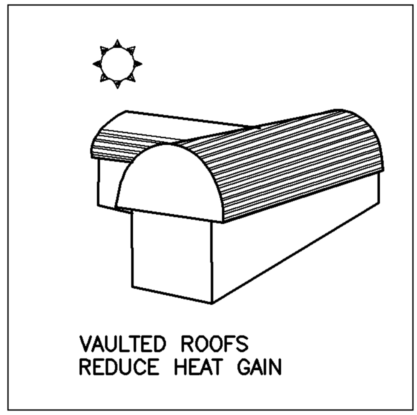


Fig. 5.14

(b) Walls: In multi-storeyed buildings, walls and glazing account for most of the heat gain. It is estimated that they contribute to about 80% of the annual cooling load of such buildings [6]. So, the control of heat gain through the walls by shading is an important consideration in building design. One can also use a wall with low U-value to reduce the heat gain. However, the effectiveness of such walls depends on the building type. For example, in a non-conditioned building, autoclaved cellular concrete block wall is not recommended; whereas it is desirable in a conditioned building.

(c) Fenestration:In hot and dry climates, minimising the window area (in terms of glazing) can definitely lead to lower indoor temperatures. It is found that providing a glazing size of 10% of the floor area gives better performance than that of 20% [6]. More windows should be provided in the north facade of the building as compared to the east, west and south as it receives lesser radiation during the year (Fig. 5.15). All openings should be protected from the sun by using external shading devices such as chajjas and fins (Fig. 5.16-5.17). Moveable shading devices such as curtains and venetian blinds can also be used. Openings are preferred at higher levels (ventilators) as they help in venting hot air. Since daytime temperatures are high during summer, the windows should be kept closed to keep the hot air out and opened during night-time to admit cooler air.

The use of 'jaalis'(lattice work) made of wood, stone or RCC may be considered as they allow ventilation while blocking solar radiation. Scheduling air changes (i.e. high air change rate at night and during cooler periods of the day, and lower ones during daytime) can

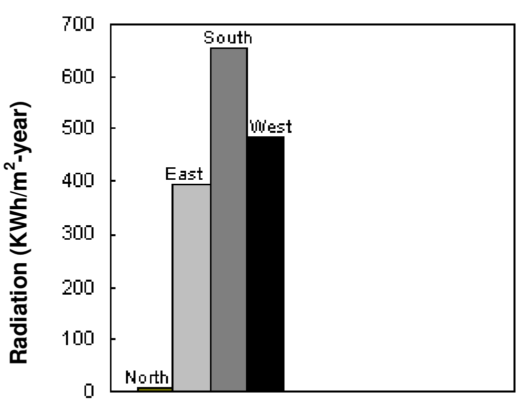


Fig. 5.15 Yearly beam radiation incident on an unshaded window (1.2m x 1.2 m)

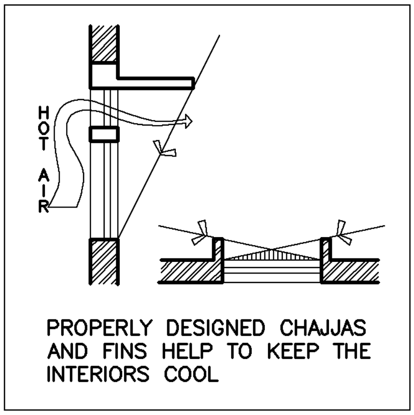


Fig. 5.16

Fig. 5.17

significantly help in reducing the discomfort. The heat gain through windows can be reduced by using glass with low transmissivity.

(a) Colour and texture: Change of colour is a cheap and effective technique for lowering indoor
temperatures. Colours having low absorptivity should be used to paint the external surface. Darker shades should be avoided for surfaces exposed to direct solar radiation. The surface of the roof can be of white broken glazed tiles (china mosaic flooring). The surface of the wall should preferably be textured to facilitate self shading.

***Remarks**:* As the winters in this region are uncomfortably cold, windows should be designed such that they encourage direct gain during this period. Deciduous trees can be used to shade the building during summer and admit sunlight during winter. There is a general tendency to think that well-insulated and very thick walls give a good thermal performance. This is true only if the glazing is kept to a minimum and windows are well-shaded, as is found in traditional architecture. However, in case of non-conditioned buildings, a combination of insulated walls and high percentage of glazing will lead to very uncomfortable indoor conditions. This is because the building will act like a green house or oven, as the insulated walls will prevent the radiation admitted through windows from escaping back to the environment. Indoor plants can be provided near the window, as they help in evaporative cooling and in absorbing solar radiation. Evaporative cooling and earth-air pipe systems can be used effectively in this climate. Desert coolers are extensively used in this climate, and if properly sized, they can alleviate discomfort by as much as 90% [7].

5.4.2 Warm and Humid Climate

The warm and humid climate is characterised by high temperatures accompanied by very high humidity leading to discomfort. Thus, cross ventilation is both desirable and essential. Protection from direct solar radiation should also be ensured by shading.

The main objectives of building design in this zone should be:

(A) Resist heat gain by:

(a) Decreasing exposed surface area

(b) Increasing thermal resistance

(c) Increasing buffer spaces

(d) Increasing shading

(e) Increasing reflectivity

(B) To promote heat loss by:

(a) Ventilation of appliances

(b) Increasing air exchange rate (ventilation) throughout the day

(c) Decreasing humidity levels

The general recommendations for building design in the warm and humid climate are as follows:

(1) Site

(a) Landform: The consideration of landform is immaterial for a flat site. However, if there are
slopes and depressions, then the building should be located on the windward side or crest to take advantage of cool breezes (Fig. 5.18).

(b) Waterbodies: Since humidity is high in these regions, water bodies are not essential.

(c) Open spaces and built form: Buildings should be spread out with large open spaces for unrestricted air movement (Fig. 5.19). In cities, buildings on stilts can promote ventilation and cause cooling at the ground level.

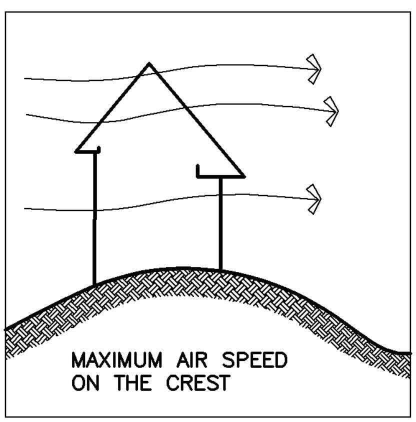


Fig. 5.18

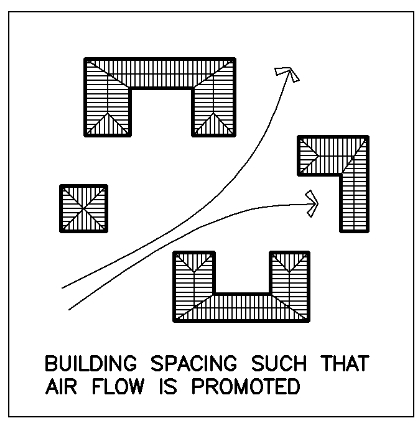


Fig. 5.19

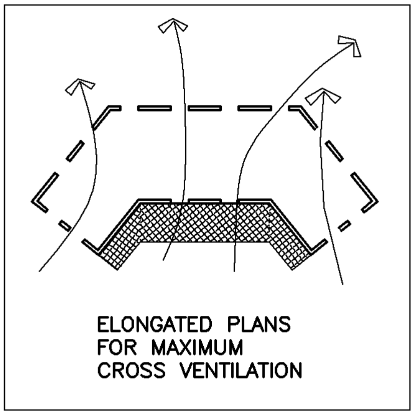


Fig. 5.20

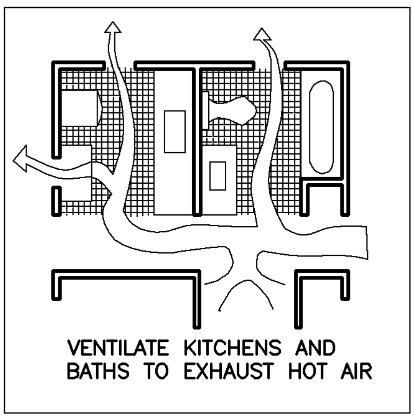


Fig. 5.21

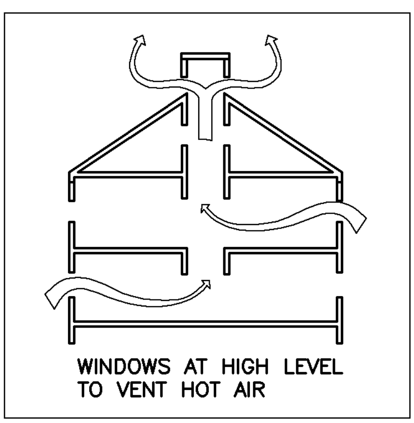


Fig. 5.22

(d) Street width and orientation: Major streets should be oriented parallel to or within 30º of the prevailing wind direction during summer months to encourage ventilation in warm and humid regions. A north-south direction is ideal from the point of view of blocking solar radiation. The width of the streets should be such that the intense solar radiation during late morning and early afternoon is avoided in summer.

(2) Orientation and planform

Since the temperatures are not excessive, free plans can be evolved as long as the house is under protective shade. An unobstructed air path through the interiors is important. The buildings could be long and narrow to allow cross-ventilation. For example, a singly loaded corridor plan (i.e. rooms on one side only) can be adopted instead of a doubly loaded one (Fig. 5.20). Heat and moisture producing areas must be ventilated and separated from the rest of the structure (Fig. 5.21) [8]. Since temperatures in the shade are not very high, semi-open spaces such as balconies, verandahs and porches can be used advantageously for daytime activities. Such spaces also give protection from rainfall. In multi-storeyed buildings a central courtyard can be provided with vents at higher levels to draw away the rising hot air (Fig. 5.22).

(3) Building envelope

(a) **Roof**: In addition to providing shelter from rain and heat, the form of the roof should be planned to promote air flow. Vents at the roof top effectively induce ventilation and draw hot air out (Fig. 5.23). As diurnal temperature variation is low, insulation does not provide any additional benefit for a normal reinforced cement concrete (RCC) roof in a non-conditioned building [6]. However, very thin roofs having low thermal mass, such as asbestos cement (AC) sheet roofing, do require insulation as they tend to rapidly radiate heat into the interiors during daytime. A double roof with a ventilated space in between can also be used to promote air flow.

(a) **Walls**: As with roofs, the walls must also be designed to promote air flow. Baffle walls, both inside and outside the building can help to divert the flow of wind inside (Fig. 5.24). They should be protected from the heavy rainfall prevalent in such areas. If adequately sheltered, exposed brick walls and mud plastered walls work very well by absorbing the humidity and helping the building to breathe. Again, as for roofs, insulation does not significantly improve the performance of a non-conditioned building [6].

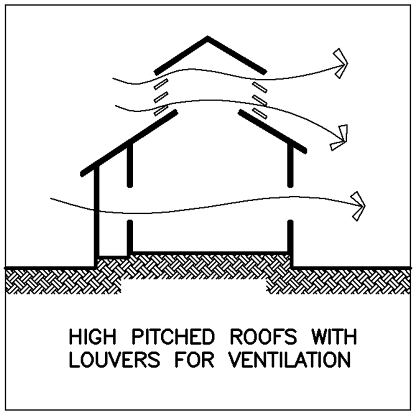


Fig. 5.23

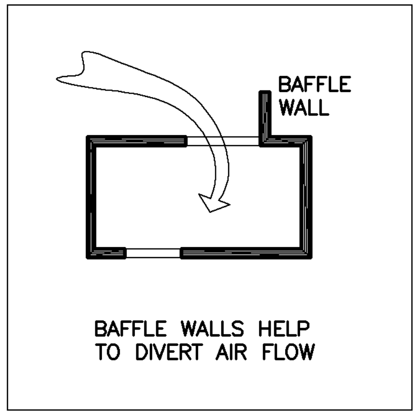


Fig. 5.24

(b) **Fenestration**: Cross-ventilation is important in the warm and humid regions. All doors and windows are preferably kept open for maximum ventilation for most of the year. These must be provided with venetian blinds or louvers to shelter the rooms from the sun and rain, as well as for the control of air movement [9]. Openings of a comparatively smaller size can be placed on the windward side, while the corresponding openings on the leeward side may be bigger for facilitating a plume effect for natural ventilation (Fig. 5.25). The openings should be shaded by external overhangs. Outlets at higher levels serve to vent hot air (Fig. 5.26). A few examples illustrating how the air movement within a room can be better distributed, are shown in Fig. 5.27 - 5.29.

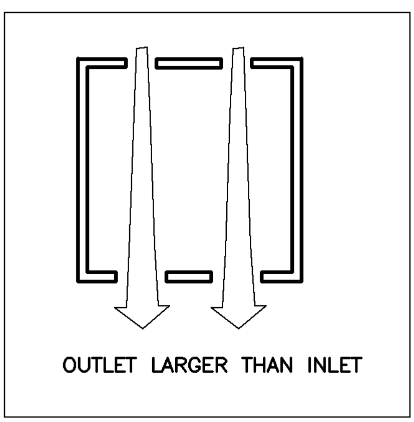


Fig. 5.25

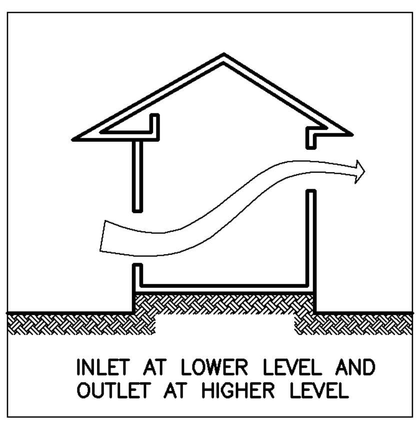


Fig. 5.26

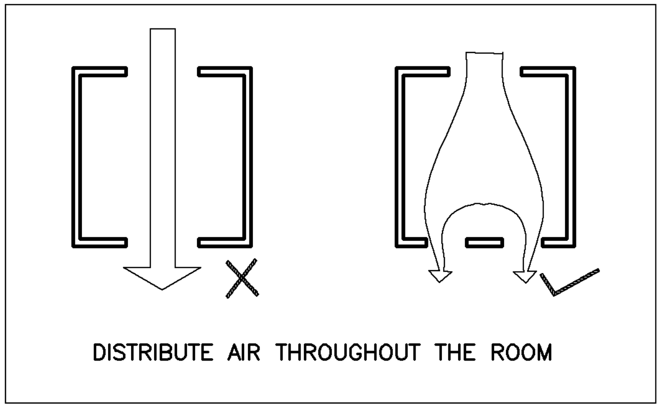


Fig. 5.27

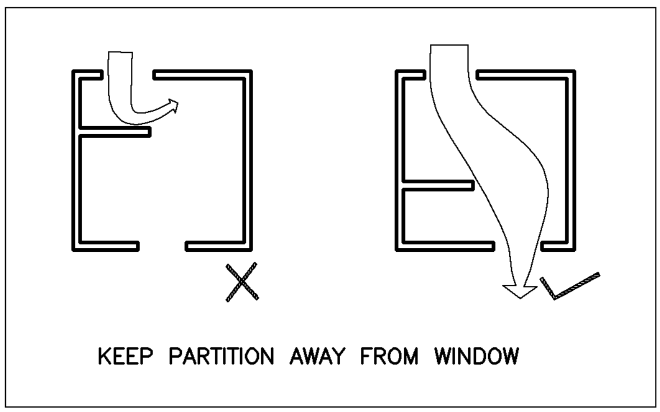


Fig. 5.28

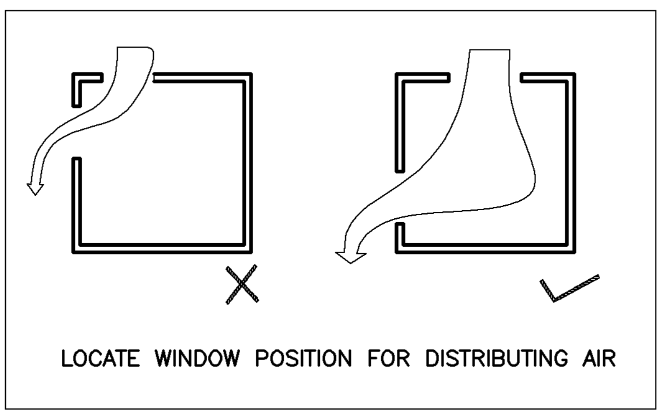


Fig. 5.29

(c) **Colour and texture**: The walls should be painted with light pastel shades or whitewashed, while the surface of the roof can be of broken glazed tile (china mosaic flooring). Both techniques help to reflect the sunlight back to the ambient, and hence reduce heat gain of the building. The use of appropriate colours and surface finishes is a cheap and very effective technique to lower indoor temperatures. It is worth mentioning that the surface finish should be protected from/ resistant to the effects of moisture, as this can otherwise lead to growth of mould and result in the decay of building elements.

Remarks: Ceiling fans are effective in reducing the level of discomfort in this type of climate. Desiccant cooling techniques can also be employed as they reduce the humidity level. Careful water proofing and drainage of water are essential considerations of building design due to heavy rainfall. In case of air-conditioned buildings, dehumidification plays a significant role in the design of the plant.

5.4.3 Moderate Climate

Temperatures are neither too high nor too low in regions with a moderate climate. Hence, simple techniques are normally adequate to take care of the heating and cooling requirements of the building. Techniques such as shading, cross ventilation, orientation, reflective glazing, etc. should be incorporated in the building. The thermal resistance and heat capacity of walls and roofs need not be high. These simple measures can reduce the number of uncomfortable hours in a building significantly. For example, in Pune, the 'uncomfortable' hours in a year can be reduced by as much as 89% by incorporating simple techniques in building design [6]. The room temperature can be brought within the comfort limit (i.e. less than 30 ºC) even in the month of May [6].

The main objectives while designing buildings in this zone should be:

(A) Resist heat gain by:

(a) Decreasing the exposed surface area
(b) Increasing the thermal resistance
(c) Increasing the shading

(B) Promote heat loss by:

(a) Ventilation of appliances
(b) Increasing the air exchange rate (ventilation)

In this region, the general recommendations are as follows:

(1) Site

(a) **Landform**: Building the structure on the windward slopes is preferable for getting cool Breezes (Fig. 5.30).
(b) **Open spaces and built form**: An open and free layout of the buildings is preferred. Large open spaces in the form of lawns can be provided to reduce reflected radiation.

.28

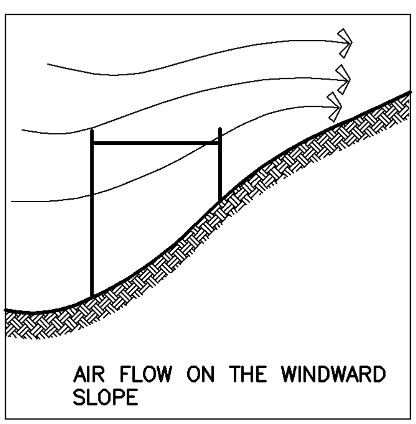


Fig. 5.30

(2) Orientation and planform

It is preferable to have a building oriented in the north-south direction. Bedrooms may be located on the eastern side, and an open porch on the south - southeast side, while the western side should ideally be well-shaded. Humidity producing areas must be isolated. Sunlight is desirable except in summer, so the depth of the interiors may not be excessive [10].

(3) Building envelope

(a) Roof: Insulating the roof does not make much of a difference in the moderate climate [6].
(b) Walls: Insulation of walls does not give significant improvement in the thermal performance of a building. A brick wall of 230 mm thickness is good enough [6].
(c) **Fenestration**: The arrangement of windows is important for reducing heat gain. Windows can be larger in the north, while those on the east, west and south should be smaller. All the windows should be shaded with chajjas of appropriate lengths. Glazing of low transmissivity should be used.
(d) **Colour and texture**: Pale colours are preferable; dark colours may be used only in recessed places protected from the summer sun.

5.4.4 Cold and Cloudy, and Cold and Sunny Climates

These regions experience very cold winters, hence, trapping and using the sun's heat whenever it is available, is of prime concern in building design. The internal heat should not be lost back to the ambient. The insulation of building elements and control of infiltration help in retaining the heat. Exposure to cold winds should also be minimized.

The main objectives while designing buildings in these zones are:

(A) Resist heat loss by:
(a) Decreasing the exposed surface area
(b) Increasing the thermal resistance
(c) Increasing the thermal capacity
(d) Increasing the buffer spaces
(e) Decreasing the air exchange rate

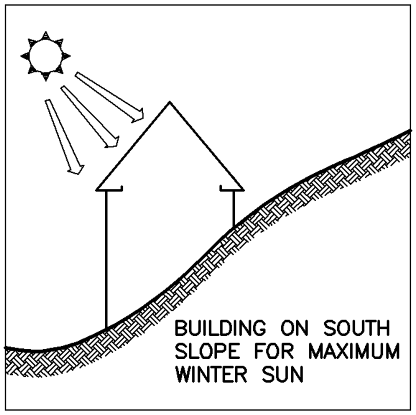
(B) Promote heat gain by:
(a) Avoiding excessive shading
(b) Utilising the heat from appliances
(c) Trapping the heat of the sun.

The general recommendations for regions with a cold and cloudy, or cold and sunny climate are given below.

(1) Site

(a) **Landform**: In cold climates, heat gain is desirable. Hence, buildings should be located on the south slope of a hill or mountain for better access to solar radiation (Fig. 5.31). At the same time, the exposure to cold winds can be minimised by locating the building on the leeward side. Parts of the site which offer natural wind barrier can be chosen for constructing a building.

(b) **Open spaces and built forms**: Buildings in cold climates should be clustered together to minimise exposure to cold winds (Fig. 5.32). Open spaces must be such that they allow maximum south sun. They should be treated with a hard and reflective surface so that they reflect solar radiation onto the building (Fig. 5.33).



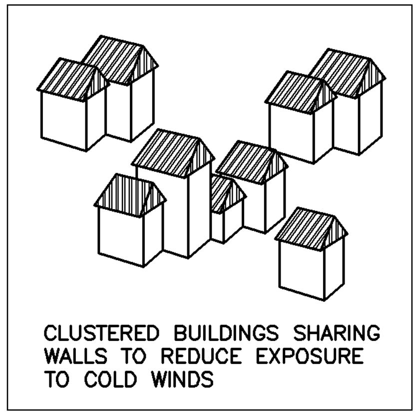
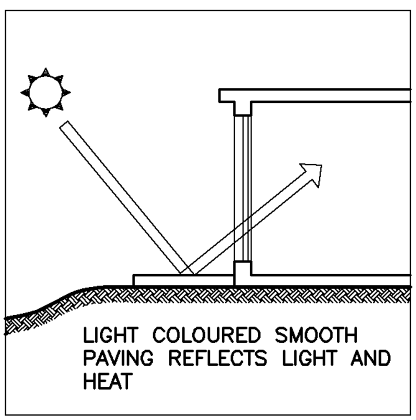


Fig. 5.31 **Fig. 5.32**

(c) **Street width and orientation**: In cold climates, the street orientation should be east-west to allow for maximum south sun to enter the building. The street should be wide enough to ensure that the buildings on one side do not shade those on the other side (i.e. solar access should be ensured) (Fig. 5.34).



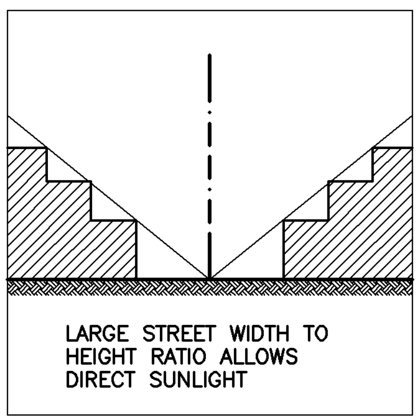


Fig. 5.33 **Fig. 5.34**

(2) Orientation and planform

In the cold zones, the buildings must be compact with small S/V ratios (Fig. 5.35). This is because the lesser the surface area, the lower is the heat loss from the building. Windows should preferably face south to encourage direct gain. The north side of the building should be well-insulated. Living areas can be located on the southern side while utility areas such as stores can be on the northern side. Air-lock lobbies at the entrance and exit points of the building reduce heat loss. The heat generated by appliances in rooms such as kitchens may be recycled to heat the other parts of the building.

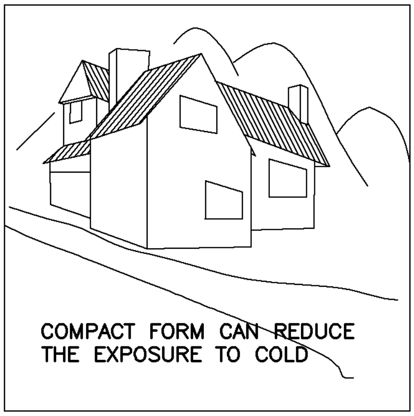


Fig. 5.35

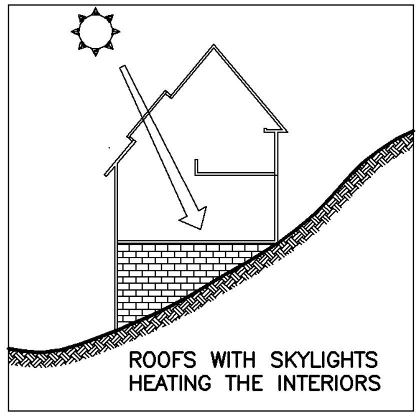


Fig. 5.36

(3) Building envelope

(a) **Roof**: False ceilings are a regular roof feature of houses in cold climates. One can also use internal insulation such as polyurethane foam (PUF), thermocol, wood wool, etc. An aluminium foil is generally used between the insulation layer and the roof to reduce heat loss to the exterior. A sufficiently sloping roof enables quick drainage of rain water and snow. A solar air collector can be incorporated on the south facing slope of the roof and hot air from it can be used for space heating purposes. Skylights on the roofs admit heat as well as light in winters (Fig. 5.36). The skylights can be provided with shutters to avoid over heating in summers.

(b) **Walls**: Walls should be of low U-value to resist heat loss. The south-facing walls (exposed to solar radiation) could be of high thermal capacity (such as Trombe wall) to store day time heat for later use. The walls should also be insulated. The insulation should have sufficient vapour barrier (such as two coats of bitumen, 300 to 600 gauge polyethylene sheet or aluminium foil) on the warm side to avoid condensation. Hollow and lightweight concrete blocks are also quite suitable [11]. On the windward or north side, a cavity wall type of construction may be adopted.

(c) **Fenestration**: It is advisable to have the maximum window area on the southern side of the building to facilitate direct heat gain. They should be sealed and preferably double glazed. Double glazing helps to avoid heat losses during winter nights. However, care should be taken to prevent condensation in the air space between the panes. Movable shades should be provided to prevent overheating in summers.

(d)Colour and texture: The external surfaces of the walls should be dark in colour for high absorptivity to facilitate heat gains.

5.4.5 Composite Climate

The composite climate displays the characteristics of hot and dry, warm and humid as well as cold climates. Designs here are guided by longer prevailing climatic conditions. The duration of 'uncomfortable' periods in each season has to be compared to derive an order of priorities. India being a tropical country, most of the design decisions would pertain to cooling. For example, the general recommendations for hot and dry climates would be applicable for New Delhi for most of the year except monsoon, when ventilation is essential.

5.5 SPECIFIC GUIDELINES

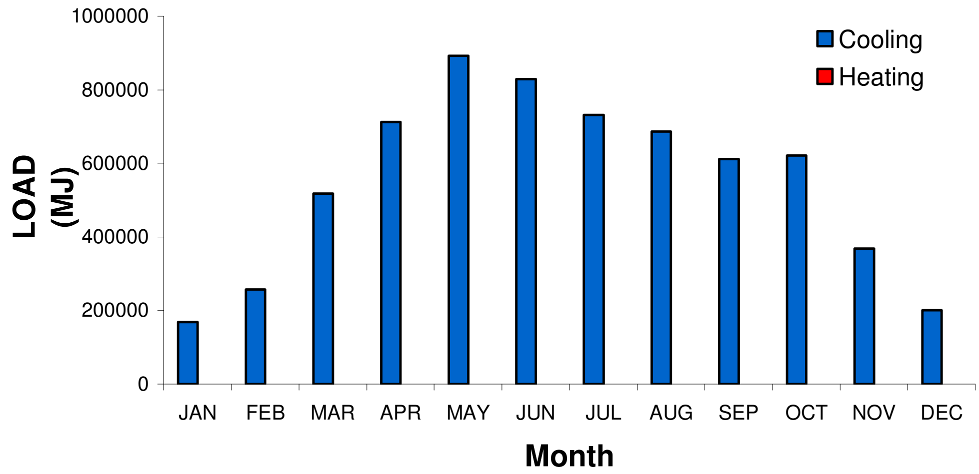
The specific guidelines for a commercial building (conditioned), an industrial building (non-conditioned) and a residential building (conditioned and non-conditioned) have been formulated based on simulation studies, and are discussed in this section.

5.5.1 Hot and Dry Climate (Representative city: Jodhpur)

5.5.1.1 Commercial Building

A large multi-storeyed building (Fig. 5.1) has been considered as an example of a commercial building; it is assumed to be centrally air-conditioned. Figure 5.37 presents the heating and cooling loads of the building on a monthly as well as annual basis for Jodhpur (hot and dry climate). The heating load is negligible whereas the cooling load is dominant, cooling being required throughout the year. The load profiles generally follow the climatic conditions; the highest cooling load occurs in summer (May), lower loads during monsoon (August and September) and the lowest loads in winter (December, January and February). The monthly variation of the percentage of loads through various building components is shown in Fig. 5.38. It is seen that the cooling requirement is primarily because of the heat gains from the surfaces and internal gains due to equipment and people. Thus, the building construction could be made more resistant to heat gain by choosing appropriate materials and paints, by shading external surfaces of the building, by reducing exposed glazing area, etc. Energy efficient equipment and lighting systems may be used to reduce the internal gains. Scheduling of air changes to promote air exchanges from November to February, when the ambient air is cooler and more comfortable compared to room air, would help to reduce the cooling loads. In summer months, air exchanges add to the cooling loads and hence need to be controlled.

Table 5.3 shows the floor-wise distribution of loads. It is seen that the usage pattern of the building has a significant impact on the loads. For instance, the energy required for cooling is maximum on the ground floor. This is because of the frequent opening of the shutters on ground floor, resulting in a high heat gain due to air exchanges. Besides, there is a significant internal gain due to operation of equipment and a high occupancy level. Similarly, the cooling loads of the second and third floors are significantly higher than those of other floors as they are occupied on a 24-hour basis throughout the week. The gain due to air exchanges may be reduced by preventing the leakage of hot ambient air from entering the building by sealing all cracks and providing air-lock lobbies on the ground floor.



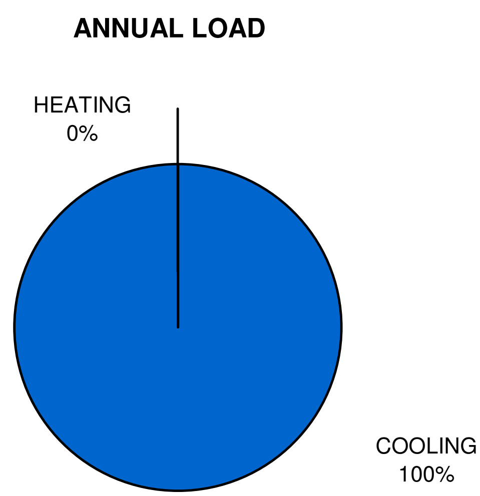


Fig. 5.37 Monthly and annual heating and cooling loads of the commercial building -Jodhpur (hot and dry climate)

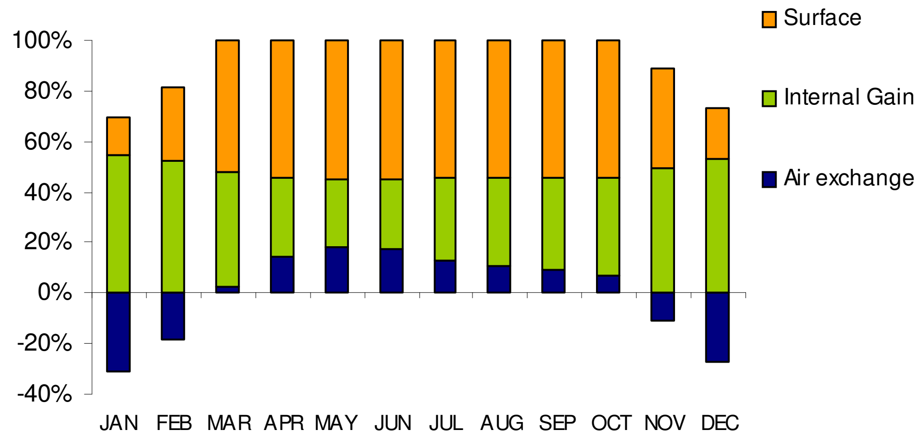


Fig. 5.38 Component-wise distribution of percentage heat gains and losses on a monthly basis of the commercial building- Jodhpur (hot and dry climate)

Table 5.3-Floorwise distribution of monthly and annual loads of the commercial building – Jodhpur (hot and dry climate)

Month	Cooling load (MJ)								
	GR	F1	F2	F3	F4	F5	F6	F7	Total
JAN	11044	23877	31676	32906	26290	15262	22024	5407	168486
FEB	33614	29955	46404	47009	32841	23368	31969	12660	257819
MAR	99715	47829	89831	91138	53215	45454	58930	31078	517190
APR	162474	57586	120609	123121	65744	61059	77418	45044	713055
MAY	208599	70259	148179	151518	81004	77330	97427	58629	892943
JUN	199222	62770	140774	144185	72729	69448	87696	52430	829255
JUL	166567	58184	124788	127597	67132	62433	79505	45738	731944
AUG	148625	57450	116923	119163	65656	59721	76557	43093	687189
SEP	135993	49582	107131	109458	56474	51120	65379	36736	611873
OCT	121739	55810	105610	107427	63100	56316	71415	39934	621350
NOV	53564	39640	65444	65913	43798	34396	44968	21124	368847
DEC	19623	25765	37659	38606	28286	18191	25204	8187	201521
Total	**1360779**	**578707**	**1135027**	**1158040**	**656269**	**574097**	**738493**	**400061**	**6601472**

Month	Heating load (MJ)								
	GR	F1	F2	F3	F4	F5	F6	F7	Total
JAN	0	0	0	0	0	0	0	64	64
FEB	0	0	0	0	0	0	0	0	0
MAR	0	0	0	0	0	0	0	0	0
APR	0	0	0	0	0	0	0	0	0
MAY	0	0	0	0	0	0	0	0	0
JUN	0	0	0	0	0	0	0	0	0
JUL	0	0	0	0	0	0	0	0	0
AUG	0	0	0	0	0	0	0	0	0
SEP	0	0	0	0	0	0	0	0	0
OCT	0	0	0	0	0	0	0	0	0
NOV	0	0	0	0	0	0	0	0	0
DEC	0	0	0	0	0	0	0	0	0
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**64**	**64**

GR=Ground Floor, F1=First floor, F2=Second floor, F3=Third Floor, F4=Fourth floor, F5=Fifth floor, F6=Sixth Floor, F7=Seventh floor

The effects of building parameters on the annual loads of the building are presented in Table 5.4. The consequent percentage load reduction for each parameter compared to the base case is also tabulated. It may be noted that the total annual load of the building is quite high. Even a one percent reduction in this load would result in significant energy savings. The following guidelines are recommended for a commercial building in a hot and dry climatic region like Jodhpur:

(a) Design Parameters

(i) Building orientation

Appropriate orientation of the building can reduce the annual load significantly. The building (Fig.5.1) with its glazed curtain wall facing northwest shows a substantial reduction in load compared to the southwest orientation (base case) – the percentage reduction being 9.4. The west and north orientations are also better than the base case.

(ii) Glazing type

Double glazing with reflective coated glass gives the best performance. It reduces the load by 2.1% compared to single pane reflective coated glass (base case). Single pane clear, double pane clear and double low-E glass increase the annual load by 10.1, 8.0 and 1.4% respectively and hence are not recommended.

(a) Window size

The reduction of the glazing size to a 1.2 m height compared to a fully glazed curtain wall decreases the annual load by 7.0%. This is due to the reduction in solar gain, and thus the use of larger expanses of glass in such a building is not desirable as it leads to higher annual loads.

(iv) Shading

The reduction in solar gain by shading of windows (by means of external projections such as chajjas) causes a decrease in the heat gain and hence the annual load is reduced. If 50% of the window areas are shaded throughout the year, the percentage load reduction is 9.2.

(v) Wall type

A wall having low U-value (insulating type such as autoclaved cellular concrete block) reduces the load compared to the concrete block wall (base case) by 2.1%. Thus, insulation of walls is recommended.

(vi) Colour of the external surface

Dark colours on the walls of such a commercial building should be avoided. For example, if dark grey is used, the percentage increase in load is 4.3 compared to a white surface (base case).

(vii) Air exchanges

A lower air change rate of 0.5 ach is preferable compared to 1, 2 and 4 ach. The percentage reduction in the annual load is 2.0 compared to the base case of 1 ach.

(b) Operational Parameters

The operational parameters such as internal gain, set point and scheduling of air changes can help in reducing the annual load of the building. The effects are summarised as follows.

(i) Internal gain

The lower the internal gain, the better is the performance of the building in reducing the annual load.

Table 5.4 Annual savings due to building design and operational parameters for the commercial building- Jodhpur (hot and dry climate)

Parameter	Annual load (MJ)			Energy saving	
	Cooling	Heating	Total	(MJ)	(%)
Base case	6601472	64	6601536	--	--
Orientation (longer axis)					
North-south	6088713	1850	6090563	510973	7.7
Northeast-southwest	5978737	1476	5980213	621323	9.4
East-west	6385516	389	6385905	215631	3.3
Glazing type					
Single clear	7269940	0	7269940	-668404	-10.1
Double clear	7128218	0	7128218	-526682	-8.0
Double low-E	6690662	0	6690662	-89126	-1.4
Double reflective coated	6465326	0	6465326	136210	2.1
Glazing size (restricted to 1.2m height)	6139193	14	6139207	462329	7.0
Shading					
10%	6479553	167	6479720	121816	1.8
20%	6357878	287	6358165	243371	3.7
50%	5995191	949	5996139	605397	9.2
Wall type					
Autoclaved cellular concrete	6460568	20	6460588	140948	2.1
Colour of external surface					
Dark grey	6883389	1	6883390	-281854	-4.3
Air exchange rate					
0.5	6469405	0	6469405	132131	2.0
2	6886651	1297	6887948	-286412	-4.3
4	7524210	28560	7552770	-951234	-14.4
Internal gain					
10%	3578640	25472	3604112	2997424	45.4
50%	4857419	1513	4858932	1742604	26.4
No internal gain	3278665	43330	3321995	3279541	49.7
Set point cooling: 25 °C heating: 20 °C	6161889	0	6161889	439647	6.7
Scheduling of air exchanges	6429115	15621	6444735	156801	2.4

(ii) Set Point

The annual load of the building reduces if the set points for comfort cooling and heating are relaxed. If the cooling and heating set points of 25 and 20^{0}C respectively are used (compared to 24 and 21^{0}C), the percentage reduction in annual load is 6.7. Thus, a change in the expectation of comfort can lead to significant savings.

(a) Scheduling of air exchanges

The scheduling of air changes to promote air entry during cooler periods (such as nights or winters) and controlling it during warmer periods (during daytime or summer) can lead to significant reduction of annual load – the percentage reduction being 2.4.

The combination of all design and operational parameters discussed (excluding building orientation and internal gain), results in a load reduction of 26.1 percent.

5.5.1.2 Industrial Building

Figure 5.3 shows the plan of an industrial building investigated for developing design guidelines. It is a non-conditioned building and hence indoor room temperatures are estimated. Table 5.5 presents the yearly minimum, maximum and average temperatures. It also shows the yearly comfortable hours, both in numbers as well as percentage, of the shed and store for the Jodhpur climate. It has been found that the maximum temperatures of the rooms (i.e. the shed on ground floor and store on first floor) can exceed 40 °C. The yearly average room temperature of the shed is 34.5 °C and is about 7.6 °C above the yearly average ambient temperature. Thus, the emphasis should be on cooling considerations. Overheating in the shed occurs due to high internal gains because of the operation of large machines, occupants, and lighting. The number of comfortable hours in a year does not exceed 35% for both the shed and the store. In other words, the shed and store are uncomfortable for more than 65% of the year.

Table 5.5 Performance of the industrial building on an annual basis- Jodhpur (hot and dry climate)

Room	Yearly room temperature (°C)			Comfortable hours in a year (h)	Percentage of yearly comfortable hours
	MIN	MAX	AVG		
Shed	22.0	45.1	34.5	3098	35
Store	17.1	40.2	30.2	4098	47
Ambient	11.4	40.3	26.9	4838	55

MIN = Minimum, MAX = Maximum, AVG = Average

Table 5.6 Performance of the industrial building on a monthly basis- Jodhpur (hot and dry climate)

Comfort index	Month	Room	
		Shed	Store
Comfort fraction	JAN	0.79	0.72
	FEB	0.56	0.91
	MAR	-0.06	0.80
	APR	-0.81	0.28
	MAY	-1.22	-0.15
	JUN	-1.19	-0.15
	JUL	-0.82	0.25
	AUG	0.02	0.19
	SEP	-0.54	0.54
	OCT	-0.36	0.66
	NOV	0.32	0.95
	DEC	0.72	0.80

Table 5.6 shows the monthly performance of the shed and store in terms of the comfort fraction. The shed is extremely uncomfortable from March to July, and from September to October. The store is relatively more comfortable during the same period. The hourly variation of room temperatures for a typical winter day of January and summer day of May are presented in Fig. 5.39 and 5.40 respectively. The figures show that in January, both the shed and the store are within or close to the comfort zone. The shed is mostly comfortable at night, while the store is mostly comfortable

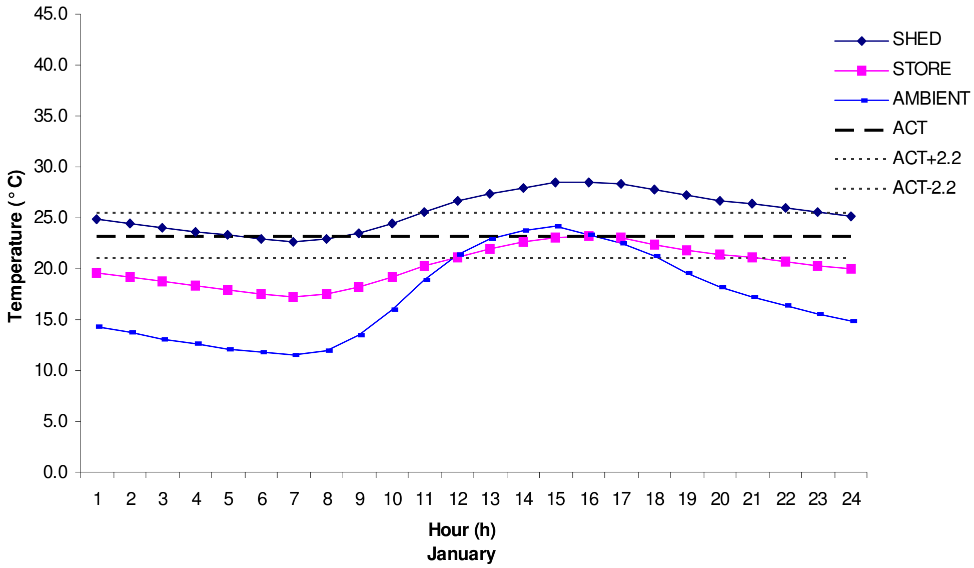


Fig. 5.39 Hourly variation of room temperatures of the industrial building in January - Jodhpur (hot and dry climate)

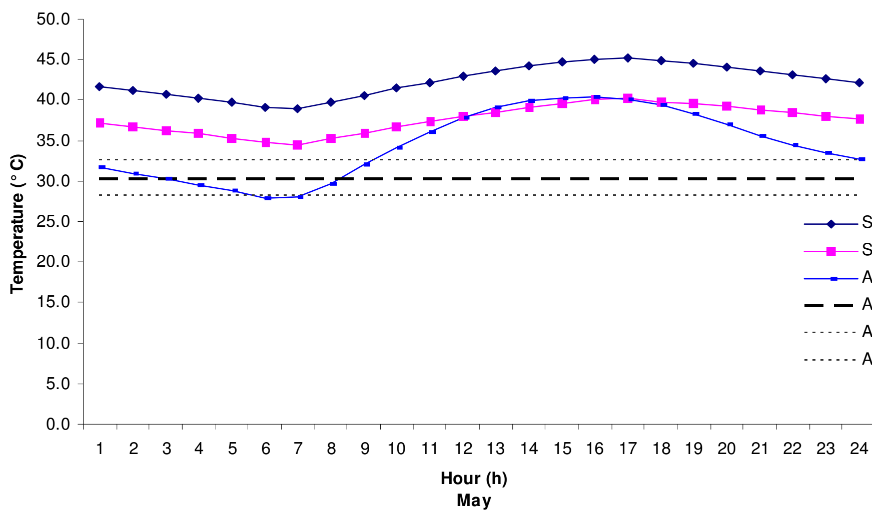


Fig. 5.40 Hourly variation of room temperatures of the industrial building in May - Jodhpur (hot and dry climate)

during daytime. In May, both the rooms are well above the comfort zone. The store temperature exceeds 35 °C almost throughout the day. The shed is even worse, with temperatures exceeding 40 °C and almost touching 45 °C. Thus both rooms are extremely hot in May. The main reason for such thermal behaviour of the building is because of its large internal gains due to equipment and occupancy level. The results show that cooling is a prime consideration for design. Comfortable conditions could be achieved by reducing heat gains and promoting heat loss. Heat gain from the building surfaces may be reduced by appropriate orientation, shading, glazing, colour, etc. Energy efficient equipment could be used for reducing the internal heat gains. Further, ventilation can promote heat loss during cooler periods (such as nights or winters) and control heat gain during warmer periods (during daytime or summers). Higher air change rates (compared to the base case of 6 ach) is recommended for all hours of the day in the summer months, and between 12 to 18 hours in the winter months (Fig. 5.39 and 5.40).

Table 5.7 presents the number of comfortable hours in a year due to various parameters for the shed. The corresponding percentage increase or decrease (-) in comfortable hours compared to the base case is also presented in the table.

(a) Design Parameters

(i) Building orientation

The building orientation has no significant because the building has substantial internal gains.

(ii) Glazing type

Single pane reflective coated glass is recommended over plain glass (base case) because it shows a marginal increase (about 3.4%) in yearly comfortable hours.

(iii) Shading

The shading of windows reduces heat gain and increases the yearly comfortable hours.

(iv) Wall type

A concrete block wall is better than the brick wall (base case); the performance improves by about 4.7%.

(v) Roof type

Insulation of the roof is not desirable. An RCC roof with bitumen felt water proofing layer increases the yearly comfortable hours by 4.1% compared to RCC with brick-bat-coba water proofing.

(vi) Colour of the external surface

White and cream colours are desirable over puff shade (base case) or dark grey. The percentage increase in comfortable hours due to these colours compared to the base case are 6.2 and 4.4 respectively.

(vii) Air exchanges

Higher air change rates are desirable; air change rates of 9 and 12 ach compared to the base case oh 6 ach improve the performance by about 12.9 and 19.1% respectively.

(b) Operational Parameters

(i) Internal gain

The lower the internal gain, the better is the performance of the building.

(ii) Scheduling of air exchanges

Promoting higher air change rates when the ambient air temperature is within the comfortable range as compared to the indoor temperature improves the performance of the building by 30.9% compared to a constant air change rate. However, in the reverse situation, air exchange needs to be minmised.

The combinations of all design and operational parameters discussed, (excluding building orientation and internal gain) significantly improves the yearly comfortable hours in the industrial shed; the percentage increase is 43.8 compared to the base case.

Table 5.7 Improvement of in the performance of the industrial building due to design and operational parameters- Jodhpur (hot and dry climate)

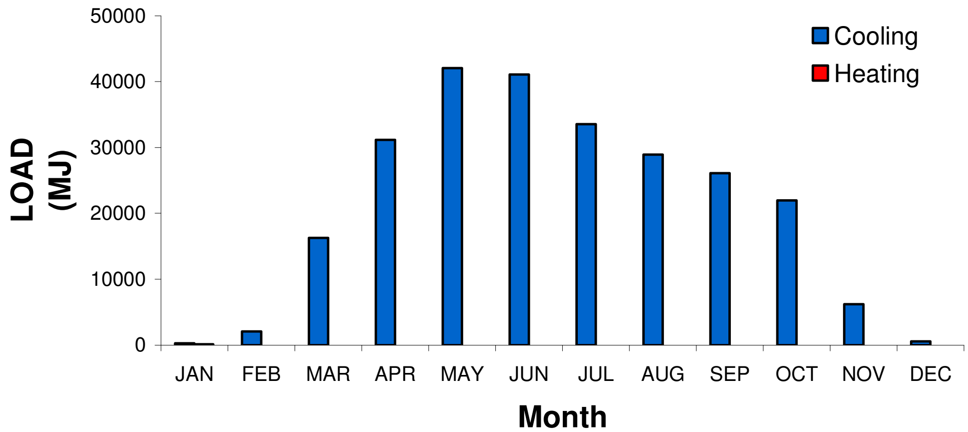
Parameter	Comfortable hours in a year (h)	Percentage increase in Comfortable hours
Base case	3089	-
Orientation		
Northwest-southeast	3106	0.6
Northeast-southwest	3110	0.7
East-west	3100	0.4
Glazing type		
Single reflective	3195	3.4
Double clear	2953	-4.4
Double low-E	2973	-3.8
Double reflective coated	3029	-1.9
Shading		
10%	3133	1.4
20%	3157	2.2
Wall type		
Thermocol (EPS) insulated brick wall	2909	-5.8
Concrete block wall	3234	4.7
Autoclaved cellular concrete block	2929	-5.2
Roof type		
RCC with bitumen felt water proofing	3215	4.1
RCC with PUF insulation	2796	-9.5
Colour of external surface		
White	3282	6.2
Cream	3224	4.4
Dark grey	2934	-5.0
Air exchanges		
3 ach	2186	-29.2
9 ach	3486	12.9
12 ach	3678	19.1
Internal gain		
20%	4569	47.9
40%	4029	30.4
Scheduling of air exchanges	4043	30.9

5.5.1.3 Residential Building (Bungalow)

Figure 5.5 shows the plan of the bungalow chosen for developing design guidelines. Both conditioned as well as non-conditioned options are considered for the building.

(A) Conditioned building

Figure 5.41 shows the distribution of the annual and monthly heating and cooling loads of the building for the Jodhpur climate. Clearly, the building requires cooling throughout the year. The general features are similar to those observed in the case of the commercial



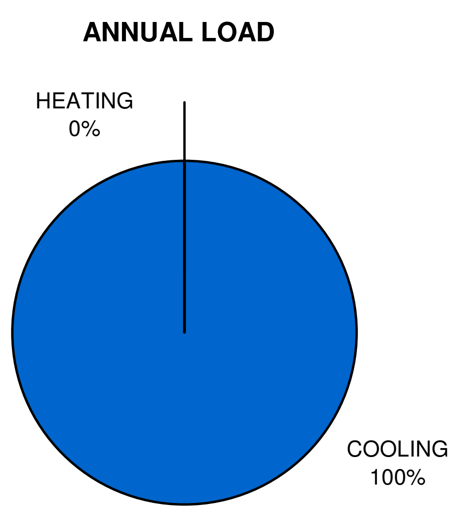


Fig. 5.41 Monthly and annual heating and cooling loads of the conditioned bungalow- Jodhpur (hot and dry climate)

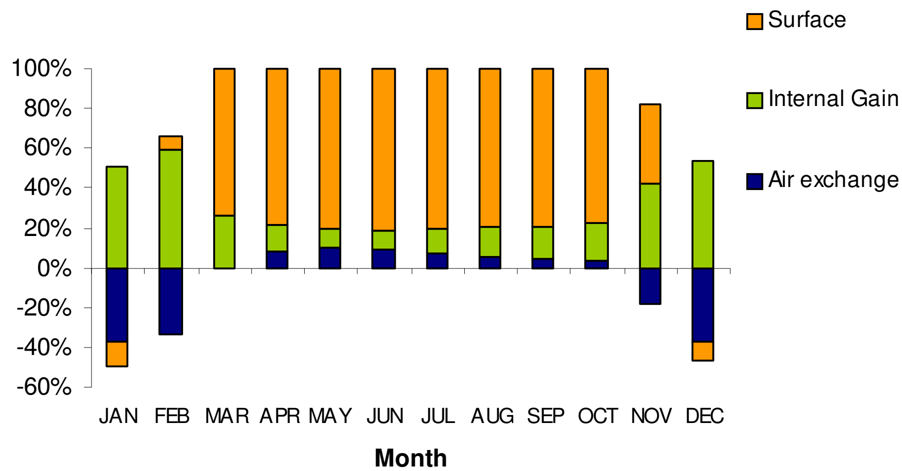


Fig. 5.42 Component-wise distribution of percentage heat gains and losses on a monthly basis of the conditioned bungalow - Jodhpur (hot and dry climate)

building (section 5.5.1.1). The highest cooling load occurs in the summer months and the lowest load in the winter months. The monthly variation of the percentage of loads through various building components is presented in Fig. 5.42. The cooling requirement is primarily due to surface gains. Hence it is essential to decrease the heat gain by choosing appropriate materials, shading, colour, reducing exposed glazing area, etc. In summer months, air exchanges add to cooling loads and hence need to be controlled. The scheduling of air change rates could reduce cooling loads. Decreasing lighting and equipment loads through energy efficient devices can reduce the internal gain. The room-wise behaviour is presented in Table 5.8. It may be noted that the usage of the building and the configuration of spaces affect the loads. For instance, the cooling load of the living room is higher than that of other rooms. This is because of the fact that this room is partly double storeyed and has a large volume. Similarly the cooling load of the kitchen is also very high due to operation of various appliances.

The effects of building parameters on the annual loads are presented in Table 5.9. The consequent percentage load reduction due to each parameter, compared to the base case are also shown in the table. The following recommendations are made for a conditioned bungalow in Jodhpur:

(a) Design Parameters

(i) Building orientation

Changing the orientation of the building does not increase the load significantly.

(ii) Glazing type

Double glazing with reflective coated glass gives the best performance. It gives a saving of 13.5% in comparison with plain glass (base case). Single reflective coated glazing shows an improvement of 9.0%. Double low-E glass and double glazing with clear glass can also be used to reduce the loads by 10.6% and 4.1% respectively.

Table 5.8 Room-wise distribution of monthly and annual loads of the conditioned bungalow - Jodhpur (hot and dry climate)

Month	Cooling load (MJ)							
	BED1	LIVDIN	KIT	BED2	BED3	BED4	BED5	Total
JAN	0	0	264	0	0	0	0	264
FEB	8	1151	775	0	8	6	124	2071
MAR	1135	6576	2630	1519	1353	1441	1665	16318
APR	2429	12229	4118	3411	2738	3070	3164	31159
MAY	3362	16432	5308	4762	3745	4221	4244	42073
JUN	3313	15960	5156	4692	3679	4136	4136	41073
JUL	2712	12886	4392	3810	3022	3368	3377	33567
AUG	2310	11118	3951	3225	2583	2857	2887	28932
SEP	2014	10249	3592	2797	2277	2516	2658	26102
OCT	1566	9158	3269	2067	1780	1918	2239	21997
NOV	217	3277	1506	182	258	223	561	6224
DEC	0	51	488	0	1	0	3	543
Total	19066	99089	35448	26465	21443	23755	25058	250324

Month	Heating load (MJ)							
	BED1	LIVDIN	KIT	BED2	BED3	BED4	BED5	Total
JAN	2	35	0	95	1	9	0	141
FEB	0	0	0	1	0	0	0	1
MAR	0	0	0	0	0	0	0	0
APR	0	0	0	0	0	0	0	0
MAY	0	0	0	0	0	0	0	0
JUN	0	0	0	0	0	0	0	0
JUL	0	0	0	0	0	0	0	0
AUG	0	0	0	0	0	0	0	0
SEP	0	0	0	0	0	0	0	0
OCT	0	0	0	0	0	0	0	0
NOV	0	0	0	0	0	0	0	0
DEC	0	0	0	0	0	0	0	0
Total	2	35	0	96	1	9	0	142

BED1=Bed room1, LIVDIN= Living and dining room, KIT=Kitchen, BED2=Bed room2, BED3=Bed room3, BED4=Bed room4, BED5=Bed room5

(iii) Shading

The reduction in solar gain by shading of windows (by means of external projections such as chajjas) can significantly reduce the heat gain and consequently the annual load. If 50% of the window areas are shaded throughout the year, the percentage load reduction is 11.7.

