An Experimental Study of Designed Passive Elements for Energy Efficiency in Buildings in Composite Climate

THESIS

Submitted in partial fulfilment
of the requirements for the degree of

DOCTOR OF PHILOSOPHY

By

MEGHANA SHRIKANT CHARDE

Under the supervision of

PROF. RAJIV GUPTA

BITS Pilani
Pilani | Dubai | Goa | Hyderabad

BIRLA INSTITUTE OF TECHNOLOGY AND SCIENCE,
PILANI (RAJASTHAN) INDIA

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CERTIFICATE

This is to certify that the thesis entitled **"An Experimental Study of Designed Passive Elements for Energy Efficiency in Buildings in Composite Climate"** submitted by **Meghana Shrikant Charde**, ID No. 2006PHXF020P for award of Ph.D. Degree of the Institute, embodies original work done by her under my supervision.

Date:

(Rajiv Gupta)

Professor
Department of Civil Engineering
BITS Pilani, Pilani Campus

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Meghana Shrikant Charde

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List of Abbreviations and Symbols

$	United States of America dollar
%	Percentage
$(A_{st})_{reqd}$	Area of tension reinforcement required
$(A_{st})_x$	Area of tension reinforcement provided (short span)
$(A_{st})_{x\ reqd}$	Area of tension reinforcement required (short span)
$(A_{st})_y$	Area of tension reinforcement provided (long span)
$(A_{st})_{y\ reqd}$	Area of tension reinforcement required (long span)
$(l/d)_{max}$	Span to effective depth ratio (maximum)
$(l/d)_{provided}$	Span to effective depth ratio (provided)
$(P_t)_{reqd}$	Percentage tension reinforcement required
$(P_t)_{x\ reqd}$	Percentage tension reinforcement required (short span)
$(P_t)_{y\ reqd}$	Percentage tension reinforcement required (long span)
^{0}	Angle in degrees
^0C	Degree centigrade
^0C-h	Degree centigrade hour
A	Apparent solar irradiation
a	Horizontal shadow angle
AAC	Autoclaved aerated concrete
A_i	Unshaded area of the window
a_i	Area of the i^{th} transparent element
An	Analytical
A_s	Surface area
A_{shade}	Shaded area of window
ASHRAE	American society of heating, refrigeration, and air-conditioning engineers
AUC_c	Area under curve outside the comfort temperature zone
b	Width
B	Atmospheric extinction co-efficient
BEPI	Building energy performance index
C	Constant
C_a	Specific heat of air
CAD	Computer aided design
CFD	Computational fluid dynamics
C_h	Rate of heat loss or gain by convection

cm	Centimeter
CO_2	Carbon di oxide
d	Effective depth
D	Overall thickness of slab
DBZ	Dynamic buffer zone
d_h	Height of the window
D_s	Depth of overhang or sunshade over the window
d_x	Effective depth (short span)
d_y	Effective depth (long span)
E	Equation of time
e	Number of transparent elements
e.g.	Example
EA	Energy analysis
EE	Emergy evaluation
E_h	Rate of evaporative heat loss
Eqn	Equation
et al.	Co-workers
Ex	Experimental
f_{ck}	Characteristic strength of concrete
FEM	Finite element method
f_i	fraction of unshaded area
Fig.	Figure
F_{r-s}	View factor of the window for radiation from the sky
f_{st}	Stress in tension reinforcement
F_{WG}	View factor from ground to the surface
F_{WS}	View factor or configuration factor
f_y	Specified yield strength of reinforcing steel
GWh	Gigawatt hour
h	Hour
H	Hour angle
HCT	Hollow clay tiles
h_i	Inside heat transfer coefficient
h_o	Outside heat transfer coefficient
HVAC	Heating ventilation and air conditioning
i	Angle of incidence of sun's rays

i	Building element
i.e.	That is/ in other words
I_d	Diffuse radiation from sky
I_{DN}	Direct radiation from sun
I_{ext}	Extraterrestrial radiation
IFC	Industry foundation classes
i_{hor}	Angle of incidence of sun's rays for horizontal surfaces
I_r	Shortwave radiation reflected from other surfaces
I_{SC}	Solar constant
I_t	Total solar irradiation
i_{ver}	Angle of incidence of sun's rays for vertical surfaces
I_w	Hourly solar radiation on a shaded window
K	Kelvin
$K.m^2/W$	Kelvin square meter per watt
kg	Kilogram
kg/m^3	Kilogram per cubic meter
k_j	Thermal conductivity of material
km	Kilometer
kN	Kilonewton
kN/m^2	Kilonewton per square meter
KN/m^3	Kilonewton per cubic meter
KNm/m	Kilonewton meter per meter
k_t	Modification factor
kW	Kilo watt
l	Width of the window
L	Latitude
LCT	Local civil time
L_e	Latent heat of evaporation
LEED	Leadership in Energy and Environmental Design
L_j	Thickness of the jth layer
LST	Local solar time
L_{st}	Standard meridian for the local time zone
l_x	Effective short span
l_y	Effective long span
m	Meter

