ENERGY RESPONSIVENESS IN TRADITIONAL RESIDENTIAL BUILDINGS OF LUCKNOW

A THESIS

Submitted in partial fulfilment of the
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by

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **ENERGY RESPONSIVENESS IN TRADITIONAL RESIDENTIAL BUILDINGS OF LUCKNOW** in partial fulfillment of the requirements for the award of the Degree of Doctor of Philosophy and submitted in the Department of Architecture and Planning of the Indian Institute of Technology Roorkee, Roorkee is an authentic record of my own work carried out during a period from August 2002 to March 2007 under the supervision of Dr. Najamuddin, Professor Emeritus, Department of Architecture and Planning, Indian Institute of Technology Roorkee, Roorkee and Dr. Pushplata, Associate Professor, Department of Architecture and Planning, Indian Institute of Technology Roorkee, Roorkee.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other Institute.

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ABSTRACT

Architecture developed in this industrial age is highly dependant on mechanical controls resulting in high level of energy consumption. Buildings consume a lot of energy, which is primarily used for heating, cooling, ventilation and lighting. Of the present total global energy consumption, 45% is used in heating cooling and lighting of buildings and a further 5% in building construction. Diminishing reserves of fossil fuels warrant the exhaustive review of the methodologies adopted for design of buildings. The energy crisis has regenerated interest in those aspects of building design, which maintain not only comfort inside but also consume less amount of energy. Around one-half of the energy could be saved by proper building design, construction and use. Conserving energy means reducing the amount of fuel and electricity used by a space. It is quite possible to achieve reductions of 50-70% (of developed world building consumption levels), and with a little extra effort by 75- 85%, by using known and tested concepts of technologically sophisticated passive, climatically adapted building design for new buildings.

Energy Responsive design involves the conscious use of climatic elements and natural process in the design of spaces. Buildings are designed to react favorably with the environment to produce balanced comfort conditions. The thermal capacity and resistance of the building material, surface characteristics, colour, texture, orientation, planning and shape of the building are a few elements important for energy conservation through building design. Passive solar building design utilizes this concept to heat or cool a building by natural means. In this approach, building components and spaces are

articulated to make maximum use of solar radiation and climatic elements producing energy responsive spaces.

The concept of energy responsive design is rooted in ancient civilizations. Many traditional cultures have used energy conserving features in their architecture, which used solar energy beneficially. The traditional buildings give us many examples of a sensitive approach to energy conscious designs for indoor comfort conditions. The use of natural and passive means in traditional houses was very effective in providing a thermally comfortable space, which was warm in winter and cool in summer. This approach has renewed our interest in our long forgotten aspects of our rich energy conscious architectural heritage.

The present study hypotheses 'that the traditionally constructed and designed houses are considered to be more energy responsive as compared to the houses designed to modern constructional designs.' It is with this background that the author has studied the three traditional residential buildings and two modern houses of Lucknow, their building features and their thermal performance in terms of temperature and relative humidity. A review of the existing literature on the subject has been undertaken to find out their appropriateness in context to climatic responsiveness and energy consumption.

The simultaneous monitoring of outdoor and indoor thermal conditions of three traditional house types together with that of two 'modern houses' in Lucknow has shown that the thermal capacity of the traditional houses has many advantages in limiting day

time internal temperature rise during the hot seasons. The factors benefiting the thermal performance of the traditional houses are the various natural and passive cooling techniques such as self shading, orientation, thick walls, heavy roofs, courtyards and surface color and texture. During the winters the thermal capacity of the traditional houses play a major part in maintaining near comfort conditions internally during the night, even when the external temperature drops as low as 7°C. The comparative analysis of thermal performance of traditional houses and modern houses has shown that the traditionally constructed and designed houses are more energy responsive as compared to the houses designed to modern constructional designs.

After going through the principles of energy conservation and the factors responsible for such a design, which have been followed, knowingly or unknowingly, in the traditional residential buildings, a process almost in the form of algorithm can be developed, which will help find the optimal solution for a given set of requirements and constraints. A mathematical model through balancing of thermal load has been formulated with the help of modified admittance procedure. The analysis and quantification of various passive cooling concepts such as orientation, overhangs, surface color, cavity walls and cavity roof and insulation in roof and walls in conditioned and non-conditioned buildings through a mathematical model has also been presented in this thesis.

Finally broad guidelines are also summarized with respect to spatial planning, daylighting, air movement, thermal comfort, material and construction techniques and landscaping.

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Man's desire to seek protection against climate's onslaught led to the necessity of shelter. Later on, with advancement of knowledge acquired about the parameters constituting the weather, he became restive to achieve thermal comfort. This mundane desire of man led to the advent of various design concepts for construction of shelters. The acquisitive nature of man to seek more and more comfort led to the discovery of different artificial sources of energy, i.e. fossil fuel like petrol and coal, tidal and hydropower. Added knowledge in the scientific field and myriad inventions helped in creating desired thermal environment inside the shelter.

This chapter begins with the general background of energy scenario and the energy consumption in the building industry and highlights the quest for the need of the study. Based on the hypothesis the objectives of the research study have been defined. The research strategy or methodology adopted and the scope and limitations of the thesis has been discussed in this chapter.

1.2 BUILDING ENERGY SCENARIO

Buildings are required to house people and equipment for practically all kinds of social and economic projects. Construction is a major industry in all countries and great deal of natural resources are consumed in buildings. When these resources are in short supply, as conventional sources of energy are today, it is vital that they be utilized efficiently in the building industry. Buildings consume energy for their construction, for operation and maintenance during their life and even for demolition and removal at the end of their life. It is important at this juncture to note the mode of use of energy in buildings. The total energy used in buildings is made up of two major components:

1. The energy used in construction, termed as the **Capital Energy Requirement** including energy needed in manufacturing, transportation of building materials and during the actual process of construction.
2. The **Operational Energy** is used in the building for cooling, heating, ventilation and lighting in buildings to create desirable thermal comfort conditions.

The relative quantum of energy used for construction and that used during the lifetime of the building can vary greatly. Energy consumed in buildings depends upon the climate (environmental factors), the design of buildings (design factors), the behaviour and expectation of the users (user factors) and the overall system within which the building is placed (external factors). The building designer or the Architect has the greatest control over the design factors but little or no control over other factors.

Current Energy Consumption Patterns

The present statistics of global energy consumption show three very significant patterns:

1. An extreme imbalance of per capita energy consumption between the developed and developing countries, where the developing countries, with

about 80% of the world's population, account for only 30% of current global energy consumption.

2. Energy consumption in the developing countries is increasing very fast, as development takes place due to increased income, changing values, aspirations, consumption pattern. If present energy consumption were to be distributed equally (at present, per capita average consumption of 56 GJ), the developing world would be able to increase its present level of consumption (on average) by 300%, whilst the developed world would have to reduce its consumption by 70% (on average). And this would still be maintaining current level of consumption and CO_2 production.

3. Of the present total global energy consumption, 45% is used in heating cooling and lighting of buildings and a further 5% in building construction. Building energy consumption is the largest single sector and is also that with the greatest, and easiest, potential for conservation. It is quite possible to achieve reductions of 50-70% (of developed world building consumption levels), and with a little extra effort by 75- 85%, by using known and tested concepts of technologically sophisticated passive, climatically adapted building design for new buildings. Much smaller savings can be achieved by retrofitting and adapting existing buildings.

1.3 NEED OF THE STUDY

Architecture developed in this industrial age is highly dependant on mechanical controls resulting in high level of energy consumption. Buildings consume a lot of energy, which is primarily used for heating, cooling, ventilation and lighting. Diminishing reserves of fossil fuels warrant the exhaustive review of the methodologies adopted for design of buildings. The energy crisis has regenerated interest in those aspects of building design, which maintain not only comfort inside but also consume less amount of energy. The energy crisis of the 1970s reshaped the design of buildings. Building design became conscious of orientation, size of windows, shading, ventilation and insulation etc. New materials, such as steel, glass and cement reshaped the volume and mass of our contemporary buildings. Design elements as pilotis, glass facades, and flat roofs were critically compared with important objectives of time, energy consumption, comfort and adaptation to regional affinities.

Inadequate concern about the transfer of technology in the past, justifies the need for alignment of attention of researchers in the field of design concepts, towards, traditional, economic and cultural aspects. The great and renewed interest in the vernacular architecture, particularly in connection with 'passive and low energy architecture' in traditional buildings, redefined our attitude towards the past. The energy crisis, the growing understanding of our limited resources and some major technological failures (on all continents) require a fresh look at our 'culture of buildings' [26]. Such requirements fostered the author's mind for undertaking the study of evaluation of thermal performance and energy responsiveness of buildings having cultural and traditional importance. The possibility of adaptations of thermal systems of traditional buildings, in buildings to be constructed in areas where the induction of artificial sources of energy, is still a dream to be accomplished in the future, merits a serious consideration.

Modern Buildings: Highly Energy Dependent

Today we live in an energy intensive built environment with the hope for better quality of life. Paradoxically in the process of creating thermal comfort to control heat gains and losses, our built environment consumes lot of conventional energy. Architecture seems to be at the forefront of consumption – energy guzzling mega-structure glass boxes ubiquitously present everywhere, irrespective of climate, location on planet and cultural context are indeed symptomatic of the runaway of consumption [26].

There is an increasing tendency for use of air-conditioning (the use of air-conditioners, heaters and evaporative coolers) in offices and homes in urban areas. The mechanical means of providing thermal comfort are prohibitive not only because of their initial and recurring costs but also because of non-availability of artificial sources of energy on a regular basis. We are heading towards an era where there is going to be a substantial gap between demand and supply of commercial energy which may go as high as 15% as against the current 9%. It is obvious that this energy shortage will certainly affect the availability of energy to the building sector as well since buildings consume substantial amount of 40% of total energy. Such constraints make it imperative to study the application of cost effective techniques for reducing the thermal load of buildings [26].

Energy Responsiveness: New Design Paradigm

Since 1973, rising fuel costs, prospective fuel shortages have made energy an extremely important consideration in building design. The recent awareness of energy and environmental problems related to town planning, architecture and construction, such as urban heat islands, pollution and energy consumption calls for a climate responsive architecture. The ever-alarming depletion of conventional energy and high cost of non-conventional energies morally enforce a statutory demand for energy conscious designs of buildings. It has now become essential to design, construct and use the building as energy efficient as possible. In recent years, the trend in design has been to integrate natural and auxiliary energy issues.

Energy consumption in buildings can be saved in several ways. Around one-half of the energy could be saved by proper building design, construction and use. Conserving energy means reducing the amount of fuel and electricity used by a space. The real challenge is to achieve maximum thermal comforts at minimum energy cost, through evolving various energy conservation measures and techniques during designing and executing of buildings. The thermal capacity and resistance of the building material, surface characteristics, colour, texture, planning and shape of the building are a few elements important for energy conservation through building design. The principle of energy responsive design is to plan buildings that interact favorably with the climate and harness the forces of nature. Trying to slow down the heat gain/loss from the building is the essence of energy conservation in building design.

Relevance of Traditional Techniques in Reducing Energy Consumption

Architecture developed in this industrial age is highly dependant on mechanical controls resulting in high level of energy consumption. Whereas people in the past coped by developing building designs that made use of the available material resources in such a way so as to gain maximum benefit from the climatic conditions. The use of natural and passive means in traditional houses was very effective in providing a thermally comfortable space, which was warm in winter and cool in summer. This approach has renewed interest in our long forgotten aspects of our rich energy conscious architectural heritage. Learning from traditional architecture of one's country gives an insight on how to design for a local climate since it is believed that the traditional buildings of the past have inbuilt thermal comfort property and are based on climatic responsive integrated passive design approach.

Therefore, the traditional buildings were direct expression of adaptation to climate and constraints of resources. The solution perhaps lies in discovering the techniques used in the traditional buildings in recreating the contemporary architectural form. Hence there is a need to establish a methodology of planning and design based on the philosophy of translating the spirits of the old in to an idiom of new design instead of mere re-enactment. This research endeavors to revive the wisdom of passive designing of the past to suite the sustainable living comforts of our society of 21st century.

1.4 HYPOTHESIS

Indigenous settlements and built forms that have evolved over a long period of time provide effective solutions to the environmental conditions. This study is based on the premise that the traditional built form have inbuilt thermal comfort property and are based on climatic responsive integrated passive design approach. The traditionally constructed and designed houses are considered to be more energy responsive as compared to the houses designed to modern constructional methods. By monitoring and analyzing the thermal performance/ built form relationship particularly with the help of mathematical models – it should be possible to evolve designs for new energy responsive buildings and settlements.

1.5 OBJECTIVES

The research aims to derive the essence and unique qualities of traditional architecture that can be integrated with the modern concepts. The thesis does not aim to reproduce traditional architecture, which may not be relevant in present day conditions. The objectives of the research are:

1. To identify well-set indigenous principles, techniques, methods, systems of energy conservation in vernacular buildings of Historical and Traditional types.
2. To understand the inputs of new scientific and technical know-how, in energy conservation in buildings by passive techniques.
3. To conduct experiments for evaluating thermal comfort in traditional buildings and comparing the thermal performance of traditional buildings with that of present modern residential houses.
4. To formulate a mathematical model for the thermal load of a non-conditioned residential building and to simulate various natural cooling techniques using Modified Admittance Procedure.
5. To evolve guidelines for energy conservation in buildings with passive design techniques.

1.6 RESEARCH METHODOLOGY

A scientific research approach utilizing validation methods, through experimentation, simulation and modelling has been adopted to achieve the research objectives. The work reported here relates to the simultaneous monitoring of outdoor and indoor thermal conditions of three traditional house types together with the two 'modern house' in Lucknow to investigate the factors which determine the thermal performance of each type, and to compare directly the performance of the 'modern' house with traditional types, and the traditional types with each other. This research involves the study of thermal performance through on-site monitoring of three traditional houses and two 'modern' dwelling units of Lucknow over the two extreme seasons, called the summer and winter season here. Both quantitative and qualitative methods of gathering data were used. These included:

- Literature Review of new scientific and technical know-how in energy conservation in buildings by solar passive techniques.
- Recording of the physical form and construction systems of the selected buildings and settlement.
- Study of Historical/ Traditional/ Socio-Cultural factors responsible for these buildings through Literature study and field surveys.
- Case study to investigate aspects of energy conservation through
  - (i) Information/ data collection: in terms of Measurements, Notes, Drawings and Photographs of Traditional buildings.
  - (ii) Identification of indigenous principles/ techniques/ methods/ systems of energy conservation in buildings of traditional types.

(iii) On site experimentation, collection of various data and its evaluation of data collected for quantification.

- Comparing the thermal performance of three traditional residential buildings with that of two modern houses built with new construction techniques and materials.
- Formulation of a mathematical model for calculation the thermal load of a non-conditioned residence.
- The analysis and evaluation of different passive cooling concepts in conditioned and non-conditioned buildings through mathematical modeling using Modified Admittance Procedure.
- Evolving guidelines for energy conservation in buildings with passive design techniques.

1.7 SCOPE AND LIMITATIONS

The study is restricted to historical or traditional residential buildings of Lucknow and does not include other non-residential historical buildings and modern buildings of Lucknow. The study has been restricted to planning stage and its extension to actual implementation stage with appropriate monitoring is to be considered.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Climatic responsiveness of a building is best judged by the thermal comfort experienced by the occupants; therefore an understanding of the basic concepts of thermal comfort is required. The internal thermal environment of a building is influenced by the external climate as well as the building characteristics. Therefore it is essential to understand the different design elements and the building characteristics. Relevant literature related to few common design elements that directly or indirectly affect thermal comfort conditions inside a building, and thereby energy consumption in a building, such as (i) Layout and surroundings of the buildings, which include Landform, Landscaping, Location of water bodies, Open Spaces and Built Form, Orientation (ii) Building characteristics such as Plan Form (i.e. shape and size of building), Building Form and Surface to Volume Ratio Fenestration i.e. location, shape, size and shading of openings provided for daylight and ventilation and thermo-physical properties of building elements have been studied.

In order to understand evaluation of energy responsiveness of buildings the basic theory of heat transfer as well as evaluation of natural cooling techniques through modified admittance procedure have been studied in detail. To have an insight into the passive cooling techniques in buildings significant literature related to solar passive architecture in earlier settlements, modern developments in solar passive architecture and various cooling techniques, which help in achieving balanced interior conditions have also been explored.

2.2 THERMAL COMFORT

Thermal comfort for a person has been described as "that condition of mind which expresses satisfaction with the thermal environment" by the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) [4]. The thermal comfort conditions in a building are dictated by the primary climatic parameters like air-temperature, mean radiant temperature, air humidity, air motion, clothing and activity level. Heating and cooling are viewed as producing conditions that provide 'human comfort' levels that people need to accomplish their task. The physical condition that determines the feeling or warmth or cold by human body is a combination of air temperature, mean radiant temperature, relative humidity and air velocity. The human response to the same conditions varies from person to person and for the same person the response depends upon the clothing on the body and the nature of activity the person is engaged in. Apart from these two factors, a number of other psychological and environmental factors also influence the feeling of thermal comfort (shown in Figure 2.1).

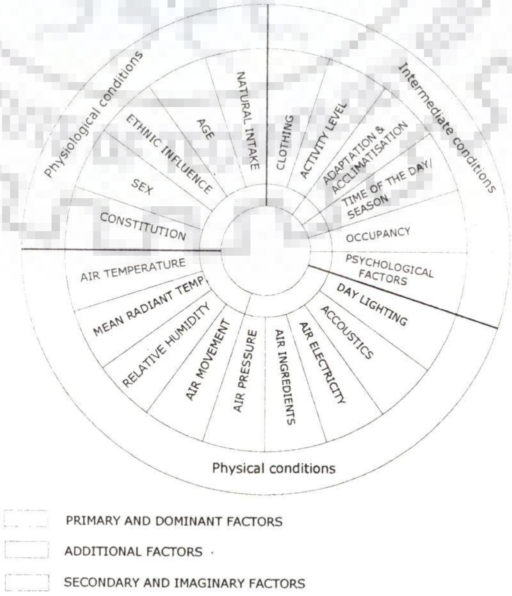


Figure 2.1 Factors influencing Thermal Comfort

The science of thermal comfort is concerned with predicting what set of conditions temperature, humidity, air speed) corresponds most closely to this neutral feeling, and how tolerant people are of deviations from it. On a scale ranging from hot to cold the state of thermal comfort is described as "neutral" by ASHRAE (Table 2.1).

Table 2.1 ASHRAE scale of thermal comfort.

Hot	+3
Warm	+2
Slightly warm	+1
Neutral	0
Slightly cool	-1
Cool	-2
Cold	-3

Source: ASHRAE Handbook Fundamentals

Various scientists have developed different techniques for determining thermal comfort over a period of time. These include Thermal Comfort Index by Givoni et al., Monograph by Sharma et al. and Bioclimatic chart by Olgay and Givoni. [16] Giovni developed an index of thermal stress to cover all the mechanisms of heat loss and heat gain by human body by taking into account various levels of work and clothing. This index is based on the assumption that if thermal equilibrium is possible, the rate of sweat production is sufficient to achieve the evaporative-cooling required to balance the metabolic heat production and its exchange with the environment [16].

The basic thermal balance equation relates three independent physiological measures - skin temperature, sweat rate and metabolic rate to the four environmental parameters and to the level of clothing. This equation gives the condition in which the bodily heat generated equals the heat lost and no lowering or raising of bodily temperature is taking place. This of course is unrelated to the level of thermal comfort experienced by an individual.

This equation can be expressed as:

$$T_{ex} = f \Delta T_a + (1-f) \Delta T_{mr}$$

$$f = F(A, C, \Delta H, V)$$

where T_{ex} is the uniform temperature which is defined as the uniform temperature on an imaginary enclosure in which a person will experience the same degree of thermal comfort as in the actual non-uniform environment,

T_{mr} = mean radiant temperature,

A is the activity level and C is the clothing insulation value.

Thus, the relative importance of air and mean radiant temperature depends upon a set of parameters and physiological factors. On the basis of assumptions concerning the conditions likely to exist in a passive solar heated building, the expression for equivalent uniform temperature can be written as:

$$T_{ex} = 0.55 \Delta T_a + 0.45 T_{mr}$$

Various researchers have attempted to combine the effect of the environmental parameters into one single index of comfort (Givoni) but there is as yet no universally applicable or universally accepted index of comfort. Till recently, the most commonly used index was the "Effective Temperature" index which has been replaced by the "Standard Effective Temperature" in which any environment, clothing and activity level is expressed in terms of a uniform environment (air temperature equals mean radiant temperature) standardized at 50% relative humidity, air velocity of 0.125/m/sec, for lightly clothed subjects in sedentary occupations.

The "operative temperature" defined in ASHRAE handbook, is related to human comfort and includes the effect of all latent-heat loss phenomenon on which comfort depends. For tropical summer conditions, Sharma *et al.,* have evolved "Tropical Summer Index" (TSI) and for Indian conditions this is the most applicable index. It is defined as the air globe temperature of still air at 50% relative humidity, which produces the same overall thermal sensation as the environment under investigation.

The equation of Tropical Summer Index (T.S.I.) is:

$$\text{T.S.I.} = 0.308\, t_w + 0.745\, t_g - 2.06\, V^{1/2} + 0.841 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.1)$$

where t_w = wet bulb temperature, t_g = globe temperature and v = air velocity in m/sec.

This equation is simplified by Sharma to

$$\text{T.S.I.} = 0.33\, t_w + 0.75\, t_g - 2.0\, V^{1/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.2)$$

For easy determination of the comfort index the comfortable range of T.S.I. given by Sharma is:

Thermal Sensation	**Range**	**Optimum Value**
Slightly cool	19.0 - 25.0°C	22.0°C
Comfortable	25.0 - 30.0°C	27.5°C
Slightly warm	30.0 – 34.0°C	32.0°C

It has been seen from equation (2.2) above that the effect of increased humidity (given by t_w) is similar to that of increased air temperature and mean radiant temperature (accounted for by t_g), while the effect of increased air velocity is to reduce the T.S.I. value. The last is strictly true only within the temperature ranges given above and at higher temperatures increased velocity does not result in lowering of the comfort index. For summer conditions in buildings, therefore, the air temperature and mean radiant temperature need to be kept low, while relative humidity and air velocity can be controlled to relieve the effect of higher temperatures.

From experiments, it has been found that the subject is more comfortable when the value of TSI equals to 27.5°C [16]. It has been further revealed that the successive thermal sensation will change at an approximate interval of 4.5°C. For Indian climatic conditions, with 50% relative humidity and air velocity between 0.5 meter/second to 20.5 meter/second, a decrease in TSI from 1.4 to 3.2 °C is observed. The comfort zone is shown in the psychometric chart (shown in Figure 2.2)

Since the internal thermal environment of a building is influenced by the external climate as well as the building characteristics, it is essential to understand the different building characteristics that affect thermal comfort conditions inside a building directly or indirectly and thereby its energy responsiveness. These are the layout and surroundings of the buildings, Landscaping, Ratio of built form to open spaces, Location of water bodies, Orientation, as well as, the building characteristics such as Plan Form and Fenestration provided for daylight and ventilation.

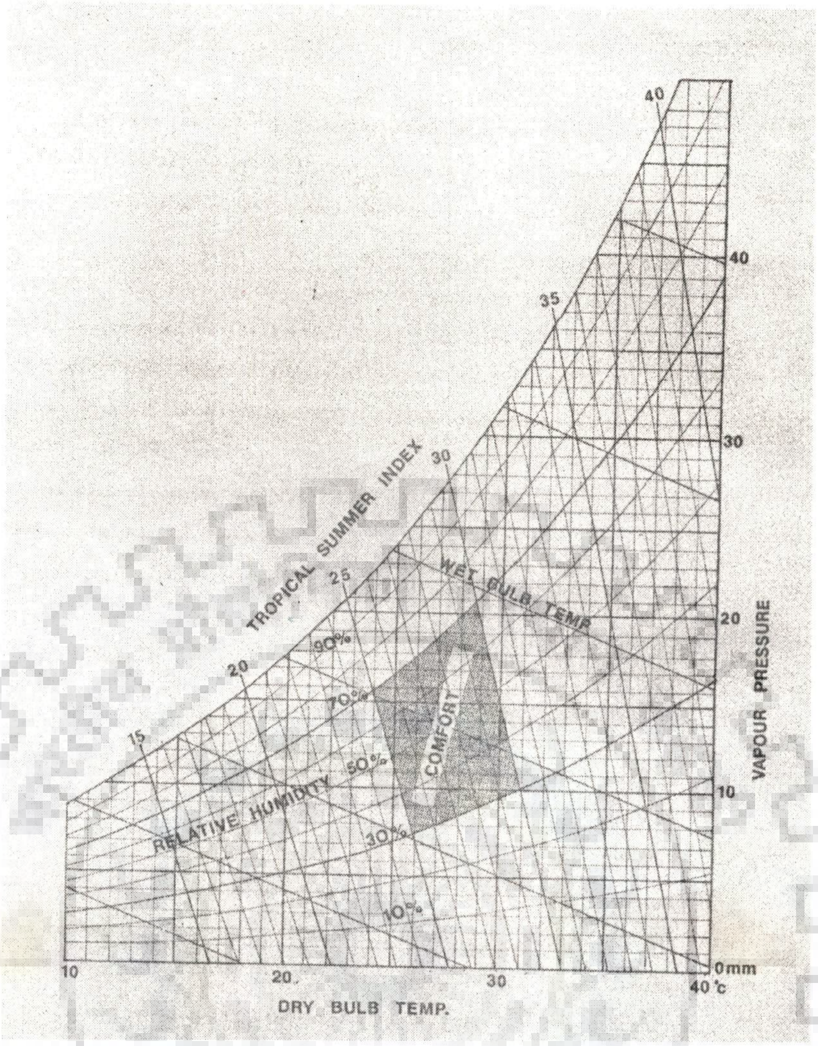


Figure 2.2 T.S.I. on a psychometric chart

2.3 LAYOUT AND SURROUNDINGS OF THE BUILDINGS

Energy Responsiveness of building is affected by the macro and microclimate of a place. The few common design elements that are related to the surrounding and layout of the buildings are:

2.3.1 LANDFORM

The landform or topography of a site and surroundings could either be flat, sloping or undulating (mounds, etc.). If the land is flat, similar conditions would prevail over the entire site. The location of the building in such a case is not dictated by climatic concerns. However, slopes and depressions lead to different levels of air temperature and air movement at different parts of the site. Cooler air tends to collect in depressions or dips in the land. As a result, the air temperature is lower in such areas. Also, air speed increases up the windward slope.

2.3.2 LANDSCAPING

Landscaping is an important clement in altering the microclimate of a place. Plants, shrubs and trees absorb radiation in the process of photosynthesis. As a result, they actually cool the environment. Proper landscaping reduces direct sun from striking and heating up building surfaces. When there is a requirement to minimize the heat gain, trees can be used to cut off the east and west sun. Planting deciduous trees is very useful in hot dry climates. They provide comforting shade in summer and shed their foliage in winters allowing sun. It prevents reflected light carrying heat into a building from the ground or other surfaces.

Landscaping creates different airflow patterns and can be used to direct or divert the wind advantageously by causing a pressure difference. This is achieved by planting trees and hedges so as to make a narrowing path for the air. This reduction of area increases air speed. Additionally the shade created by trees and the effect of grass and shrubs reduce air temperatures ad the building and pro evaporative cooling. The understanding of these pressure changes and the consequent air paths can be used to our advantage in building design. Properly designed roof gardens help to reduce heat loads in a building. A study shows that the ambient air under a tree adjacent to the wall is about 2ºC to 2.5ºC lower than that for unshaded areas (Bansal, Minke 1994).

2.3.3 LOCATION OF WATER BODIES

Water is a good modifier of microclimate. Water has a relatively high latent heat of evaporation as well as specific heat. In other words, water uses up a comparatively large amount of heat in evaporating. It also absorbs or releases a comparatively large amount of heat for a unit rise or fall of temperature. So, when water evaporates by the movement of air, it cools the air. This is evaporative cooling. As a result, during the daytime areas around water bodies are generally cooler. At night, however, water bodies release relatively large amounts of heat to the surroundings. This heat can be used for warming purposes.

In the process of evaporative cooling, the humidity rises. Evaporation is slow if the relative humidity is already high. Water has a high specific heat, a little more than twice that of concrete. This means that the same volume of water would absorb about twice as much heat as concrete for the same rise of temperature. This can either reduce heat gain or if desired the radiation absorbed can be used as an indirect source of heat. In hot-dry climates, water/water bodies can be used both for evaporative cooling as well as minimizing heat gain. Taking into account wind patterns and vegetation they can be used to direct cool breeze into the house.

2.3.4 OPEN SPACES AND BUILT FORM

Open spaces have to be seen in conjunction with built form. Together they can allow for freer air movement and increased heat loss or gain. The proportion of the space between the buildings will determine the quantity and the quality of the solar radiation falling onto the facades as well as the availability of breeze, with wider spaces permitting increased illumination and better air movement. The proportion will also affect the amount of light falling on the facades. Heat loss at night by re-radiation also increases with more open spaces.

During the day, buildings receive radiation from the sun and sky. At night this heat is reradiated to the sky. The greater the exposure of the buildings to the sky, the more the heat loss. So not just the roof, the walls also lose heat. If, however, buildings are tightly packed then all walls face each other and have little exposure to the sky. Then, heat loss occurs only from the roof.

2.3.5 ORIENTATION

Building orientation is significant design consideration, mainly with regard to solar radiation and wind. The orientation of building means the amount of solar radiation received on the longer/shorter axis in summers and winters respectively. Building orientation affects the indoor climate in two respects by its regulation of the influence of two distinct climate factors:

i. Solar radiation and its heating affect on walls and rooms facing different directions.
ii. Ventilation problems associated with the relation between the direction of the prevailing winds and the orientation of the building.

The solar radiation received by a building element is dependent upon its orientation. The solar radiation intercepted by the building can be greatly reduced by choosing a proper building form and by orienting it with due regard to solar geometry. For an isolated building with each of the four walls and the roof of equal area, the relative heat load due to direct solar radiation is given in Table 2.2.

Table 2.2 Direct Solar Heat Load on Different Building Surfaces for Latitudes 17°C To 31°C North And South.

Seasons	Roof	Walls			
		North	South	East	West
Summer (22 June)	48-51%	6-13%	0-2%	19-20%	19-20%
Winter (Dec. 21)	28-34%	0%	35-44%	14-15%	14-15%

The amount of solar radiation received on the south oriented facade is higher in comparison with other facades in northern hemisphere. In addition to the direct radiation, the building receives diffuse and reflected radiation also. Measured value of solar radiation (Mani, 1981) show that during the summer months in India the diffused radiation is about one third of the total radiation and during monsoons it is more than half of the total radiation. Irrespective of their orientation walls receive equal amounts of diffuse radiation while the roof receives about twice as much.

2.4 BUILDING CHARACTERISITICS

Energy Responsiveness of building is affected by the buildings characteristics. The two important building characteristics are the planform and the fenestration design for daylight and ventilation. They are discussed as follows:

2.4.1 PLANFORM

The planform of a building plays a role in ventilation, heat loss and heat gain. The plan form of a building affects the airflow around and through it. It could either aid or hinder natural ventilation. The physical obstacles in the path of airflow create pressure differences. This causes a new airflow pattern. Air tends to flow from high pressure to low pressure areas. Knowing the direction of air movement, the plan form can be determined also as to create high pressure and low pressure areas. Building openings connecting the high pressure areas to low pressure areas would cause effective natural ventilation. The perimeter to area ratio of the building is also an important indicator of heat loss and gain. A large perimeter to area *(PIA)* ratio means that a small area is being bounded by a large perimeter. A small *P/A* ratio means that the same area would be bound by a much smaller perimeter. Greater the *P/A* ratio the greater the radiative heat gain during the day and the greater the heat loss at night. Similarly, smaller the *P/A* ratio, the lesser will the heat gain be during the day and the lesser the loss at night. Thus, the *P/A* ratio is an important factor in controlling heat gain and loss.

2.4.2 BUILDING FORM AND SURFACE TO VOLUME RATIO

The volume of space inside a building that needs to he heated or cooled and its relationship with the area of the envelope enclosing the volume affect the thermal performance of the building. This parameter, known as the S/V (surface-to-volume) ratio is determined by the building form. The surface area to volume *(S/V)* ratio (the three dimensional extrapolation of the *P/ A* ratio) is an important factor determining heat loss and gain. The greater the surface area the more the heat gain/loss through it. So small *S/V* ratios imply minimum heat gain and minimum heat loss. For any given building volume, the more compact the shapes, the less wasteful it is in gaining/losing heat. Hence in hot and dry regions and cold climates, buildings arc compact in for with a low S/V ratio to reduce heat gain and losses, respectively. Also, the building determines the airflow pattern around the building directly affecting its ventilation. The depth of a building also determines the requirements for artificial lighting, greater the depth higher the need for artificial light.

2.4.3 FENESTRATION FOR DAYLIGHT AND VENTILATION

Of all the elements in the building envelope, window and other glazed areas are most vulnerable to heat gain or losses. Proper location, sizing and detailing of windows and shading form an important part of bioclimatic design as they help to keep the sun and wind out of a building or allow them when needed. Fenestration pattern, orientation and configuration for the provision for daylight and ventilation are discussed as follows:

2.4.3.1 PROVISIONS FOR DAY LIGHTING

Lighting of building interiors is a fundamental necessity for human beings. Daylight is a natural way to reduce the energy consumption in the buildings. Admittance of the daylight during daytime is an efficient method of lighting the interiors of the buildings. This is for two reasons. Firstly the Luminous Efficacy, i.e. the useful visible light in relation to the total energy of the radiation is high. The heating effect of the daylight is about 1 watt per 100 lumen of light, between ½ and 1/10 of the typical artificial lighting alternatives. Secondly daylight is free. Artificial lighting consumes electricity, usually 'on-peak' electricity, and larger buildings often constitute the largest single category of energy cost.

The quantitative parameters, which describes a building's the daylighting is the Daylight Factor (D.F). It is defined as the ratio of the daylight illuminance in the building to the outside.

$$D.F = \frac{Ei}{Eo} \times 100\% \qquad (2.3)$$

where E_i = illumination indoors, at the point taken.

E_o = illumination outdoors from an unobstructed sky hemisphere.