(iv) Wall type

Insulation of walls helps to improve the performance appreciably. Thermocol insulation can save annual loads by upto 12.0% and autoclaved cellular concrete block walls (e.g., Siporex) can save 10.1% as compared to a brick wall (base case).

Plain concrete block wall increases cooling load by 9.5% and hence needs to be avoided.

Table 5.9 Annual savings due to building design and operational parameters for the conditioned bungalow - Jodhpur (hot and dry climate)

Parameter	Annual load (MJ)			Energy saving	
	Cooling	Heating	Total	(MJ)	(%)
Base case	250324	142	250466	--	--
Orientation (longer axis)					
North-south	927	250535	251462	-996	-0.4
Glazing type					
Double clear	240182	0	240182	10284	4.1
Single reflective coated	226874	1020	227894	22572	9.0
Double reflective coated	216658	12	216670	33795	13.5
Double low-E	224032	0	224032	26433	10.6
Shading					
10%	244027	283	244310	6155	2.5
20%	237835	500	238335	12131	4.8
50%	219795	1453	221247	29218	11.7
Wall type					
Thermocol (EPS) insulated brick wall	220314	3	220316	30149	12.0
Concrete block wall	272527	1828	274354	-23888	-9.5
Autoclaved cellular concrete block	225114	2	225116	25350	10.1
Roof type					
Uninsulated RCC roof	261057	551	261608	-11143	-4.4
PUF insulated RCC roof	228671	32	228703	21763	8.7
Colour of external surface					
White	237743	530	238273	12192	4.9
Cream	241921	367	242288	8178	3.3
Dark grey	263125	43	263168	-12702	-5.1
Air exchanges					
0.5 ach	245244	40	245283	5182	2.1
1.5 ach	255363	509	255872	-5406	-2.2
Internal gain					
50%	229586	587	230173	20293	8.1
No internal gain	210426	1564	211989	38476	15.4
SET POINT cooling: 26 ℃ heating: 19 ℃	220150	0	220150	30316	12.1
Scheduling of air exchanges	245211	38	245250	5216	2.1

(v) Roof type

Insulation of the roof improves the performance of the building. Polyurethane foam insulation (PUF) brings down the cooling loads by 8.7%. In contrast, a plain uninsulated RCC slab increases the cooling load by 4.4%.

(vi) Colour of the external surface

Light colours are suitable due to their lower absorptivity. White improves performance by upto 4.9%. Similarly, cream colour also improves performance by 3.3%. Dark colours must be avoided as the performance decreases by 5.1%.

(vii) Air exchanges

A lower air change rate of 0.5 ach is desirable for reducing loads; the reduction is 2.1% as compared to the base case of 1.0 ach. Increasing the air change rate to 1.5 increases the load by 2.2%. Although lower air change rates decrease the load, they may be undesirable for reasons of health.

(b) Operational Parameters

The operational parameters such as internal gain, set point and scheduling of air changes can help in reducing the annual load of the building. The effects are summarised as follows.

(i) Internal gain

The lower the internal gain, the better is the performance of the building in reducing the annual load. The annual load can be reduced by 8.1% if internal gains are reduced by 50%. Therefore, more energy efficient equipment should be used.

(ii) Set point

Lowering the operating parameters for comfort cooling and heating can reduce the cooling loads by 12.1%. Thus a change in the expectation of comfort can lead to significant savings.

(iii) Scheduling of air exchanges

The scheduling of air changes to promote air entry during cooler periods (such as nights or winters) and controlling air entry during warmer periods (during daytime or summer) can reduce the annual load by 2.1 percent.

By combining all design and operational parameters discussed (excluding building orientation and internal gain), an appreciable load reduction of 60.7% can be obtained in a conditioned bungalow for Jodhpur climate.

(B) Non-conditioned building

Table 5.10 gives the yearly minimum, maximum and average temperatures, and the number of comfortable hours in a year for all the rooms of a non-conditioned bungalow, for the Jodhpur climate. The maximum temperatures of all rooms exceed 37.8 °C in a year, indicating acute discomfort. The average room temperatures are generally high, ranging from 29.2 °C to 30.2 °C. Thus, cooling of the building is required in summers. The range of comfortable hours for all the rooms lies between 46 to 55% only. In other words, all rooms are uncomfortable for more than 45% of the year. Table 5.11 presents the performance of the building for each room on a monthly basis in terms of the comfort fraction (CF). It is seen that most of the rooms are comfortable in the months of February and November (having CF values of more than 0.9). December, January, March and October are also comparatively comfortable months. Most rooms are uncomfortable from April to July. June is the most uncomfortable month with values of CF ranging from -0.1 to 0.11. Thus a change in design is desirable to reduce discomfort. The hourly values of room temperatures for a typical winter day of January and summer day of May are plotted in Figs. 5.43 and 5.44 respectively. In January, all rooms are close to the lower limit of the comfort zone, hence some heating may be required. In May, all the rooms are well above the comfort zone with temperatures exceeding

Table 5.10 Performance of the non-conditioned bungalow on an annual basis - Jodhpur (hot and dry climate)

Room	Yearly room temperature (°C)			Comfortable hours in a year(h)	Percentage of yearly comfortable hours
	MIN	MAX	AVG		
BED1	18.1	37.8	29.2	4745	54
LIVDIN	18.1	38.5	29.6	4911	56
KIT	19.2	39.6	30.2	4788	55
BED2	17.5	38.8	29.5	3997	46
BED3	18.2	38.4	29.5	4168	48
BED4	18.0	38.2	29.6	4141	47
BED5	18.5	38.3	30.1	4530	52
Ambient	11.4	40.3	26.9	4838	55

MIN = Minimum, MAX = Maximum, AVG = Average
BED1=Bed room1, LIVDIN= Living and dining room, KIT=Kitchen, BED2=Bed room2, BED3=Bed room3, BED4=Bed room4, BED5=Bed room5

Table 5.11 Performance of the non-conditioned bungalow on a monthly basis - Jodhpur (hot and dry climate)

Comfort index	Month	Room						
		BED1	**LIVDIN**	**KIT**	**BED2**	**BED3**	**BED4**	**BED5**
Comfort fraction	JAN	0.73	0.8	0.91	0.6	0.67	0.71	0.88
	FEB	0.95	0.96	1	0.93	0.97	0.97	0.99
	MAR	0.97	0.88	0.85	0.95	0.97	0.95	0.86
	APR	0.50	0.48	0.37	0.37	0.37	0.35	0.31
	MAY	0.14	0.12	0.01	-0.06	-0.04	-0.04	-0.04
	JUN	0.11	0.10	0	-0.10	-0.08	-0.07	-0.05
	JUL	0.46	0.46	0.34	0.29	0.32	0.32	0.33
	AUG	0.64	0.63	0.5	0.49	0.51	0.51	0.5
	SEP	0.76	0.69	0.58	0.65	0.65	0.63	0.56
	OCT	0.90	0.75	0.71	0.87	0.87	0.86	0.70
	NOV	0.99	0.99	0.99	0.98	1	1	1
	DEC	0.83	0.88	0.96	0.74	0.81	0.84	0.94

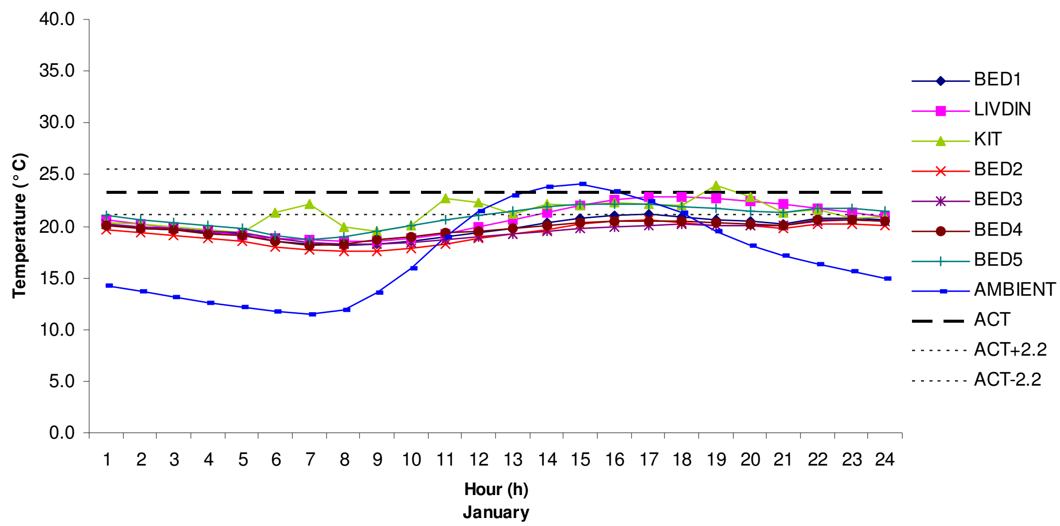
35 °C. Thus heat gain needs to be reduced in May, and heat loss promoted. Since temperatures are in excess of 35 °C, additional cooling features are required for alleviating discomfort.

Table 5.12 presents the change in the number of comfortable hours in a year due to various parameters for a bedroom (Bed2). The numbers in brackets show the percentage increase or decrease (-) of comfortable hours compared to the base case.

(a) Design Parameters

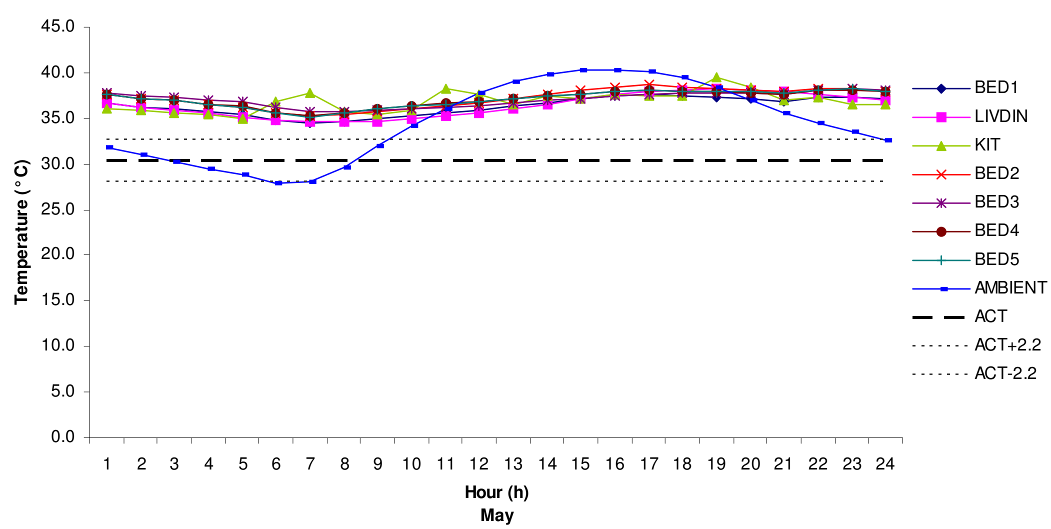
(i) Building orientation

The north-south orientation of the building vis-à-vis the base case (east-west) reduces the yearly comfortable hours by 5.9 percent.



BED1=Bed room1, LIVDIN= Living and dining room, KIT=Kitchen, BED2=Bed room2, BED3=Bed room3, BED4=Bed room4, BED5=Bed room5

Fig. 5.43 Hourly variation of room temperatures of the non-conditioned bungalow in January - Jodhpur (hot and dry climate)



BED1=Bed room1, LIVDIN= Living and dining room, KIT=Kitchen, BED2=Bed room2, BED3=Bed room3, BED4=Bed room4, BED5=Bed room5

Fig. 5.44 Hourly variation of room temperatures of non-conditioned bungalow in May - Jodhpur (hot and dry climate)

Table 5.12 Improvement in the performance of the non-conditioned bungalow due to building design and operational parameters - Jodhpur (hot and dry climate)

Parameter	Comfortable hours in a year(h)	Percentage increase in comfortable hours
Base case	3997	-
Orientation (longer axis)		
North-south	3761	-5.9
Glazing type		
Double clear	3874	-3.1
Double low-E	3996	0.0
Single reflective coated	4181	4.6
Double reflective coated	4132	3.4
Shading		
10%	4077	2.0
20%	4133	3.4
50%	4327	8.3
Wall type		
Concrete block wall	4102	2.6
Thermocol (EPS) insulated brick wall	4014	0.4
Autoclaved cellular concrete block	4001	0.1
Roof type		
Uninsulated RCC roof	3940	-1.4
PUF insulated RCC roof	4245	6.2
Colour of external surface		
Cream	4085	2.2
Dark grey	3913	-2.1
White	4125	3.2
Air exchanges		
0.5 ach	3744	-6.3
1.5 ach	3763	-5.9
6 ach	4270	6.8
9 ach	4590	14.8
Internal gain		
No internal gain	4206	5.2
50%	4123	3.2
Scheduling of air exchanges	5072	26.9

(ii) Glazing type

A single pane reflective coated glass increases the yearly comfortable hours by 4.6% compared to plain glass (base case). This type of glazing is therefore recommended.

(iii) Shading

Reduction in solar radiation by shading windows can reduce the heat gain and consequently increase comfort. If windows are shaded by 50% throughout the year, the number of comfortable hours can be increased by 8.3%.

(iv) Wall type

A concrete block wall increases the yearly comfortable hours by 2.6% compared to the brick wall (base case). Wall insulation is not recommended.

(v) Roof type

Insulating the roof with polyurethane foam insulation (PUF) increases performance by 6.2% as compared to a roof with brick-bat-coba waterproofing. However, an uninsulated roof i.e., plain RCC roof having a higher U-value decreases the number of comfortable hours by about 1.4%.

(vi) Colour of the external surface

White and cream colours are desirable rather than puff shade (base case) or dark grey. The percentage increase in comfortable hours compared to the base case is 3.2 and 2.2 respectively.

(vii) Air exchanges

An air change rate of 9 ach is better than both 6 and 3 ach (base case); it gives an improvement of about 14.8%. Comparatively, an air change rate of 6 ach gives an improvement of 6.8%. Reducing air change rate reduces the yearly comfortable hours.

(b) Operational Parameters

(i) Internal gain

The lower the internal gain, the better is the performance. The performance increase is about 3.2% if the internal gains are reduced by 50%. Thus, energy efficient lights and equipment should be employed to reduce discomfort.

(ii) Scheduling of air changes

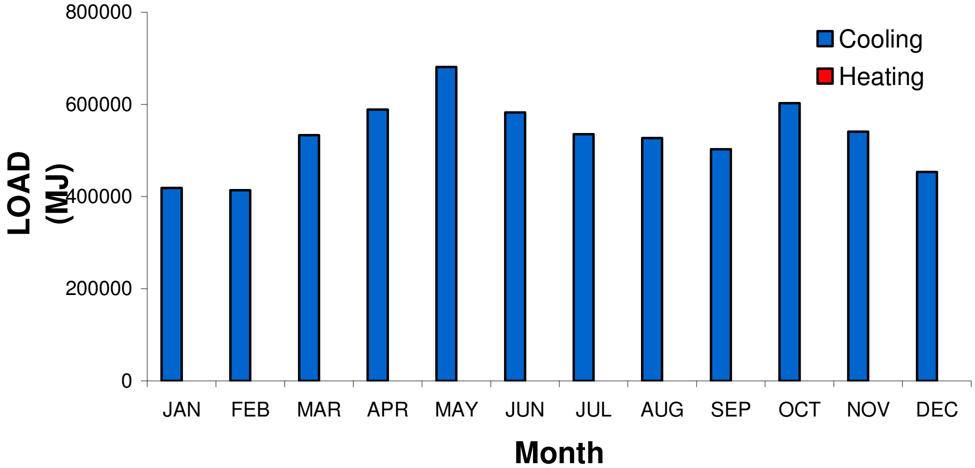
Scheduling of air changes to promote more air during cooler periods and controlling it during warmer periods (during daytime or summers) can increase the number of comfortable hours by about 26.9%.

Combining all the best parameters (excluding building orientation and internal gain) can significantly improve the building's performance, resulting in a 37.3% increase in the yearly number of comfortable hours in a non-conditioned bungalow in Jodhpur.

5.5.2 Warm and Humid Climate (Representative city: Mumbai)

5.5.2.1 Commercial Building

A distribution of the annual and monthly heating and cooling loads of the commercial building in Mumbai is shown in Fig. 5.45. On an annual basis, the heating load is zero and the cooling load is predominant. The monthly load profiles generally follow the climatic conditions; the highest cooling load occurs in May (summer), the lowest in January (winter), and relatively lower cooling loads occur during the monsoons (June to September). Figure 5.46 shows the monthly variation of the percentage of loads through various building components. The heat gain through surfaces dominates from February to December (i.e. eleven months). However in January, the convective heat gain due to people and equipment is higher. In the months from April to June, air exchanges cause significant heat gain, while they reduce cooling loads from December to February. Hence, a scheduling of air changes (more in winter and less in summer) could lead to a reduction in cooling loads. It is essential to reduce surface gains in all months to bring down the cooling loads. This could be achieved by reducing glazing areas and by shading of surfaces exposed to direct solar radiation.



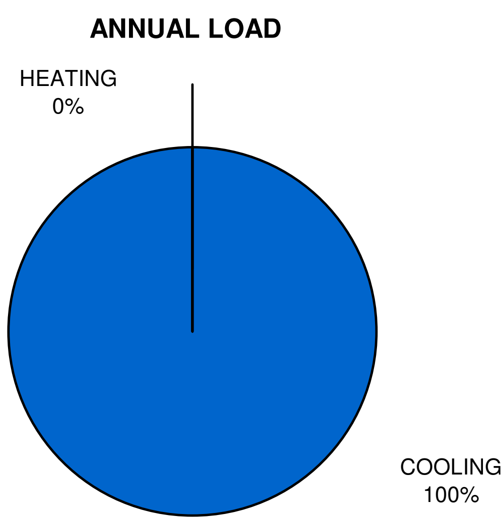


Fig. 5.45 Monthly and annual heating and cooling loads of the commercial building -Mumbai (warm and humid climate)

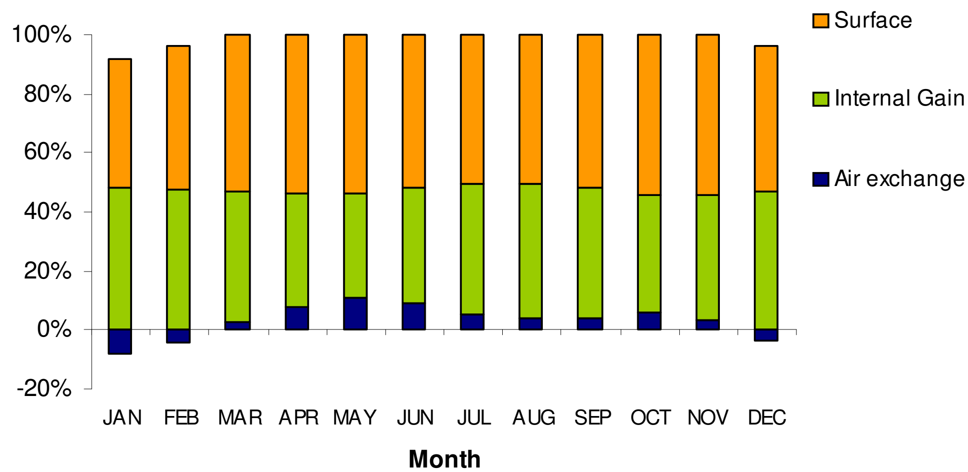


Fig. 5.46 Component-wise distribution of percentage heat gains and losses on a monthly basis of the commercial building - Mumbai (warm and humid climate)

The floor-wise monthly and annual loads are presented in Table 5.13. It is seen that the usage pattern of the building has a significant impact on the loads. For instance, the energy required for cooling is maximum on the ground floor. This is because of the frequent opening of the shutters on the ground floor resulting in a high heat gain due to air exchanges. Besides, there is a significant internal gain due to operation of equipment and a high occupancy level. Similarly, the cooling loads of the second and third floors are significantly higher than those of other floors, as they are occupied on a 24-hour basis throughout the week. The heat gain due to air exchanges may be reduced by preventing the leakage of hot ambient air into the building by sealing all cracks and providing air-lock lobbies on the ground floor.

Table 5.14 presents the effects of building parameters on the annual loads of the building. The consequent percentage load reduction for each parameter compared to the base case are also tabulated. It may be noted that the total annual load of the building is quite high. Even a one percent reduction in this load would result in a significant energy saving. The following guidelines are recommended for a commercial building in a warm and humid place like Mumbai:

(a) Design Parameters

(i) Building orientation

Appropriate orientation of the building can reduce the annual load significantly. The building (Fig.5.1) with its glazed curtain wall facing northwest shows a substantial reduction in load compared to the base case (southwest orientation); the percentage reduction being 7.7. The west and north orientations are also better than the base case.

(ii) Glazing type

Double glazing with reflective coated glass gives the best performance. It reduces the load by 2.2% compared to single pane reflective coated glass (base case). Single pane clear glass, double pane clear glass and double low-E glass increase the annual load by 9.3, 6.9 and 0.9% respectively, and hence are not recommended.

Table 5.13-Floorwise distribution of monthly and annual loads of the commercial building - Mumbai (warm and humid climate)

Month	Cooling load (MJ)								
	GR	F1	F2	F3	F4	F5	F6	F7	Total
JAN	63878	43936	73654	74247	48404	39123	51070	24833	419144
FEB	70627	40956	72662	73512	45207	37590	48882	24797	414232
MAR	103451	48620	92718	94162	54319	46871	60836	32231	533207
APR	125044	50069	101305	103159	56709	50748	65563	35974	588571
MAY	147294	57340	115473	117634	65336	59358	76643	42895	681973
JUN	129676	48239	101056	102988	54892	48833	63268	34207	583158
JUL	114413	46072	93601	95163	52262	45253	58999	30421	536185
AUG	107454	47059	91791	93103	53085	45294	59327	30162	527274
SEP	107236	42681	89342	90985	48199	41685	54246	28213	502587
OCT	118927	53848	103541	105250	60870	53958	69072	37730	603195
NOV	102219	49975	93345	94776	55988	48677	62227	33656	540863
DEC	80902	43263	80849	82028	47986	40190	51772	26514	453505
Total	1271121	572056	1109337	1127008	643258	557579	721904	381631	6383894

Month	Heating load (MJ)								
	GR	F1	F2	F3	F4	F5	F6	F7	Total
JAN	0	0	0	0	0	0	0	0	0
FEB	0	0	0	0	0	0	0	0	0
MAR	0	0	0	0	0	0	0	0	0
APR	0	0	0	0	0	0	0	0	0
MAY	0	0	0	0	0	0	0	0	0
JUN	0	0	0	0	0	0	0	0	0
JUL	0	0	0	0	0	0	0	0	0
AUG	0	0	0	0	0	0	0	0	0
SEP	0	0	0	0	0	0	0	0	0
OCT	0	0	0	0	0	0	0	0	0
NOV	0	0	0	0	0	0	0	0	0
DEC	0	0	0	0	0	0	0	0	0
Total	0	0	0	0	0	0	0	0	0

GR=Ground Floor, F1=First floor, F2=Second floor, F3=Third Floor, F4=Fourth floor, F5=Fifth floor, F6=Sixth Floor, F7=Seventh floor

(iii) Window size

The reduction of the glazing size to a 1.2 m height, compared to a fully glazed curtain wall, decreases the annual load by 6.5%. This is due to the reduction in solar gain, and thus the use of larger expanses of glass in such buildings can lead to higher annual loads.

(iv) Shading

The reduction in solar gain by shading of windows (by means of external projections such as chajjas) causes a decrease in the heat gain and hence reduces annual loads. If 50% of the window areas are shaded throughout the year, the percentage load reduction is 8.5.

(v) Wall type

A wall having low U-value (insulating type such as autoclaved cellular concrete block) reduces the load compared to the concrete block wall (base case) by 2.4%.

Table 5.14 Annual savings due to building design and operational parameters for the commercial building- Mumbai (warm and humid climate)

Parameter	Annual load (MJ)			Energy saving	
	Cooling	Heating	Total	(MJ)	(%)
Base case	6383894	0	6383894	--	--
Orientation (longer axis)					
North-south	6002430	0	6002430	381464	6.0
Northeast-southwest	5892333	0	5892333	491561	7.7
East-west	6252495	0	6252495	131400	2.1
Glazing type					
Single clear	6979643	0	6979643	-595749	-9.3
Double clear	6826246	0	6826246	-442352	-6.9
Double low-E	6441024	0	6441024	-57130	-0.9
Double reflective coated	6244698	0	6244698	139196	2.2
GLAZING SIZE(restricted to 1.2m height)	5970620	0	5970620	413274	6.5
Shading					
10%	6274825	0	6274825	109069	1.7
20%	6165743	0	6165743	218151	3.4
50%	5838423	0	5838423	545471	8.5
Wall type					
Autoclaved cellular concrete block	6233224	0	6233224	150670	2.4
Dark grey	6642237	0	6642237	-258342	-4.0
AIR CHANGE RATE					
0.5	6276724	0	6276724	107170	1.7
2	6605700	0	6605700	-221806	-3.5
4	7072726	0	7072726	-688832	-10.8
Internal gain					
10%	3091302	0	3091302	3292592	51.6
50%	4527790	0	4527790	1856104	29.1
No internal gain	2738870	0	2738870	3645024	57.1
Set point - cooling: 25 °C - heating: 20 °C	5929078	0	5929078	454816	7.1
Scheduling of air exchanges	6293870	0	6293870	90024	1.4

(vi) Colour of the external surface

Dark colours on the walls of such a commercial building should be avoided. For example, if dark grey is used, the percentage increase in load is 4.0 compared to white colour (base case).

(vii) Air exchanges

A lower air change rate of 0.5 ach is better than higher rates of 1, 2 and 4 ach. The percentage reduction in the annual load is 1.7 compared to the base case of 1 ach.

(b) Operational Parameters

The operational parameters such as internal gain, set point and scheduling of air changes can help in reducing the annual load of the building. The effects are summarised as follows.

(i) Internal gain

The performance of the building in reducing annual loads is better when the internal gains are lower.

(ii) Set Point

The annual load of the building reduces if the set points for comfort cooling and heating are relaxed. If the cooling and heating set points of 25 and 20^0C respectively are used (compared to 24 and 21^0C), the percentage reduction in annual load is 7.1. Thus, a change in the expectation of comfort can lead to significant energy savings.

(iii) Scheduling of air exchanges

The scheduling of airchanges to promote air entry during cooler periods (such as nights or winters) and controlling during warmer periods (during daytime or summer) can reduce annual load by 1.4%.

The combination of all design and operational parameters discussed so far (excluding building orientation and internal gain), results in a significant load reduction of 23.2 percent in the commercial building.

5.5.2.2 Industrial Building

Table 5.15 presents the yearly minimum, maximum and average temperatures for the industrial building. It also shows the yearly comfortable hours, both in numbers as well as in percentage, of the shed and store for the Mumbai climate. It is found that the maximum temperatures of the rooms (i.e. the shed on the ground floor and store on the first floor) can exceed 35°C. The yearly average room temperature of the shed is 34.4°C, which is about 7.6 °C above the yearly average ambient temperature. Thus, the emphasis should be on cooling considerations. Overheating in the shed occurs due to high internal gains because of the operation of large machines, occupants and lighting. The number of comfortable hours in a year does not exceed 8% for the shed; the store relatively more comfortable (about 57% of the year). In other words, the building is uncomfortable for more than 86% of the year.

Table 5.15 Performance of the industrial building on an annual basis- Mumbai (warm and humid climate)

Room	Yearly room temperature (°C)			Comfortable hours in a year (h)	Percentage of yearly comfortable hours
	MIN	MAX	AVG		
Shed	27.8	39.5	34.4	711	8
Store	23.5	35.7	30.1	5011	57
Ambient	18.4	32.4	26.8	6394	73

MIN = Minimum, MAX = Maximum, AVG = Average

Table 5.16 shows the monthly performance of the shed and store in terms of the comfort fraction. The shed is extremely uncomfortable from March to July, and from September to November. The store is relatively more comfortable during the same period. The hourly variation of room temperatures for a typical winter day of January and summer day of May are presented in Fig. 5.47 and 5.48 respectively. The figures show that in January, the store is within or close to the comfort zone unlike the shed. In May, both the rooms are hot and well above the comfort zone – the store touching 36^{o}C and the shed reaching 40^{o}C. The main reason for such thermal behaviour of the building is the large internal gain due to equipment and occupancy. The results show that the prime consideration for design is cooling, which could be achieved by reducing heat gains and promoting heat loss. Heat gain from the building surfaces may be reduced by appropriate orientation, shading, glazing, colour, etc. Energy efficient equipment could be used for reducing the internal heat gains. Further, higher air change rates can be encouraged to promote heat loss.

Table 5.16 Performance of the industrial building on a monthly basis- Mumbai (warm and humid climate)

Comfort index	Month	Room	
		Shed	Store
Comfort fraction	JAN	0.18	0.95
	FEB	0.14	0.90
	MAR	-0.14	0.8
	APR	-0.50	0.62
	MAY	-0.70	0.41
	JUN	-0.50	0.61
	JUL	-0.30	0.83
	AUG	0.46	0.71
	SEP	-0.25	0.84
	OCT	-0.37	0.70
	NOV	-0.21	0.79
	DEC	0.04	0.91

Table 5.17 presents the change in the number of comfortable hours in a year due to various parameters for the industrial shed. The corresponding percentage increase or decrease (-) of comfortable hours compared to the base case is also presented in the table.

(a) Design Parameters

(i) Building orientation

There is an improvement of 3.7 and 3.4 %, if the building orientation is taken as northeast-southwest or northwest-southeast compared to north-south (base case) orientation.

(ii) Glazing type

Single pane reflective coated glass is recommended. It increases the yearly comfortable hours by 13.1% compared to the single pane clear glass (base case).

(iii) Shading

The shading of windows reduces heat gain and increases the yearly comfortable hours.

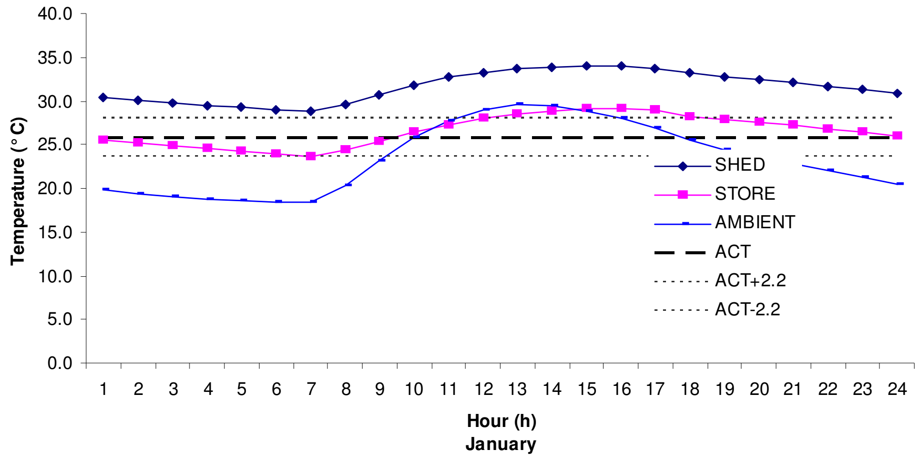


Fig. 5.47 Hourly variation of room temperatures of the industrial building in January - Mumbai (warm and humid climate)

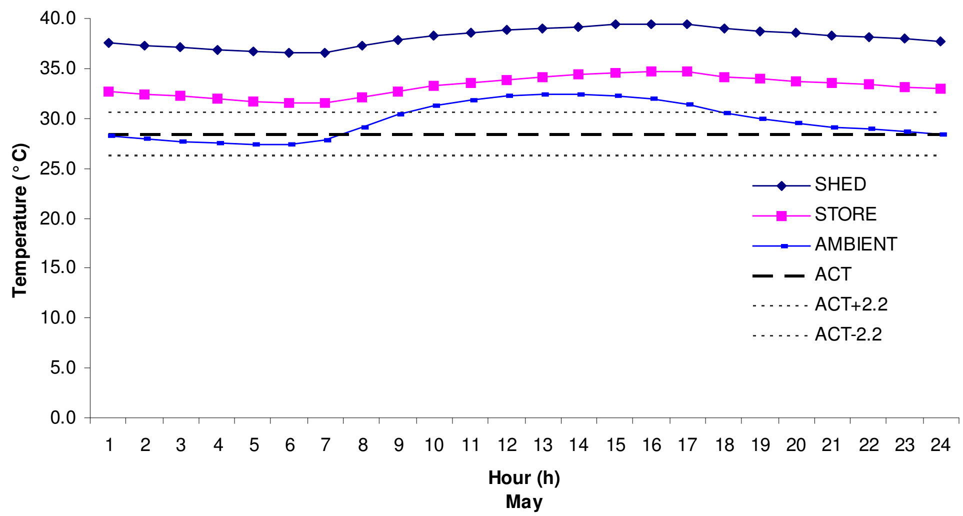


Fig. 5.48 Hourly variation of room temperatures of the industrial building in May - Mumbai (warm and humid climate)

(iv) Wall type

A concrete block wall is better than the brick wall (base case); the performance improves by about 32.9%.

(v) Roof type

Insulation of the roof is not desirable. An RCC roof with bitumen felt water proofing layer increases the yearly comfortable hours by 34.6% compared to RCC with brick-bat-coba water proofing.

(vi) Colour of the external surface

White and cream colours are desirable rather than puff shade (base case) or dark grey. The increase in comfortable hours due to these colours compared to the base case are 40.9 and 25.3 respectively.

Table 5.17 Improvement in the performance of the industrial building due to building design and operational parameters- Mumbai (warm and humid climate)

Parameter	Comfortable hours in a year (h)	Percentage increase in comfortable hours
Base case	711	-
Orientation		
Northwest-southeast	735	3.4
Northeast-southwest	737	3.7
East-west	710	-0.1
Glazing type		
Single reflective	804	13.1
Double clear	516	-27.4
Double low-E	543	-23.6
Double reflective coated	586	-17.6
Shading		
10%	733	3.1
20%	754	6.0
Wall type		
Thermocol (EPS) insulated brick wall	563	-20.8
Concrete block wall	945	32.9
Autoclaved cellular concrete block	548	-22.9
Roof type		
RCC with bitumen felt water proofing	957	34.6
RCC with PUF insulation	361	-49.2
Colour of external surface		
White	1002	40.9
Cream	891	25.3
Dark grey	516	-27.4
Air exchanges		
3 ach	94	-86.8
9 ach	1548	117.7
12 ach	2353	230.9
Internal gain		
20%	6190	770.6
40%	3885	446.4

(vii) Air exchanges

There is a good improvement in the number of yearly comfortable hours when the air changes are higher. The number of such hours increase from 711 h to 1548 h for air change rate of 9 ach, and from 711 to 2353 h for 12 ach.

(b) Operational Parameters

(i) Internal gain

The reduction in the internal gain substantially improves the building performance. If 20% of the base case internal gain exists, there is a nine-fold increase in the yearly comfortable hours (from 711 h to 6190 h)., whereas if it is 40%, the yearly comfortable hours increase only 3.5 times. Thus the lower the internal gain , the better is the performance of the building.

The combination of all design and operational parameters discussed (excluding building orientation and internal gain) results in a five-fold increase in the yearly comfortable hours in the shade (from 711 h to 3624 h).

5.5.2.3 Residential Building (Bungalow)

(A) Conditioned building

Figure 5.49 shows the distribution of the annual and monthly heating and cooling loads of a conditioned bungalow for the Mumbai climate. The figure shows that the building requires cooling throughout the year. The general features are similar to those observed in the case of the commercial building (section 5.5.2.1). The highest cooling load occurs in summer months and the lowest in winter months. The monthly variation of the percentage of loads through various building components is presented in Fig. 5.50, which shows that the cooling requirement is primarily due to surface gains. Hence, decreasing the heat gain by choosing appropriate materials, shading, colour, reducing exposed glazing area, etc. is essential. Likewise, the internal gain needs to be reduced by decreasing lighting and equipment loads through energy efficient devices. The room-wise behaviour is presented in Table 5.18. It may be noted that the usage of the building and the configuration of spaces have an impact on the loads. The cooling load of the living room is higher than that of other rooms. This is because this room is partly double storeyed and has a large volume. The cooling load of the kitchen is also very high due to operation of various appliances.

The effects of building parameters on the annual loads are presented in Table 5.19. The table also shows that the consequent percentage load reduction compared to the base case. Accordingly, the following recommendations can be made for a conditioned bungalow:

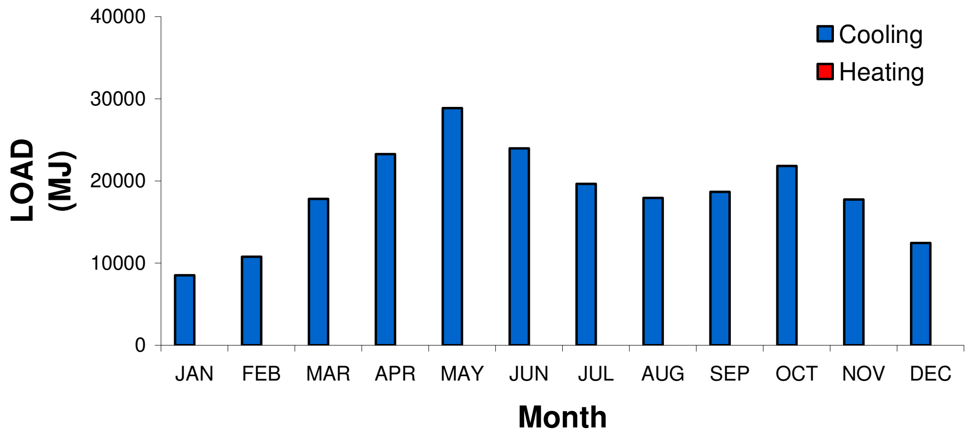
(i) Design Parameters

(i) Building orientation

Changing the building orientation with respect to the base case (east-west) does not increase the load significantly.

(ii) Glazing type

Double glazing with reflective coated glass gives the best performance. It gives a saving of 12.9% in comparison with plain glass (base case). Single reflective coated glazing shows an improvement of 12.3%. Double low-E glass and double glazing with clear glass can also be used to reduce the loads by 8.5% and 1.3% respectively.



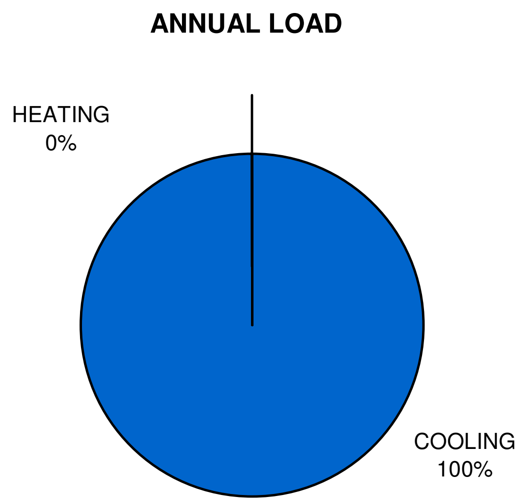


Fig. 5.49 Monthly and annual heating and cooling loads of the conditioned bungalow - Mumbai (warm and humid climate)

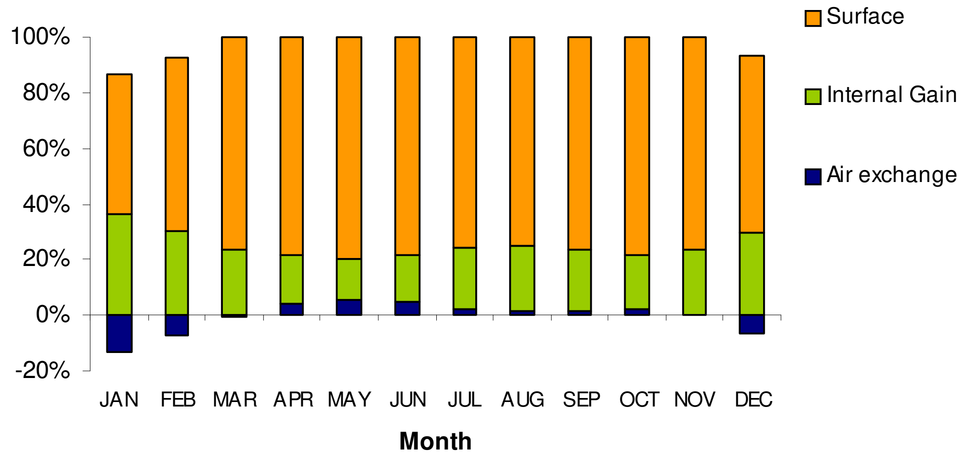


Fig. 5.50 Component-wise distribution of percentage heat gains and losses on a monthly basis of the conditioned bungalow - Mumbai (warm and humid climate)

Table 5.18-Room-wise distribution of monthly and annual loads of the conditioned bungalow - Mumbai (warm and humid climate)

Month	Cooling load (MJ)							
	BED1	LIVDIN	KIT	BED2	BED3	BED4	BED5	Total
JAN	426	3939	1824	471	568	488	822	8540
FEB	683	4566	1967	853	844	808	1063	10786
MAR	1310	7021	2777	1794	1537	1616	1773	17827
APR	1826	8918	3253	2582	2088	2273	2319	23259
MAY	2311	11030	3889	3287	2619	2863	2851	28850
JUN	1941	9026	3409	2697	2174	2372	2357	23976
JUL	1599	7236	2992	2179	1784	1936	1935	19660
AUG	1446	6592	2844	1958	1620	1748	1755	17963
SEP	1487	7046	2814	2035	1673	1793	1843	18693
OCT	1635	8747	3201	2230	1861	1983	2167	21824
NOV	1223	7461	2806	1592	1423	1481	1789	17774
DEC	754	5496	2273	888	917	880	1257	12466
Total	16641	87078	34048	22567	19107	20243	21933	221617

Month	Heating load(MJ)							
	BED1	LIVDIN	KIT	BED2	BED3	BED4	BED5	Total
JAN	0	0	0	0	0	0	0	0
FEB	0	0	0	0	0	0	0	0
MAR	0	0	0	0	0	0	0	0
APR	0	0	0	0	0	0	0	0
MAY	0	0	0	0	0	0	0	0
JUN	0	0	0	0	0	0	0	0
JUL	0	0	0	0	0	0	0	0
AUG	0	0	0	0	0	0	0	0
SEP	0	0	0	0	0	0	0	0
OCT	0	0	0	0	0	0	0	0
NOV	0	0	0	0	0	0	0	0
DEC	0	0	0	0	0	0	0	0
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

BED1=Bed room1, LIVDIN= Living and dining room, KIT=Kitchen, BED2=Bed room2, BED3=Bed room3, BED4=Bed room4, BED5=Bed room5

Table 5.19 Annual savings due to building design and operational parameters for the conditioned bungalow - Mumbai (warm and humid climate)

Parameter	Annual load (MJ)			Energy saving	
	Cooling	Heating	Total	(MJ)	(%)
Base case	221617	0	221617	--	--
Orientation (longer axis)					
North-south	219606	0	219606	2011	0.9
Glazing type					
Double clear	218761	0	218761	2856	1.3
Single reflective coated	194390	0	194390	27227	12.3
Double reflective coated	193129	0	193129	28488	12.9
Double low-E	202750	0	202750	18867	8.5
Shading					
10%	214403	0	214403	7214	3.3
20%	207234	0	207234	14383	6.5
50%	185830	0	185830	35787	16.1
Wall type					
Thermocol (EPS) insulated brick wall	200848	0	200848	20769	9.4
Concrete block wall	232880	0	232880	-11263	-5.1
Autoclaved cellular concrete block	205102	0	205102	16515	7.5
Roof type					
Uninsulated RCC roof	229563	0	229563	-7946	-3.6
PUF insulated RCC roof	203093	0	203093	18524	8.4
Colour of external surface					
White	207068	0	207068	14549	6.6
Cream	211869	0	211869	9748	4.4
Dark grey	236069	0	236069	-14452	-6.5
Air exchanges					
0.5 ach	220817	0	220817	800	0.4
1.5 ach	222415	0	222415	-798	-0.4
Internal gain					
50%	196190	0	196190	25427	11.5
No internal gain	171078	0	171078	50539	22.8
Set point - cooling: 26 °C - heating: 19 °C	183290	0	183290	38327	17.3
Scheduling of air exchanges	218542	0	218542	3075	1.4

(iii) Shading

Shading of windows (by means of external projections such as chajjas) can significantly reduce the solar heat gain and consequently the annual load. If 50% of the window areas are shaded throughout the year, the load reduction is 16.1%.

(iv) Wall type

Insulation of walls helps to improve the thermal performance. Thermocol insulation can save annual loads by upto 9.4% and autoclaved cellular concrete block walls (e.g., Siporex) can save 7.5% as compared to a brick wall (base case). A plain concrete block wall increases the cooling load by 5.1% and hence should be avoided.

(v) Roof type

Insulation of the roof improves the performance of the building. Polyurethane foam insulation (PUF) brings down the cooling loads by 8.4%, whereas, a plain uninsulated RCC slab increases the cooling load by 3.6%.

(vi) Colour of the external surface

Light colours are suitable due to their lower absorptivities. White improves performance by upto 6.6%. Similarly, cream colour also improves performance by 4.4%. Dark colours should be avoided as the performance decreases by 6.5%.

(vii) Air exchanges

A lower air change rate of 0.5 ach is desirable for reducing loads; the resultant reduction is 0.4% as compared to the base case of 1.0 ach. Increasing the air change rate to 1.5 increases the load by 0.4%. Thus, there is no significant effect on loads; the rate can be decided on the basis of creating a healthier indoor environment.

(b) Operational Parameters

The operational parameters such as internal gain, set point and scheduling of air changes can help in reducing the annual load of the building. The effects are summarised as follows.

(i) Internal gain

The lower the internal gain, the better is the performance of the building in reducing the annual load. The annual load is reduced by 11.5%, if internal gains are reduced by 50%. Therefore, more energy efficient equipment should be used.

(ii) Set point

Lowering the operating parameters for comfort cooling and heating can reduce the cooling loads by 17.3%. Thus a change in the expectation of comfort can lead to significant savings.

(iii) Scheduling of air exchanges

The scheduling of air changes to promote air entry during cooler periods (such as nights or winters) and controlling it during warmer periods (during daytime or summer) can lead to a 1.4% reduction of annual load.

The combination of all design and operational parameters discussed so far (excluding building orientation and internal gain), results in a significant load reduction. The percentage load reduction is 58.6.

(B) Non-conditioned building

Table 5.20 gives the yearly minimum, maximum and average temperatures, and the number of comfortable hours in a year for all the rooms in a non-conditioned bungalow for the Mumbai climate. It is seen that the maximum temperatures of all rooms exceed 33.5 °C. The average room temperatures are generally high, ranging from 29.2 °C to 30.0 °C. The performance of the building on a monthly basis is presented in terms of the comfort fraction (CF) in Table 5.21. The table shows that the rooms are mostly comfortable in the winter months of November to March, and in the monsoon months of July to September (i.e. CF values of more than 0.9). Generally, the house is comfortable throughout the year except in summer i.e. April and May. May is the most uncomfortable month with values of CF ranging from 0.44 to 0.62. The hourly values of room temperatures for a typical winter day of January and summer day of May are plotted in Figs. 5.51 and 5.52 respectively. The figures show that in January, all rooms are mostly comfortable, whereas in May, all the rooms are well above the comfort zone by about 2 to 3 °C. The room temperatures exceed 30 °C, indicating discomfort. Thus heat gain needs to be reduced and heat loss must be promoted by higher air change rates.

Table 5.20 Performance of the non-conditioned bungalow on an annual basis -- Mumbai (warm and humid climate)

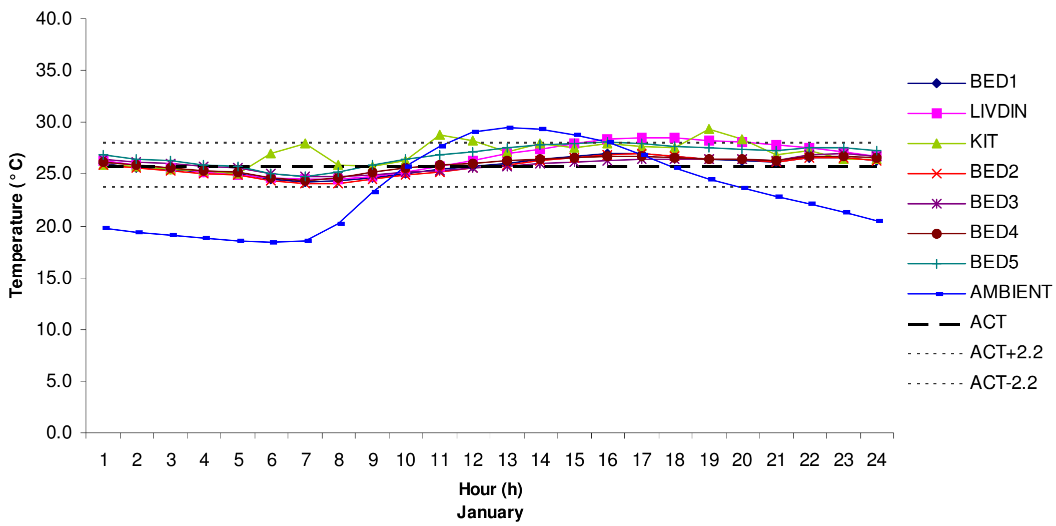
Room	Yearly room temperature(°C)			Comfortable hours in a year(h)	Percentage of yearly comfortable hours
	MIN	MAX	AVG		
BED1	24.1	33.5	29.2	6756	77
LIVDIN	24.1	33.7	29.4	6472	74
KIT	24.9	34.8	30.0	5473	62
BED2	24.0	34.4	29.5	6263	71
BED3	24.7	34	29.5	6297	72
BED4	24.2	33.9	29.6	6264	72
BED5	24.6	33.8	29.9	5891	67
Ambient	18.4	32.4	26.8	6394	73

MIN = Minimum, MAX = Maximum, AVG = Average
BED1=Bed room1, LIVDIN= Living and dining room, KIT=Kitchen, BED2=Bed room2, BED3=Bed room3, BED4=Bed room4, BED5=Bed room5

Table 5.21 Performance of the non-conditioned bungalow on a monthly basis -- Mumbai (warm and humid climate)

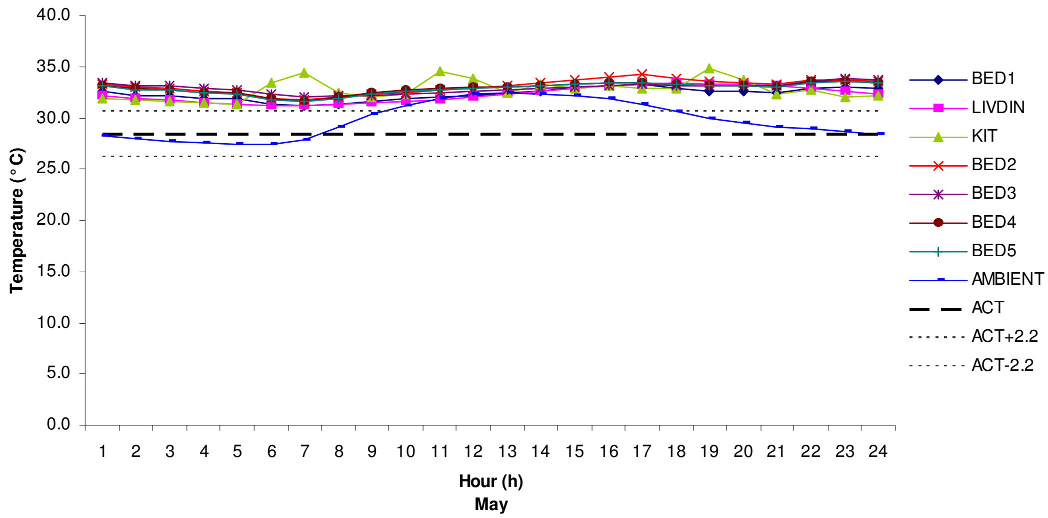
Comfort index	Month	Room						
		BED1	LIVDIN	KIT	BED2	BED3	BED4	BED5
Comfort fraction	JAN	1	0.98	0.97	1	1	1	1
	FEB	1	0.95	0.93	1	1	1	0.97
	MAR	0.96	0.89	0.84	0.92	0.94	0.93	0.86
	APR	0.78	0.77	0.69	0.65	0.67	0.66	0.65
	MAY	0.61	0.62	0.51	0.44	0.47	0.47	0.49
	JUN	0.77	0.80	0.65	0.64	0.66	0.66	0.68
	JUL	0.96	0.96	0.84	0.89	0.91	0.90	0.90
	AUG	0.99	0.98	0.87	0.94	0.95	0.94	0.94
	SEP	0.96	0.94	0.85	0.89	0.92	0.91	0.89
	OCT	0.89	0.81	0.74	0.82	0.83	0.83	0.74
	NOV	0.98	0.85	0.82	0.97	0.97	0.97	0.83
	DEC	1	0.94	0.93	1	1	1	0.96

BED1=Bed room1, LIVDIN= Living and dining room, KIT=Kitchen, BED2=Bed room2, BED3=Bed room3, BED4=Bed room4, BED5=Bed room5



BED1=Bed room1, LIVDIN= Living and dining room, KIT=Kitchen, BED2=Bed room2, BED3=Bed room3, BED4=Bed room4, BED5=Bed room5

Fig. 5.51 Hourly variation of room temperatures of the non-conditioned bungalow in January - Mumbai (warm and humid climate)



BED1=Bed room1, LIVDIN= Living and dining room, KIT=Kitchen, BED2=Bed room2, BED3=Bed room3, BED4=Bed room4, BED5=Bed room5

Fig. 5.52 Hourly variation of room temperatures of the non-conditioned bungalow in May - Mumbai (warm and humid climate)

Table 5.22 presents the change in the number of comfortable hours in a year due to various parameters for a bedroom (Bed2). The numbers in brackets show the percentage increase or decrease (-) in comfortable hours compared to the base case.

(a) Design Parameters

(i) Building orientation

Changing the orientation of the building with respect to the base case does not affect its thermal performance.

(ii) Glazing type

A single pane reflective coated glass increases the yearly comfortable hours by 10.3% compared to plain glass (base case). This type of glazing is, therefore, recommended.

(iii) Shading

Reduction in solar radiation by shading windows can reduce the heat gain and consequently increase the comfort. An increase of 12.6% in the number of comfortable hours can be achieved, if windows are shaded by 50% throughout the year.

(iv) Wall type

A concrete block wall increases the yearly comfortable hours by 2.8% compared to the brick wall (base case). However, wall insulation is not recommended.