M	Number of minutes from local solar noon
m/s	Meter per second
m^2	Square meter
m^3	Cubic meter
Ma	Mathematical
MATLAB	Matrix laboratory
m_e	Rate of evaporation
M_h	Metabolic heat generation rate
MJ/m^2day	Megajoule per square meter day
mm	Millimeter
mm^2/m	Square millimeter per meter
MPa	Megapascal
MS	Mild steel
M_{ux}	Maximum short span factored moment (per unit width)
M_{uy}	Maximum long span factored moment (per unit width)
MWh	Megawatt hour per square meter per year
n	Day of the year
N	Number of air changes per hour
N_c	Number of components
NV	With night ventilation
P/A	Perimeter to area
PCC	Plain cement concrete
PECW	Passive evaporative cooling wall
$P_{t,x}$	Percentage tension reinforcement (short span)
Q_c	Rate of heat conduction
Q_e	Rate of cooling by evaporation
Q_i	Heat flow rate due to internal heat gain
Q_s	Solar heat gain
Q_v	Heat flow rate due to ventilation
r	Aspect ratio
R1	Room 1
R2	Room 2
R3	Room 3
R4	Room 4
RCC	Reinforced cement concrete

R_h	Rate of heat loss or gain by radiation
r_p	Relative projection
Rs.	Indian rupee
R_T	Total thermal resistance
r_w	Relative width
R_x	Constant (short span)
R_y	Constant (long span)
S	Rate at which heat is being stored within the body.
S/V	Surface area to volume
SDBZ	Solar dynamic buffer zone
S_{gi}	Daily average value of solar radiation (including the effect of shading) on the i^{th} transparent element
Si	Simulation
SO_2	Sulfur di oxide
ST	Standard time
S_T	Daily average value of hourly solar radiation incident on the surface
T(Out)	Outdoor air temperature
T(Outv)	Outdoor air temperature when rooms were ventilated
T(R1)	Indoor air temperature in Room R1
T(R1v)	Indoor air temperature in Room R1 with night ventilation
T(R2)	Indoor air temperature in Room R2
T(R2v)	Indoor air temperature in Room R2 with night ventilation
T(R3)	Indoor air temperature in Room R3
T(R3v)	Indoor air temperature in Room R3 with night ventilation
T(R4)	Indoor air temperature in Room R4
T(R4v)	Indoor air temperature in Room R4 with night ventilation
TBP	Total building performance
T_i	Indoor temperature
TLL	Thermal load leveling
T_{max}	Maximum temperature
T_{min}	Minimum temperature
T_o	Daily average value of hourly ambient temperature
TRNSYS	Transient system simulation tool
T_{so}	Sol-air temperature
U	Thermal transmittance

UAE	United Arab Emirates
V	Volume of the room or space
VBA	Visual basic for applications
V_r	Ventilation rate
W	Watt
w	Total load on slab
W/m^2	Watt per square meter
W/mK	Watt per meter kelvin
W_m	Work rate of mechanical energy leaving the body
WNV	Without night ventilation
w_u	Factored load
z	number of layers
α	Solar altitude angle
α_b	Absorptance of the surface for solar radiation
α_s	Mean absorptivity of the space
α_x	Moment coefficient (short span)
α_y	Moment coefficient (long span)
β	Solar azimuth angle
γ	Vertical shadow angle
δ	Declination angle
ΔR	Difference between the long wavelength radiation incident on the surface from the sky and the surroundings, and the radiation emitted by a black body at ambient temperature
ΔT	Temperature difference between inside and outside air
ε	Emissivity of the surface
θ	Longitude of the location
θ_z	Zenith angle
ξ	Surface azimuth angle
ρ	Reflectivity
ρ_a	Density of air
ρ_g	Reflectivity of ground surface
τ_i	Transmissivity of the i^{th} transparent element
μ	Angle made by the plane surface with the horizontal