The value of the daylight factor at a point in a room decreases with the increase in the distance of the point from the window. For diffused uniform sky, the day light factor for a point in the room is a function of the distance of that point from the window. Tropical sky for India, conditions, as has been expressed by Sharma *et al.*, is given below:

$$B_\theta = B_z \operatorname{cosec}\theta \qquad (2.4)$$

The Indian standard code I.S.I-2440, has adopted Equation.2.4 for outdoor sky condition where θ = 15°. This corresponds to a period of 1 to 1.5 hours after sunrise and a tropical period before sunset as this period represents the habitual working hours. It corresponds to low level of sunlight in the open and any light during working hours. The availability of daylight at any is a direct function of the light components, area of openings, room height, sill height, reflectance of walls, and aspect ratio of openings. They are summarized as follows:

(i) Light Component: The day light illumination at a point in a building comprises of following three components: (Figure 2.3).

- The sky component is the light flux, which comes directly from the unobstructed part of the sky of the considered point.
- The externally reflected component is the light flux reaching the considered point after reflection from a surface external to the room.

- The internally reflected component is the light flux reaching the point after reflection from the internal surface of the room (Figure 2.4).

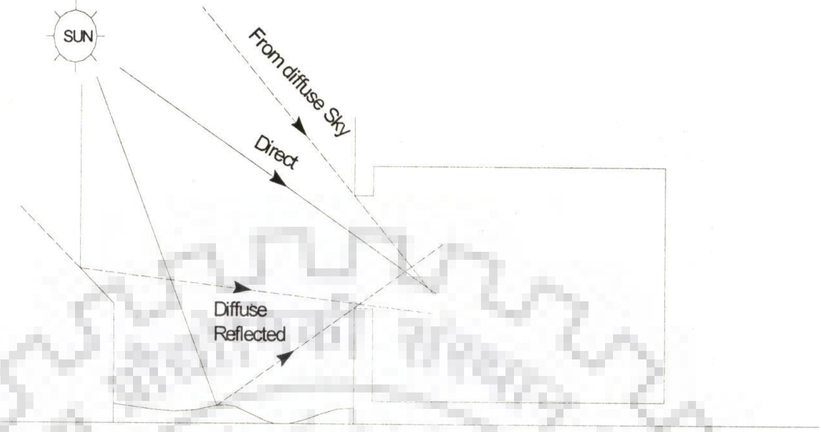


Figure 2.3 Components of Light entering into the room

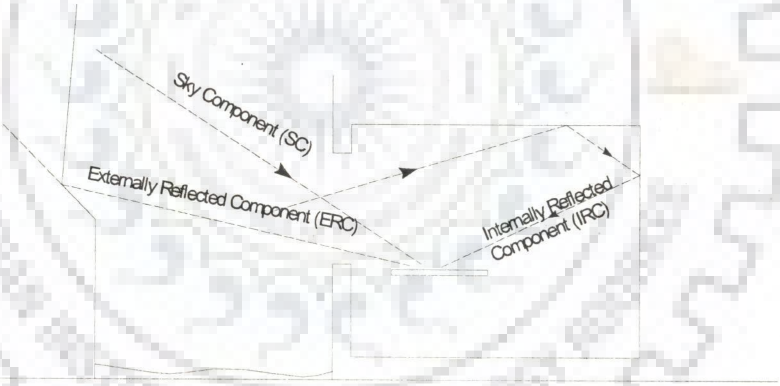


Figure 2.4 Components of Day Light falling on the work plane

In temperate climates, where occupants rarely approach condition of heat stress, the provision of minimum day light level for reasonable proportions of the occupied day is important. Depending upon the type of building daylight factor entering the building ranges from 5% to 15%. In tropical buildings, the sky brightness is higher and less variable seasonally. The sunlight, which is between 5 to 10 times more intense than the diffused component, increases the problem of illumination. Tropical buildings are equipped with heavy shading devices successfully. In case of movable shades the daylight factor can vary to suit conditions thus making the design less critical. The size and placements of the window affect the illumination levels indoor. Normally the size and the area of windows is taken as 15% of the covered area of the room. The sill level (level above floor level from where the window starts) is taken as 900 mm, but varies according to the design of the building. The recommended day light factors based on the building types are given in National Building Code (19).

(ii) *Area of Openings:* Openings include both windows and ventilators, which differ in sill and opening heights. The area of the opening is normally expressed as a percentage of floor area. The area of the opening varies from 5% to 30% in steps of 5%.

(iii) *Room Height:* The illumination level varies with room height even for fixed fenestration area. Internally reflected component changes with increased room height according to split flux principle.

(iv) *Sill Height as compared to Working Plane Height:* The sill height of windows does not always coincide with the working place height. Working place height varies from -50 % to + 100% of the window height, in steps of 25%.

(v) *Reflectance of walls:* Reflectance of walls which affects the delighting inside the room ranges from 0.4 (grey or dark surface) to 0.85 (polished white washed surface). As a normal practice the ceiling and working plane reflectance are kept constant, i.e. at 0.35 and 0.7 respectively. Reflectance of white wash analyzed.

(vi) *Aspect Ratio of Openings:* In general, it is known that high windows provide more penetration and correspondingly the spread is diffused. In practice normally the width to height ratio of windows is taken as 1:1, 1:1.3 or 1:1.6. The hot air changes its state to vapour there by getting converted to latent heat of vapourizations through the process of evaporation.

2.4.3.2 PROVISIONS FOR VENTILATION

i. Ventilation due to wind Forces: Wind striking a building generates a region of higher pressure in the direction of its incidence (windward wall) while the sides, i.e., leeward wall and roof are subjected to a reduced pressure. A pressure gradient created in the direction of the incident wind causes the air to flow through openings in the buildings.

The rate of flow can be calculated by expression given below,

$$Q_V = KAV_o$$

The coefficient of effectiveness K depends upon the direction of wind relative to the opening and on the ratio between the areas of the two openings.

ii. Out Door Wind Management: Local Topography and surface texture affect the wind conditions considerably. Spacing of buildings at six times their height in a gridiron pattern results in proper wind movement with the uniform flow and removal of stagnant zones. The air stream near the building creates a vortex leading to a high-pressure build-up and an increased wind velocity at the ground level. A shelter block behind the tall building experiences reverse flow due to negative pressure.

iii. Indoor Natural Ventilation: Windows play a dominant role in inducing ventilation. Ventilation rate is affected by climate, wind direction, size of inlet and outlet openings, volume of the room, shading devices and the internal partitions. Evans et. al. [1980], studied the effect of air flow related to the position of inlet and outlets in the wall.

iv. Ventilation due to Combined Effect of Wind Thermal Forces: The actual wind flow in a building result from the combined effect of thermal and wind forces. The two forces either reinforce or oppose each other, depending upon the direction of wind reinforce or oppose each other, depending upon the direction of wind and internal or external temperature. The rate of airflow is given by the equation:

$V_R^2 = V_W^2 + V_T^2$

If the window inlet/outlet are assumed to be of equal sizes, then

$V_i = 0.45\ (e\text{-}e^{-3.84x})\ V_o$

In a square room the window inlets and outlets are assumed to be of equal size. For different sill heights, the average available wind velocity V_s at still level can be calculated using equation.

$V_s = V_{0.9} + 0.02\ (1\text{-}s)\ Vo$

In case of the room having unequal openings and the outlet being larger, then the wind velocities are higher (Bansal et. al. [1989]).

2.4.4 THERMOPHYSICAL PROPERTIES OF BUILIDING ELEMENTS

The response of the building fabric to the outdoor environment depends upon certain thermophysical properties of the building elements. These are:

(1) Outer Surface Characteristics - Absorptivity, reflectivity and emissivity for radiation; outer surface coefficient of heat transfer.

(2) Material Characteristics - Thermal conductivity, heat capacity, density.

(3) Building Element Characteristics

2.4.4.1 Outer Surface Characteristics

Of the total radiation incident on an opaque surface, a part is reflected and a part is absorbed. Reflectivity of the surface is that part of the total incident radiation, which is reflected while absorptivity of the surface, is that part of the total radiation, which is absorbed. Both these properties are wavelength dependent. In general it can be said that polished metallic surfaces are good reflectors at all wave-lengths while light coloured painted surfaces are good reflectors for solar radiation but not for thermal radiation. Emissivity, which defines the radiation emission properties of a surface at a particular wavelength, is the emissive power of the surface as compared to the emissive power of a perfect radiator or black body. For a given wavelength the surface emissivity equals the absorptivity. However, in practice, absorptivity is of interest only at wavelengths of "solar radiation while emissivity is to be measured for far-infra-red wave-length radiation that is emitted by terrestrial objects. *For* most materials these two are not same. The colour of a surface is a good indicator of absorptivity but not of emissivity, which depends only upon surface structure. White wash and oxidized Aluminium foil have nearly equal absorptivity (0.12 and 0.15 respectively) but their emissivity is very different (0.90 and 0.12 respectively). Table 2.3 shows the reflectivity and emmisivity of surfaces of different materials.

Table 2.3 Reflectivity of surface and Emissivity in long wave region

Materials	Solar Reflectivity	Emissivity (Long Wave)
Al. foil (Bright)	0.95	0.05
Al. Paint	0.50	0.30
Polished Al.	0.80	0.05
Galvanized Steel	0.75	0.25
White Wash	0.88	0.90
Gray Colour (Light)	0.60	0.90
Red Brick	0.40	0.90
Glass	0.08	0.90

The radiative part of the surface coefficient depends upon the emissivity of the surface and upon the temperatures of the radiation exchanging surfaces. The convective part of the surface coefficient depends upon the velocity of air near the surface as well as on the texture of the surface. Vertical surfaces are usually exposed to other vertical surfaces at near equal temperatures in contrast with horizontal surfaces, which are exposed to the sky. Therefore the radiative component of vertical surface coefficient becomes very small as compared to that of horizontal surfaces and it is usually neglected in calculation.

2.4.4.2 Material Characteristics

The most important property of building material is its thermal conductivity (k), which determines the rate at which; heat is conducted through the material. The inverse of thermal conductivity is the resistivity, which as the name implies, is a measure of the resistance, which the material offers to the passage of heat. Another important property of the building material is the volumetric heat capacity, which is the quantity of heat required to raise the temperature of a unit volume of the material by 1°C This is given by the product of specific heat (c) and the density (r) of the material. For non-air-conditioned buildings another property of the material called "thermal diffusivity" (or in more descriptive terms, “temperature conductivity”) is useful. This is the ratio of the heat conducted by the material to the heat stored up in it and is given by $\frac{k}{r.c.}$ and is measured in m^2/deg. hour.

2.4.4.3 Building Element Characteristics

Structural elements of a building usually consist of more than one material. For instance, a simple brick wall usually has a plaster layer on both sides of it. A typical reinforced concrete roof has a plaster layer underneath and various waterproofing layers above it. The properties of the building element are then derived from the thermophysical properties of different material layers. Three of these properties are important in the present context. The U-value of an element is its conductance for heat and it depends upon the thermal conductivity of the materials and the thickness of the different layers. For composite elements the U-value is the inverse of the sum of the resistances of the individual layers. Air to air U-values also take into account the resistance between the building element surfaces and the surrounding air and are a useful measure of the heat conducted by the building element under steady-state conditions, i.e. when the temperatures on both sides of the element remain constant. When building elements are subjected to temperature fluctuations, not only the heat transmitted by the element but also the time taken for heat to travel through the element becomes important. Another property of building element called 'time-lag' may now be defined. A fluctuating temperature wave outside the building element, gives rise to another temperature wave with lower amplitude on the inside. The two temperature waves are out of phase by an angle called time lag, which depends upon the thermal 'diffusivity', and thickness of the building element. In Figure 2.5 time lag is given by the difference in hours between the occurrence of the peak temperature outdoors and the corresponding peak temperature indoors. The ratio of the amplitude of internal temperature wave to the amplitude of external temperature wave is called the "decrement factor". Massive building elements such as brick walls usually have a large time lag and lower decrement factor than thinner elements of lightweight materials.

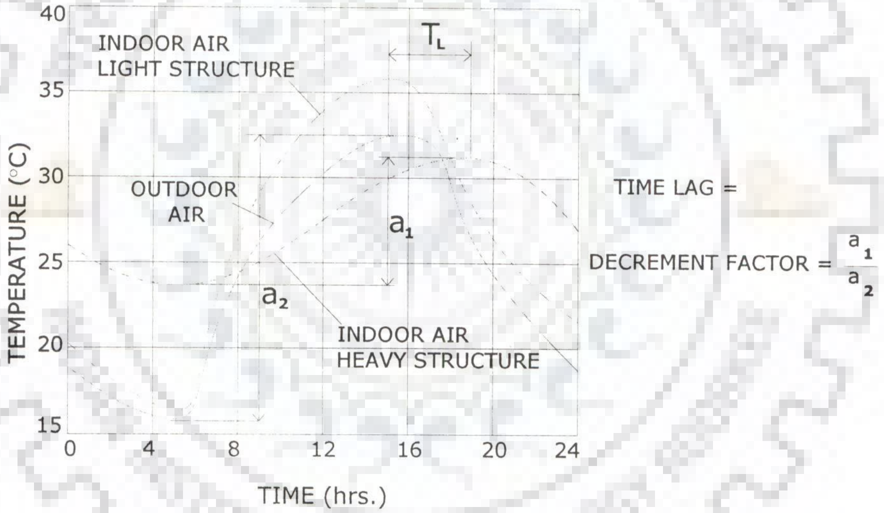


Figure 2.5 Effect of thermal capacity of building on time lag and decrement factor

2.5 EVALUATION OF HEAT TRANSFER IN BUILDINGS

The thermal behavior of a building under different weather conditions can be quantitatively predicted by a mathematical model. To set up exact heat balance across various building components and within various zones in which building is divided at discrete time steps, a basic understanding of heat transfer and the balancing of thermal load through modified admittance procedure is required.

2.5.1 BASICS OF HEAT TRANSFER

In any solar system, the transfer of mass accompanies the heat transfer. The inclusion of mass transfer makes the heat transfer process more complex. Therefore to understand the fundamental of heat transfer, the three basic process of heat transfer i.e. conduction, convection and radiation has bee discussed here.

i) **Conduction:** The heat transfer takes place from one part to and other due to the difference in their temperatures. The study of heat conduction involves space-time variation of temperature (T), i.e., referred to as transient temperature field.

$$T = f(x, y, z, t) \qquad (2.5)$$

The temperature is said to be of steady –state kind if it remains constant at each point with respect to time, viz,

$$T = f(x, y, z); \frac{\delta^T}{\delta t} = 0 \qquad (2.6)$$

The basic law of heat conduction is known as Fourier's law and can be mathematically expressed as:

$$q = -KA\frac{\delta T}{\delta x}, \qquad (2.7)$$

The value of thermal conductivity, which varies from place to place, and with temperature is generally considered to be constant for building applications. Its values for certain common building materials are listed in Table 2.4.

Table 2.4 Physical Properties of Some Common Building Materials

Material	Density (kg/m^2)	Thermal conductivity (W/m °C)	Specific heat (J/kg-°C)
Air	1.2	0.026	1006
Asbestos sheet	3060	0.36	
Brick	2300	0.8	800
Concrete	2400	1.4	3350
Cork	240	0.05	2050
Fibre board	300	0.057	1000
Glass (Crown)	2600	1.0	670
Glass (Flint)	4200	0.8	500
Plaster	1180	0.48	
Polyvinyl chloride (rigid)	1700	0.04	1000
Rubber (Polysprene)	910	0.15	1600
Sand (dry)	1500	0.3	
Timber (fir)	640	0.11	1210
Water	998	0.591	4190
Wood wool	500	0.1	1000

The three-dimensional heat conduction Equation can be written by using Fourier's law (Equation 2.7) as,

$$\rho C \frac{\delta T}{\delta t} = v(kvT) + q_v \qquad (2.8)$$

where ρ is the density, C the specific heat of the material and q the heat generated by inner heat sources per unit volume of the medium per unit time. If k is independent of space and there is no inner heat source, (Equation 2.8) reduces to,

$$\frac{\delta^T}{\delta t} = \alpha v^2 T \qquad (2.9)$$

where, $\alpha = \frac{k}{\rho c}$ and is called thermal diffusivity.

It determines the rate at which a non-uniform temperature distribution approaches equilibrium condition (δT/δt) = 0 for steady flow, then (Equation 2.9) reduces to:

$$v^2\,T = 0 \qquad (2.10)$$

where the Laplace coefficient in Cartesian rectangular coordinates is

$$v^2 = \frac{\delta^2}{\delta x^2} + \frac{\delta^2}{\delta y^2} + \frac{\delta^2}{\delta z^2} \qquad (2.11)$$

Heat conduction equation can be solved either analytically or numerically subjected to appropriate initial and boundary conditions. It may be mentioned that assuming heat transfer in one dimension only may, satisfactorily solve many steady state heat conduction problems. For a flat-wall whose face dimensions are large as compared to its thickness, the Fourier's law, (Equation 2.11) can be integrated to get as:

$$q + \left[\frac{KA}{L_w}\right](T_1 - T_2) \qquad (2.12)$$

where T_1 and T_2 are temperatures of the wall surfaces. It is assumed that the thermal conductivity is a constant quantity. The term l_w/ka, expresses the thermal resistance to conductive heat transfer. The reciprocal of it is known as the thermal conductance. Heat transfer through an enclosed plane air space is expressed in terms of thermal conductance, which is useful in the design of cavity wall or roof of buildings. Values of thermal conductance for plane air spaces are presented in Table 2.5.

Table 2.5 Thermal Conductance “C” For Plane Air Space (Threkeld (1970])

Position of air space	Direction of heat flow	Mean with temp.		Temp. diff.	C(W/m^2 °C)			
		(m)	(°C)		Effective emissivity			
					0.82	0.52	0.20	0.05
Horizontal	Up	0.02	10	5.6	6.53	4.89	3.35	2.56
		0.10	10	5.6	6.08	4.43	2.84	2.10
		0.02	32	5.6	7.50	5.45	3.47	2.50
		0.10	32	5.6	7.04	5.00	3.01	2.05
Horizontal	Down	0.02	10	--	5.57	3.92	2.39	1.59
		0.04	10	--	5.00	3.35	1.76	0.97
		0.10	10	--	4.60	2.95	1.42	0.63
		0.02	32	--	6.76	4.66	2.73	1.76
		0.04	32	-	6.88	4.03	2.05	1.08
		0.10	32	--	5.74	3.64	1.70	0.68
Sloping 45°		0.02	10	5.6	6.02	4.37	2.84	2.05
		0.10	10	5.6	5.91	4.20	2.67	1.87
		0.02	32	5.6	7.04	4.94	3.01	2.05
		0.10	32	5.6	6.87	4.83	2.90	1.87
Sloping 45°	Down	0.02	10	5.6	5.57	3.92	2.39	1.59
		0.10	10	5.6	5.28	3.644.	2.05	1.31
		0.02	32	5.6	6.76	6	2.73	1.76
		0.10	32	5.6	6.31	4.20	2.27	1.31
Vertical	Horizontal	0.02	10	5.6	5.62	3.98	2.39	1.65
		0.10	10	5.6	5.62	3.98	2.45	1.65
		0.02	32	5.6	6.76	4.66	2.73	1.76
		0.10	32	5.6	6.65	4.60	2.61	1.65

(ii) Convection: The heat transfer from one part of a fluid at higher temperature to another part at a lower temperature by net displacement of fluid particles is known as the thermal convection.

The temperature difference between the fluid and the contact surface produces a density gradient in the fluid resolution. The fluid motion is caused by externally imposed forces (pressure difference) and is known as forced convection. Sometimes, these two processes occur simultaneously. The rate of heat transfer (q) from a surface of area A, by convection between the fluid and the boundary surface may be evaluated by:

$$q = h\,A\,\Delta T \tag{2.13}$$

The heat transfer coefficient h, is a complicated function of the nature and origin of the fluid flow of the thermo-physical properties and of the geometric arrangements of the system. However, the appropriate mathematical form of h, in a limited domain of applicability is evaluated fro the empirical equations obtained by correlating experimental results with the method of dimensional analysis.

The convection parameters contain the following dimensionless terms

$N_u = \frac{hX}{H}$, Nusselt number

$R_e = \frac{\rho.vX}{\mu}$, Reynolds number

$Pr = \frac{\mu C_p}{K}$, Prandtl number

$Gr = \frac{\beta g \Delta T x^3 \rho^2}{\mu^2}$, Grashoff number

A number of empirical formulae in terms of dimensionless parameters are desired on the basis of various experimental results, are available for free and forced convection.

a) *Free convection:* The heat transfer by free convection is given by the equation

$$N_u - C'(Gr.Pr.)^n.K' \qquad (2.14)$$

where the constants "C" and "n" are determined by the correlation of experimental data. The correlation factor K, is introduced to represent the entire physical behaviour of the problem and increases the range of the parameters.

A summary of the evaluations for convective heat transfer for different geometries is given in ASHRAE handbook of fundamentals [1967] and Wong [1977].

b) *Forced convection:* The heat transfer by forced convection is given by the equation

$$Nu - C'.(Re)^m.(Pr)^n.K' \qquad (2.15)$$

where, C', m and n are constants for a given type of fluid flow and body geometry (Wong [1977]).

c) *Heat transfer due to wind:* In building problems wind induced heat loss is experienced very frequently. Forced convection phenomenon has been discussed in the study separately. Mc Admas [1954] has suggested a relation for convective heat transfer due to wind and is given below.

$$H_c = 5.7 + 3.8\ V \qquad (2.16)$$

Duffie and Beckman [1980] have suggested that in the above equation, the effect of free convection and radiation are included. Due to this reason, Wantmuff et al. [1977], have given a modified relation for convective heat transfer due to wind velocity only and is reproduced below.

$$h_c = 2.8 + 3.0\ V \tag{2.17}$$

In case of low wind velocity, free convection conditions dominate the heat flow scenario.

iii) Thermal Radiation: All substances emit thermal radiation by virtue of their temperature. Thermal radiation is an electromagnetic wave not requiring any medium to propagate. A part of the incident energy of a body is reflected and a part is absorbed. Balance of the energy is transmitted through it. Because of the conservation of energy, their sum equals to the incident radiation, i.e.

$$\rho' + \alpha' + \gamma = 1 \tag{2.18}$$

where ρ', α' and γ respectively are the reflectivity, absorptivity and transmissivity of the intercepting body. The ratio of the energy reflected to the incident energy is called reflectivity. The ratio of energy absorbed to the incident energy to us is called absorptivity. The ratio of energy transmitted to the incident is referred to as transmissivity.

For an opaque surface the value T - ϕ, therefore $\rho' + \alpha' = 1$. If for a surface $\rho' = \gamma = 0$ then $\alpha' = 1$, i.e., the surface absorbs the whole of the energy incident on it. Such a surface is called a black surface. Table 2.6 gives the emissivity and absorptivity of common building surfaces. The absorptivity is equal to the emissivity provided it is measured at the same temperature as the radiating source.

Table 2.6 Emmisivity and Refllectivity of Surfaces (Threlkald, [1970])

Surface	Emissivity		Reflectivity solar radiation
	Low Temp.	Solar Radiation	
Aluminium	0.05	0.20	0.80
Asbestos Cement	0.95	0.60	0.40
Brick	0.90	0.60	0.40
Concrete	0.90	0.65	0.35
Marble (White)	0.95	0.45	0.55
Paint (White)	0.90	0.30	0.70
Paint (Black)	0.90	0.90	0.10

Thus, in addition to emitting radiation, a body also has the capacity for absorbing all or part of the radiation coming from the surroundings towards it. Therefore, the estimation of heat exchange by radiation between surfaces at different temperature is very important in all heat transfer problems. Various laws such as Kirchof's law, Plank's law, Wein's law and Stefan-Boltzmann law govern thermal radiation. For estimating the heat transmission in buildings, the following two aspects about thermal radiation are required to be known:

a) Thermal radiation emitted by a body of surface area and at a temperature of T_K is equal to $\sigma\varepsilon T^4$, where s is the emissivity of the surface of the body and is the Stefan-Boltzmann constant whose value is equal to 5.6697×10^{-8} W/m^2K^4.

b) Radiation exchange between two surfaces, maintained at absolute temperature T_1 and T_2 and having emissivity ε_1 and ε_2 respectively, can be estimated from the geometries of the two surfaces.

In case of buildings, external walls and roof are always exposed to the atmosphere. Therefore, the radiation exchange between the exposed parts of the building and atmosphere is important. This is given by:

$$q = A\varepsilon\sigma\left(T^4 - T_{sky}^4\right) \qquad (2.19)$$

where ε is the emissivity of building exposed, T and T_{sky} are surface and the sky temperatures respectively.

2.5.2 EVALUATION OF NATURAL COOLING TECHNIQUES THROUGH MODIFIED ADDMITANCE PROCEDURE

A modified admittance procedure technique was developed by Sodha et al (1985), in which the matrix size is kept only (2 x 2) irrespective of the number of layer of the building components and therefore the boundary conditions making it simpler to deal with the resulting mathematical expressions. The basis of mathematical model used in the modified admittance procedure is to set up exact thermal heat balance across various building components and within various zones in which the building is divided at discrete time steps.

The energy balance equation is a indicator of the relationship between the various thermal forces at play within a building; the heat generated by building occupancy, the heat of the sun entering the building, and the transfer of energy across the building enclosure due to the difference in temperature between building and environment. As a measure of the dynamic interplay of several variables, the energy balance equation is a powerful conceptual tool used to evaluate the energy flows between a given building and its surroundings. The average part of temperature can be written by simply equating the average heat gain to average heat losses through the various components of a room. The various components are explained as below:

2.5.2.1 Heat Transfer through Building Elements

Heat flow in and out of an enclosed space (apart from solar radiation) takes place along two main paths i.e. Conduction through the building envelope and the ventilation air exchange. The internal heat gain is through various building components such as walls, roof, doors, openings, floor and also through the heat radiated by the number of person present and mechanical/ electronic equipments. Since the heat gained by floor, and the heat radiated by the people and equipments is negligible, they have not been considered for the study. The heat transfer from each individual building component is shown in Figure 2.6.

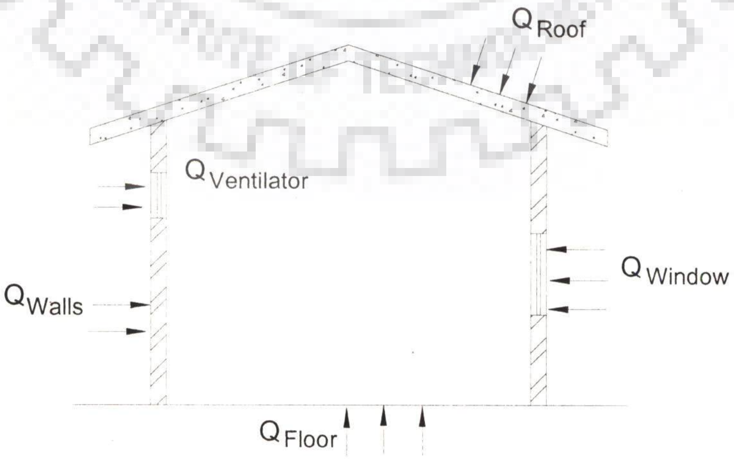


Figure 2.6 Various heat gains in a building

Rate of heat transmission through elements are:

a) Heat gain through Opaque Elements: Roof and Walls

The average value of the rate of heat transferred through an opaque building element can be written as

$$Q_{opaq} = A_{opaq}\, U_{opaq}\, (T_{so} - T_{Ro})$$

where,

T_{so} = Average Sol-air Temperature or effective temperature of the opaque surface (°C),

T_{Ro} = Average Room Temperature (°C),

U_{opaq} = Overall Conductivity of Opaque surface ($W/m^2\,{}^oC$), and

A_{opaq} = Surface Area of opaque component (m^2).

b) Heat Gain through Windows: The total heat gained through windows admits solar heat through direct penetration and through combined effect of conduction, convection and radiation. The total heat gain through window can be written as:

$$Q_{win} = A_g\, U_g\, (T_{ao} - T_{Ro}) + gI_{win}\, A_g \qquad (2.20)$$

where,

A_g = Area of glazing (m^2),

U_g = Overall heat transmission coefficient of the window (W/m^2K),

g = Solar gain factor,

I_{win} = Average sol-air intensity incidents on windows (W/m^2),

T_{ao} = Average ambient temperature (°C), and

T_{Ro} = Average room temperature (°C).

c) Heat Gain through Ventilation

The ventilation heat gain are given by the expression

$$Q' = m' C_a (T_{ao} - T_{Ro}) \tag{2.21}$$

where,

m' = volumetric flow rate of air (m^3/sec), and

C_a = specific heat capacity of air (J/kgK).

These are, however, expressed in terms of the air changes per hour, N and can be written as

$$Q_v = 0.33\, NV(T_{ao} - T_{Ro})$$

where,

N = number of recommended air changes, and

V = volume of the inside space.

2.5.2.2 Heat gained in Non-conditioned Building

In non-conditioned building the heat gain/losses to the floor is negligible. These are calculated only for the fluctuations of the room air temperatures over its average value. This is because it is assumed that the ground is at a steady state temperature with no hourly variations in the temperatures.

2.5.2.2.1 Average Room Temperature (T_{Ra})

The average part of the inside air temperature can be calculated by simply equating the total heat loss to the total heat gain by the room air thereby giving the expression.

$$\sum_{i=4walls+Roof} A_{iw}U_{iw}\left(T_{soi}-T_{m}\right)+\sum_{g\,\mathrm{Im}} A_{ig}+\left(\sum U_{ig}A_{ig}\right)\left(T_{ao}-T_{Ro}\right)+0.33NV\left(T_{ao}-T_{Ro}\right)=0$$

….(2.22)

where, A_{iw} is opaque wall area i.e., $(A_{iw}-A_{ig})$

From Equation (2.22) T_{Ro} can be expressed as:

$$T_{Ro}=\frac{\sum\limits_{i=1}\left(A_{iw}-A_{ig}\right)T_{in}U_{w}+\left(\sum\limits_{i=1}^{4}A_{ig}U_{in}+0.33Nv\right)T_{in}+\sum\limits_{i=1}^{4}gI_{in}A_{ig}+A_{R}U_{R}T_{SOR}}{\sum\limits_{i=1}^{4}\left(A_{ig}U_{in}+0.33Nv+\sum\limits_{i=1}^{4}\left(A_{iw}-A_{ig}\right)U_{w}+A_{R}U_{R}\right)}$$

……(2.23)

where,

T_{Sa}, T_{Na}, T_{Ea}, T_{Wa}, T_{SOR} are the average part of sol-air temperature of South, North, East and West walls roof respectively,

A_{Sw}, A_{Nw}, A_{Ew}, A_{W}, A_{R} are the area of the South, North, East and West walls roof respectively,

T_{ao} = average part of ambient temperature, and

I_{no} = the average part of solar radiation incident on window.

2.5.2.2.2 Time Dependent Room Temperature (T_{Rn})

The fluctuation over the mean of the sol-air temperature and the rate of heat transfer between the sol-air and exposed surface of the building component with multilayered construction are found to be given by following matrix equation (Sodha al 1985).

$$\begin{bmatrix} T_{sn} \\ q_{sn} \end{bmatrix}=\begin{bmatrix} E_{n} & F_{n} \\ G_{n} & H_{n} \end{bmatrix}\begin{bmatrix} T_{Rn} \\ q_{Rn} \end{bmatrix}$$

……(2.24)

where,

E_n, F_n, G_n, H_n are calculated from:

$$\begin{bmatrix} E_n & F_n \\ G_n & H_n \end{bmatrix} = \begin{bmatrix} 1 & 1/h_0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} A_{n1} & B_{n1} \\ D_{n1} & A_{n1} \end{bmatrix} \cdots \begin{bmatrix} A_{nk} & B_{nk} \\ D_{nk} & A_{nk} \end{bmatrix} \begin{bmatrix} 1 & 1/h_1 \\ 0 & 1 \end{bmatrix}$$

where, n corresponds to the nth harmonic and k is the number of kth of building component. A_n, B_n and D_n are given by the following expressions:

$$A_{kn} = \cosh\,(1+i)\varphi_{kn} \qquad \varphi_{kn} = \sqrt{\frac{n\varpi L_k^2}{2D_k}}$$

$$B_{kn} = \frac{R_k}{(1+i)\varphi_{kn}} \sinh(1+i)\varphi_{kn} \qquad D_{kn} = \frac{(1+i)\varphi_{kn}}{R_k} \sinh(1+i)\varphi_{kn}$$

$$R_k = \frac{L_k}{k_k} \qquad D_k = \frac{k_k}{\rho_k C_k}$$

where,

L_k = thickness of the nth layer (m),

C_k = specific hat of the kth layer $\left(\frac{J}{kgK}\right)$, and

ρ_k = dnsity of the kth layer (kg/m^3)

T_{sn} and q_{sn} refer to the nth harmonic of the sol-air temperature and the heat flux on the exposed surface of the building component while T_m and q_m refer to the respective quantities of the temperature and heat flux on the inner surface of the building component. h_o and h_i are the two heat transfer coefficient on the outer and inner side of the building component respectively.

The values of A_{n}'s, B_{n}'s, and D_{n}'s and hence the matrix terms E_n, F_n, G_n, H_n, are calculated for each of the room component. The thermophysical properties of the building materials used in these calculations are given in the Table 2.7.

Table 2.7 Thermo Physical Properties of the building materials

S. No.	**Materials**	**k (w/mK)**	**c (J/kgK)**	**ρ (kg/m^2)**
1.	Bricks	0.81	880	1820
2.	Cement Plaster	0.72	840	1760
3.	R.C.C.	1.58	800	2280
4.	Mud phuska	0.52	880	1622
5.	Roof tiles	0.82	880	1820
6.	Cavity (air)	0.14	3600	0.34
7.	Insulation	0.039	840	50
8.	Plain Cement concrete	1.4	840	2100
9.	Sand	0.35	800	1450
10.	Soil	1.210	840	1958

Assuming o and j to the outside and inside surface respectively, q_j will represent the amount of heat flux entering to the room through the building component, Q_j can be expressed as:

$$Q_j = \left[\frac{T_{Ro} - E_n T_{Rn}}{F_n}\right] \times A_j \qquad (2.25)$$

where,

A_j = surface area of the building element.