(v) Roof type

Insulating the roof using polyurethane foam insulation (PUF) increases performance by 2.2% as compared to a roof with brick-bat-coba waterproofing. However, an uninsulated roof i.e. plain RCC roof having a higher U-value decreases the number of comfortable hours by about 16.8%.

Table 5.22 Improvement in the performance of non-conditioned bungalow due to building design and operational parameters - Mumbai (warm and humid climate)

Parameter	Comfortable hours in a year (h)	Percentage increase in comfortable hours
Base case	6263	-
Orientation (longer axis)		
North-south	6210	-0.8
Glazing type		
Double clear	5698	-9.0
Double low-E	6172	-1.5
Single reflective coated	6906	10.3
Double reflective coated	6472	3.3
Shading		
10%	6442	2.9
20%	6599	5.4
50%	7054	12.6
Wall type		
Concrete block wall	6438	2.8
Thermocol (EPS) insulated brick wall	5433	-13.3
Autoclaved cellular concrete block	5506	-12.1
Roof type		
Uninsulated RCC roof	5208	-16.8
PUF insulated RCC roof	6401	2.2
Colour of external surface		
Cream	6448	3.0
Dark grey	5800	-7.4
White	6565	4.8
Air exchanges		
0.5 ach	4148	-33.8
1.5 ach	5337	-14.8
6 ach	6849	9.4
9 ach	7010	11.9
Internal gain		
No internal gain	6849	9.4
50%	6585	5.1
Scheduling of air exchanges	7215	15.2

(vi) Colour of the external surface

White and cream colours are desirable compared to puff shade (base case) or dark grey. The percentage increase in comfortable hours compared to the base case are 4.8 and 3.0 respectively.

(vii) Air exchanges

An air change rate of 9 ach is better than 3 ach (base case), giving an improvement of about 11.9%. An air change rate of 6 ach gives an improvement of 9.4%. The reduction of air change rate below 3 ach is not desirable.

(b) Operational Parameters

(i) Internal gain

The lower the internal gain, the better is the performance. The performance increase is about 5.1% if the internal gains are reduced by 50%. Thus, energy efficient lights and equipment should be employed to reduce internal gains and subsequently improve comfort.

(ii) Scheduling of air changes

Air change rates of 3 ach during cooler periods and 9 ach during warmer and humid periods lead to an increase in the number of comfortable hours by about 15.0%.

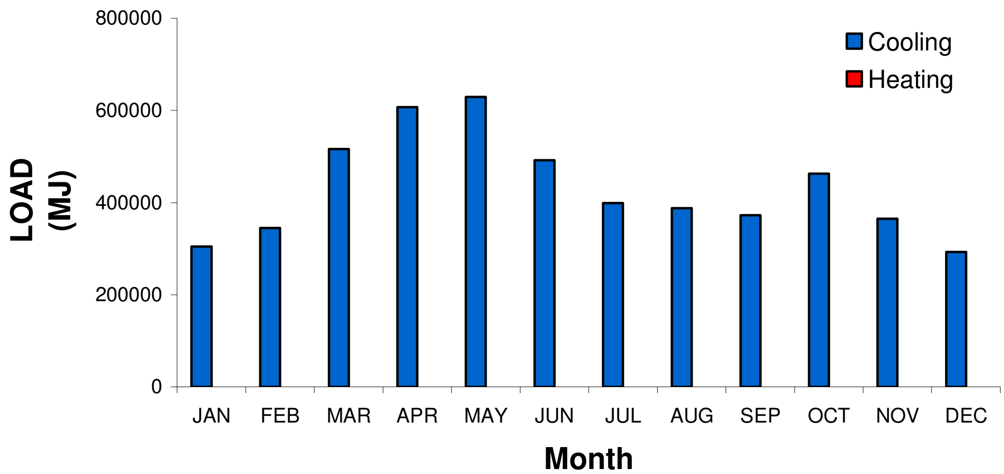
Combining all the best parameters (excluding building orientation and internal gain) can significantly improve the buildings performance, resulting in a 28.6% increase in the yearly number of comfortable hours.

5.5.3 Moderate Climate (Representative city: Pune)

5.5.3.1 Commercial Building

A distribution of the annual and monthly heating and cooling loads of the commercial building is shown in Fig. 5.53 for the Pune climate. On an annual basis, the heating load is zero and the cooling load is predominant. The monthly load profiles generally follow the climatic conditions; the highest cooling load occurs in May (summer) and the lowest cooling load occurs in December (winter). Relatively lower cooling loads occur during the monsoons (June to September). Figure 5.54 shows the distribution of percentage of loads through various building components on a monthly basis. Convective heat gain dominates from July to February (i.e. eight months). This indicates that the cooling requirements are primarily due to internal gains, which need to be dissipated. In contrast, in the summer months from March to June, the surface gains are more. Air exchanges help to reduce heat gains in the 8 months from July to February. In the summer months, infiltration adds to the cooling loads. Hence, a scheduling of air changes to promote ventilation from July to February and the control of infiltration in summer could reduce cooling loads. Additionally, it is essential to reduce surface gains in all months to aid the cooling process. This could be achieved by reducing glazing areas and shading of surfaces exposed to direct solar radiation.

The floor-wise monthly and annual loads are presented in Table 5.23. It is seen that the usage pattern of the building has a significant impact on the loads. For instance, the maximum energy required for cooling is on the ground floor. This is because the shutters are frequently opened here, resulting in a high heat gain due to air exchanges. Additionally, there is a significant internal gain due to operation of equipment and a high occupancy level. Similarly, the cooling loads of the second and third floor are much higher than those of other floors as they are occupied on a 24-hour basis throughout the week. The gain due to air exchanges may be reduced by preventing the leakage of hot ambient air into entering the building by sealing all cracks and providing air lock lobbies on the ground floor.



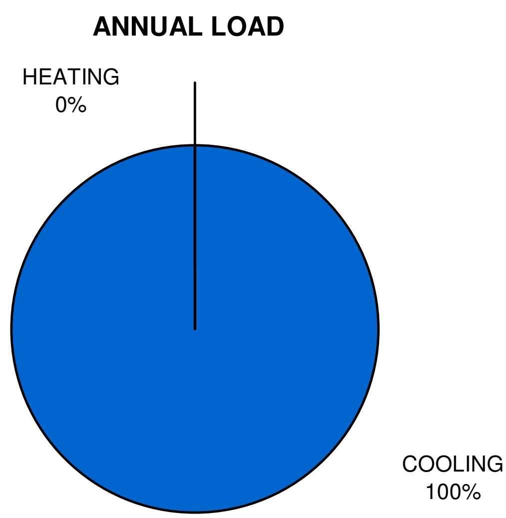


Fig. 5.53 Monthly and annual heating and cooling loads of the commercial building -Pune (moderate climate)

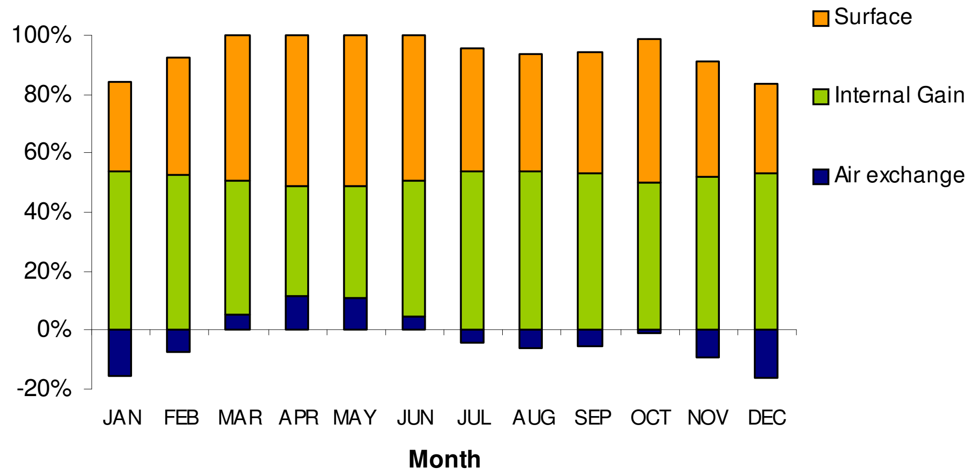


Fig. 5.54 Component-wise distribution of percentage heat gains and losses on a monthly basis of the commercial building - Pune (moderate climate)

Table 5.23 Floor wise distribution of monthly and annual loads of the commercial building - Pune (moderate climate)

Month	Cooling load (MJ)								
	GR	F1	F2	F3	F4	F5	F6	F7	Total
JAN	39660	34426	53481	54629	39196	28498	38914	16031	304835
FEB	55746	35206	59772	60748	40034	31524	42040	19727	344797
MAR	99113	47121	88910	90530	53517	45796	59855	31536	516380
APR	130446	50901	103158	105360	58529	52711	68140	37946	607192
MAY	130746	54214	105858	107962	62307	55661	72614	39955	629316
JUN	98045	43254	86047	87731	49552	42485	56319	29027	492459
JUL	69526	38064	71601	72664	43340	34786	47184	21601	398767
AUG	62226	38774	69732	70557	43896	34530	47202	21083	388000
SEP	65412	35331	67738	68870	39982	32069	43452	20185	373038
OCT	77635	44941	80920	82089	50921	42359	56020	28044	462929
NOV	52855	38249	64760	65522	43316	33979	45314	20961	364956
DEC	39849	32095	52742	53722	36402	26735	36331	15074	292949
Total	921259	492576	904719	920382	560992	461134	613386	301171	5175618

Month	Heating load (MJ)								
	GR	F1	F2	F3	F4	F5	F6	F7	Total
JAN	0	0	0	0	0	0	0	0	0
FEB	0	0	0	0	0	0	0	0	0
MAR	0	0	0	0	0	0	0	0	0
APR	0	0	0	0	0	0	0	0	0
MAY	0	0	0	0	0	0	0	0	0
JUN	0	0	0	0	0	0	0	0	0
JUL	0	0	0	0	0	0	0	0	0
AUG	0	0	0	0	0	0	0	0	0
SEP	0	0	0	0	0	0	0	0	0
OCT	0	0	0	0	0	0	0	0	0
NOV	0	0	0	0	0	0	0	0	0
DEC	0	0	0	0	0	0	0	0	0
Total	0	0	0	0	0	0	0	0	0

GR=Ground Floor, F1=First floor, F2=Second floor, F3=Third Floor, F4=Fourth floor, F5=Fifth floor, F6=Sixth Floor, F7=Seventh floor

The effects of building parameters on the annual loads of the commercial building are presented in Table 5.24 for Pune. The consequent percentage load reduction for each parameter compared to the base case are also tabulated. It may be noted that the total annual load of the building is quite high. Even a one percent reduction in this load would result in significant energy savings. The following guidelines are recommended for a commercial building located in Pune, which has a moderate climate.

(a) Design Parameters

(i) Building orientation

Appropriate orientation of the building can reduce the annual load significantly. The building (Fig.5.1) with its glazed curtain wall facing northwest shows a substantial reduction in load compared to the southwest orientation (base case) – the percentage reduction being 9.2. The west and north orientations are also better than the base case.

(ii) Glazing type

Single pane reflective coated glass (base case) is recommended for the moderate climate. All other glazing types increase the annual load of the building.

(iii) Window size

The reduction of the glazing size to a 1.2 m height, compared to a fully glazed curtain wall, decreases the annual load by 6.3%. This is due to the reduction in solar gain, and thus the use of larger expanses of glass in such a building is not desirable as it leads to higher annual loads.

(b) Shading

Shading of windows (by means of external projections such as chajjas) reduces solar gains and subsequently the heat gain, and hence the annual load is also reduced. If 50% of the window areas are shaded throughout the year, loads can be reduced by 10.6%.

(c) Wall type

A wall having a low U-value (insulating type such as autoclaved cellular concrete block) increases the load compared to the concrete block wall (base case) by 2.2%. Thus insulation of walls is not recommended.

(d) Colour of the external surface

Dark colours on the walls of such a commercial building should be avoided. For example, using dark grey increases the cooling load by 5% compared to white (base case).

(e) Air exchanges

A lower air change rate of 0.5 ach is more effective than 1, 2 and 4 ach. The percentage reduction in the annual load is 1.0 compared to the base case of 1 ach.

(b) Operational Parameters

The operational parameters such as internal gain, set point and scheduling of air changes can help in reducing the annual load of the building. The effects are summarised as follows.

(i) Internal gain

The lower the internal gain, the better is the performance of the building in reducing annual loads.

Table 5.24 Annual savings due to building design and operational parameters for the commercial building- Pune (moderate climate)

Parameter	Annual load (MJ)			Energy saving	
	Cooling	Heating	Total	(MJ)	(%)
Base case	5175618	0	5175618	--	--
Orientation (longer axis)					
North-south	4794997	0	4794997	380621	7.4
Northeast-southwest	4701236	0	4701236	474382	9.2
East-west	5032393	0	5032393	143225	2.8
Glazing type					
Single clear	5774996	0	5774996	-599378	-11.6
Double clear	5773435	0	5773435	-597817	-11.6
Double low-E	5413338	0	5413338	-237720	-4.6
Double reflective coated	5198221	0	5198221	-22603	-0.4
Glazing size (restricted to 1.2m height)	4847464	0	4847464	328154	6.3
Shading					
10%	5065938	0	5065938	109680	2.1
20%	4956314	0	4956314	219304	4.2
50%	4628063	0	4628063	547555	10.6
Wall type					
Autoclaved cellular concrete block	5291517	0	5291517	-115899	-2.2
Colour of external surface					
Dark grey	5434774	0	5434774	-259156	-5.0
Air exchange rate					
0.5	5123889	0	5123889	51729	1.0
2	5298637	0	5298637	-123019	-2.4
4	5604347	720	5605068	-429450	-8.3
Internal gain					
10%	2084676	0	2084676	3090941	59.7
50%	3389009	0	3389009	1786609	34.5
No internal gain	1788504	106	1788611	3387007	65.4
Set point - cooling: 25 °C - heating: 20 °C	4725865	0	4725865	449753	8.7
Scheduling of air exchanges	5004165	124	5004289	171329	3.4

(ii) Set Point

The annual load of the building reduces if the set points for comfort cooling and heating are relaxed. If cooling and heating set points of 25 and 20^0C respectively are used (instead of 24 and 21^0C), the percentage reduction in annual load is 8.7. Thus a change in the expectation of comfort can lead to significant savings.

(iii) Scheduling of air exchanges

The scheduling of air changes to promote air entry during cooler periods (such as nights or winters) and controlling the same during warmer periods (during daytime or summer) can reduce the annual load significantly – the percentage load reduction being 3.4.

The combination of all design and operational parameters discussed (excluding building orientation and internal gain), results in a significant load reduction 24.7%.

5.5.3.2 Industrial Building

Table 5.25 gives the yearly minimum, maximum and average temperatures, and the number of comfortable hours in a year for the shed and store for the Pune climate. The average temperature of the store room is about 3.2 °C higher than the ambient, while that of the shed is about 7.5 °C. The yearly maximum temperatures of both rooms exceed 35 °C, indicating acute discomfort. The comfortable hours in a year for the shed is about 25% indicating acute discomfort. The store is more comfortable i.e. for 72% of the year. The monthly comfort fractions (Table 5.26) show that the shed is acutely uncomfortable in the months from March to June and October (negative values indicate discomfort). It is most uncomfortable in the month of May (CF=-0.58). August is the most comfortable month (CF=0.76). The store is generally much more comfortable than the shed with CF values ranging from 0.51 in April to 0.98 in July. The hourly values of room temperatures for a typical winter day of January and summer day of May are plotted in Figs. 5.55 and 5.56 respectively. It is seen that in January, the store is within or close to the comfort zone. The shed temperature is mostly above the comfort zone except in the morning. Hence, it is desirable to have higher air change rates during periods (10 h to 24 h) when the shed temperature is higher than the comfort zone. In May, both the rooms are above the comfort zone. So, a higher change rate throughout the day would be desirable.

Table 5.25 Performance of the industrial building on an annual basis- Pune (moderate climate)

Room	Yearly room temperature (°C)			Comfortable hours in a year(h)	Percentage of yearly comfortable hours
	MIN	MAX	AVG		
Shed	24.6	40.8	32.5	2155	25
Store	20.1	35.5	28.2	6326	72
Ambient	13.4	37.3	25.0	5000	57

MIN = Minimum, MAX = Maximum, AVG = Average

Table 5.26 Performance of the industrial building on a monthly basis- Pune (moderate climate)

Comfort index	Month	Room	
		Shed	Store
Comfort fraction	JAN	0.44	0.90
	FEB	0.30	0.88
	MAR	-0.09	0.75
	APR	-0.57	0.51
	MAY	-0.58	0.52
	JUN	-0.29	0.77
	JUL	0.03	0.98
	AUG	0.76	0.93
	SEP	0.07	0.96
	OCT	-0.05	0.88
	NOV	0.24	0.95
	DEC	0.45	0.93

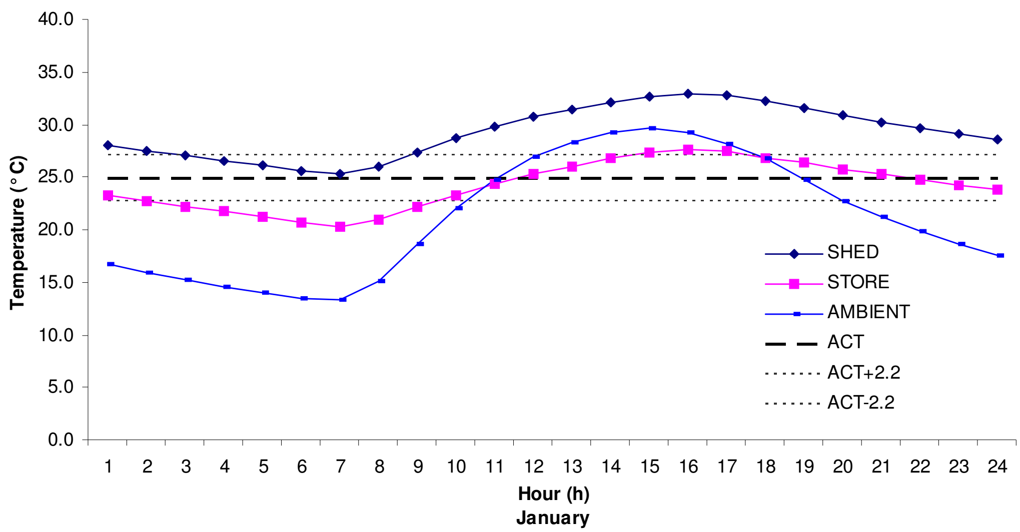


Fig. 5.55 Hourly variation of room temperatures of the industrial building in January - Pune (moderate climate)

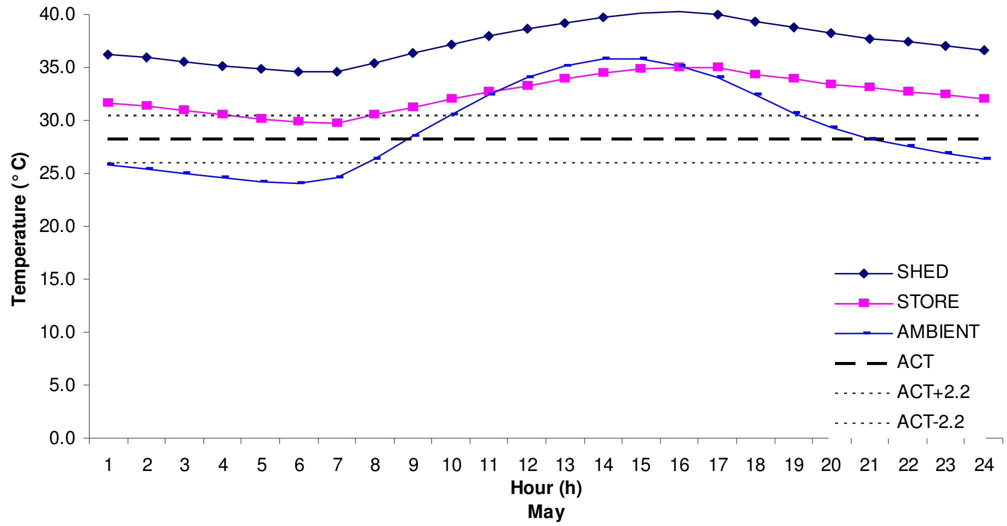


Fig. 5.56 Hourly variation of room temperatures of the industrial building in May - Pune (moderate climate)

Table 5.27 presents the number of comfortable hours in a year due to various parameters for the shed. The corresponding percentage increase or decrease (-) in comfortable hours compared to the base case is also presented in the table.

(a) Design Parameters

(i) Building orientation

There is a marginal improvement in performance if the building orientation is taken as northeast-southwest or northwest-southeast compared to the north-south (base case) orientation.

(ii) Glazing type

Single pane reflective coated glass is recommended, it increases the yearly comfortable hours by 11.6% compared to the single pane clear glass (base case).

(iii) Shading

The shading of windows reduces heat gain and increases the yearly comfortable hours.

(iv) Wall type

A concrete block wall is better than the brick wall (base case); the performance improves by about 18.9%. Insulation on walls is not recommended.

(v) Roof type

An RCC roof with a bitumen felt water proofing layer increases the yearly comfortable hours by 19.9% compared to one with brick-bat-coba water proofing. Insulation of the roof is not desirable.

(vi) Colour of the external surface

White and cream colours are desirable compared to puff shade (base case) or dark grey. The percentage increase in comfortable hours due to these colours as compared to the base case is 23.6 and 15.6 respectively.

Table 5.27 Improvement in the performance of the industrial building due to building design and operational parameters- Pune (moderate climate)

Parameter	Comfortable hours in a year (h)	Percentage increase in comfortable hours
Base case	2155	--
Orientation		
Northwest-southeast	2202	2.2
Northeast-southwest	2199	2.0
East-west	2188	1.5
Glazing type		
Single reflective	2405	11.6
Double clear	1930	-10.4
Double low-E	1970	-8.6
Double reflective coated	2058	-4.5
Shading		
10%	2204	2.3
20%	2293	6.4
Wall type		
Thermocol (EPS) insulated brick wall	1933	-10.3
Concrete block wall	2563	18.9
Autoclaved cellular concrete block	1928	-10.5
Roof type		
RCC with bitumen felt water proofing	2583	19.9
RCC with PUF insulation	1695	-21.3
Colour of external surface		
White	2664	23.6
Cream	2492	15.6
Dark grey	1876	-12.9
Air exchanges		
3 ach	617	-71.4
9 ach	4015	86.3
12 ach	4953	129.8
Internal gain		
20%	6658	209.0
40%	6137	184.8
Scheduling of air exchanges	5089	136.1

(vii) Air exchanges

Higher air change rates will considerably improve the number of yearly comfortable hours. Compared to the base case air change rate of 3 per hour (that yields 2155 comfortable hours in a year), promoting air change rates of 9 and 12 per hour will yield 4015 and 4953 hours respectively.

(b) Operational Parameters

(i) Internal gain

The building performance improves substantially when internal gains are reduced.

(ii) Scheduling of air exchanges

Promoting higher air change rates when the ambient air temperature is within the comfortable range as compared to the indoor temperature improves the performance of the building significantly. It shows approximately a two and half-fold increase over the base case of 2155 h. However, when the ambient temperatures not within the comfortable range, then the air exchange needs to be restricted.

The combination of all design and operational parameters discussed (excluding building orientation and internal gain), results in a significant improvement in the yearly comfortable hours of the shed – the increase is about three fold, from 2155 h to 6115 h in a year.

5.5.3.3 Residential Building (Bungalow)

(A) Conditioned building

Figure 5.57 shows the distribution of the annual and monthly heating and cooling loads of the conditioned residential building for the Pune climate. Clearly, the building requires cooling throughout the year. The general features are similar to those observed in the case of the commercial building (section 5.5.3.1). The highest cooling load occurs in the summer months and the lowest in the winter months. The monthly variation of the percentage of loads through various building components is presented in Fig. 5.58, which shows that the cooling requirement is primarily due to surface gains. Hence it is essential to decrease heat gain by choosing appropriate materials, shading, colour, reducing exposed glazing area, etc. The internal gain needs to be reduced by decreasing lighting and equipment loads through energy efficient devices.

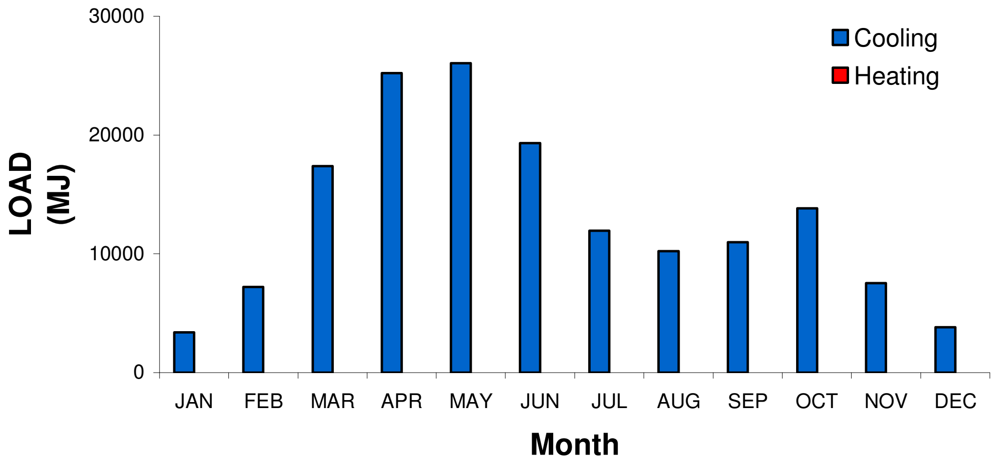
Table 5.28 presents the room-wise behaviour. It may be noted that the usage of the building and the configuration of spaces appreciably affect the loads. For instance, the cooling load of the living room is higher than that of other rooms. This is because of the fact that this room is partly double storeyed and has a large volume. Similarly, the cooling load of the kitchen is also very high due to the operation of various appliances.

Table 5.29 presents the effects of building parameters on the annual loads. The percentages of the consequent load reduction due to these parameters compared to the base case are also shown in the table. The following recommendations are made based on the results, for a conditioned bungalow in the Pune climatic conditions:

(a) Design Parameters

(i) Building orientation

Changing the orientation of the building with respect to the base case (east-west) does not increase the load significantly.



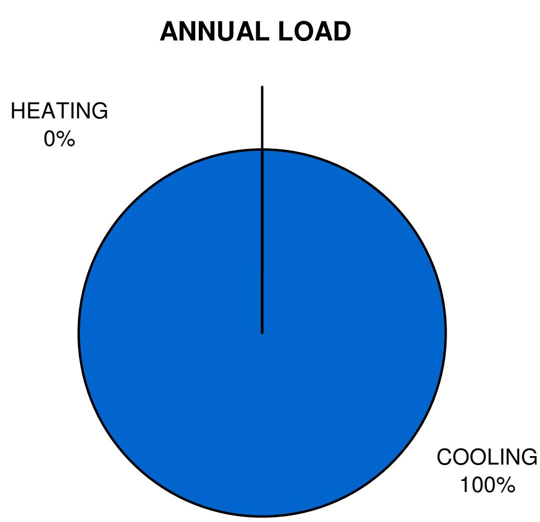


Fig. 5.57 Monthly and annual heating and cooling loads of the conditioned bungalow- Pune (moderate climate)

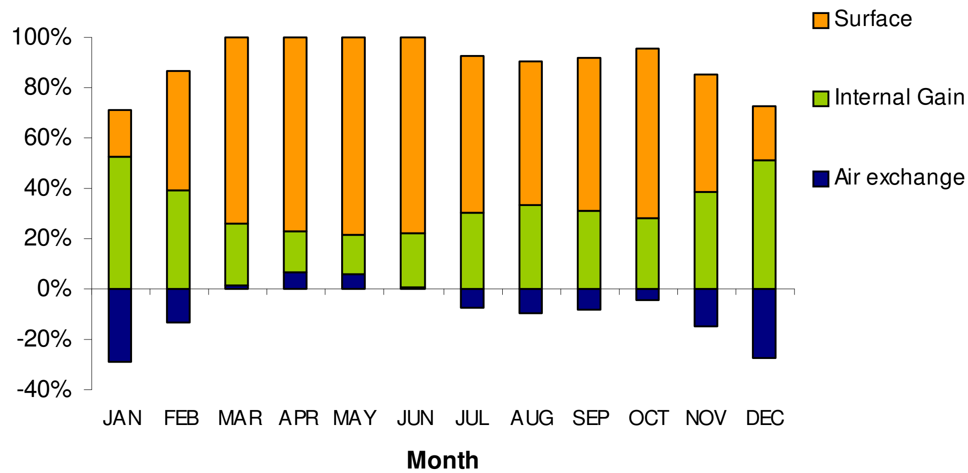


Fig. 5.58 Component-wise distribution of percentage heat gains and losses on a monthly basis of the conditioned bungalow - Pune (moderate climate)

Table 5.28 Room-wise distribution of monthly and annual loads of the conditioned Bungalow - Pune (moderate climate)

Month	Cooling load (MJ)							
	BED1	LIVDIN	KIT	BED2	BED3	BED4	BED5	Total
JAN	29	1998	1023	9	44	28	226	3357
FEB	319	3503	1485	387	427	414	663	7198
MAR	1241	6839	2722	1701	1491	1604	1772	17371
APR	1956	9654	3485	2772	2261	2525	2568	25221
MAY	2046	9846	3637	2917	2377	2625	2606	26054
JUN	1530	7155	2921	2132	1777	1907	1884	19306
JUL	951	4132	2179	1264	1117	1152	1147	11941
AUG	793	3465	2018	1045	955	969	974	10219
SEP	819	3913	2035	1102	1001	1032	1082	10984
OCT	948	5453	2387	1264	1166	1213	1406	13837
NOV	350	3497	1648	393	478	429	720	7514
DEC	58	2168	1130	23	83	54	277	3793
Total	11038	61623	26670	15009	13179	13952	15327	156798

Month	Heating load (MJ)							
	BED1	LIVDIN	KIT	BED2	BED3	BED4	BED5	Total
JAN	0	0	0	0	0	0	0	0
FEB	0	0	0	0	0	0	0	0
MAR	0	0	0	0	0	0	0	0
APR	0	0	0	0	0	0	0	0
MAY	0	0	0	0	0	0	0	0
JUN	0	0	0	0	0	0	0	0
JUL	0	0	0	0	0	0	0	0
AUG	0	0	0	0	0	0	0	0
SEP	0	0	0	0	0	0	0	0
OCT	0	0	0	0	0	0	0	0
NOV	0	0	0	0	0	0	0	0
DEC	0	0	0	0	0	0	0	0
Total	0	0	0	0	0	0	0	0

BED1=Bed room1, LIVDIN= Living and dining room, KIT=Kitchen, BED2=Bed room2, BED3=Bed room3, BED4=Bed room4, BED5=Bed room5

Table 5.29 Annual savings due to building design and operational parameters for the conditioned bungalow - Pune (moderate climate)

Parameter	Annual load (MJ)			Energy saving	
	Cooling	Heating	Total	(MJ)	(%)
Base case	156798	0	156798	--	--
Orientation (longer axis)					
North-south	156279	0	156279	519	0.3
Glazing type					
Double clear	161446	0	161446	-4648	-3.0
Single reflective coated	131052	0	131052	25745	16.4
Double reflective coated	136708	0	136708	20089	12.8
Double low-E	147103	0	147103	9695	6.2
Shading					
10%	149955	0	149955	6843	4.4
20%	143111	0	143111	13687	8.7
50%	123066	0	123066	33731	21.5
Wall type					
Thermocol (EPS) insulated brick wall	150178	0	150178	6619	4.2
Concrete block wall	161525	0	161525	-4727	-3.0
Autoclaved cellular concrete block	153101	0	153101	3697	2.4
Roof type					
Uninsulated RCC roof	163082	0	163082	-6285	-4.0
PUF insulated RCC roof	144658	0	144658	12140	7.7
Colour of external surface					
White	142979	0	142979	13819	8.8
Cream	147583	0	147583	9215	5.9
Dark grey	170869	0	170869	-14071	-9.0
Air exchanges					
0.5 ach	158718	0	158718	-1920	-1.2
1.5 ach	155209	0	155209	1588	1.0
Internal gain					
50%	133253	0	133253	23544	15.0
No internal gain	111028	0	111028	45770	29.2
Set point - cooling: 26 °C - heating: 19 °C	122370	0	122370	34428	22.0
Scheduling of air exchanges	150669	0	150669	6128	3.9

(ii) Glazing type

Single pane reflective coated glass gives the best performance; it gives a saving of 16.4% in comparison with plain glass (base case). Double pane reflective coated glazing and double low-E glass show an improvement of 12.8 and 6.2% respectively.

(iii) Shading

The reduction in solar gain by shading of windows (by means of external projections such as chajjas) can significantly reduce the heat gain and consequently the annual load. If 50% of the window areas are shaded throughout the year, the load can be reduced by 21.5%.

(iv) Wall type

Insulation of walls helps to improve the thermal performance of the building. Thermocol insulation can save annual loads by upto 4.2%, and autoclaved cellular concrete block walls (e.g., Siporex) can save 2.4% as compared to the base case (brick wall). A plain concrete block wall increases the cooling load by 3.0% and hence should be avoided.

(v) Roof type

Insulation of the roof improves the performance of the building. Polyurethane foam (PUF) insulation brings down the cooling load by 7.7%. In contrast, a plain uninsulated RCC slab increases the cooling load by 4.0%.

(vi) Colour of the external surface

Light colours are suitable due to their lower absorptivities. White improves the performance by upto 8.8%. Similarly, cream colour also improves the performance by 5.9%. Dark colours should be avoided as the performance decreases by 9.0%.

(vii) Air exchanges

A higher air change rate of 1.5 ach (compared to base case of 0.5 ach) is desirable in this climate as the ambient conditions are quite comfortable. Bringing the ambient air into the building is recommended.

(b) Operational Parameters

The operational parameters such as internal gain, set point and scheduling of air changes can help in reducing the annual load of the building. The effects are summarised as follows.

(i) Internal gain

Lowering the internal gain, improves the performance of the building in reducing the annual load. The annual load reduces by 15.0% if internal gains are reduced by 50%. Therefore, more energy efficient equipment should be used.

(ii) Set point

Lowering the operating parameters for comfort cooling and heating can reduce the cooling loads by 22.0%. Thus, a change in the expectation of comfort can bring about good savings.

(iii) Scheduling of air exchanges

The scheduling of air changes to promote air entry during cooler periods (such as nights or winters) and controlling the same during warmer periods (during daytime or summer) can reduce of annual load by 3.9%.

The combination of all design and operational parameters discussed (excluding building orientation and internal gain), results an appreciable reduction of 68.4%.

(B) Non-conditioned building

Table 5.30 gives the yearly minimum, maximum and average temperatures, and the number of comfortable hours in a year for all the rooms of a non-conditioned bungalow for the Pune climate. It is seen that the maximum temperatures of all rooms exceed 33.0 °C in a year, indicating acute discomfort. The average temperatures are quite comfortable ranging from 27.4 °C to 28.3 °C. Thus, cooling may be required only in summers. Table 5.31 presents the performance of the building on a monthly basis in terms of the comfort fraction (CF). It is seen that the rooms are comfortable in the winter months of November to February, and in the monsoon months of July to October (indicated by CF values of more than 0.9). Generally, the house is comfortable throughout the year except in summer from April and May. April is the most uncomfortable month with values of CF ranging from 0.57 to 0.72. The hourly variation of room temperatures for a typical winter day of January and summer day of May are plotted in Figs. 5.59 and 5.60 respectively. It is seen that in January, all the rooms are comfortable throughout the day. In May, all the rooms are above the comfort zone by about 2 to 3 °C. Hence, it is desirable to have lower air change rates during periods (11 h to 17 h) when the ambient temperature is higher than the comfort zone, and higher air change rates during remaining hours.

Table 5.32 presents the change in the number of comfortable hours in a year due to various parameters for a bedroom (Bed2). The numbers in brackets show the percentage increase or decrease (-) in comfortable hours compared to the base case.

(a) Design Parameters

(a) Building orientation

Changing the orientation of the building does not affect its thermal performance. The base case is in fact marginally better.

(b) Glazing type

A single pane reflective coated glass increases the yearly comfortable hours by 4.8% compared to the plain glass base case. This type of glazing is therefore recommended.

(iii) Shading

Reducing solar radiation by shading windows can reduce the heat gain and consequently increase the comfort. If windows are shaded by 50% throughout the year, the number of comfortable hours can be increased by 4.7%.

(c) Wall type

A brick wall (base case) is better than other wall types.

(d) Roof type

Insulating the roof with polyurethane foam (PUF) insulation increases performance by 3.1% as compared to a roof with brick-bat-coba waterproofing. However, an uninsulated roof i.e. plain RCC roof decreases the number of comfortable hours.

(vi) Colour of the external surface

White and cream colours are desirable as compared to puff shade (base case) or dark grey. The percentage increases in comfortable hours due to these colours compared to the base case are 2.6 and 2.4 respectively.

Table 5.30 Performance of the non-conditioned bungalow on an annual basis - Pune (moderate climate)

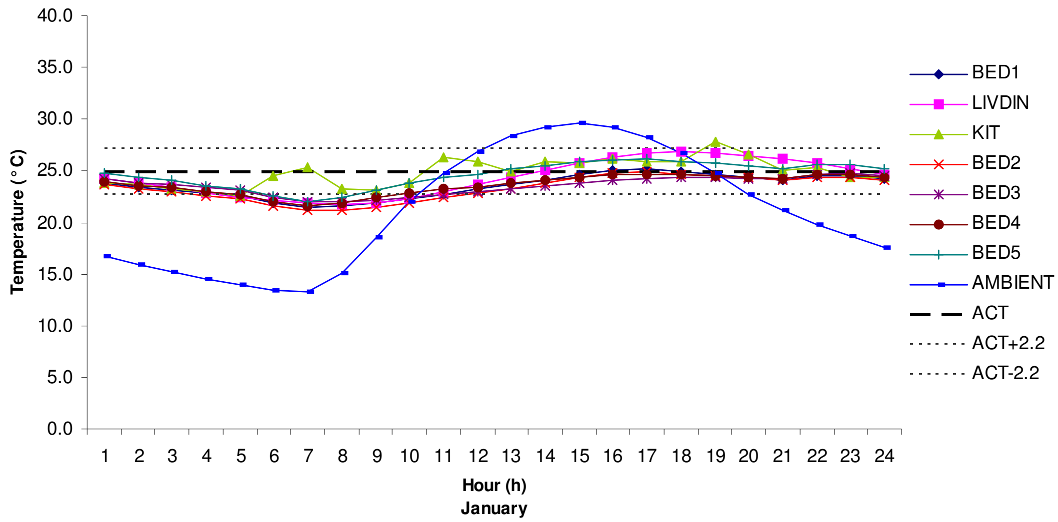
Room	Yearly room temperature(°C)			Comfortable hours in a year(h)	Percentage of yearly comfortable hours
	MIN	MAX	AVG		
BED1	21.4	33.2	27.4	7159	82
LIVDIN	21.3	33.9	27.6	7072	81
KIT	22.4	34.9	28.3	6853	78
BED2	21.1	34.0	27.6	6612	75
BED3	21.9	33.3	27.7	6887	79
BED4	21.5	33.6	27.8	6836	78
BED5	21.9	33.7	28.2	6741	77
Ambient	13.4	37.3	25.0	5000	57

MIN = Minimum, MAX = Maximum, AVG = Average
BED1=Bed room1, LIVDIN= Living and dining room, KIT=Kitchen, BED2=Bed room2, BED3=Bed room3, BED4=Bed room4, BED5=Bed room5

Table 5.31 Performance of the non-conditioned bungalow on a monthly basis - Pune (moderate climate)

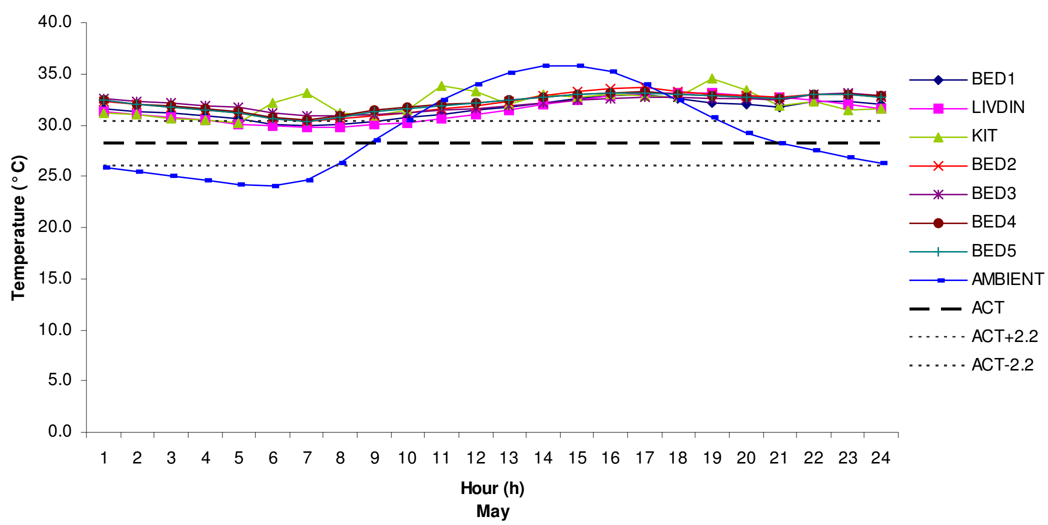
Comfort index	Month	Room						
		BED1	**LIVDIN**	**KIT**	**BED2**	**BED3**	**BED4**	**BED5**
Comfort fraction	JAN	0.96	0.97	0.99	0.94	0.98	0.97	0.99
	FEB	0.99	0.97	0.97	0.99	1	1	1
	MAR	0.94	0.86	0.83	0.91	0.94	0.91	0.84
	APR	0.72	0.69	0.60	0.61	0.62	0.58	0.57
	MAY	0.73	0.74	0.61	0.60	0.62	0.58	0.60
	JUN	0.90	0.90	0.79	0.81	0.84	0.82	0.83
	JUL	1	1	0.95	1	1	1	1
	AUG	1	1	0.97	1	1	1	1
	SEP	1	1	0.96	1	1	1	1
	OCT	1	0.95	0.91	0.99	1	0.99	0.94
	NOV	1	0.99	0.98	1	1	1	1
	DEC	0.98	0.99	0.99	0.96	0.99	0.99	1

BED1=Bed room1, LIVDIN= Living and dining room, KIT=Kitchen, BED2=Bed room2, BED3=Bed room3, BED4=Bed room4, BED5=Bed room5



BED1=Bed room1, LIVDIN= Living and dining room, KIT=Kitchen, BED2=Bed room2, BED3=Bed room3, BED4=Bed room4, BED5=Bed room5

Fig. 5.59 Hourly variation of room temperatures of the non-conditioned bungalow in January - Pune (moderate climate)



BED1=Bed room1, LIVDIN= Living and dining room, KIT=Kitchen, BED2=Bed room2, BED3=Bed room3, BED4=Bed room4, BED5=Bed room5

Fig. 5.60 Hourly variation of room temperatures of the non-conditioned bungalow in May - Pune (moderate climate)

Table 5.32 Improvement in the performance of the non-conditioned bungalow due to building design and operational parameters - Pune (moderate climate)

Parameter	Comfortable hours in a year (h)	Percentage increase in comfortable hours
Base case	6612	-
Orientation (longer axis)		
North-south	6547	-1.0
Glazing type		
Double clear	6493	-1.8
Double low-E	6686	1.1
Single reflective coated	6932	4.8
Double reflective coated	6863	3.8
Shading		
10%	6719	1.6
20%	6829	3.3
50%	6921	4.7
Wall type		
Concrete block wall	6516	-1.5
Thermocol (EPS) insulated brick wall	6447	-2.5
Autoclaved cellular concrete block	6418	-2.9
Roof type		
Uninsulated RCC roof	6504	-1.6
PUF insulated RCC roof	6815	3.1
Colour of external surface		
Cream	6771	2.4
Dark grey	6416	-3.0
White	6787	2.6
Air exchanges		
0.5 ach	6392	-3.3
1.5 ach	6429	-2.8
6 ach	6712	1.5
9 ach	6732	1.8
Internal gain		
No internal gain	6812	3.0
50%	6724	1.7
Scheduling of air exchanges	7426	12.3

(vii) Air exchanges

The effects of higher air change rates are marginal. For an air change rate of 9 per hour, the number of yearly comfortable hours increases by 1.8 over the base case of 3 ach; for 6 ach, the corresponding increase over the base case is 1.5%.

(b) Operational Parameters

(a) Internal gain

Reducing internal gains increases the performance. The performance increase is about 1.7% if the internal gains are reduced by 50%. Thus, energy efficient lights and equipment should be considered to reduce discomfort.

(ii) Scheduling of air changes

Scheduling of air changes to promote more air during cooler periods (nights or winters) and controlling it during warmer periods (during daytime or summers) can increase the number of comfortable hours by about 2.3%.

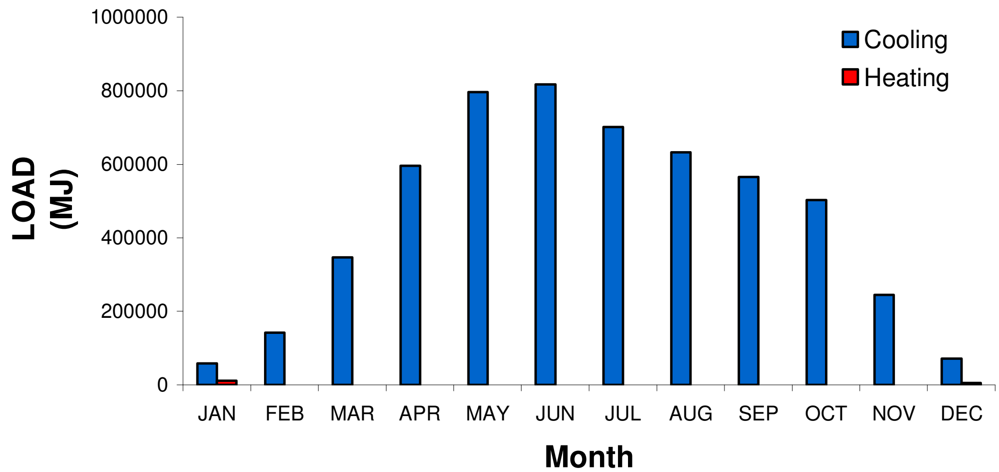
Combining all the best parameters (excluding building orientation and internal gain) can significantly improve the buildings performance and increase the yearly number of comfortable hours by 11.6% in Pune's climate.

5.5.4 Composite Climate (Representative city: New)

5.5.4.1 Commercial Building

A distribution of the annual and monthly heating and cooling loads of the commercial building in New Delhi is shown in Fig. 5.61. On an annual basis, the heating load is negligible and the cooling load is predominant. The monthly load profiles generally follow the climatic conditions, the highest cooling load occurring in June (summer) and the lowest in January (winter). In fact, some heating is also required in December and January. The months from April to October display relatively higher cooling loads. Lesser cooling is required in the winter months of November to March. The table shows that the cooling loads of May and June are almost equal to the sum of the cooling loads of the five cooler months. Figure 5.62 shows the distribution of percentage of loads through various building components on a monthly basis. The convective heat gain dominates from November to March (five months), whereas from April to October, the surface gains are more. Air exchanges help to reduce heat gains from November to March, while it adds to the cooling loads during the other months. Hence, a scheduling of air changes to promote ventilation from November to March and control of infiltration in summer could lead to a reduction in cooling loads. It is also essential to reduce surface gains in all months except December and January, to reduce the cooling loads. This can be achieved by reducing glazing areas and shading of surfaces exposed to direct solar radiation.

The floor-wise monthly and annual loads of the commercial building are presented in Table 5.33. It is seen that the usage pattern of the building has a significant impact on the loads. For instance, the energy required for cooling is maximum on the ground floor. This is because of the high heat gain due to air exchanges caused by the frequent opening of the shutters on ground floor. Besides, there is a significant internal gain due to operation of equipment and a high occupancy level. Similarly, the cooling loads of the second and third floors are significantly higher than those of other floors as the former are occupied on a 24-hour basis throughout the week. The heat gain due to air exchanges may be reduced by preventing the leakage of hot ambient air into the building by sealing all cracks and providing air lock lobbies on the ground floor.



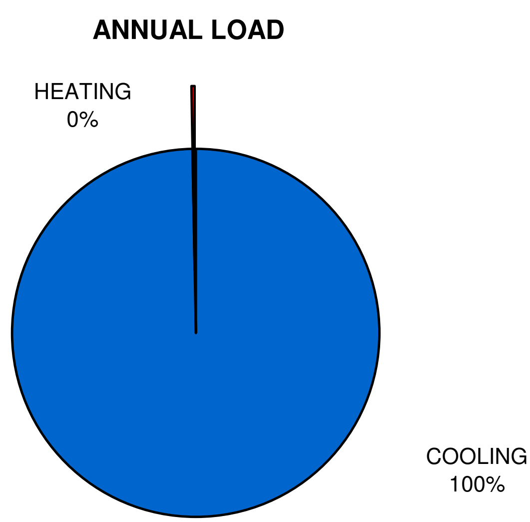


Fig. 5.61 Monthly and annual heating and cooling loads of the commercial building -New Delhi (composite climate)

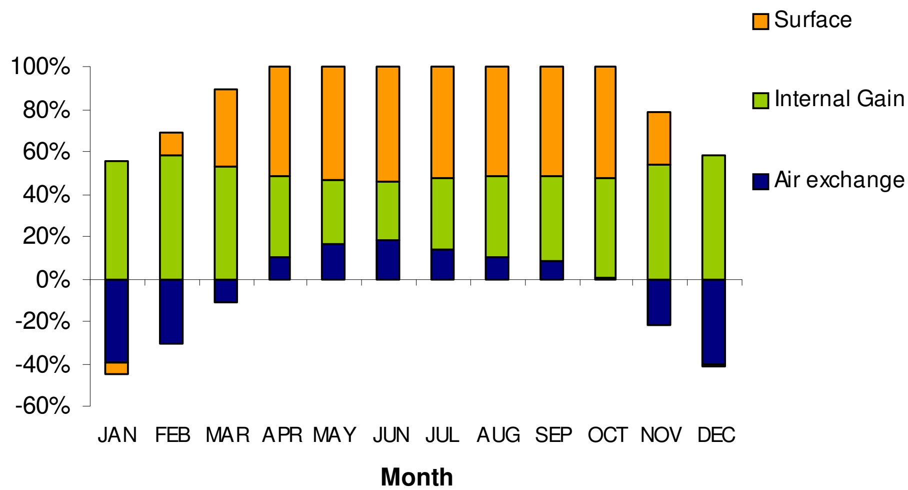


Fig. 5.62 Component-wise distribution of percentage heat gains and losses on a monthly basis of the commercial building – New Delhi (composite climate)

Table 5.33 Floor wise distribution of monthly and annual loads of the commercial building - New Delhi (composite climate)

Month	Cooling load (MJ)								
	GR	F1	F2	F3	F4	F5	F6	F7	Total
JAN	0	9473	12849	14683	12233	2894	6423	0	58557
FEB	8694	19394	27126	28415	22338	12626	19076	4213	141882
MAR	50245	36431	62380	63129	41177	31572	43002	19037	346974
APR	124501	50414	102382	104513	57973	52021	67132	37277	596214
MAY	176467	64293	133099	136203	74723	69966	89101	52372	796222
JUN	192241	61932	138818	142454	72613	69193	87508	52295	817054
JUL	156901	55512	120234	123234	65118	60141	76880	43637	701657
AUG	132146	53123	108588	110882	61724	55245	71386	39047	632142
SEP	120884	46214	100080	102492	53513	47741	61554	33738	566215
OCT	84925	47710	87763	89299	54610	46621	60460	31546	502935
NOV	23878	29759	44457	45468	33957	23358	32313	12000	245188
DEC	12	11595	14991	16665	14228	5037	9121	30	71679
Total	1070894	485851	952766	977437	564208	476415	623956	325192	5476720

Month	Heating load (MJ)								
	GR	F1	F2	F3	F4	F5	F6	F7	Total
JAN	236	7	2230	3518	142	1373	1154	3093	11753
FEB	0	0	0	0	0	0	0	32	32
MAR	0	0	0	0	0	0	0	0	0
APR	0	0	0	0	0	0	0	0	0
MAY	0	0	0	0	0	0	0	0	0
JUN	0	0	0	0	0	0	0	0	0
JUL	0	0	0	0	0	0	0	0	0
AUG	0	0	0	0	0	0	0	0	0
SEP	0	0	0	0	0	0	0	0	0
OCT	0	0	0	0	0	0	0	0	0
NOV	0	0	0	0	0	0	0	0	0
DEC	0	0	853	1313	2	645	461	1813	5087
Total	236	7	3084	4831	144	2017	1614	4938	16872

GR=Ground Floor, F1=First floor, F2=Second floor, F3=Third Floor, F4=Fourth floor, F5=Fifth floor, F6=Sixth Floor, F7=Seventh floor

The effects of building parameters on the annual loads of the building are presented in Table 5.34 for the New Delhi climatic conditions. The consequent percentages of load reduction due to these parameters compared to the base case are also tabulated. It may be noted that the total annual load of the building is quite high. Significant savings are possible by effecting even a one percent reduction in total loads. The following guidelines are recommended for a commercial building in New Delhi, which has a composite climate:

(a) Design Parameters

(i) Building orientation

Appropriate orientation of the building can reduce the annual load appreciably. The building (Fig.5.1) with glazed curtain wall facing northwest shows a substantial reduction in load compared to southwest orientation (base case); the percentage reduction being 8.6. The west and north orientations are also better than the base case.

(ii) Glazing type

Double glazing with reflective coated glass gives the best performance. It reduces the load by 1.4% compared to single pane reflective coated glass (base case). Plain glass, double glazing and double low-E glass increase the annual load by 10.7, 9.5 and 2.5% respectively and hence are not recommended.

(iii) Window size

The reduction of the glazing size to a height of 1.2 m instead of a fully glazed curtain wall, decreases the annual load by 7.2%. This is due to the reduction in solar gain, and thus the use of larger expanses of glass in such a building is not desirable as it leads to higher annual loads.

(iv) Shading

The reduction in solar gain by shading of windows (by means of external projections such as chajjas) causes a decrease in the heat gain, hence reducing the annual loads. If 50% of the window areas are shaded throughout the year, loads can be reduced by 9.3%.

(v) Wall type

A wall having a low U-value (insulating type such as autoclaved cellular concrete block) increases the load compared to the concrete block wall (base case) by 0.3%.

(vi) Colour of the external surface

Dark colours on the walls of such a commercial building should be avoided. For example, if dark grey is used in place of white (base case), the increase in load is 4.3%.

(vii) Air exchanges

A lower air change rate of 0.5 ach is better than higher rates of 1, 2 and 4 ach. The percentage reduction in the annual load is 1.7 compared to the base case of 1 ach.