Abstract

Renewable energy sources offer an unlimited supply of energy. Abundantly available solar energy can be utilized to supplement energy needs of a building either passively or actively. It is feasible to reduce consumption of energy usage for heating, cooling and lighting requirements of a building by adopting a climate sensitive approach in the design of a building. Passive solar building design aims to maximize solar heat gain in winter, minimize it in summer and bring the indoor air temperature near the comfort temperature zone (18-27^{0}C). In the composite climate zone in India, the need is to design a building that would keep the indoor air temperature more in winter and less in summer as compared to outdoor air temperature. There are various possibilities in architectural design to conserve energy. This can be achieved by designing the building elements considering climate of the place taking into account the seasonal variations. Since ultimately the building elements have to respond to the actual climate, it is only justifiable that they be implemented in actual buildings of habitable dimensions and be tested in the outdoor climatic conditions.

In present study, effect of designed passive elements (independently and combined with each other) on indoor air temperature, has been analyzed by constructing four rooms of habitable dimensions (3.0m x 4.0m x 3.0m high). Each room has a different combination of type of static sunshade, wall and roof. Hence the difference in indoor air temperature of the four rooms will mainly be due to difference in heat transferred through these building elements. The static sunshade and brick cavity wall with brick projections have been designed using sunpath diagram and shadow angles. Optimum brick projections have been provided in the brick cavity wall by taking into account solar angles at the considered geographical location in India such that maximum area of the wall is in shade in summer and minimum area is in shade in winter. Air vents that open in the wall cavity have also been provided to ventilate the air cavity according to seasonal needs. Air cavity has been introduced in the reinforced cement concrete (RCC) roof by laying hollow stoneware pipes.

Thermal performance of the four rooms has been compared by steady state method based on total heat load in every month and on representative days in different seasons. Results showed that room with designed passive elements gained minimum heat in summer and moderate summer, while it lost minimum heat in winter and moderate winter.

Indoor air temperature in the four rooms and outdoor air temperature was recorded every hour throughout the day for eighteen months and analysis was carried out. The designed

static sunshade was effective in increasing the indoor air temperature in winter while its effect on indoor air temperature in summer was not significant due to the higher altitude angle of sun. The brick cavity wall with brick projections was effective in lowering the minimum indoor air temperature in summer. In winter, it was effective in increasing the indoor air temperature in the evening and night as it gained more heat as compared to a solid wall during the daytime and radiated it indoors later. The hollow roof was effective in lowering the maximum indoor air temperature and swing in indoor air temperature in summer as it insulated the room interiors during hotter part of the day. In winter also, it resulted in lower indoor air temperature and reduced temperature swing. When the designed building elements were used in combination, their effect on indoor air temperature was equivalent to additive effect of these elements when used independently. In the comparison of performance of any single building element, the other building elements also influenced the indoor air temperature and hence room performance. The designed static sunshade and brick cavity wall with brick projections together lowered indoor air temperature in summer mornings and increased it during winter evenings and nights. The brick cavity wall with brick projections and hollow roof together lowered indoor air temperature throughout the year. The combined effect of designed static sunshade, brick cavity wall with brick projections and hollow roof lowered the maximum, minimum indoor air temperature in summer and winter. In winter, their combined effect raised the indoor air temperature in mornings and nights. Therefore, the combined effect of these building elements is useful for energy conservation in buildings as per seasonal needs.

The air vents in the brick cavity walls were opened to facilitate ventilation of wall cavity and further analysis was carried out. The ventilated brick cavity wall with brick projections helped to lower maximum and minimum indoor air temperature for five months in summer. When it was combined with designed static sunshade, it lowered indoor air temperature for hotter part of the day in the study period and also at night from July to September. The ventilated brick cavity wall with brick projections combined with hollow roof was effective to lower indoor air temperature throughout the day except in June nights (when difference in indoor air temperature was not significant), maximum, minimum indoor air temperature and swing in indoor air temperature in summer. The combined effect of ventilated brick cavity wall with brick projections, designed static sunshade and hollow roof helped to lower maximum and minimum indoor air temperature (except in June due to slower heat loss caused by insulating effect of energy efficient building elements) and reduce the swing in indoor air temperature in summer. The four rooms were ventilated during night by opening windows to study the effect of night ventilation on indoor air temperature. It can be inferred that night ventilation was a good proposition in moderate summer month to maintain indoor air temperature at a lower value throughout the day. While in the summer months, when the outdoor air temperature was high, night ventilation was effective in reducing indoor air temperature only at night. Effect of night ventilation on indoor air temperature in any room depended upon outdoor air temperature. Night ventilation was equally effective in all the rooms.