For the ground, h_o is replaced by the equivalent conductivity. Since the fluctuations in ground temperature are negligible, we gets

$$\begin{bmatrix} 0 \\ q_{sn} \end{bmatrix} = \begin{bmatrix} E_{Gn} & F_{an} \\ G_{Gn} & H_{Gn} \end{bmatrix} \begin{bmatrix} T_{Rn} \\ q_{Rn} \end{bmatrix} \tag{2.26}$$

$$\begin{bmatrix} E_{Gn} & F_{Gn} \\ G_{Gn} & H_{Gn} \end{bmatrix} = \begin{bmatrix} 1 & 1/h_{if} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} A_{1n} & B_{1n} \\ D_{1n} & A_{1n} \end{bmatrix} \cdots \begin{bmatrix} A_{kn} & B_{kn} \\ D_{kn} & A_{kn} \end{bmatrix} \begin{bmatrix} 1 & 1/k_G\beta_{Gn} \\ 0 & 1 \end{bmatrix}$$

where,

K_G = conductivity of the ground.

$$\beta_{Gn} = (1+i)\sqrt{\frac{n\omega\rho c}{2k_G}}$$

where,

h_{if} = heat transfer coefficient between room air and floor, and

T_R = room air temperature.

From Eq.(2.26) the rate of heat transmission from the floor is given by

$$q_{Ha} = \frac{H_{Gn}}{F_{Gn}} T_{Ra} \exp(in\,wt) \tag{2.27}$$

The fluctuations over the average value of the room air temperature can be obtained by the heat balance equation, which can be expressed by:

$$M_R C_R \frac{dT_R}{dt} = \sum_{N,E,W,S} q_i + \sum_{roof} q_i + floor + \sum g_n I_n A_{un} - 0.33NV(T_R - T_a) \quad \ldots(2.28)$$

The fluctuations over the average value of the room air temperature can be obtained by Fourier series. From Eq. (2.28) one gets T_{Rn} can be expressed as::

$$T_R(t) = T_{\mathrm{Re}} + \sum_{n=1}^{\infty} T_{Rn} e^{in\,\omega t} \tag{2.29}$$

where,

T_{Ro} = the average part of the room temperature, and

T_{Rn} = the time dependent part of the room temperature

Since $\dfrac{dT_{Ra}}{dt} = 0$, T_{Rn} can be expressed as:

$$T_{Rn} = \frac{\frac{1}{F_n}\sum_{i=1}^{4} T_{in}\left(A_{iw} - A_{ig}\right) + \frac{T_{Hn}A_R}{F_{Rn}} + \sum_{i=1}^{4} gI_{in}A_{ig} + C_vT_{an}}{\frac{E_n}{F_n}\sum_{i=1}^{4} T_{in}\left(A_{iw} - A_{ig}\right) + \frac{E_{Rn}}{F_{Rn}}A_R + \frac{H_{Gn}}{F_{Gn}}A_F + \sum_{i=1}^{4} U_{ig}A_{ig} + C_v + M_RC_R in\ \omega t} \quad (2.30)$$

where,

$C_v = 0.33$ NV,

M_R = Mass of the room air,

C_R = Specific heat of the room air,

F_n, E_n, F_{Rn}, E_{Rn}, F_{Gn}, E_{Gn} are coefficient of wall, roof and ground,

A_R = area of the roof, and

A_F = area of the floor.

2.5.2.3 Balancing of thermal load in Conditioned Building

For an air conditioned building the room temperature is constant. The total cooling load can be written as:

2.5.2.3.1 Average Heat Gain

The average heat gain of building components in a conditioned building can be calculated as:

$$Q_o = (\sum_{i=1}^{4} U_w \times (A_{iw} - A_{ig}) + A_RU_R)(T_{Ro} - T_{ao)} + (\sum_{i=1}^{4} A_{ig}U_{ig} + 0.33NV)(T_{Ro} - T_{ao}) + \sum_{i=1}^{4} gI_{in}A_{ig}$$

………(2.31)

2.5.2.3.2 Time Dependent Heat Gain

$$Q_n = \sum_{i=1}^{4} \left(\frac{T_{Ro}}{F_n} \right)A_{iw} + \left(\frac{T_{Ro}}{F_{Rn}} \right)A_R \quad (2.32)$$

By substituting the average part and time dependent part of above Equations (2.31) and (2.32), the total heat gain in a room is calculated as follows:

$$Q_T = Q_o + \sum_{n=1}^{\infty} Q_n e^{in\omega t} \tag{2.33}$$

Based on the above mathematical formulation, simulation with various cooling techniques has been done.

2.6 SOLAR PASSIVE ARCHITECTURE

Passive solar design uses the sun's energy for the heating and cooling of living spaces. Integration of heating and cooling devices into the building is referred to as passive concepts. The building design takes advantage of the basic natural processes associated with radiation, conduction, and natural convection that are created in building materials by exposure to the sun. Energy responsive design encompasses the principle of passive solar design. The use of solar passive features in earlier settlements and the modern advancement made in the field of solar passive architecture has been summarized as follows:

2.6.1 SOLAR PASSIVE ARCHITECTURE IN EARLIER SETTLEMENTS

Deeply rooted in environmentally responsive building techniques, many cultures throughout the world have used passive features for centuries in traditional structures. Solar Architecture is not a new phenomenon but has been used as far as 2500 years ago by all early civilizations. The concept of using orientation and architecture to accept warmth from the sun in winter while denying entrance to excessive sunshine in summer was prevalent in ancient civilization.

The use of solar radiation for heating and cooling of buildings can be traced to the Greek Period. The Greeks appreciated the importance of natural systems for producing comfortable indoor conditions in the buildings. They began orienting their buildings to best capture the sun's rays. The streets of Olynthus, for example, ran east to west to enable the houses to capture the sun. Their buildings had open south-facing porticoes, which permitted winter sunshine into the main living rooms, but provided shade during the hottest parts of summer when the sun was directly overhead. After the Greeks, the Romans advanced the technology further by using clear glass for windows. The Romans also constructed entire villages underground to take advantage of the cool earth. These underground dwellings also included central atriums and roof ponds for solar heating and cooling. The Roman baths of Caracalla had large windows that transmitted heat and daylight deep into the interior spaces.

The Pueblo Americans of New Mexico purposely chose building sites that welcomed the winter sun, but rejected the summer sun. Montezuma's Castle and the Indian Cliff dwellings are classical examples of natural solar-heated buildings. Montezuma's Castle was recessed within a south-facing cliff. The overhanging ledge of the cliff above acted as an awning and provided summertime shade.

Around 1500 B.C. the turfs and earth were extensively used as insulators of migratory hunters in Europe. Their pit-homes, round in shape with a wall of turfs above, the frame work of wood, led to the construction of earth lodges in Europe, North America and Asia. More advanced traditional designs are found in archaeological excavations at Harappa and Mohenjodaro, Nalanda and other places in India. The Indus valley civilization showed remarkable understanding of the environmental conditions and their architecture evolved as a response to the local climatic conditions. The rooms were arranged around courtyards, which served the purpose of natural ventilation and also provided lighting in the absence of too many windows. At the same time windows were small to prevent the entry of radiation. These buildings were constructed with massive mud brick walls, which served as heat stores in addition to providing insulation. Ancient Iranians exploited the passive concept of solar and wind-energy for circulation of cool-air through the buildings. The clustering of dwelling units, thick walls, proper orientation, plantation and earth-berming in basements are common features in Iranian architecture.

2.6.2 MODERN DEVELOPMENTS IN SOLAR PASSIVE ARCHITECTURE

As an endeavor towards energy responsive design, solar energy was introduced for space heating in the 1930s. Passive techniques began to enter residential architecture just before World War II. Among the pioneers were the Keck brothers of Chicago who were responsible for Solar Park, at Glenview and for a solar home project at Rockford in the early 1940s.

The work on fenestration carried out at ASHRAE Laboratory in Cleveland laid the foundation for procedures for calculating solar heat gains through windows. The technological advancement led to the extensive use of solar radiating materials like glass in revolutionizing architectural concepts.

Prof. E.L. Morse initiated the concepts of keeping the house warm by using the blackened surface on sunny side of the house. This concept was further advanced on an experimental basis by Hollingworth, [1947] in Massachuessets Institute of Technology

(MIT). Warm air heaters mounted on vertical south facing glazed wall, were used for room heating by Dr. Maria Telkes and Miss.E Raymond. A series of houses were built by using Morse's concept by Felix Trombe, [1972-74].

Solar houses were designed by using direct gain concepts (Simon, [1947], under sponsorship of Libby-Owen Ford Glass and Co). The concepts of roof-pond for heating and cooling of buildings were introduced by Hay and Yellot, [1969]. To analyze the dynamic behaviour of heat-flow in building structures, a test structure based on the sky therm principle was evaluated by Hay and Yellot, [1970].

The real awareness about solar as an alternative source of energy dawned after the 1973 oil embargo. Jain et al (1974) have studied the performance of different evaporative cooling techniques, to compare the relative performance of roof, roof pond, flowing water and wetted gunny bags. Extensive experimental and theoretical studies were conducted by Jain (1977) and Nayak et al (1984). Both the studies suggest that the spray system and the wetted gunny bag system are the most efficient indirect evaporative cooling systems.

Gupta (1981) analyzed that for achieving cooling by natural means one can adapt various methods; the most direct being the interception of solar radiation by overhangs, insulation, cavity walls etc. A quantitative study in terms of the heat flux for conditioned building and in terms of room temperatures for non-conditioned buildings has also been undertaken by Singh (1982). Bansal et al (1983) developed an analytical model and calculated the annual variation of the ground temperature as a function of depth for the climate of Delhi, India, considering the effect of the surface.

A study by Verma et al (1986) employed modified admittance procedure to study the comparative performance of different passive cooling concepts such as surface color, cavity, insulation and evaporative cooling on roof. Explicit expressions were obtained for time variation of the room temperature. The calculation performed with respect to the orientation also confirms the earlier belief that east-west orientation of the long side gives the best results.

Sodha et al (1986) and Hoffman (1976) calculated the heating/cooling load in buildings by using periodic solutions and the admittance procedures leading to explicit expressions easily amenable to computation. Mathews et al (1989) have included external color of the building as parameter in their computer program to evaluate performance of conditioned and a non-conditioned building. They have assumed that the entire exterior colors fall between absorption coefficient values of 0.3 to 0.7.

Several authors have worked in the area of natural ventilation. Mathur (1994) studied various ventilation systems by developing analytical models based on stack effect. The system provides ventilation during sunshine hours. Steady state analysis of the systems has been presented for solar induced ventilation during the day as well as a system with thermal storage for day/night ventilation. But the actual performance of the system for cooling of a building will depend on a total thermal analysis with different climatic conditions as input to the model.

Goel (1997) studied the effect of building shape from the point of view of reducing solar gain, and a study of hypocaust system coupled with heat source like a Solar air heater, exhaust gases of cook stove in the kitchen and exhaust gases of a diesel generation set. Sahu S. (2006) has evolved a relationship between external surface area and enclosed floor area of the building envelope, in the form of surface area to floor area ratio, which is directly proportional to solar heat gain to the building envelope and determines its thermal efficiency.

Few scientists and architects have also studied the traditional and vernacular architecture with reference to climatic responsiveness and energy conservation. Vinod Gupta analyzed the Natural Cooling Systems of Jaisalmer in 1984. Osama with the help of wind tunnel and computer simulation programs simulated the thermal and ventilation conditions in the Traditional Courtyard Houses in Saudi Arabia. In 1986, Hasan Fathy studied the natural energy and vernacular architecture of Egypt with reference to Hot Arid Climate. Arvind Krishnan and A.N. Young studied the thermal performance of traditional houses of North India in 1995. Vijaya Lakshmi Akella studied the Thermal Performance of Traditional and Modern Buildings in Kerala. G.N. Tiwari and Lugani N analyzed the thermal Performance of Passive Cooled Mahal of Benaras, India through energy balance equation in 1996.

Various Building Environment Assessments methods have been developed to identify and evaluate the environmental effects of building development or operation. The Green Star, an environmental rating system for buildings has been created to set a standard of measurement for green buildings, to promote integrated whole-building design and to identify building life-cycle impacts. Many countries have developed their own standards of energy efficiency for buildings. Some of them are BREEAM-UK, ECO-PRO (Germany), EcoProP & PIMWAQ (Finland), EQUER (France), ECO QUANTUM (Netherlands), BREEAM & BEPAC (Canada), LEED (USA), BEES-for building products(USA), BEAM (HongKong), Japan Green Building Guide (Japan), Korea Green Building Rating System (Korea), Taiwan Green Building Label (Taiwan).

Many computers operated building simulation programs have also been developed for doing the quantitative thermal performance analysis. These programs help in calculating the various variables of thermal comfort analysis such as air velocity, relative humidity, dayligting levels etc. Some of the building simulations are APACHE, ASEAM, BDA, DATAPLUS, DOE2, ECOTECT, ENERGY-10, ENERGY PLUS, HEED, NORMA, SOLAR 5, TRACE 700, TRNSYS etc. But these computer simulation programs for calculating the thermal load of a building have hindered their practical applicability due to non-incorporation of effects of all the parameters. Hence the thermal behavior of an existing building under different weather conditions can be quantitatively predicted by a mathematical model, which is being used for analysis and quantification of various natural cooling techniques.

2.7 PASSIVE COOLING CONCEPTS

Energy responsive design encompasses the principle of passive solar design. A 'passive' solar design involves the use of natural processes for heating or cooling to achieve balanced interior conditions. The flow of energy in passive design is by natural means: radiation, conduction, or convection. To prevent heat from entering into the building or to remove once it has entered is the underlying principle for accomplishing cooling in passive cooling concepts. This depends on two conditions: the availability of a heat sink which is at a lower temperature than indoor air, and the promotion of heat transfer towards the sink. Environmental heat sinks are:

- Outdoor air (heat transfer mainly by convection through openings)
- Water (heat transfer by evaporation inside and / or outside the building envelope)
- The (night) sky (heat transfer by long wave radiation through the roof and/or other surface adjacent to a building
- Ground (heat transfer by conduction through the building envelope)

Natural and passive techniques can reduce the peak cooling load in buildings, thus reducing the size of the air conditioning equipment and the period for which it is generally required. Cooling can be achieved by proper orientation of building, appropriate layout, proper shading devices, properly designed roof, overhangs, external surface finish and vertical shadings using best orientation with respect to sun and wind. These techniques minimize the incident solar radiation and cool the building effectively.

The important cooling concepts like shading are discussed in details:

2.7.1 SHADING

2.7.1.1 Shading of Buildings

Shading from the effects of direct solar radiation can be achieved in many ways:

- Shade provided by the effect of recesses in the external envelope of the building
- Shade provided by static or moveable external blinds or louvers
- Transient shading provided by the orientation of the building on one or more of its external walls
- Permanent or transient shading provided by the surrounding buildings, screens or vegetation.

The shading of buildings is achieved by clustering of buildings. Sodha et. al. [1986], have classified the building clusters into three groups:

a. Pavilion: Isolated single or in clusters surrounded by large open spaces.

b. Streets:Building blocks arranged in parallel rows separated by actual street in open spaces.

c. Courts:They are open spaces surrounded by buildings on all sides.

Shading is a function of street width, distance between the two buildings, obstruction angle and remains constant for different heights of building for the same street width as given below. It is also expressed as the percentage of over shadowing of one building by another (Figure 2.7).

$$\theta = Obstruction\ \ Angle$$

$$H_W = \frac{Building\ \ Height}{Street\ \ Width} = 2$$

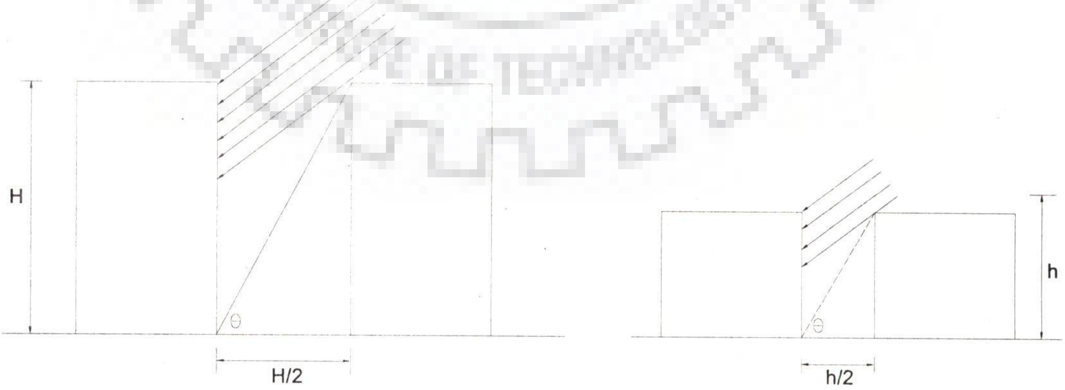


Figure 2.7 Shading of a building is a function of street width.

2.7.1.2 Shading by Trees and Vegetation

Proper Landscaping can be one of the important factors for energy conservation in buildings. Vegetation and trees in particular, very effectively shade and reduce heat gain. Trees can be used with advantage to shade roof, walls and windows. The solar radiation absorbed by the leaves is utilized in photosynthesis and evaporative heat losses.

2.7.1.3 Shading by Overhangs, Louvers

The shading devices can be classified as given below:

a. Movable opaque: Roller blind curtains, etc. reduce solar gains but impede air movement and cut the view.

b. Louvers: They are adjustable or can be fixed. To a certain extent impede air movement and provide shade to the building from the solar radiation.

c. Fixed: Overhangs of chajjas provide protection to the wall and opening against sun and rain. (Figure 2.8)

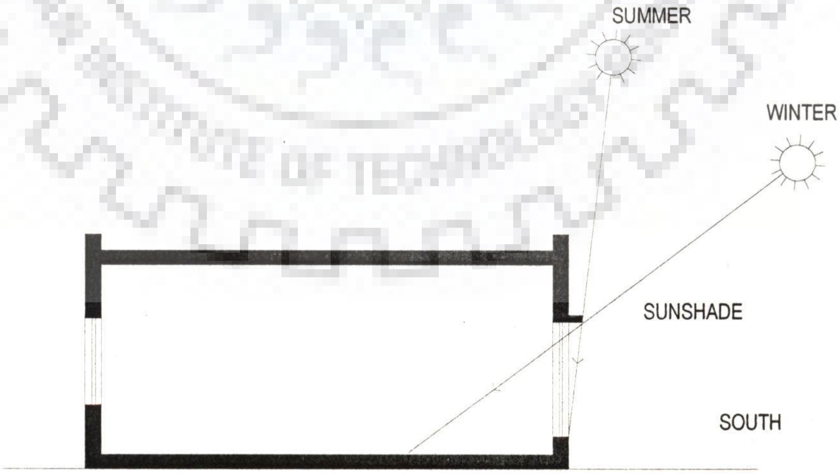


Figure 2.8 Sunshading by horizontal projection on south wall

In hot and dry climates, the movable blinds help to reduce the convective heat gain caused by the hot ambient air. In warm and humid climates where the airflow is desirable, they impede ventilation. In composite climates, the light colored/ reflective blinds block the solar radiation effectively. The movable blinds reduce the cooling load in air-conditioned buildings. Alternatively, reflective plastic films are permanently integrated with the glazing systems. The criteria of shading for various climatic zones is given in Table 2.8

Table 2.8 Criteria of Shading for Various Climatic Zones (Bansal et. al. 1988)

Climatic zones	Requirements
Hot and Dry	Complete year round shading
Warm and humid	Complete year round shading, but design should be made such that ventilation is not affected
Temperate	Complete year round shading but only during major sunshine hours
Cold and cloudy	No shading
Cold and sunny	Shading during summer months only
Composite	Shading during summer months only

2.7.1.4 Shading by Textured Surfaces

Surface shading can be provided as an integral part of the building element also. Highly textured walls have a portion of their surface in shade (Bansal et. al. [1993]) as shown in Figure 2.9. The increased surface area of such a wall results in an increased outer surface coefficient, which permits the sunlit surface to stay cooler as well as to cool down faster at night.

Figure 2.9 Shading due to surface texture.

2.7.1.5 Shading of Roofs and Walls

(a) Roofs and walls can be shaded by providing roof cover of concrete or sheet or plants or canvas or earthen pots etc. Shading provided by external means, particularly a roof, should not interfere with nighttime cooling. A cover over the roof, made of concrete or galvanized iron sheets, provides protection from direct radiation. Disadvantage of this system is that it does not permit escaping of heat to the sky at nighttime (Figure 2.10)

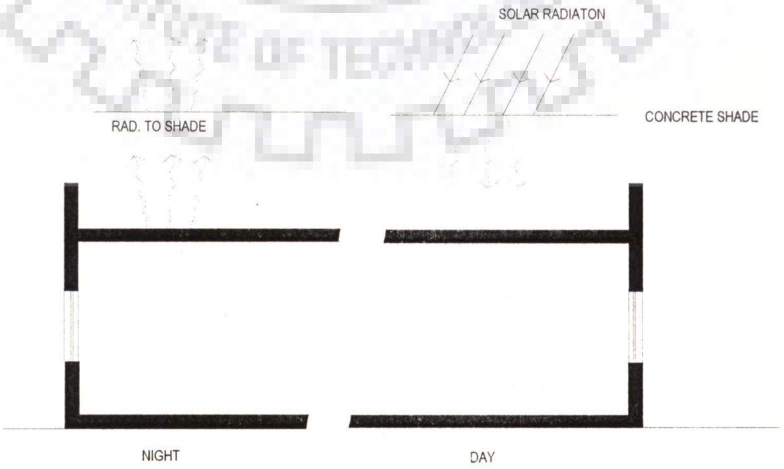


Figure 2.10 Roof Shading by solid cover

(b) A cover of deciduous plants and creepers is a better alternative. Evaporation from the leaf surfaces brings down the temperature of the roof to a level than that of the day time air temperature. At night, it is even lower than the sky temperature. (Figure 2.11)

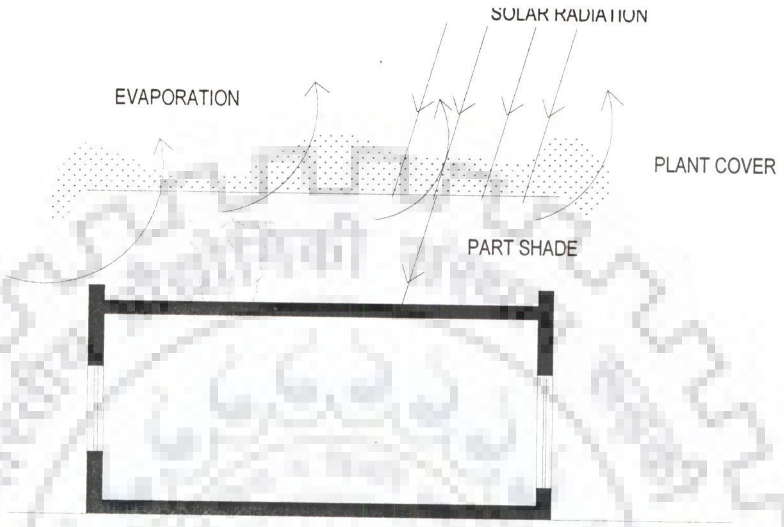


Figure 2.11 Roof shading by plant cover

(c) Covering of the entire surface area with the closely packed inverted earthen pots, as was being done in traditional buildings, increases the surface area for radiative emission. Insulating cover over the roof impedes heat flow into the building. However, it renders the roof unusable and maintenance difficult. (Figure 2.12)

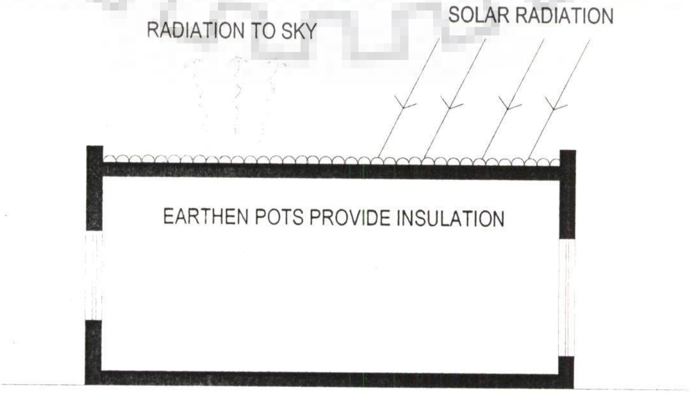


Figure 2.12 Roof Shading by Earthen Pots

(d) Another inexpensive and effective device is a removable canvas cover mounted close to the roof. During daytime it prevents entry of heat and its removal at night, radiative cooling. Painting of the canvas white minimizes the radiative and conductive heat gain (Figure 2.13).

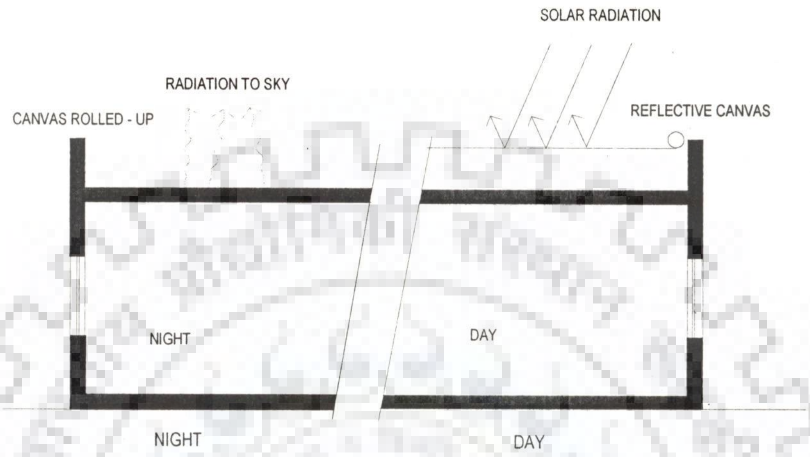


Figure 2.13 Removable Roof Shades

2.7.2 Insulation

Under steady-state conditions the heat flow through a building element is proportional to its thermal conductance (U-value). Strictly speaking the steady state condition is never obtained in practice as outside conditions do change continuously to a greater or lesser extent, but the concept can be useful in determining the thermal performance of air-conditioned buildings in temperate and humid climates. Under non-steady state conditions which are found in buildings without mechanical heating or cooling in all climates and even for air-conditioned buildings in hot-day climates, apart from its U-value, the thermal capacity of the element also determines the heat flow and the 'thermal diffusivity', 'time-lag' and 'decrement factor' become important. Time lag and decrement factor are both properties of the building element and not of the building materials. For building elements of massive construction the time lag is larger and the decrement factor smaller than for a lightweight element, even though both may have the same U-value.

In warm climates with a large diurnal range it is advantageous to use massive building elements. The effect of massive construction is to lower the maximum internal daytime temperature and to raise the minimum nighttime temperature while in lightweight construction; the internal temperatures follow closely the pattern of outdoor temperatures. Thermally heavyweight construction is part of the climate responsive strategy for both the cool and the warm period. Masonry construction provides heat storage within the building structure due to its thermal capacity, which helps contain indoor temperature fluctuations and acts as interim heat sink. The importance of heat storage increases with larger swings in outdoor temperature. Heat dissipation is then achieved overnight by exposing the building structure to the cooler night-time outdoor air. As no single material possesses all the desirable structural and thermal properties, combinations of materials with different properties are used to provide the necessary properties in an element. In such cases the time lag and decrement factor are also determined by the specific order in which the different layers are placed. Resistance insulation placed outside a brick wall gives substantially higher time-lag and lower decrement factor than if the same insulation is placed on the inner side of the wall. High time lag and low decrement factor are two important cooling concepts used in traditional buildings of Lucknow and they are discussed in detail in the subsequent chapter.

Air cavities can be used in place of resistance insulation. By ventilating these cavities to the outside at certain times of the day or during a particular season their resistance value can be decreased with benefit. Used in this way, air cavities can create a wall or roof element with variable resistance. A similar effect is achieved by applying movable insulation, although at much greater cost. Hay and Yellott have reported the use of movable insulation for natural cooling of a building.

2.7.3 Courtyard Effect

Courtyards and patio houses are quite common in areas with hot or maritime climates. In both cases, the building encloses fully or partly an open space – enclosed or attached, semi-enclosed open space. Such spaces are commonly referred to as microclimate modifiers. They have better climatic conditions than the surrounding open areas, and have a positive effect on the microclimate of the enclosing building volume. In hot and arid regions, the courtyard stores the cool night air until the early hours of the following day. Due to incident solar radiation in the courtyard, the air becomes warm and rises up. Cool air flowing from the ground level through the louvered openings, thus, producing the airflow replaces it (Figure 2.14).

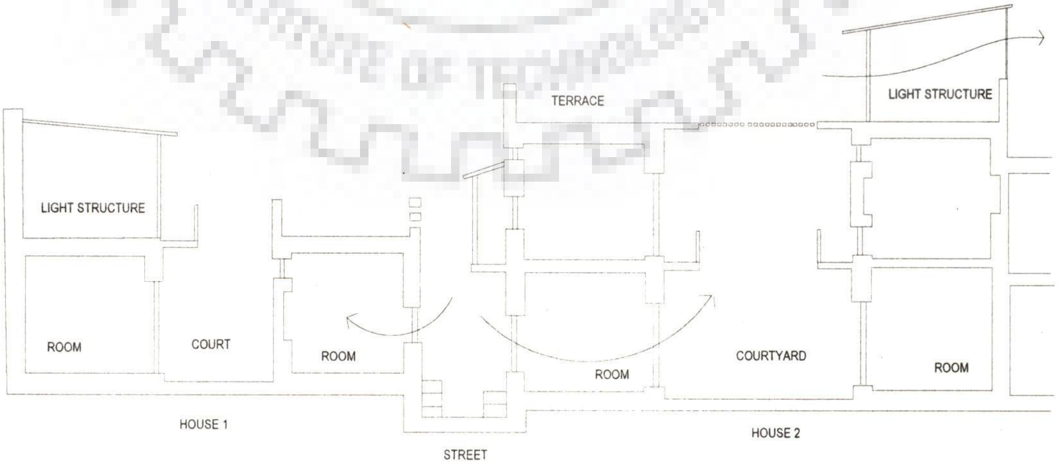


Figure 2.14 Thermal effect airflow due to courtyard.

During the night, the courtyard effect is reversed. The air temperature falls rapidly as the courtyard begins to radiate rapidly to the clear night sky. When the night sky temperature is lower than ambient temperature further cooling takes place. Cool night air begins to descend into the courtyard, completing the cycle. If the roof surface is sloped towards the internal courtyard, the cooled air sinks into the courtyard and enters the living space through the low level openings (Figure 2.15). To make it work efficiently, a parapet wall is raised around the roof to prevent air mixing. The courtyards are designed for maximum solar radiation to produce a draft through the interiors.

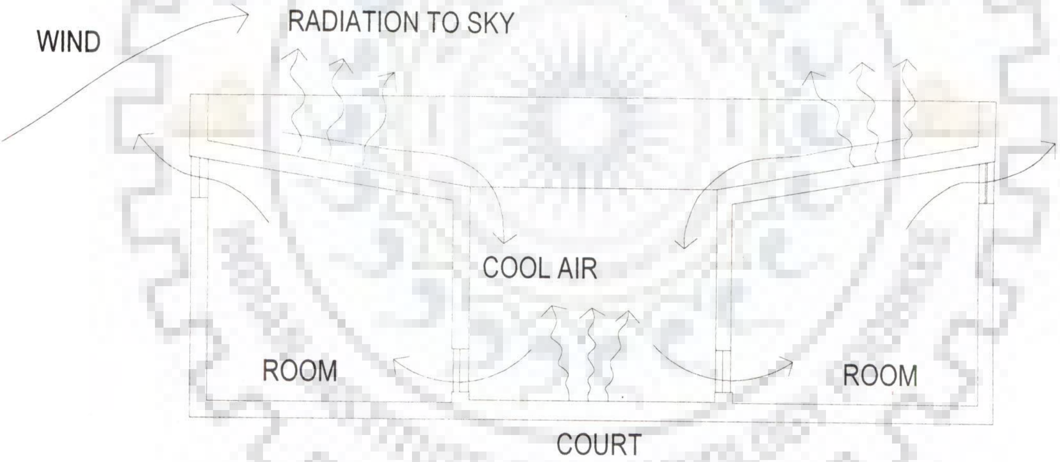


Figure 2.15 Courtyards permit cool air to flow into the building at night

The airflow in the courtyard, can be maintained by dual courtyard concept where one courtyard is kept cool by shady tree and vegetation and the other courtyard is exposed to sun. Smaller courtyards work efficiently in hot and dry climates where daytime ventilation is undesirable.

2.7.4 Air Vents

Air vents are employed in the areas where dusty winds make it impossible for wind tower to work. Suited for single units, they work well in hot and dry and warm and humid climates. A hole in the apex of the domed or cylindrical roof with the protective cap over the vent directs the wind across it. Increase in the velocity of the air flowing over the curved surface, results in lowering of the pressure at the apex of the roof. To cool the air, which moves up to the vent by the principle of evaporation, the air vents are usually placed over the living room (Figure 2.16)

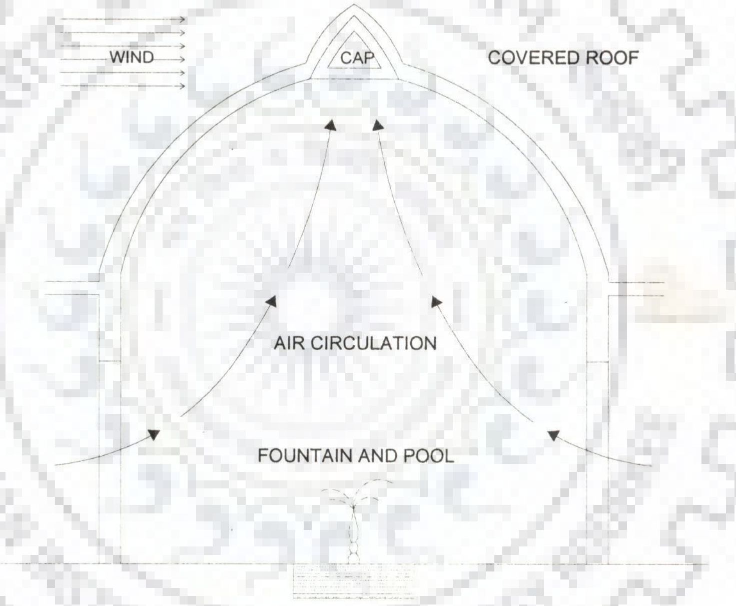


Figure 2.16 Design of an Air Vent

2.7.5 Wind Tower

Wind Towers (masonry structures) are designed to harness the wind, cool the air and circulate it through the buildings. They resemble a chimney, with one end in the basement and the other in the roof. The top part is divided into several vertical air spaces ending in the openings in the sides of the tower.