(b) Operational Parameters

The operational parameters such as internal gain, set point and scheduling of air changes can help in reducing the annual load of the building. The effects are summarised as follows:

Table 5.34 Annual savings due to building design and operational parameters for the commercial building- New Delhi (composite climate)

Parameter	Annual load (MJ)			Energy saving	
	Cooling	Heating	Total	(MJ)	(%)
Base case	5476720	16872	5493592	--	--
Orientation (longer axis)					
North-south	5066737	45454	5112191	381402	6.9
Northeast-southwest	4976333	46828	5023161	470431	8.6
East-west	5299057	28293	5327351	166241	3.0
Glazing type					
Single clear	6073518	5849	6079368	-585776	-10.7
Double clear	6018065	21	6018086	-524494	-9.5
Double low-E	5633546	65	5633611	-140019	-2.5
Double reflective coated	5417676	452	5418128	75465	1.4
GLAZING SIZE (restricted to 1.2m height)	5093091	7577	5100668	392924	7.2
Shading					
10%	5369469	19776	5389245	104347	1.9
20%	5263000	23096	5286096	207496	3.8
50%	4948807	35581	4984387	509205	9.3
Wall type					
Autoclaved cellular concrete block	5503977	7244	5511221	-17629	-0.3
Colour of external surface					
Dark grey	5720660	10504	5731164	-237572	-4.3
Internal gain					
10%	2805208	242265	3047473	2446119	44.5
50%	3897213	87621	3984834	1508758	27.5
No internal gain	2552194	300215	2852410	2641182	48.1
AIR CHANGE RATE					
0.5	5393737	6260	5399997	93596	1.7
2	5677914	58825	5736739	-243147	-4.4
4	6158970	181916	6340886	-847294	-15.4
Set point - cooling: 25 °C - heating: 20 °C	5062976	3574	5066550	427042	7.8
Scheduling of air exchanges	5379180	73365	5452545	41047	0.8

(i) Internal gain

Lower the internal gain, better is the performance of the building in reducing the annual load.

(ii) Set Point

The annual load of the building reduces if the set points for comfort cooling and heating are relaxed. If cooling and heating set points of 25 and 20^{0}C respectively are used (compared to 24 and 21^{0}C), the percentage reduction in annual load is 7.8. Thus, a change in the expectation of comfort can lead to significant energy savings.

(iii) Scheduling of air exchanges

The scheduling of air changes to promote air entry during cooler periods (such as nights or winters) and controlling it during warmer periods (during daytime or summer) does not show any significant load reduction; the percentage of load reduction is 0.8.

The combination of all design and operational parameters discussed (excluding building orientation and internal gain), results in a significant load reduction 23.0%.

5.5.4.2 Industrial Building

Table 5.35 gives the yearly minimum, maximum and average temperatures, and the number of comfortable hours in a year for the shed and store for the New Delhi climate. The average temperature of the store room is about 3.3 °C higher than the ambient, while that of the shed is about 7.6 °C. The yearly maximum temperatures of both rooms exceed 39 °C, indicating acute discomfort. Even the average temperatures are quite high – more than 28 °C in the store and 32 °C in the shed. The shed is comfortable for about 42% in terms of number of comfortable hours in a year indicating acute discomfort for more than half the year. The store is only slightly better, being comfortable for 46% of the year. The values of monthly comfort fractions (Table 5.36) show that the shed is acutely uncomfortable in the months from April to July, September and October (as shown by negative CF values) and is most uncomfortable in the month of June (CF = -1.16). In contrast, January is the most comfortable month (CF = 0.97). The store is generally more comfortable than the shed with CF values ranging from -0.15 in June to 0.96 in March. The hourly values of room temperatures for a typical winter day of January and summer day of May are plotted in Figs. 5.63 and 5.64 respectively. It is seen that in January, the shed is within or close to the comfort zone. The store is cool, with temperatures going below the comfort zone. In May, the shed is very uncomfortable with temperatures exceeding 38 °C and reaching a high of 44 °C. At this time, the store temperature ranges between 32 °C and 38 °C. Thus both rooms are extremely hot in May. Consequently, higher air change rate is desirable to promote heat loss in summer, while in winter, higher air change between 13 and 17 h would reduce discomfort.

Table 5.37 presents the change in the number of comfortable hours in a year due to various parameters for the shed. The corresponding percentage increase or decrease (-) of comfortable hours compared to the base case is also shown in the table. The effect of building orientation, glazing type, wall type, roof type, colour of external surfaces, air exchanges and shading of windows do not show any significant effect in this climate due to large internal gain of the building. If the internal gain is 20% of the base case, then the performance of the building improves by 28%. Promoting higher air changes when the ambient air temperature is within the comfortable range as compared to the indoor temperature improves the performance of the building by 25%. However, when the reverse situation prevails, then the air exchange needs to be minimized.

Table 5.35 Performance of the industrial building on an annual basis- New Delhi (composite climate)

Room	Yearly room temperature(°C)			Comfortable hours in a year(h)	Percentage of yearly comfortable hours
	MIN	MAX	AVG		
Shed	18.9	44.1	32.5	3662	42
Store	13.9	39.9	28.2	3982	46
Ambient	8.7	38.5	24.9	5146	59

MIN = Minimum, MAX = Maximum, AVG = Average

Table 5.36 Performance of the industrial building on a monthly basis- New Delhi (composite climate)

Comfort index	Month	Room	
		Shed	Store
Comfort fraction	JAN	0.97	0.35
	FEB	0.80	0.78
	MAR	0.35	0.96
	APR	-0.52	0.53
	MAY	-0.99	0.07
	JUN	-1.16	-0.15
	JUL	-0.76	0.31
	AUG	0.19	0.35
	SEP	-0.43	0.62
	OCT	-0.09	0.84
	NOV	0.61	0.90
	DEC	0.95	0.45

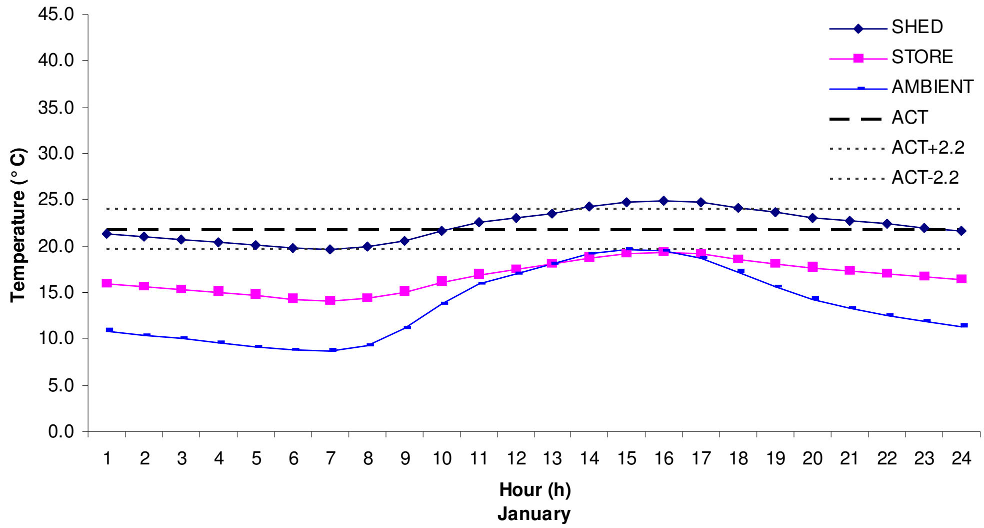


Fig. 5.63 Hourly variation of room temperatures of the industrial building in January - New Delhi (composite climate)

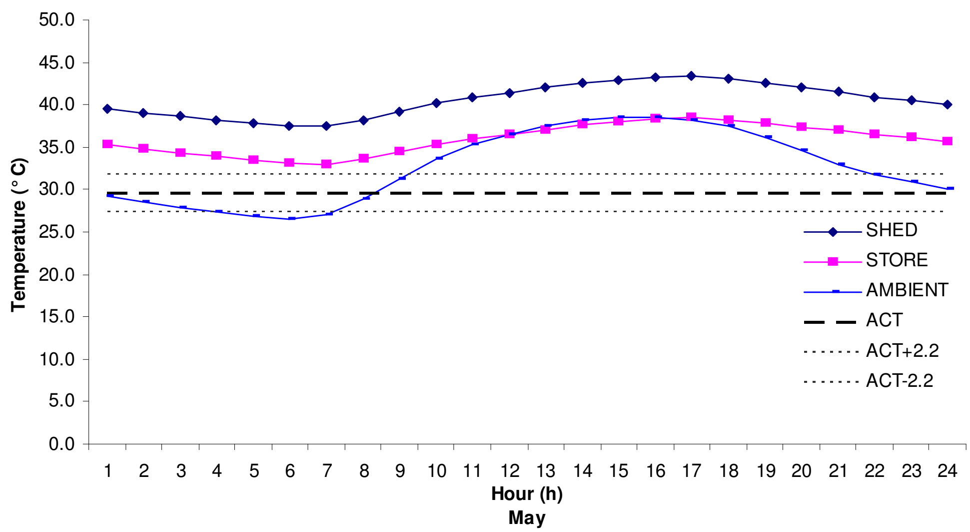


Fig. 5.64 Hourly variation of room temperatures of the industrial building in May - New Delhi (composite climate)

Table 5.37 Improvement in the performance of the industrial building due to building design and operational parameters- New Delhi (composite climate)

Parameter	Comfortable hours in a year (h)	Percentage increase in comfortable hours
Base case	3662	--
Orientation		
Northwest-southeast	3677	0.4
Northeast-southwest	3678	0.4
East-west	3706	1.2
Glazing type		
Single reflective	3648	-0.4
Double clear	3663	0.0
Double low-E	3672	0.3
Double reflective coated	3688	0.7
Shading		
10%	3671	0.2
20%	3659	-0.1
Wall type		
Thermocol (EPS) insulated brick wall	3647	-0.4
Concrete block wall	3563	-2.7
Autoclaved cellular concrete block	3621	-1.1
Roof type		
RCC with Bitumen felt water proofing	3571	-2.5
RCC with PUF insulation	3517	-4.0
Colour of external surface		
White	3666	0.1
Cream	3672	0.3
Dark grey	3641	-0.6
Air exchanges		
3 ach	2996	-18.2
9 ach	3622	-1.1
12 ach	3735	2.0
Internal gain		
20%	4689	28.0
40%	4158	13.5
Scheduling of air exchanges	4577	25.0

The combination of all design and operational parameters discussed (excluding building orientation and internal gain), results in an increase in the yearly comfortable hours of the shed by 27.2% compared to the base case.

5.5.4.3 Residential Building (Bungalow)

(A) Conditioned building

Figure 5.65 shows the distribution of the annual and monthly heating and cooling loads of the conditioned bungalow for the New Delhi climate. The building requires cooling throughout the year and the general features are similar to those observed in the case of the commercial building (section 5.5.4.1). The highest cooling load occurs in the summer months and the lowest in the winter months. The monthly variation of the percentage of loads through various building components is presented in Fig. 5.66. As the cooling requirement is primarily due to surface gains, it is essential to reduce the heat gain by choosing appropriate materials, shading, colour, reducing exposed glazing area, etc. In summer months, air exchanges add to cooling loads and hence need to be controlled. The scheduling of air change rates can reduce cooling loads. The internal gain during winter months is responsible for cooling loads and hence can be reduced by decreasing lighting and equipment loads through energy efficient devices. The room-wise distribution of monthly and annual loads is presented in Table 5.38. It may be noted that the usage of the building and the configuration of spaces have a significant impact on the loads. The cooling load of the living room is higher than that of the other rooms. This is because of the fact that this room is partly double storeyed and has a large volume. The cooling load of the kitchen is also very high due to operation of various appliances.

Table 5.39 presents the effects of building parameters on the annual loads of a conditioned bungalow. The consequent percentages of load reduction due to these parameters as compared to the base case are also shown in the table. The following recommendations are made for such a building for the New Delhi climatic conditions:

(a) Design Parameters

(i) Building orientation

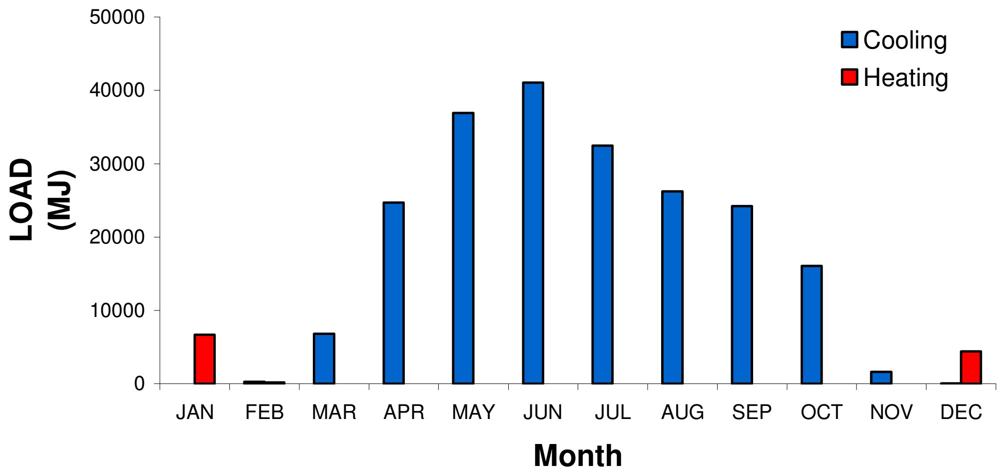
Changing the orientation of the building does not increase the load significantly. In fact, the east-west orientation (base case) is better than the north-south orientation.

(ii) Glazing type

Double glazing with reflective coated glass gives the best performance. It gives a saving of 13.9% in comparison with plain glass (base case). Single reflective coated glazing shows an improvement of 7.0%. Double low-E glass and double glazing with clear glass can also be used to reduce the loads by 11.9% and 6.3% respectively.

(iii) Shading

The reduction in solar gain by shading of windows (by means of external projections such as chajjas) can significantly reduce the heat gain and consequently the annual load. If 50% of the window areas are shaded throughout the year, the percentage load reduction is 8.9.



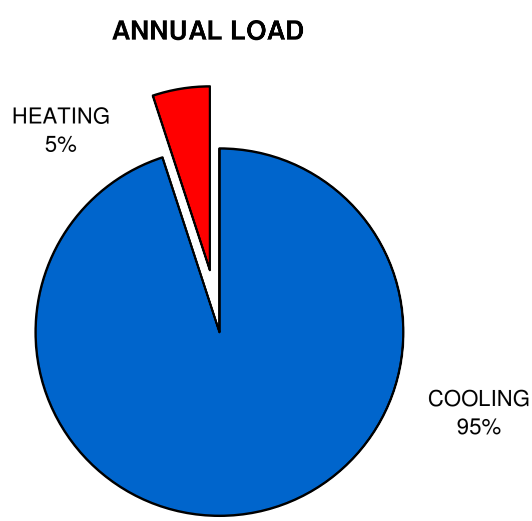


Fig. 5.65 Monthly and annual heating and cooling loads of the conditioned bungalow - New Delhi (composite climate)

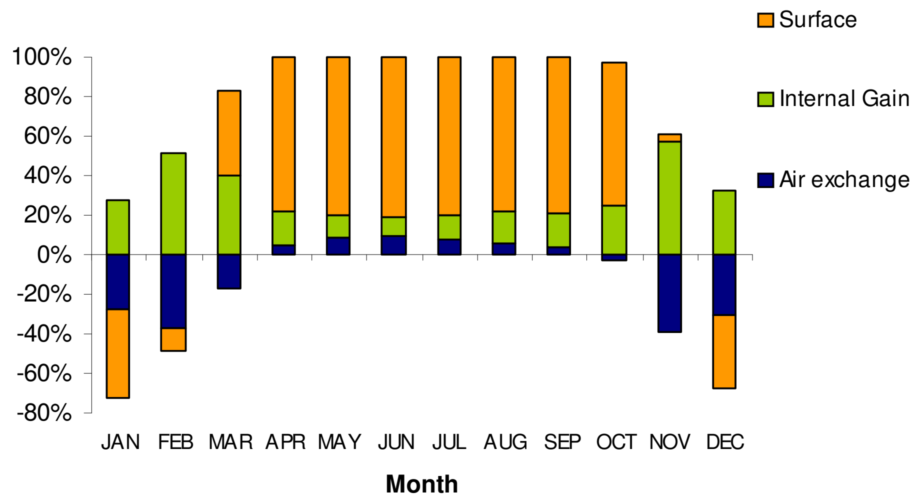


Fig. 5.66 Component-wise distribution of percentage heat gains and losses on a monthly basis of the conditioned bungalow – New Delhi (composite climate)

(iv) Wall type

Insulation of walls helps to improve the building's thermal performance significantly. Thermocol insulation can save annual loads by upto 13.9% and autoclaved cellular concrete block walls (e.g., Siporex) can save 12.0% as compared to a brick wall (base case). Plain concrete block wall increases the cooling load by 11.4% and hence needs to be avoided.

(v) Roof type

Insulation of the roof improves the performance of the building. Polyurethane foam (PUF) insulation brings down the cooling loads by 9.7%. In contrast, a plain uninsulated RCC slab increases the cooling load by 5.0%.

(vi) Colour of the external surface

Light colours are suitable due to their lower absorptivities. White improves the performance by 3.9%. Similarly, cream colour improves the performance by 2.6%. Dark colours should be avoided as the performance decreases by 4.0%.

(vii) Air exchanges

A lower air change rate of 0.5 ach is desirable for reducing the loads; the reduction is 2.7% as compared to the base case of 1.0 ach. Increasing the air change rate to 1.5 increases the load by 2.7%. Although, lower air change rates decrease the load, they may be undesirable for reasons of health.

Table 5.38 Room-wise distribution of monthly and annual loads of the conditioned bungalow - New Delhi (composite climate)

Month	Cooling load (MJ)							
	BED1	LIVDIN	KIT	BED2	BED3	BED4	BED5	Total
JAN	0	0	0	0	0	0	0	0
FEB	0	0	296	0	0	0	0	296
MAR	319	3017	1537	404	458	435	634	6803
APR	1881	9670	3435	2639	2164	2393	2494	24676
MAY	2916	14434	4779	4133	3289	3680	3710	36940
JUN	3296	16055	5197	4653	3660	4104	4112	41077
JUL	2624	12428	4309	3668	2912	3248	3261	32450
AUG	2089	10041	3696	2902	2336	2579	2616	26258
SEP	1869	9495	3414	2581	2112	2321	2455	24247
OCT	1090	6691	2641	1406	1283	1333	1629	16073
NOV	13	772	770	12	20	15	59	1661
DEC	0	0	38	0	0	0	0	38
Total	16097	82602	30112	22398	18234	20108	20969	210520

Month	Heating load (MJ)							
	BED1	LIVDIN	KIT	BED2	BED3	BED4	BED5	Total
JAN	619	2369	275	1287	699	900	556	6704
FEB	13	69	5	30	14	17	13	161
MAR	0	0	0	0	0	0	0	0
APR	0	0	0	0	0	0	0	0
MAY	0	0	0	0	0	0	0	0
JUN	0	0	0	0	0	0	0	0
JUL	0	0	0	0	0	0	0	0
AUG	0	0	0	0	0	0	0	0
SEP	0	0	0	0	0	0	0	0
OCT	0	0	0	0	0	0	0	0
NOV	0	0	0	0	0	0	0	0
DEC	370	1620	183	951	418	599	284	4425
Total	1002	4058	463	2268	1131	1516	852	11290

BED1=Bed room1, LIVDIN= Living and dining room, KIT=Kitchen, BED2=Bed room2, BED3=Bed room3, BED4=Bed room4, BED5=Bed room5

Table 5.39 Annual savings due to building design and operational parameters for the conditioned bungalow - New Delhi (composite climate)

Parameter	Annual load (MJ)			Energy saving	
	Cooling	Heating	Total	(MJ)	(%)
Base case	210520	11290	221810	--	--
Orientation (longer axis)					
North-south	211536	13744	225280	-3470	-1.6
Glazing type					
Double clear	202246	5566	207812	13998	6.3
Single reflective coated	191024	15177	206201	15609	7.0
Double reflective coated	182608	8437	191045	30765	13.9
Double low-E	188869	6444	195313	26497	11.9
Shading					
10%	205267	12179	217446	4364	2.0
20%	200027	13152	213179	8631	3.9
50%	185162	16871	202033	19777	8.9
Wall type					
Thermocol (EPS) insulated brick wall	185365	5617	190982	30828	13.9
Concrete block wall	228622	18571	247193	-25383	-11.4
Autoclaved cellular concrete block	189369	5739	195108	26702	12.0
Roof type					
Uninsulated RCC roof	219638	13286	232924	-11113	-5.0
PUF insulated RCC roof	191699	8546	200245	21565	9.7
Colour of external surface					
White	199945	13242	213187	8623	3.9
Cream	203436	12556	215991	5819	2.6
Dark grey	221290	9486	230776	-8966	-4.0
Air exchanges					
0.5 ach	206859	8900	215759	6051	2.7
1.5 ach	214225	13655	227879	-6069	-2.7
Internal gain					
50%	192340	14203	206544	15266	6.9
No internal gain	175219	18152	193371	28439	12.8
Set point - cooling: 26 °C - heating: 19 °C	183830	6590	190420	31390	14.2
Scheduling of air exchanges	206834	9023	215858	5953	2.7

(b) Operational Parameters

The operational parameters such as internal gain, set point and scheduling of air changes can help in reducing the annual load of the building. The effects are summarised as follows:

(i) Internal gain

Lower the internal gain, better is the performance of the building in reducing the annual load. The annual load can be reduced by 6.9% if internal gains are reduced by 50%. Therefore, more energy efficient equipment should be used to facilitate load reduction.

(ii) Set point

Lowering the operating parameters for comfort cooling and heating can reduce the cooling loads by 14.2%. Thus, a change in the expectation of comfort can lead to significant savings.

(iii) Scheduling of air exchanges

The scheduling of air changes to promote air entry during cooler periods (such as nights or winters) and controlling air entry during warmer periods (during daytime or summer) can lead to a 2.7% reduction of the annual load.

The combination of all design and operational parameters discussed (excluding building orientation and internal gain), results in a significant load reduction of 62.6%.

(B) Non-conditioned building

Table 5.40 gives the yearly minimum, maximum and average temperatures, and number of comfortable hours in a year for all the rooms of a non-conditioned bungalow for New Delhi. It is seen that the maximum temperatures of all rooms exceed 37.0 °C in a year, indicating acute discomfort. The average temperatures are quite comfortable ranging from 27.4 °C to 28.3 °C. Thus, cooling may be required only in summers. The percentage of comfortable hours in a year for all rooms is between 49 and 56 only. In other words, all rooms are uncomfortable for more than 44% of the year. Thus, a change in design is indicated to reduce discomfort. The performance of the building on a monthly basis is presented in terms of the comfort fraction (CF) in Table 5.41. It is seen that the rooms are comfortable in the months of March, October and November. Generally, June is the most uncomfortable month with values of CF ranging from -0.11 to 0.10. Most rooms are also uncomfortable in the months of January, May and December. The hourly variation of room temperatures for a typical winter day of January and summer day of May are plotted in Figs. 5.67 and 5.68 respectively. It is seen that in January, all the rooms are uncomfortably cold throughout the day with temperatures ranging from 15 to 20°C. Thus, heating is required in winter and lower air change rates throughout the day is desirable. In May, all the rooms are well above the comfort zone by about 2 to 3 °C. The room temperatures exceed 32.5 °C, indicating acute discomfort. Thus, heat gain needs to be reduced in May, and heat loss promoted. Higher air change rates during nights, and lower air change rates during days are desirable in summers.

Table 5.40 Performance of the non-conditioned bungalow on an annual basis - New Delhi (composite climate)

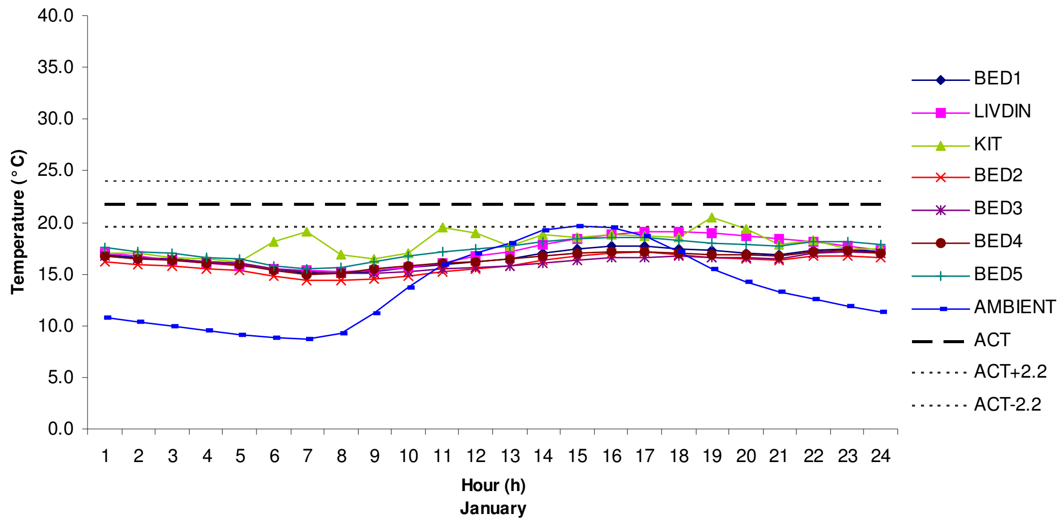
Room	Yearly room temperature(°C)			Comfortable hours in a year(h)	Percentage of yearly comfortable hours
	MIN	MAX	AVG		
BED1	15.0	37.6	27.4	4918	56
LIVDIN	14.9	38.1	27.7	4783	55
KIT	16.0	39.3	28.3	4700	54
BED2	14.3	38.6	27.6	4276	49
BED3	15.0	38.3	27.7	4605	53
BED4	14.9	38.1	27.8	4505	51
BED5	15.3	38.1	28.2	4360	50
Ambient	8.7	38.5	24.9	5146	59

MIN = Minimum, MAX = Maximum, AVG = Average
BED1=Bed room1, LIVDIN= Living and dining room, KIT=Kitchen, BED2=Bed room2, BED3=Bed room3, BED4=Bed room4, BED5=Bed room5

Table 5.41 Performance of the non-conditioned bungalow on a monthly basis - New Delhi (composite climate)

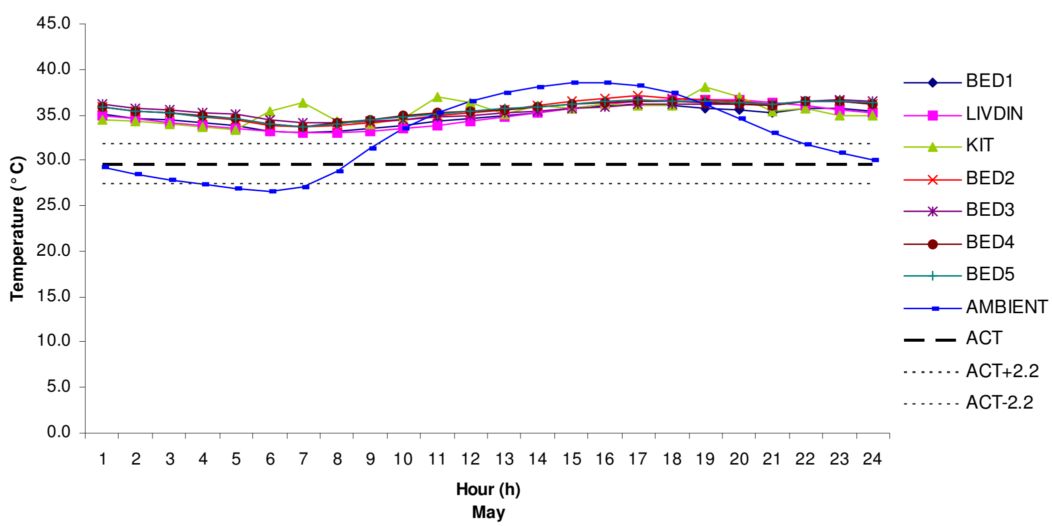
Comfort index	Month	Room						
		BED1	LIVDIN	KIT	BED2	BED3	BED4	BED5
Comfort fraction	JAN	0.32	0.45	0.63	0.17	0.23	0.29	0.5
	FEB	0.82	0.84	0.94	0.74	0.79	0.84	0.92
	MAR	1	1	0.98	1	1	1	1
	APR	0.73	0.68	0.60	0.62	0.62	0.60	0.55
	MAY	0.32	0.30	0.18	0.14	0.16	0.15	0.15
	JUN	0.1	0.09	-0.01	-0.11	-0.09	-0.07	-0.06
	JUL	0.52	0.51	0.38	0.36	0.38	0.38	0.39
	AUG	0.75	0.75	0.61	0.63	0.64	0.63	0.62
	SEP	0.82	0.76	0.65	0.72	0.72	0.71	0.64
	OCT	0.99	0.89	0.87	0.98	0.99	0.99	0.88
	NOV	0.93	0.95	1	0.89	0.94	0.95	0.98
	DEC	0.43	0.58	0.73	0.28	0.35	0.39	0.62

BED1=Bed room1, LIVDIN= Living and dining room, KIT=Kitchen, BED2=Bed room2, BED3=Bed room3, BED4=Bed room4, BED5=Bed room5



BED1=Bed room1, LIVDIN= Living and dining room, KIT=Kitchen, BED2=Bed room2, BED3=Bed room3, BED4=Bed room4, BED5=Bed room5

Fig. 5.67 Hourly variation of room temperatures of the non-conditioned bungalow in January - New Delhi (composite climate)



BED1=Bed room1, LIVDIN= Living and dining room, KIT=Kitchen, BED2=Bed room2, BED3=Bed room3, BED4=Bed room4, BED5=Bed room5

Fig. 5.68 Hourly variation of room temperatures of the non-conditioned bungalow in May - New Delhi (composite climate)

Table 5.42 Improvement in the performance of the non-conditioned bungalow due to building design and operational parameters - New Delhi (composite climate)

Parameter	Comfortable hours in a year (h)	Percentage increase in comfortable hours
Base case	4276	-
Orientation (longer axis)		
North-south	4192	-2.0
Glazing type		
Double clear	4129	-3.4
Double low-E	4398	2.9
Single reflective coated	4747	11.0
Double reflective coated	4629	8.3
Shading		
10%	4382	2.5
20%	4557	6.6
50%	4778	11.7
Wall type		
Concrete block wall	4245	-0.7
Thermocol (EPS) insulated brick wall	4004	-6.4
Autoclaved cellular concrete block	4015	-6.1
Roof type		
Uninsulated RCC roof	4019	-6.0
PUF insulated RCC roof	4488	5.0
Colour of external surface		
Cream	4392	2.7
Dark grey	4090	-4.3
White	4506	5.4
Air exchanges		
0.5 ach	3660	-14.4
1.5 ach	3945	-7.7
6 ach	4630	8.3
9 ach	4751	11.1
Internal gain		
No internal gain	4625	8.2
50%	4467	4.5
Scheduling of air exchanges	5171	20.9

Table 5.42 presents the change in the number of comfortable hours in a year due to various parameters for a bedroom (Bed2). The numbers in brackets show the percentage increase or decrease (-) of comfortable hours compared to the base case.

(a) Design Parameters

(i) Building orientation

East-west orientation of the building is better than the north-south orientation.

(ii) Glazing type

Single pane reflective coated glass is recommended over plain glass (base case). It shows an increase in the yearly comfortable hours by 11.0%. Insulation in the form of double glazing with reflective coated glass and double low-E glass improve the performance by 8.3 and 2.9% respectively.

(iii) Shading

Reducing solar radiation by shading windows can reduce heat gain and consequently increase the comfort. If windows are shaded by 50% throughout the year, an increase of 11.7% in the number of comfortable hours can be achieved.

(iv) Wall type

A brick wall (base case) is better than all other wall types.

(v) Roof type

Insulating the roof with polyurethane foam (PUF) insulation increases performance by 5.0% as compared to a roof with brick-bat-coba waterproofing. However, an uninsulated roof i.e., plain RCC roof decreases the number of comfortable hours by about 6.0%.

(vi) Colour of the external surface

White and cream colours are preferable to puff shade (base case) or dark grey. The percentage increases of comfortable hours compared to the base case are 5.4 and 2.7 respectively.

(vii) Air exchanges

An air change rate of 9 ach is better than one of 3 ach (base case). It gives an improvement of about 11.1%. Comparatively, an air change rate of 6 per hour gives an improvement of 8.3%.

(b) Operational Parameters

(a) Internal gain

Lowering the internal gain betters the performance. The performance increase is about 4.5% if the internal gains are reduced by 50%. Thus, energy efficient lights and equipment may be considered to reduce discomfort.

(ii) Scheduling of air changes

Scheduling of air changes to promote more air during cooler periods and controlling it during warmer periods (during daytime or summers) can lead to an increase in the number of comfortable hours by about 18.8%.

Combining all the best parameters (excluding building orientation and internal gain) can significantly improve the non-conditioned building's performance, resulting in an increase in the yearly number of comfortable hours by 27.9% in New Delhi.

5.5.5 Cold and Cloudy Climate (Representative city: Srinagar)

5.5.5.1 Commercial Building

A distribution of the annual and monthly heating and cooling loads of the commercial building in Srinagar is shown in Fig. 5.69. Although the heating load is predominant on an annual basis, the building tends to overheat in summer and hence cooling is also required (922.79 GJ/year). The heating season starts from November and ends in March, the heating load being highest in January. Heating as well as cooling loads are small in April, May and October. The cooling requirement is predominant from June to September, the cooling load being highest in July. June and August also display significantly high cooling loads. Out of twelve months, five months require only heating, four months require only cooling, and in remaining three months both heating and cooling are required. Figure 5.70 shows the distribution of percentage of loads through various building components on a monthly basis. The building loses net heat from October to April primarily due to air exchanges and surface losses. The heat loss through surfaces is generally higher than that through air exchanges. The building gains net heat from May to September, the main gain being from people and equipment. In the months of July and August, heat is also gained through surfaces. Air exchanges help to lose heat in these months and hence, a scheduling of air changes to promote ventilation in July and August, and their control in other months could lead to a reduction in the annual loads. It is essential to reduce surface gains and losses in all months to reduce the heating and cooling loads. This could be achieved by reducing glazing areas, using appropriate building materials, and through control of surfaces exposed to direct solar radiation.

Table 5.43 gives the floor-wise monthly and annual loads for the commercial building. It is seen that the usage pattern of the building has a significant impact on the loads. For instance, the energy required for heating is maximum on the ground floor. This is because the shutters are opened frequently on ground floor resulting in high heat loss due to air exchanges. Such loss may be reduced by sealing all cracks, providing air lock lobbies, etc. on ground floor. Similarly, the loads of the second and third floor are significantly higher than those of other floors as they are occupied on a 24-hour basis throughout the week.

The effects of building parameters on the annual loads of the building are presented in Table 5.44 for the Srinagar climatic conditions. The consequent percentage load reduction for each parameter compared to the base case are also tabulated. It may be noted that the total annual load of the building is quite high. Energy can be well saved by even one percent reduction in this load. The following guidelines are recommended for a commercial building in Srinagar, which belongs to cold and cloudy climatic zone:

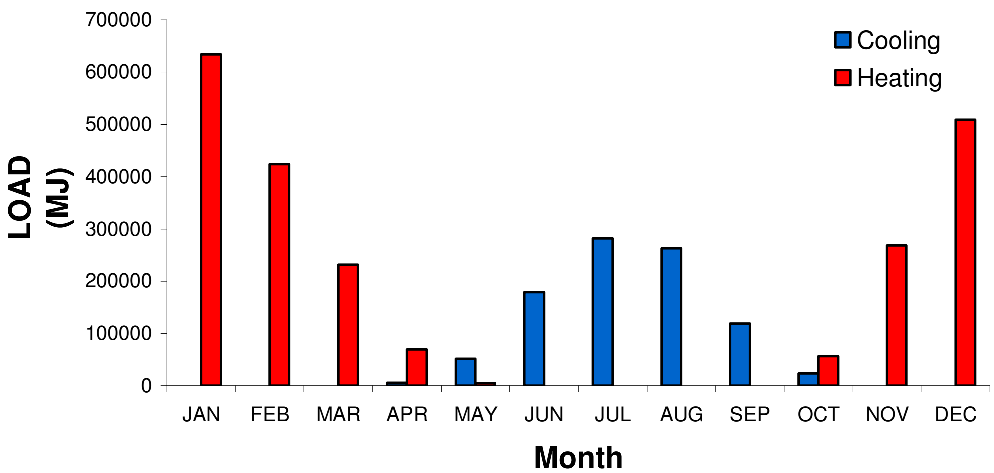
(b) Design Parameters

(i) Building orientation

The building (Fig.5.1) with its glazed curtain wall facing south-west (base case) is recommended. Other orientations show an increase in annual loads.

(ii) Glazing type

A double glazing with low-E glass gives the best performance. It reduces the load by 20.6% compared to single pane reflective coated glass (base case). Double glazing and double reflective coated glass decrease the annual load by 16.0 and 20.1 respectively.



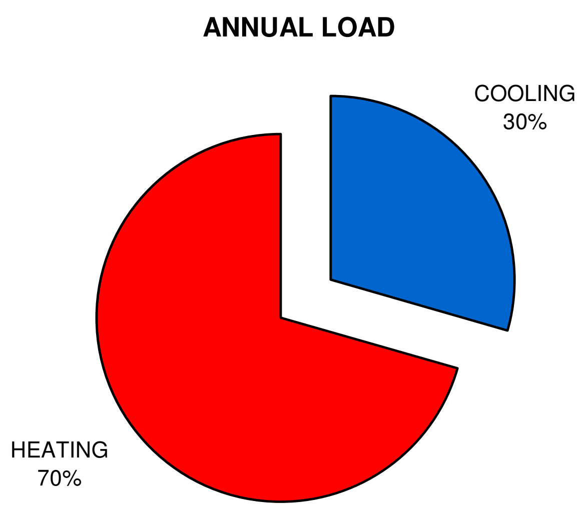


Fig. 5.69 Monthly and annual heating and cooling loads of the commercial building -Srinagar (cold and cloudy climate)

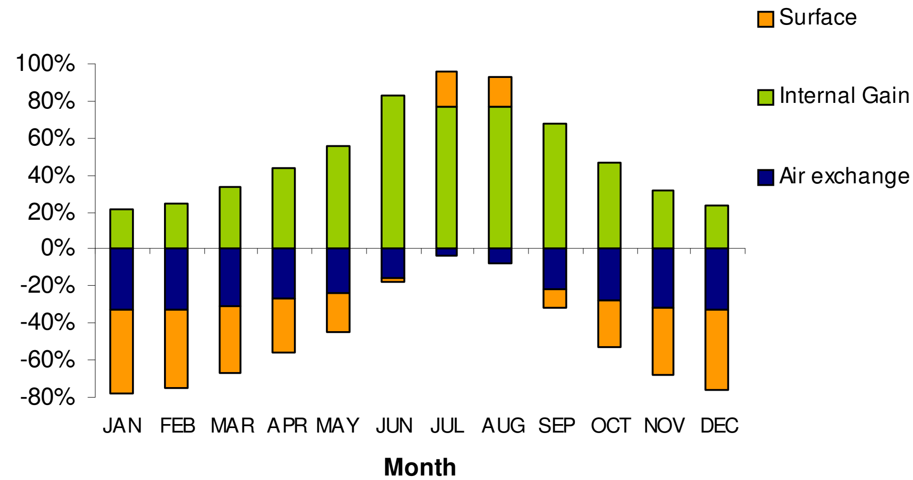


Fig. 5.70 Component-wise distribution of percentage heat gains and losses on a monthly basis of the commercial building – Srinagar (cold and cloudy climate)

(iii) Window size

The reduction of the glazing size to 1.2 m height, compared to a fully glazed curtain wall, decreases the annual load by 11.8%. Thus, the use of larger expanse of glass in such a building is not desirable as it leads to higher annual loads. This is due to high internal gains of the commercial building.

(iv) Shading

The shading effect is insignificant in this climate for the commercial building because the internal gain of the building is very high.

(v) Wall type

Walls having a low U-value (insulating type such as autoclaved cellular concrete block) reduce the load compared to the concrete block wall (base case) by 10.9%. Thus insulation of walls is recommended.

(vi) Colour of the external surface

Dark colour of the external surfaces does not show any significant effect as the building has high internal gains.

(vii) Air exchanges

A lower air change rate of 0.5 ach is better than air change rates of 1, 2 and 4 ach. The percentage reduction in the annual load is 8.8 compared to the base case of 1 ach.

(b) Operational Parameters

The operational parameters such as internal gain, set point and scheduling of air changes can help in reducing the annual load of the building. The effects are summarised as follows.

(i) Internal gain

In cold climates, the internal gains help to keep the building warm and hence are preferable.

Table 5.43 Floor wise distribution of monthly and annual loads of the commercial building - Srinagar (cold and cloudy climate)

Month	Cooling load (MJ)								
	GR	F1	F2	F3	F4	F5	F6	F7	Total
JAN	0	0	0	0	0	0	0	0	0
FEB	0	0	0	0	0	0	0	0	0
MAR	0	0	0	0	0	0	0	0	0
APR	0	0	1478	3339	1229	0	0	0	6047
MAY	0	3517	11508	14201	11829	2142	7977	0	51173
JUN	9883	17572	34228	36904	27459	17183	27999	7399	178626
JUL	25395	26280	53368	55946	37098	27543	40478	15708	281816
AUG	19102	25444	49888	52270	36722	26267	39097	14207	262997
SEP	1092	12179	23721	26577	21004	11248	19520	3214	118555
OCT	0	583	6454	8913	6040	95	1489	0	23575
NOV	0	0	0	0	0	0	0	0	0
DEC	0	0	0	0	0	0	0	0	0
Total	55472	85575	180645	198149	141382	84479	136559	40528	922789

Month	Heating load (MJ)								
	GR	F1	F2	F3	F4	F5	F6	F7	Total
JAN	178128	35510	101613	104134	35993	57958	60757	59898	633991
FEB	123511	21975	70088	71399	20343	37772	37959	40963	424010
MAR	67180	9604	41164	42306	6464	20666	17327	26949	231659
APR	17256	2278	14728	15328	1092	4683	3067	10709	69141
MAY	938	91	1205	1325	3	270	62	1332	5226
JUN	0	0	0	0	0	0	0	0	0
JUL	0	0	0	0	0	0	0	0	0
AUG	0	0	0	0	0	0	0	0	0
SEP	0	0	0	0	0	0	0	0	0
OCT	18088	2170	11088	12006	864	3431	2474	6473	56594
NOV	84242	11018	45823	46936	8254	22645	20549	28866	268332
DEC	147753	25877	86554	88122	24981	43914	45030	46678	508909
Total	637097	108521	372262	381556	97994	191339	187225	221867	2197862

GR=Ground Floor, F1=First floor, F2=Second floor, F3=Third Floor, F4=Fourth floor, F5=Fifth floor, F6=Sixth Floor, F7=Seventh floor

Table 5.44 Annual savings due to building design and operational parameters for the commercial building- Srinagar (cold and cloudy climate)

Parameter	Annual load (MJ)			Energy saving	
	Cooling	Heating	Total	(MJ)	(%)
Base case	922789	2197862	3120651	--	--
Orientation (longer axis)					
North-south	834912	2386840	3221752	-101100	-3.2
Northeast-southwest	798639	2398312	3196951	-76299	-2.4
East-west	889677	2298717	3188394	-67743	-2.2
Glazing type					
Single clear	1171012	1989599	3160611	-39959	-1.3
Double clear	1290793	1329102	2619895	500756	16.0
Double low-E	1149217	1327081	2476298	644353	20.6
Double reflective coated	1039267	1452705	2491972	628679	20.1
Glazing size (restricted to 1.2m height)	845570	1906361	2751931	368721	11.8
Shading					
10%	879800	2238764	3118564	2087	0.1
20%	837786	2280564	3118350	2301	0.1
50%	718081	2410994	3129074	-8423	-0.3
Wall type					
Autoclaved cellular concrete block	1380828	1399604	2780432	340219	10.9
Colour of external surface					
Dark grey	1020408	2094909	3115317	5334	0.2
Air change rate					
0.5	956856	1890403	2847259	273392	8.8
2	879446	2813760	3693206	-572555	-18.3
4	852113	4034756	4886869	-1766218	-56.6
Internal gain					
10%	109948	4140111	4250060	-1129408	-36.2
50%	371609	3187899	3559509	-438858	-14.1
No internal gain	68812	4405124	4473937	-1353285	-43.4
Set point - cooling: 25 °C - heating: 20 °C	739562	1971306	2710868	409783	13.1
Scheduling of air exchanges	907997	1971302	2879299	241352	8.4

(ii) Set Point

The annual load of the building reduces if the set points for comfort cooling and heating are relaxed. If the cooling and heating set points of 25 and 20^{0}C respectively are used (compared to 24 and 21^{0}C), the annual load is reduced by 13.1%. Thus, a change in the expectation of comfort can lead to significant savings.

(iii) Scheduling of air exchanges

The scheduling of air changes to control air entry during cooler periods (such as nights or winters) and promote the same during warmer periods (during daytime or summer) can reduce annual loads by 8.4%.

The combination of all design and operational parameters discussed (excluding building orientation and internal gain) results in a load reduction of 38.4%.

5.5.5.2 Industrial Building

Table 5.45 gives the yearly minimum, maximum and average temperatures, and the number of comfortable hours in a year for the shed and store of the industrial building for the Srinagar climate. The average temperature of the store room is about 3.1 °C higher than the ambient, while that of the shed is about 7.5 °C. The winters are very cool and minimum temperatures can be as low as 1.6 °C in store and 5.3 °C in the shed, making heating essential in winters. The yearly maximum temperatures of both rooms exceed 29.8 °C and the shed can attain a temperature as high as 34.1 °C. Hence cooling is required in summers to alleviate discomfort. The shed is comfortable for about 49% in terms of number of comfortable hours in a year indicating discomfort for nearly half the time. The store is slightly more comfortable i.e. for 53% of the year. The values of the monthly comfort fractions (Table 5.46) show that the shed is very uncomfortable in the month of January with a CF of -0.23 (negative values of CF indicate acute discomfort). It is comfortable in the months of April, May, August and October (CF values being more than 0.9). The store is uncomfortably cold for a number of months (November to March), January being the most uncomfortable month. June to September are comfortable months for the store. The hourly values of room temperatures for a winter typical day of January and summer day of May are plotted in Figs. 5.71 and 5.72 respectively. It is seen that in January, both the rooms are extremely cold and well below the comfort zone. The temperature in the store is always lower than 5 °C, while the shed temperature varies and is about 10 °C. Hence, heating is required in January and the air change rate should be minimum in this month. In May, both the rooms are more or less comfortable.

Table 5.47 presents the change in the number of comfortable hours in a year due to various parameters for the shed. The corresponding percentage increase or decrease (-) of comfortable hours compared to the base case is also shown in the table. The effect of building orientation, glazing type, wall type, roof type, colour of external surfaces, air exchanges and shading of windows do not show any significant effect in this climate due to the large internal gain of the building. Single pane reflective coated glass is marginally better in increasing the yearly comfortable hours (by about 2%) than plain glass. Having an insulated roof increases the yearly comfortable hours by 2.6% compared to the base case. If the internal gain is 20% of the base case, then the performance of the building improves by 14.5%. Promoting higher air changes when the ambient air temperature is within the comfortable range compared to indoor temperature improves the performance of the building by 31.8% compared to a constant air change rate.

Table 5.45 Performance of the industrial building on an annual basis- Srinagar (cold and cloudy climate)

Room	Yearly room temperature(℃)			Comfortable hours in a year(h)	Percentage of yearly comfortable hours
	MIN	MAX	AVG		
Shed	5.3	34.1	20.4	4245	49
Store	1.6	29.8	16.0	4666	53
Ambient	-1.1	28.8	12.9	3911	45

MIN = Minimum, MAX = Maximum, AVG = Average

Table 5.46 Performance of the industrial building on a monthly basis- Srinagar (cold and cloudy climate)

Comfort index	Month	Room	
		Shed	Store
Comfort fraction	JAN	-0.23	-1.59
	FEB	0.07	-1.12
	MAR	0.70	-0.38
	APR	1	0.26
	MAY	0.90	0.75
	JUN	0.48	0.99
	JUL	0.19	0.95
	AUG	0.98	0.96
	SEP	0.73	0.91
	OCT	0.98	0.30
	NOV	0.60	-0.60
	DEC	0.02	-1.29

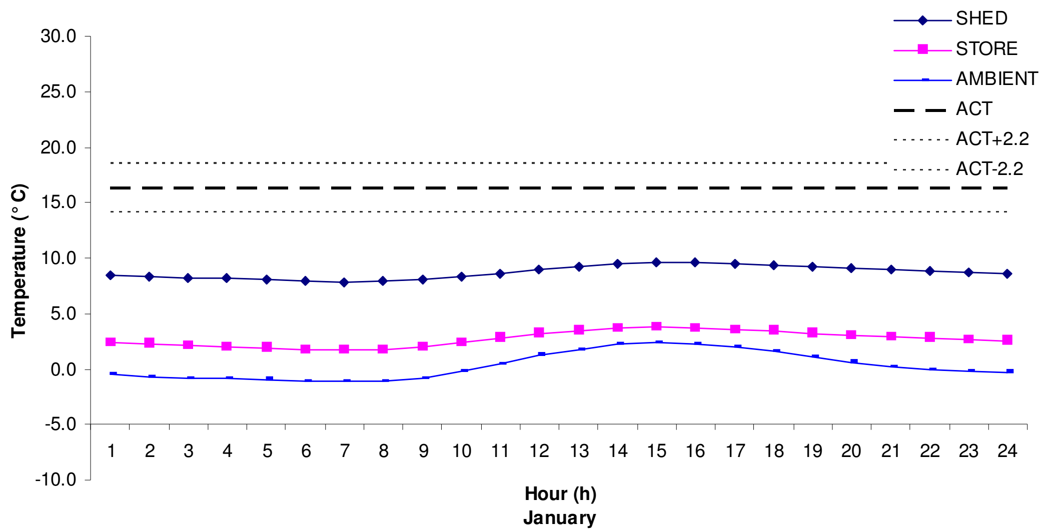


Fig. 5.71 Hourly variation of room temperatures of the industrial building in January - Srinagar (cold and cloudy climate)

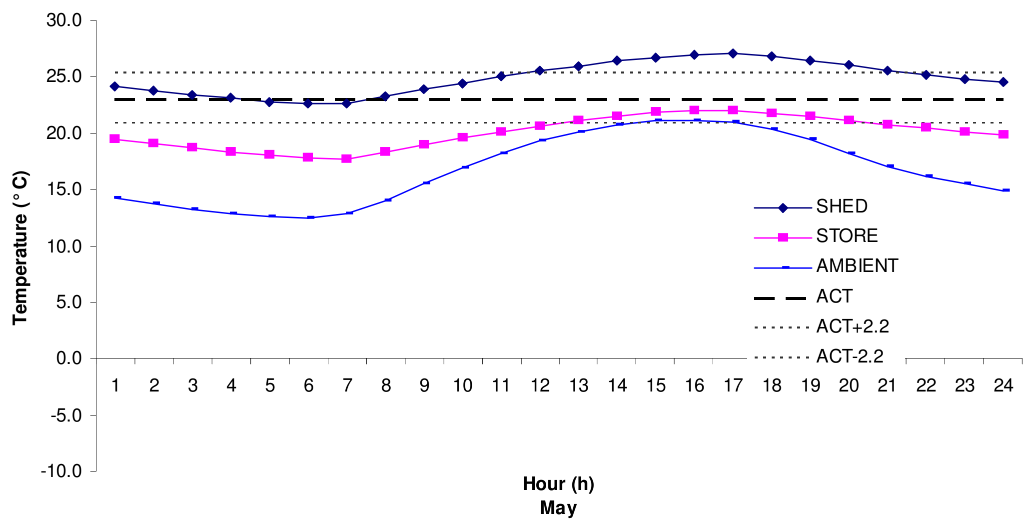


Fig. 5.72 Hourly variation of room temperatures of the industrial building in May - Srinagar (cold and cloudy climate)

Table 5.47 Improvement in the performance of the industrial building due to building design and operational parameters- Srinagar (cold and cloudy climate)

Parameter	Comfortable hours in a year (h)	Percentage increase in comfortable hours
Base case	4245	--
Orientation		
Northwest-southeast	4266	0.5
Northeast-southwest	4253	0.2
East-west	4301	1.3
Glazing type		
Single reflective	4330	2.0
Double clear	4254	0.2
Double low-E	4264	0.4
Double reflective coated	4267	0.5
Shading		
10%	4265	0.5
20%	4288	1.0
Wall type		
Thermocol (EPS) insulated brick wall	4246	0.0
Concrete block wall	4279	0.8
Autoclaved cellular concrete block	4238	-0.2
Roof type		
RCC with bitumen felt water proofing	4221	-0.6
RCC with PUF insulation	4355	2.6
Colour of external surface		
White	4382	3.2
Cream	4360	2.7
Dark grey	4160	-2.0
Air exchanges		
3 ach	4363	2.8
9 ach	4495	5.9
12 ach	4675	10.1
Internal gain		
20%	4862	14.5
40%	4796	13.0
Scheduling of air exchanges	5595	31.8

The combined effect of all the best design and operational parameters (excluding building orientation and internal gain), results in an increase of the yearly comfortable hours of the shed by 40.4% compared to the base case.

5.5.5.3 Residential Building (Bungalow)

(A) Conditioned building

A distribution of the annual and monthly heating and cooling loads of the conditioned bungalow in Srinagar is shown in Fig. 5.73. The figure shows that on an annual basis, the heating load is predominant (91%) with heating being required throughout the year except in June, July and August. The load profiles generally follow the climatic conditions. For example, the highest heating load occurs during the peak winter period in January. The heating load in December is also quite high. Only cooling loads occur in the summer months from June to August. The monthly variation of the percentage of loads through the various building components is presented in Fig. 5.74. The heating requirement is primarily due to surface losses. During most of the year, the combined heat loss through surfaces and air exchanges is higher than heat gain due to people and equipment. Therefore, insulation of surfaces and control of air exchanges could lower the heating loads. In May and September, which represents the spring and autumn months respectively, the heat gains and losses more or less balance each other and hence, the loads are small. In the summer months of July and August, heat gain through surfaces needs to be minimised. It could be done by reducing the glazing area and by shading of surfaces exposed to direct solar radiation.

Table 5.48 presents the room-wise annual loads for the conditioned bungalow in Srinagar. It is seen that the heating load of the living and dining room is significantly higher than that of other rooms. This is because of the fact that this room is very large and is also partly double storeyed. The heating load of the kitchen is the least due to internal gains from appliances (refrigerator and cooking range). A comparison of the bedrooms shows that the first floor bedroom (Bed3) facing north and having only one window is the warmest. The ground floor bedroom (Bed1) in the northwest corner of the house is also warm. The bedroom located directly above it is the coolest. This is primarily due to heat losses from larger exposed surfaces and glazed area.

The effects of building parameters on annual loads are presented in Table 5.49. The table also shows the consequent percentage load reduction for each parameter compared to the base case. Based on the results, the following are recommended for a conditioned bungalow in Srinagar:

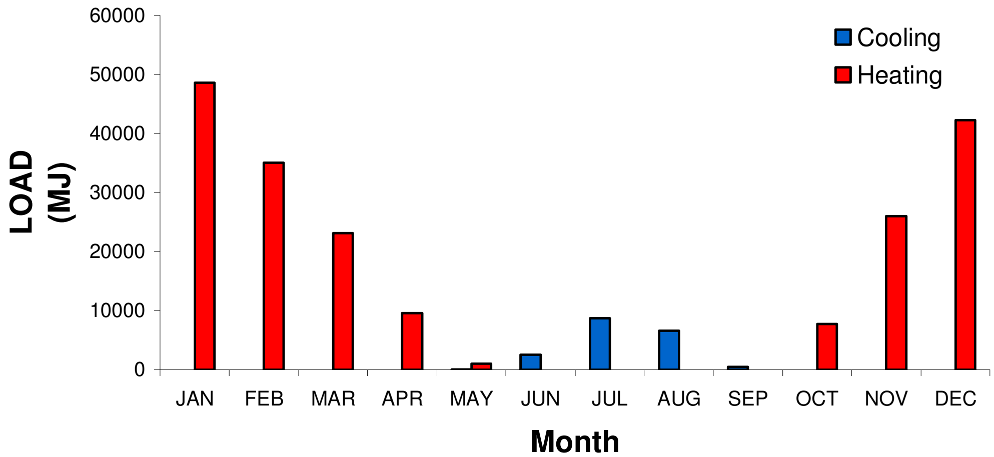
(a) Design Parameters

(i) Building orientation

East-west orientation (base case) is better than a north-south orientation.