The future scope of this study would be to optimize thickness of wall, air cavity and roof to maximize thermal comfort. The effect of designed static sunshade, brick cavity wall with brick projections and hollow roof on all climatic variables like solar radiation, relative humidity, wind speed can be analyzed. Modelling of the rooms can be done using mathematical approach or using computer software to predict the room performance due to the building elements which could help in designing new buildings in the climate zone. The same study can also be extended to other climate zones by designing building elements considering requirements of those climate zones.

Keywords: passive solar architecture, climate, energy conservation, static sunshade, brick cavity wall, brick projections, hollow roof, temperature

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Chapter 1

Introduction

1.1 Background

The sun is an enormous source of energy and basis of life on earth. Energy radiated by the sun is constantly replenished. The earth receives almost all of its energy from the sun in the form of radiation. Thus the sun is a dominant influence on climates. Since time immemorial, man's life pattern is dependent on climatic conditions. Man has tried to modify the climate within the building vis-a-vis that outside, through the use of technology. The building industry has depended heavily on energy-intensive materials and resources. Population growth has led to increase in energy demands. Energy consumption, which is mostly of fossil fuel origin, has caused environmental problems. In the present energy crisis, researchers have rightly drawn the attention to limitations of available energy resources and this has raised the need of alternative energy resources for consumption. The main challenge is to promote growth and development, without depleting world's resources and adversely affecting the environment.

Environmental impacts of buildings over their entire life cycle have been recognized as serious problems for the construction industry (Ball 2002). The close connection between energy use in buildings and environmental damage arises because energy intensive solutions sought to construct a building and meet its demands for heating, cooling, ventilation and lighting cause depletion of invaluable environmental resources (Ministry of Non-conventional Energy Sources and Tata Energy Research Institute 2001). However it is possible to design buildings with reduced level of energy and resources consumption without compromising their main purpose of giving thermal and visual comfort to the occupants. By adopting energy efficient building technologies, it is possible to reduce construction wastage compared to conventional designs and practices (The Energy and Resources Institute 2012). Similarly, the consumption of energy for heating, cooling and lighting requirements of a building can be reduced by adopting a climate sensitive approach in the design of a building. Solar energy can be used to reduce the environmental impact of burning fossil fuels by supplementing energy needs in buildings. Therefore, it is necessary to integrate energy efficiency considerations in buildings right from the planning stage (Mathur and Chand 2003).

Kibert (2005) has defined sustainable construction as the creation and responsible management of a healthy built environment on resource efficient and ecological principles. **S**ustainable architecture seeks to minimize the negative environmental impact of buildings by enhancing efficiency and moderation in the use of materials and energy. An energy-efficient building balances all aspects of energy use in a building viz lighting, space-conditioning, and ventilation, by providing an optimized mix of passive solar design strategies, energy-efficient equipment, renewable sources of energy, besides use of materials with low embodied energy. Energy efficiency in buildings can be achieved through a multi pronged approach involving adoption of bioclimatic architectural principles responsive to the climate of the particular location, use of materials with low embodied energy, reduction of transportation energy, incorporation of efficient structural design, implementation of energy efficient building systems, design of building elements based on passive solar principles and effective use of renewable energy sources to power the building (Ministry of Non-conventional Energy Sources and Tata Energy Research Institute 2001). It is possible to measure climate, thermal performance of buildings and physics of building performance as they are numerically quantifiable and applicable in similar localities across the world. However it is difficult to recommend universal solutions as the regional resources, micro climate and local requirements need to be considered.

Solar energy based systems can be primarily categorized as active and passive. In active systems solar energy is collected, stored, converted and transferred using electrical or mechanical equipment, such as pumps and fans (Chan et al. 2010). Active systems need separate collectors, storage devices and distribution system. The term passive solar building emphasizes the reliance on direct utilization of solar energy in buildings without the use of electrical or mechanical equipment. It relies on utilization of solar energy directly in a building or storage of solar energy in the thermal mass of the building, to make the overall process more efficient, thus saving a significant amount of energy in transferring heat by mechanical means (Athienitis and Santamouris 2002). The concept emphasizes design of buildings to reduce energy consumption, based on natural energy flows (radiation, conduction and natural convection) by integrating conventional energy efficient devices with passive design elements such as thermal mass, an efficient envelope and appropriate fenestration design to facilitate increased daylight and natural ventilation (Athienitis and Santamouris 2002).