During the daytime, the hot ambient air enters the tower through the openings in the tower. The air gets cooled when it contact with the cool tower and thus becomes heavier and sinks down. When an inlet is provided to the rooms with an outlet on the other side, there is a draft of cool air. After a day of heat exchange, the wind tower becomes warm in the evening (Figure 2.17a)

DAY (a)

NIGHT (b)

Figure 2.17 Day Time and Night time Operation of the Wind Tower

During the night, the reverse happens. The cooler ambient air comes in contact with the bottom of the tower through the room. It gets heated up by warm surface of wind tower and begins to rise due to buoyancy, maintaining an air flow in reverse direction (Figure 2.17b)

The concept of wind tower works well in individual units and not in multi-storey apartments. In dense urban areas, wind towers have to be very high to harness the wind. The surface of wind tower accumulates dust making the heat transfer from the surface of the wind tower to the air slower. Its protection against driving rain is difficult.

2.7.6 Cooling by Evaporation

Evaporation of water takes place by conversion of sensible heat into latent heat. A large amount of heat is therefore removed through thus method. The process lowers the dry bulb temperature and increases the humidity content. This process is referred to as adiabatic cooling. There are many ways to achieve evaporative cooling. Since evaporation occurs only at liquid air interface, it is best to create as much surface area as possible between water and the air.

Outdoor Air Cooling: It is estimated that the temperature under the shade of a tree, is $3^{o}C$ to $4^{o}C$ lower than that of the ambient air temperature.

Vegetation allows free flow of air into the building causing the cooling of ambient air.

Indoor Air Cooling: This can be achieved either by increasing the humidity level or by keeping it at normal level depending upon the choice of the operating system.

In direct evaporative cooling (passive) systems, the room air is in direct contact with the water surface. The evaporation of water into the air increases humidity. This process is referred to as direct evaporative cooling system. In such cases, it is possible to cool a small building by placing wetting pads in the windows or porches, facing the wind direction. Water bodies created by fountains, pools or flowing channels along with the natural wind, provide cooling for living spaces.

The water in a form of a film (intermittent spray of water) or flowing water over the roof, is another method of indirect evaporative cooling. The water draws heat from the roof surface, leaves a cooler ceiling surface below, which acts as a radiative cooling panel for the space. The indoor temperature gets lowered without elevating the humidity level. The use of water retentive materials such as gunny bags, help to reduce the frequency of intermittent water spraying. Experimental and theoretical studies to compare the relative performance of roof spray-pond, flowing water, and wetter gunny bags, were conducted by Jain and Nayak. These studies revealed that the spray system is most efficient for indirect evaporative cooling. Additionally, the spray system causes the air above to get cooled which in turn becomes heavier and drifts into the building to add to the thermal comfort. The indirect evaporative cooling by roof pond becomes more effective if the roof is covered with plants and movable insulation. Leakage of water into the roofs can be best avoided by using bituminized Hessian cloth, provision of uniform and steep gradients towards spouts and proper sealing of joints in brick tiles over mud phuska.

2.7.7 The Earth as a Cooling Surface

The earth mass under and around the building serves to act as a source of natural cooling of building. It is possible to lower the temperature of the building below the natural temperatures at a given location by the process given below.

i. Earth Air Tunnel: The use of earth as a heat sink or a source for cooling/heating air in buried pipes or underground tunnels has been a testimony to Islamic and Persian architecture. The temperature of the ground, a few metres below is almost constant throughtout the year. Hence the air passing through a tunnel or a buried pipe at a depth of few meters gets cooled in summers and heated in winters (shown in Figure 2.18). Parameters like surface area of pipe, length and depth of the tunnel below ground, dampness of the earth, humidity of inlet air velocity, affect the exchange of heat between air and the surrounding soil. The earth tunnel system in the hospital complex in Mathura near Delhi has been studied by Sodha et. al. [1987].

ii. Earth Sheltered Buildings or Earth Bermed Structure: In an earth sheltered building the reduced infiltration of outside air and the additional thermal resistance of the surrounding earth considerably reduces the average thermal load. Further the addition of earth mass of the building reduces the fluctuations in the thermal load. Hence with reference to thermal comfort, an earth sheltered building presents a significant passive approach.

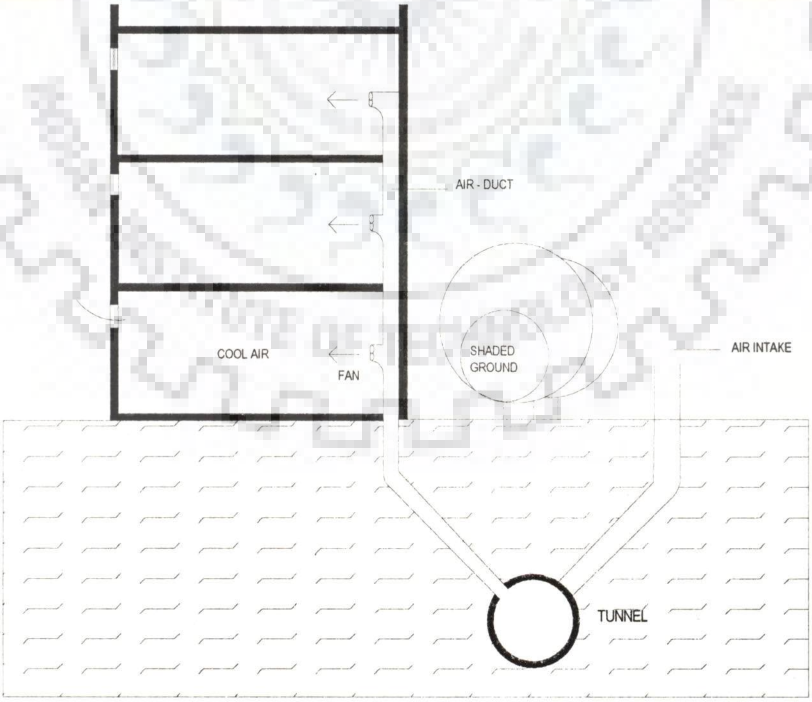


Figure 2.18 Earth Air Tunnel

2.8 CONCLUSIONS

In this chapter various background study related to energy conservation in buildings has been discussed. Significant literature related to few design elements that directly or indirectly affect thermal comfort conditions inside a building, and thereby energy consumption in a building, such as (i) Layout and surroundings of the buildings, which include Landform, Landscaping, Location of water bodies, Open Spaces and Built Form, Orientation (ii) Building characteristics such as Plan Form (i.e. shape and size of building), Building Form and Surface to Volume Ratio Fenestration i.e. location, shape, size and shading of openings provided for daylight and ventilation and thermo-physical properties of building elements have been studied.

The basic theory of heat transfer as well as evaluation of natural cooling techniques through Modified Admittance Procedure has been studied in detail. The literature related to solar passive architecture in earlier settlements, modern developments in solar passive architecture and various cooling techniques have also been studied in this chapter. An overview of the city of Lucknow, which forms the context of my study, is discussed in the next chapter

CHAPTER 3

LUCKNOW: THE RESEARCH CONTEXT

3.1 INTRODUCTION

Learning from the traditional wisdom of previous generations through the lessons of traditional buildings can be a powerful tool for improving the buildings of the future. The city of Lucknow has been selected for the case studies because India's major population lives in composite climate zone in which the city of Lucknow lies and hence the findings will be beneficial to a large population. Moreover, the city of Lucknow is one of the famous historical cities of India that has rich architectural heritage. This chapter gives an overall view of the city of Lucknow. The historical background of Lucknow, its architecture, climate and finally the traditional built form describing the settlement pattern, street layout, house form and its building construction, which form the context of this study, have been discussed in this chapter.

3.2 LUCKNOW: THE RESEARCH CONTEXT

Lucknow, the historical city of Nawabs and the present capital of Uttar Pradesh, the most populous state of India is situated in the plains of Northern India, on the banks of river Gomti (Figure 3.1). It lies near the tropic of cancer at 26.52°N Latitude and 80.56°E Longitude at an elevation of 111m from the Mean Sea Level. The city of Lucknow is a very important administrative and commercial centre, which lies at the junction of numerous roads and rail lines. The city is famous for its rich Nawabi culture and traditions and their richly carved buildings. The city has two discernible entities i.e. the older habitations in the central part, and the newer settlements all around it. The older areas of the city (south of the Gomti River) are characterised by high density and pre-colonial settlement structures. The older dense settlements and relatively newer areas built during colonial period make up the core of the city. The outer and peripheral have primarily been settled in the post-independence period (Figure 3.2)

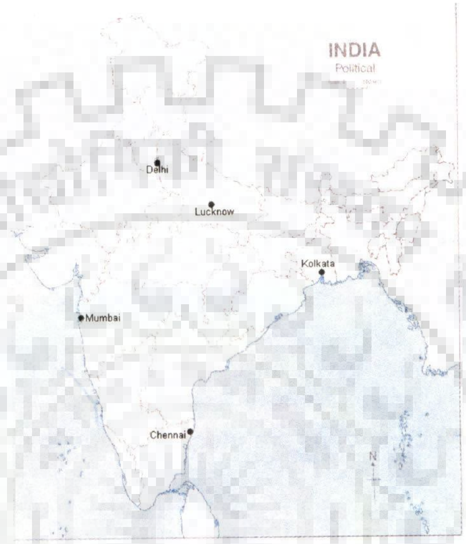


Figure 3.1 Map of India showing location of Lucknow

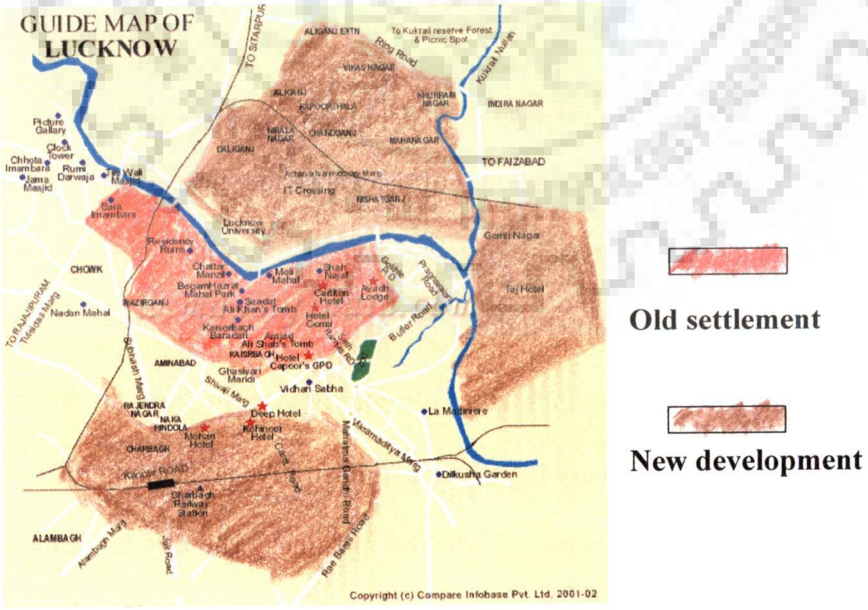


Figure 3.2 Map of Lucknow showing old settlement and new development

3.3 HISTORY AND EVOLUTION OF LUCKNOW

The birth of this historical city is said to date back to the Suryavanshi dynasty of Ayodhya in ancient times, and derives its name from Lakshman, brother of Lord Rama the hero of the Indian epic, Ramayana. Avadh (as it was originally called) remained under Mughal rule till Aurangzeb's reign (1658-1707), shortly after whose death the Nawabs were able to establish themselves in Avadh. In 1732, Muhammad Shah, one of the later kings of the Mughal dynasty, appointed Mohammad Amir Saadat Khan, a Persian adventurer of noble lineage, to the viceroyalty of the area known as Avadh, of which Lucknow was a part. Lucknow became the most important city in Avadh province in medieval times. The rapid growth of Lucknow began when the fourth Nawab, Asaf-ud-Daula (1775-98) transferred the capital of Avadh from Faizabad to Lucknow and set about gifting to the city some of its most splendid architectural marvels, a tradition that was sustained by his successors. It was during his reign that some of the city's most beautiful monuments were constructed. (Tandan Banmali, 2001)

After the Mughal Empire crumbled in the early part of the 18th century, the centre of the highly developed Indo-Mughal culture and arts shifted from Delhi to Lucknow where it reached the zenith of splendor, sophistication and refinement. It was an ancient seat of learning. It has been a city of gardens and impressive historical monuments. The city became known for its poetry and courtly diction, and transformed into an oasis of learning, music and poetry during the reign of Nawab Wajid Ali Shah, the last of the Nawabs of Avadh. In 1855 Lord Hardinge, the British Governor General resolved that Avadh should be annexed to the East India Company, and its throne and king be abolished. In 1856 Lucknow came under British control, which allowed the Nawabs to remain as figureheads, having no administrative control but drawing an annual stipend. The annexation fanned growing resentment amongst the people and became one of the factors contributing towards the Indian uprising of 1857. Lucknow became the battleground of intense fighting before the uprising was finally quelled.

After independence in 1947, the change in political system and fast industrialisation brought changes in the architecture of Lucknow. Traditional styles and beautiful carving lost its place in modern architecture in absence of traditional skilled craftsmen. As the capital of the state of Uttar Pradesh, Lucknow today is growing as a sprawling, industrialized city. The present city is growing along the highways which lead to Kanpur, Faizabad, Rai Bareilly and Sitapur resulting into the expansion of city, physically at a higher rate.

3.4 CLIMATE DATA OF LUCKNOW

Lucknow, the city under study, falls within the composite category, within which can be identified four main seasons, the summer, which is hot and fairly dry, the monsoon, which is less hot but humid, a period of moderate temperatures and humidities, and a slightly cold winter period. The cold or winter starts by late November and extends to about February. This is followed by a short spring till March. The hot season i.e. summer starts after spring and continues until the end of June. July to September is the Monsoon season. October and November constitute a transitional temperature period between the monsoon and winter with moderate temperatures.

January is the coldest month when the mean daily maximum temperature is about 21°C, with the mean minimum about 7°C. In the winter months the temperature goes down to freezing point. From about the middle of March, temperatures begin to rise rapidly. May and June are the hottest months. From April, the hot westerly winds below and the heat is extreme. In May and June the temperature may sometimes reaches 47°C. With the advance of the monsoons, the day temperature drops appreciably while the night temperature continues to be high. The weather is damp and between the spells of rain, the ambient conditions are uncomfortable. In October, the day temperature is as high as during the monsoon but the nights are cooler.

The air is dry during for the greater part of the year. However, during the monsoon months, the humidity is high. April and May are the driest months, humidity in the afternoon being less than 20%. The average annual rainfall is 41 mm. Winds are generally light during the post-monsoon and winter months and are a little stronger in the summer and monsoon months. April to June is the period with the highest incidence of thunderstorms and dust storms.

The climatic data of last twenty years published by the meteorological department is summarized below:

Air Temperature: The monthly mean maximum temperature during the hottest month (May) is 41.2°C and the monthly mean minimum temperature during the coldest month (Jan) of the year is 8.9°C. The diurnal range of temperature is from 15°C to 20°C.

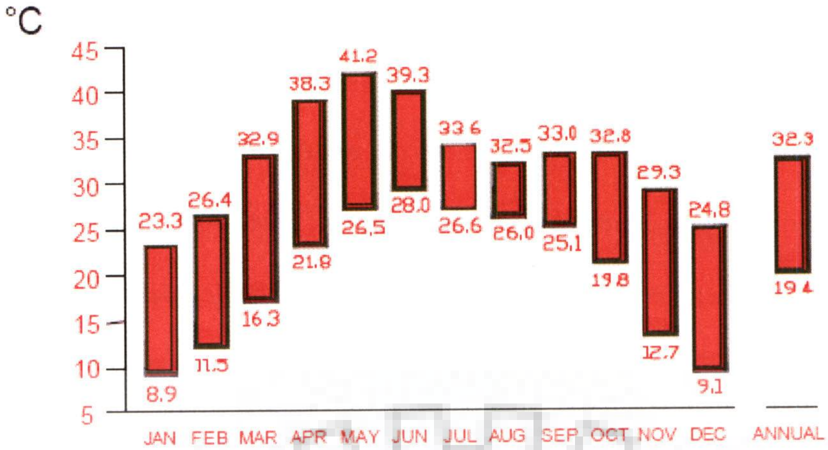


Figure 3.3 Air Temperature Data of Lucknow

(Source: Indian Meteorological Department, Lucknow Airport)

Relative Humidity: The relative humidity during summer can be less than 25% and during the most humid months the relative humidity is in the range of 78% to 82%, whereas the air temperature is in the range of 32.5°C to 34°C.

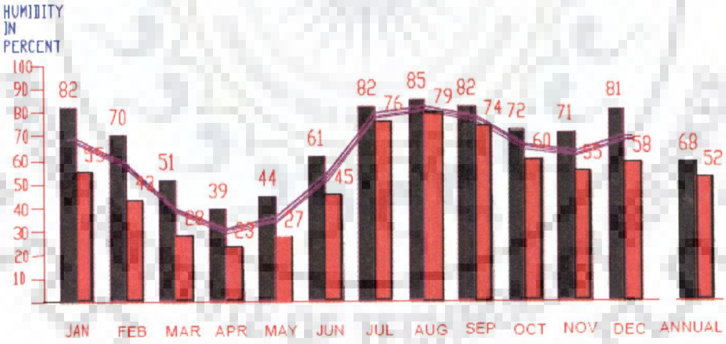


Figure 3.4 Relative Humidity Data of Lucknow

(Source: Indian Meteorological Department, Lucknow Airport)

Rainfall: The seasonal wind flow patterns coupled with topographic features determine the rainfall time and distribution. The rainfall starts with the arrival of the Monsoon in the middle of June. The regular rainy season continues up to the middle of September. During this period, it rains in average 12 to 13 days per month. The monthly rainfall is 290mm, 265mm, 190mm, during July August and September respectively. The total annual rainfall is 940 mm.

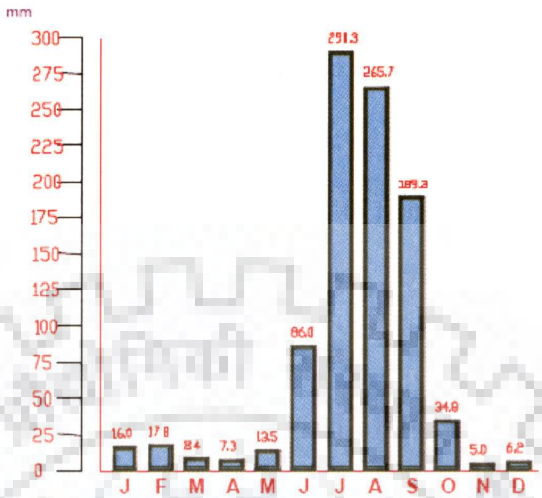


Figure 3.5 Rainfall Data of Lucknow

(Source: Indian Meteorological Department, Lucknow Airport)

Solar Radiation and Sunshine: The sky is mostly clear throughout the year. The average solar radiation on a horizontal surface in June is 20.2 MJ/m^2 day. Lucknow experiences 8 to 10 hours of sunshine for eight months from October to June and 5 to 6 hours during the remaining three months. The sky remains normally overcast during the rainy season.

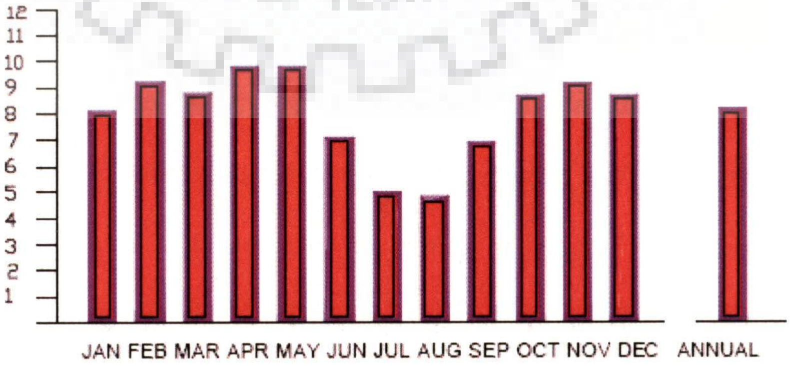


Figure 3.6 Sunshine Hours Chart of Lucknow

(Source: Indian Meteorological Department, Lucknow Airport)

Wind Speed: The wind speed is in the range of 3.4 to 5 km / hour from May to September. The predominant wind direction is east.

3.5 THE ARCHITECTURE OF LUCKNOW

The architecture of Lucknow reflects the prevalent culture, an amalgamation of both Mughal-Islamic and European elements and styles. Most of the monuments in Lucknow are from the 18th and 19th century. The buildings of Lucknow constructed between 1723 and 1847 can be divided into two parts: those buildings that predominantly show Mughal-Islamic characters and those built after Lucknow was colonised by the British. However what is common between all these buildings is that they fulfilled a demand for a 'new' architecture that was different to what had existed in Lucknow before the Nawabi rule.

For the Nawabs and the other new entrants to the aristocratic club, architecture was a physical manifestation of their newly acquired status. The new rulers of Lucknow wanted a style of architecture that not only symbolised their total dominance in Avadh, but also wanted to show that their distinction from the Mughals. A universal desire for an outward splendor, characteristic of the late Mughal period, was one of the reasons that resulted in the widespread use of brick and stucco, instead of stone, a material which had become obligatory in the best buildings of the Mughals in their heyday. The Nawabs of Lucknow not only built fine structures in traditional styles and experimented in European ones, but also created a novel hybrid style, which was a amalgamation of both Indian and European elements. The civic buildings, a novelty for Lucknow, used by the Indians like the colleges, hospitals, post offices, and courts were presented in this style. Buildings used solely by the British, like the churches, were made in appropriate 'European' style.

The buildings of Lucknow can be classified into two types:

(i) Secular and Civic Buildings: The secular buildings built by the Nawabs consisted of six types i.e. (i) Forts (ii) Palaces (Mahals, Kothis etc.) (iii) Houses (iv) Baradaris and Gardens (v) Gateways and (vi) Baolis, Tanks, Ghats etc. These six types contain some of the most magnificent Nawabi architecture, for in their palaces, houses, baradaris, gardens and gateways. Apart from these the British commissioned many civic buildings such as schools, colleges, hospitals, post offices, courts etc.

(ii) Religious Buildings: They were built for ritual and sacred purposes or came to be put to such uses, by the Nawabs and their officials and courtiers. Nawabi religious buildings predominantly represented a continuation of early Indian building traditions. The planning and the style of most of the religious edifices did not represent a serious break from the past. The traditional religious buildings of Nawabi architecture consisted of 5 main types i.e. Mosques, Imambaras, Karbalas, Mausolea, and Temples

3.5.1 EUROPEAN INFLUENCE ON THE ARCHITECTURE OF LUCKNOW

The European influence was seen in the field of town planning. Here the architectural influences were purely ‘European’. A prime example is Hazratganj built by Nawab Sadat Ali Khan. The street of Hazratganj was similar in essence to the Esplanade in Calcutta and Regent Street in London, the capital of the British Empire. This was followed by the construction of many new houses built in the 'European' villa style, (later called 'kothis') on both sides of Hazratganj. The kothis were freestanding, centrally organized structures with dominant facades. This style of architecture challenged the existing traditional courthouses, which were very introverted. Many of these kothis were built by Major General Claude Martin, a Frenchman. These buildings were probably the best example of European Influence in an Indian state. Only his extraordinary buildings remain as evidence of his independent spirit. The most important is Constantia, which is both a mausoleum of Claude Martin and now houses the famous La Martiniere College. Constantia has been a paradox for most historians and art critics for its hybrid and cross-cultural nature.

As the 19th century progressed, European motifs sometimes freely began to invade elevations, and were adopted in the interior decoration of shrine chambers of religious buildings. Even the plan forms and the profiles of domes of religious edifices also underwent radical alterations under the impact of European architecture.

3.5.2 ISLAMIC INFLUENCE ON THE ARCHITECTURE OF LUCKNOW

The earliest Nawabi buildings commissioned between 1722 and about 1765 employed the Islamic style. Many of the architectural monuments built during this time could be classified under what is known as Nawabi architecture, which is the last phase of Mughal Architecture. It should be noted that the Nawabs were primarily Muslims and, therefore, the buildings to be used by their family and those for worship portrayed all the basic principles of Islamic architecture. Walled gardens like Kaiserbagh, which are present in large numbers in Lucknow, are one type of structure that has its roots in Mughal architecture. However the other types of buildings such as the Imambaras, which are religious buildings, were an innovation.

Since the rulers belonging to the Nawabi dynasty were Shias from Iran, Imambaras, whish are essential and peculiar to the Shiite way of life, being places of mourning during Moharram, were built in large numbers, some monumental other small. The most imposing among them is the Asafi Imambara built by Nawab Asaf-ud-Daula in 1784 as a famine relief measure. Designed by Persian architect Kifayatullah, the building is 164 feet long and 52 feet wide. It is covered by a large honeycombed vaulted roof and has a labyrinth. Asafi Imambara is in the process of being declared as a world heritage building. The Nawabi religious buildings represented a continuation of earlier Indian building traditions and the planning and the style of most of the religious edifices have characteristics of the late Mughal period.

3.6 THE TRADITIONAL BUILT FORM OF LUCKNOW

Lucknow has its own traditions and culture, which was largely influenced by the religion and beliefs of the people. These factors have a great influence on the design of the houses people live in. The houses and residential edifices have a variety of nomenclatures in Hindustani, Urdu and Persian such as Kothi, Haveli, Manzil, Makan, among others. The traditional built form of Lucknow through its street patterns, thermal mass and mutual shading creates a comfortable urban environment, each house enhances the experience by way of thermal mass and courtyards.

3.6.1 SETTLEMENT PATTERN

In the absence of technological influence of electricity supply, mechanized transport and modern building construction techniques, the builders of the Medieval Indian town of Lucknow has done a remarkable job of creating an urban environment that is in tune with nature and provide for more than just the basic needs of the inhabitants. The city has two discernible entities viz.: the older habitations in the central part, and the newer settlements all around it. The older areas of the city (largely south of the Gomti River such as Kaiser Bagh, Chowk, Nakkhas etc.) are characterized by high density and pre-colonial settlement structures and ethos (Figure 3.7). The oldest dense settlements and relatively newer areas built during colonial period make up the core of the city. The older urban settlement was compact and mostly planned around courtyards with respect to the climate and the need for social interactions. The outer and peripheral have primarily been settled in the post - independence period.

Figure 3.7 Settlement Pattern of old Lucknow

3.6.2 STREET LAYOUT

The streets in the older settlements are narrow and winding. The major streets are oriented almost E-W and minor streets at right angles to these. Streets act as linkages, activity and interaction spaces. The height of the building compared with the width of the streets is large to create shaded environment for the pedestrians and social activities on the streets. A study of street section design in response to sun movement reveals a close relationship between street width, building height and projections to create a cool shaded environment in hot summers by mutual shading. The city when viewed from above gives the impression of cubical grains arranged in close proximity. The houses open on narrow streets through a hierarchy of spaces such as verandah, entrance lobby etc. that become the interface between the street and the house.

3.6.3 HOUSE FORM

Depending upon the socio- economic status of inhabitants there are two types of traditional residential buildings. The first type of traditional houses consists of kothis and palaces, which were commissioned by the Nawabs and their courtiers. These were examples of outstanding Nawabi domestic architecture. Their plan forms and their stylistic character were subjected to wide variations from one Nawabi authority to another. The second type of house belongs to the middle-income people. The house plan and design is characterized by a courtyard type house, sometimes with an underground level. A single or two-storey structure, this house type can be considered the typical house of Lucknow. It consists of a simple plan with a verandah and a courtyard surrounded by rooms on all sides.

The traditional houses of Lucknow were built with three main considerations i.e. privacy, the segregation between men and women and response to the hot climate. With compact organization, the house and the streets become very close to each other, so the most natural thing was to close the house to the exterior and open it to the interior thus making the courtyard an extremely important feature of the house. The idea of an inward looking house is also reinforced because of climatic reasons. The upper storey comprises one or two rooms with terraces, balconies and pavilions. They are used differently in summer and in winter. These traditional houses are well integrated with the urban fabric of Lucknow.

3.6.4 BUILDING CONSTRUCTION AND MATERIAL

The most common building material used in traditional houses of Lucknow is lakhauri bricks and lime. The thick masonry walls are constructed with lakhauri bricks and mortar of lime and surkhi. The thickness of masonry walls generally varies from 45cm to 90 cm (Figure 3.8). Two types of construction are used for roofs and floors. One method used is by laying closely spaced timber beams covered with reed or grass matting and a thick layer (30-45 cm) of lime concrete on top (Figure 3.9). The second type of roof construction comprises of vaulted ceiling of bricks on steel girders covered with thick lime concrete with brick ballasts. In both cases the roofs and floor are finished with lime and cement plaster.

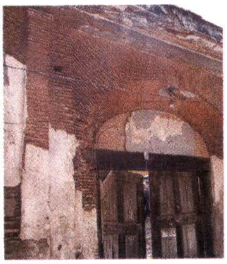


Figure 3.8 Thick Masonry of Lakhauri bricks

Figure 3.9 Heavy Timber roof

The walls are sometimes pointed or mostly finished with lime and stucco plaster. The elevation of a typical traditional house is treated with stucco on motifs and floral patterns made up of lime plaster (Figure3.10). The dressing of doors and windows is done with standard runs of mouldings made up of lime mortar.

Figure 3.10 Articulated Street facades of traditional houses

3.7 CONCLUSIONS

Lucknow, the historical city of Nawabs, which has a composite climate, had a very novel hybrid style of architecture. The architecture of Lucknow reflects an amalgamation of both Mughal- Islamic and European elements and styles. Study of the traditional built form of Lucknow reveals that the comfortable urban environment was created through the settlement pattern, dense clustering of buildings, narrow winding streets and mutual shading. Thermal comfort of traditional houses is further enhanced by the house form, sun control through orientation and structural projections, massive construction of roofs and walls, courtyards and air ducts for ventilation and construction material and systems.

Response to the hot climate along with privacy and segregation between men and women were the three main determinants of traditional built form of Lucknow.

Out of these traditional houses of Lucknow, three houses were selected for further detailed study, which are discussed in detail in Chapter 5. Various passive design features and techniques that have been employed in the traditional residential buildings of Lucknow have been identified, which is elaborated in the next chapter.

CHAPTER 4

PASSIVE COOLING CONCEPTS IN TRADITIONAL BUILT FORM OF LUCKNOW

4.1 INTRODUCTION

In the past, people built their houses in harmony with the environment as well as with optimally utilizing the locally available building materials. The traditional buildings of Lucknow were direct expression of adaptation to climate and constraints of resources. The use of natural and passive means in traditional houses was very effective in providing a thermally comfortable space, which was warm in winter and cool in summer. Since these cases embody a great deal of experience, wisdom and cleverness, the layout, orientation, thermal mass and basic design of traditional buildings are worth studying in detail for valuable clues and ideas. Hence by identifying the features used in the traditional buildings, the contemporary architectural form can be made more energy responsive.

The traditional residential buildings of Lucknow have inbuilt thermal comfort property and are based on climatic responsive integrated passive design approach. Various passive design features that have been employed in the traditional residential buildings in old settlement of Lucknow such as settlement pattern, orientation, vegetation, water body, verandah, courtyards, high ceilings, massive walls, heavy roofs, openings, jharokhas, skylight, overhangs and balconies, jaalis etc have been identified and explained in this chapter.

4.2 IDENTIFICATION OF NATURAL AND PASSIVE TECHNIQUES IN TRADITIONAL BUILT FORM OF LUCKNOW

The traditional buildings in Lucknow have employed some ingenious natural and passive techniques in order to maintain thermal comfort within the building. The indigenous architecture of Lucknow evolved through the entire spectrum from individual building to settlement pattern, responds through form, thermal mass, spatial hierarchy, activity pattern, material and construction. Various natural and passive features that have been used in the traditional residential buildings of Lucknow have been identified and explained in terms of its climatic implication, the conceptual understanding thereof and its effect on the building design. They are summarized as follows:

4.2.1 SETTLEMNT PATTERN

The layout of the old town is the first defense against the harsh climate in Lucknow. The buildings are joined close to each other to form a dense cluster. The houses, share walls and this minimize the surface exposed to the sun. The town has large open spaces to serve the community. The houses open on to narrow streets through a hierarchy of spaces that become the interface between the street and the houses.

There is a significant difference in the street patterns of the new regions and the older settlement of Lucknow. The radial pattern in the new areas of the city is contrasted by the somewhat irregular gridiron pattern in the old regions of the city. The streets are narrow which helped the buildings to shade one another as well as to shade the streets by the balcony and sunshade projections or by the buildings opposite. With fairly high buildings and width of streets rarely more than three meters, one can move around the town in cool shade. The street section design with reference to the movement of the sun reveals a close relationship between street width, building height and projections to create a cool shaded environment in hot summers by mutual shading. The major streets are oriented almost E-W and minor streets at right angles to these and are in the direction of the prevailing wind, which creates a low-pressure area in the open space thus moving the air from the streets into the living spaces.

Figure 4.1 Narrow streets providing a cool shaded environment

4.2.2 ORIENTATION

The houses generally open on the major streets (E-W orientation) and onto the minor street (N-S) orientation. Considering (for simplicity) an E-W street orientation, in summer the sun would be shining on the south facade from 9.30 a.m. to 2.30 p.m. The corresponding solar altitudes during this time are 54° to 86° and even small horizontal projections are sufficient to shade the south facing building. The north face of the building receives solar radiation before 8 a.m. and after 4 p.m. with solar altitude being less than 35°. At this time the building opposite shades the northern facade even if the street is relatively wide. For streets oriented N-S, the summer sun shines on the east facade till 11.30 a.m. and the west facade after 12.30 p.m. The solar altitude during these periods varies from 0° to 79°. With a narrow street, the building facades would be shaded before 10.30 a.m. and after 1.30 p.m. Thus, solar radiation would be incident on the E-W facades for no more than an hour each which is taken care of by the massive wall construction.

4.2.3 VEGETATION

The bigger traditional houses or kothis of Lucknow have bigger gardens and baradaries. A baradari is a pavilion (summer house) having twelve doors or arched openings set within a garden. It is a building for the purpose of free movement of air while it shelters the inmates from the sun and rain. The smaller traditional houses have a few small trees and shrubs planted mostly in the courtyard. The vegetation near the vicinity of the building helps in creating comfortable environmental. Plants and grassy covers reduce temperatures by absorption of solar radiation and cool by evaporation. Sometimes the trees also shade the building as well as the nearby spaces, which reduces the heat gain.