(ii) Glazing type

Double-glazing with low-E coated glass gives the best performance. It reduces the load by 20.2% in comparison with plain glass (base case). Single reflective coated glazing is not recommended. Double-glazing with reflective coated glass and double-glazing with clear glass can also be used to reduce the loads by 16.7 and 19.1% respectively.



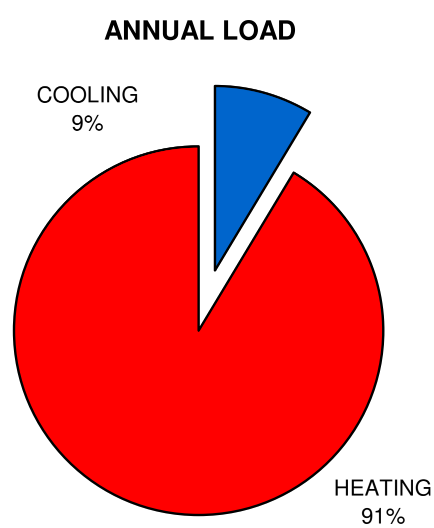


Fig. 5.73 Monthly and annual heating and cooling loads of the conditioned bungalow - Srinagar (cold and cloudy climate)

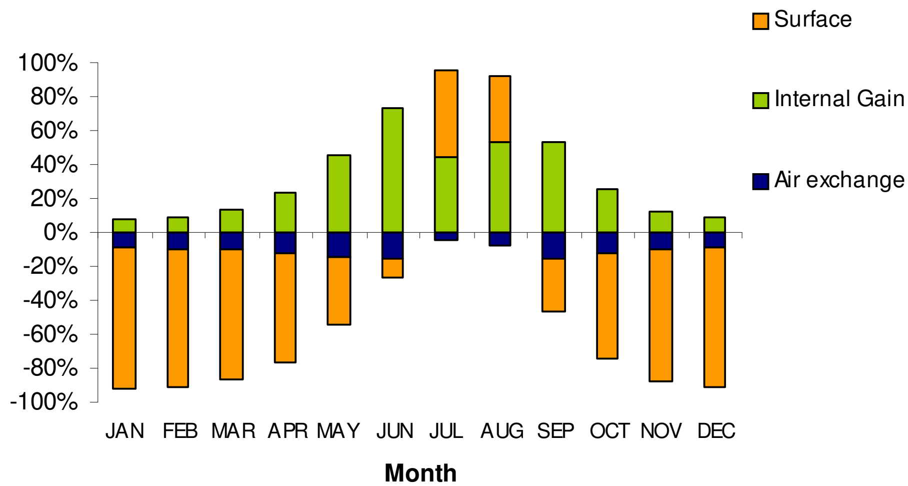


Fig. 5.74 Component-wise distribution of percentage heat gains and losses on a monthly basis of the conditioned bungalow- Srinagar (cold and cloudy climate)

Table 5.48 Room-wise distribution of the monthly and annual loads of the conditioned bungalow - Srinagar (cold and cloudy climate)

Month	Cooling load (MJ)							
	BED1	LIVDIN	KIT	BED2	BED3	BED4	BED5	Total
JAN	0	0	0	0	0	0	0	0
FEB	0	0	0	0	0	0	0	0
MAR	0	0	0	0	0	0	0	0
APR	0	0	0	0	0	0	0	0
MAY	0	0	60	0	0	0	0	60
JUN	47	713	789	277	316	197	203	2542
JUL	459	2851	1497	1119	1019	883	900	8728
AUG	270	2252	1297	780	772	602	659	6633
SEP	1	9	487	6	12	4	6	525
OCT	0	0	7	0	0	0	0	7
NOV	0	0	0	0	0	0	0	0
DEC	0	0	0	0	0	0	0	0
Total	777	5825	4137	2182	2119	1686	1769	18495

Month	Heating load (MJ)							
	BED1	LIVDIN	KIT	BED2	BED3	BED4	BED5	Total
JAN	4187	20852	2908	6	4223	5299	5219	48634
FEB	3094	14916	2011	4	3040	3864	3757	35029
MAR	2112	10079	1134	3	1935	2561	2461	23168
APR	964	4262	467	1	686	1043	977	9592
MAY	59	737	119	0	13	24	23	1010
JUN	0	3	0	0	0	0	0	3
JUL	0	0	0	0	0	0	0	0
AUG	0	0	0	0	0	0	0	0
SEP	0	0	0	0	0	0	0	0
OCT	864	3005	382	1	628	984	731	7768
NOV	2429	10712	1302	3	2330	3037	2752	26026
DEC	3724	17860	2409	5	3711	4690	4541	42225
Total	17434	82426	10731	24	16565	21502	20461	193452

BED1=Bed room1, LIVDIN= Living and dining room, KIT=Kitchen, BED2=Bed room2, BED3=Bed room3, BED4=Bed room4, BED5=Bed room5

Table 5.49 Annual savings due to building design and operational parameters

for the conditioned bungalow - Srinagar (cold and cloudy climate)

Parameter	Annual load (MJ)			Energy saving	
	Cooling	**Heating**	**Total**	**(MJ)**	**(%)**
Base case	18495	193452	211948	--	--
Orientation (longer axis)					
North-south	19860	197797	217657	-5710	-2.7
Glazing type					
Double clear	20635	150914	171549	40399	19.1
Single reflective coated	12540	207456	219996	-8048	-3.8
Double reflective coated	14725	161847	176572	35376	16.7
Double low-E	17355	151847	169202	42746	20.2
Shading					
10%	16847	197154	214001	-2053	-1.0
20%	15239	200872	216110	-4163	-2.0
50%	10978	212205	223183	-11235	-5.3
Wall type					
Thermocol (EPS) insulated brick wall	20055	135295	155350	56598	26.7
Concrete block wall	18461	241827	260288	-48340	-22.8
Autoclaved cellular concrete block	20176	139658	159834	52114	24.6
Roof type					
Uninsulated RCC roof	20096	206701	226797	-14849	-7.0
PUF insulated RCC roof	15791	168847	184637	27310	12.9
Colour of external surface					
White	15137	201122	216259	-4311	-2.0
Cream	16228	198554	214782	-2834	-1.3
Dark grey	22063	186040	208103	3845	1.8
Air exchanges					
1.0 ach	17444	211442	228886	-16938	-8.0
1.5 ach	16525	228943	245469	-33521	-15.8
Internal gain					
50%	12331	207650	219981	-8033	-3.8
No internal gain	7689	222912	230601	-18653	-8.8
Set point - cooling: 26 ℃ - heating: 19 ℃	175620	11120	186740	25208	11.9
Scheduling of air exchanges	17152	193458	210610	1338	0.6

(iii) Shading

Shading of windows is not desirable in this cold and cloudy climate. If 50% of the window areas are shaded throughout the year, the annual load increases by 5.3%.

(iv) Wall type

Insulation of walls helps to improve the performance significantly. Thermocol insulation can save annual loads by 26.7% and autoclaved cellular concrete block walls (e.g., Siporex) can save 24.6% as compared to a brick wall (base case). Plain concrete block wall increases the load by 22.8% and hence needs to be avoided.

(v) Roof type

Insulation of the roof improves the performance of the building. Polyurethane foam (PUF) insulation brings down the loads by 12.9%. In contrast, a plain uninsulated RCC roof increases the load by 7.0%.

(vi) Colour of the external surface

Dark grey colour is suitable due to its higher absorptivity.

(vii) Air exchanges

A lower air change rate of 0.5 ach is desirable for reducing the loads.

(b) Operational Parameters

The operational parameters such as internal gain, set point and scheduling of air changes can help in reducing the annual load of the building. The effects are summarised as follows.

(i) Internal gain

In cold climates, internal gains help to keep the building warm and hence are preferable.

(ii) Set point

Lowering the operating parameters for comfort cooling and heating can reduce the cooling loads by 11.9%. Thus, a change in the expectation of comfort can lead to significant savings.

(iii) Scheduling of air exchanges

The scheduling of air changes does not have a significant effect on the annual load.

The combination of all design and operational parameters discussed (excluding building orientation and internal gain), results in a load reduction of 73.4% for a conditioned bungalow in Srinagar.

(B) Non-conditioned building

The yearly minimum, maximum and average temperatures and the number of comfortable hours in a year for all the rooms are given in Table 5.50 for a non-conditioned bungalow in the Srinagar climatic conditions. It is seen that the yearly minimum values of room temperatures are about 1.8 to 3.4°C indicating acute discomfort in winters. The room attaining the lowest temperature of 1.8 °C is the bedroom on the first floor (Bed2), in the northwest corner of the house. The maximum temperatures are quite comfortable ranging from 27.6 to 29.5 °C. The warmest room is the kitchen, attaining a maximum temperature of 29.5 °C and average temperature of 16.7 °C in a year. Thus, the minimum and maximum values of room temperatures are higher than those of the ambient. In terms of number of hours in a year,

Table 5.50 Performance of the non-conditioned bungalow on an annual basis

- Srinagar (cold and cloudy climate)

Room	Yearly room temperature(℃)			Comfortable hours in a year(h)	Percentage of yearly comfortable hours
	MIN	MAX	AVG		
BED1	2.6	27.6	15.6	5112	58
LIVDIN	2.3	28.3	15.8	5134	59
KIT	3.4	29.5	16.7	5090	58
BED2	1.8	28.7	15.8	5035	57
BED3	2.2	28.7	15.9	5053	58
BED4	2.4	28.3	15.9	5128	59
BED5	2.5	28.4	16.3	5138	59
Ambient	-1.1	28.8	12.9	3911	45

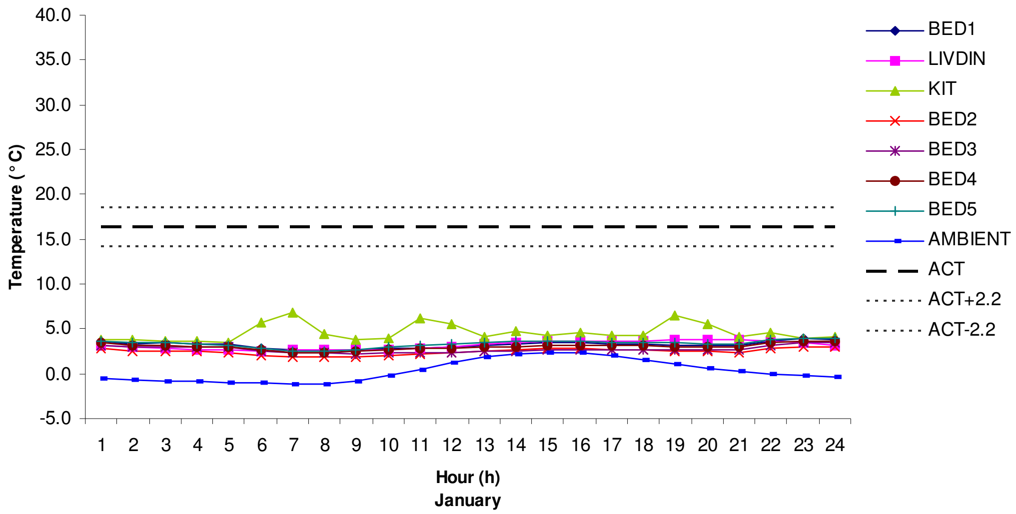
MIN = Minimum, MAX = Maximum, AVG = Average
BED1=Bed room1, LIVDIN= Living and dining room, KIT=Kitchen, BED2=Bed room2, BED3=Bed room3, BED4=Bed room4, BED5=Bed room5

Table 5.51 Performance of the non-conditioned bungalow on a monthly basis
(a) Srinagar (cold and cloudy climate)

Comfort index	Month	Room						
		BED1	LIVDIN	KIT	BED2	BED3	BED4	BED5
Comfort fraction	JAN	-1.48	-1.49	1.18	-1.65	-1.59	-1.53	-1.46
	FEB	-1.02	-0.99	0.72	-1.13	-1.08	-1.03	-0.94
	MAR	-0.36	-0.32	0.09	-0.38	-0.34	-0.31	-0.24
	APR	0.27	0.28	0.45	0.32	0.35	0.36	0.40
	MAY	0.71	0.73	0.84	0.84	0.84	0.84	0.86
	JUN	1	1	1	1	1	1	1
	JUL	1	1	0.98	1	1	1	1
	AUG	1	1	0.99	1	1	1	1
	SEP	0.93	0.94	0.98	0.97	0.99	0.98	0.99
	OCT	0.21	0.36	0.51	0.23	0.29	0.28	0.44
	NOV	-0.61	-0.45	0.26	-0.71	-0.63	-0.61	-0.41
	DEC	-1.2	-1.17	0.88	-1.36	-1.29	-1.24	-1.13

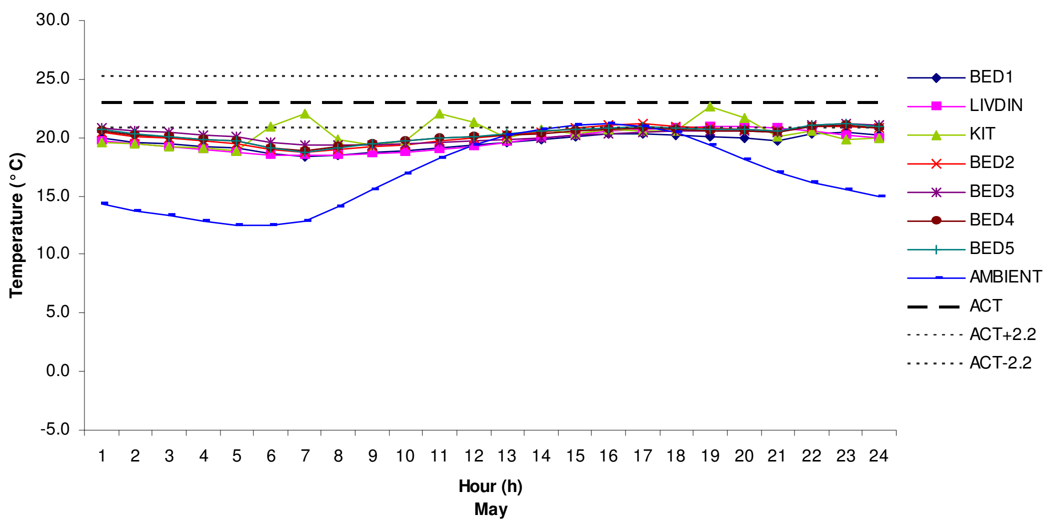
BED1=Bed room1, LIVDIN= Living and dining room, KIT=Kitchen, BED2=Bed room2, BED3=Bed room3, BED4=Bed room4, BED5=Bed room5

all the rooms are comfortable for 57 to 59% of the time. In other words, all rooms are uncomfortable for more than 40% of the year. The performance of the building on a monthly basis is presented in terms of the comfort fraction (CF) in Table 5.51. It is seen that the rooms are very uncomfortable in winters (November to March), as negative CF values indicate acute discomfort. January is the most uncomfortable month with CF values ranging from -1.18 to -1.59. Hence, heating is a prime requirement from the design point of view. The house is comfortable from June to September. The hourly variation of room temperatures for a typical winter day of January and summer day of May are plotted in Figs. 5.75 and 5.76 respectively. It is seen that in January, all the rooms are uncomfortably cool throughout the day with temperatures being less than 5°C. Thus, heating is required in winter and the air change rate should be minimum in this season. In May, all the rooms are very close to the lower limit of the comfort zone.



BED1=Bed room1, LIVDIN= Living and dining room, KIT=Kitchen, BED2=Bed room2, BED3=Bed room3, BED4=Bed room4, BED5=Bed room5

Fig. 5.75 Hourly variation of room temperatures of the non-conditioned bungalow in January - Srinagar (cold and cloudy climate)



BED1=Bed room1, LIVDIN= Living and dining room, KIT=Kitchen, BED2=Bed room2, BED3=Bed room3, BED4=Bed room4, BED5=Bed room5

Fig. 4.76 Hourly variation of room temperatures of the non-conditioned bungalow in May - Srinagar (cold and cloudy climate)

Table 5.52 presents the change in the number of comfortable hours in a year due to various parameters for a bedroom (Bed2). The corresponding percentage increase or decrease (-) in comfortable hours compared to the base case is shown in the table. None of the parameters show any significant effect, which implies that the **base case design** of the bungalow is reasonably satisfactory in this climate.

Table 5.52 Improvement in the performance of the non-conditioned bungalow due to building design and operational parameters - Srinagar (cold and cloudy climate)

Parameter	Comfortable hours in a year (h)	Percentage increase in comfortable hours
Base case	5035	-
Orientation (longer axis)		
North-south	4893	-2.8
Glazing type		
Double clear	4852	-3.6
Double low-E	5045	0.2
Single reflective coated	5103	1.4
Double reflective coated	5116	1.6
Shading		
10%	5107	1.4
20%	5110	1.5
50%	5061	0.5
Wall type		
Concrete block wall	4937	-1.9
Thermocol (EPS) insulated brick wall	4747	-5.7
Autoclaved cellular concrete block	4805	-4.6
Roof type		
Uninsulated RCC roof	4861	-3.5
PUF insulated RCC roof	5071	0.7
Colour of external surface		
Cream	5101	1.3
Dark grey	4861	-3.5
White	5105	1.4
Air exchanges		
0.5 ach	4869	-3.3
1.0 ach	4925	-2.2
Internal gain		
No internal gain	5078	0.9
50%	5092	1.1

5.5.6 Cold and Sunny Climate (Representative city: Leh)

5.5.6.1 Commercial Building

Figure 5.77 shows a distribution of the annual and monthly heating and cooling loads of a commercial building located at Leh. On an annual basis, the heating load is predominant. It is significantly high during the months from October to April, being maximum in January. The months from May to September require comparatively less heating. In addition to heating, cooling is also required for about four months, from June to September. Figure 5.78 shows the distribution of percentage of loads through various building components on a monthly basis. The building loses net heat throughout the year primarily due to air exchanges and surface losses. The heat loss through surfaces is generally higher than that through air exchanges. In the months of July and August, the heat gains and losses more or less balance each other out, the main gain being due to people and equipment. During the other months, annual loads can be reduced by controlling air exchanges and surface losses. This could be achieved by reducing glazing areas, using appropriate building materials, and controlling the surfaces exposed to direct solar radiation.

The floor-wise monthly and annual loads are presented in Table 5.53 It is seen that the usage pattern of the building has a significant impact on the loads. For instance, the energy required for heating is maximum on the ground floor. This is because the shutters are frequently opened on ground floor, resulting in a high heat loss due to air exchanges. Measures such as sealing all cracks, providing air lock lobbies, etc. on ground floor can reduce such heat loss. Similarly, the loads of the second and third floor are significantly higher than those of the other floors as they are occupied on a 24-hour basis throughout the week.

Table 5.54 presents the effects of building parameters on the annual loads of the commercial building for Leh conditions. The consequent percentage load reductions compared to the base case are also tabulated. It may be noted that the total annual load of the building is quite high and hence even a one percent reduction in this load would result in significant energy savings. The following guidelines are recommended for improving the performance of the commercial building for the Leh climate:

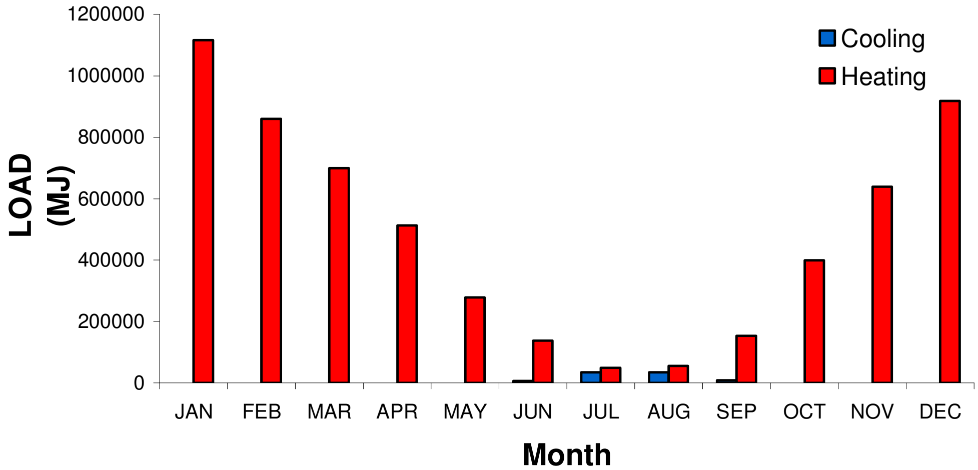
(a) Design Parameters

(i) Building orientation

Appropriate orientation of the building can reduce the annual load significantly. The building (Fig.5.1) with its glazed curtain wall facing south-west (base case) is recommended over other orientations.

(ii) Glazing type

Both double-glazing with low-E glass and double clear glass perform better than single pane reflective coated glass (base case); the annual load is reduced by 29.7% in both cases. Plain glass and double reflective coated glass also decrease the annual load by 7.2 and 25.4 respectively.



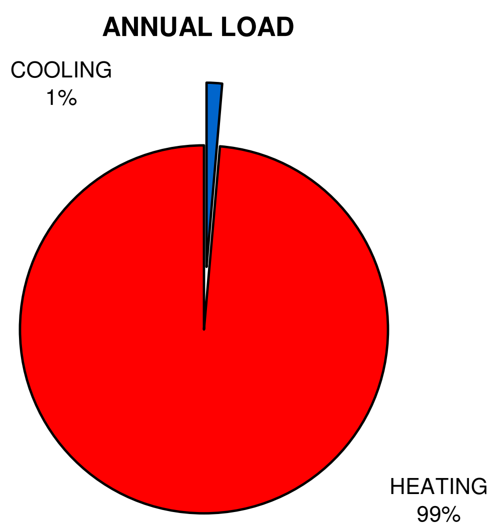


Fig. 5.77 Monthly and annual heating and cooling loads of the commercial building -Leh (cold and dry climate)

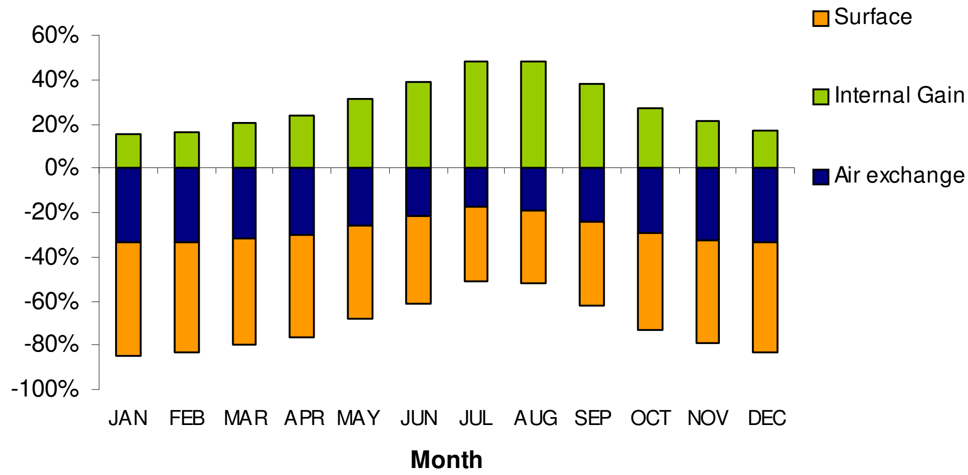


Fig. 5.78 Component-wise distribution of percentage heat gains and losses on a monthly basis of the commercial building – Leh (cold and dry climate)

Table 5.53 Floor wise distribution of the monthly and annual loads of the commercial building - Leh (cold and dry climate)

Month	Cooling load (MJ)								
	GR	F1	F2	F3	F4	F5	F6	F7	Total
JAN	0	0	0	0	0	0	0	0	0
FEB	0	0	0	0	0	0	0	0	0
MAR	0	0	0	0	0	0	0	0	0
APR	0	0	0	0	0	0	0	0	0
MAY	0	0	0	6	0	0	0	0	6
JUN	0	0	1534	3401	957	0	0	0	5893
JUL	0	454	8087	10949	8154	790	5437	0	33871
AUG	0	396	8308	11282	8412	745	5158	0	34301
SEP	0	0	2383	4206	1583	0	33	0	8205
OCT	0	0	0	15	0	0	0	0	15
NOV	0	0	0	0	0	0	0	0	0
DEC	0	0	0	0	0	0	0	0	0
Total	0	850	20312	29860	19106	1535	10628	0	82291

Month	Heating load (MJ)								
	GR	F1	F2	F3	F4	F5	F6	F7	Total
JAN	335259	63826	174469	178341	66427	95462	106071	95428	1115284
FEB	268276	47500	138344	140984	48059	70437	76172	70219	859990
MAR	223315	38232	114101	115390	35279	56810	58422	57821	699369
APR	167668	26507	85522	86725	22043	41009	39571	43124	512171
MAY	94480	13758	47187	47344	8414	21792	17109	27757	277840
JUN	49381	6303	25935	25867	2694	8189	5788	13583	137740
JUL	19402	2243	9720	9749	351	2039	1100	4117	48720
AUG	23316	2674	9972	10116	369	2302	1360	4657	54766
SEP	56770	6912	28752	28541	3260	8792	6843	13299	153167
OCT	138321	20098	65259	65704	14216	31100	28992	36117	399806
NOV	210467	34418	101885	103109	30414	51515	53521	53524	638853
DEC	287767	49286	151585	154298	49934	73305	79488	72890	918553
Total	1874423	311756	952731	966167	281459	462751	474437	492535	5816259

GR=Ground Floor, F1=First floor, F2=Second floor, F3=Third Floor, F4=Fourth floor, F5=Fifth floor, F6=Sixth Floor, F7=Seventh floor

Table 5.54 Annual savings due to building design and operational parameters

for the commercial building- Leh (cold and dry climate)

Parameter	Annual load (MJ)			Energy saving	
	Cooling	Heating	Total	(MJ)	(%)
Base case	82291	5816259	5898550	--	--
Orientation (longer axis)					
North-south	56723	6312067	6368790	-470240	-8.0
Northeast-southwest	41363	6378534	6419897	-521347	-8.8
East-west	77314	6057868	6135182	-236632	-4.0
Glazing type					
Single clear	168325	5307770	5476094	422456	7.2
Double clear	241331	3907648	4148979	1749571	29.7
Double low-E	181171	3963253	4144425	1754126	29.7
Double reflective coated	136910	4264346	4401255	1497295	25.4
Glazing size (restricted to 1.2m height)	65854	5271611	5337465	561086	9.5
Shading					
10%	70201	5914816	5985017	-86467	-1.5
20%	59284	6014895	6074179	-175629	-3.0
50%	33554	6324528	6358082	-459532	-7.8
Wall type					
Autoclaved cellular concrete block	343802	3855500	4199302	1699248	28.8
Colour of external surface					
Dark grey	107487	5567823	5675310	223240	3.8
Air exchange rate					
0.5	97199	5192740	5289939	608611	10.3
2	62926	7043581	7106507	-1207956	-20.5
4	43126	9444231	9487358	-3588807	-60.8
Internal gain					
10%	0	8840177	8840177	-2941626	-49.9
50%	324	7422661	7422985	-1524435	-25.8
No internal gain	0	9209868	9209868	-3311317	-56.1
Set point - cooling: 25 ℃ - heating: 20 ℃	32268	5434517	5466785	431766	7.3
Scheduling of air exchanges	96520	5320991	5417511	481039	8.2

(iii) Window size

Compared to a fully glazed curtain wall, the reduction of the glazing size to a 1.2 m height decreases the annual load by 9.5%. Thus, the use of larger expanse of glass in such a building is not desirable as it leads to higher annual loads. This is due to high internal gains of the commercial building.

(iv) Shading

The shading of windows in this climate is not desirable. If 50% of the window areas are shaded throughout the year, the percentage load increase is 7.8.

(v) Wall type

Walls having a low U-value (insulating type such as autoclaved cellular concrete block) reduce loads compared to the concrete block wall (base case) by 28.8%. Thus, insulation of walls is recommended.

(vi) Colour of external surface

Dark colours should be preferred for external surfaces due to their high absorptivities. For example, if dark grey is used, the percentage reduction in load is 3.8 compared to white surfaces (base case).

(vii) Air exchanges

A lower air change rate (0.5 ach) is more effective than higher ones of 1, 2 and 4 per hour. It reduces the annual load by 10.3% compared to the base case of 1 ach.

(b) Operational Parameters

The operational parameters such as internal gain, set point and scheduling of air changes can help in reducing the annual load of the building. The effects are summarised as follows.

(i) Internal gain

In cold climates, the internal gains help to keep the building warm and hence are preferable.

(ii) Set Point

The annual load of the building reduces if the set points for comfort cooling and heating are relaxed. If the cooling and heating set points of 25 and 20^0C respectively are used (compared to 24 and 21^0C), the percentage reduction in annual load is 7.3. Thus, a change in the expectation of comfort can lead to significant savings.

(iii) Scheduling of air exchanges

The scheduling of air changes to control air entry during cooler periods (such as nights or winters) and promote it during warmer periods (during daytime or summer) can lead to significant reduction of annual load; the percentage load reduction is 8.2.

The combination of all design and operational parameters discussed (excluding building orientation and internal gain), results in a significant load reduction of 62.3% for the commercial building at Leh.

5.5.6.2 Industrial Building

The yearly minimum, maximum and average temperatures, and the number of comfortable hours in a year for the shed and store are given in Table 5.55 for the Leh climate. Winters are very cold with the minimum temperature going as low as -8.7 °C in store and -3.4 °C in the shed, making heating essential in this season. The yearly maximum temperatures of both rooms are quite comfortable, ranging from 22.7 to 27.7 °C, and the average temperatures are quite cool – 7.7 °C in

Table 5.55 Performance of the industrial building on an annual basis- Leh (cold and dry climate)

Room	Yearly room temperature(°C)			Comfortable hours in a year (h)	Percentage of yearly comfortable hours
	MIN	MAX	AVG		
Shed	-3.4	27.7	12.2	4535	52
Store	-8.7	22.7	7.7	3769	43
Ambient	-13.9	24.5	4.5	2839	32

MIN = Minimum, MAX = Maximum, AVG = Average

Table 5.56 Performance of the industrial building on a monthly basis- Leh (cold and dry climate)

Comfort index	Month	Room	
		Shed	Store
Comfort fraction	JAN	-1.41	-2.74
	FEB	-1.13	-2.3
	MAR	-0.44	-1.55
	APR	0.16	-1.01
	MAY	0.72	-0.23
	JUN	0.91	0.25
	JUL	0.87	0.65
	AUG	0.91	0.83
	SEP	0.83	0.08
	OCT	0.35	-0.76
	NOV	-0.36	-1.55
	DEC	-1.01	-2.29

the store and 12.2 °C in the shed. The shed is comfortable for about 52% in terms of number of comfortable hours in a year. The store is slightly less comfortable i.e. for 43% of the year. The values of monthly comfort fractions (Table 5.56) show that the shed is very uncomfortable in the months from November to March (negative values of CF indicate acute discomfort). January is the most uncomfortable month with CF value of -1.41; June and August are relatively comfortable months. The store is very uncomfortable from October to May, January being the most uncomfortable month. August is the most comfortable month for the store. The hourly values of room temperatures for a typical winter day of January and summer day of May are plotted in Figs. 5.79 and 5.80 respectively. It is seen that in January, both the rooms are close to or below the freezing line, indicating acute discomfort. The shed temperature varies between -2.5 to 2.5 °C. The store temperature is much lower, varying between -7.5 to -4.0 °C. However, the temperatures of both rooms are higher than the ambient. In May, the shed is comfortable in the late afternoons and evenings. During nights and early mornings, the shed temperature is below the comfort zone. The store temperature in May ranges between 10 and 15 °C and is therefore quite uncomfortable. Thus, heating is required and the air change rate should be minimum

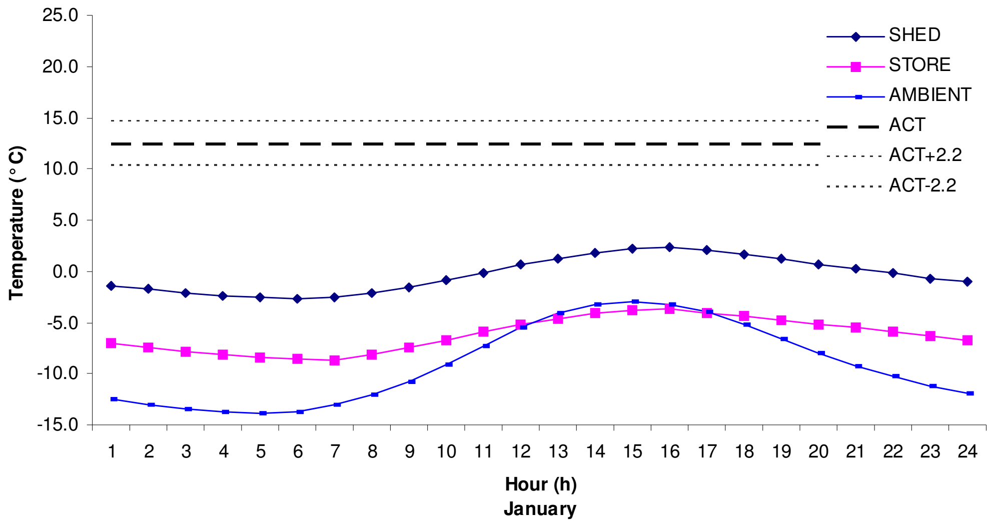


Fig. 5.79 Hourly variation of room temperatures of the industrial building in January - Leh (cold and dry climate)

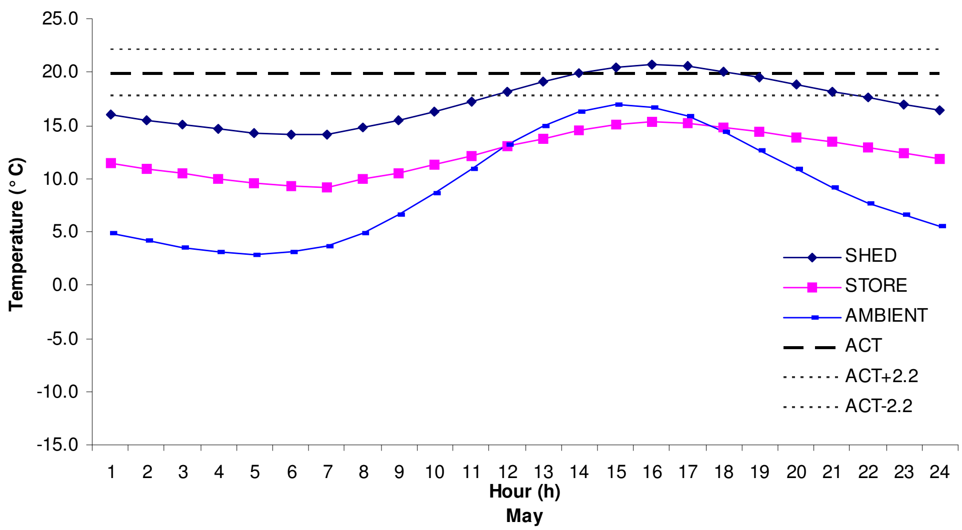


Fig. 5.80 Hourly variation of room temperatures of the industrial building in May - Leh (cold and dry climate)

Table 5.57 Improvement in the performance of the industrial building due to building design and operational parameters- Leh (cold and dry climate)

PARMETERS	Comfortable hours in a year (h)	Percentage increase in comfortable hours
Base case	4535	--
Orientation		
Northwest-southeast	4539	0.1
Northeast-southwest	4536	0.0
East-west	4579	1.0
Glazing type		
Single reflective	4417	-2.6
Double clear	4633	2.2
Double low-E	4631	2.1
Double reflective coated	4585	1.1
Shading		
10%	4512	-0.5
20%	4471	-1.4
Wall type		
Thermocol (EPS) insulated brick wall	4624	2.0
Concrete block wall	4376	-3.5
Autoclaved cellular concrete block	4619	1.9
Roof type		
RCC with bitumen felt water proofing	4534	0.0
RCC with PUF insulation	4760	5.0
Colour of external surface		
White	4357	-3.9
Cream	4386	-3.3
Dark grey	4643	2.4
Air exchanges		
3 ach	4674	3.1
9 ach	4137	-8.8
12 ach	4031	-11.1
Internal gain		
20%	3623	-20.1
40%	3971	-12.4

Table 5.57 presents the change in the number of comfortable hours in a year due to various parameters for shed. The corresponding percentage increase or decrease (-) in comfortable hours compared to the base case is shown in the table.

(a) Design Parameters

(i) Building orientation

The effect of building orientation does not show any significant effect. East-west orientation is better than the north-south (base case) orientation.

(ii) Glazing type

There is no significant effect of different glazing types compared to plain glass (base case). Double-glazing with clear glass as well as with low-E glass show a marginal increase (about 2.2 %) in yearly comfortable hours.

(iii) Shading

Shading of windows is not desirable in this climate, since the solar gain is needed in this climate. If 20% of the window areas are shaded throughout the year, the annual load increases by 1.4%.

(iv) Wall type

Insulation of walls shows a marginal increase in yearly comfortable hours compared to brick walls (base case).

(v) Roof type

Insulation of the roof improves the performance of the building. Polyurethane foam (PUF) insulation increases the yearly comfortable hours by 5.0%.

(vi) Colour of the external surface

Dark grey is suitable due to its higher absorptivity as compared to light colours.

(vii) Air exchanges

Air change needs to be reduced compared to the base case of 6 ach.

(b) Operational Parameters

(i) Internal gain

In cold climates, internal gains help to keep the building warm and hence are preferable.

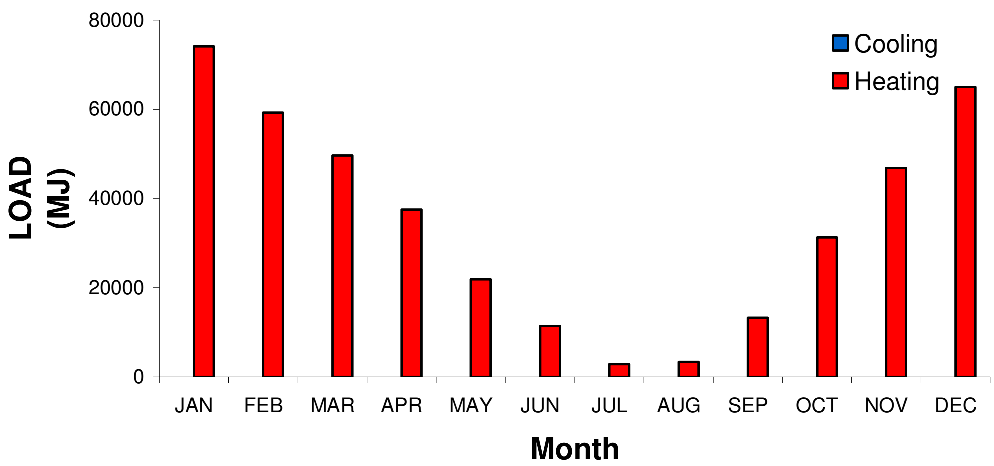
The combination of all design and operational parameters discussed (excluding building orientation and internal gain), results in a 7.9% increase in the yearly comfortable hours for the shed compared to the base case design.

5.5.6.3 Residential Building (Bungalow)

(A) Conditioned building

Figure 5.81 shows the distribution of the annual and monthly heating and cooling loads of the conditioned building for the cold and sunny climate of Leh. On an annual basis, the heating load is predominant, heating being required throughout the year. The load profiles generally follow the climatic conditions. For example, the highest heating load occurs in January, which is the peak winter month. The load in December is also significantly high. The months from June to September display relatively lower heating loads.

The monthly variation of the percentage of loads through various building components is presented in Fig. 5.82. It shows that the heating requirement is primarily due to surface losses. The heat loss through surfaces and air exchanges are higher than the heat gain due to people and equipment throughout the year. Therefore, insulation of surfaces and control of air exchanges could lower the heating loads. In July and August, which represents summer months, the heat gains and losses more or less balance each other and hence the loads are small.



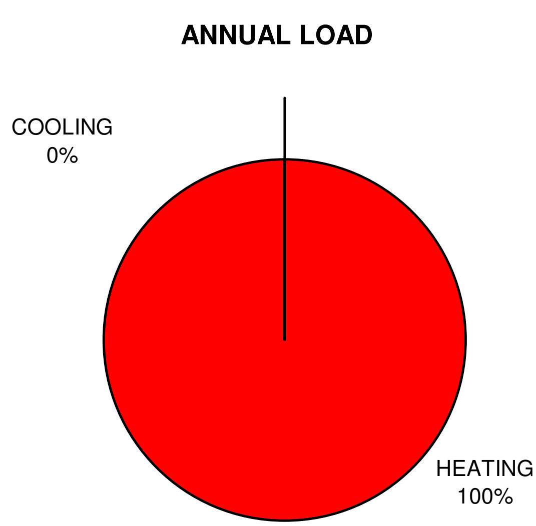


Fig. 5.81 Monthly and annual heating and cooling loads of the conditioned bungalow - Leh (cold and dry climate)

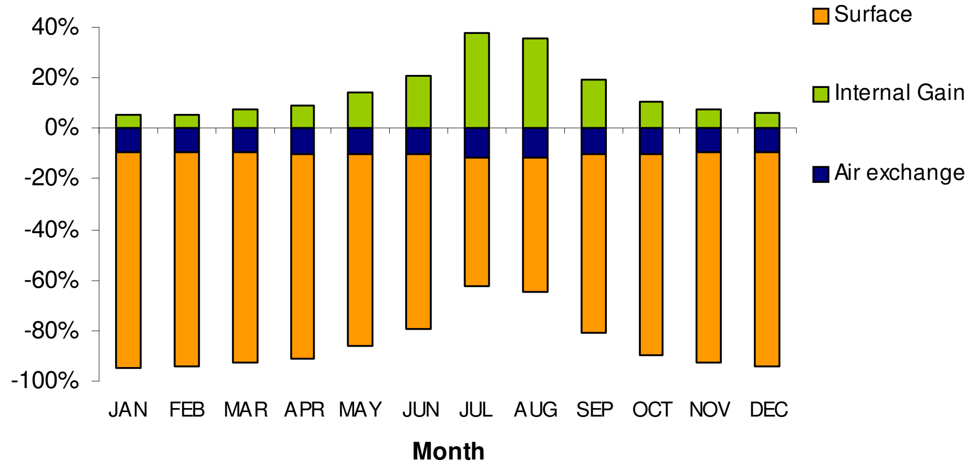


Fig. 5.82 Component-wise distribution of percentage heat gains and losses on a monthly basis of the conditioned bungalow- Leh (cold and dry climate)

Table 5.58 presents the room-wise annual loads for the conditioned bungalow. It is seen that the heating load of the living and dining room is significantly higher than that of other rooms. This is because of the fact that this room is very large and is also partly double storeyed. The heating load of the kitchen is the least due to internal gains from appliances (refrigerator and cooking range). The comparison of bedrooms shows that, the first floor bedroom on the north (Bed3) is the warmest in the house. The bedroom located in the north-west corner (Bed3) on the same floor is the coolest. This is primarily due to heat losses from larger exposed surfaces and glazed windows.

The effects of building parameters on the annual load are presented in Table 5.59. The consequent percentage load reductions due to these parameters compared to the base case are also shown in the table. Based on the data, the following recommendations are made for increasing the performance of the conditioned bungalow at Leh:

(a) Design Parameters

(i) Building orientation

The east-west orientation (base case) is better than a north-south orientation.

(ii) Glazing type

Double-glazing with clear glass gives the best performance. It reduces the load by 20.9% in comparison with plain glass (base case). Double-glazing with low-E glass and reflective coated glass can also be used to reduce the loads by 20.2 and 15.5% respectively.

(iii) Shading

Shading of windows is not recommended for this climate. If 50% of the window areas are shaded throughout the year, the annual load increases by 9.0%.

Table 5.58 Room-wise distribution of the monthly and annual loads of the conditioned bungalow - Leh (cold and dry climate)

Month	Cooling load (MJ)							
	BED1	LIVDIN	KIT	BED2	BED3	BED4	BED5	Total
JAN	0	0	0	0	0	0	0	0
FEB	0	0	0	0	0	0	0	0
MAR	0	0	0	0	0	0	0	0
APR	0	0	0	0	0	0	0	0
MAY	0	0	0	0	0	0	0	0
JUN	0	0	0	0	0	0	0	0
JUL	0	0	0	0	0	0	0	0
AUG	0	0	0	0	0	0	0	0
SEP	0	0	0	0	0	0	0	0
OCT	0	0	0	0	0	0	0	0
NOV	0	0	0	0	0	0	0	0
DEC	0	0	0	0	0	0	0	0
Total	0	0	0	0	0	0	0	0

Month	Heating load (MJ)							
	BED1	LIVDIN	KIT	BED2	BED3	BED4	BED5	Total
JAN	6531	31004	4961	9093	6482	8160	7914	74145
FEB	5294	24627	3953	7299	5178	6567	6344	59262
MAR	4484	20923	3255	6035	4232	5455	5286	49669
APR	3474	15839	2412	4525	3114	4106	4006	37476
MAY	2116	9706	1291	2516	1643	2335	2293	21899
JUN	1215	5312	676	1210	686	1157	1141	11398
JUL	356	1719	264	158	31	160	159	2847
AUG	438	1939	282	252	32	251	209	3403
SEP	1476	5411	722	1717	1028	1572	1339	13264
OCT	3017	12640	1886	4037	2732	3653	3289	31254
NOV	4349	18898	2991	6023	4190	5395	4957	46803
DEC	5849	26845	4241	8115	5737	7256	6952	64995
Total	38599	174863	26934	50979	35083	46066	43889	416414

BED1=Bed room1, LIVDIN= Living and dining room, KIT=Kitchen, BED2=Bed room2, BED3=Bed room3, BED4=Bed room4, BED5=Bed room5

Table 5.59 Annual savings due to building design and operational parameters for the conditioned bungalow - Leh (cold and dry climate)

Parameter	Annual load (MJ)			Energy saving	
	Cooling	Heating	Total	(MJ)	(%)
Base case	0	416414	416414	--	--
Orientation (longer axis)					
North-south	11	421989	421999	-5585	-1.3
Glazing type					
Double clear	7	329279	329286	87128	20.9
Single reflective coated	0	444371	444371	-27957	-6.7
Double reflective coated	0	351721	351721	64693	15.5
Double low-E	0	332115	332115	84299	20.2
Shading					
10%	0	423797	423797	-7383	-1.8
20%	0	431212	431212	-14798	-3.6
50%	0	454003	454003	-37589	-9.0
Wall type					
Thermocol (EPS) insulated brick wall	197	299289	299487	116927	28.1
Concrete block wall	14	513533	513547	-97133	-23.3
Autoclaved cellular concrete block	122	308259	308381	108033	25.9
Roof type					
Uninsulated RCC roof	0	442260	442260	-25846	-6.2
PUF insulated RCC roof	0	369257	369257	47157	11.3
Colour of external surface					
White	0	431877	431877	-15463	-3.7
Cream	0	426690	426690	-10276	-2.5
Dark grey	36	401241	401277	15137	3.6
Air exchanges					
1.0 ach	0	451872	451872	-35458	-8.5
1.5 ach	0	486393	486393	-69979	-16.8
Internal gain					
50%	0	438643	438643	-22229	-5.3
No internal gain	0	462050	462050	-45636	-11.0
Set point - cooling: 26 °C - heating: 19 °C	0	391280	391280	25134	6.0
Scheduling of air exchanges	0	416414	416414	0	0.0

(iv) Wall type

Insulation of walls helps to improve the performance significantly. Thermocol insulation can save annual loads by 28.1% and autoclaved cellular concrete block walls (e.g., Siporex) can save annual loads by 25.9% as compared to a brick wall (base case). Plain concrete block wall increases the load by 23.3% and hence should be avoided.

(v) Roof type

Insulation of the roof improves the performance of the building. Polyurethane foam (PUF) insulation brings down the loads by 11.3%. In contrast, a plain uninsulated RCC roof increases the load by 6.2%.

(vi) Colour of the external surface

Dark grey is suitable due to its higher absorptivity, it improves performance by 3.6%.

(vii) Air exchanges

A lower air change rate of 0.5 ach is desirable for reducing loads.

(b) Operational Parameters

The operational parameters such as internal gain, set point and scheduling of air changes can help in reducing the annual load of the building. The effects are summarised as follows.

(i) Internal gain

In cold climates, internal gains help to keep the building warm and hence are desirable.

(ii) Set point

Lowering the operating parameters for comfort cooling and heating can reduce the cooling loads by 6.0%. Thus a change in the expectation of comfort can lead to significant savings.

(iii) Scheduling of air exchanges

The scheduling of air changes is not desirable in this cold climate.

The combination of all design and operational parameters discussed (excluding building orientation and internal gain), results an appreciable load reduction of 73.0% for a conditioned bungalow at Leh.

(B) Non-conditioned building

Table 5.60 presents the yearly minimum, maximum and average temperatures, and the number of comfortable hours in a year for all the rooms of the non-conditioned bungalow for Leh. It is seen that the yearly minimum values of room temperatures are below freezing point, indicating acute discomfort in winters. The room attaining the lowest temperature of -7.2 °C is the bedroom on the first floor (Bed2) in the northwest corner of the house. The maximum temperatures are quite comfortable ranging from 20.1 to 22.2 °C. The warmest room is the kitchen, which attains a maximum temperature of 22.2 °C and has an average temperature of 9.2 °C in a year. Therefore, summers are comfortable whereas winters are extremely uncomfortable. In terms of the number of hours in a year, all rooms are comfortable in a range of 42 to 47% of the year only. In other words, all rooms are uncomfortable for more than 53% of the year. Thus, a change in design is indicated to reduce discomfort. Table 5.61 presents the performance of the building on a monthly basis in terms of the comfort fraction (CF). The rooms are very uncomfortable from October to May, as shown by negative CF values, which

Table 5.60 Performance of the non-conditioned bungalow on an annual basis - Leh (cold and dry climate)

Room	Yearly room temperature(℃)			Comfortable hours in a year(h)	Percentage of yearly comfortable hours
	MIN	MAX	AVG		
BED1	-6.0	20.1	7.8	3676	42
LIVDIN	-6.0	21	8.4	3963	45
KIT	-4.7	22.2	9.2	4097	47
BED2	-7.2	21.3	7.8	3686	42
BED3	-6.3	21.4	8.1	3708	42
BED4	-6.4	21.0	8.1	3691	42
BED5	-6.0	21.1	8.7	4014	46
Ambient	-13.9	24.5	4.5	2839	32

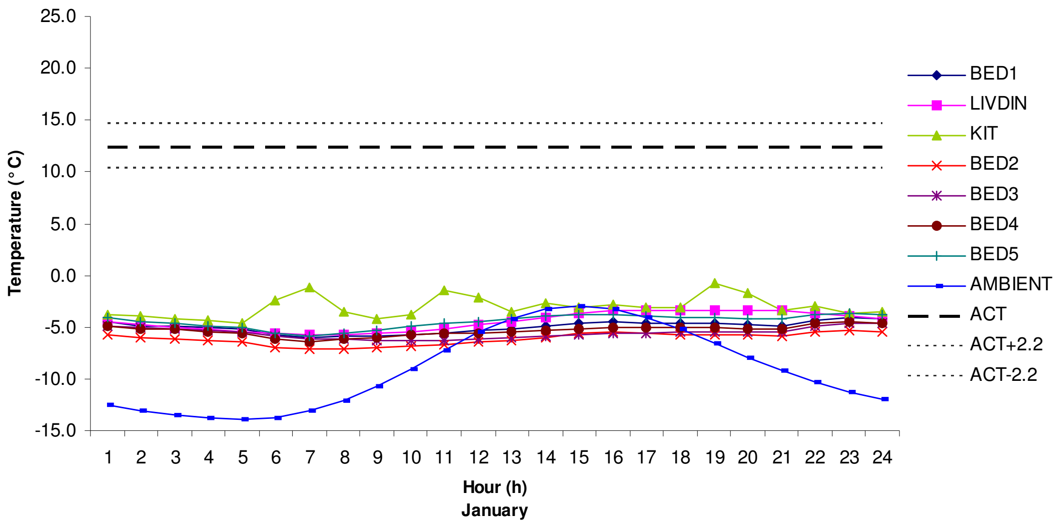
MIN = Minimum, MAX = Maximum, AVG = Average
BED1=Bed room1, LIVDIN= Living and dining room, KIT=Kitchen, BED2=Bed room2, BED3=Bed room3, BED4=Bed room4, BED5=Bed room5

Table 5.61 Performance of the non-conditioned bungalow on a monthly basis - Leh (cold and dry climate)

Comfort index	Month	Room						
		BED1	LIVDIN	KIT	BED2	BED3	BED4	BED5
Comfort fraction	JAN	-2.47	-2.35	-2.03	-2.72	-2.6	-2.55	-2.35
	FEB	-2.03	-1.91	-1.64	-2.23	-2.12	-2.09	-1.89
	MAR	-1.37	-1.27	-1.03	-1.45	-1.37	-1.35	-1.22
	APR	-0.85	-0.81	-0.61	-0.85	-0.79	-0.78	-0.70
	MAY	-0.23	-0.19	-0.01	-0.11	-0.08	-0.10	-0.07
	JUN	0.15	0.18	0.33	0.33	0.35	0.33	0.33
	JUL	0.57	0.64	0.73	0.80	0.82	0.78	0.79
	AUG	0.51	0.60	0.69	0.71	0.74	0.69	0.74
	SEP	-0.05	0.13	0.25	0.05	0.10	0.07	0.23
	OCT	-0.76	-0.52	-0.39	-0.81	-0.71	-0.74	-0.49
	NOV	-1.46	-1.17	-1.01	-1.63	-1.5	-1.51	-1.18
	DEC	-2.09	-1.92	-1.64	-2.31	-2.18	-2.15	-1.91

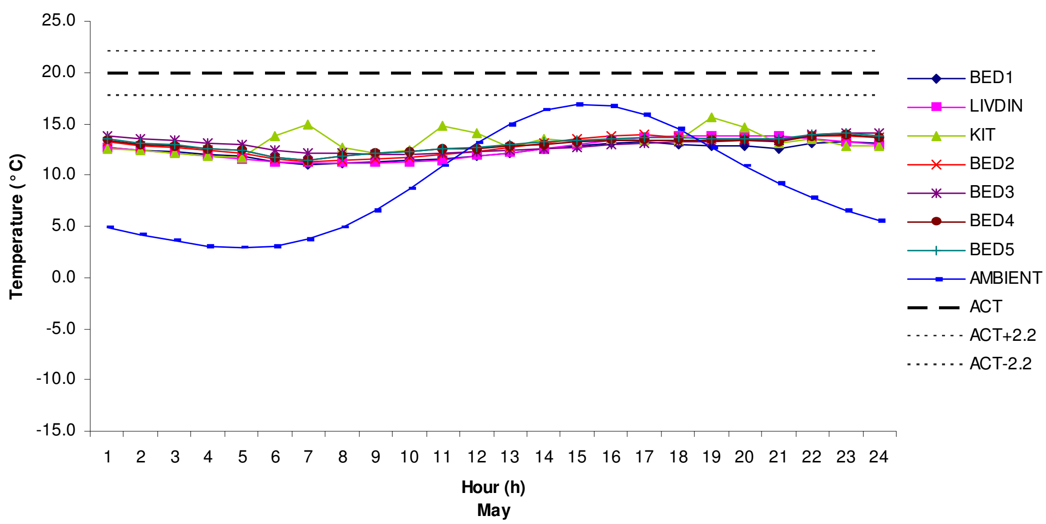
BED1=Bed room1, LIVDIN= Living and dining room, KIT=Kitchen, BED2=Bed room2, BED3=Bed room3, BED4=Bed room4, BED5=Bed room5

indicate acute discomfort. January is the most uncomfortable month with CF values ranging from -2.03 to -2.72. Hence, heating is a prime requirement from the design point of view. The house is relatively comfortable in July (CF values ranging from 0.57 to 0.82), and August (CF values ranging from 0.51 to 0.74). The hourly variation of room temperatures for a typical winter day of January and summer day of May are plotted in Figs. 5.83 and 5.84 respectively. It is seen that in January, all rooms are below the freezing line. In fact, the temperatures are below the comfort zone in the month of May as well. Hence, heating is essential not just in winter but also in the month of May.