The basic idea of passive solar design is to selectively allow entry of daylight, heat and airflow into a building at appropriate times and to store and distribute the hot and cool air at a later time when needed. Many passive solar design options can be introduced at little or no additional cost. The various building elements can themselves act as a collector system. The building can be designed properly in such a manner that it functions as a solar collector, collecting heat when the sun is shining and storing it for later use. The building can function as a solar storage house that can store heat for cool times, as well as increase thermal comfort during warm and hot periods (Ralegaonkar 2004).

1.2 Climate and architecture

Climate plays a major role in the day-to-day and overall life of human beings. Man's energy and health depend in large measure on the direct effects of his environment. It is a common experience to find that on some days the atmospheric conditions stimulate and invigorate our activities, while at other times they depress the physical and mental effort. Man's physical strength and mental activity are at their best within a given range of climatic conditions (Olgyay and Olgyay 1963). The basic elements, viz. air temperature, solar radiation, humidity, rainfall and wind form the general climate of a place and affect human behaviour, activities and life patterns. Variations in the levels of these elements occur throughout India. Based upon these variations, India has been divided into five climate zones as per National Building Code of India: 2005 (Bureau of Indian Standards 2005). Climate classification for building types is an aid to the functional design of buildings. It implies zoning of the country into several regions such that the differences in climate from region to region are reflected in building design, warranting some special provision for each region. The constituents of climate which promote a particular mode of heat dissipation from the human body and thus require certain specific features in building design are grouped together to form a climatic zone [SP-41:1987 (Bureau of Indian Standards 1987)].

The physical environment consists of many elements viz. light, sound, climate and space in a complex relationship. Man strives for the point at which minimum expenditure of energy is needed to adjust himself to his environment. Conditions under which he succeeds in doing so can be defined as the "comfort zone" wherein most of his energy is available for productivity. The shelter or building is the main instrument for fulfilling the requirements of comfort (Olgyay and Olgyay 1963). It modifies the natural environment to approach optimum conditions of livability. The building should filter, absorb or repel environmental elements according to their beneficial or adverse contributions to man's comfort. Ideally, the satisfaction of all physiological needs would constitute the criterion of an environmentally balanced shelter. The major elements of climate which affect human comfort are: air temperature, solar radiation, air movement, rainfall and humidity. The basis of climate-responsive design is to make use of solar and internal gains to heat buildings when the outdoor temperature is below comfort, and to contain or dissipate heat gains when the outdoor temperature is too high for comfort (Yannas 2001). During the underheated period, it is desirable to enhance heat preservation and minimize heat loss. Similarly at overheated times, when shade protection is needed heat gain should be minimized and heat loss should be maximized. The required elements viz. sun radiation for cold periods, shade for hot periods and ventilation for humid periods, can be considered in relation to specific needs. It is possible to estimate the indoor thermal environment in a building when the climatic elements and bioclimatic needs of a site are thoroughly analyzed. The ideal structure in ideal location might be able to keep physical sensations wholly within the comfort range. However, mostly due to extreme natural stresses and blocking of the compensating forces by interaction of building components or practical considerations, it is difficult to achieve an ideal indoor thermal environment. But it is possible to achieve a building that provides comfort at lowered cost through reduction of mechanical conditioning. The building, which in a given environmental setting reduces undesirable stresses and at the same time utilizes all natural resources favorably for human comfort may be called "climate balanced" (Olgyay and Olgyay 1963).

1.3 Thermal performance of a building

The desirable procedure would be to work with the forces of nature and to make use of their potential to create better living conditions and attain energy efficiency in buildings. Energy efficiency in buildings broadly implies reducing energy wastage due to non judicious use of electrically operated gadgets, development of energy efficient appliances and optimum utilization of non-conventional sources of energy through judicious planning and design of buildings (Mathur and Chand 2003). The first aspect is concerned with the design, installation and operation of electrical appliances, whereas the second aspect is related to incorporation of appropriate passive features at the initial design stage of the building.

The thermal environment in a building depends upon the heat flow through building envelope, distribution pattern of air, radiation exchanges between the various components of an enclosure and relative humidity. Of all these parameters, heat flow contributes the most. Thus thermal behaviour of a building can be judged by the total peak heat flow resulting from collation of individual heat flows. Thermal design of buildings is influenced by various parameters, such as site planning, plan form and orientation, design of various building elements like wall, roof, building materials and fabric specification, building orientation, glass area, insulation, shading, fenestration, heating and cooling loads, ventilation rates and location of rooms. Indoor thermal conditions up to a certain extent can be improved by appropriate selection and design of these parameters to minimize solar heat gain in summer and maximize it in winter. But it may not be possible by passive features alone to create comfortable conditions indoors, and thus mechanical devices may be needed to reduce the thermal loads [SP-41:1987 (Bureau of Indian Standards 1987)]. An evaluation of indoor thermal conditions conducive to well being of occupants must be made, followed by analysis of climatic data and physical properties of structural materials to ensure best possible control of living and working environments.