Figure 4.2 Vegetation giving cooling effect due to evapotranspiration

4.2.4 WATER BODIES

Water bodies in the form of fountains and water cascades can be found in most of the palatial residential buildings of Nawabs. Water bodies have been provided in front of the building, within the building or on the terraces. Baoli or underground steps well have been provided in few of the bigger buildings or kothis. The smaller residential houses generally do not have any water body, but in few buildings water fountains can be found which are located in the central courtyard. Evaporative cooling takes place due to the presence of water that makes the environment cool.

Figure 4.3 Evaporative cooling due to water fountain

4.2.5 VERANDAH

Verandahs are found widely in the traditional buildings of Lucknow. The verandahs are generally located at entrance or around the courtyard, shading the peripheral rooms. They function as transitional space between enclosed rooms and outdoor spaces. Verandah also serves as covered corridors and provides intermediate space for living and working that is neither indoors nor outdoors. Verandah provides shade to the walls to reduce heat gain. Verandah on the southern face is the most effective building element, which allows the heat of the sun to reach the interiors in winters, and prevents it in summers. The verandah hence screen interior space from penetrating rays of the subtropical sun and prevents driving rain from entering living space. Ventilation of living space therefore is possible through the openings in the walls facing the courtyard, even under the worst of conditions.

Figure 4.4 Verandah acting as a buffer space in traditional houses of Lucknow

4.2.6 COURTYARDS

The courtyards are found in most of the traditional buildings of Lucknow. The courtyards in the traditional buildings of Lucknow tend to differ in size and shape according to the building typology and space requirements. They are mostly centrally located and are completely opened to the clear sky or partially shaded with overhangs in some of the cases. This also provides shaded spaces which results in reducing heat gain. The centrally placed courtyard provides light to all the spaces and also provides air movement due to induced ventilation through the openings on the walls facing the courtyard. For example, in hot-humid seasons, large courtyards provide good ventilation, especially when opening on to another courtyard or street such that cross ventilation is promoted. On the other hand, small courtyards provide more protection against hot, dusty winds in summers. Some courtyards contain fountains and trees to promote evaporative cooling and provide shade.

The functioning of the courtyard during the 24-hour cycle can be subdivided into three phases. In the first phase, cool night air descends into the courtyard and into the surrounding rooms. The structure, as well as the furniture, are cooled and remain so until late afternoon. During the second phase, at midday, the sun strokes the courtyard floor directly. Some of the warm air begins to rise and also leaks out of the surrounding rooms. This induces convective currents, which may provide further comfort. At this phase the courtyard acts as a chimney and the outside air is at its peak temperature. The massive walls do not allow the external heat to penetrate immediately. The penetration is delayed and depends on the time lag of the walls. During the last phase, by late afternoon, the courtyard floor and the interior rooms become warmer. Most of the trapped cool air spills out by sunset. After sunset the air temperature falls rapidly as the courtyard begins to radiate rapidly to the clear night sky. Cool night air begins to descend into the courtyard, completing the cycle.

Figure 4.5 Courtyard inducing air movement

4.2.7 HIGH CEILINGS

One of the features associated with most of the traditional buildings of Lucknow is a high ceiling. The height of ceiling in traditional buildings depends on the building typology. The bigger palatial houses or kothis have a greater ceiling height, which varies from 4.5m to 5.4m whereas the ceiling height in smaller traditional houses generally varies from 3.6m to 4.2m. Greater ceiling heights improve environmental conditions in summer time by permitting warm air to rise. Greater ceilings height increases the volume of the enclosed space, thus it takes more time for the internal air to get heated up as compared to the buildings of low height ceilings.

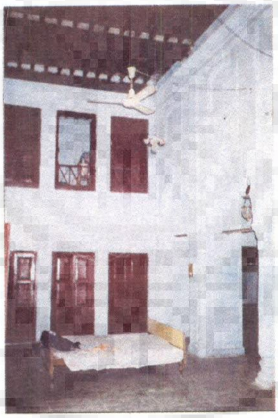


Figure 4.6 High ceiling increase the volume of air space to heat up

4.2.8 MASSIVE WALLS

The walls of traditional buildings are massive with a thickness varying from 45 cm to 60 cm. The thick masonry walls are constructed with lakhauri bricks and mortar of lime and surkhi. The walls are sometimes pointed or mostly finished with lime and stucco plaster.

Thermally heavyweight construction is part of the climate responsive strategy for both the cool and the warm period. Buildings with high mass structure utilize their thermal storage capabilities to achieve cooling in two different ways: (i) Damping out interior daily temperature swings (ii) Delaying daily temperature extremes. Furthermore, the thick walls, in addition to their insulating properties, act as a heat reservoir. During the hot day, the heat flow from exterior (due to solar radiation) to the inside is retarded and during cooler hours a part of the stored heat in the walls is released to the interior. This results in a minimization of temperature change inside the building. On the other hand, in winter, heating requirements are reduced due to the heat stored in the walls and which is radiated during the night.

Figure 4.7 Massive walls increases time lag

4.2.9 HEAVY ROOFS

As walls have been protected from solar radiation due to orientation and mutual shading, the main area of solar heat gain in buildings becomes the roof. The thickness of roof varies from 30 cm to 45 cm. The construction of roof generally comprises of Jack Arch Roof with Lakhauri bricks on steel girders covered with thick lime concrete with brick ballasts and surkhi. Finally the roof and floor are finished with lime and cement concrete. The massive roof construction of thickness ensures a very small decrement factor and a large time lag.

Figure 4.8 Heavy roofs provide insulation

4.2.10 OPENINGS

At higher temperatures ensuring air movement in the built space through openings provides human thermal comfort in traditional buildings. Natural air movement through a building is caused either by wind or by temperature differences between interior and exterior. When buildings are tightly clustered together, it is generally difficult to let winds into the house and air movement due to temperature differentials being too sluggish to cause any comfort unless special design features augment it. Hence the windows in traditional houses of Lucknow are bigger in size to facilitate ventilation. They are efficiently shaded from direct solar radiation. At temperature less than 35°C a slow current of air always provides better comfort than a slightly lower temperature with no air movement (Givoni, 1967). However, in winter when there is no special need for air movement, window apertures are opened during the day to store the thermal radiation and are kept shut at night. Windows also provide sufficient daylight into the interiors of the buildings. More window openings can be found on the north and east side of most of the traditional buildings which facilitates natural light and air movement to reach indoors without increasing heat gain. Small or less openings are provided on the south and southwest side to prevent heat gain. The windows are sometimes glazed and mostly they are unglazed with wooden shutters on the outside to ensure privacy and to keep out dust, sun and rain.

Figure 4.9 Shaded windows as openings

Ventilators are prominent features that are found in almost all the traditional buildings. They are manually operated and provided just below the ceiling. The warmer air rises and leaves the space and cooler air from the court enters the room to take its place. Thus it creates a stack effect. A typical vent near the ceiling increases the velocity of air entering into the building and hence resulting in lowering of the pressure at the ceiling level, thereby inducing the hot air under the roof to flow out through the vent. In this way air is kept circulating through the room under the roof. Ventilators also function as clerestory windows. This is used to light the interior spaces, which do not have any exposed surface to admit light through windows openings.

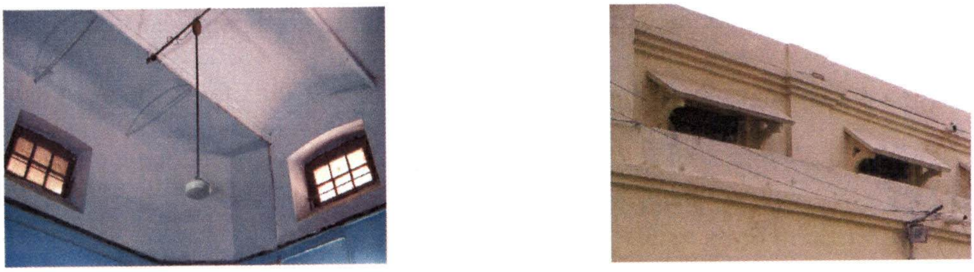


Figure 4.10 Ventilators expelling warm air

4.2.11 JHAROKHAS

Jharokhas are another characteristic feature of traditional buildings of Lucknow. These are infact, small size openings that can be found on the outer surface of the building facade. They create suction effect to facilitate forced air movement from the exterior environment into the interiors of the building. In most of the buildings Jharokhas are provided on the upper floors. Sometimes they are projected in the form of small bay window and are richly carved.

Figure 4.11 Jharokha induces forced air

In tune with the need for privacy for women, facades are characterized by small openings often in the form of jharokhas, elements essentially generated by social customs of allowing women to peep out without being seen.

4.2.12 SKYLIGHT

Skylights can be found in some of the traditional buildings of Lucknow, especially in the bigger residential buildings such as kothis and havelis. The skylight above the central space lights the interior space naturally. Skylights provide satisfactory lighting for activities that can tolerate large variations in illumination level. They are mostly located on the North side of the building and even allow these areas to gain some heat. Openings in the skylight create stack effect or induced ventilation in the surrounding spaces. They are sometimes fixed with tinted glass for decorative effect.

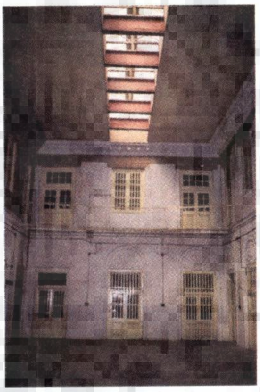


Figure 4.12 Skylight for light and ventilation

4.2.13 OVERHANGS AND BALCONIES

Balconies and building projections are another characteristic features of traditional buildings in Lucknow. The advantage of projections is to shade the building from direct solar radiation, which results in the reduction of heat gain. The depth of balconies and overhangs has been judiciously provided so as to cut off the solar radiations in summer and allow the winter sun to come into the building. Balconies have been projected in front of large openings to prevent direct solar radiation to enter the rooms through these openings.

Figure 4.13 Overhangs and projections provides shade from direct solar radiation

4.2.14 JALIS

If the courtyards are the largest holes in a traditional house of Lucknow then on the other end of the scale are the intricately carved stone jalis. The advantage of a jali is that it blocks the direct rays of the sun and yet permits air to enter the room and is designed to grant privacy. Jalis and screen not only have the advantage of interrupting solar gain, but also reduce glare, facilitate cross ventilation, filter light, allow controlled view, and cast intricate and playful shadow pattern that continually change.

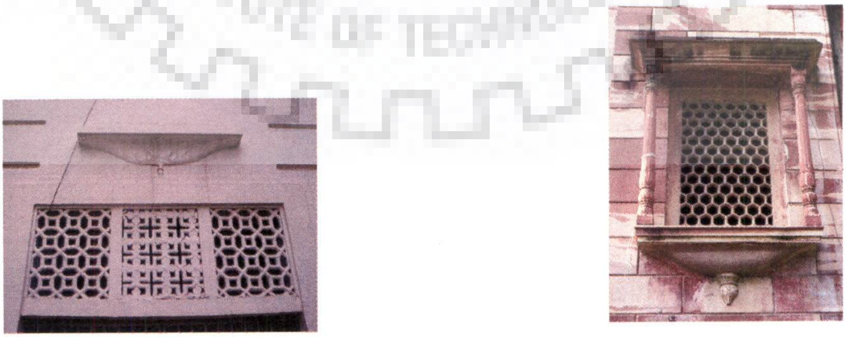


Figure 4.14 Jali facilitate ventilation and screening effect

4.2.15 SURFACE TEXTURE AND COLOUR

In Lucknow textured surfaces are used in the exterior finish of the building facades, which are likely to be exposed to sun. The use of decorative carved surfaces is not governed by the need for sun control only and in the traditional buildings of Lucknow, there are bound to be exceptions where the carved surface is used in completely shaded portions only for its decorative effect. It may be pointed out that the cooling effect of surface texture is useful only for thin walls. Because of their thermal load leveling characteristics, thick walls of materials like brick, stone or mud are capable of' reducing heat gain due to solar radiation, even without surface texture.

The external surface of traditional buildings in Lucknow are generally painted with such colours that reflect solar radiation (in order to have minimum absorption), but the emission in the long wave region is high, then the heat flux transmitted into the building is reduced considerably. Whitewashing reduces the absorptivity of the wall surface, minimizing the effect of solar radiation on internal climate and tends to stabilize the internal temperature.

Figure 4.15 Textured exterior surfaces for less absorption of solar radiation

4.3 CONCLUSIONS

In Lucknow, the layout of town is the first control mechanism against the climate. The buildings tended to be very closely clustered together, separated only by narrow shaded streets. The dense, compact settlement generates a large thermal mass weakening the external ambient conditions. The street orientation ensures that the building facades are either shaded by overhangs, balconies, jharokhas, chajjas projections, or by the opposite building. Due to the shadow patterns, the building receives minimum radiation from direct solar exposure, which results in reducing peak heat flux into the building.

Greater ceiling heights increase the volume of the enclosed space, taking more time for the internal air to get heated up. The verandah served as a buffer space between the interiors and the outside environment. There is a time lag due to thick masonry wall and heavy roof construction system found in traditional houses of Lucknow. Due to a large thermal capacity, the outside conditions are attenuated to provide comfort conditions in inside the buildings. The carvings and textured surface mainly on the front facade minimizes the heat gain by providing shading due to texture. The courtyard system ensures ventilation through the building even during the calm outdoor conditions. The openings such as windows, ventilators and skylight provided cross ventilation, by creating stack effect. The ventilation apertures such as jharokhas, jaalis induces forced ventilation into the interiors of the buildings. The vegetation near the vicinity of the building reduces the heat gain by shading the building from direct solar radiation and cooled the interiors by evapotranspiration. The other landscape elements such as fountain, baoli (an underground step well or water tank) provided thermal comfort by lowering the air temperature due to evaporative cooling.

Various passive design features and systems that have been employed in the traditional residential buildings in old settlement of Lucknow had been studied in this chapter. Out of these traditional buildings, three traditional houses were selected for the purpose of detailed case study, which has been discussed in the next chapter.

CHAPTER 5

CASE STUDIES

5.1 INTRODUCTION

The case studies and their critical appraisal are the major part of any research to verify the hypothesis. The present study hypotheses "that the traditionally constructed and designed houses are considered to be more energy responsive as compared to the modern houses built with new construction techniques and materials. The three traditional residential houses and two modern day residences were selected for conducting experiments and analyzing the thermal performance of each building. In this chapter the settings of the experimentation, three traditional residential buildings namely Roshan ud Daula kothi, Rizvi House, Kaiser Jahan House and two modern houses, their building features and their thermal performance in terms of temperature and relative humidity have been discussed and finally comparative analysis of the traditional houses with the modern houses with respect to their thermal performance has been summarized in this chapter.

5.2 THE SETTINGS OF THE INVESTIGATIONS

Measurements serve the limited purpose of giving a quantitative understanding of how specific design features in an existing building respond to outdoor environment. In the first case, precise measurements of the outdoor variables (air temperature, wind velocity and relative humidity) and the resulting indoor conditions (air temperature, air velocity and relative humidity) are required over a period which should be two or three times the time taken by the building to respond to the external conditions. This can be done for simple buildings but in real-life situations the model can be only approximate because of the near impossibility of measuring the outdoor parameters accurately. Solar radiation, for instance, will be incident on different building surfaces at different times of the day and even on one building element such as a wall, not only is it necessary to measure the radiation intensity but also to know the area which falls under direct solar radiation for each hour of the day.

One may assume that the temperature of ambient air is the same all around the building but for a building that is surrounded by other buildings in an urban area; this assumption can lead to gross errors. Air velocity (which affects ventilation and outer surface heat transfer coefficient) is the most difficult of all outdoor variables to measure, as it can vary considerably over short distances and over short periods of time. Finally, the thermal properties of building materials when used in a building may be quite different from calculated or laboratory measured values due to the unpredictable moisture content. Because of these inherent difficulties, thermal models of complex existing buildings can become self-limiting. The large number of measurements required cannot be taken for any appreciable number of buildings and the usefulness of detailed measurements of one or two buildings is doubtful because they may not be sufficiently representative of the range of building types found in a given context.

Rather than attempting detailed measurements of one building, it was considered that it would be more fruitful to take limited measurements in all the five buildings with the specific purpose of obtaining an overall view of the outdoor thermal environment (such as at a meteorological observatory located at Amausi, near Lucknow) instead of the highly variable microclimate around the building. Since the impact of relative humidity is during summer and monsoon and it is not of greater significant during winter in composite climate of Lucknow. Hence only the relative humidity was measured during summers in all the five buildings. The main outdoor climatic parameters (air temperature and solar radiation) vary considerably through the year. The rate of change of air temperature is also variable and therefore the period of observation should be one in which the air temperatures are stable and vary-little from day to day. The outdoor climatic data of Lucknow during the experiment period were obtained from the Indian Meteorological Department, which is located at Amausi Airport, 12 km away from Lucknow. Figure 3.3 shows the air temperatures in Lucknow throughout the year. Two stable zones are found in June and December-January and these are also the periods for climatic extremes and therefore the obvious periods for temperature observations. Experiments were conducted in the peak seasons in all the five buildings between 2nd June 2004 to 10th June 2004 in summers and in between 14th January 2005 to 22nd January 2005.

Measurements of this type can:

i. Show the thermal behaviour of specific building elements.
ii. Provide a basis for comparing the indoor thermal conditions obtaining in different parts of a building.
iii. Provide a basis for comparing the overall performance of different buildings.

5.3 THE CRITERIA OF INSTRUMENTS USED

The methods of measuring environmental parameters normally used in the laboratory need to be modified in order to meet the very different needs of a field situation. In the laboratory it is customary to measure temperatures with thermocouples (or other similar sensors) planted at appropriate locations and connected to a central monitoring point. There is considerable, time and effort required in setting up such remote sensors, but having been once calibrated and tested, the measurements from such sensors can be handled easily by a single individual. The time and effort required in setting up is worthwhile only if the experiment is to be continued in the same place for a reasonably long period. In case data is to be obtained for many different situations for short durations, it is better to rely on portable instruments that need no installation or can be quickly installed. While this method cuts down on installation time, the time taken for each set of observations is considerably increased, as the person taking observations has to physically move from one place to another. In a large building such as a kothi, a set of observations consisting temperature measurement, surface temperatures and air velocity measurement can easily take up to 20 minutes and the observations cannot be considered to have taken place at the same point of time. The error with such observations will obviously depend upon the interval between observations and a correction needs to be applied for the time difference.

The instruments available for measurement of indoor parameters in this study were rather limited. Air temperatures and relative humidity were measured with a digital Thermo Hygrometer. Surface temperature measurement was carried out with a portable non contact digital thermometer. Air movement measurements presented a problem, a portable digital wind vane type instrument was used for this purpose, but being a directional instrument it could be used only at ventilation apertures where the wind direction was predictable. The air velocity measured at windows can provide an index of the relative airflow through a room at different times of the day, but not the actual air velocity in the room at any given time.

Since the detailed effect of wind was excluded from the scope of this study because of the non-availability of hourly outdoor wind velocity as mentioned earlier, the absence of air velocity measurements was not a great problem in itself. However, without air velocity measurements a globe thermometer could also not be used for direct measurement of mean radiant temperature. This was partly compensated by taking a large number of surface temperature measurements from which the radiant temperature was calculated. As this calculation cannot take account of the radiant temperature of windows, doors and other openings (which depends upon the temperature of buildings or sky seen through the window) the value of mean radiant temperature so obtained is likely to be different from the globe temperature.

5.4 CASE STUDIES

5.4.1 CASE STUDY 1: ROSHAN UD DAULA KOTHI

Roshanuddaula Kothi is one of the classic examples of Indo-French architecture and was built by Nawab Roshanuddaula, the chief minister of Avadh, as his personal residence around 1836 A.D. During Wajid All Shah's time, it was renamed 'Kaiser-Pasand' and made the residence of his favourite queen, Mashooq Mahal. It was converted into the court office during the British period. Presently, it houses U.P. State Department of Archaeology (Figure 5.1).

The Roshanuddaula kothi is a huge building with a basement level, which was originally 5 storied high but only 3 storeys exist now. Its basic form is rectangular, but it acquired a complex polygonal outline, as it had canted corners on one front, projecting rectangular bays on another front, a grand hexastyle portico on a third front and yet other tiny balconies, colonnaded verandahs and staircases on each and every front. At the ground floor level of its north east and the north west corners are two edifices designed in the standard Nawabi mosque form, of which the northeast one is a functional mosque, but a the north west one is a only a ceremonial replica just to maintain symmetrical balance (Figure 5.2). The south front is dominated by a huge chamfered projection which rose through three levels, each with arched colonnades, and culminated in coffered half-domes. Walls are about 1.0 m thick and the roof is 70 cm thick. The height of the rooms is 5.6 m and few halls are of double height. The height of the openings is 3 m. There is also a 'Baoli' (a stepped water tank) on the ground floor. The first floor of the Kothi is accessible from ground from all the sides.

Figure 5.1 View of Roshan ud Daula Kothi

Figure 5.2 Northwest corner of the building

5.4.1.1 PASSIVE FEATURES OF ROSHAN UD DAULA KOTHI

The plan of Roshan-Ud-Duala kothi is compact and centrally planned about a central hall. The orientation is North-South, which is supposed to be the best, and consideration for prevailing wind direction has been made by aligning the openings in its direction. On the outer periphery of the building verandahs, toilets and other non-habitable rooms have been provided to protect the main living areas from the heat of sun. Rooms located in two rows facilitate winter and summer living spaces. Rooms located on the inner side are for summer living and those on the outer side are used for winter living, which act as a buffer for the summer living spaces.

The main element of the building is the verandah on the southern side, which invites sun in winter, and protect from it in summer as per the orientation of sun, and the seasonal requirement. The double height central hall is covered with the sky light, which lights the interior spaces mainly those located on the northern side. Openings in the walls have been aligned in such a way that the air from outside passes through these openings, reaches the central hall, rises and moves out though the openings in the sky light thus creating stack effect. Vaulted roof, high ceilings are ventilated through the openings at the ventilator level.

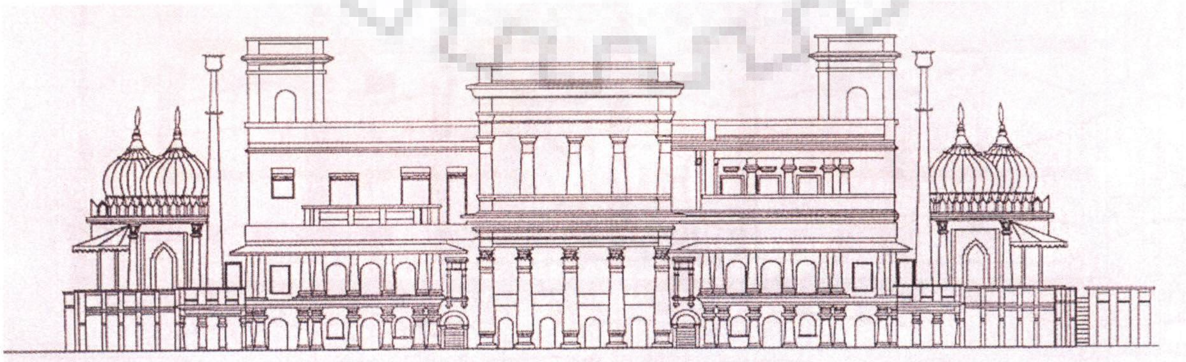


Figure 5.3 Elevation of Roshan ud Daula Kothi

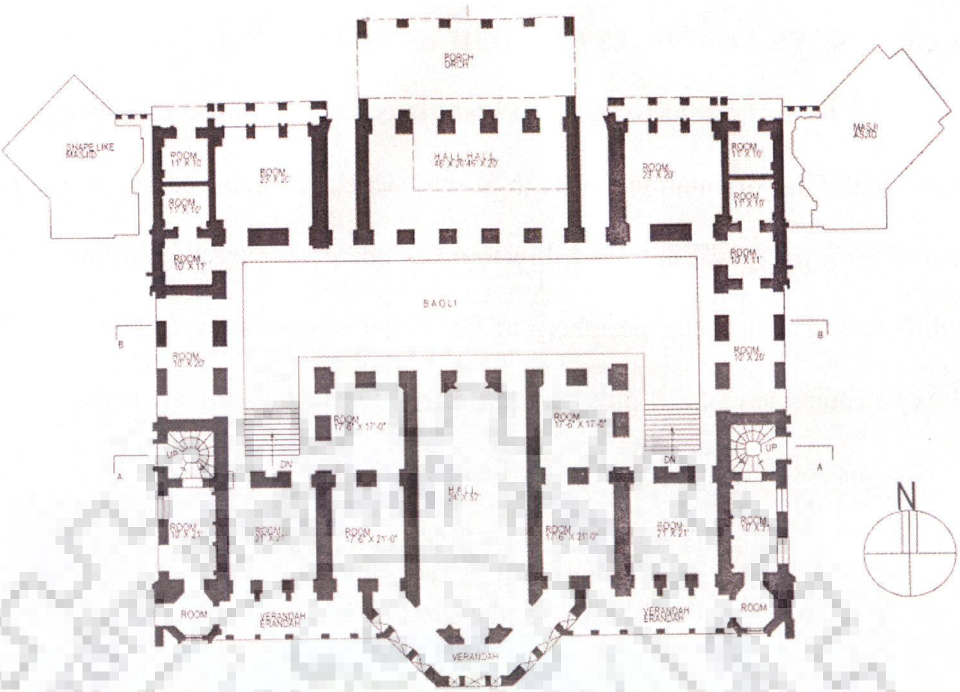


Figure 5.4 Ground Floor Plan of Roshan ud Daula Kothi

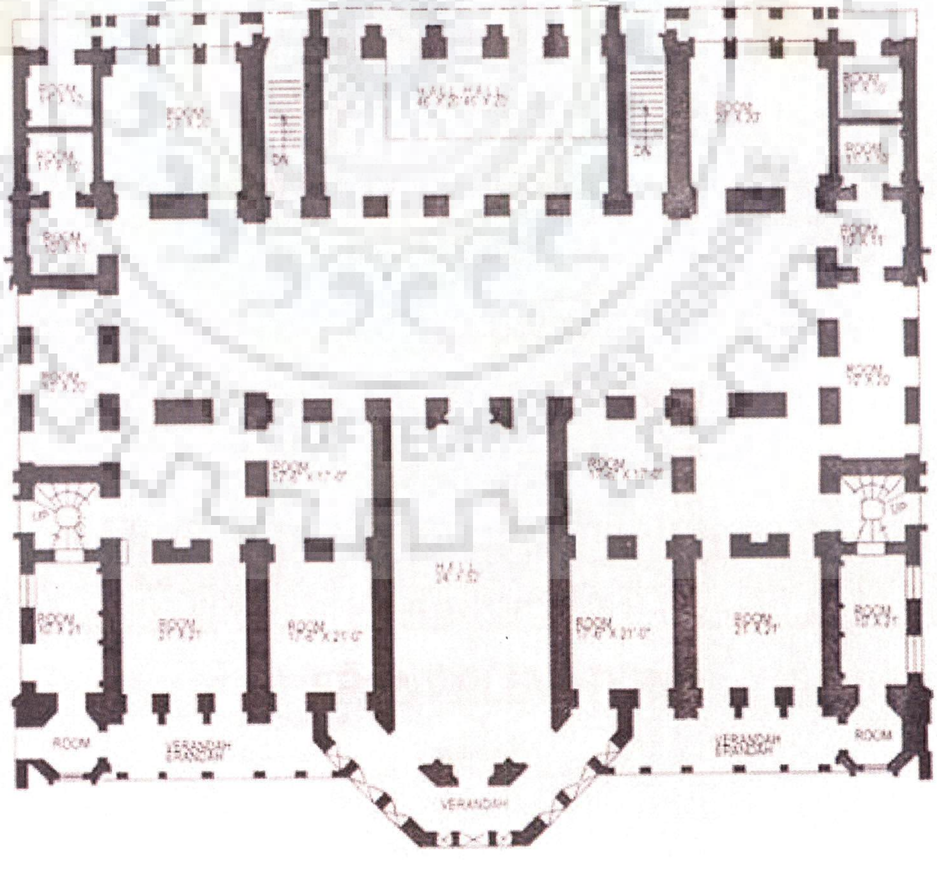


Figure 5.5 First Floor Plan of Roshan ud Daula Kothi

The thickness of the roof is 45cm, which reduces heat gain, and the curvature below dissipates the heat and maintains the comfortable conditions inside. Thickness of the walls varies from 45cm to 68cm, which creates temperature differential thus maintaining comfortable condition indoors irrespective of outdoor conditions. Sun shading devices in the form of projection of eaves, cornices and balconies shade the windows and exposed wall surfaces, which prevent direct solar radiation to enter the building, and help to reduce heat gains through the envelope. Dense vegetation surrounding the building also acts as an environmental buffer space and maintains comfortable conditions due to evaporative cooling. Light coloured exterior surfaces tend to reflect solar radiations.

5.4.1.2 THERMAL PERFORMANCE OF ROSHAN-UD-DAULA KOTHI

The summer temperature measurements were taken outside the building in the open space adjacent to the building and in various peripheral rooms and the central room of the building on 2 June 2004 and the winter temperature measurements were taken on 22 January 2005.

Thermal performance of Roshan-ud-Daula kothi in summer

The Figure 5.6 shows the thermal performance of the different spaces in the building and outside the building on 2nd June 2004. The temperatures in the central rooms were found to be more stable in the central room as compared to the peripheral rooms. This is to be expected, as there was continuous flow of hot air into the peripheral rooms while the rate of air exchange in the central hall was much lower. The temperature in the central hall was around 1°C lower as compared to the surrounding rooms.

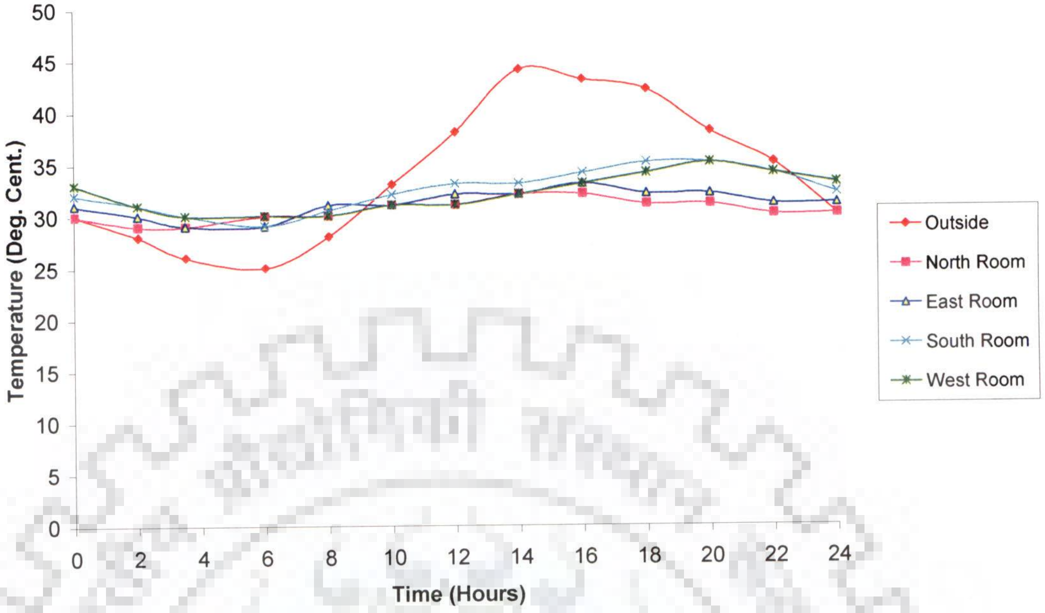


Fig. 5.6 Air Temperature in different spaces of Roshan ud Daula Kothi in summer

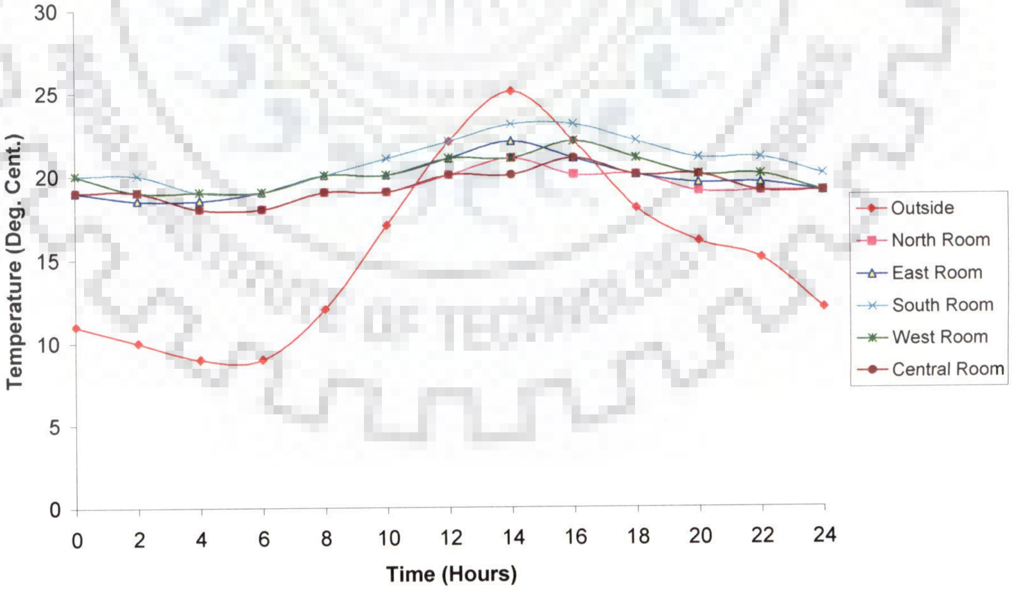


Fig. 5.7 Air Temperatures in different spaces of Roshan ud Daula Kothi in winter

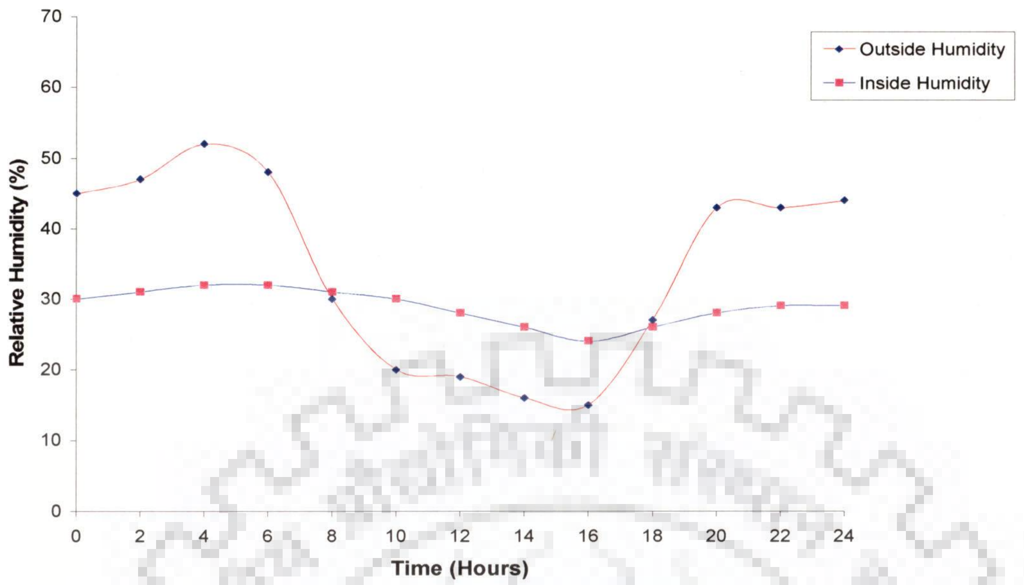


Figure 5.8 Relative Humidity in Roshan ud Daula Kothi in summer

This can be due to the reason that the external walls of the peripheral rooms were exposed to the radiant heat from the surroundings. The heat accumulated in the central hall is again dissipated through the skylight and aperture at the top due to stack effect. The amplitude of indoor air temperatures in different spaces of the building was not more than 3-4°C while the outdoor temperature fluctuation was of the order of 20°C. The mean maximum indoor temperatures of different rooms of traditional house was 10-12°C lower and mean minimum temperature was 3-4°C higher than the outdoor minimum temperature. The maximum external surface temperature of the exposed wall in the afternoon was found to be 55°C whereas the internal surface temperature of the wall was 34°C. This can be attributed to the time lag due to the massive wall of 1.0 m thickness. The maximum external surface temperature of the exposed terrace in the afternoon was found to be 58°C whereas the maximum temperature reached by the ceiling was found to be 35°C. This is because of the heavy roof construction of 70 cm.

thickness. The outdoor relative humidity varies from 15% to 52%, but the relative humidity in different spaces varied from 32% to 44%, which was within the comfort zone.