BED1=Bed room1, LIVDIN= Living and dining room, KIT=Kitchen, BED2=Bed room2, BED3=Bed room3, BED4=Bed room4, BED5=Bed room5

Fig. 5.83 Hourly variation of room temperatures of the non-conditioned bungalow in January - Leh (cold and dry climate)



BED1=Bed room1, LIVDIN= Living and dining room, KIT=Kitchen, BED2=Bed room2, BED3=Bed room3, BED4=Bed room4, BED5=Bed room5

Fig. 5.84 Hourly variation of room temperatures of the non-conditioned bungalow in May - Leh (cold and dry climate)

Table 5.62 Improvement of the non-conditioned bungalow performance due to building design and operational parameters - Leh (cold and dry climate)

Parameter	Comfortable hours in a year(h)	Percentage increase in comfortable hours (%)
Base case	3686	-
Orientation (longer axis)		
North-south	3698	0.3
Glazing type		
Double clear	3824	3.7
Double low-E	3722	1.0
Single reflective coated	3654	-0.9
Double reflective coated	3693	0.2
Shading		
10%	3674	-0.3
20%	3665	-0.6
50%	3641	-1.2
Wall type		
Concrete block wall	3614	-2.0
Thermocol (EPS) insulated brick wall	3937	6.8
Autoclaved cellular concrete block	3911	6.1
Roof type		
Uninsulated RCC roof	3681	-0.1
PUF insulated RCC roof	3702	0.4
Colour of external surface		
Cream	3674	-0.3
Dark grey	3700	0.4
White	3669	-0.5
Air exchanges		
1.0 ach	3679	-0.2
1.5 ach	3671	-0.4
Internal gain		
No internal gain	3653	-0.9
50%	3669	-0.5

Table 5.62 presents the change in the number of comfortable hours in a year due to various parameters for a bedroom (Bed 2). The corresponding percentage increase or decrease (-) in comfortable hours compared to the base case is shown in the table.

(a) Design Parameters

(i) Building orientation

Changing the orientation of the building with respect to the base case (east-west) does not affect its thermal performance.

(ii) Glazing type

Double-glazing with clear glass gives the best performance. It increases the yearly comfortable hours by 3.0%. compared to plain glass (base case). Double-glazing with low-E glass shows a marginal improvement.

(iii) Shading

Shading of windows is not desirable in this climate.

(iv) Wall type

Insulation of walls helps to improve the performance significantly. Thermocol insulation and autoclaved cellular concrete block walls increase the yearly comfortable hours by 6.8 and 6.1% respectively.

(v) Roof type

Insulating the roof using polyurethane foam (PUF) insulation increases the performance marginally (0.4%) compared to a roof with brick-bat-coba waterproofing.

(vi) Colour of the external surface

Dark grey colour shows an improvement in the building's performance, but the effect is not very significant over other colours.

(vii) Air exchanges

A lower air change is desirable in this climate.

(b) Operational Parameters

(i) Internal gain

In cold climates, internal gains help to keep the building warm and hence are preferable.

(ii) Scheduling of air exchanges

The scheduling of air changes is not desirable in this climate.

The combination of all design and operational parameters (excluding building orientation and internal gain) significantly improves the building's thermal performance, resulting in an increase in the yearly comfortable hours by 41.5% in the cold and sunny climate of Leh.

5.6 SUMMARY

In this chapter we have seen how adopting energy efficient practices in architectural design can appreciably reduce the annual loads of buildings. While the first part this chapter (section 5.4) has dealt with general recommendations for designing of buildings in different climates, the major part has been devoted to the detailed analysis of design and operational parameters for three building types (commercial, industrial and residential bungalow) for each of the six climatic zones of India.

For quick and easy reference, the information has been summarised in a set of tables and presented in this section. Table 5.63 summarises the comfort requirements for each climatic zone based on the characteristics of the climate. The corresponding physical manifestations are also given alongside the comfort requirements. Table 5.64 presents the passive techniques that can be used in different climates. The specific guidelines and recommendations for each of the three building types that were elaborated in section 5.5 are summarised in the Tables 5.65 through 5.68.

Passive solar aspects should become an integral part of the overall process of architectural design. Figure 5.85 elucidates such integration process of design step by step. The upper layer shows the normal sequence that an architect follows, whereas the lower layer shows additional considerations for incorporating the passive solar aspects. While the process of design is essentially iterative, the given diagram is shown to be linear for the sake of simplicity.

The importance of evaluating the thermal performance of the building being designed using simulation techniques, to understand the effectiveness of the design in achieving energy efficiency, cannot be overemphasised. The ultimate benefits of incorporating passive principles far outweigh any apprehensions that an architect may have of the additional work involved.

Table 5.63 Comfort requirements and physical manifestation

1)Hot and Dry Region

OBJECTIVES	PHYSICAL MANIFESTATION
1)Resist heat gain	
a)Decrease exposed surface area	Orientation and shape of building
b)Increase thermal resistance	Insulation of building envelope
c)Increase thermal capacity (Time lag)	Massive structure
d)Increase buffer spaces	Air locks/ lobbies/balconies/verandahs
e)Decrease air exchange rate (Ventilation during day-time)	Weather stripping and scheduling air changes
f)Increase shading	External surfaces protected by overhangs, fins and trees
g)Increase surface reflectivity	Pale colour, glazed china mosaic tiles etc.
2)Promote heat loss	
a)Ventilation of appliances	Provide windows/ exhausts
b)Increase air exchange rate (Ventilation during night-time)	Courtyards/ wind towers/ arrangement of openings
c)Increase humidity levels	Trees, water ponds, evaporative cooling

2)Warm and Humid Region

OBJECTIVES	PHYSICAL MANIFESTATION
1)Resist heat gain	
a)Decrease exposed surface area	Orientation and shape of building
b)Increase thermal resistance	Roof insulation and wall insulation. Reflective surface of roof
c)Increase buffer spaces	Balconies and verandahs
d)Increase shading	Walls, glass surfaces protected by overhangs, fins and trees
e)Increase surface reflectivity	Pale colour, glazed china mosaic tiles, etc.
2)Promote heat loss	
a)Ventilation of appliances	Provide windows/ exhausts
b)Increase air exchange rate (Ventilation throughout the day)	Ventilated roof construction. Courtyards, wind towers and arrangement of openings
c)Decrease humidity levels	Dehumidifiers/ desiccant cooling

3)Moderate Region

OBJECTIVES	PHYSICAL MANIFESTATION
1)Resist heat gain	
a)Decrease exposed surface area	Orientation and shape of building
b)Increase thermal resistance	Roof insulation, and east and west wall insulation
c)Increase shading	East and west walls, glass surfaces protected by overhangs, fins and trees
d)Increase surface reflectivity	Pale colour, glazed china mosaic tiles, etc.
2)Promote heat loss	
a)Ventilation of appliances	Provide windows/ exhausts
b)Increase air exchange rate (Ventilation)	Courtyards and arrangement of openings

4)Cold and Cloudy Region/Cold and Sunny Region

OBJECTIVES	PHYSICAL MANIFESTATION
1)Resist heat loss	
a)Decrease exposed surface area	Orientation and shape of building. Use of trees as wind barriers
b)Increase thermal resistance	Roof insulation, wall insulation and double glazing
c)Increase thermal capacity (Time lag)	Thicker walls
d)Increase buffer spaces	Air locks/ Lobbies
e)Decrease air exchange rate	Weather stripping
f)Increase surface absorptivity	Darker colours
2)Promote heat gain	
a)Reduce shading	Walls and glass surfaces
b)Utilise heat from appliances	
c)Trapping heat	Sun spaces/ green houses/ Trombe walls etc.

5)Composite Region

OBJECTIVES	PHYSICAL MANIFESTATION
1)Resist heat gain in summer and Resist heat loss in winter	
a)Decrease exposed surface area	Orientation and shape of building. Use of trees as wind barriers.
b)Increase thermal resistance	Roof insulation and wall insulation
c)Increase thermal capacity (Time lag)	Thicker walls
d)Increase buffer spaces	Air locks/ Balconies
e)Decrease air exchange rate	Weather stripping
f)Increase shading	Walls, glass surfaces protected by overhangs, fins and trees.
g)Increase surface reflectivity	Pale colour, glazed china mosaic tiles, etc.
2)Promote heat loss in summer/ monsoon	
a)Ventilation of appliances	Provide exhausts
b)Increase air exchange rate (Ventilation)	Courtyards/ wind towers/ arrangement of openings
c)Increase humidity levels in dry summer	Trees and water ponds for evaporative cooling
d)Decrease humidity in monsoon	Dehumidifiers/ desiccant cooling

Table 5.64 Advanced techniques in different climates

CLIMATE	TECHNIQUES																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Hot and dry				•		•	•		•	•			•	•	•	•			•
Warm and humid											•	•							•
Moderate	No advanced techniques required																		•
Cold and cloudy Cold and sunny	•	•	•	•	•	•	•	•					•				•		•
Composite*																		•	•

* If cooling is the major requirement, the techniques listed under hot and dry climate may be adopted. In case of heating requirement, the techniques for cold climates may be used. Techniques such as roof pond, roof radiation trap, solar chimney, earth berming, etc. which find dual usage can also be incorporated.

1. Direct gain
2. Trombe wall
3. Water wall
4. Solar chimney
5. Transwall
6. Roof pond
7. Roof radiation trap
8. Solarium
9. Evaporative cooling
10. Nocturnal radiation cooling
11. Desiccant cooling
12. Induced ventilation
13. Earth berm
14. Wind tower
15. Earth-air tunnel
16. Curved roof / air vents
17. Cavity wall / insulation
18. Varytherm wall
19. Daylighting

Table 5.65 Design recommendations for the commercial building

Parameter	**Jodhpur (Hot & Dry Climate)**	**Mumbai (Warm & Humid Climate)**	**Pune (Moderate Climate)**	**New Delhi (Composite Climate)**	**Srinagar (Cold & Cloudy Climate)**	**Leh (Cold & Sunny Climate)**
Building Orientation (Due direction of the glazed curtain wall)	NE-SW (south east)	NE-SW (south east)	NE-SW (south east)	NE-SW (south east)	NW-SE (south west)	NW-SE (south west)
Glazing Type	Reflective coated glass (double pane)	Reflective coated glass (double pane)	Reflective coated glass (single pane)	Reflective coated glass (double pane)	Low-E glass (double pane)	Low-E glass (double pane)
Shading of glazing (percent of the total area)	50	50	50	50	0	0
Wall Type	Autoclaved cellular concrete block	Autoclaved cellular concrete block	Concrete block	Concrete block	Autoclaved cellular concrete block	Autoclaved cellular concrete block
Surface Colour (External)	White	White	White	White	Dark grey	Dark grey
Air exchanges (ach)	0.5	0.5	0.5	0.5	0.5	0.5

NE-SW: Northeast-southwest; NW-SE: Northwest-southeast

Table 5.66 Design recommendations for the industrial building

Parameter	**Jodhpur (Hot & Dry Climate)**	**Mumbai (Warm & Humid Climate)**	**Pune (Moderate Climate)**	**New Delhi (Composite Climate)**	**Srinagar (Cold & Cloudy Climate)**	**Leh (Cold & Sunny Climate)**
Building Orientation	NE-SW	NE-SW	NW-SE	E-W	E-W	E-W
Glazing Type	Reflective coated glass (single pane)	Reflective coated glass (single pane)	Reflective coated glass (single pane)	Reflective coated glass (double pane)	Reflective coated glass (single pane)	Clear glass (double pane)
Shading	20	20	20	10	20	0
Wall Type	Concrete block	Concrete block	Concrete block	Brick	Concrete block	Brick wall with thermocol insulation
Roof Type	RCC with bitumen felt waterproofing	RCC with bitumen felt waterproofing	RCC with bitumen felt waterproofing	RCC with brick-bat-coba waterproofing	RCC with PUF insulation	RCC with PUF insulation
Surface Colour (External)	White	White	White	Cream	White	Grey
Air exchanges (ach)	12	12	12	12	12	3

NE-SW: Northeast-southwest; NW-SE: Northwest-southeast; E-W: east-west

Table 5.67 Design recommendations for the bungalow (conditioned)

Parameter	**Jodhpur (Hot & Dry Climate)**	**Mumbai (Warm & Humid Climate)**	**Pune (Moderate Climate)**	**New Delhi (Composite Climate)**	**Srinagar (Cold & Cloudy Climate)**	**Leh (Cold & Sunny Climate)**
Building Orientation	NE-SW (south east)	NE-SW (south east)	NE-SW (south east)	NE-SW (south east)	NW-SE (south west)	NW-SE (south west)
Glazing Type	Reflective coated glass (double pane)	Reflective coated glass (double pane)	Reflective coated glass (single pane)	Reflective coated glass (double pane)	Low-E glass (double pane)	Clear glass (double pane)
Shading	50	50	50	50	0	0
Wall Type	Brick wall with thermocol insulation	Brick wall with thermocol insulation	Brick wall with thermocol insulation	Brick wall with thermocol insulation	Brick wall with thermocol insulation	Brick wall with thermocol insulation
Roof Type	RCC with PUF insulation	RCC with PUF insulation	RCC with PUF insulation	RCC with PUF insulation	RCC with PUF insulation	RCC with PUF insulation
Surface Colour (External)	White	White	White	White	Dark grey	Dark grey
Air exchanges (ach)	0.5	0.5	1.5	0.5	0.5	0.5

NE-SW: Northeast-southwest; NW-SE: Northwest-southeast

Table 5.68 Design recommendations for the bungalow (non-conditioned)

Parameter	**Jodhpur (Hot & Dry Climate)**	**Mumbai (Warm & Humid Climate)**	**Pune (Moderate Climate)**	**New Delhi (Composite Climate)**	**Srinagar (Cold & Cloudy Climate)**	**Leh (Cold & Sunny Climate)**
Building Orientation	Base case (East-west)	Base case (East-west)	Base case (East-west)	Base case (East-west)	Base case (East-west)	North-south
Glazing Type	Reflective coated glass (single pane)	Reflective coated glass (single pane)	Reflective coated glass (single pane)	Reflective coated glass (single pane)	Reflective coated glass (double pane)	Clear glass (double pane)
Shading	50	50	50	50	20	0
Wall Type	Concrete block	Concrete block	Brick	Brick	Brick	Brick wall with thermocol insulation
Roof Type	RCC with PUF insulation	RCC with PUF insulation	RCC with PUF insulation	RCC with PUF insulation	RCC with PUF insulation	RCC with PUF insulation
Surface Colour (External)	White	White	White	White	White	Grey
Air exchanges (ach)	9	9	9	9	1.5	0.5

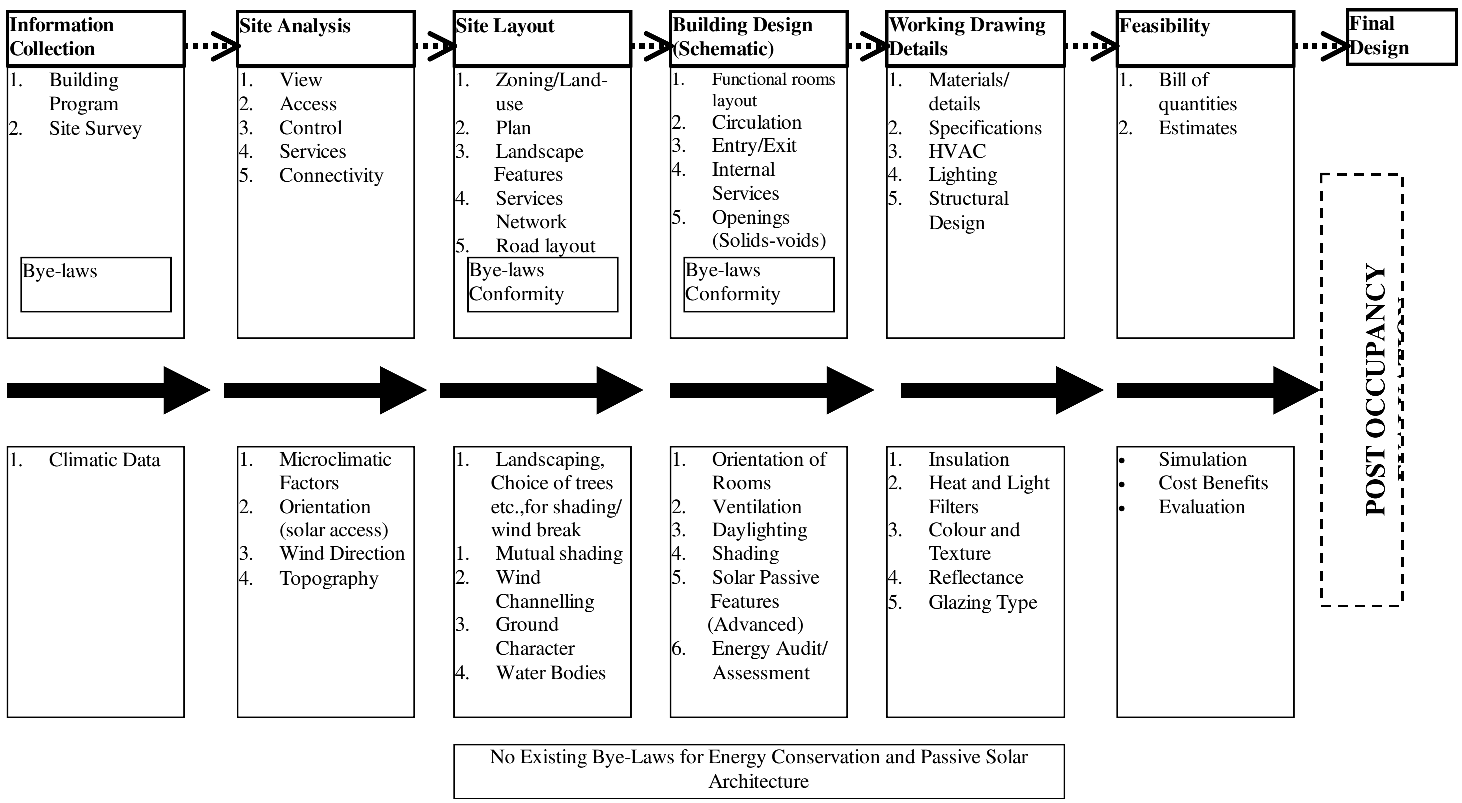


Fig. 5.85 Integrated design process

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APPENDIX V.1

ROOF SURFACE EVAPORATIVE COOLING (RSEC)

Roof surface evaporative cooling (RSEC) can reduce the ceiling surface temperature, consequently leading to a drop in indoor temperatures and cooling loads. This technique is generally adopted in warm climates. We have examined the effect of RSEC for an industrial shed and a residential bungalow (Fig. 5.3 and 5.5). The performance studies of these buildings have been carried out for Jodhpur, Mumbai, Pune and New Delhi which represent hot and dry, warm and humid, moderate and composite climates respectively. Further, the effect of the U-value of the roof on the indoor temperatures of the bungalow and industrial shed has been studied for the climate of Jodhpur. (The U-value of the roof for the base case is taken as 2.07 W/m^{2}K). The effect of the set point on the cooling loads of the bungalow incorporating RSEC has also been found. We have used the bio-climatic chart to identify the months during which cooling is required in the cities mentioned, and the calculations for RSEC have been done for these months.

Table V.1 presents the effect of RSEC on the maximum indoor temperature of the industrial shed as compared to a shed without RSEC in the month of May for Jodhpur, Mumbai, Pune and New Delhi. It is seen that RSEC is effective in Jodhpur, Pune and New Delhi; the temperature drops are about 2.3, 2.2 and 2.0^{o}C respectively in comparison with a shed without RSEC. In humid climate of Mumbai, the RSEC is not very effective with a drop in temperature of 1.1 °C only.

Table V.1 Performance of roof surface evaporative cooling on the room temperature of the industrial building in May in four cities representing warm climates

Place	Month	Maximum temperature of room(°C)		Difference in temperature (°C)
		Without RSEC	With RSEC	
Jodhpur	**May**	45.6	43.2	2.4
Mumbai	May	39.8	38.7	1.1
Pune	May	40.7	39.4	1.3
New Delhi	May	43.9	41.9	2.0

RSEC= Roof surface evaporative cooling

The effect of the U-value of the roof on the performance of RSEC in Jodhpur has also been studied. In this case, a higher U-value of 3.48 W/m^2-K has been considered compared with the base case U-value of 2.07 W/m^2-K. The results for the industrial shed are presented in Tables V.2. It is seen from these tables that the RSEC system is more effective when the U-value of the roof is high; the difference in temperature between indoors and outdoors can be as high as 5.1 °C in May. The table also shows the maximum room temperatures for various months. The RSEC is most effective in the months of May and June and least effective in the month of August (when the humidity is high due to monsoons).

The effect of RSEC on the maximum room temperature of Bedroom 2 of the bungalow in various months has been studied for all the four cities. It is seen from Table V.3 that in Jodhpur, RSEC is most effective in May with a difference in room temperature of about 2.7 °C. In Mumbai, there is hardly any difference in the performance during various months, the temperature difference ranging from 1.2 to 1.3 °C only. In Pune, the RSEC system is most effective in April with a difference in temperature of 1.9 °C. In New Delhi, the system is effective in May and June; the temperature difference being 2.3 °C.

The effect of the RSEC system on the cooling load of the conditioned bungalow has also been studied in order to determine how much load can be saved in the cooling season. In this case, the cooling load in kitchen has been ignored. The set point for cooling has been considered as 25 °C. The results of the study are presented in Table V.4. It is seen from the table that the savings effected are quite high, ranging from 15.5 % in New Delhi to 22.7% in Pune.

Table V.5 presents the effect of set points on the cooling loads of the conditioned bungalow incorporating the RSEC system. The set points considered for cooling were 24, 25, 26 and 27 °C. The table shows that for all cities, the higher the set point, the better is the performance in reducing cooling loads. For example in Jodhpur, the savings achieved can be upto 22.4 % for a set point of 27 °C as compared to 17.4% for the base case (25 °C).

Table V.2 Effect of U-value of roof on RSEC (Place: Jodhpur; Building : Industrial shed)

Month	U = 2.07 W/m^2-K			U = 3.14 W/m^2-K		
	Maximum temperature of room (°C)		Difference in temperature (°C)	Maximum temperature of room (°C)		Difference in temperature (°C)
	without RSEC	**with RSEC**		**without RSEC**	**with RSEC**	
March	**37.9**	**36.5**	**1.6**	**39.0**	**35.5**	**3.5**
April	**42.7**	**40.6**	**2.1**	**44.0**	**39.3**	**4.7**
May	**45.6**	**43.2**	**2.4**	**46.9**	**41.8**	**5.1**
June	**44.8**	**42.9**	**1.9**	**45.9**	**41.7**	**4.2**
July	**41.3**	**40.1**	**1.2**	**42.1**	**39.3**	**2.8**
August	**39.9**	**38.9**	**1.0**	**40.7**	**38.1**	**2.6**
September	**39.8**	**38.8**	**1.0**	**40.7**	**38.0**	**2.7**
October	**39.5**	**38.1**	**1.4**	**40.4**	**37.1**	**3.3**

RSEC= Roof surface evaporative cooling

Table V.3 Performance of roof surface evaporative cooling on the temperature of bedroom2 of the residential bungalow

Place	Month	Maximum temperature of room (°C)		Difference in temperature (°C)
		Without RSEC	With RSEC	
Jodhpur	March	30.8	29.0	1.8
	April	35.9	33.5	2.4
	May	39.1	36.4	2.7
	June	38.8	36.6	2.2
	July	35.6	34.1	1.5
	August	34.2	32.9	1.3
	September	33.4	32.2	1.2
	October	32.3	30.5	1.8
Mumbai	March	31.0	29.7	1.3
	April	32.9	31.7	1.2
	May	34.5	33.2	1.3
Pune	March	31.6	29.9	1.7
	April	34.1	32.2	1.9
	May	34.1	32.5	1.6
	June	31.6	30.3	1.3
	July	28.6	27.8	0.8
	August	28.2	27.4	0.8
	September	28.5	27.7	0.8
	October	29.5	28.4	1.1
New Delhi	April	33.7	31.8	1.9
	May	37.4	35.1	2.3
	June	38.8	36.5	2.3
	July	35.1	33.8	1.3
	August	33.2	32.1	1.1
	September	32.8	31.7	1.1

RSEC= Roof surface evaporative cooling

Table V.4 Effect of roof surface evaporative cooling on the cooling loads of the conditioned residential bungalow

Place (Period)	Set point (°C)	Cooling Load (GJ)		Difference	
		Without RSEC	With RSEC	GJ	%
Jodhpur (March to October)	25	366.7	302.8	63.9	17.4
Mumbai (March to May)	25	102.5	86.4	16.1	15.7
Pune (March to October)	25	189.3	146.3	43.0	22.7
New Delhi (April to September)	25	281.8	238.0	43.8	15.5

Table V.5 Effect of cooling set points on the loads of the conditioned bungalow with RSEC system

Place (Period)	Set point (°C)	Cooling Load (GJ)		Difference	
		Without RSEC	With RSEC	GJ	%
Jodhpur (March to October)	24	410.3	346.1	64.2	15.6
	25	366.7	302.8	63.9	17.4
	26	322.8	259.3	63.5	19.7
	27	280.1	217.4	62.7	22.4
Mumbai (March to May)	24	118.9	102.8	16.1	13.5
	25	102.5	86.4	16.1	15.7
	26	86.1	70.1	16.0	18.6
	27	70.1	54.4	15.7	22.4
Pune (March to October)	24	232.2	188.4	43.8	18.9
	25	189.3	146.3	43.0	22.7
	26	148.1	106.9	41.2	27.8
	27	109.6	72.1	37.5	34.2
New Delhi (April to September)	24	314.5	270.9	43.6	13.9
	25	281.8	238.0	43.8	15.5
	26	249.0	204.6	44.4	17.8
	27	215.9	172.1	43.8	20.3

To summarise, the RSEC system works well in hot and dry weather with low humidity levels. If installed over a roof having a high U-value, indoor temperatures appreciably reduced compared to that of a roof with low U-value. From the point of view of conserving energy, the set points for cooling may be raised to 27 °C (as recommended by Indian Standard).

APPENDIX V.2

PERFORMANCE OF A COMMERCIAL BUILDING WITH ZERO INTERNAL GAIN IN A COMPOSITE CLIMATE - (NEW DELHI).

The effects of building parameters on the annual loads of a conditioned commercial building with zero internal gain are discussed in this Appendix. The results of these studies are presented in Table V.6. The possible percentage of savings that could be achieved compared to the base case is also presented in the table. Table 5.1 lists the various parameters investigated. The following conclusions are drawn:

(i) Restricting the glazing size to a height of 1.2m instead of a fully glazed curtain wall can reduce the annual load by 14.7%. Thus, reduction in the penetration of direct solar radiation can cause significant savings. It can also be surmised that larger expanses of glass in a building can lead to higher cooling loads.

(ii) Double-glazing with reflective coated glass is most effective, being better than the base case (single reflective coated glass) by 14.9%. Double low-E glass also improves the performance by 11.8%. Double clear glass shows the same performance as the base case. Plain glass should be avoided as it increases the loads by 12.9%. It may be noted that double-glazing per se is better than single glazing.

(iii) Appropriate orientation can reduce cooling loads by upto 2.8%. In general, a building with its glass wall facing north-west shows better performance than one facing west, north or southwest (base case).

(iv) Lowering the operating parameters for comfort cooling and heating can reduce the cooling loads by 13.7%. Thus, a change in the expectation of comfort can lead to significant savings.

(v) Reduction in solar radiation by shading windows causes a decrease in the heat gains, and consequently the cooling loads are reduced. The shading of windows by 50% throughout the year can improve the performance by upto 8.8%.

(vi) Dark colours on walls should be avoided. If dark grey is used in place of white, the cooling load can increase by 4.7%.

(vii) A wall type having low U-value (i.e. insulating property) improves the performance significantly as compared to the base case (concrete block wall). The loads are reduced by 8.8%.

Table V.6 Annual savings due to building design and operational parameters for Commercial building with zero internal gains (New Delhi)

PARAMETER	ANNUAL LOAD (GJ)			ENERGY SAVING	
	COOLING	HEATING	TOTAL	(GJ)	(%)
BASECASE	2552.19	300.22	2852.41	N.A.	N.A.
GLAZING SIZE (restricted to 1.2m height)	2142.88	290.18	2433.05	419.36	14.7
GLAZING TYPE					
Single clear	3011.32	208.49	3219.80	-367.39	-12.9
Double clear	2743.27	109.07	2852.34	0.07	0.0
Double low-E	2389.09	127.84	2516.93	335.48	11.8
Double reflective coated	2261.73	166.42	2428.15	424.26	14.9
ORIENTATION (longer axis)					
North-south	2345.12	489.62	2834.74	17.67	0.6
Northeast-southwest	2270.46	501.33	2771.79	80.62	2.8
East-west	2469.92	384.48	2854.41	-2.00	-0.1
SETPOINT - cooling: 25 °C heating: 20 °C	2236.83	224.54	2461.37	391.04	13.7
SHADING					
10%	2473.42	321.99	2795.41	57.00	2.0
20%	2395.52	345.80	2741.32	111.09	3.9
50%	2172.30	428.37	2600.67	251.74	8.8
WALL COLOUR - dark grey	2735.70	251.52	2987.21	-134.80	-4.7
WALL TYPE Autoclaved cellular concrete block (e.g. Siporex)	2343.97	257.91	2601.87	250.53	8.8

CHAPTER 6

INTEGRATION OF EMERGING TECHNOLOGIES

Contents:

A large number of technologies are now available which when integrated into buildings would result in substantial reductions in their demand for conventional energy. These pertain to renewable energy sources and energy conservation measures. Energy used in buildings for cooking, lighting, pumping of water and providing hot water (to bath rooms and kitchens) can be saved substantially by using appropriate renewable systems. Besides, proper energy conservation and management practices would lead to additional energy savings. To promote extensive use of renewable energy technology, the Ministry of Non-conventional Energy Sources, Government of India has been operating an interest subsidy scheme through the Indian Renewable Energy Development Agency (IREDA), and a few designated banks. Co-operative housing societies and developers of real estates are eligible to seek soft loans from these institutions for installing renewable systems.

In this chapter, we will examine the various ways in which renewable energy technology and energy conservation features can be adopted. The basic principle of each option has been explained. We have described a few case studies to help the reader appreciate the overall integration of these features in building design. More information is available in the references listed at the end of this chapter.

6.1 RENEWABLE ENERGY TECHNOLOGIES

Systems based on renewable energy sources that are being used in the building sector include solar hot water systems, solar hot air systems, solar cookers, solar photovoltaic units, gasifiers and biogas plants. These are commercially available and can easily be integrated into a building for reducing its dependence on conventional power. Some of them can become elements of the architectural design; examples have been presented to demonstrate how this is done.

6.1.1 Solar Water Heating

Solar water heating is one of the most economically attractive applications of solar energy and is widely used throughout the world. There are broadly two types of water heating systems: (i) Forced and (ii) Thermosyphon. Also known as active systems, the former are suitable for large capacity systems and find applications in hotels, hostels, hospitals, multistoreyed buildings, industries, etc. The latter are usually meant for small capacity systems, and are commonly used in low-rise buildings or bungalow-type buildings. They are also called natural-circulation or passive systems.

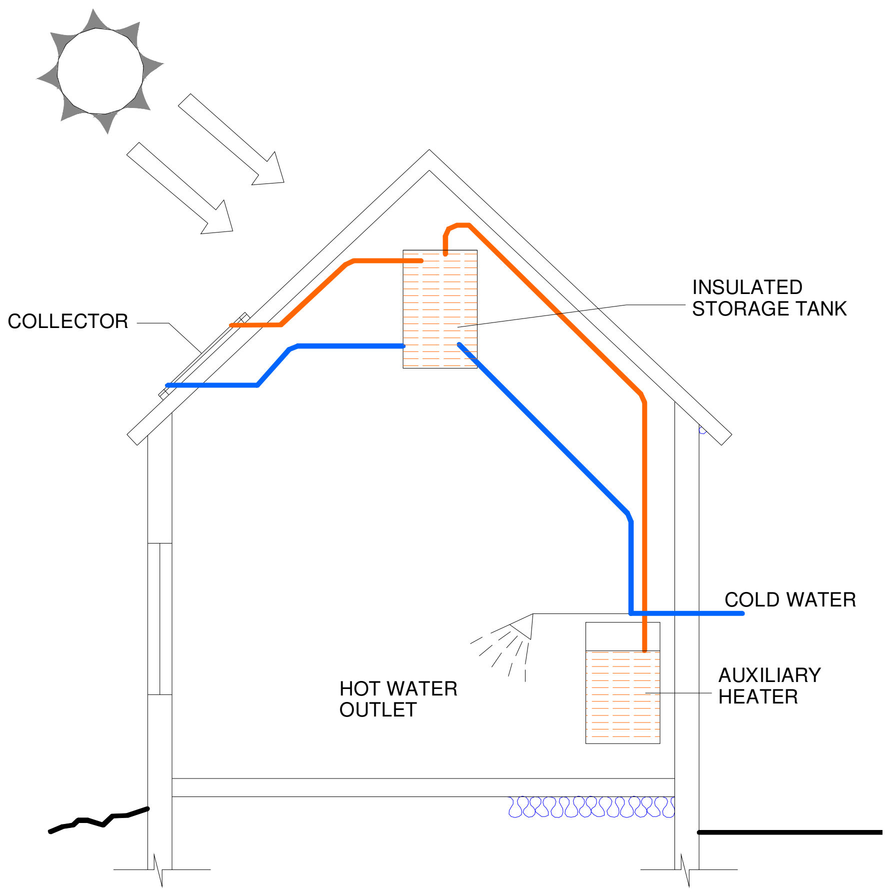

Fig. 6.1 Thermosyphon solar water heating system

(A) Thermosyphon water heating system

The thermosyphon water heating system consists of a solar liquid flat-plate collector and a storage tank (Fig. 6.1). Water in the collector gets heated up by solar energy, becomes lighter and rises to the top of the storage tank. The cooler water from the tank moves to the collector, setting up a natural circulation loop. For such a loop to work, the storage tank must necessarily be located at a higher level than the collector. Hot water is withdrawn from the top of the tank and cold water enters into the bottom of the tank. The typical temperature variation of hot water in the thermosyphon system over a day (with no hot water withdrawals) is shown in Fig. 6.2. As solar radiation incident on the collector plane increases with the time of the day, the temperature of hot water increases. If water is withdrawn, the temperature would be lower than the values shown in the figure. The nature of variation would strongly depend on the water withdrawal pattern.

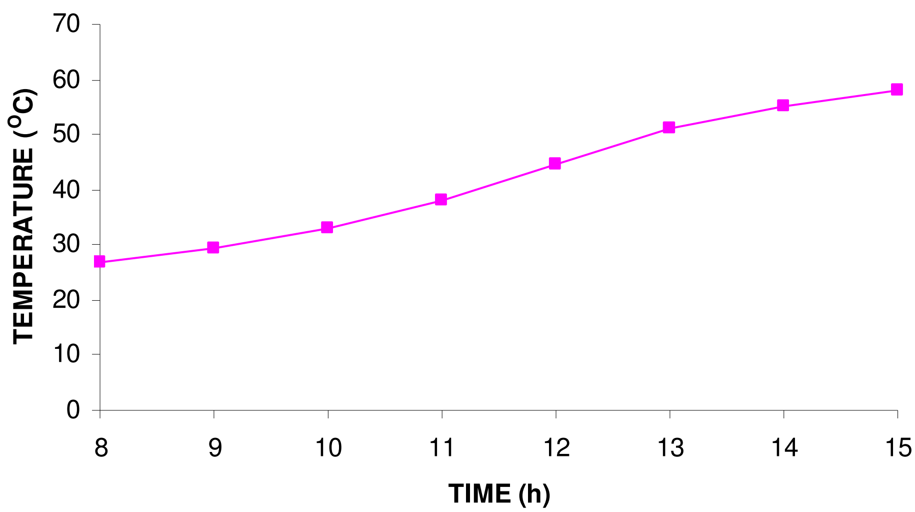

Fig. 6.2 Typical variation of storage water temperature over a few hours in a day

The system is quite simple to install and operate. Most of these systems have capacities of 100 or 150 litres per day, and use one flat plate collector having a face area of 2 m^2. The installed cost is about Rs.110 per litre per day, and the temperature of the hot water ranges from 50 to 80°C. A provision for auxiliary heating may be required for use on cloudy or rainy days. An electrical back-up heating is available with many systems. The technical feasibility and economic viability of solar water heating are beyond doubt. Depending on the site, type of utilisation and electricity or fuel pricing, the payback period varies from 3 to 5 years. A 100 litres capacity system can replace an electric geyser for residential use, saving about 1500 units of electricity annually [1]. The life of such a system is normally 15 to 20 years.

A large number of such systems are successfully being used in the country. Thermosyphon water heating systems can be located on the roof of a building. Such installations exist at the Solar Energy Centre, Gwal Pahari (Gurgaon) and LEDeG Trainees Hostel, Leh among others [2]. The hot water systems may also be easily installed on parapets or the roof of a lift house, and be an integral part of the architecture. Such installations are being used at the residence of Mahendra Patel, Ahmedabad, Tapasya Block, Aurobindo Ashram (New Delhi), and the residence of Sudha and Atam Kumar, New Delhi to name a few [2]. The additional load due to the entire set-up consisting of a storage tank of 125 litres capacity, one collector and associated stands would be approximately 215 kg. Figure 6.3 shows a photograph of Sudha and Atam Kumar's residence with solar hot water system.

Fig. 6.3 Solar hot water systems in Sudha and Atam Kumar's residence in New Delhi [2]

Another version of a natural circulation water heating system is shown in Fig. 6.4. This has a simpler design with the functions of the collector and storage tank combined into one unit. It consists of a rectangular box kept in a housing, and is insulated on all sides except the top which has a glass cover. The box is filled with water in the morning, which gets heated through the day and is withdrawn for use in the evening. It can also have an insulated lid for covering the glazing to reduce overnight loss of heat from the storage. It may be mentioned that the cost of a collector-cum-storage solar water heater is relatively less. However, it is less efficient and yields water at a lower temperature compared to the thermosyphon-type (Fig 6.1)

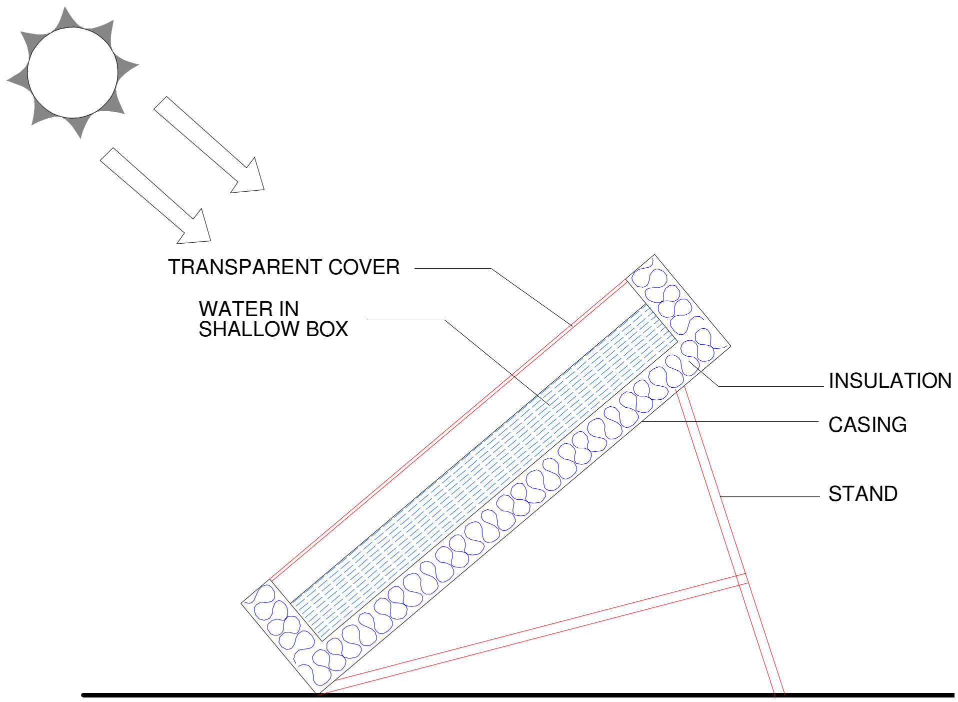

Fig. 6.4 Collector-cum-storage solar water heating system

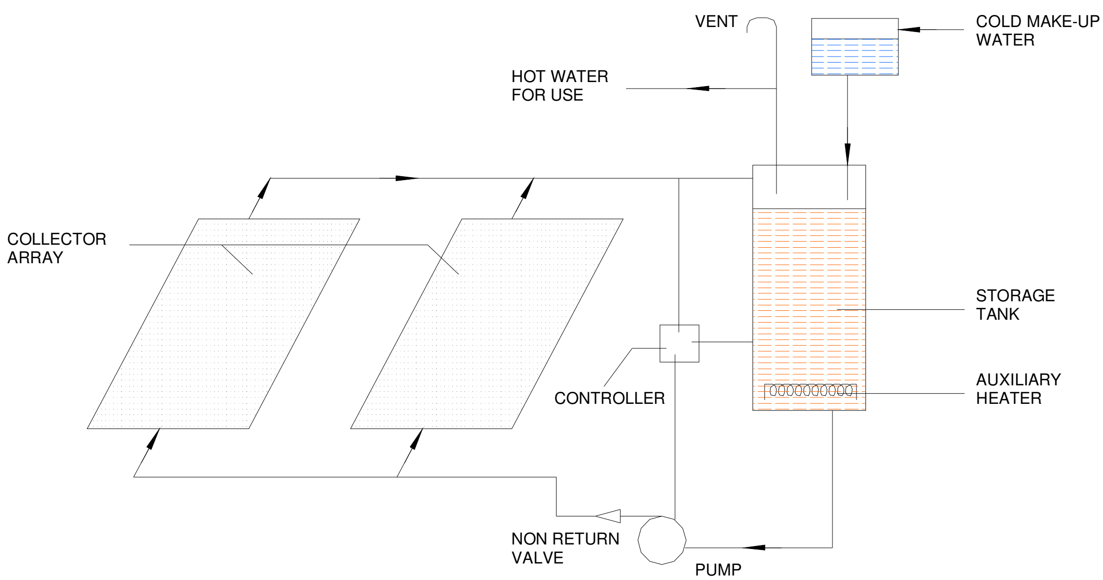

Fig. 6.5 Forced circulation solar water heating system

(B) Forced circulation solar water heating system

Figure 6.5 shows the schematic of a forced circulation system. It consists of an array of collectors (connected appropriately), storage tank, pump, controller and vent. It uses a water pump for maintaining the flow through the collector. The storage tank can be placed in any position and need not be at a higher level than the collectors. Whenever hot water is withdrawn for use, cold make-up water replaces it. A controller takes care of the schedule of flow circulation in the system. The pump is switched on or off based on the difference between the temperature of the exit water from the collectors, and the temperature of the storage water measured at a suitable location. Auxiliary heating is usually provided for meeting the hot water demand. These systems are suitable for hospitals, hotels, hostels, etc. The rows of collectors are spread out such that one bank of collectors does not shade the other bank.

Forced hot water systems are used in many buildings such as MLA Hostel, Shimla and Solar Passive Hostel, Jodhpur [2]. There are many variations possible in the configuration shown in Fig 6.5. For locations where freezing conditions can occur, antifreeze mixture is used as the working fluid. In such cases, an expansion tank and a pressure relief valve are used in the collector loop to accommodate the thermal expansion of water.

The forced water heating systems are more complex than other types. As mentioned earlier, they are more suitable when a large amount of hot water is required. In addition to providing hot water for the building, these systems can be also used for space heating purposes. Hot water from the storage tank can be used to heat air using a water-to-air heat exchanger and the hot air can be used to heat the desired space. However, the systems, meeting both the requirements, become expensive and are not commonly used in India.

6.1.2 Solar Air Heating

The space heating system using water-to-air heat exchanger has been explained in the previous section. An alternative approach is to heat air directly in the collectors and store the heat in a tank packed with rock, gravel or pebbles. Such a system is shown in Fig 6.6. When hot air is needed for a living space, cool air is pushed through the storage to get heated up before it is circulated in the room. Auxiliary heating may be required to augment the solar heat. Figure 6.7 shows the photograph of an installation of an air heating system in H.P. State Co-operative Bank, Shimla [2]. In principle, one can also obtain hot water for the building through an air to water heat exchanger. Such systems are, however, expensive and are not commonly used in India.

It may be mentioned that in addition to space heating, hot air can also be used for drying purposes. Many types of solar dryers are available to suit different needs.

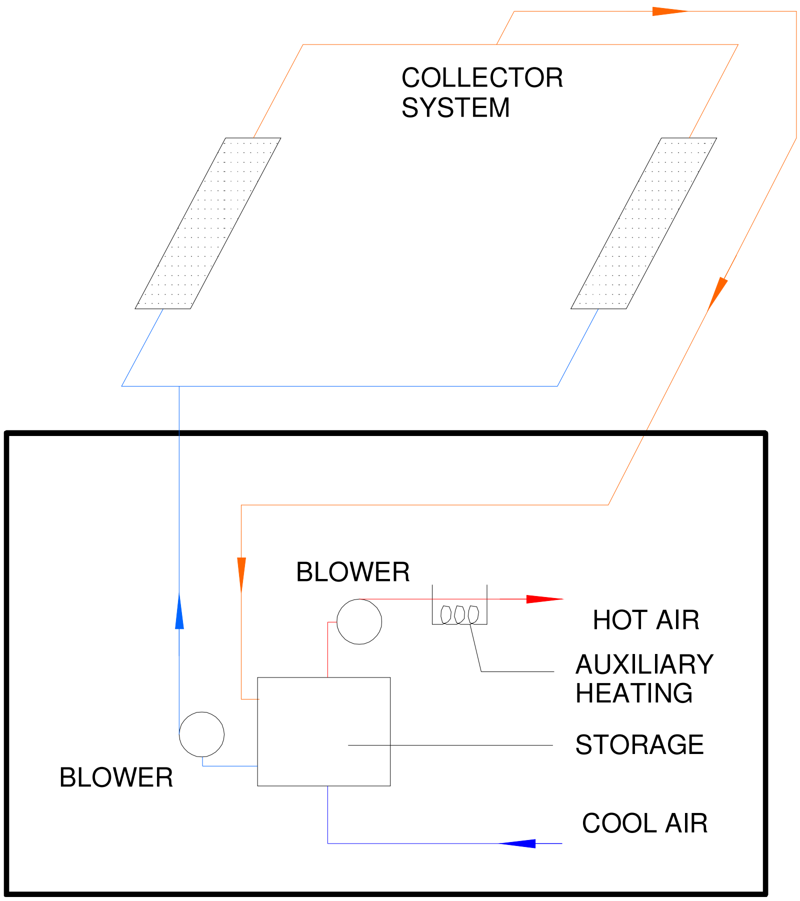

Fig. 6.6 Solar space heating system

Fig. 6.7 Photograph of solar air heating system at the HP State Co-operative Bank, Shimla [2]

6.1.3 Solar Cooking

Cooking is another important and successful domestic thermal application of solar energy. Though a number of designs have been developed, it is the box type cooker that is widely used in India. It consists of a square box insulated on the bottom and sides and having double glazing on the top. Solar radiation gets transmitted through the top and heats up the cooking vessels kept inside the box. A typical size is about 50 cm x 50 cm and 10-15 cm deep. On sunny days, a temperature of about 100^{o} C can be easily achieved inside, and pulses, vegetables, rice etc. can be readily cooked. The time required for cooking varies depending on the level of solar radiation; it may be from half an hour to $2^{1}/_{2}$ hours. A solar cooker can cook four dishes at a time and save three to four LPG (liquefied petroleum gas) cylinders a year, if used regularly. Cookers with electrical back up are also available for use during non-sunshine hours.

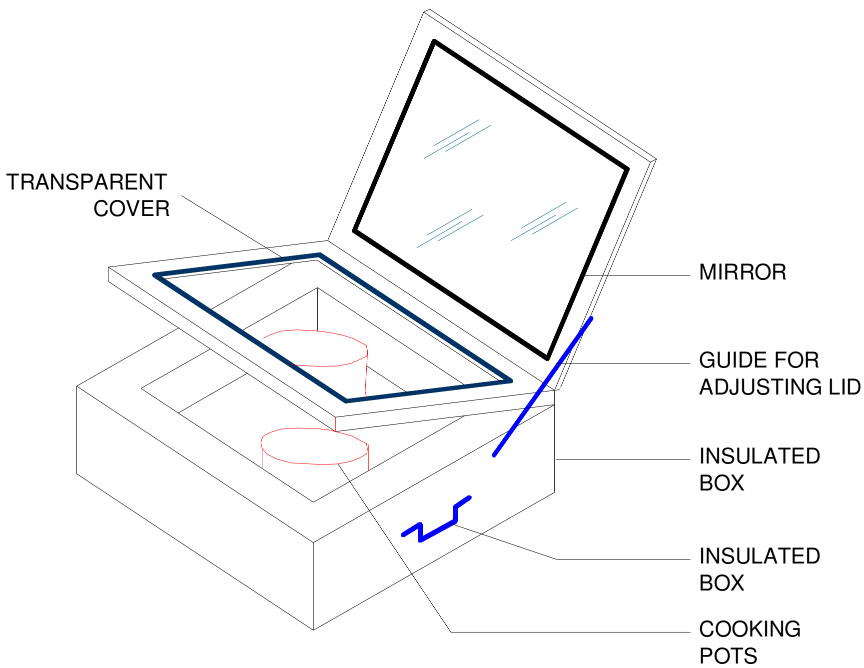

Fig. 6.8 Schematic view of a box type solar cooker

The box is provided with an insulated lid fitted with a mirror in the inner side. The lid can be adjusted to reflect radiation onto the cooking vessels and augment the level of radiation. Figure 6.8 shows a sketch of the box type cooker. Such cookers have been integrated into kitchen walls (Fig. 6.9) [2]. There are many other designs of the solar cooker available in literature [3]. Not all of these can be integrated into the building. A noteworthy model is the community solar cooker (also known as Scheffler cooker), which can be used for indoor cooking. It has a large reflector standing outside the kitchen and is automatically tracked. Solar rays are reflected into the kitchen through an

Fig. 6.9 Box type solar cooker integrated in MLA hostel, Shimla [2]

opening in its north wall (in the northern hemisphere). A secondary reflector further concentrates the radiation onto the bottom of the cooking pot. The community solar cooker can cook all types of food for about 40-50 people, and can save upto 30 LPG cylinders in a year.

6.1.4 Solar Photovoltaic Devices

Photovoltaic conversion is the direct conversion of sunlight into electricity by means of solar cells. The main advantage of solar photovoltaic devices is that they can produce power from microwatts upto kilowatts. Consequently, they are used in many applications such as calculators, watches, water pumps, buildings, communications, satellites, space vehicles, etc.

To obtain desired voltages and currents, individual cells are connected in series and parallel to form a module. A number of modules are interconnected to form an array. Based on the power requirement, arrays of appropriate sizes are used. Currently the cost of solar photovoltaic modules is around Rs.125-130 per peak watt (W_p). The Ministry of Non-conventional Energy Sources, Government of India is promoting five different configurations of solar home systems. They are: 18 W_p PV module (typically 532 mm x 448 mm) with one 9W compact fluorescent lamp (CFL); 40 W_p PV module (typically 828 mm x 433 mm) with two 9W CFLs or one 9 W CFL and a fan; and 75 W_p PV module (typically 1208 mm x 538 mm) with four 9W CFLs or two 9W CFLs and a fan/TV [1]. As far as applications in buildings are concerned, there are various usages such as, domestic lighting, street lighting, water pumping, etc.

The photovoltaic industry is growing rapidly. As a result of technological innovations, the Building Integrated Photovoltaic (BIPV) systems have become a reality [4]. Photovoltaic panels can be made to form components of a building. Positioned on the façades or roof of a building, PV panels can generate electricity either for internal use or for distribution to an external network. They may become elements of the architectural design. Examples of such buildings including the RETREAT, Gwal Pahari (Gurgaon) and residence of Mahendra Patel, Ahmedabad are discussed by Majumdar [2].

Figures 6.10 – 6.13 show a few configurations of PV integration in buildings. Table 6.1 summarises the advantages and disadvantages of different types of PV modules as far as integration into buildings is concerned. It is desirable to use non-corrosive construction materials because small current leakages invariably occur on PV façades. Secondly, the construction should not shade the PV modules and dust and rainwater should not accumulate on it.