Thermal performance of Roshan-ud-Daula kothi in winter

The temperatures in the various rooms were found to be in slightly cool zone with slight variation in temperature. As it is clear from the graph in Figure 5.7, the outdoor temperature fluctuated from 9°C to 25°C, but the internal temperature of different spaces was never less than 18°C even though very little direct solar radiation was received within the building. The indoor temperature fluctuation of different rooms was of the order of 3-4°C. The six rooms placed on the southern side of the building are slightly warmer than the rooms located on other three side of the building. This is due to the orientation of the buildings. The verandah projected on the south side of the building allows the winter sun to penetrate into the rooms and cuts off the direct sun into the rooms. Ventilation fenestrations are kept close throughout the day on all the three sides of the building except the south side so as to store the thermal mass received from the sun and during night all the fenestrations are closed.

5.4.2 CASE STUDY 2: RIZVI HOUSE

This traditional house belongs to Mr. S.M.M. Rizvi, and is located in an old settlement of Chowk at Lucknow. This building was built around 1915 basically to serve the purpose of 'Janana Imambara' or Ladies Mourning Place. The mourning still takes place at the time of Moharram (first month of Islamic calendar in the Majlisi or the ‘mourning hall’ and for the rest of the time of the year the building is used as a residence.

5.4.2.1 PASSIVE FEATURES OF RIZVI HOUSE

This is a traditional courtyard house with three imambaras and two mosques at each level. The central courtyard is of dimension 7.05m X 6.4m, which is surrounded by living rooms on three sides and entrance on the north side of the courtyard (Figure 5.9). The double height 'majlisi' which is 4.8m high, faces entry court on the south side of the courtyard (Figure 5.10). The Majlisi is a double height hall (Figure 5.11), which opens to an Imambara and a masjid (mosque) at both level on its right and a room on its left. There are two Jharokhas on the upper floor on the northern face of the building. There is a parapet wall of one meter made up of brick jali. The shops at the ground level face the streets outside towards the south side.

Very few openings are provided on the south side and southeast side of the building. Walls at the entrance of masjid (mosque) are slightly curved to create an illusion. The other two flanges of the court have pavilion type spaces for living. The walls on the ground floor are 90 cm thick and on the first floor the wall thickness decreases to 60 cms.

Figure 5.9 View of Rizvi House

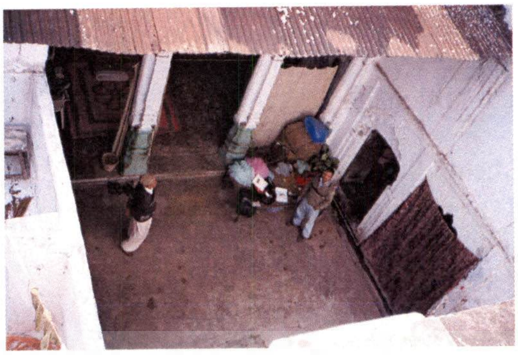


Figure 5.10 View of Central Courtyard

Figure 5.11 Double Height of Imambara

The orientation of the house is such that it keeps the room around the courtyard cool. The exposed surfaces do not have any openings except on the fist floor on the Northern side where the 'Jharokhas' have been provided resulting in induced ventilation. The absence of the openings on exterior surfaces helps in reducing heat gains. The white wash of the exterior surfaces reflects the solar radiation. Courtyard facilitates shaded spaces and induces ventilation in the interiors through the openings facing the courtyard. 'Jharokhas' have been aligned with the openings on the wall facing the courtyard such that outside air passing through these openings rises in the courtyard to create stack effect. Terraces have been provided at different levels to create shaded spaces to reduce heat gain through the roof.

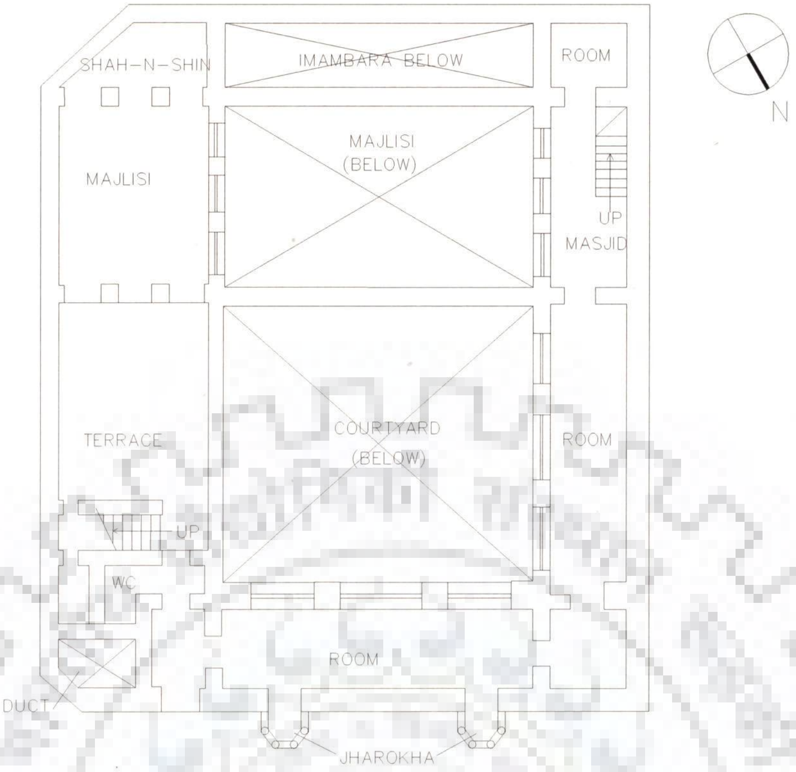


Figure 5.12 First Floor Plan of Rizvi House

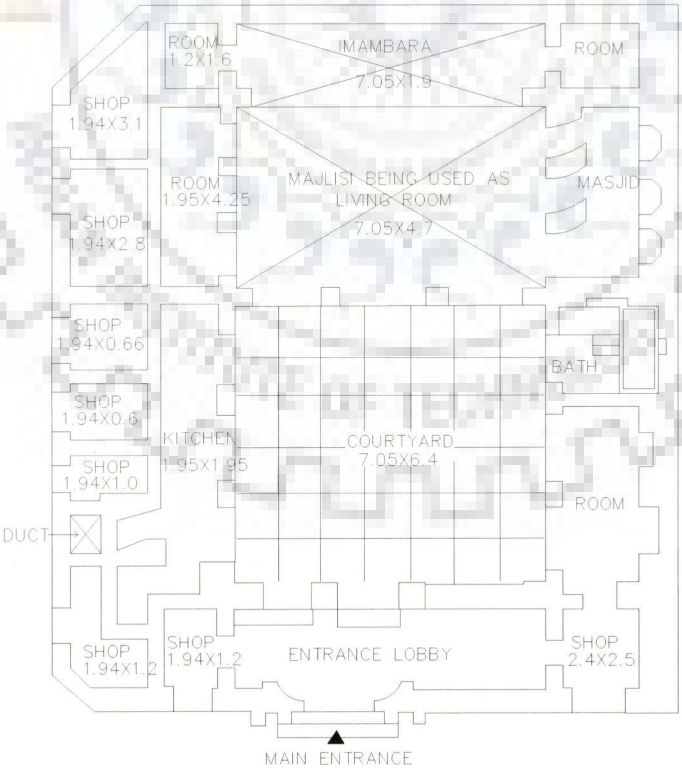


Figure 5.13 Ground Floor Plan of Rizvi House

5.4.2.2 THERMAL PERFORMANCE OF RIZVI HOUSE

The summer temperatures measurements were observed in various peripheral rooms and the central courtyard of Rizvi House. The summer temperature measurement of different spaces was recorded on 4th June 2004 and the winter temperature measurements were taken on 24th January 2005.

Thermal Performance of Rizvi House in summer

The Figure 5.14 shows the thermal performance of the different spaces in the building and outside the building on 4th June. The temperature in the room on the north side was found to be more stable as compared to other rooms. The outdoor temperature fluctuation was in the order of 17-18°C whereas the indoor temperature fluctuation was around 5-6°C. The maximum indoor temperature was 8-9°C lower than the corresponding outdoor temperature. While the outdoor air temperatures changed from 25°C to 43°C, the air temperature in the courtyard fluctuated from 26°C to 33°C. This was due to the small double height shaded courtyard, which induces cool air inside the semi-opened rooms and ensures ventilation through the building even during the calm outdoor condition. The outdoor relative humidity varies from 22% to 55%, but the relative humidity in different spaces varied from 32% to 45%, which was within the comfort zone. The relative humidity in this case was more as compared to Roshanud daula Kothi because of its compact plan and less cross ventilation in the rooms. The maximum external surface temperature of the exposed wall in the afternoon was found to be 54°C whereas the internal surface temperature of the wall was 33°C. This can be attributed to the time lag due to the massive wall of 45 cm thickness. The first floor temperatures of different spaces were consistently higher by 1°C to 1.5°C.

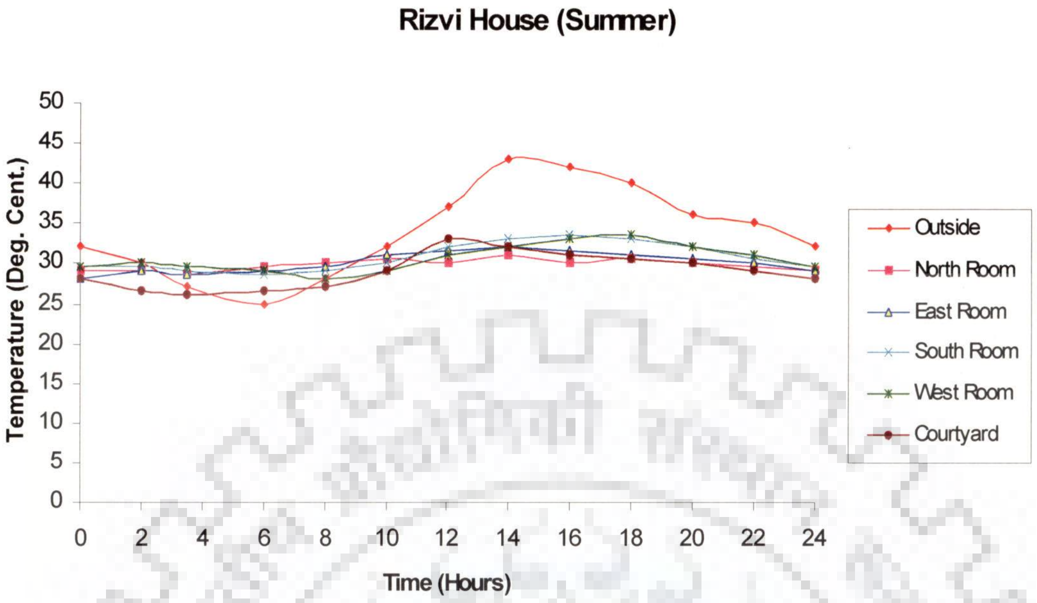


Figure 5.14 Air Temperatures in different spaces of Rizvi House in summer

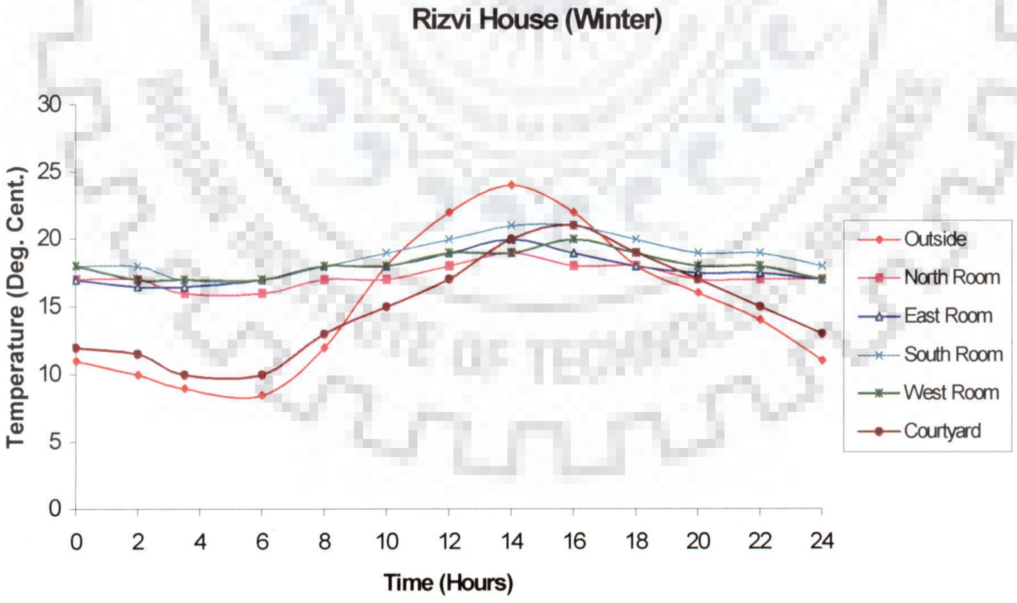


Figure 5.15 Air Temperatures in different spaces of Rizvi House in winter

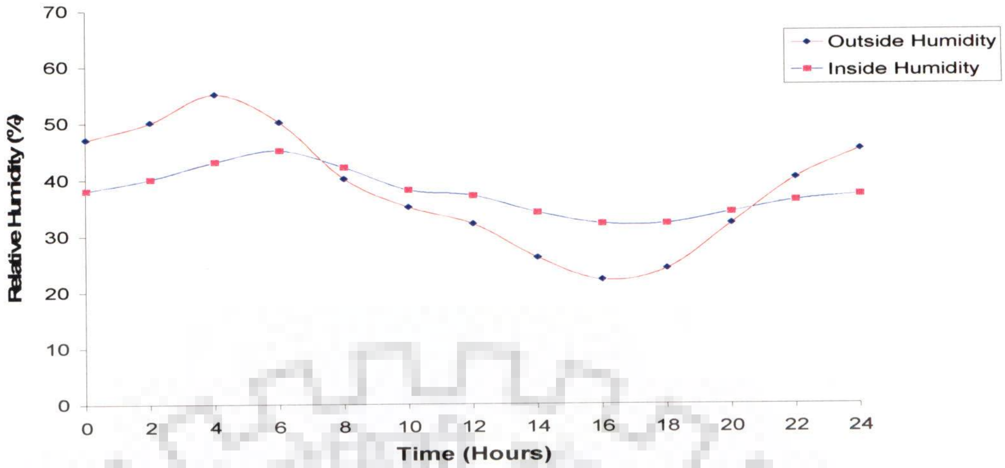


Figure 5.16 Relative Humidity in Rizvi House in summer

Thermal Performance of Rizvi House in winter

The temperature measured in various rooms of Rizvi House were found to be slightly warmer during daytime and slightly cooler during night as compared to the Roshanud Daula Kothi. This can be attributed to the presence of the courtayard in Rizvi House. As it is clear from the graph in Figure 5.15, the outdoor temperature fluctuated from 8.5°C to 22°C, but the internal temperature of different spaces was never less than 16°C even though very little direct solar radiation was received within the building. The indoor temperature fluctuation of different rooms was of the order of 4-5°C.

5.4.3 CASE STUDY: 3 QAISER JAHAN HOUSE

This is a courtyard house of late Mrs. Qaiser Jahan Begum in Nakkhas at Lucknow. The house is around 125 years old. The entrance of the house opens into a narrow street (Figure 5.18). There is an entrance lobby, which opens directly into the courtyard. The square shaped courtyard of dimensions 10.75m X 10.0m is centrally located, enclosed by rooms on three sides and an entrance on the west side. The eastern side of the courtyard has a double height hall (Figure5.19) and on the other three side of the court are single height structures. The double height hall opens into an Imambara and two bedrooms. This double height hall is also used as a 'majlisi' or mourning place during Moharram. On the north side of courtyard is the kitchen, a bathroom and a toilet and on the southern side of the courtyard are two living rooms.

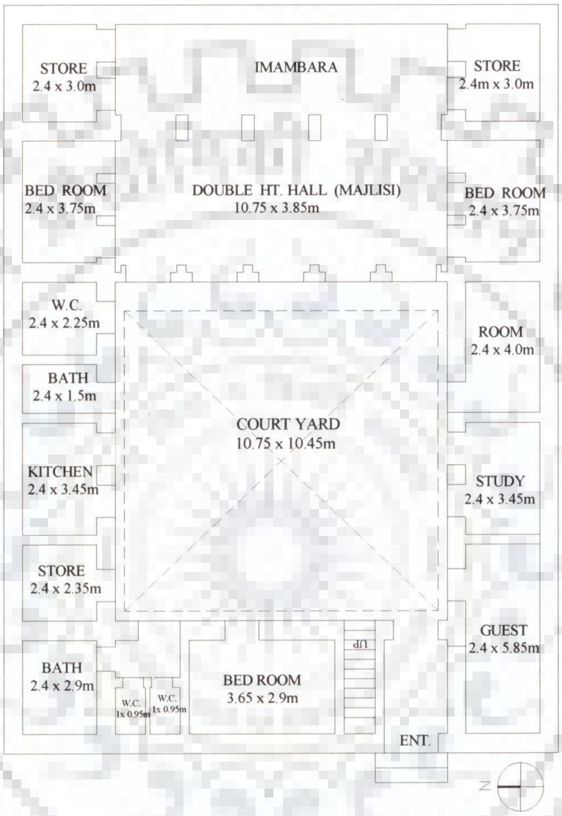


Figure 5.17 Ground Floor Plan of Qaiser Jahan House

Figure 5.18 Front view from the street

Figure 5.19 Double Height hall

5.4.3.1 PASSIVE FEATURES OF QAISER JAHAN HOUSE

The house opens into the narrow street, which is shaded by the balcony and projections of the buildings on both sides. The entrance of a house is through a lobby, which opens into a central courtyard. As the courtyard gets heated up during the day the hotter air rises and denser, cool air, which is drawn from the shaded streets, rushes into the courtyard and hence induces ventilation in the interiors of the rooms, which opens into the courtyard (Figure5.20).

Figure 5.20 View of Courtyard

The absence of the openings on exterior surfaces helps in reducing heat gains. The double height entrance on the south west side provides shade to the building from the afternoon sun. The thickness of the wall is 24" and constructed of lakhori bricks finished with lime surkhi plaster. The roof is 18" thick constructed of brick ballast mixed with lime surkhi mortar laid on timber sheets supported by timber beams (Figure5.19). The massive walls, heavy roof and timber ceiling offer greater thermal insulation and hence increase the time lag. The ventilators near the ceiling facilitate stack effect and extract the warm air from the rooms.

There is also evaporative cooling due to vegetation in surroundings (Figure 5.22). The exterior of the building is plastered with lime mortar and whitewashed, which reflects the solar radiation to some extent. There is also a reduction of heat gain by providing textural shading due to ornamentation and stuccowork on the building facade.

Fig. 5.21 Double Height (Imambara) Hall

Fig. 5.22 Rooms around the courtyard

5.4.3.2 THERMAL PERFORMANCE OF KAISER JAHAN HOUSE

The summer temperatures measurements were observed in various peripheral rooms and the central courtyard of Qaiser Jahan House. The summer temperature measurement of different spaces was recorded on 6 June 2004 and the winter temperature measurements were taken on 26 January 2005.

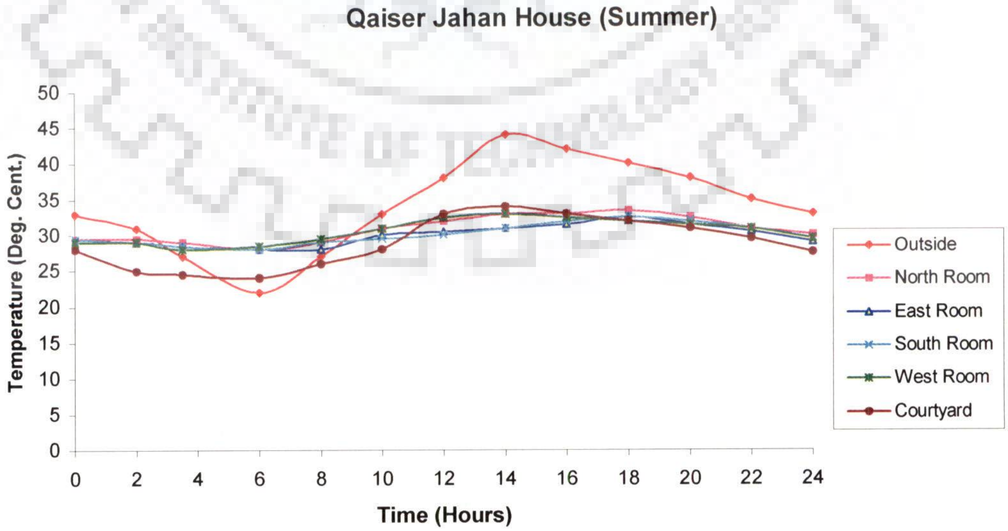
Thermal performance of Kaiser Jahan House in summer

The Figure 5.23 shows the thermal performance of the different spaces in the house and outside the building on 6th June. The outdoor temperature fluctuation was in the order of 12-13°C whereas the indoor temperature fluctuation was around 4-5°C. The maximum indoor temperature was 9-10°C lower than the corresponding outdoor temperature. While the outdoor air temperatures changed from 22°C to 44°C, the air temperature in the courtyard fluctuated from 24°C to 34°C. The temperature in the courtyard of Qaiser Jahan House was found to be a little greater than Rizvi House in the afternoon and a little less than in the early morning. This can be attributed to the bigger size of courtyard in Qaiser Jahan House as compared to that of Rizvi House.

The outdoor relative humidity varies from 20% to 56%, but the relative humidity in different spaces varied from 31% to 46%, which was within the comfort zone. The overall relative humidity in this case was less as compared to Rizvi House because of its bigger courtyard and more cross ventilation in the rooms. The maximum external surface temperature of the exposed wall in the afternoon was found to be 55°C whereas the internal surface temperature of the wall was 34°C. This can be attributed to the time lag due to the massive wall of 60 cm thickness.

Thermal performance of Kaiser Jahan House in winter

The temperatures measured in various rooms of Qaiser Jahan House was found to be slightly warmer during daytime and slightly cooler during night as compared to Rizvi House. This can again be attributed to the presence of bigger courtyard in Qaiser Jahan House. As shown in Figure 5.24, the outdoor temperature fluctuated from 7.5°C to 23°C, but the internal temperature of different spaces was never less than 12°C. The indoor temperature fluctuation of different rooms was of the order of 4-5°C.



Qaiser Jahan House (Summer)

Fig. 5.23 Air Temperatures in different spaces of Kaiser Jahan House in summer

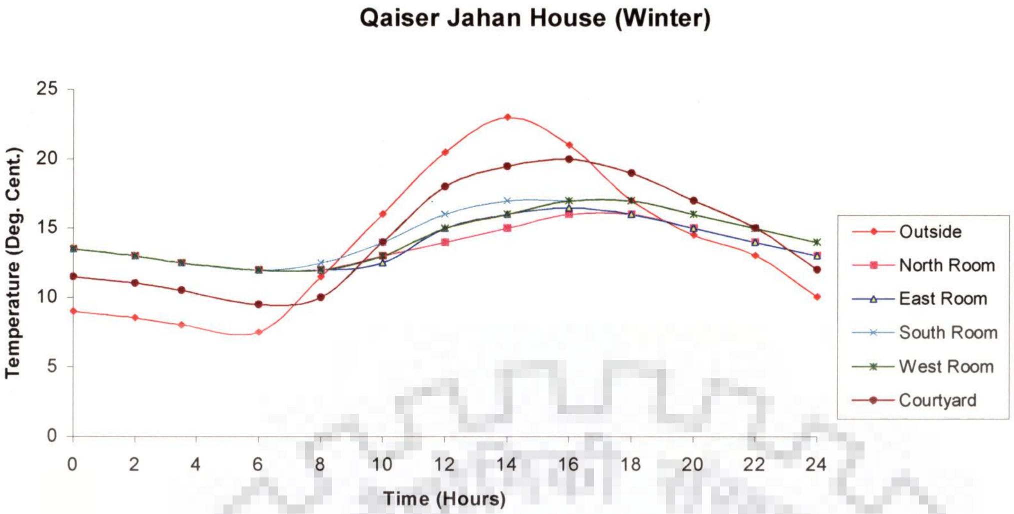


Figure 5.24 Air Temperatures in different spaces of Kaiser Jahan House in winter

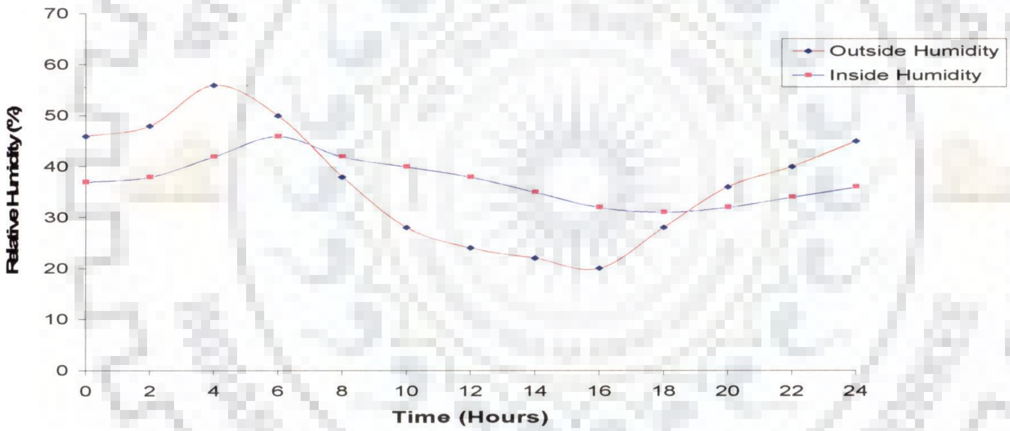


Figure 5.25 Relative Humidity in Qaise Jahan House in summer

5.4.4 CASE STUDY 4: L.D.A. HOUSE I

This building is a MIG house, which was built by the Lucknow Development Authority in Aishbagh, Lucknow around 40 years back (Figure5.26). It is a double storey building with living room, kitchen, toilet and one bedroom on the ground floor and one bedroom and toilet on the upper floor. The construction consists of 23 cm thick load bearing brick masonry walls and 6" thick roof. The heights of the rooms are 3.0m and openings are of dimensions 0.9m X 1.2m.

Figure 5.26 Front View of the L.D.A. House I

5.4.4.1 SALIENT FEATURES OF THE BUILDING

This building is a part of semi detached row housing and it is compactly planned with a small front and rear yard. The energy consumption in these houses was not considered as a design criterion. There are only few openings, which opens into the front and rear yard, which obstructs the free movement of the air and doe not provide cross ventilation. The living room is located on the western side without proper shading, which causes discomfort in summers.

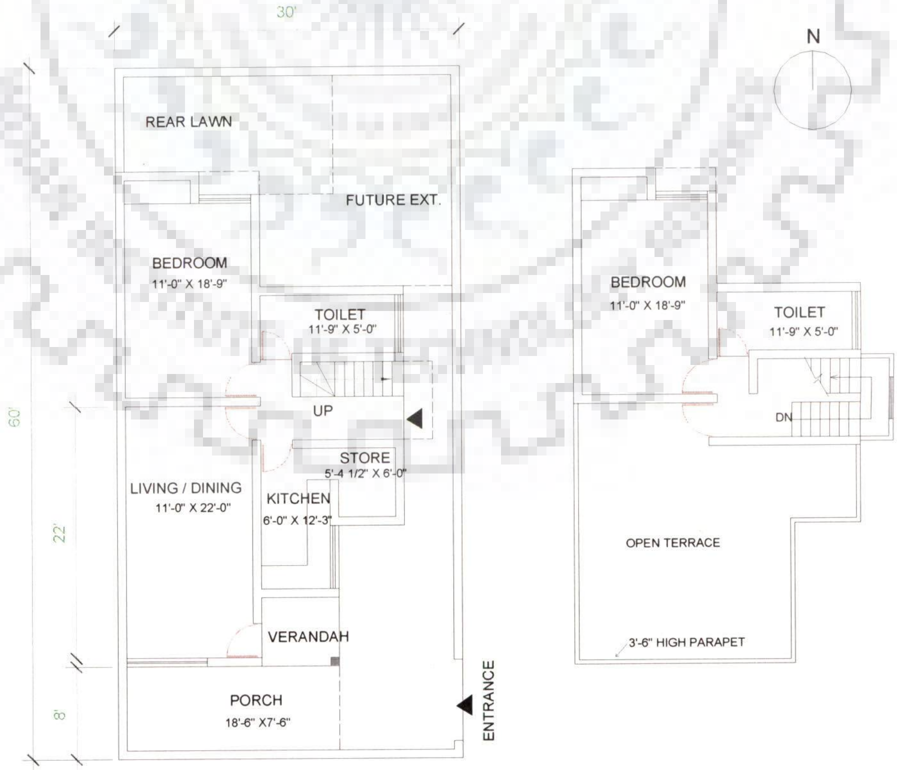


Figure 5.27 Ground and First Floor Plan of L.D.A. House.

The roof of the first floor is 10 cm thick R.C.C. construction finished with small brick ballast and cement sand mortar. The roof is a major source of heat gain for the upper floor due to absence of appropriate terracing. There is no proper sunshade over the openings on the first floor on south and west side, hence it does not cut the solar radiation in the afternoon and heats up the interiors due to high transmissivity of glass. There is no proper projection on the terrace level on south and west side to shade the walls on first floor. This causes the walls to heat up and hence permits the heat into the rooms through conduction. The plastered exterior surface with whitewash reflects solar radiation to some extent.

5.4.4.2 THERMAL PERFORMANCE OF LDA HOUSE I

The summer temperatures measurements were observed in various rooms in the L.D.A. House on 9 June 2004 and the winter temperature measurements were taken on 28 January 2005.

Thermal Performance of LDA House I in summer

The room temperature in different spaces was found to be above the slightly warm zone. The temperature fluctuation in the outdoors was in the order of 19°C whereas the indoor temperature fluctuation was of the order of 7°C. The maximum indoor temperature was 6-7°C lower than the corresponding outdoors temperature. Here it can be very well observed that the indoor temperature of this house is 4-5°C higher than the temperature of traditional house for the corresponding hours of the day. This can be attributed to the thin walls and the R.C.C construction without proper shading of walls. The outdoor relative humidity varies from 23% to 54%, but the relative humidity in different spaces varied from 28% to 42%. The overall relative humidity with reference to thermal comfort was slightly less as compared to any traditional house.