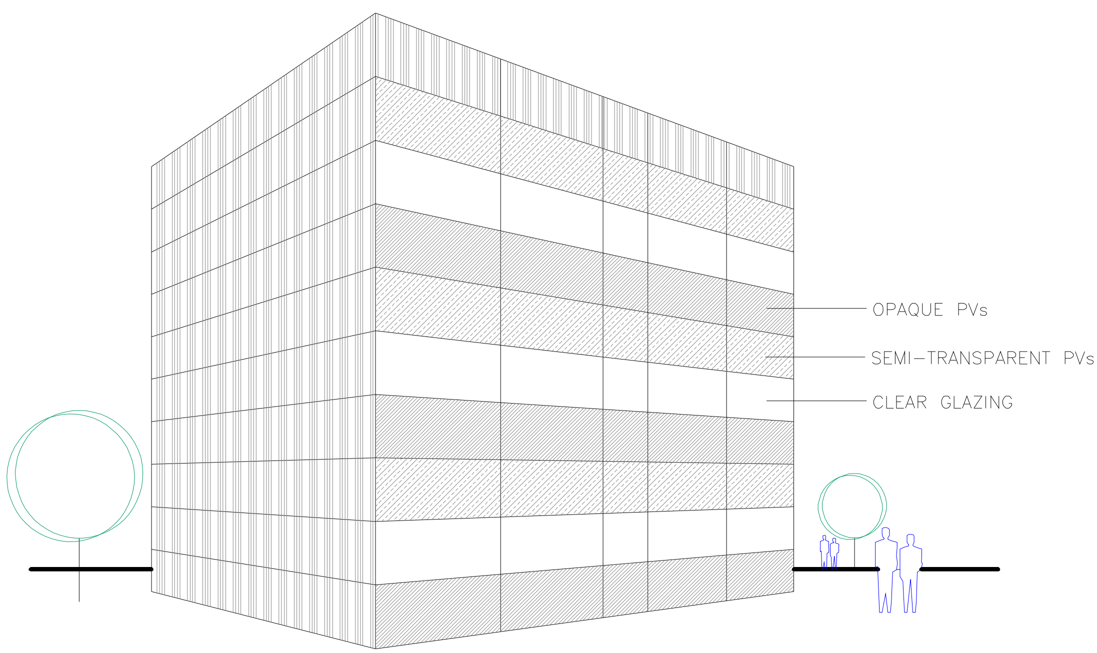

Fig. 6.10 Curtain wall with PV panels

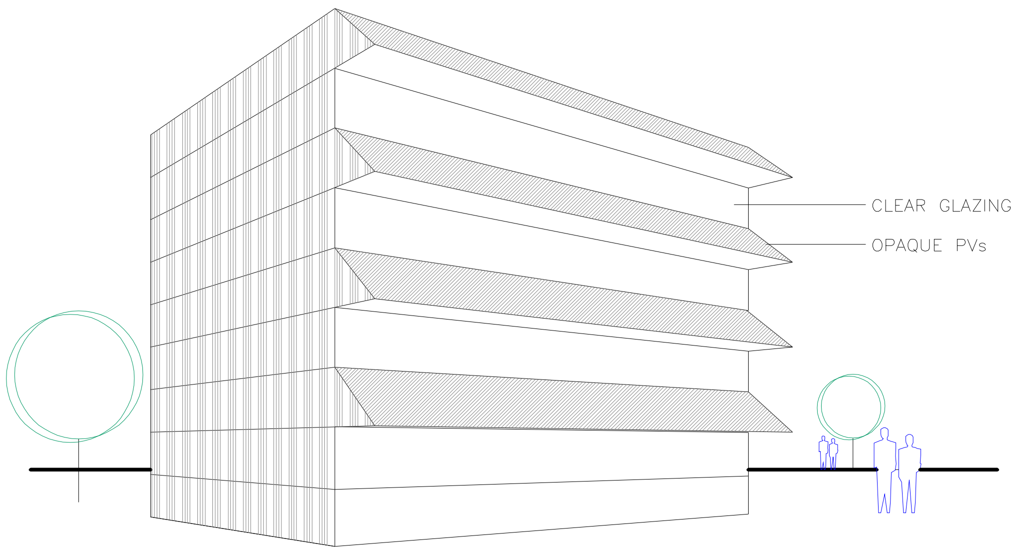

Fig. 6.11 PV panels on shading devices

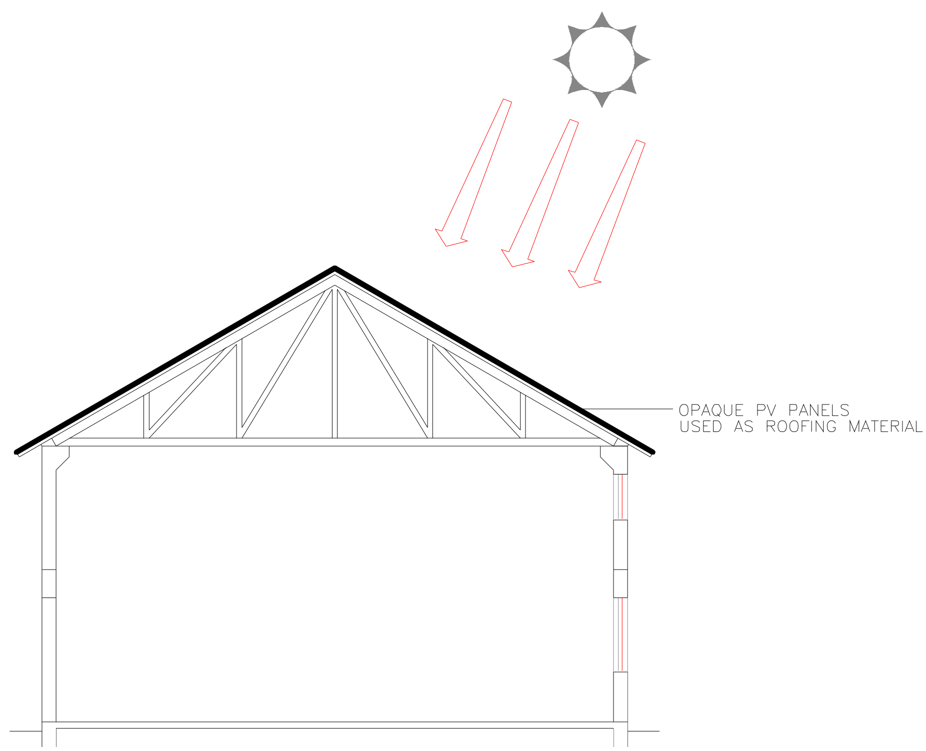

Fig. 6.12 Roof integrated PV panels

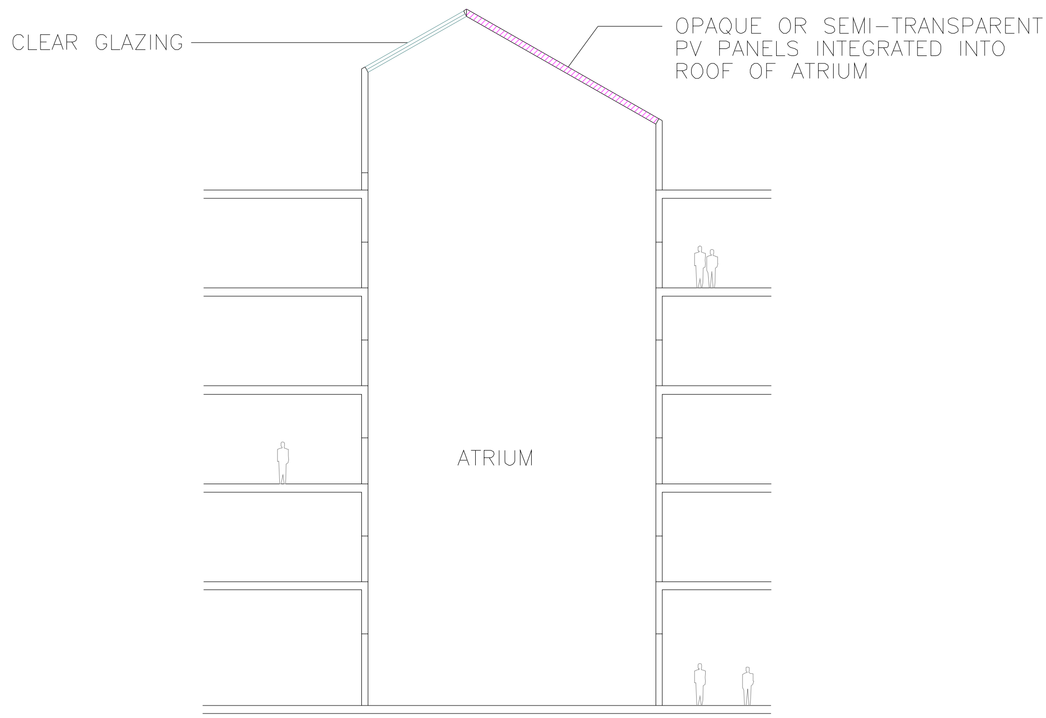

Fig. 6.13 Atrium with PV panel skylight

Table 6.1 Suitability of module types for building integration [4]

Module Type	Application suitability				
	Sloped roof	**Flat roof**	**Wall**	**Windows**	**Shading**
Standard laminates without frames	+	+	+	-	+
Standard modules with plastic or metal frame (glass multi-layer non-transparent back sheet)	+	0	0	-	0
Roofing modules (tiles/slates)	+	-	-	-	0
Glass-glass modules with predefined transparency	0	0	+	+	+
Glass modules with transparent plastic back sheet (predefined transparency possible)	0	0	+	+	+
Module with metal back sheet and plastic cover	+	+	+	-	+
Custom-designed modules	+	+	+	+	+

+ = high suitability
0 = low suitability
- = not suitable

6.1.5 Biomass

Biomass is a versatile source of energy. It can be burnt directly for heat, fermented for alcohol fuels, anaerobically digested for biogas production, or gasified to get producer gas. It includes all plant life (trees, agricultural plants, bush, grass, algae, etc.), agricultural residues (crop and agro-processing), and wastes (municipal waste, animal and human wastes). The resource is highly decentralized and scattered.

In India, the potential of biomass as an energy resource is very large. The aim of biomass conversion is to convert biomass into more useful forms: gaseous or liquid fuels. Examples of conversion to gaseous fuels include anaerobic fermentation of wet livestock (or human) wastes to produce *biogas*, a mixture of methane (45 to 70%) and carbon dioxide; and high temperature gasification of dry biomass to produce *producer gas*, a mixture of carbon monoxide, hydrogen, methane, carbon dioxide and nitrogen. As far as conversion of biomass to liquid fuel is concerned, one route is the fermentation of sugars to ethanol; another is the thermochemical conversion of biomass to pyrolysis oils or methanol. The processing of vegetable oils to biodiesel is also a method to produce liquid fuel. The resulting liquid and gaseous fuels can be used to produce heat and power. When burnt in silk mantle lamps, biogas serves as a source of lighting. It can also be used in dual-fuel engines to substitute upto 75 per cent diesel oil for motive powers. Besides, biomass can be converted to heat and power by directly burning it − the examples are boilers and steam power plants.

Gasification systems with 5 kW to 1000 kW unit capacity suitable for using a variety of biomass, have been developed in the country. There are various types of gasifiers; the suitability of a particular type depends on the application and type of biomass. For engine applications, a downdraft gasifier is the most suitable. Updraft and crossdraft gasifiers are suitable for thermal applications. Figure 6.14 shows the sketch of a downdraft gasifier.

The Ministry of Non-conventional Energy Sources has been promoting the family type of biogas plants. The models promoted include:

- Floating gas holder type. It is called as "KVIC (Khadi and Village Industries Commission) model"
- Fixed dome type, commonly known as "Deenbandhu model"
- Bag type portable digester made of rubberized nylon fabric

A sketch of a floating dome type biogas plant is shown in Fig. 6.15.

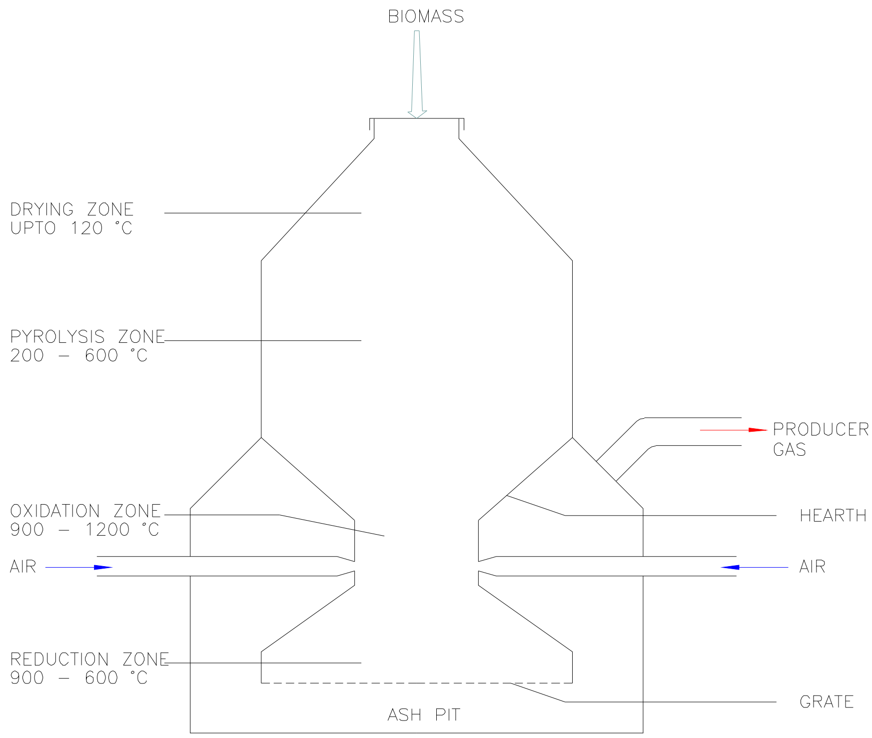

Fig. 6.14 Sketch of a downdraft gasifier

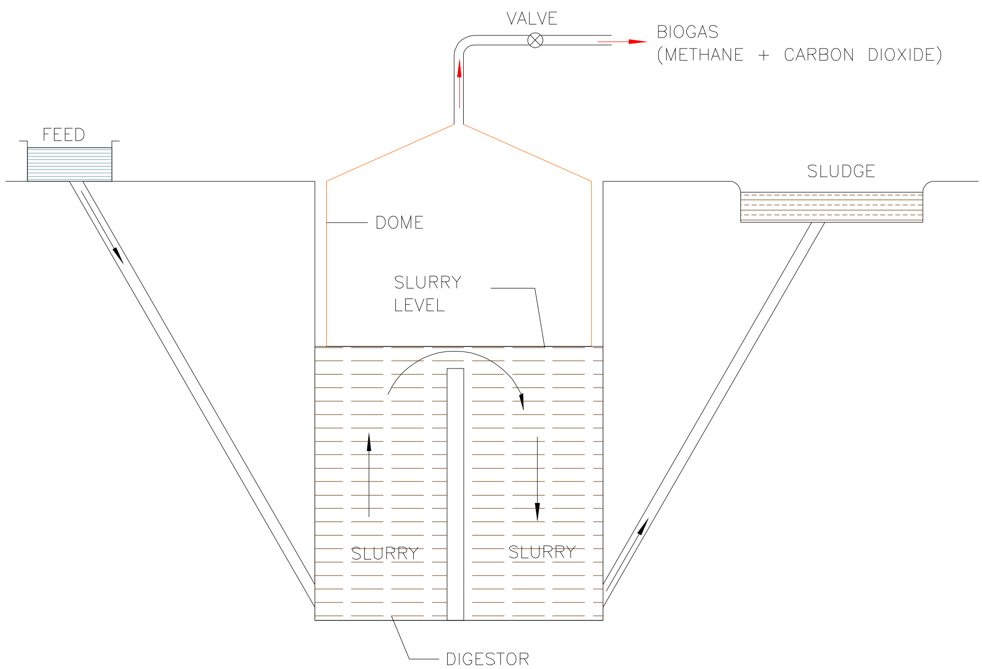

Fig. 6.15 Sketch of a floating dome-type biogas plant

As far as applications in buildings are concerned, the output of a biomass gasifier can be used for a variety of purposes such as cooking, drying, heating water, generating steam, etc. The producer gas can be used as fuel in internal combustion engines to obtain mechanical shaft power or electrical power. Similarly, biogas is an excellent fuel for cooking and lighting. It can also be used as fuel in engines. As cooking accounts for a significant proportion of household energy consumption, integration of the use of the above options with buildings leads to considerable energy savings.

6.2 PROMOTIONAL INCENTIVES

The Ministry of Non-conventional Energy Sources (MNES) as well as various state governments provide many incentives for adoption of renewable energy technologies. The MNES provides partial assistance for preparation of detail project reports (DPR) of buildings based on energy conscious design. According to the current scheme, 50% of the cost of the DPR, subject to a maximum of Rs. 2 lakhs, is paid for preparation of DPRs, including building plan and architectural drawings for public/private institutional buildings. A maximum of 10 DPRs are supported in each state. Besides, partial funding (currently 10% of the cost of the construction subject to a maximum of Rs. 50 lakhs for each project) is provided towards the construction of demonstration buildings. The support is available for buildings of state nodal agencies and other public/government buildings. Active solar systems installed in such buildings are not covered under the scheme. Two buildings in each state are currently supported through this scheme. The state government of Himachal Pradesh has made it mandatory for all government buildings situated at 2000m above MSL to have passive solar techniques incorporated in them.

There are various types of promotional schemes floated by central as well as state government as far as solar water heating, air heating, cooking, biomass gasification, biogas etc are concerned. For example, the States of Andhra Pradesh, Haryana, Himachal Pradesh, Madhya Pradesh, Punjab, Rajasthan & Union Territory of Dadra & Nagar Haveli have made it mandatory to install water heating systems in state government buildings. A few municipal bodies such as Thane in Maharashtra and Rajkot in Gujarat have modified building bye-laws to enforce solar water heating systems in new buildings. In addition to government incentives, certain companies also offer promotional schemes. For example, the Bangalore Electricity Supply Company Limited currently offers Rs.0.40 rebate on every unit of electricity used subject to a maximum of Rs.40/- per month.

The MNES has been implementing a soft loan programme for various renewable energy systems. Under this, loans at reduced interest rates are currently available to customers from IREDA and seven designated banks (Andhra Bank, Bank of Maharashtra Canara Bank, Punjab National Bank, Punjab & Sind Bank, Union Bank of India and Syndicate Bank). Also, for certain areas and for certain types of renewal energy systems, subsidies are available from the MNES through state nodal agencies.

6.3 CONSERVATION MEASURES

In addition to designing building along bioclimatic principles and using appropriate materials, it is desirable to adopt proper conservation and management practices for a building to remain both economically and environmentally viable. Both designer and user must work together to achieve this objective. While the designer should provide facilities, the user must properly understand, apply and practice the conservation measures. Recycling household wastes (such as bio-waste, kitchen waste, water, etc.), buying energy-efficient home appliances and non-hazardous products, reducing consumption of water and electricity, are some of the measures that should be implemented. Some of these can be achieved through very moderate investments. Using auto flush and auto taps in washrooms for air handling units, and water management systems such as hydro-pneumatic system including sewage pump, transfer pump and water pressurisation pumps, can also result in substantial energy saving. Similarly, vermiculture can be adopted for waste management. Biodegradable kitchen-waste can be decomposed by vermiculture to produce good quality manure, which can be used in lawns, parks etc.

Energy consumption can be reduced by the use of energy efficient home appliances, or building management systems (BMS) in offices and public buildings [5]. These work automatically depending on the building occupation status. But some of these systems may require substantial investment.

Water is a precious commodity and water conservation measures are very essential. Rainwater harvesting and recycling of water are important measures for tackling the growing shortage of pure and safe water.

(A) Rain water harvesting

Rainwater is an ideal source that can be conserved and used by people. Broadly, water harvesting is defined as the direct collection of rainwater. The total amount of rainfall over an area is called as the “Rain Water Endowment” of that area, and the part that can be effectively collected is called as the “Water Harvesting Potential”. One can devise any technique to collect and store rain water in an open land. However, for urban and semi urban areas, two most suitable systems are [6]:

- Roof top rain water harvesting
- Artificial ground water recharge

In the first case, water is collected in tanks through roof gutters and down-take pipes (Fig.6.16). There should be a provision for discarding water after the first rainfall so that dust, soot, leaves etc. are drained away. The water tank should be located in an area protected from contamination by any other water. The water should not be allowed to stagnate for a long period, and it must be chlorinated appropriately.

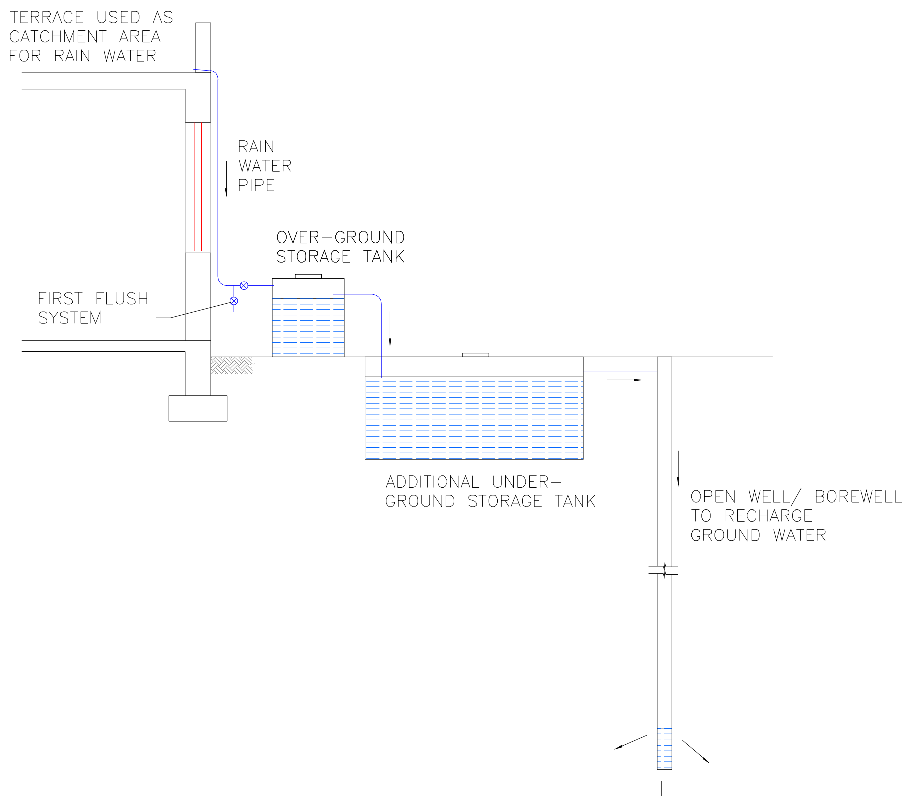

Fig. 6.16 Sketch of a rooftop rain water harvesting system

Alternatively, the rain water may be used to recharge the ground water by artificial means. Figure 6.17 shows a schematic sketch of a recharging structure usable in any urban and semi-urban area. It is important that the well be terminated at least 5 m above any natural source of water so that the rain water flows through naturally, and contamination hazards from ground water is avoided [6]. These wells should not be used for drawing water for any purpose. A publication from Centre for Science and Environment [7] provides detailed information on water harvesting.

Rain water harvesting has been practiced in many parts of the country. In fact, it is mandatory in many cities, facing scarcity of water. In many places, the withdrawal rate of ground water is very high compared to its replenishment. Artificial recharge programmes are already being implemented for increasing the level of ground water in some places [8]. One of the very successful programs is the construction of percolation tanks for holding rain water. This recharges the underground water of the area so that any well dug on the slopes downstream of the embankment will have plenty of water. The most successful example has been the Ralegan Siddhi area of Ahmednagar, Maharashtra [9]. It has resulted in an overall development of that area.

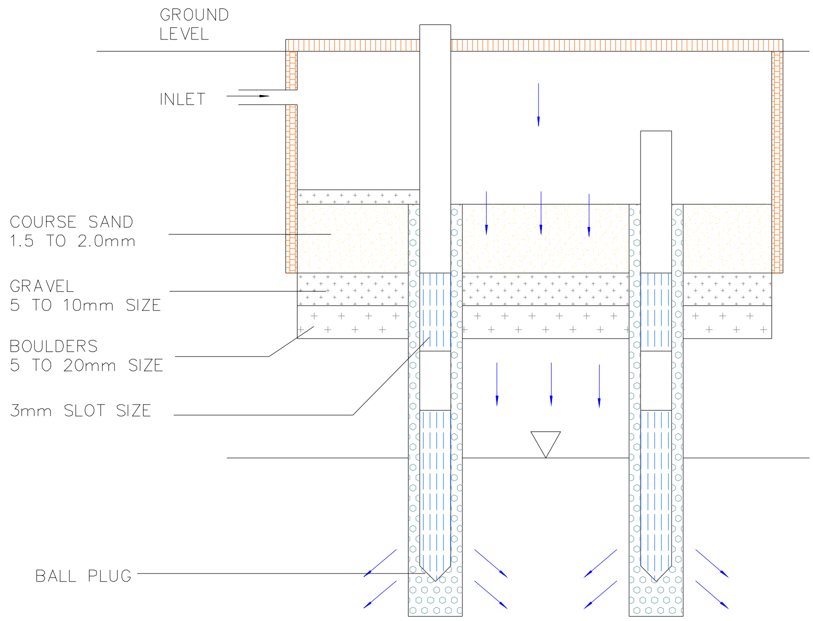

Fig. 6.17 Sketch of a recharging structure

(B) Recycling of water

Recycling of water is another important aspect of water conservation. One way of recycling is by using aquatic plants [10]. Raw sewage is recycled using aquatic plants (such as duckweed, water hyacinth, etc.) to produce clean water suitable for re-use in irrigation and industry. The plants themselves can be harvested and used for producing biogas, thus providing additional benefits. The technique can also be used for treating animal manure and other farm wastes. The main energy saving in these ecological/biological systems occurs due to the fact that natural processes are fully utilised in the cleaning process.

(C) Energy-efficient lighting

The lighting load in some buildings could be very high and hence energy efficient lighting assumes prime importance. This depends on:

- the illuminance level for an application (Appendix VI.1 provides a list of recommended values of illuminance)
- the efficiency of various components (lamps, ballasts, luminaires)
- control

- maintenance

There are a number of ways through which energy can be conserved by lighting systems. To name a few, one can install automatic voltage stabilizers for the entire lighting circuits. This increases the bulb life as also its efficiency; it can save upto 20% of the lighting bill. Compact fluorescent lamps (CFL) can be used in areas such as lobbies, corridors, showrooms, etc. These are highly energy efficient lamps. The chokes (magnetic ballasts) of tube lights can be replaced by energy conserving electronic ballasts. Key card systems in hotel rooms and offices, or circuit breakers for lighting and appliances in residential buildings can help reduce energy wastage. Dimmers can also be used to reduce lighting levels when bright light is not required.

6.4 EXAMPLES

There are a number of buildings that use renewable energy and energy conservation measures. Majumdar [2] has reviewed such buildings in great detail . Table 6.2 presents a few of such buildings; it lists the renewable energy features incorporated in these buildings.

Table 6.2 List of buildings using renewable energy and energy conservation measures [2]

S. No.	Name of the building	Location	Features
1.	Himurja Office	Shimla	Water heating, PV for lighting
2.	HP State Co-operative Bank	Shimla	Air heating
3.	Residence of Mohini Mullick	Bhowali Nainital	Integrated solar cooker, water heating
4.	MLA Hostel	Shimla	Integrated solar cooker, water heating
5.	LEDeG Trainees Hostel	Leh	Water heating
6.	Residence of Madhu and Anirudth	Panchkula	Water heating, PV for lighting
7.	PEDA Office Complex	Chandigarh	BIPV, water heating
8.	Tapasya Block, Sri Aurbindo Ashram	New Delhi	Water heating
9.	Residence of Sudha and Atam Kumar	New Delhi	Water heating, integrated solar cooker
10.	RETREAT	Gwal Pahari, Gurgaon	BIPV, gasifier, water heating, water recycling, building management system
11.	Solar Energy Centre	Gwal Pahari, Gurgaon	Water heating
12.	National Media Centre Cooperating Housing Complex	Gurgaon	Rain water harvesting, solid waste recycling, water heating
13.	American Institute of Indian studies	Gurgaon	Water heating
14.	Sangath	Ahmedabad	Rain water harvesting
15.	Residence of Mahendra Patel	Ahmedabad	Roof integrated PV, water heating, building automation system
16.	Solar Passive Hostel	Jodhpur	Water heating
17.	Residence of Mary Mathew	Bangalore	Water heating
18.	TERI office building	Bangalore	Rain water harvesting, PV, water heating
19.	WBREDA	Kolkata	Roof-mounted grid-interactive PV
20.	WB Pollution Control Board Laboratory	Kolkata	Waste water recycling
21.	Silent valley	Kalasa	Water harvesting, waste water and sewage recycling, biomass heater for water heating
22.	Vikas Apartments	Auroville, Pondicherry	Waste water treatment, PV, water heating, solar pumps

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APPENDIX VI.1

Recommended values of illumination for a few building types [11]

Buildings and Processes	Recommended Illumination (lux)
A. Offices, Schools and Public Buildings	
Airport buildings	
Reception area (desks)	300
Customs and immigration halls	300
Circulation areas, lounges	150
Assembly and concert buildings	
Foyers, auditoria	100 to 150
Platforms	450
Corridors	70
Stairs	100
Banks	
Counters, typing, accounting book area	300
Public areas	150
Cinemas	
Foyers	150
Auditoria	50
Corridors	70
Stairs	100
Offices	
Entrance halls and reception areas	150
Conference rooms, executive offices	300
General offices	300
Business machine operation	450
Assembly halls of schools and colleges	
General	150
When used for examinations	300
Platforms	300
Class room desks	300
Class room blackboards	200 to 300
B. Homes	
Kitchens	200
Bathrooms	100
Stairs	100
Workshops	200
Garages	70
Reading (Casual)	150
Homework and sustained reading	300

CHAPTER 7

CASE STUDIES

Contents:

This chapter presents examples of buildings incorporating various aspects of energy conscious design. They demonstrate the successful use of passive solar architecture, sustainable materials, conservation of resources, and integration of renewable energy technologies. The examples are chosen from different climatic zones so as to present a wide variety of techniques.

7.1 INSPECTOR GENERAL OF POLICE (IGP) COMPLEX, GULBARGA [1]

Location : Gulbarga, Karnataka
Climate : Hot and dry

Brief description of the building:

This building is a ground and two-storeyed structure designed by Kembhavi Architecture Foundation to house the offices of the Inspector General of Police, Gulbarga. The building is constructed using innovative materials. For example, the external walls are composite walls (i.e. granite blocks on the outer side and rat-trap bond brick walls on the inner side) and the roof is made of filler slab. The U-values of the walls and roof are 1.53 W/m^2-K and 2.15 W/m^2-K respectively. The building is roughly rectangular with the longer axis along the north-south direction. Most windows face east or west. A layout plan of the building is given in Fig. 7.1. As the building is located in a hot and dry climate, evaporative cooling has been used for providing comfort. Most of the offices are cooled by passive downdraft evaporative cooling (PDEC) tower system. Figure 7.2 shows a photograph of the building as well as a sketch section of a typical PDEC tower to explain its principle.

Energy conscious features:

- Passive downdraft evaporative cooling (PDEC) towers for providing comfort
- Tinted glasses to reduce glare
- Alternative building materials such as composite walls to reduce heat gain and filler slabs to reduce the quantity of concrete in the structure
- A central atrium to enhance cross ventilation and provide daylighting
- Solar PV lighting and pumps, rainfall harvesting and water conservation facilities incorporated

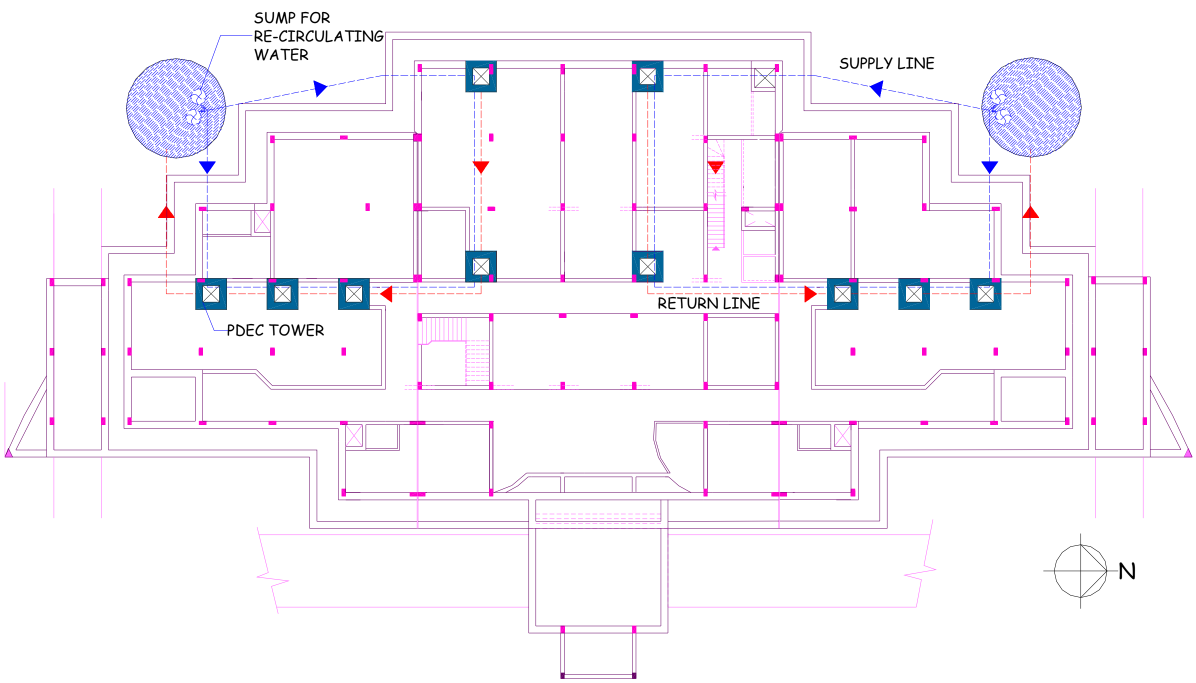


Fig. 7.1 Layout plan of I.G.P. Complex, Gulbarga

Performance of the PDEC system:

The building is in the final stage of construction. The PDEC system's design is based on the "shower tower" (discussed in Chapter 3) concept developed by Givoni [2]. Preliminary measurements taken in May and September, 2005 showed that the temperature of the air exiting from the tower is lower by about 10°C and 4°C respectively, compared to that of ambient air. Figure 7.3 presents the hourly values of the temperature of air exiting from the tower on a typical day in September. The corresponding measured values of ambient temperature are also plotted for comparison. Additionally, the figure shows the theoretically calculated values based on Givoni's model of the shower tower. It is seen that the measurements agree reasonably well with the predictions. Figure 7.4 shows the estimated performance of a tower in various months during daytime. It presents the results of exit temperature of air leaving the tower and the corresponding ambient dry bulb temperature. It is seen from the figure that the performance of the cooling tower is quite satisfactory in the summer months. The drop in temperature is about 12 - 13 °C in March, April and May. Considering that the PDEC system is used in these months, the predictions of the energy savings of the building per annum, as compared to an air-conditioned building maintained at 27.5 °C, are as follows:

Estimated Cost of PDEC system	= Rs. 17,50,000
Estimated savings per annum	= Rs. 3,52,000
Simple payback period	= 5 years (approximately)

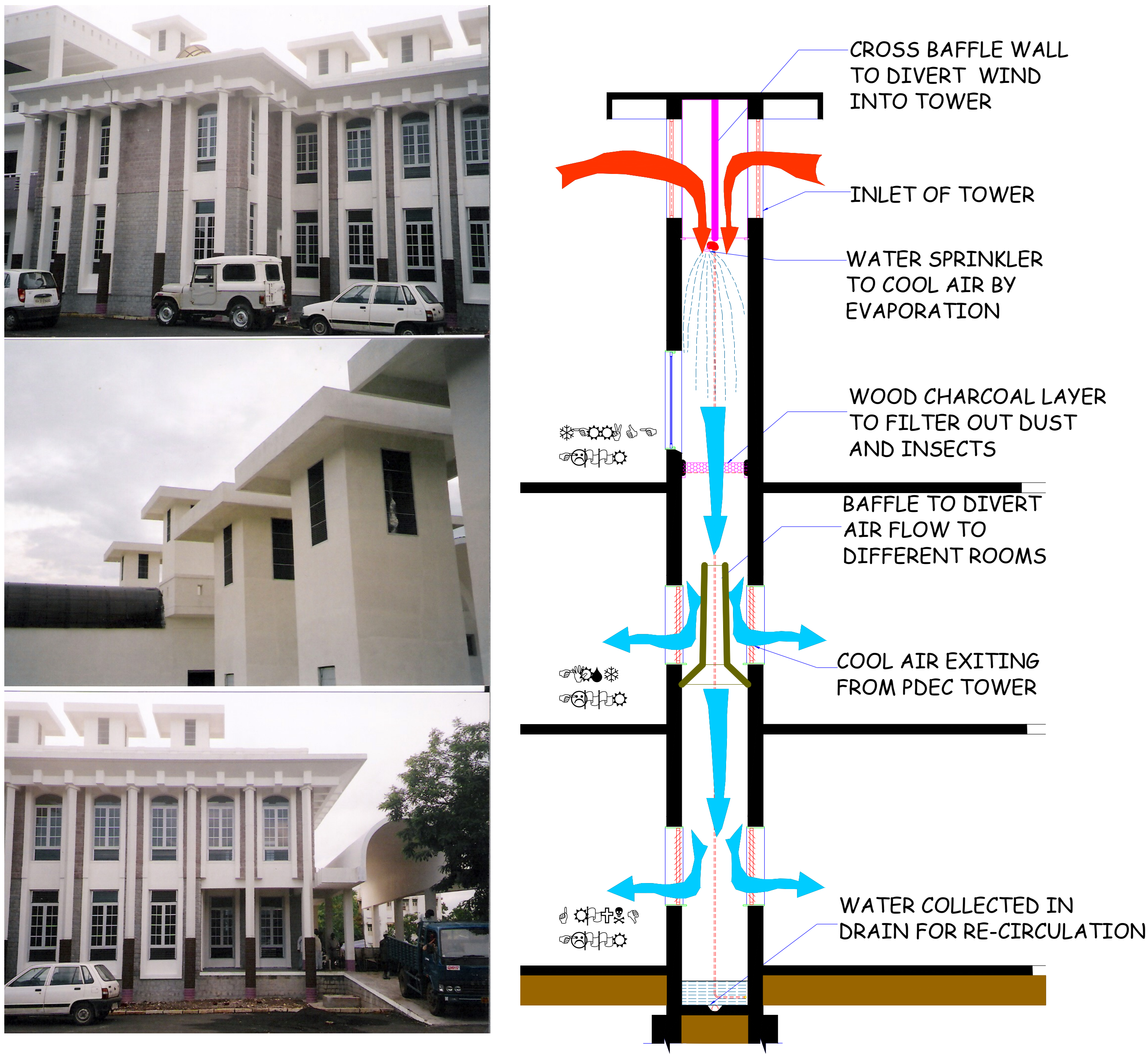


Fig. 7.2 Photgraphs of IGP Complex, Gulbarga and sketch showing the principle of a PDEC tower

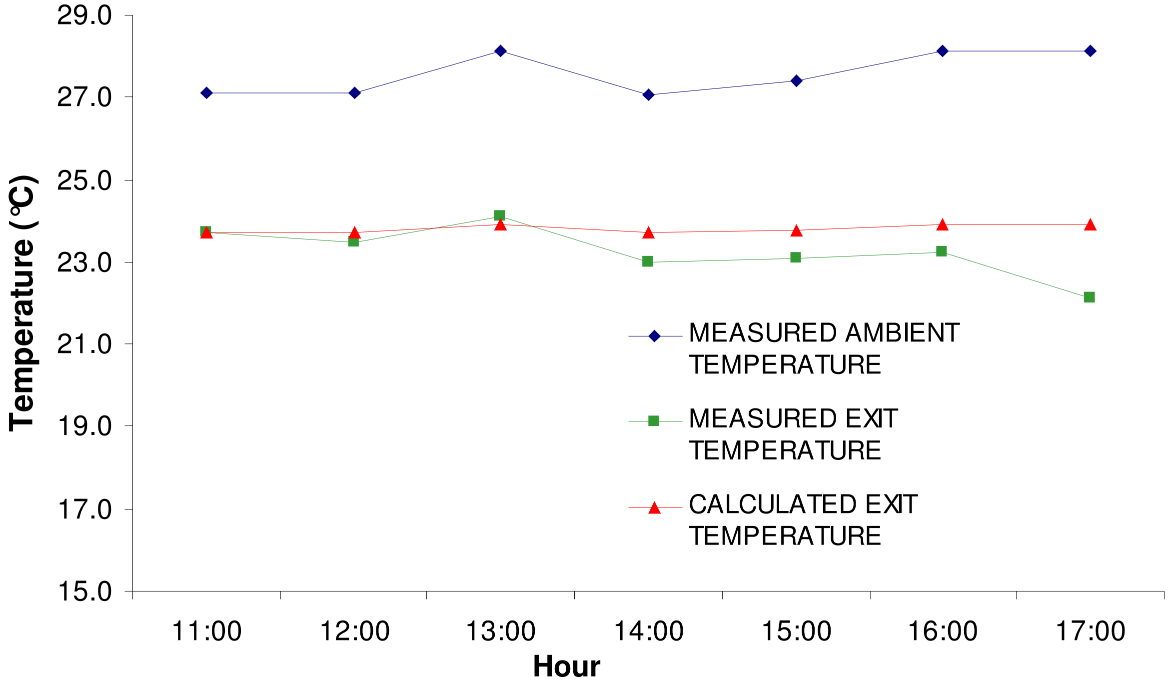


Fig. 7.3 Comparison of measured and predicted temperature of air exiting PDEC tower

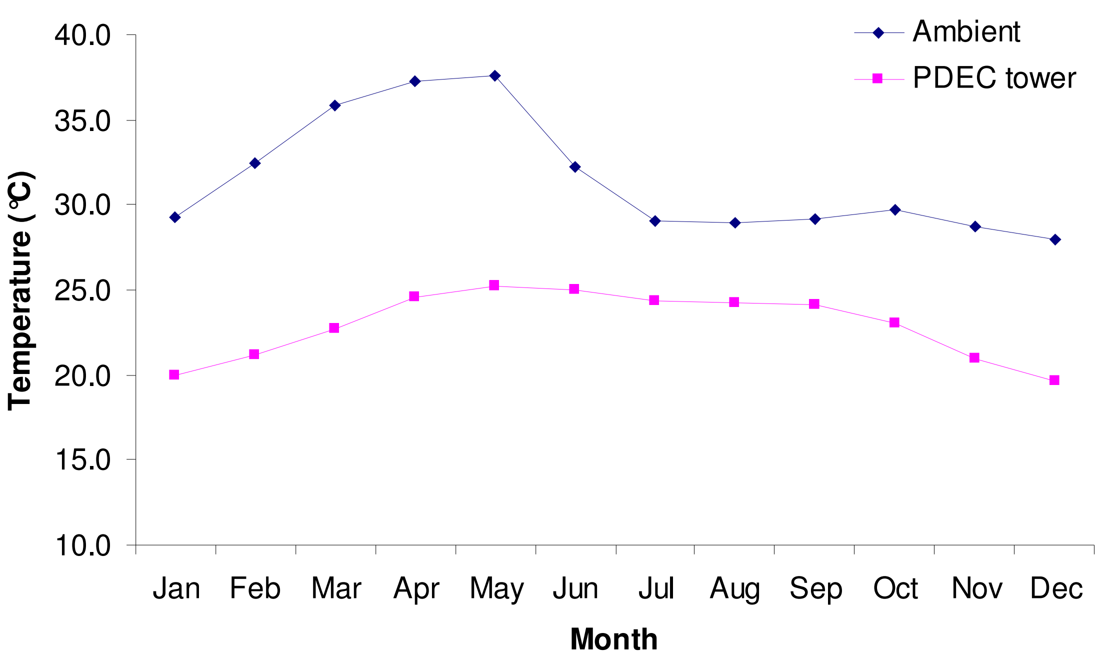


Fig. 7.4 Monthly prediction of the temperature of air exiting the PDEC tower

7.2 AUROVILLE ECOHOUSE, AUROVILLE [3]

Location : Auroville, Pondicherry
Climate : Warm and humid

Brief description of the building:

The Ecohouse was built in 1976 by a team co-ordinated by Dr. C. L. Gupta at Auroville. This house can be considered as one of the first prototypes of an ecologically sustainable building to be constructed in India in modern times. It is a two storeyed structure with longer axis along the east-west direction, designed for catching wind. A courtyard is provided in the building which is cooled by Venturi effect. The overhangs above the windows and doors are designed for optimal shading from the sun. A sketch plan and section of the Ecohouse are given in Fig. 7.5.

Energy conscious features:

- Optimum orientation of built form for cooling by ventilation
- Shading of windows to reduce heat gain
- Alternative building materials such as (i) structurally insulated roof units (size 1.0m X 0.5m), developed by Central Building Research Institute, Roorkee, (ii) jack arches of hollow ceramic Gunna tiles
- A courtyard to enhance cross ventilation and provide daylighting
- Other features such as solar cooker integrated in south facing kitchen, rainfall harvesting system, biogas plant for waste management and production of methane gas for cooking, an aero- generator for domestic electric load and a thermosyphon solar water heater are also incorporated into the building design

Performance of the house:

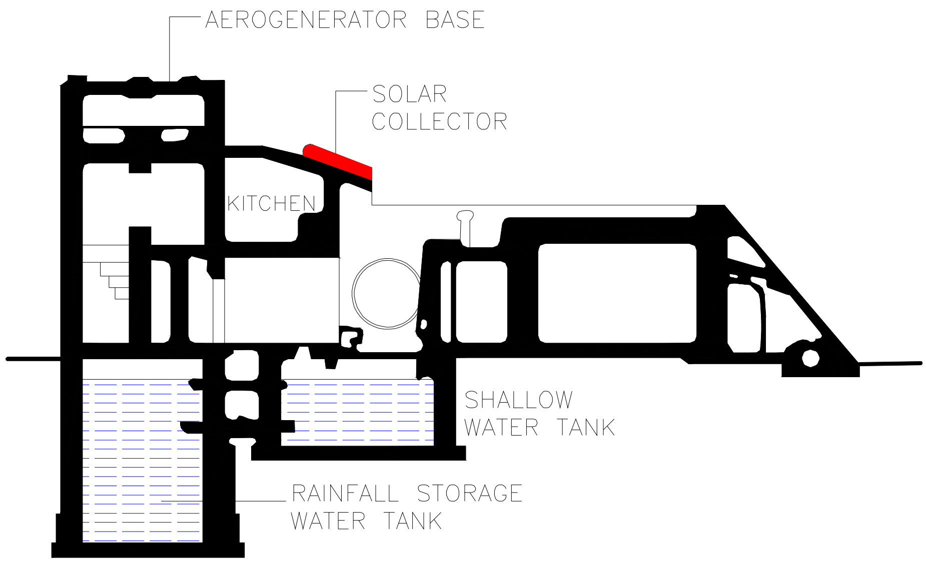
The house has no fans and is reported to be one of the coolest houses in Auroville as observed by the occupants.

7.3 CENTRE FOR APPLICATION OF SCIENCE AND TECHNOLOGY FOR RURAL AREAS (ASTRA), BANGALORE [4]

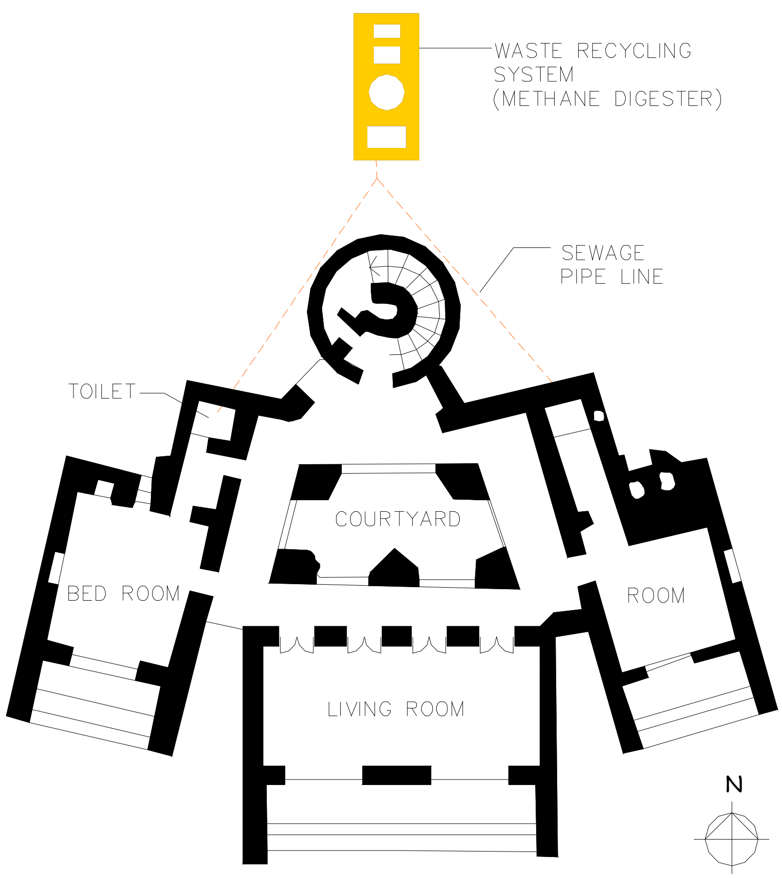
Location : Bangalore, Karnataka
Climate : Moderate

Brief description of the building:

The building is a ground and one-storeyed structure and is used as an office building. The salient feature of the building is the use of various alternative building



(a) Section of Ecohouse



(b) Sketch plan of Ecohouse

Fig. 7.5 Section and sketch plan of Ecohouse, Auroville

materials that are affordable, environment friendly and energy efficient. It was built in 1999 in the campus of the Indian Institute of Science, Bangalore. Figure 7.6 shows the typical floor plan of the building. A photograph of the building is given in Fig. 7.7.

Energy conscious features:

- Sized stone masonry with composite mortars in foundations, steam-cured stabilized blocks for ground floor load-bearing walls, and soil-cement blocks for the first floor walls. The external exposed walls are coated with transparent silicone paint for protection from erosion
- Precast chajjas and brackets are made of ferrocement
- Reinforced blockwork lintels are used above openings such as doors and windows
- Soil-cement block filler slabs are used for floors and roof. An additional weatherproof course using tiles is provided on the roof

Performance of the building:

The cost of construction of this building was Rs. 4247 per square metre of plinth area in 1999. The component-wise cost of the building and the corresponding percentage of total cost are presented in Table 7.1.

7.4 SOLAR ENERGY CENTRE, GURGAON [5,6]

Location : Gurgaon, Haryana.
Climate : Composite (predominantly hot)

Brief description of building :

It is a single storeyed research centre. The buildings include a guest house, a workshop, offices and laboratories. Being situated on a large open plot of land, the buildings are spread out and possess courtyards around which the various activities are clustered. A plan and section of the administrative block of the same is given in Fig. 7.8.

Energy conscious features:

- Roof surface evaporative cooling system
- Appropriate planning in which laboratories requiring air conditioning are put together in a well-insulated building
- Hollow concrete block walls to resist heat gain by conduction
- Reflective finish on roof surface
- Windows designed for cross ventilation and daylighting. The east and west-facing windows incorporate openable louvered shutters

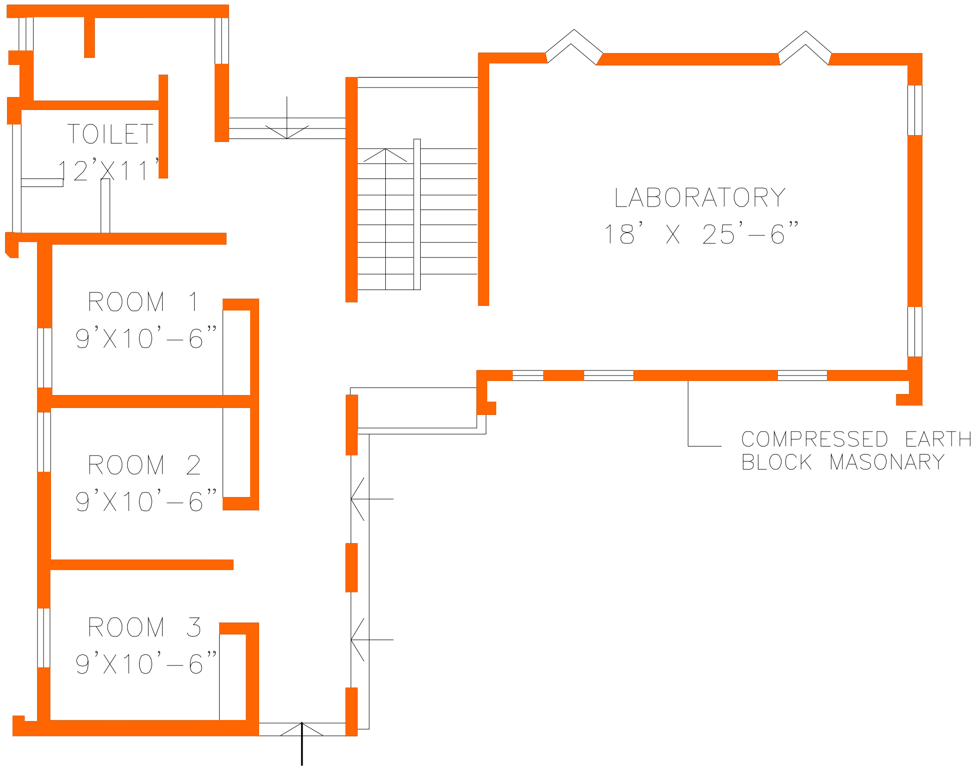


Fig. 7.6 Ground floor plan of ASTRA building, Bangalore

Fig. 7.7 Photograph of ASTRA building, Bangalore

Table 7.1 Component-wise distribution of costs of ASTRA building at I.I.Sc., Bangalore

Effective plinth area = 280m^2, Carpet area = 223.64m^2
Cost of construction per m^2 of plinth area = Rs.4247/m^2 (Rs.395/ft^2)

Component	Cost (Rs.)	% of total cost
Structure		
• Foundation	1,01,799.00	8.8
• Plinth	6,797.00	0.6
• Walls/beams	3,28,022.00	28.2
• Roof & Floor slabs	1,88,811.00	16.3
• Staircase	10,828.00	0.93
Sub-total	6,36,257.00	54.8
Openings		
• Doors & Windows	1,08,720.00	9.4
• Lintel & Chajjas	16,039.00	1.4
Sub-total	1,24,759.00	10.8
Finishes		
• Flooring	38,233.00	3.3
• Painting	32,377.00	2.8
Sub-total	70,610.00	6.1
Services		
• Plumbing & Sanitary	1,40,861.00	12.1
• Electrical	1,58,829.00	13.7
Sub-total	2,99,690.00	25.8
Architect fee	30,000.00	2.5
Miscellaneous	27,942.00	
Total cost	11,89,258.00	

<u>Materials used:</u>

(A) Cement: 842 bags (B) Lime: 5.5 tonnes (C) Steel: 2.66 1MT

1) Volume of bed concrete (1:4:8) : 9.86 m^3
2) Size tone masonry in foundation : 71.68m^3
3) Plinth beam: a) Concrete : 1.497m^3, b) steel : 420 kgs (Reinforced masonry)
4) Volume of masonry walls (load bearing) : 101.33 m^3
5) a) Roof area : 271.56m^2 a) Concrete: 34.03m^3, b) Steel: 2.241MT
   b) Floor area : 223.64 m^2
6) Area: a) Doors: 24.80 m^2, b) Windows : 24.08 m^2

<u>Miscellaneous items:</u>
Jali works, Parapet

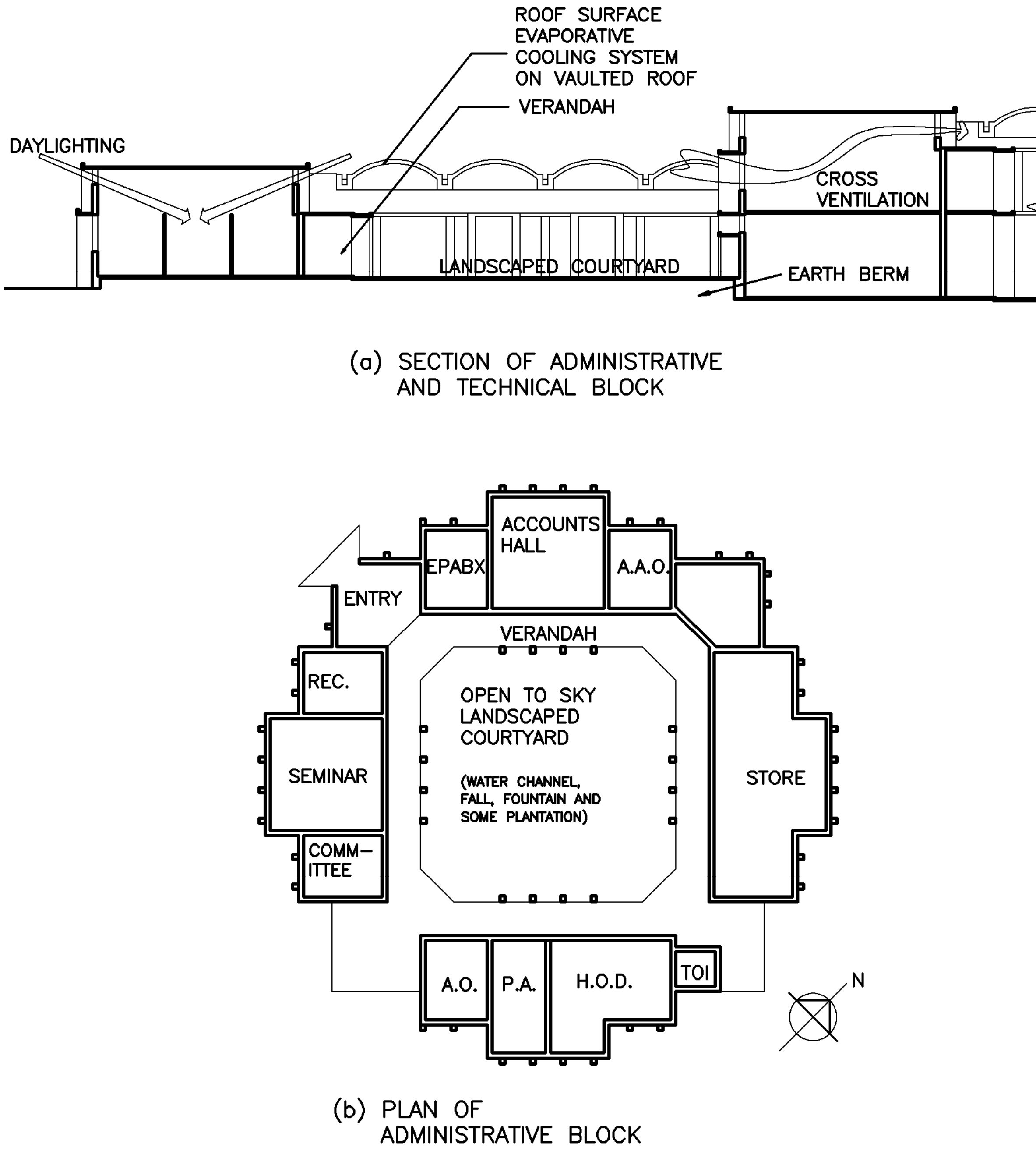


Fig. 7.8 Administration block of Solar Energy Centre, Gurgaon

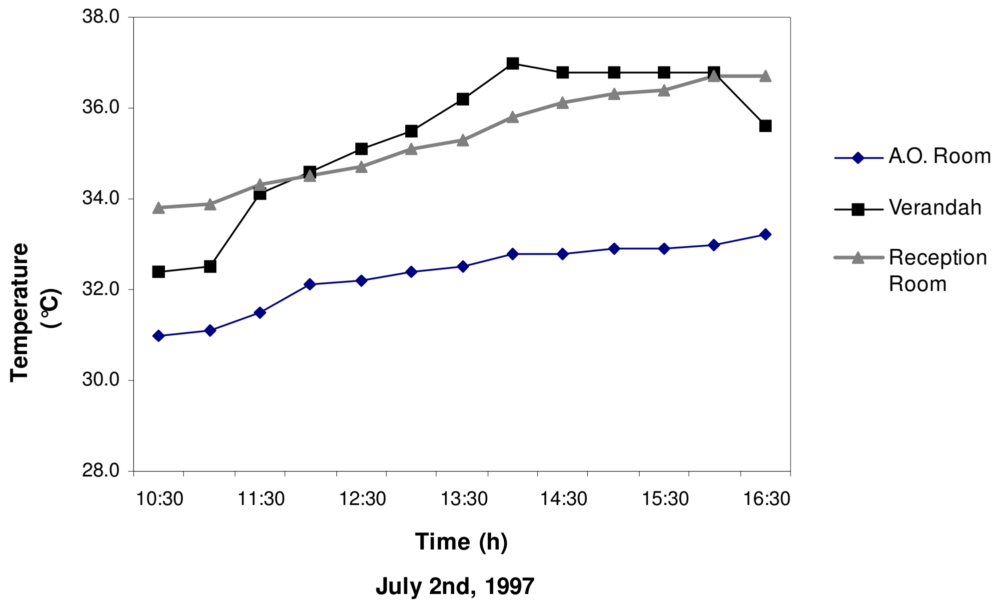


Fig. 7.9 Comparison of indoor temperatures – Solar Energy Centre, Gurgaon

Performance of the building:

The Solar Energy Centre conducted a post-occupancy evaluation of this building [5]. It was observed that the roof surface evaporative cooling (RSEC) system caused a lowering of temperature by 2-3ºC in comparison with rooms without RSEC system. Figure 7.9 shows the comparison of measured temperatures of the reception room (with RSEC system) with those of A.O. room and verandah, both being without RSEC system. One advantage of the RSEC system is that it cools in a healthy manner as it does not humidify the ambient air of the room. On the other hand if a desert cooler were to be used, it would pump moist air inside the room and increase the humidity, which would cause discomfort and affect the health of occupants.