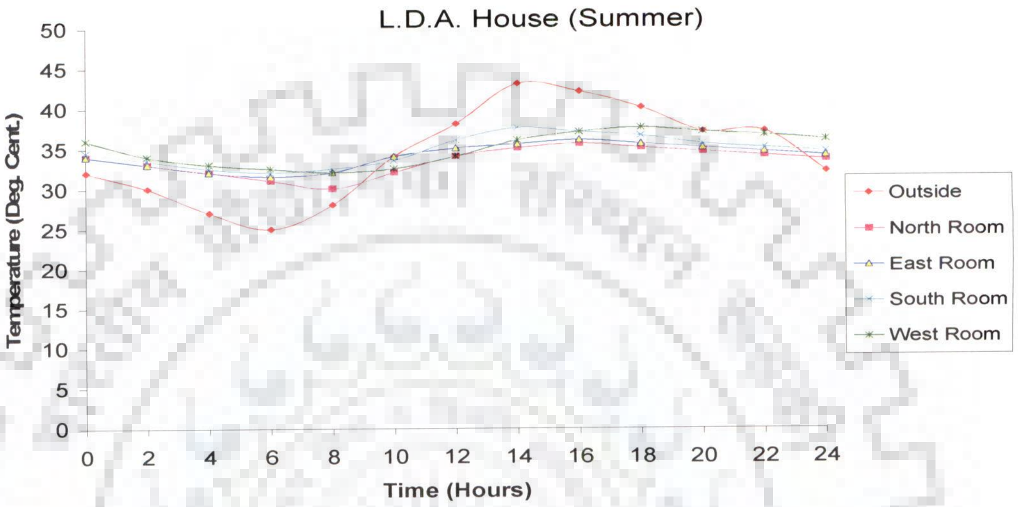


Figure5.28 Air Temperatures in different spaces of L.D.A. House I in summer

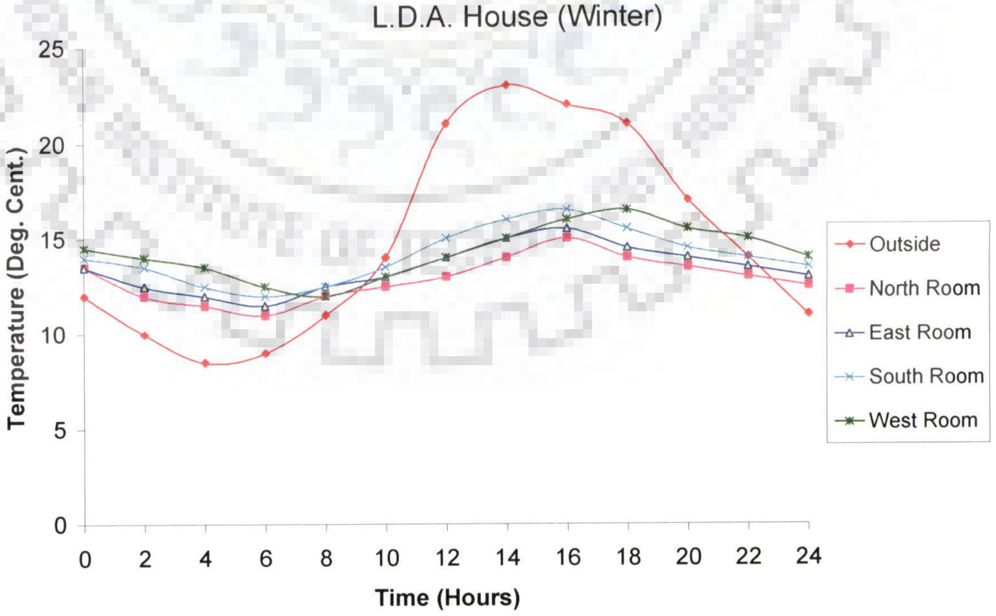


Figure 5.29 Air Temperatures in different spaces of L.D.A. House I in winter

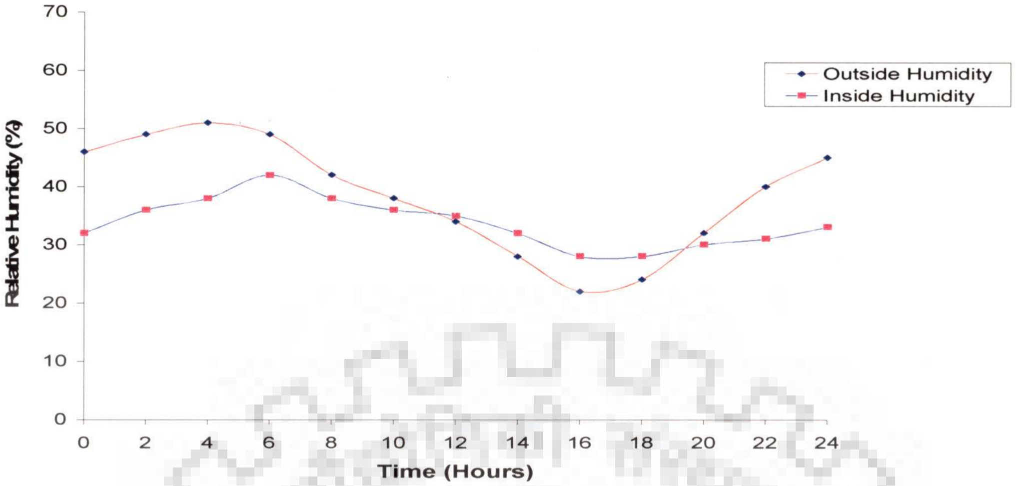


Figure 5.30 Relative Humidity in LDA House I in summer

Thermal Performance of LDA House I in winter

The room temperature in different spaces was found to be below the slightly cool zone. The temperature fluctuation in the outdoors was in the order of 15°C whereas the indoor temperature fluctuation was of the order of 6°C. The minimum indoor temperature was 3°C lower than the corresponding outdoors temperature. Here it can be very well observed that the indoor temperature of this house is 4-5°C lower than the temperature of traditional house for the corresponding hours of the day. This can be attributed to the thin walls of 23 cm brick masonry construction and 10 cm R.C.C construction without proper shading of walls.

5.4.5 CASE STUDY: 5 L.D.A. HOUSE II

This house is another MIG house built around 40 years back by Lucknow Development Authority in Aishbagh, Lucknow (Figure5.31). This house is similar to LDA House I on the ground floor but few changes in spaces on the first floor and slight modification in terms of projections and number of window openings. It is a duplex with a living room, a lounge, a kitchen, a toilet and one bedroom on the ground floor and one lounge,a kitchen, two bedroom and toilet on the upper floor. The construction consists of 23 cm thick load bearing brick masonry walls and 6” thick roof. The heights of the rooms are 3.0m and openings are of dimensions 0.9m X 1.2m.

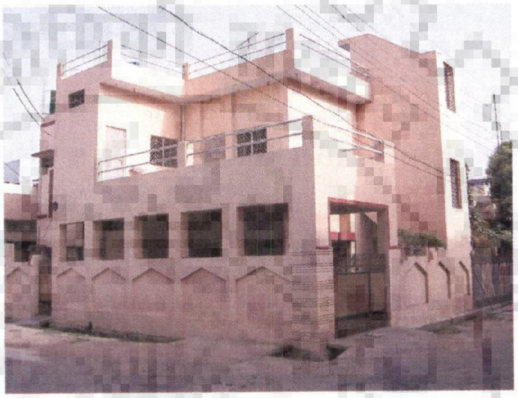


Figure 5.31 Front View of the L.D.A. House II

5.4.5.1 SALIENT FEATURES OF THE BUILDING

This building is a part of semi detached row housing and it is compactly planned with a small front and rear yard. There are only few openings, which opens into the front and rear yard, which obstructs the free movement of the air and doe not provide cross ventilation. The living room is located on the western side without proper shading, which causes discomfort in summers.

The roof of the first floor is 10 cm thick R.C.C. construction finished with small brick ballast and cement sand mortar. The roof is a major source of heat gain for the upper floor due to absence of appropriate terracing. There is no sunshade over the openings on the first floor on south and west side, hence it does not cut the solar radiation in the afternoon and heats up the interiors. The only projection that is provided at the terrace level is of 45 cm wide. There is no proper projection on the terrace level on south and west side to shade the walls on first floor. This causes the walls to heat up and hence permits the heat into the rooms through conduction. The plastered exterior surface is finished with light beige colored distemper which reflects solar radiation to some extent.

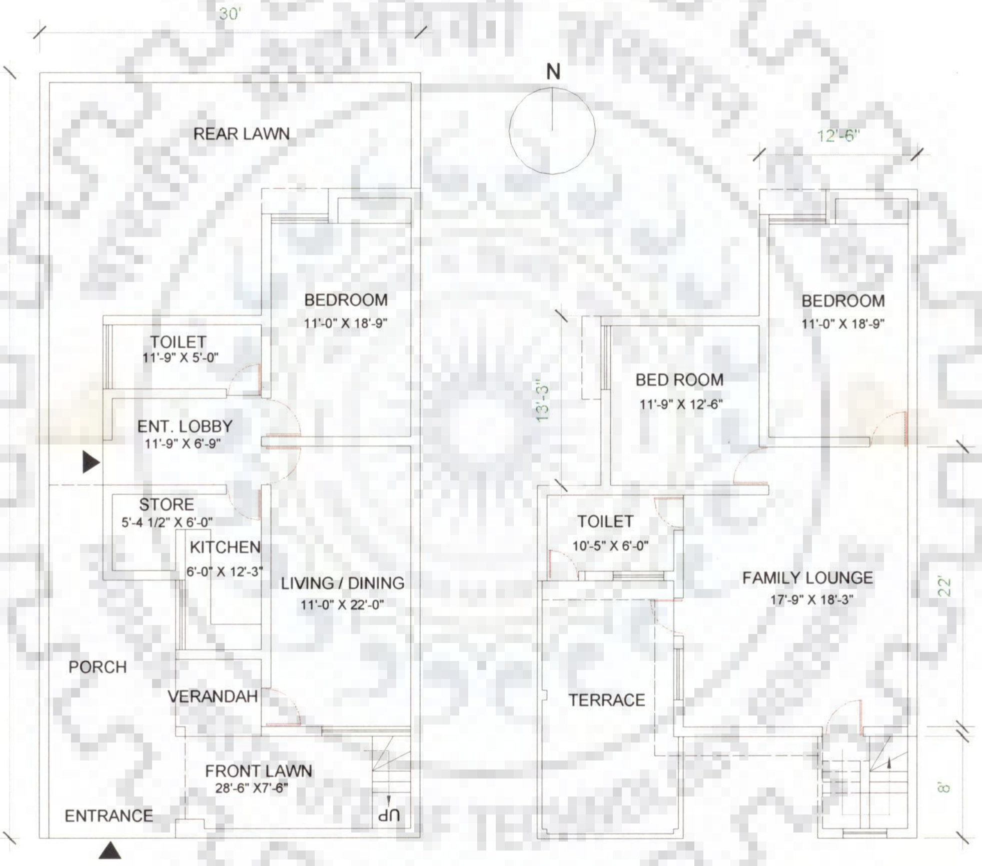


Figure 5.32 Ground and First Floor Plan of L.D.A. House II.

5.4.5.2 THERMAL PERFORMANCE OF LDA HOUSE II

The summer temperatures measurements were observed in various rooms in the L.D.A. House on 9 June 2004 and the winter temperature measurements were taken on 28 January 2005.

Thermal performance of LDA House II in summer

The room temperature in different spaces was found to be above the slightly warm zone. The temperature fluctuation in the outdoors was in the order of 19°C whereas the indoor temperature fluctuation was of the order of 7°C. The maximum indoor temperature was 6-7°C lower than the corresponding outdoors temperature. Here it can be very well observed that the indoor temperature of this house is 4-5°C higher than the temperature of traditional house for the corresponding hours of the day. This can be attributed to the thin walls and the R.C.C construction without proper shading of walls. The outdoor relative humidity varies from 23% during day to 55% in early morning, but the relative humidity in different spaces varied from 27% to 41%. The overall relative humidity in this case was less as compared to any traditional house, which was slightly less than the comfort zone.

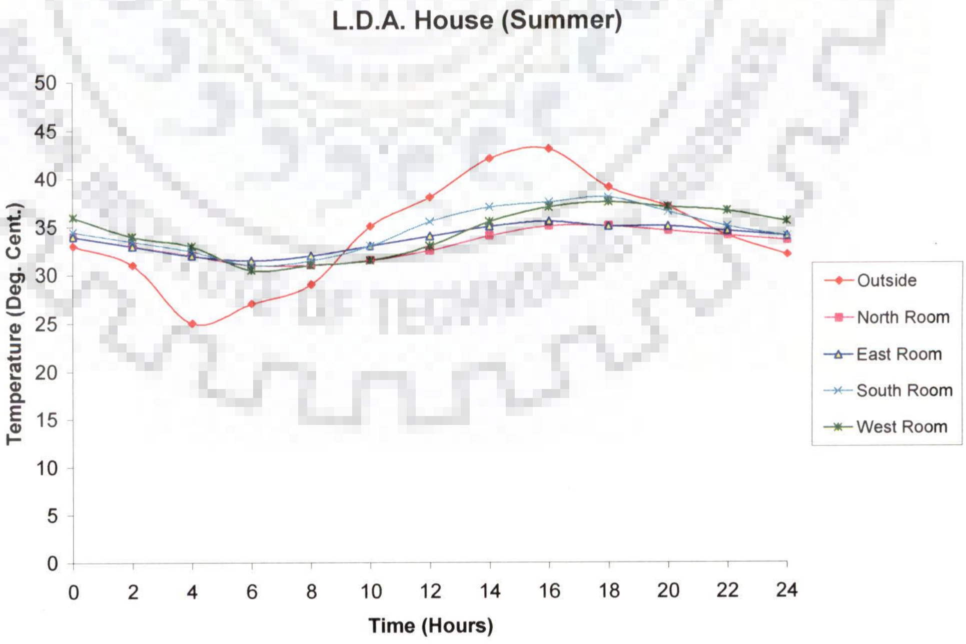


Figure5.33 Air Temperatures in different spaces of L.D.A. House II in summer

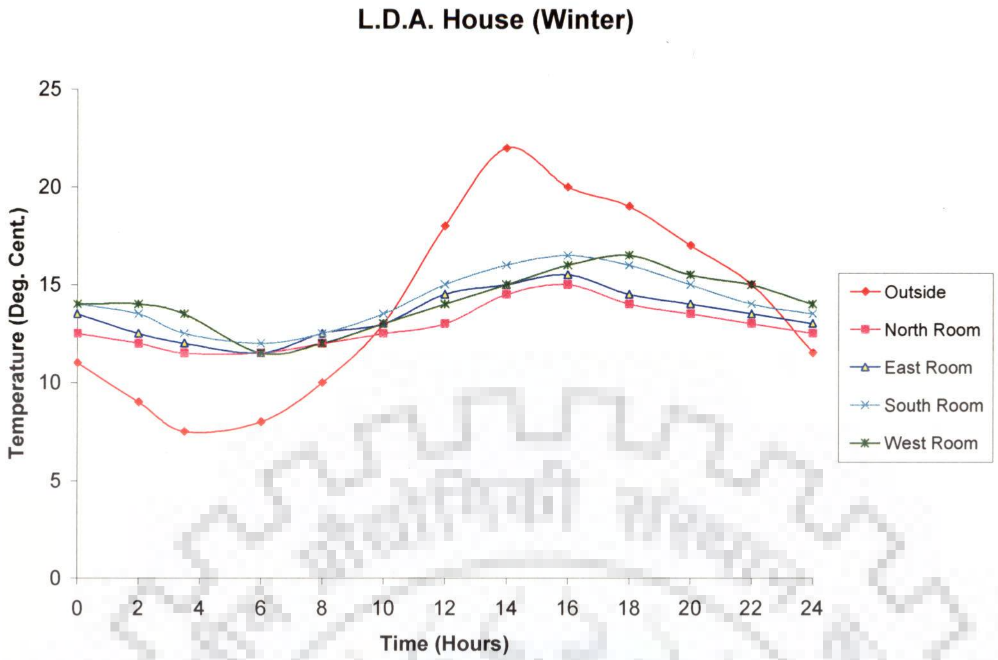


Figure5.34 Air Temperatures in different spaces of L.D.A. House II in winter

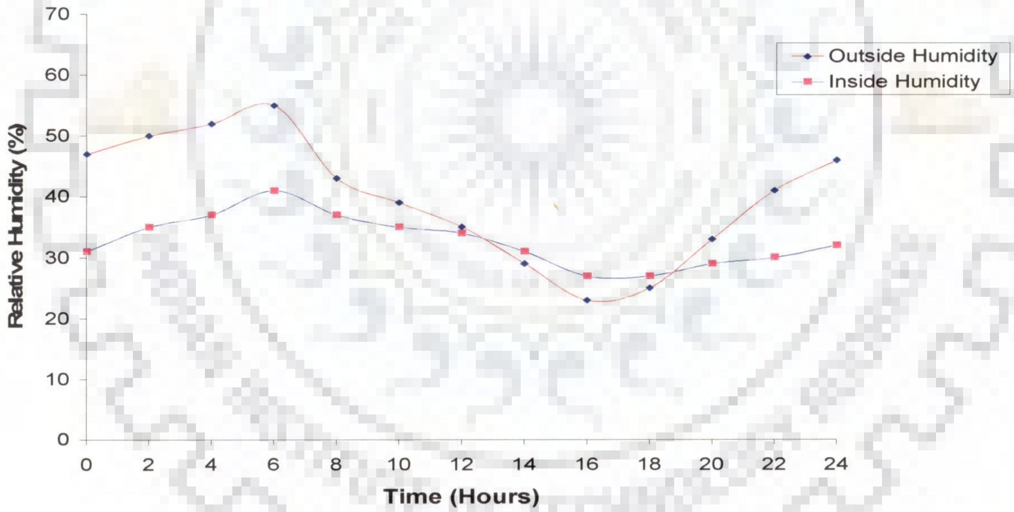


Figure 5.35 Relative Humidity in LDA House II in summer

Thermal performance of LDA House II in winter

The room temperature in different spaces was found to be below the slightly cool zone. The temperature fluctuation in the outdoors was in the order of 15°C whereas the indoor temperature fluctuation was of the order of 6°C. The minimum indoor temperature was 3°C lower than the corresponding outdoors temperature. Here it can be very well observed that the indoor temperature of this house is 4-5°C lower than the temperature of traditional house for the corresponding hours of the day. This can be attributed to the thin walls of 23 cm brick masonry construction and 10 cm R.C.C construction without proper shading of walls.

5.5 SUMMARY OF FINDINGS

The simultaneous monitoring of outdoor and indoor thermal conditions of three traditional house types together with that of two 'modern houses' in Lucknow has shown that the thermal capacity of the traditional houses, having courtyards together with their compact and self-shading design, has many advantage in limiting day time internal temperature rise during the hot seasons. During the winters the thermal capacity of the traditional houses play a major part in maintaining near comfort conditions internally during the night, even when the external temperature drops as low as 7°C. The comparative analysis of thermal performance of traditional houses and modern houses are summarized as followings:

1. The data collected shows that the indoor air temperature in the two traditional buildings is 3-4°C lower in summers and 2-3°C higher temperatures in winters as compared to the indoor temperatures in L.D.A house (Figure 11).
2. The difference between the sky and indoor temperature in traditional buildings is greater than the indoor temperature in L.D.A. house suggesting more comfort level in traditional buildings.
3. In summer, the amplitude of indoor air temperature in traditional houses was not more than 4-5°C, whereas in the modern houses the amplitude of indoor air

temperature was not more than 7-8°C while the outdoor temperature fluctuation was of the order of 19-21°C

4. In summer the mean maximum indoor temperature of different rooms of traditional house was 10-12°C lower and mean minimum temperature was 3-4°C higher than the outdoor minimum temperature whereas in L.D.A. house the mean maximum indoor temperature was 5-6°C lower and mean minimum temperature was 7-8°C higher than the outdoor minimum temperature.
5. In winter, in traditional houses there was 4-5°C temperature difference between mean maximum indoor temperature of different rooms and maximum outdoor temperature and 5-6°C temperature difference between mean minimum indoor temperature and the minimum outdoor temperature whereas in L.D.A. house there was difference of 8-9°C between mean maximum indoor temperature of different rooms and maximum outdoor temperature and 4-5°C temperature difference between mean minimum indoor temperature and the minimum outdoor temperature.
6. The indoor peak temperatures occurs at about the same time as the outdoor peak temperature in traditional buildings i.e. the time lag is around 24 hours due to massive thickness of walls whereas in L.D.A. house the indoor peak temperature is around 5 p.m. in the evening as the outdoor peak temperature is around 2 in the afternoon.
7. The courtyard system in traditional buildings ensured ventilation through the building even during the periods when the outdoor conditions were calm. The courtyard temperature was 1-2°C higher in late afternoons and 2-3°C lower in early morning as compared to the indoor temperatures of the rooms.

8. The areas of the building directly exposed to the sun were 2-3°C higher in traditional buildings due to thick massive walls whereas in L.D.A. house it was at times 8-10°C higher than the corresponding ambient air temperature.
9. The relative humidity in different spaces of modern houses in summer was less as compared to the relative humidity in different spaces of traditional houses.
10. Ventilation apertures in traditional houses were kept open during the day to provide greater thermal comfort through air movement in summers and were kept closed in winters to retain the heat gained whereas there was no provision of ventilators in L.D.A. house.

5.6 CONCLUSIONS

The settings of the experimentation and the criteria of the instruments used have been discussed in this chapter. It had been analyzed that the traditional residential buildings of Lucknow have shown better thermal performance as compared to that of modern houses. The simultaneous monitoring of outdoor and indoor thermal conditions of three traditional house types together with that of two ‘modern houses’ in Lucknow has shown that the factors benefiting the thermal performance of the traditional houses such as shading devices, thermally heavyweight construction, deep cavernous design buffer spaces, wind catchers, screens, recessed openings, water body, vegetation etc. which smooth the diurnal variation of temperatures whereas there are hardly any or few features which can be found in modern day houses. Finally the finding of the experimentation and comparative analysis with respect to thermal performance of the ‘modern’ house with traditional types had been discussed in this chapter.

CHAPTER 6

EVALUATION OF PASSIVE COOLING TECHNIQUES

6.1 INTRODUCTION

It has been observed in the previous chapter that the thermal performances of traditional residential buildings of Lucknow have been better as compared to that of modern houses. Various natural and passive cooling techniques benefiting the thermal performance of the traditional houses are self-shading, orientation, thick walls, heavy roofs, courtyards, surface color and surface texture. In order to evaluate the performance of different passive cooling concepts quantitatively, some of which have been used in traditional buildings and are still being relevant in modern buildings and some which are not used in traditional buildings, but have great potential for use as passive cooling techniques in the present context for possible energy savings have been evaluated. Consequently the minimum amount of energy required for different cooling techniques have been arrived at. Different cooling techniques considered for application of mathematical model in this chapter are Orientation, Overhangs, Surface color, Cavity in walls and roof and Insulation in roof and walls. The simulations results have been obtained by using Modified Admittance Procedure, which is being discussed at the beginning of the chapter. The analysis and quantification of passive cooling concepts in conditioned and non-conditioned buildings has been formulated through a mathematical model in this chapter.

6.2 MODIFIED ADDMITANCE PROCEDURE

The modified admittance procedure is a mathematical model developed by Sodha et al (1985) to set up heat balance across various building components and within various zones in which the building is divided. In this procedure an energy balance for each component of a building is numerically computed at different time of the day. The matrix size is kept only (2 x 2) irrespective of the number of layer of the building components and therefore the boundary conditions making it simpler to deal with the resulting mathematical expressions.

6.2.1 Heat Transfer through Building Components

Heat flow in and out of an enclosed space (apart from solar radiation) takes place along two main paths i.e. Conduction through the building envelope and the ventilation air exchange. The internal heat gain is through various building components such as walls, roof, doors, openings, floor and also through the heat radiated by the number of person present and mechanical/ electronic equipments. Since the heat gained by floor, and the heat radiated by the people and equipments is negligible, they have not been considered for the study. The heat transfer from each individual building component is shown in Fig. 6.1.

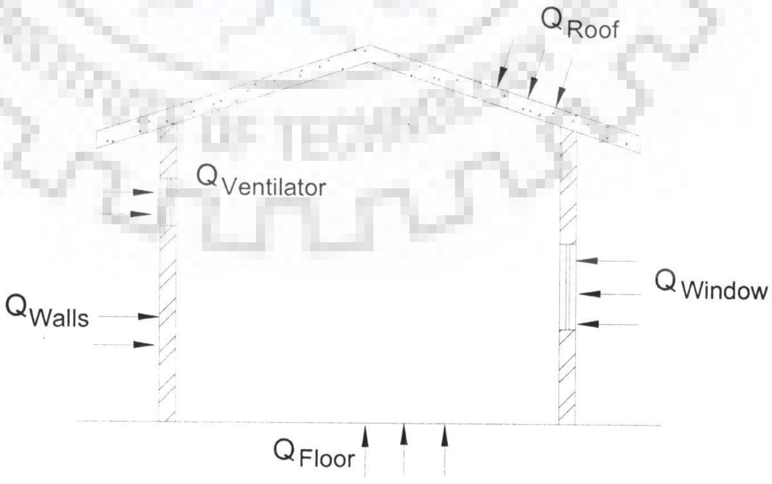


Fig. 6.1 Various heat gains in a building

a) Heat gain through Opaque Elements: Roof and Walls

The average value of the rate of heat transferred through an opaque building element can be written as

$$Q_{opaq} = A_{opaq} U_{opaq} (T_{so} - T_{Ro})$$

where,

T_{so} = Average Sol-air Temperature or effective temperature of the opaque surface (^{o}C),

T_{Ro} = Average Room Temperature (^{o}C),

U_{opaq} = Overall Conductivity of Opaque surface (W/m^{2} ^{o}C), and

A_{opaq} = Surface Area of opaque component (m^{2}).

b) Heat Gain through Windows: The total heat gained through windows admits solar heat through direct penetration and through combined effect of conduction, convection and radiation. The total heat gain through window can be written as:

$$Q_{win} = A_g U_g (T_{ao} - T_{Ro}) + gI_{win} A_g \qquad \ldots (6.1)$$

where,

A_g = Area of glazing (m^{2}),

U_g = Overall heat transmission coefficient of the window (W/m^{2}K),

g = Solar gain factor,

I_{win} = Average sol-air intensity incidents on windows (W/m^{2}),

T_{ao} = Average ambient temperature (^{o}C), and

T_{Ro} = Average room temperature (^{o}C).

c) Heat gain through Ventilation

The ventilation heat gain are given by the expression

$$Q' = m' C_a (T_{ao} - T_{Ro})$$

where,

m' = Volumetric flow rate of air (m^3/sec), and

C_a= Specific heat capacity of air (J/kgK).

These are, however, expressed in terms of the air changes per hour, N and can be written as

$$Q_v = 0.33\ NV\ (T_{ao} - T_{Ro})$$

where,

N= Number of recommended air changes, and

V= Volume of the inside space.

6.2.2 Heat gained in Non-conditioned Building

In non-conditioned building the heat gain/losses to the floor is negligible. These are calculated only for the fluctuations of the room air temperatures over its average value. This is because it is assumed that the ground is at a steady state temperature with no hourly variations in the temperatures.

6.2.2.1 Average Room Temperature (T_{Ra})

The average part of the inside air temperature can be calculated by simply equating the total heat loss to the total heat gain by the room air thereby giving the expression.

$$\sum_{i=4\,walls+Roof} A_{iw} U_{iw} (T_{soi} - T_m) + \sum_{g\,\mathrm{lm}} A_{ig} + \left(\sum U_{ig} A_{ig}\right)(T_{ao} - T_{Ro}) + 0.33NV (T_{ao} - T_{Ro}) = 0 \quad (6.2)$$

where, A_{iw} is opaque wall area i.e., $(A_{iw} - A_{ig})$

From Equation (6.2), T_{Ro} can be expressed as:

$$T_{Ro} = \frac{\sum_{i=1} \left(A_{iw} - A_{ig}\right)T_{in}U_w + \left(\sum_{i=1}^{4} A_{ig}U_{in} + 0.33Nv\right)T_{in} + \sum_{i=1}^{4} gI_{in}A_{ig} + A_R U_R T_{SOR}}{\sum_{i=1}^{4} \left(A_{ig}U_{in} + 0.33Nv + \sum_{i=1}^{4} \left(A_{iw} - A_{ig}\right)U_w + A_R U_R\right)} \tag{6.3}$$

where,

T_{Sa}, T_{Na}, T_{Ea}, T_{Wa}, T_{SOR} are the average part of sol-air temperature of South, North, East, West walls and Roof respectively,

A_{Sw}, A_{Nw}, A_{Ew}, A_W, A_R are the area of the South, North, East, West walls and Roof respectively,

T_{ao} = average part of ambient temperature, and

I_{no} = the average part of solar radiation incident on window.

6.2.2.2 Time Dependent Room Temperature (T_{Rn})

The fluctuation over the mean of the sol-air temperature and the rate of heat transfer between the sol-air and exposed surface of the building component with multilayered construction are found to be given by following matrix equation (Sodha al 1985).

$$\begin{bmatrix} T_{sn} \\ q_{sn} \end{bmatrix} = \begin{bmatrix} E_n & F_n \\ G_n & H_n \end{bmatrix} \begin{bmatrix} T_{Rn} \\ q_{Rn} \end{bmatrix} \qquad \text{.........(6.4)}$$

where,

E_n, F_n, G_n, H_n are calculated from:

$$\begin{bmatrix} E_n & F_n \\ G_n & H_n \end{bmatrix} = \begin{bmatrix} 1 & 1/h_0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} A_{n1} & B_{n1} \\ D_{n1} & A_{n1} \end{bmatrix} \cdots \begin{bmatrix} A_{nk} & B_{nk} \\ D_{nk} & A_{nk} \end{bmatrix} \begin{bmatrix} 1 & 1/h_1 \\ 0 & 1 \end{bmatrix}$$

where, n corresponds to the nth harmonic and k is the number of kth of building component. A_n, B_n and D_n are given by the following expressions:

$$A_{kn} = \cosh(1+i)\varphi_{kn} \qquad \varphi_{kn} = \sqrt{\frac{n\varpi L_k^2}{2D_k}}$$

$$B_{kn} = \frac{R_k}{(1+i)\varphi_{kn}}\sinh(1+i)\varphi_{kn} \qquad D_{kn} = \frac{(1+i)\varphi_{kn}}{R_k}\sinh(1+i)\varphi_{kn}$$

$$R_k = \frac{L_k}{k_k} \qquad D_k = \frac{k_k}{\rho_k C_k}$$

where,

L_k = thickness of the nth layer (m),

C_k = specific hat of the kth layer $\left(\frac{J}{kgK}\right)$, and

ρ_k = dnsity of the kth layer (kg/m^3)

T_{sn} and q_{sn} refer to the nth harmonic of the sol-air temperature and the heat flux on the exposed surface of the building component while T_m and q_m refer to the respective quantities of the temperature and heat flux on the inner surface of the building component. h_o and h_i are the two heat transfer coefficient on the outer and inner side of the building component respectively.

The values of $A_{n's}$, $B_{n's}$, and $D_{n's}$ and hence the matrix terms E_n, F_n, G_n, H_n, are calculated for each of the room component. The thermophysical properties of the building materials used in these calculations are given in the Table 6.1.

Table 6.1: Thermo Physical Properties of the building materials

S. No.	Materials	k (w/mK)	c (J/kgK)	ρ (kg/m^2)
1.	Bricks	0.81	880	1820
2.	Cement Plaster	0.72	840	1760
3.	R.C.C.	1.58	800	2280
4.	Mud phuska	0.52	880	1622
5.	Roof tiles	0.82	880	1820
6.	Cavity (air)	0.14	3600	0.34
7.	Insulation	0.039	840	50
8.	Plain Cement concrete	1.4	840	2100
9.	Sand	0.35	800	1450
10.	Soil	1.210	840	1958

Assuming o and j to the outside and inside surface respectively, q_j will represent the amount of heat flux entering to the room through the building component, Q_j can be expressed as:

$$Q_j = \left[\frac{T_{Ro} - E_n T_{Rn}}{F_n}\right] \times A_j \tag{6.5}$$

where,

A_j = surface area of the building element.

For the ground, h_o is replaced by the equivalent conductivity. Since the fluctuations in ground temperature are negligible, the equation can be expressed as:

$$\begin{bmatrix} 0 \\ q_{sn} \end{bmatrix} = \begin{bmatrix} E_{Gn} & F_{an} \\ G_{Gn} & H_{Gn} \end{bmatrix} \begin{bmatrix} T_{Rn} \\ q_{Rn} \end{bmatrix} \tag{6.6}$$

$$\begin{bmatrix} E_{Gn} & F_{Gn} \\ G_{Gn} & H_{Gn} \end{bmatrix} = \begin{bmatrix} 1 & 1/h_{if} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} A_{1n} & B_{1n} \\ D_{1n} & A_{1n} \end{bmatrix} \cdots \begin{bmatrix} A_{kn} & B_{kn} \\ D_{kn} & A_{kn} \end{bmatrix} \begin{bmatrix} 1 & 1/k_G \beta_{Gn} \\ 0 & 1 \end{bmatrix}$$

where,

K_G = conductivity of the ground.

$$\beta_{Gn} = (1+i)\sqrt{\frac{n\omega\rho c}{2k_G}}$$

where,

h_{if} = heat transfer coefficient between room air and floor, and

T_R = room air temperature.

From Eq.(6.6) the rate of heat transmission from the floor is given by

$$q_{Ha} = \frac{H_{Gn}}{F_{Gn}} T_{Ra} \exp(in\,wt) \qquad (6.7)$$

The heat balance for the room air temperature can be written as

$$M_R C_R \frac{dT_R}{dt} = \sum_{N,E,W,S} q_i + \sum_{roof} q_i + floor + \sum g_n I_n A_{un} - 0.33NV(T_R - T_a) \qquad (6.8)$$

The fluctuations over the average value of the room air temperature can be obtained by Fourier series. From Eq. (6.8) T_{Rn} can be expressed as:

$$T_R(t) = T_{\mathrm{Re}} + \sum_{n=1}^{\infty} T_{Rn} e^{in\,\omega t} \qquad (6.9)$$

where,

T_{Ro} = the average part of the room temperature, and

T_{Rn} = the time dependent part of the room temperature

since $\frac{dT_{Ra}}{dt} = 0$, T_{Rn} can be expressed as:

$$T_{Rn} = \frac{\frac{1}{F_n}\sum_{i=1}^{4} T_{in}\left(A_{iw} - A_{ig}\right) + \frac{T_{Hn}A_R}{F_{Rn}} + \sum_{i=1}^{4} gI_{in}A_{ig} + C_v T_{an}}{\frac{E_n}{F_n}\sum_{i=1}^{4} T_{in}\left(A_{iw} - A_{ig}\right) + \frac{E_{Rn}}{F_{Rn}}A_R + \frac{H_{Gn}}{F_{Gn}}A_F + \sum_{i=1}^{4} U_{ig}A_{ig} + C_v + M_R C_R in\ \omega t} \tag{6.10}$$

where,

$C_v = 0.33$ NV,

M_R = Mass of the room air,

C_R = Specific heat of the room air,

A_R = Area of the roof, and

A_F = Area of the floor.

and F_n, E_n, F_{Rn}, E_{Rn}, F_{Gn}, E_{Gn} are coefficient of wall, roof and ground,

6.2.3 Balancing of Thermal Load in Conditioned Building

For an air-conditioned building, in which the room temperature is constant. The total cooling load can be written as:

6.2.3.1 Average Heat Gain

The average heat gain of building components in a conditioned building can be calculated as:

$$Q_o = (\sum_{i=1}^{4} U_w \times (A_{iw} - A_{ig}) + A_R U_R)(T_{Ro} - T_{ao)} + (\sum_{i=1}^{4} A_{ig}U_{ig} + 0.33NV)(T_{Ro} - T_{ao}) + \sum_{i=1}^{4} gI_{in}A_{ig}$$

.........(6.11)

6.2.3.2 Time Dependent Heat Gain

$$Q_n = \sum_{i=1}^{4} \left(\frac{T_{Ro}}{F_n}\right)A_{iw} + \left(\frac{T_{Ro}}{F_{Rn}}\right)A_R \tag{6.12}$$

By substituting the average part and time dependent part of above Equations (6.11) and (6.12), the total heat gain in a room is calculated as follows:

$$Q_T = Q_o + \sum_{n=1}^{\infty} Q_n e^{in\omega t} \tag{6.13}$$

Based on the above mathematical formulation, simulations with various passive cooling techniques have been presented in the study. The results have been analyzed in the following section.