7.5 H.P. STATE CO-OPERATIVE BANK BUILDING, SHIMLA [6,7]

Location : Shimla, Himachal Pradesh
Climate : Cold and Cloudy

Brief description of building :

This building is a ground and three-storeyed structure with its longer axis facing the east-west direction. The smaller northern wall faces the prevailing winter winds from the north-eastern direction. The building shares a common east wall with an adjoining structure. Its west façade overlooks a small street from which the building draws its main requirements of ventilation and daylighting. A plan and section of the building showing the various passive techniques incorporated is given in Fig. 7.10.

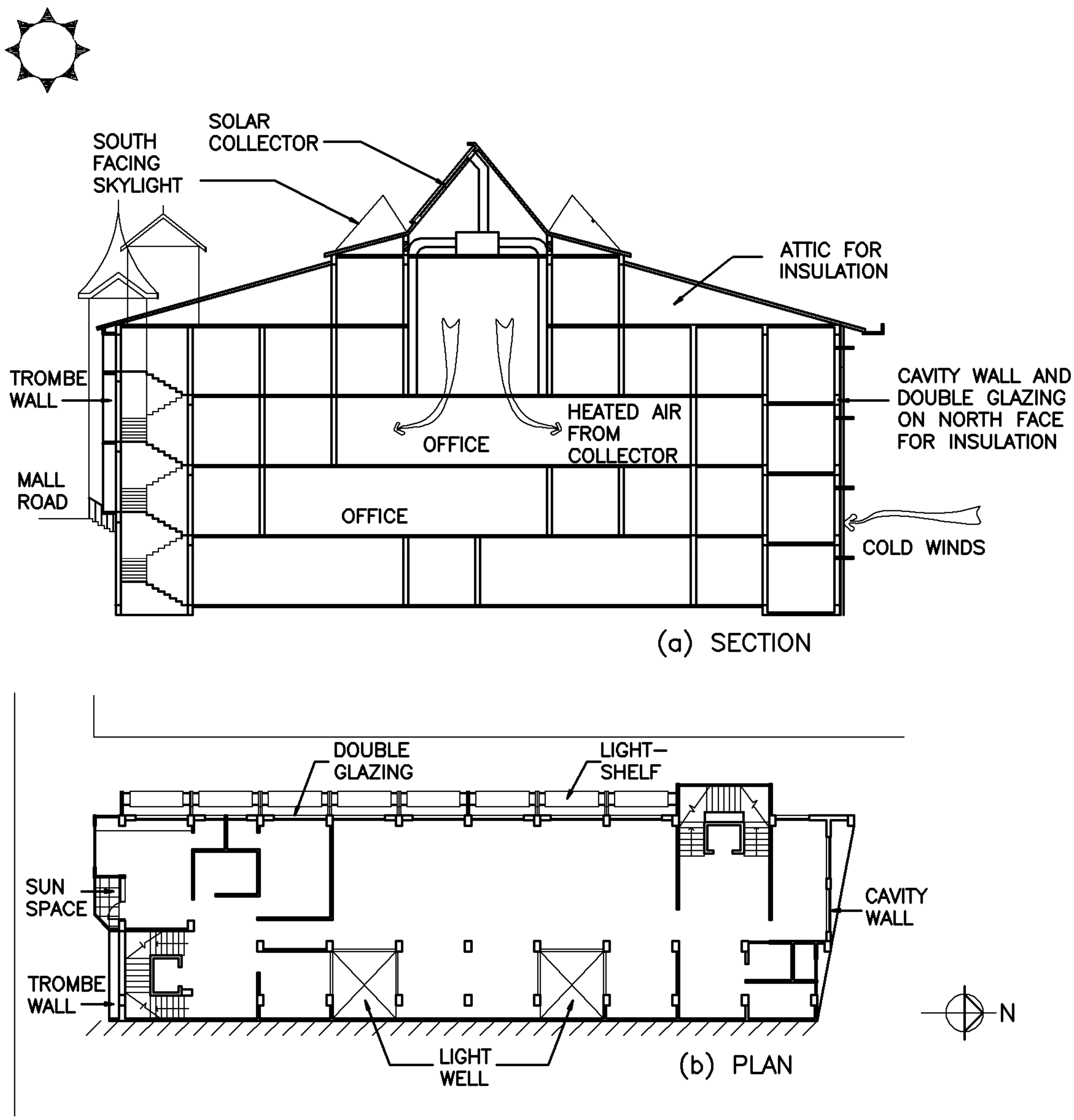


Fig. 7.10 Section and plan of H. P. state co-operative bank, Shimla

Energy conscious features:

- South-facing Trombe wall and sunspace heats up the interior
- South-facing solar collectors on the roof provide warm air, which is circulated by means of ducts

- North face is protected by a cavity wall that insulates the building from prevailing winter winds
- Western wall is provided with insulation as well as double glazing
- Daylighting is enhanced by providing light shelves. Skylight on the terrace also provides daylighting
- Air lock lobbies are provided to reduce air exchange

Performance of the building:

The predictions of the energy savings of the building (component-wise) per annum, as compared to a conventional building are as follows:

West wall (double glazing and insulation) =	43248 kWh
Roof insulation =	23796 kWh
Roof top solar collector =	10278 kWh
Trombe wall =	7398 kWh
Total =	84720 kWh

7.6 S.O.S. TIBETAN CHILDREN'S VILLAGE, CHOGLAMSAR [8]

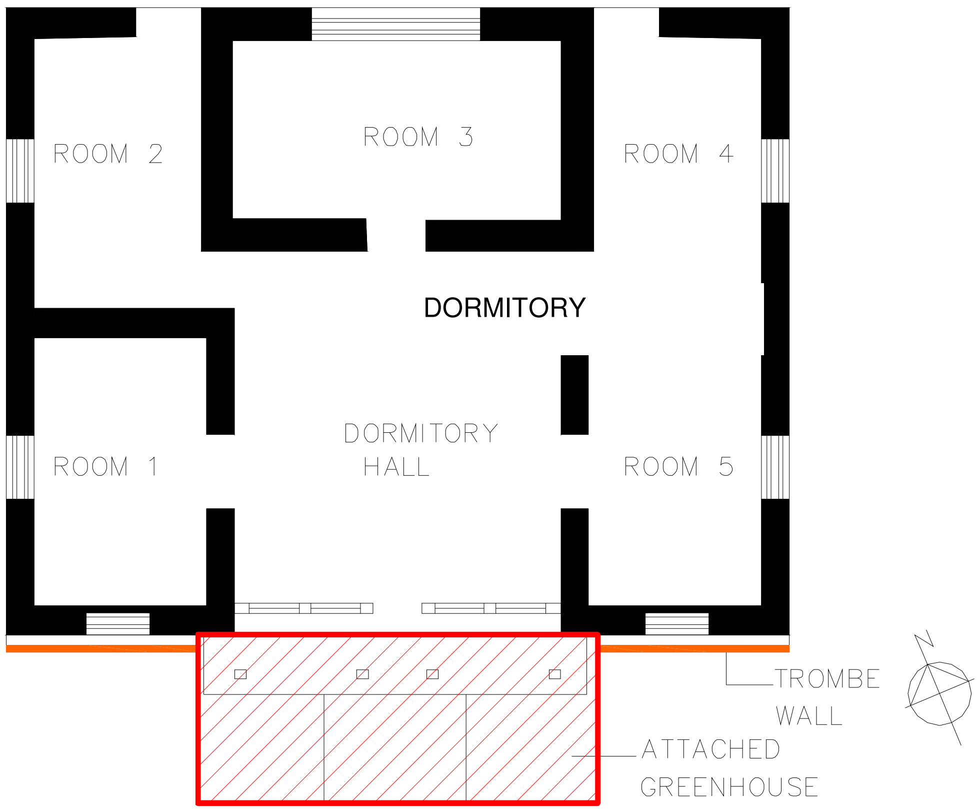
Location : Choglamsar, Leh
Climate : Cold and dry

Brief description of the building:

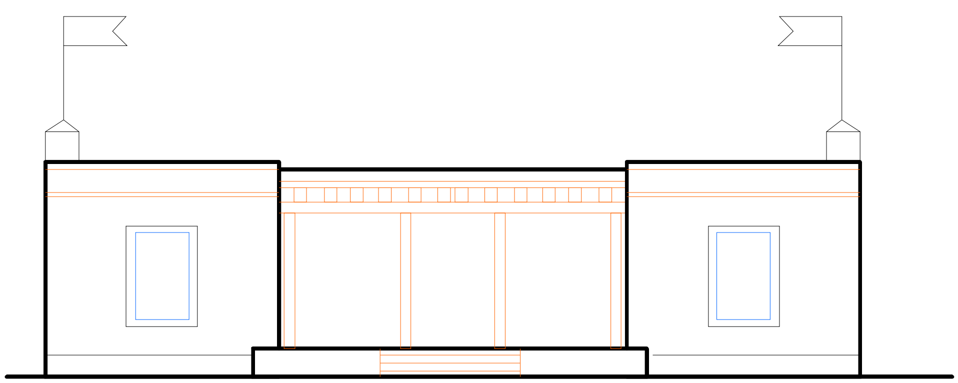
Twenty existing ground storey structures acting as dormitories have been retrofitted with an attached green house and vented Trombe walls, in the extremely cold region of Leh. The original construction consists of solid adobe for walls (U-value 1.64 W/m^2-K) and wooden roof with mud topping (U-value 2.44 W/m^2-K). The floor is of wooden deck over a crawl space. A sketch plan and section of a typical building are given in Fig. 7.11.

Techniques:

- The common room in the centre is provided with an attached green house facing south for trapping heat. The extended floor of the green house consists of solid masonry to provide good thermal storage mass of 1.44 MJ/m^2-K. The green house is fitted with a movable internal shade for the ceiling. The common room receives heated air by opening the vents of the adjacent glass wall of the green house.
- Two end rooms on the south side are provided with double glazed, vented Trombe walls for heating.



(a) Sketch plan



(b) Elevation

Fig. 7.11 Sketch plan and elevation of S.O.S building, Choglamsar

Performance of the building:

Table 7.2 gives the measured temperature data, namely, the maxima and minima for the Trombe wall room, green house, a room without solar heating (control room) and ambient temperature. It is seen that in winter months, the maximum and minimum temperature can be appreciably higher than both the ambient temperature as well as the room without solar heating (control room).

Table 7.2 Monthly mean measured temperature – (S.O.S. Tibetan children's village)

Year	Month	Maximum Temperature (^OC)					Minimum Temperature (^OC)				
		Trombe		Greenhouse		Ambient	Trombe		Greenhouse		Ambient
		Solar	Control	Solar	Control		Solar	Control	Solar	Control	
1980	September	32.2	27.0	29.6	26.2	17.4	20.0	16.6	17.6	14.5	6.3
	October	29.4	20.7	25.6	-	11.6	16.2	11.4	13.4	-	1.2
	November	21.8	13.7	20.5	-	7.1	11.6	5.9	5.8	-	-5.6
	December	21.6	10.2	17.0	-	2.8	6.8	2.4	4.6	-	-9.4
1981	April	24.0	19.0	24.8	-	11.6	17.0	14.0	15.0	-	-1.6
	May	25.8	23.6	25.2	22.2	16.6	21.0	19.0	19.0	17.0	3.2
	June	27.8	26.8	29.4	25.0	19.6	21.0	20.4	21.0	20.0	7.0
	July	31.1	29.2	31.8	28.6	25.0	25.4	23.6	24.0	23.0	12.8

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GLOSSARY

Absolute humidity – the weight of water vapour per unit volume.
Absorbent – a material which due to an affinity for certain substances, extracts one or more such substances from a liquid or gaseous medium with which it contacts, and which changes physically or chemically or both during the process. Calcium chloride is an example of a solid absorbent, while solutions of lithium chloride, lithium bromide, and ethylene glycol are liquid absorbents.
Absorber – the blackened surface in a solar collector that absorbs solar radiation and converts it to heat.
Absorptance – the ratio of the radiation absorbed by a surface to the total energy falling on that surface.
Active solar energy system – a system that requires auxiliary energy for its operation, e.g., energy to operate fans and pumps.
Activated alumina – a form of aluminium oxide which adsorbs moisture readily and is used as a drying agent.
Adfreezing – the process whereby wet soils freeze to below grade materials such as fountains, walls or insulation, forcing movement of the material.
Adiabatic process – a thermodynamic process during which no heat is extracted from or added to the system.
Adsorbent – a material which has the ability to cause the molecules of gases, liquids, or solids to adhere to its internal surfaces without changing itself physically or chemically. Certain solid materials such as silica gel and activated alumina have this property.
Air barrier – a material carefully installed within a building envelope assembly to minimize the uncontrolled passage of air into and out of a dwelling.
Air change – the replacement of a quantity of air in a volume within a given period of time. This is expressed in number of changes per hour. If a house has 1 air change per hour, all the air in the house will be replaced in a 1-hour period.
Air change per hour (ach) – a unit that denotes the number of times a house exchanges its entire volume of air with outside air in an hour.
Air cleanser - a device used to remove airborne impurities.
Air leakage – the uncontrolled flow of air through a component of the building envelope, or the building envelope itself, when a pressure difference is applied across the component. Infiltration refers to inward flowing air leakage and exfiltration refers to outward flowing air leakage.
Air permeability – the property of a building component to let air pass when it is subjected to a differential pressure.
Air pressure – the pressure exerted by air. This may refer to static (atmospheric) pressure, or dynamic components of pressure arising from airflow, or both acting together.
Air sealing – the practice of sealing unintentional gaps in the building envelope (from the interior) in order to reduce uncontrolled air leakage.
Air tightness – the degree to which unintentional openings have been avoided in a buildings structure.
Air, ambient –surrounding air.
Air, saturated – moist air in which the partial pressure of water vapour equals the vapour pressure of water at the existing temperature. This occurs when dry air and saturated water vapour co-exist at the same dry-bulb temperature.
Air, standard – dry air at a pressure of 101.325 kPa at a temperature of exactly 20 °C. Under these conditions, the density is 1.2041 kg/m^3
Altitude angle – the angular height of a point above the horizontal plane, i.e. solar altitude – the angle between the line joining the center of the sun and its projection on the horizontal plane.
Anemometer – an instrument for measuring the velocity of air.

Angle of incidence – the angle that the sun's rays subtend with a line perpendicular to a surface.
Atomize – reduce to fine spray.
Attached sunspace – solar collector that doubles as useful building space; also attached greenhouse, solarium. The term 'attached' specifically implies a space that shares one common wall with the associated building. Compare with semi-enclosed sunspace.
Awning – an exterior, movable and usually flexible element. Protects detaining or diffusing solar radiation at certain angles.
Azimuth angle, solar – the angle on a horizontal surface between true south and the projection of sun's ray on the horizontal surface (negative before noon, positive after noon.)
Backdraft – (flow reversal) the reverse flow of chimney gases into the building through the barometric damper, draft hood, or burner unit. This can be caused by chimney blockage or it can occur when the pressure differential is too high for the chimney to draw.
Beam or direct radiation – radiation coming directly from the sun without its direction undergoing any change.
Berm – a man-made mound or small hill of earth.
Bimetallic element - an element formed of two metals having different coefficients of thermal expansion, used as a temperature control device.
Black body – a perfect absorber and emitter of radiation. A cavity is a perfect black body. Lampblack is close to a black body, while aluminium (polished) is a poor absorber and emitter of radiation.
Brightness – the subjective human perception of luminance.
Building orientation – the siting of a building on a plot, generally used to refer to solar orientation.
Calorific value – the energy content per unit mass (or volume) of a fuel, which will be released in combustion. (kWh/kg, MJ/kg, kWh/m^3, MJ/m^3)
Candela (cd) – an SI unit of luminous intensity . An ordinary candle has a luminous intensity of one candela .
Chimney effect – the tendency of air or gas in a duct or other vertical passage to rise when heated, due to its lower density in comparison with that of the surrounding air or gas. In buildings, the tendency towards displacement (caused by the difference in temperature) of heated internal air by unheated outside air, due to the difference in their densities.
Clear sky – A sky condition with few or no clouds, usually taken as 0-2 tenths covered with clouds. Clear skies have high luminance and high radiation, and create strong shadows relative to more cloudy conditions. The sky is brightest nearest the sun, whereas away from the sun, it is about three times brighter at the horizon then at the zenith.
Clerestory – a window that is placed vertically (or near vertical) in a wall above one's line of vision to provide natural light in a building.
Clo – clothing factor , a measure of the insulating value of clothing. For example, 0.3 clo is typical for light summer clothing and 0.8 is typical for heavy winter clothing.
Collector, flat plate – an assembly containing a panel of metal or other suitable material, usually a flat and black in colour on its sun side, that absorbs sunlight and converts it into heat. This panel is usually in an insulated box covered with glass or plastic on the sun side to take advantage of the greenhouse effect. In the collector, the heat transfers to a circulating fluid such as air, water, oil or antifreeze.
Collector, focusing – a collector that has a parabolic or other reflector which focuses sunlight onto a small area for collection. A reflector of this type can obtain considerably higher temperatures but will only work with direct beam sunlight.
Collector, solar – a device for capturing solar energy, ranging from ordinary windows to complex mechanical devices.
Combustion air – the air required to provide adequate oxygen for fuel burning appliances in the building. The term 'combustion air' is often used to refer to the total air requirement of a fuel

burning appliance including both air to support the combustion process and air to provide chimney draft (dilution air).

Comfort chart – a chart showing dry-bulb temperatures and humidities (and sometimes air motion) by which the effects of various air conditions on human comfort may be compared.

Comfort zone – on the bioclimatic chart , the area of combined temperatures and humidities that 80% of people find comfortable. People are assumed to be in the shade, fully protected from wind, engaged in light activity, and wearing moderate levels of clothing that increases slightly in winter.

Condensation – the process of vapour changing into the liquid state. Heat is released in the process.

Conditioned and unconditioned spaces - conditioned spaces need air treatment such as heat addition , heat removal , moisture removal, or pollution removal. Unconditioned spaces do not need such air conditioning , and no effort is made to control infiltration.

Conductance (C) - a measure of the ease with which heat flows though a specified thickness of a material by conduction. Units are W/m^2 °C.

Conduction – the process by which heat energy is transferred through materials (solids, liquids or gases) by molecular excitation of adjacent molecules.

Conductivity – the quantity of heat that will flow through one square metre of material, one metre thick, in one second, when there is a temperature difference of 1ºC between its surfaces.

Convection – the transfer of heat between a moving fluid medium (liquid or gas) and a surface, or the transfer of heat within a fluid by movements within the fluid.

Cooling load – a load with net cooling required.

Cross ventilation – ventilative cooling of people and spaces driven by the force of wind. When the outside air is cooler than the inside air , heat can be transferred from the space to the ventilation air. Cross ventilation also removes heat from people by convection and by increasing the rate of sweat evaporation . The cooling rate from cross ventilation is determined by wind speed , opening sizes and temperature difference between the inside and outside. See also, stack ventilation.

Daylight – illuminance from radiation in the visible spectrum from the diffuse sky, reflected light, and direct sun that lights a room.

Daylight envelope – the maximum buildable volume on a site that will not unduly restrict daylight available to adjacent buildings.

Daylight factor (DF) – the proportion of interior horizontal illuminance (usually taken on the work plane) to exterior horizontal illuminance under an unobstructed sky . It is sum of the sky component and the internal reflected component. The range is 0-100%, but for most rooms it is usually limited to 1-10%.

Decrement factor – ratio of the maximum outer and inner surface temperature amplitudes taken from the daily mean.

Density – the mass of a substance, expressed in kilograms per cubic metre.

Diffuse radiation – radiation that has travelled an indirect path from the sun because it has been scattered by particles in the atmosphere such as air molecules, dust and water vapour. Indirect sunlight comes from the entire skydome.

Direct gain – the transmission of sunlight through glazing directly in to the spaces to be heated , where it is converted to heat by absorption on interior mass surfaces.

Direct sunlight – the component of visible spectrum radiation that comes directly from the sun without being diffused or reflected.

Direct radiation – the component of solar radiation that comes directly from the sun without being diffused or reflected.

Diffuse reflectance – reflectance is the ratio of reflected radiation to incident radiation. Diffuse reflectance spreads the incident flux over a range of reflected angles/directions.

Diurnal – relating to a 24-hr cycle. A diurnal temperature swing is the cycle of temperatures over the course of one 24-hr period.
Downdraft evaporative cooling tower - a cooling system that humidifies and cools warm dry air by passing it though a wetted pad at the top of a tower. The cooled air being denser, falls down the tower and into the occupied spaces below, drawing in more air through the pads in the process. Consequently, no distribution fans are required.
Dry bulb temperature – the temperature of a gas of mixture or gases indicated by an accurate thermometer after correction for radiation.
Earth-air heat exchangers – a strategy of pre-tempering fresh air for ventilation , and in some cases , providing building cooling by passing incoming air through buried ducts.
Earth contact - the strategy of placing building surfaces in contact with the ground to reduce the temperature difference between inside and outside, reduce infiltration, and /or use the subsurface soil temperature to cool the building.
Emissivity – the property of emitting heat by radiation, possessed by all materials to a varying extent. "Emittance" is the numerical value of this property.
Envelope heat gain or loss – heat transferred through the skin of a building or via infiltration /ventilation.
Equinox – meaning equal light. The dates during the year when the hours of daylight are equal to the hours of darkness. On the equinox, the sun rises from the horizon at due east and sets due west. The equinoxes fall on March 21 and September 21.
Evaporation – phase change of a material from liquid to vapour at a temperature below the boiling point of the liquid. Cooling occurs during the process of evaporation.
Evaporative cooling - A heat removal process in which water vapour is added to air, increasing its humidity while lowering its temperature. The total amount of heat in the air stays constant, but is transferred from sensible heat in the air to latent heat in the moisture. In the process of changing from liquid to vapour (evaporating), the water must absorb large amount of heat.
Evaporative cooling , Direct – a cooling process where the warm and dry air moves through a wetted medium to evaporate moisture in the air. The cool humid air is then used to cool a place.
Evaporative cooling , Indirect – a cooling process where the evaporative process is remote from the conditioned space. The cooled air is then used to lower the temperature of the building surface, such as in a roof spray, or is passed through a heat exchanger to cool indoor air. The indirect process has the advantage of lowering temperatures without adding humidity to the air, thus extending the climate conditions and regions in which evaporate cooling is effective.
Glare – the perception caused by a very bright light or a high contrast of light, making it uncomfortable or difficult to see.
Glazing – Transparent or translucent materials, usually glass or plastic, used to cover an opening without impeding (relative to opaque materials) the admission of solar radiation and light.
Greenhouse effect – refers to the characteristic tendency of some transparent materials such as glass to transmit shortwave radiation and block radiation of longer wavelengths.
Heat exchanger – a device usually consisting of a coiled arrangement of metal tubing used to transfer heat through the tube walls from one fluid to another.
Heat gain – an increase in the amount of heat contained in a space, resulting from direct solar radiation and the heat given off by people, lights, equipment, machinery and other sources.
Heat island – the increased temperatures, relative to surrounding open load, found in the centre cities and areas of high development density. Heat islands are caused by concentrations of heat sources, decreased vegetation cover, increased massive and dark surfaces , decreased wind flows , and narrow sky view angles.
Heat loss – a decrease in the amount of heat contained in a space, resulting from heat flow through walls, windows, roof and other building envelope components.
Heat pump – a thermodynamic device that transfers heat from one medium to another; the first medium cools while the second warms up.

Humidity – water vapour within a given space.
HVAC – mechanical system for heating, ventilating and air-conditioning that controls temperature, humidity , and air quality.
Hybrid system – a solar heating or cooling system that combines active and passive elements.
Hygroscopic – absorptive of moisture , readily absorbs and retains moisture.
Illuminance – the measure of light intensity striking a surface . Specifically, the concentration of incident luminous flux, measured in foot –candle(I-P) or Lux(SI).
Illumination – lighting of the surface by daylight or electric light.
Index of refraction – a property of glazing materials that determines the reflection/refraction characteristics of the glazing.
Infiltration – the uncontrolled movement of outdoor air into the interior of a building through cracks around windows and doors or in walls, roofs and floors. This may work by cold air leaking in during winters, or the reverse in summers.
Infrared radiation – Electromagnetic radiation having wavelength above the wavelength range of visible light. This is the predominant form of radiation emitted by bodies with moderate temperatures such as the elements of a passive building.
Internal gains – the energy dissipated inside the heated space by people and appliances. A portion of this energy contributes to the space heating requirement.
Isothermal – an adjective used to indicate a change taking place at constant temperature.
Jalousie (jali) – an exterior fixed element made up of a perforated frame which covers the whole window. It allows natural ventilation and protects against direct solar radiation and view from the exterior.
Latitude – the angular distance north(+) or south (-) of the equator, measured in degrees of arc.
Latent heat – change of enthalpy during a change of state , usually expressed in J/kg(Btu per lb). With pure substances, latent heat is absorbed or rejected at constant temperature at any pressure.
Lighting, diffused – lighting in which the light on a working plane or on an object is not incident predominantly from a particular direction.
Longwave radiation – radiation emitted between roughly 5 and 30 m wavelength , as in thermal radiation from the surface of a room, or from the outside surface of the roof.
Longitude – the arc of the equator between the meridian of a place and Greenwich meridian measured in degrees east or west.
Louvre - an assembly of sloping vanes intended to permit air to pass through and to inhibit transfer of water droplets
Lumen – SI unit of luminous flux; it is the luminous flux emitted in unit solid angle by a uniform point source having a luminous intensity of 1 candela.
Lux – SI unit of illuminance; it is the illuminance produced on a surface of unit area (square metre) by a luminous flux of 1 lumen uniformly distributed over that surface.
Masonry – concrete, concrete block, brick, adobe, stone, and similar other building materials.
Negative pressure – a pressure below the atmospheric. In residential construction, negative pressure refers to pressure inside the house envelope that is less than the outside pressure. Negative pressure will encourage infiltration.
Night insulation – movable insulation that covers a glazing at night and is removed during the day.
Night ventilation of mass - a cooling process whereby a building is closed during the hot daytime hours. Its heat gains are stored during that time in the building's structure or other thermal mass. At night, the building is opened and cooler outdoor air is used to flush heat from the mass, lowering its temperature, to prepare for another cycle.
Night sky radiation - a reversal of the day time insolation principle. Just as the sun radiates energy during the day through the void of space, so also heat energy can travel unhindered at night from the earth's surface back into space. On a clear night, any warm object can cool itself

by radiating longwave heat energy to the cooler sky. On a cloudy night, the cloud cover acts as an insulator and prevents the heat from travelling to the cooler sky.

Opaque - not able to transmit light; for example, unglazed walls.

Passive system - a system that uses non-mechanical and non-electrical means to satisfy heating, lighting, or cooling loads. Purely passive systems use radiation, conduction, and natural convection to distribute heat, and daylight for lighting.

Pond, spray – arrangement for lowering the temperature of water in contact with outside air by evaporative cooling of the water. The water to be cooled is sprayed by nozzles in to the space above a body of previously cooled water and allowed to fall into it by gravity.

Positive pressure – a pressure above atmospheric. In residential construction, this refers to pressure inside the house envelope that is greater than the outside pressure; a positive pressure difference will encourage exfiltration.

Pressure – the normal force exerted by a homogenous liquid or gas, per unit area, on the wall of container.

Pressure difference – the difference in pressure between the volume of air enclosed by the building envelope and the air surrounding the envelope.

Pressure , vapour – the pressure exerted by the molecules of a given vapour.

Radiant heat transfer – the transfer of heat by radiation. Heat radiation is a form of electromagnetic radiation. Radiant heating due to infrared radiation is commonly employed in passive systems.

Radiant temperature - the average temperature of surfaces surrounding a person or surface, with which the person or surface can exchange thermal radiation.

Reference design – a detailed specification of the passive solar features of a hypothetical passive solar building used as the subject of performance analysis.

Reflectance - the ratio of radiation reflected by a surface to the radiation incident on it. The range is 0-1.0.

Reflection – process by which radiation is returned by a surface or a medium, without change of frequency of its monochromatic component.

Relative humidity - the percentage of water vapour in the atmosphere relative to the maximum amount of water vapour that can be held by the air at a given temperature.

Resistivity – the thermal resistance of unit area of a material of unit thickness to heat flow caused by a temperature difference across the material.

Reverse thermocirculation – thermocirculation in the reverse direction, that is, from the heated space to the solar collector. This can occur at night when the heated space is warmer than the collector. In the reference design, the process is assumed to be prevented by dampers.

Roof pond system - an indirect gain heating and cooling system in which the mass, which is water in plastic bags, is located on the roof of the space to be heated or cooled and covered with a movable insulation. A roof pond system absorbs solar radiation for heating in the winter and radiates heat to the sky for cooling in the summer.

Selective coating – finishes applied to materials to improve their performance in relation to radiation of different wavelengths. Those applied to solar absorbers have a high absorptance of solar radiation accompanied by a low emittance of long wave radiation, while those for glazing have a high transmittance to solar radiation and high reflectance of long wavelengths.

Selective surface - a surface used to absorb and retain solar heat in a solar heating system such as a Trombe wall or in a solar collector. Selective surfaces have high absorptance and low emittance.

Sensible heat - heat that results in a change in air temperature, in contrast with latent heat.

SI units - Standard International units; the metric system.

Sky component - the portion of the daylight factor (at a point indoors) contributed by luminance from the sky, excluding direct sunlight.

Sky cover - a measure of the fraction of the sky covered in clouds. Range is 0-10 tenths.

Skylight - a roof window, horizontal or sloped.
Sol-air temperature – an equivalent temperature which will produce the same heating effect as the incident radiation in conjunction with the actual external air temperature.
Solar absorptance - the fraction of incident solar radiation that is absorbed by a surface. The radiation not absorbed by an opaque surface is reflected. The range is 0-1.0.
Solar gain - heat transferred to a space by solar radiation through glazing.
Solar heat gain coefficient (SHGC) - the fraction of incident solar radiation (for the full spectrum) which passes though an entire window assembly, including the frame, at a specified angle. Range is 0-0.85. A higher SHGC is preferred in solar heating applications to capture maximum sun, whereas in cooling applications, a low SHGC reduces unwanted solar heat gain.
Solar load - the demand for energy required at any moment to compensate for the difference between desired indoor conditions and heat gains from solar radiation.
Solar radiation - radiation emitted by the sun, including infrared radiation, ultraviolet radiation, and visible light. The radiation received without change of direction is called beam or direct radiation. The radiation received after its direction has been changed by scattering and reflection is called diffuse radiation. The sum of the two is referred to as global or total radiation.
Specific heat – a measure of the ability of a material to store heat. Specifically**,** the quantity of heat required to raise the temperature of unit mass of a substance by one degree. (kJ/kg °C).
Stack ventilation - the cooling process of natural ventilation induced by the chimney effect, where a pressure differential occurs across the section of a room. Air in the room absorbs heat gained in the space, loses density, thus rising to the top of the space. When it exits through high outlet openings, a lower pressure is created low in the space, drawing in cooler outside air from low inlets.
Sunlight - beam daylight from the sun only, excluding diffuse light from the sky dome.
Surface resistance – the surface resistance is the resistance to heat flow at the surface of a material. It has two components , the surface resistance for convection and for conduction.
Task light - lighting on a specific area used for a specific task. Task lighting is usually from an electric source and is of a higher illuminance level than the surrounding ambient light level. It is a good strategy to combine task light with ambient daylight.
Temperature swing – the range of indoor temperatures in the building between the day and night.
Thermal break (thermal barrier) – an element of low thermal conductivity placed within a composite envelope construction in such a way as to reduce the flow of heat across the assembly.
Thermal bridge - an element of high thermal conductivity within a construction of otherwise low thermal conductivity. Small areas of materials that conduct heat at high rates can substantially reduce the insulating effectiveness of an assembly. Examples are metal frame windows without thermal brakes and metal stud walls, where the metal conducts heat at a much higher rate than the insulation in between.
Thermal conductivity (k) - a measure of the ease with which heat flows though a unit thickness of a material by conduction; specifically, the heat flow rate in Watt per metre of material thickness, and degree of temperature difference. Units is W/m-^{0}C
Thermal radiation - energy transfer in the form of electromagnetic waves from a body by virtue of its temperature, including infrared radiation, ultraviolet radiation, and visible light.
Thermal resistance - a measure of the insulation value or resistance to heat flow of building elements or materials; specifically, the reciprocal of the thermal conductance.
Thermal storage mass - high-density building elements, such as masonry or water in containers, designed to absorb solar heat during the day for later release when heat is needed.
Thermal storage wall - a Trombe wall or water wall.
Thermocirculation - the circulation of a fluid by convection . For example, the convection from a warm zone (sunspace or Trombe wall air space) to a cool zone through openings in a common wall.

Thermosyphon – the convective circulation of a fluid which occurs in a closed system where warm fluid rises and is replaced by a cooler fluid in the same system.
Tilt – the angle of a plane relative to a horizontal plane.
Time-lag – the period of time between the absorption of solar radiation by a material and its release into a space. Time-lag is an important consideration in sizing a thermal storage wall or Trombe wall.
Transmittance – the ratio of the radiant energy transmitted through a substance to the total radiant energy incident on its surface.
Ultraviolet radiation – electromagnetic radiation having wavelengths shorter than those of visible light. This invisible form of radiation is found in solar radiation and plays a part in the deterioration of plastic glazing materials, paint and furnishing fabrics.
U-value (coefficient of heat transfer) - the number of Watts that flow through one square metre of building component (e.g. roof, wall, floor, glass), in one second, when there is a 1 ºC difference in temperature between the inside and outside air, under steady state conditions. The U-value is the reciprocal of the resistance.
Ventilation load - the energy required to bring outdoor air to the desired indoor conditions. In this book, ventilation load refers to fresh air ventilation, which may be provided either naturally or by a mechanical system. The rate of required ventilation varies with the use of the space and the number of occupants. Ventilation load depends on the rate of fresh air ventilation and on the temperature difference between inside and outside. It may be reduced by pre-tempering or the use of heat exchangers.
Ventilation losses – the heat losses associated with the continuous replacement of warm , stale air by fresh cold air.
Ventilation (natural) - air flow through and within a space stimulated by either the distribution of pressure gradients around a building, or thermal forces caused by temperature gradients between indoor and outdoor air.
Visible spectrum – that part of the solar spectrum which is visible to the human eye; radiation with wavelength roughly between 380 and 700 nm.
Visible transmittance (VT) - the fraction of incident visible light that passes though glazing.
Watt (W) - a measure of power commonly used to express heat loss or heat gain, or to specify electrical equipment. It is the power required to produce energy at the rate of one joule per second.
Weather stripping – narrow or jamb-width sections of thin metal or other material to prevent infiltration of air and moisture around windows and doors.
Wet-bulb temperature - the air temperature measured using a thermometer with a wetted bulb moved rapidly through the air to promote evaporation. The evaporating moisture and changing phase lowers the temperature measured relative to that measured with a dry bulb. Wet bulb temperature accounts for the effects of moisture in the air. It can be used along with the dry-bulb temperature on a psychrometric chart to determine relative humidity.
Zenith - the top of the sky dome. A point directly overhead, 90^o in altitude angle above the horizon.

SI Units

Quantity	SI Unit	Symbol
Base units		
amount of substance	mole	mol
electric current	ampere	A
length	metre	m
luminous intensity	candela	cd
mass	kilogram	kg
thermodynamic temperature	Kelvin	K
time	second	s
Supplementary units		
plane angle	radian	rad
solid angle	steradian	sr
Some derived units		
area	square metre	m^2
density	kilogram per cubic metre	kg/m^3
energy	joule	J (N m)
force	Newton	N (kg m/s^2)
power	Watt	W (J/s)
pressure	Pascal	Pa (N/m^2)
velocity	metre per second	m/s
volume	cubic metre	m^3

SI Prefixes

Prefix	Symbol	Multiplication factor
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}

Greek Alphabets

Α	α	Alpha	Ν	ν	**Nu**
Β	β	Beta	Ξ	ξ	Xi
Γ	γ	Gamma	Ο	ο	Omicron
Δ	δ	Delta	Π	π	Pi
Ε	ε	Epsilon	Ρ	ρ	Rho
Ζ	ζ	Zeta	Σ	σ	Sigma
Η	η	Eta	Τ	τ	Tau
Θ	θ	Theta	ϒ	υ	Upsilon
Ι	ι	Iota	Φ	φ	Phi
Κ	κ	Kappa	Χ	χ	Chi
Λ	λ	Lambda	ψ	ψ	Psi
Μ	μ	Mu	Ω	ω	Omega

Conversion Factors

Unit	Multiplying Factor	Resulting Unit	Physical Quantity
Acre	$4.356\ 0 \times 10^{4}$	Square feet	Area
Acre	$4.046\ 9 \times 10^{-1}$	Hectares	Area
Acre	$4.046\ 9 \times 10^{3}$	Square meters	Area
Acre	$1.562\ 5 \times 10^{-3}$	Square miles	Area
Acre	$4.840\ 0 \times 10^{3}$	Square yards	Area
Atmosphere	$7.600\ 0 \times 10^{1}$	Centimeters of mercury	Pressure
Atmosphere	$2.992\ 1 \times 10^{1}$	Inches of mercury	Pressure
Atmosphere	$1.033\ 2 \times 10^{4}$	Kilograms/square meter	Pressure
Atmosphere	$1.013\ 3 \times 10^{5}$	Newtons/square meter	Pressure
Atmosphere	$1.469\ 6 \times 10$	Pounds/square inch	Pressure
Bar	$9.869\ 2 \times 10^{-1}$	Atmospheres	Pressure
Bar	$1.000\ 0 \times 10^{6}$	Dynes/square centimeter	Pressure
Bar	$7.500\ 6 \times 10^{2}$	Millimeters of mercury	Pressure
Bar	$1.000\ 0 \times 10^{5}$	Newtons/square meter	Pressure
Bar	$1.450\ 4 \times 10$	Pounds/square inch	Pressure
Barrel (U.S.)	$3.150\ 0 \times 10$	Gallons	Volume
Barrel (U.S.)	$1.192\ 4 \times 10^{-1}$	Cubic meters	Volume
British thermal unit (Btu)	$2.518\ 0 \times 10^{2}$	Calories	Energy
British thermal unit (Btu)	$7.781\ 7 \times 10^{2}$	Foot-pounds	Energy
British thermal unit (Btu)	$1.055\ 1 \times 10^{10}$	Ergs	Energy
British thermal unit (Btu)	$3.930\ 1 \times 10^{-4}$	Horsepower-hours	Energy
British thermal unit (Btu)	$1.055\ 1 \times 10^{3}$	Joules	Energy
British thermal unit (Btu)	$1.055\ 1 \times 10^{3}$	Newton-meters	Energy
British thermal unit (Btu)	$2.930\ 2 \times 10^{-4}$	Kilowatt-hours	Energy
British thermal unit (Btu)	$1.055\ 1 \times 10^{3}$	Watt-seconds	Energy
British thermal unit/minute (Btu/min)	$4.199\ 9$	Calories/second	Power
British thermal unit/minute (Btu/min)	$1.754\ 8 \times 10^{8}$	Ergs/second	Power
British thermal unit/minute (Btu/min)	$1.297\ 0 \times 10$	Foot-pounds/second	Power
British thermal unit/minute (Btu/min)	$2.358\ 1 \times 10^{-2}$	Horsepower	Power
British thermal unit/minute (Btu/min)	$1.754\ 8 \times 10$	Joules/second	Power
British thermal unit/minute (Btu/min)	$1.793\ 1$	Kilogram-meters/second	Power
British thermal unit/minute (Btu/min)	$1.754\ 8 \times 10$	Watts	Power
Calorie (cal)	$3.968\ 3 \times 10^{-3}$	British thermal units	Energy

Calorie (cal)	3.088 0	Foot-pounds	Energy
Calorie (cal)	$4.186\ 8 \times 10^{7}$	Ergs	Energy
Calorie (cal)	4.186 8	Joules	Energy
Calorie (cal)	$1.163\ 0 \times 10^{-6}$	Kilowatt-hours	Energy
Calorie (cal)	4.186 8	Watt-seconds	Energy
Centimeter (cm)	$3.280\ 8 \times 10^{-2}$	Feet	Distance
Centimeter (cm)	$3.937\ 0 \times 10^{-1}$	Inches	Distance
Centimeter (cm)	$1.000\ 0 \times 10^{-5}$	Kilometers	Distance
Centimeter (cm)	$1.000\ 0 \times 10^{-2}$	Meters	Distance
Centimeter (cm)	$1.093\ 6 \times 10^{-2}$	Yards	Distance
Centipoise	$6.719\ 7 \times 10^{-4}$	Pounds(mass)/second-foot	Viscosity
Centipoise	3.600 0	Kilograms/hour-meter	Viscosity
Cord	$1.280\ 0 \times 10^{2}$	Cubic feet	Volume
Cubic centimeter (cm^3)	$1.000\ 0 \times 10^{-3}$	Cubic decimeters	Volume
Cubic centimeter (cm^3)	$3.531\ 5 \times 10^{-5}$	Cubic feet	Volume
Cubic centimeter (cm^3)	$6.102\ 4 \times 10^{-2}$	Cubic inches	Volume
Cubic centimeter (cm^3)	$1.000\ 0 \times 10^{-6}$	Cubic meters	Volume
Cubic centimeter (cm^3)	$1.308\ 0 \times 10^{-6}$	Cubic yards	Volume
Cubic inch (in^3)	$1.638\ 7 \times 10$	Cubic centimeters	Volume
Cubic inch (in^3)	$1.638\ 7 \times 10^{-2}$	Cubic decimeters	Volume
Cubic inch (in^3)	$5.787\ 0 \times 10^{-4}$	Cubic feet	Volume
Cubic inch (in^3)	$1.638\ 7 \times 10^{-5}$	Cubic meters	Volume
Cubic inch (in^3)	$2.143\ 3 \times 10^{-5}$	Cubic yards	Volume
Curie	$3.700\ 0 \times 10^{10}$	Disintegrations/second	Radioactivity
Degree (deg)	$6.000\ 0 \times 10$	minutes	Angle
Degree (deg)	$1.745\ 3 \times 10^{-2}$	radians	Angle
Degree (deg)	$2.777\ 8 \times 10^{-3}$	revolutions	Angle
Degree (deg)	$3.600\ 0 \times 10^{3}$	seconds	Angle
dyne	$1.019\ 7 \times 10^{-3}$	grams	Force
dyne	$1.019\ 7 \times 10^{-6}$	kilograms	Force
dyne	$1.000\ 0 \times 10^{-5}$	newtons	Force
dyne	$3.597\ 0 \times 10^{-5}$	ounces	Force
dyne	$2.248\ 1 \times 10^{-6}$	pounds	Force
dyne/square centimeter	$2.953\ 0 \times 10^{-5}$	inches of mercury	Pressure
dyne/square centimeter	$1.019\ 7 \times 10^{-2}$	kilograms/square meter	Pressure
dyne/square centimeter	$7.500\ 6 \times 10^{-4}$	millimeters of mercury	Pressure
dyne/square centimeter	$1.000\ 0 \times 10$	newtons/square meter	Pressure
dyne/square centimeter	$1.450\ 4 \times 10^{-5}$	pounds/square inch	Pressure
electron volt (eV)	$3.826\ 8 \times 10^{-20}$	calories	Energy
electron volt (eV)	$1.602\ 2 \times 10^{-12}$	ergs	Energy
erg	$9.478\ 2 \times 10^{-11}$	British thermal units	Energy

erg	$2.388\ 5 \times 10^{-8}$	calories	Energy
erg	1.000 0	dyne-centimeters	Energy
erg	$7.375\ 6 \times 10^{-8}$	foot-pounds	Energy
erg	$1.000\ 0 \times 10^{-7}$	joules	Energy
erg/second	$5.68\ 69 \times 10^{-9}$	British thermal units/minute	Power
erg/second	$2.388\ 5 \times 10^{-8}$	calories/second	Power
erg/second	$7.375\ 6 \times 10^{-8}$	foot-pounds/second	Power
erg/second	$1.000\ 0 \times 10^{-7}$	joules/second	Power
erg/second	$1.000\ 0 \times 10^{-7}$	watts	Power
flow rate, fuel (lb/h)	$4.535\ 9 \times 10^{-1}$	kilograms/hour	Mass Flow
foot-pound (ft-lb)	$1.285\ 1 \times 10^{-3}$	British thermal units	Energy
foot-pound (ft-lb)	$1.355\ 8 \times 10^{7}$	ergs	Energy
foot-pound (ft-lb)	$5.050\ 5 \times 10^{-7}$	horsepower-hours	Energy
foot-pound (ft-lb)	1.355 8	joules	Energy
foot-pound (ft-lb)	$3.766\ 2 \times 10^{-7}$	kilowatt-hours	Energy
foot-pound (ft-lb)	1.355 8	newton-meters	Energy
furlong	1.000 0 x 10	chains	Distance
furlong	$2.200\ 0 \times 10^{2}$	yards	Distance
furlong	$2.011\ 7 \times 10^{2}$	meters	Distance
US gallon (gal)	$1.336\ 8 \times 10^{-1}$	cubic feet	Volume
US gallon (gal)	3.785 4	liters	Volume
US gallon (gal)	$3.785\ 4 \times 10^{-3}$	cubic meters	Volume
US gallon (gal)	8.000 0	pints	Volume
US gallon (gal)	4.000 0	quarts	Volume
Gram (g)	$1.000\ 0 \times 10^{-3}$	kilograms	Mass
Gram (g)	$3.527\ 4 \times 10^{-2}$	ounces	Mass
Gram (g)	$2.204\ 6 \times 10^{-3}$	pounds	Mass
Gram (g)	$9.806\ 7 \times 10^{2}$	dynes	Mass
Gram (g)	$9.806\ 7 \times 10^{-3}$	newtons	Mass
hectare	2.471 1	acres	Area
hectare	$1.000\ 0 \times 10^{2}$	ares	Area
hectare	$1.000\ 0 \times 10^{4}$	square meters	Area
hectare	$3.861\ 0 \times 10^{-3}$	square miles	Area
Horsepower (hp)	4.243 6 x 10	British thermal units/minute	Power
Horsepower (hp)	$5.500\ 0 \times 10^{2}$	foot-pounds/second	Power
Horsepower (hp)	$3.300\ 0 \times 10^{4}$	foot-pounds/minute	Power
Horsepower (hp)	$7.457\ 0 \times 10^{2}$	joules/second	Power
Horsepower (hp)	7.604 0 x 10	kilogram-meters/second	Power
Horsepower (hp)	$7.457\ 0 \times 10^{2}$	watts	Power
imperial gallon	2.7742×10^{2}	cubic inches	Volume
imperial gallon	1.2009	US gallons	Volume

imperial gallon	4.546	liters	Volume
Joule (J)	$9.477\ 1 \times 10^{-4}$	British thermal units	Energy
Joule (J)	$2.388\ 9 \times 10^{-1}$	calories	Energy
Joule (J)	$1.000\ 0 \times 10^{7}$	dyne-centimeters	Energy
Joule (J)	$1.000\ 0 \times 10^{7}$	Ergs	Energy
Joule (J)	$7.375\ 6 \times 10^{-1}$	foot-pounds	Energy
Joule (J)	1.000 0	newton-meters	Energy
Joule (J)	1.000 0	watt-seconds	Energy
Kilogram (kg)	$1.000\ 0 \times 10^{3}$	Grams	Mass
Kilogram (kg)	3.527 4 x 10	Ounces	Mass
Kilogram (kg)	2.20 46	Pounds	Mass
Kilogram (kg)	$6.852\ 1 \times 10^{-2}$	Slugs	Mass
Kilogram (kg)	9.806 7	Newtons	Mass
Kilogram (kg)	7.929 0 x 10	Poundals	Mass
km/h	$9.113\ 0 \times 10^{-1}$	feet/second	Speed
km/h	$5.396\ 0 \times 10^{-1}$	knots	Speed
km/h	$6.213\ 7 \times 10^{-1}$	miles/hour	Speed
km/h	$2.777\ 8 \times 10^{-1}$	meters/second	Speed
kW/h	$3.412\ 8 \times 10^{3}$	British thermal units	Energy
kW/h	$2.656\ 0 \times 10^{6}$	foot-pounds	Energy
kW/h	1.341 4	horsepower-hours	Energy
kW/h	$3.600\ 0 \times 10^{6}$	joules	Energy
kW/h	$3.672\ 1 \times 10^{5}$	kilogram-meters	Energy
kW/h	$3.600\ 0 \times 10^{6}$	watt-seconds	Energy
Liter (l)	6.102 4 x 10	cubic inches	Volume
Liter (l)	$3.531\ 5 \times 10^{-2}$	cubic feet	Volume
Liter (l)	$2.641\ 7 \times 10^{-1}$	gallons	Volume
Liter (l)	$1.000\ 0 \times 10^{-3}$	cubic meters	Volume
meter/second	3.280 8	feet/second	Speed
metric horsepower	$9.863\ 2 \times 10^{-1}$	horsepower	Power
metric horsepower	$7.355\ 0 \times 10^{-1}$	kilowatts	Power
mile/hour	1.466 7	feet/second	Speed
Newton (n)	$1.000\ 0 \times 10^{5}$	dynes	Force
pound (mass) (lb)	$4.535\ 9 \times 10^{2}$	grams	Mass
pound (force) (lbf)	4.448 2	newtons	Force
pound/square inch (psi)	$6.804\ 6 \times 10^{-2}$	atmospheres	Pressure
pound/square inch (psi)	$6.894\ 8 \times 10^{4}$	dynes/square centimeter	Pressure
pound/square inch (psi)	2.036 0	inches of mercury	Pressure
pound/square inch (psi)	2.768 1 x 10	inches of water	Pressure
pound/square inch (psi)	$7.030\ 7 \times 10^{2}$	kilograms/square meter	Pressure

pound/square inch (psi)	$6.894\ 8 \times 10^{3}$	newtons/square meter	Pressure
Radian (rad)	$5.729\ 6 \times 10$	degrees	Angle
Radian (rad)	$3.437\ 8 \times 10^{3}$	minutes	Angle
Radian (rad)	$1.591\ 6 \times 10^{-1}$	revolutions	Angle
Radian (rad)	$2.062\ 6 \times 10^{5}$	seconds	Angle
Revolution (rev)	$3.600\ 0 \times 10^{2}$	degrees	Angle
Revolution (rev)	$2.160\ 0 \times 10^{4}$	minutes	Angle
Revolution (rev)	6.283 2	radians	Angle
Revolution (rev)	$1.296\ 0 \times 10^{6}$	seconds	Angle
Second (angle) (sec)	$2.777\ 8 \times 10^{-4}$	degrees	Angle
Second (angle) (sec)	$4.848\ 1 \times 10^{-6}$	radians	Angle
Watt (joule/second) (W)	3.412 1	British thermal units/hour	Power
Watt (joule/second) (W)	$2.390\ 0 \times 10^{-1}$	calories/second	Power
Watt (joule/second) (W)	$1.000\ 0 \times 10^{7}$	ergs/second	Power
Watt (joule/second) (W)	$7.375\ 6 \times 10^{-1}$	foot-pounds/second	Power
Watt (joule/second) (W)	$1.341\ 0 \times 10^{-3}$	horsepower	Power
Watt (joule/second) (W)	$1.019\ 7 \times 10^{-1}$	kilogram-meters/second	Power