6.3 EVALUATION OF DIFFERENT PASSIVE COOLING TECHNIQUES

The Modified Admittance procedure can be used to evaluate the different passive cooling concepts. The basic strategies for any natural cooling methods can be to:

i. Reduce interception of solar radiation and its absorption by building components,

ii. Reduce transmission of heat into buildings, and

iii. Maximize heat losses from the buildings.

Within the context of these basic passive-cooling concepts, the effect of orientation, overhangs, surface color, double-glazing, cavity (in walls and roof) and insulation have been studied. Since thick masonry walls are uneconomical in terms of space due to scarcity of land and high cost of the construction. Therefore in place of thick masonry and heavy roofs, an equally effective technique of providing cavity in wall and roofing has been considered. For evaluation of surface colour as a cooling concept, only whitewash, which is the most commonly used surface colour in residential buildings in urban areas, has been considered. Since small openings were provided in traditional buildings to prevent the incoming solar radiation, which may heat up the interiors, therefore the concept of double-glazing, to restrict the solar radiation from penetrating into the building, has been considered for the study.

Energy gain or losses take place through windows, walls, roof and floor. In addition, ventilation losses contribute to the energy consumption for cooling or heating in conditioned buildings. For comparing the effect of cooling strategies, a unit/ module of single zone building of the dimension 15m x 10m x 3m as shown in the Figure 6.2, with simple construction of brick, cement, mortar and R.C.C., with a window area of 20% to floor area has been considered for the purpose of study. This has been considered as a base case.

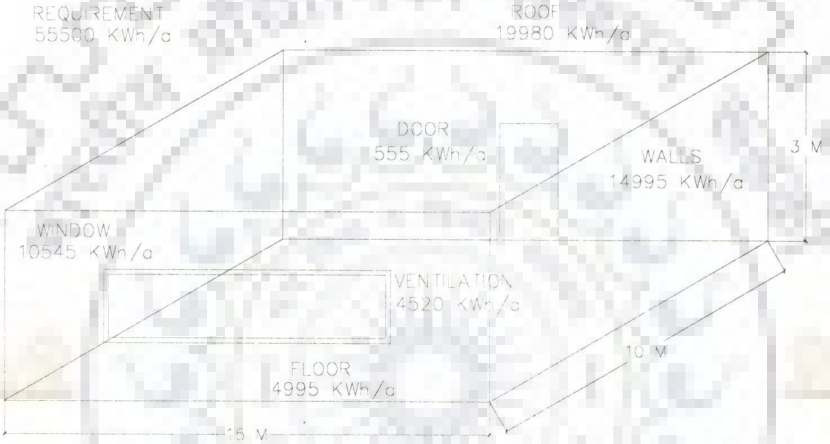


Fig. 6.2 Annual Energy demand in building of 150 m^2 floor area (Lucknow)

The total annual energy requirement is found to be 55500 kWh/a. The heat gained through different component of buildings of 150 m^2 floor area is shown in the Figure 6.2 and summarized as followings:

i.	Roof	19,980 kWh/a
ii.	Walls	14,995 kWh/a
iii.	Window	10,545 kWh/a
iv.	Floor	4,995 kWh/a
v.	Ventilation	4,520 kWh/a
vi.	Door	555 kWh/a

It is evident that the roof has maximum contribution to the heat gains followed by walls and windows. Treating this case as a base case, the effect of different techniques used to reduce heat gain has been quantified by calculating the total heat gained in the buildings after incorporating different passive cooling concepts to the base case. The hourly values of all the climatic parameters have been considered for the corresponding test reference year. The thermo physical properties of the building materials used in the base module are given in Table 6.1. Starting from zero glazing, the results have been simulated first with increasing glass area and the specific energy needed required was studied. The specific energy consumption (kWh/m^2a) is found to be increasing with the increase in glass area of the window placed in south wall. If the window is placed on west wall, north wall and east wall, the specific energy consumptions as calculated for annual simulation are given in Table 6.2. The best orientation from cooling energy point of view is 180° i.e. window in north wall and shorter walls facing east/west and longer side of the building facing north/south.

Table 6.2: Specific Energy of various Glazing areas on different orientations

S. No.	% of Glazing	S. Glazing (kWh/m^2-a)				D. Glazing (kWh/m^2-a)			
		South Wall	West Wall	North Wall	East Wall	South Wall	West Wall	North Wall	East Wall
1.	0	314	315	313	315	314	315	313	315
2.	5	343	342	331	342	338	333	323	331
3.	10	384	383	357	379	362	373	346	369
4.	15	410	415	377	408	394	401	362	396
5.	20	450	444	394	437	430	425	374	418
6.	25	494	487	441	482	469	462	402	458

The thermal performance of a non-conditioned module incorporating various passive cooling concepts is compared in terms of maximum and average temperatures. Average temperature and reduction in average temperature and maximum operative temperature of the simulated space by various measures are given in Table 6.3

Table 6.3: Performance of operative temperature in non-conditioned building

S. No.	**Case**	**Operative Temp. for Lucknow**	
		Max.	**Average Temp.**
1.	Normal Construction	41.5	38.25
2.	Orientation 180	40.4	38.2(-0.05)
3.	Normal Cons. + Cavity Roof	38.8	37.45(-0.8)
4.	Cavity Wall +Cavity Roof	38.5	37.3(-0.95)
5.	Normal Cons. + Roof Insulation	38.1	36.7(-1.55)
6.	Cavity Wall + Roof insulation	37.5	36.3(-1.95)
7.	Insulation on Wall & Roof	37.2	35.9(-2.35)
8.	White Wash on W all & Roof	37.1	35.7(-2.55)
9.	White Wash on wall + Ins. on Roof	36.5	35.2(-3.05)
10.	White Wash on wall + Ins. on Roof + Double Glazing + Shading	36.2	35.05(-3.2)

In the simulation analysis of non-conditioned buildings in composite climate of Lucknow the orientation of 180° i.e. shorter walls facing east/west and longer side of the building facing north/south brings down the maximum air temperature of the room from 41.5° C to 40.4° C, cavity in wall and cavity in the roofing lowers the air temperature from 41.5° C to 38.5° C, insulation on wall and roof reduces the maximum air temperature from 41.5° C to 37.2° C, white wash on walls and roof can bring down the maximum of room air temperature from 41.5°C to 37.1°C. The most significant change in the room air temperature can be observed when white wash on walls, Insulation on roof, double-glazing and shading is simultaneously incorporated in the base case. The Figure 6.3 below shows the comparative performances of hourly variations of temperatures in a day for the month of June. From the above-simulated results it is observed that, there is possibility to reduce the operative temperature of living space by 5-6°C only.

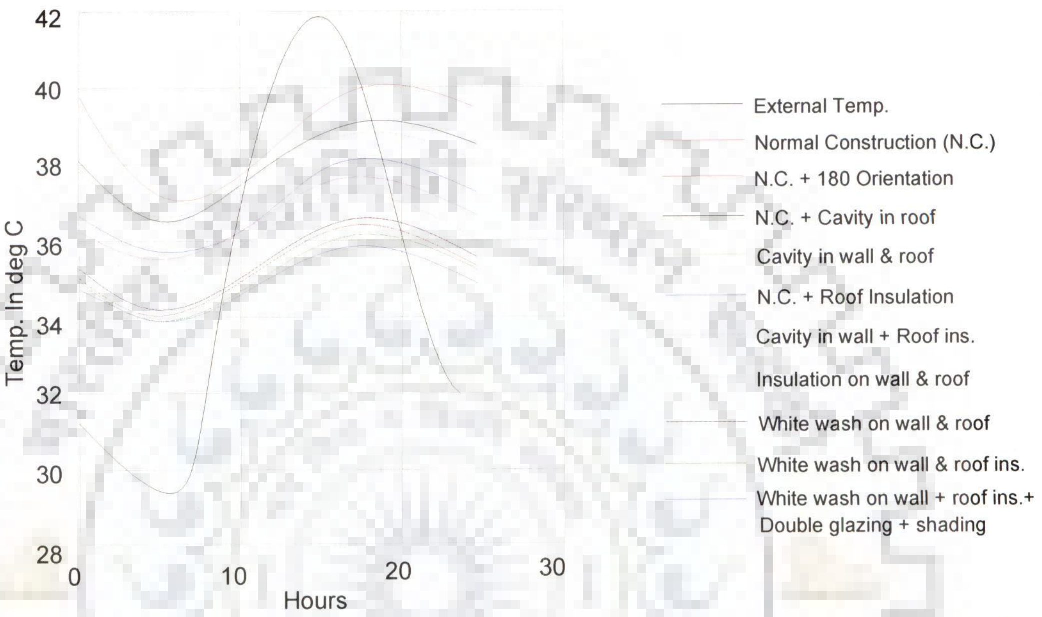


Fig. 6.3 Comparative performance of hourly variations of room temperature for different passive cooling techniques during summer

For air-conditioned building the simulation has been done for each of the climatic data for calculating the specific energy consumption of various passive-cooling techniques. After studying the simulation results in conditioned buildings the following inferences can be drawn:

a) Shading devices (overhang/side fins) can reduce cooling demand by 5-9%

b) Orientation of 180° i.e. shorter walls facing east/west and longer side of the building facing north/south reduces the cooling demand by 5.4%

c) Double glazing can reduce cooling demand by 7.5% to 10%

d) Cavity in walls and roof improves the performance by 44%

e) Cavity walls and roof insulation improve the performance by 59%

f) Insulation of 5 cm (k = 0.039) on walls and roof can reduce the cooling demand by 68%, further use of shading devices and set point temperature of 26°C can further reduce the cooling demand by 72%, i.e. the specific energy can be brought down from 400 kWh/m^2 a to 102 kWh/m^2 a in Lucknow climate.

From the results it has been observed that large energy savings are possible. The results are given the Table 6.4 for a set point temperature of 26 °C, with percentage reductions given in brackets.

Table 6.4: Annual cooling energy demand (kWh/m^2a) for different variations in the building design

Sl. No.	**Case**	**Cooling energy demand (kWh/m^2a)**
1.	Base case	370.88
2.	Orientation (180°)	350 (5.4)
3.	Over-hang & side-fins	336 (9.2)
4.	Double-Glazing	333 (10)
5.	Base case + Cavity Roof	256 (31)
6.	Cavity Wall & Roof	207 (44)
7.	Base case + Roof insulation	199 (46)
8.	Cavity wall + Roof Ins.	152 (59)
9.	Insulation on Roof & Wall	116 (68)
10.	White wash on Wall & Roof	218 (35.6)
11.	White wash on Walls + ins. on roof	163 (55.8)
12.	Overhang & side fins + Insulation on Roof & Wall + Double Glazing	102 (72.4)
13.	Overhang & side fins + Ins. on Roof & Wall + Double Glazing + 26° C set point temp.	77 (79.2)
14.	Overhang & side fins + White wash on Walls + ins. on roof + 26° C set point temp.	107 (71)

Table 6.5 shows the percentage reduction in the specific energy, while incorporating the individual or combined passive cooling concepts for conditioned buildings.

Table 6.5: Percentage reduction in Specific Energy (kWh/m^{2}a) for different Passive concepts.

S. No.	Passive Concepts	% Reduction in Sp. Energy
1.	Orientation (180° Window on north wall)	4-8
2.	Over-hang & side-fins	5-9
3.	Double-Glazing	7.5-11
4.	Cavity on Roof only	28-31
5.	Cavity on Wall & Roof	41-44
6.	Roof insulation only	44-46
7.	Cavity on Wall & Roof Insulation	57-60
8.	Insulation on Roof & Wall	66-69
9.	White wash on Wall & Roof	35-44
10.	White was on Walls & insulation on Roof	55-57
11.	Over-hang & side-fins + Insulation on Roof & Wall + Double Glazing.	71-74

6.4 CONCLUSIONS

The results presented in this chapter for single zone building with 10% of floor area as a window towards north direction is considered to be the best orientation in hot and composite kind of climates The application of whitewash and reflective coating on surfaces of walls and roof in non-conditioned building has given better performance and also cavity walls and roof has been given a moderate reduction in operative temperatures. In conditioned building insulation on walls and roof with double-glazing on windows with shading devices gives best results. The specific energy reductions are possible by even 79%. It has been observed that the passive techniques used in traditional residential buildings have a lot of potential to bring down specific energy consumption of buildings. The building designers or the Architects should use these energy saving measures to bring down the specific energy consumption of building.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 INTRODUCTION

The results of the study carried out-and discussed in earlier chapters, particularly those that are relevant for designing thermally comfortable buildings in composite climate have been summararised here. Recommendations in the from of design guidelines that have made corresponding to the conclusions drawn from the study with respect to Landscaping, Spatial Planning, Building Envelope, Ventilation, Day Lighting, External Finish and Colour etc. are summarized in this chapter.

7.2 CONCLUSIONS

In view of the increasing demand and consumption of energy by modern buildings, it has now become essential to develop alternative technologies associated with primitive aspects for energy conservation. So the techniques used in traditional buildings that have been rediscovered through this study and other similar studies, which is suitable to our requirements should be extracted and utilized in creating contemporary architecture. There are many simple ways in which, without recourse to new technologies and systems, buildings have been found to be much less wasteful than the overlit, overheated, overcooled, under insulated glass prisms that are today's commercial norm. By a greater sensitivity to local climatic conditions, a more tactful respect for surroundings and topography, for trees and the environmental values of planting, by careful design and by in many cases a return to traditional materials and methods of building, there are long term economic benefits in fuel savings and energy conservation.

The traditional buildings give us many examples of a sensitive approach to energy conscious designs for indoor comfort conditions. The study of traditional buildings has been found to be achieving adequate level of thermal comfort in all the components of buildings. The concept of orientation, use of locally available materials, clustering of buildings, selection of proper shading devices, courtyard concepts etc. have been investigated and found suitable for providing adequate thermal comfort in buildings at places where artificial sources of energy on regular basis are not available. Provision of small sized windows fitted in thick brick walls, having their outer areas larger than inside areas provides adequate protection against diffused and reflected radiation. Horizontal projections on south walls have been found effective in excluding the summer sun and permitting infiltration of light in winters. Plantation of deciduous trees provides evaporative cooling and reduces the temperature of air in the immediate contact of the building. Shading of courtyard walls reduces the solar heat gain in summers.

After going through the principles of energy conservation and the factors responsible for such a design, which have been followed, knowingly or unknowingly, in the traditional residential buildings, a process almost in the form of algorithm can be developed, which will help find the optimal form/ solution for a given set of requirements and constraints. The basis of energy responsive design involves considering climate as a parameter of design in every aspect of building and built environment. Conclusions drawn from the study can be put in a logical sequence, which proceeds from the macro level details to micro level details. They are summarized as follows:

Landscaping

1. Proper Landscaping can be one of the important factors for energy conservation in buildings. Vegetation and trees in particular, very effectively shade and reduce heat gain. Trees can be used with advantage to shade roof, walls and windows. They can also create wind effects improving indoor air motion. It also causes pressure differences, thereby, increasing and decreasing air speed or directing airflow. They can, therefore, direct air into a building or deflect it away.
2. Vegetation around a building absorbs solar radiations to facilitate evaporative cooling. Ground surface around the building also influence air temperature by their properties and characteristics. Absorption by the paved areas, solar angles and type of surface will control majority of heat reflected onto most of the buildings.
3. Water absorbs relatively large amounts of radiation. Water bodies when planned in the vicinity of a building create moderating effects of extreme temperature variations. Due to evaporative cooling it results in an environment of controlled humidity and temperature. As a result, during the daytime areas around water bodies are generally cooler. At night, however, water bodies release relatively large amounts of heat to the surroundings. This heat can be used for warming purposes.

Spatial Planning

4. The plan form of a building affects the airflow around and through it. It could either aid or hinder natural ventilation. The perimeter to area ratio of the

building is an important indicator of heat loss and gain. It, therefore, plays a role in ventilation, heat loss and heat gain.

5. The building orientation determines the amount of radiation it receives. The orientation, with respect to air patterns, affects the amount of natural ventilation possible. Location or orientation of an individual room may depend on the type of occupancy and the time of use. Interior spaces can be subdivided so as to separate heating and cooling zones.
6. Courtyard is an effective means of attenuating internal thermal conditions. It provides shaded spaces but it is effective only when it has a plan area and volume relationship proportional to built-up area and its volume. Provision of a central courtyard is preferable which helps in achieving shaded spaces, natural light in most of the spaces and better circulation of air without providing much openings on the exterior surfaces.
7. When buffer spaces are provided between exterior and interior spaces, heat from outside dissipates here before entering the interiors.

Building Envelope

8. Overall planning of a building can be centrifugal and compact. The surface area to volume *(S/V)* ratio (the three dimensional extrapolation of the *P/ A* ratio) is an important factor determining heat loss and gain. The greater the surface area the more the heat gain/loss through it. So small *S/V* ratios imply minimum heat gain and minimum heat loss.
9. Conductive heat gains resulting from the solar radiation take time to penetrate the building envelope. The length of time is dependent upon the thermal inertia of the building and hence its thermal response. It is also dependent

upon the location of the thermal insulation sandwich within the building envelope. Thick walls provided in the traditional buildings create thermal time-lag thus creating comfortable conditions. Heat through the exposed wall is not transmitted immediately in the daytime itself but it reaches the interiors at night, as required in winters. At a summer night this heat can be removed by providing proper ventilation.

10. For a building whose external envelope is either massive or well insulated thermally, with windows recessed or shaded from direct solar radiation, peak indoor mean radiant temperature is delayed until the evening.
11. The most important factor for thermal comfort conditions in the interiors of a building is to minimize heat gain through roof, walls and openings. Comparatively there is not much effect due to exposed surfaces on heat load but the major heat gain is through roof therefore, roof shading is essential.
12. Curved roof offers many-advantages over flat roof. These are structurally stronger and there can be a saving in material. Curved roof has a larger convection heat-transfer area and transfers hat more efficiently than a flat roof therefore, a curved roof is more easily cooled.
13. Sloping roof absorbs less heat than the flat one due to its shape and less exposure to solar radiations. A structure with domical roof permits the warm air to rise at the top above living area maintaining comfort in this area.

Ventilation

14. Air movement is required in the interiors mainly in the rainy seasons to bring high humidity to a lower level. Stack effect, suction effect, Venturi effect etc.

created due to the size and location of the openings, help in enhancing the movement of air in the interiors.

15. Heat gain resulting from solar radiation through glazed windows is instantaneous. Sun protection of glazed windows is essential due to greenhouse effect but it should be provided in such a way that air movement is not restricted. The peak seasonal heat gain occurs when the sum of the instantaneous heat gain through the glazing and the heat gain through the opaque portion of the building envelope is a maximum.
16. Increased height of the building improves ventilation by providing circulation of air through the ventilator, located just below the ceiling.

Day Lighting

17. Height of the ceiling if reduced increases illumination effectiveness in larger rooms with light finish. Curved ceilings facilitate equal distribution of light thus less openings are required on the outer wall which reduces heat gain.
18. Window location makes a difference to the quality of light obtained indoors. High windows (ventilators) provide the best distribution of the direct and diffuse light. As the position of a window goes higher, light penetration increases with lesser heat gain.

External Finish and Colour

19. The colour and texture of a material's surface determines its reflectivity. The lighter the colour and smoother the surface, more the reflectivity of the material. The darker the surface and rougher it is, the lower the reflectivity. Such materials would store more heat and reradiate it at a later time.

20. Surface colour of the external wall affects both the percentage of solar radiation absorbed by the external surface and also the long wave radiation emission. Hence, the heat flux transmitted into the building is considerably reduced when external surface is painted with a colour with minimum absorption of solar radiation and high emission in long wave region.

7.3 RECOMMENDATIONS

Recommendations of the study have been made in the form of design guidelines that have been made corresponding to the conclusions drawn from the study with proposed modification to suit the present day architecture. Design guidelines with respect to Landscaping, Spatial Planning, Building Envelope, Ventilation, Provisions for Daylighting, External Finish and Colour etc. are summarized as follows:

Design Guidelines for Landscaping

1. Landscape should be planned in such a way that it creates environmental corridors to enhance air movement in the interiors of the building. Excessive vegetation should be provided in the surroundings of a building to maintain comfortable conditions due to evaporative cooling.
2. Trees with high canopies and good spread should be planted on south east, south and south west positions. Trees with low stem should be planted on the west side to cut low evening sun. Deciduous trees and shrubs provide summer shade yet allow winter access. The best locations for deciduous trees are on the south and the southwest side of a house.

3. Exterior walls with plantings should be covered to reduce heat transmission and solar gain. Plant material should be selected carefully so that planting shall not damage the building.
4. Plants, shrubs, lawns should be provided between the building and the street to reduce heat build up, if maintenance is possible.
5. Terrace gardens should be provided to reduce heat gain through exposed roof. A roof pond can also be planned to minimize heat gain through the roof. Roof slab when over hanged shades a part of wall area below.
6. Water/water bodies should be used both for evaporative cooling as well as minimizing heat gain. Taking into account the wind patterns and vegetation they should be used to direct cool breeze into the house. Water bodies such as pools, fountains etc. should be planned in the wind direction to provide maximum comfort indoors.

Design Guidelines for Spatial Planning

7. Plan should be centrifugal and compact. To minimize heat transmission for a given enclosed volume, a building should be constructed with a minimum exposed surface area. A round building has less surface area, hence, less heat gain or loss than any other shape for an equal amount of total floor space. A square building has fewer surfaces than a rectangular building of equal area per floor, and so experiences less thermal transmission loss or heat gain.
8. Rectangular form of the building should be elongated along east-west direction. This means that the orientation of the building should be north south. Non-habitable rooms should be provided as heat barriers in the worst orientations on the outer periphery of the building.

9. The shape should be such that it resists unwanted heat gains or losses. Consider exotic shapes for special considerations. Zig-zag exterior wall configurations, rhomboid shaped buildings, and other forms can all be used to control heating, cooling and lighting. Zig-zag configurations of east and west walls provide self shading to reduce summer solar loads, and provide natural wind breaks. South facing Zig-zag walls permit low rays to enter the building in winter to supplement the heating system. The Zig-zag configuration is only one example of manipulating form to achieve maximum energy benefits.
10. Shaded courtyards can be quite effective as reservoirs of cool air in hot climates. The size of the courtyard in proportion to the height of the building should be such that it provides shaded spaces. At night, cool air tends to collect in the court. A central courtyard fulfills the requirement of natural light and induced ventilation in the surrounding spaces, maintaining comfort condition. In the present day buildings, presence of a non-functional duct is mostly found for the purpose of lighting and ventilating a few spaces. Instead of such provisions, building can be planned in such a way that a multifunctional open to- sky space is provided at one place, which fulfills the requirements of light and ventilation.
11. Planning should be done in terms of open, semi-open and enclosed spaces. Verandahs, balconies, galleries, toilets, stores, staircases and even overhangs can be provided as buffer spaces between the exterior and the interior spaces. Covered verandah on the west side and pergola covered with creepers can be provided on the south side.
12. To provide sun shading, projected eaves and balconies should be provided. Verandahs should be provided on the western and the southern sides along

with certain offsets in the plan depending upon the activities, on the east and west sides to provide self-shading taking the advantage of the direction of movement of sun.

Design Guidelines for Building Envelope

13. Minimize outside wall and roof areas (ratio of exterior surface to enclosed volume Surface to volume ratio i.e. SVR) is one way to express the relationship between outside building surface area and the enclosed space that can be used in order to compare differently shaped buildings containing equal volumes of space.
14. Minimum glass area should be provided on the western side or the windows should be made deeply recessed because even curtains or internal blinds cannot prevent heat to accumulate inside the room due to green-house effect. If unavoidable, traditional bamboo screens can be used outside the windows, moved in guide rails. To operate it easily, simple rope and pulley arrangement can be made.
15. The external envelope of course must be designed in such a way so as to delay the effect of the outdoor heat gains on the mean radiant temperature indoors till evening. If this is done the cooling will normally only be required to offset the instantaneous solar heat gains through the glazed windows. With suitable external and choice of glass, the peak seasonal cooling load for a building can be reduced.
16. Temperature differential should be created between outer and inner surfaces of an exposed wall to achieve thermal time-lag. This can be done either by providing thick masonry walls as it was done in the past, which is not

affordable in the present circumstances. Instead we can create time-lag by providing cavity / air gap or Insulation within the wall. However, air gap/ cavity is not required on the north side.

17. The best location for the thermal insulation is at the outside surface. This will reduce impact of solar heat gains indoors and have a beneficial effect on the energy consumption required for seasonal cooling.
18. Greater ceiling heights improve environmental conditions in the summer time by permitting warm air to rise. However greater ceiling heights increase the perimeter areas, thus increasing heat transmissions through the walls.
19. Shape of the roof should be designed such a way that it receives oblique radiations from the sun, which have low intensity, or some provisions can be made for the flat roof to fulfill this requirement.
20. Wherever possible, curved ceiling should be preferred to the flat one for saving in material and rapid cooling of the roof.

Design Guidelines for Openings

21. The configuration of building and the openings should be adjusted in such a way that cross ventilation is allowed through occupied spaces. ‘Air tunnel system’ can be implemented in the modem buildings. Large overhangs should be provided to promote air motion in the working zone inside the building. Verandahs open on three sides, should be provided to increase room air motion.
22. Wing walls, overhangs & louvers to direct summer wind flow into the interiors should be used. ‘Open Plan’ interior should be used to promote interior airflow.

23. On the leeward side opening can be made larger to create suction effect to increase air movement indoors. They should be provided in two levels to create stack effect. Openings should be provided in the skylight for the same purpose. It is also possible to implement 'wind tower system' with the tower located over the staircase and the openings in it facing wind direction. In such case, openings in the walls on the leeward side create induced ventilation.
24. Screens or 'jalis' should be provided on certain openings to create forced ventilation by passing breezes, also interrupting solar gain. These screens should mainly be provided at the openings located in the direction of wind and can be designed in such a way that privacy is maintained inside the building.
25. The building should be oriented so as to use cooling breezes in summer and avoid cold winds in winter.

Design Guidelines for provisions for Day Lighting

26. Curved ceilings should be provided to facilitate equal distribution of light. This can be done by using precast channel units of this shape.
27. Individual spaces should be arranged in such a way that more natural light reaches the interiors.
28. Clerestory windows should be provided for light penetration with lesser heat gain and skylights should be provided to light the inner dark spaces.

Design Guidelines for External Finish and Colour

29. Surface colours should be light while textures should be rough. This will result in greater reflectivity, shading and reradiation. Heat reflective materials should be used on surfaces oriented to summer sun. External surface of the walls and

roofs should be light coloured or made reflective with the use of material of such quality.

30. Whitewashing reduces the absorptivity of the wall surface, minimizing the effect of solar radiation on internal climate and tends to stabilize the internal temperature.

7.4 AN EXTENDED CRITIQUE AND POTENTIAL FOR FUTURE RESEARCH

Learning from the traditional wisdom of previous generations through the lessons of traditional buildings can be a very powerful tool for improving the buildings of futures. Inspite of advancements made to control the parameters of weather affixation of and highest priority to the power generation, there is adequate justification to review the existing design methodologies, make observations on their efficacy and suggest suitable modifications for deployment of existing techniques either singly or in combination for cooling the building. Non-linearity in the heat flow, which has been considered as nonexistent and deserves to be studied by extending the mathematical models included in the present study. The present study has been confined to accomplish thermal comfort in individual buildings. Obtaining of thermal comfort by thermal modeling at a sector urban level needs to be researched into.

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DIRECT SOLAR RADIATION CHART (WH /SQ. M) FOR LUCKNOW ON 10 JUNE 2004

HOURS	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
HORIZONTAL SURFACE	0	81	270	472	649	795	891	914	891	795	649	472	270	81	0
NORTH WALL	0	147	158	98	27	4.0	0	0	0	4.0	27	98	158	147	0
SOUTH WALL	0	0	0	0	0	36	75	89	75	36	0	0	0	0	0
EAST WALL	0	385	597	634	555	410	220	0	0	0	0	0	0	0	0
WEST WALL	0	0	0	0	0	0	0	0	220	410	555	634	597	385	0
NORTHEAST WALL	0	376	531	520	413	265	101	0	0	0	0	0	0	0	0
SOUTH EAST WALL	0	170	310	378	372	315	209	63	0	0	0	0	0	0	0
NORTH WEST WALL	0	0	0	0	0	0	0	0	101	265	413	520	531	376	0
SOUTH WEST WALL	0	0	0	0	0	0	0	63	209	315	372	378	310	170	0

DIRECT SOLAR RADIATION CHART (WH /SQ. M) FOR LUCKNOW ON 15 JANUARY 2005

HOURS	6	7	8	9	10	11	12	13	14	15	16	17	18
HORIZONTAL SURFACE	0	1	93	242	374	459	489	459	374	242	93	1	0
NORTH WALL	0	0	0	0	0	0	0	0	0	0	0	0	0
SOUTH WALL	0	19	252	427	548	612	635	612	548	427	252	19	0
EAST WALL	0	34	352	421	343	187	0	0	0	0	0	0	0
WEST WALL	0	0	0	0	0	0	0	187	343	421	352	34	0
NORTHEAST WALL	0	11	69	1	0	0	0	0	0	0	0	0	0
SOUTH EAST WALL	0	35	428	601	627	568	447	301	146	8	0	0	0
NORTH WEST WALL	0	0	0	0	0	0	0	0	0	1	69	11	0
SOUTH WEST WALL	0	0	0	8	146	301	447	568	627	601	428	35	0

GLOSSARY

Awadh	A key province of Mughal Empire built during the reign of Emperor Akbar in 1590.
Bagh	A garden, An orchard or a plantation.
Baoli	An underground stepped water tank.
Baradari	(Barah- twelve, dari- a door). A house or a building having twelve doors, an open building, a summer house, a pavilion.
Chattri	A Kiosk. or small pavilions, acting as a turrets on the roof.
Darwaza	A Gateway or portal
Ganj	A Market or a market centre
Haveli	A palatial residence. The word corresponds to the word Mansion in English
Imambara	A building in which the festival of Muharram is celebrated and the services in commemoration of the martyrdom of Ali (Prophet Mohammad's son-in- law) and his sons Hasan and Hussein in Karbala, Iraq in the year 680.
Indo-Saracenic	Many colonial style buildings were built during the british era. Later, the traditional style and the Mughal style were incorporated into this. This blended style is called the Indo-Saracenic style.
Jaali	Stone latticework on walls and entrance through which, one could look outdoor and let sunlight and air. Usually 3 to 5 mm thick, with arabesque or geometrical patterns.

Jharokha	small size decorative openings, sometimes projected, induce forced air movement into the interiors of the building.
Kothi	Houses commissioned by the Nawabs, A Mansion.
Lakhauri bricks	Thin or narrow bricks, Brick Tiles
Lucknow	The capital of Uttar Pradesh, a state of Northern India.
Mahal	An Estate, A Palace
Majlisi	A Mourning place, a space meant for mourning during the month of Muharram
Muharram	The first month of Islamic calendar, the first ten days of the month are held as a festival, sometimes celebrated by strict religious rites.
Nawab	The title of a governor or a nobleman in the Indian subcontinent.
Nawabi	Of or belonging to, or dating from native rule (i.e. of Nawabs of Awadh).
Shia	Member of Mohammedan sect that put Ali, son-in-law of Prophet Muhammad in the rank of Caliph.
Shikhara	A Spire or tower.
Zenana	The female quarters or household, in a palace or house, generally closed to outsiders.

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APPENDICES

ANNUAL SOLAR RADIATION CHART (WH /SQ. M/DAY) FOR LUCKNOW IN 2005

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
HORIZONTAL SURFACE	3231.0	4249.0	5390.0	6462.0	7079.0	7230.0	7079.0	6462.0	5390.0	4249.0	3231.0	2827.0
EAST/WEST WALL	1529.0	1952.0	2288.0	2689.0	2798.0	2801.0	2798.0	2689.0	2288.0	1952.0	1529.0	1337.0
NORTH EAST/NORTH WEST	160.0	441.0	844.0	1535.0	2032.0	2206.0	2032.0	1535.0	844.0	441.0	160.0	810.0
SOUTH EAST/SOUTH WEST	3242.0	3259.0	2962.0	2496.0	2011.0	1817.0	2011.0	2496.0	2962.0	3259.0	3242.0	3161.0
SOUTH FACE	4371.0	3978.0	2988.0	1520.0	581.0	311.0	581.0	1520.0	2988.0	3978.0	4371.0	4351.0
NORTH FACE	0.0	0.0	0.0	156.0	610.0	868.0	610.0	156.0	0.0	0.0	0.0	0.0

DIRECT SOLAR RADIATION CHART (WH /SQ. M) FOR LUCKNOW ON 10 JUNE 2004

HOURS	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
HORIZONTAL SURFACE	0	81	270	472	649	795	891	914	891	795	649	472	270	81	0
NORTH WALL	0	147	158	98	27	4.0	0	0	0	4.0	27	98	158	147	0
SOUTH WALL	0	0	0	0	0	36	75	89	75	36	0	0	0	0	0
EAST WALL	0	385	597	634	555	410	220	0	0	0	0	0	0	0	0
WEST WALL	0	0	0	0	0	0	0	0	220	410	555	634	597	385	0
NORTHEAST WALL	0	376	531	520	413	265	101	0	0	0	0	0	0	0	0
SOUTH EAST WALL	0	170	310	378	372	315	209	63	0	0	0	0	0	0	0
NORTH WEST WALL	0	0	0	0	0	0	0	0	101	265	413	520	531	376	0
SOUTH WEST WALL	0	0	0	0	0	0	0	63	209	315	372	378	310	170	0

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