1.4 Factors affecting thermal performance of a building

For climate control in buildings, a universally applicable method based on broader foundations, accompanied by a careful analysis of a specific area is necessary. The process of making a climate balanced building using passive solar features can be divided into four intermediate steps viz. study of the variables in climate, biology, technology and their architectural expression (Olgyay and Olgyay 1963).

1. *Climate:* Climatic data of a specific region with the yearly characteristics of constituent elements such as temperature, relative humidity, radiation, rainfall and wind effects should be analyzed. The modified effects of the microclimatic conditions should be considered.
2. *Biology:* Biological evaluation should be based on human sensations. A diagnosis of the region with the relative importance of various climatic elements should be done. The result of the above process can be tabulated on the yearly time table from which measures needed to restore comfort conditions can be obtained for any date.
3. *Technology:* Technological solutions may be sought after the requirements are stated to stop the adverse and utilize the advantageous impacts of climate at the right time. This necessary function of a balanced building should be analyzed by calculative methods.
4. *Architectural Expression:* Architectural application of the findings of the first three steps must be developed and balanced according to importance of different elements.

Energy efficient building design involves constructing buildings that conserve energy through appropriate materials, insulation and architectural design and thus reduce cooling, heating and lighting requirements in buildings. Construction of building is an energy intensive process which consumes energy in each stage right from site clearance to operation and maintenance throughout its life cycle (Dakwale et al. 2011). The main factors that need to be considered for design of climate responsive, energy efficient buildings are site planning, plan form and orientation, openings and sunshades design, design of building elements, construction materials, surface finishes and energy use when the building is occupied.

1.4.1 Site planning

Depending on various micro climatic factors, local conditions of a place can differ substantially from the prevailing climate of the region. The following components of the site have an effect on the building:

i. *Topography:* Topography or modulations of earth either in natural undisturbed state or as manipulated by man, has the ability to modify, ameliorate or accentuate climatic variations in different ways (Vig 2003). Flat lands have similar conditions over the entire area. However slopes and depressions lead to different levels of air temperature and air movement at different parts of the site. Cooler air with higher density tends to collect in depressions, leading to lower air temperature while hot air rises up. Air speed increases up the windward slope and is maximum at the crest and minimum on the leeward side. Obstacle to air flow causes high pressure area on the windward side and low pressure area on leeward side (Krishnan et al. 2001).

ii. *Vegetation:* Plants, shrubs and trees absorb radiation in the process of photosynthesis and thus cool the environment. Thick vegetation can effectively cut off air flow while careful placement of trees and hedges can direct and increase the air speed (Krishnan et al. 2001). Air speed can be increased by narrowing the path of airflow by planting trees. Planting trees or shrubs in the path of air flow causes a low pressure zone on the leeward side. In the case of hedges this shifts the path downwards while airflow below the canopy of a tree is shifted upwards (Olgyay and Olgyay 1963).

iii. *Water bodies:* Water has a relatively high latent heat of evaporation and specific heat. So water uses a comparatively large amount of heat in evaporating. It also absorbs or releases a large amount of heat for unit rise or fall of temperature. So when water evaporates by the movement of air, it cools the air due to which humidity increases. This is called evaporative cooling (Krishnan et al. 2001). As a result during daytime, areas around water bodies are generally cooler and at nights water bodies release relatively large amount of heat to the surroundings (Olgyay and Olgyay 1963).

iv. *Ground character:* Incident radiation can be absorbed, reflected or stored and reradiated later depending on the ground surface. The color and texture of a material's surface determines it reflectivity. Smoother surfaces with lighter color have more reflectivity. Darker and rougher surfaces have lower reflectivity and would store more heat and reradiate it at a later time. This re radiation mostly takes place at night when the surroundings are at a lower temperature (Krishnan et al. 2001).

1.4.2 Plan form and orientation

The plan form of a building affects the air flow around and through it as it creates an obstacle in the path of airflow and thus creates pressure difference. The perimeter to area ratio and surface area to volume ratio are important indicators of heat loss or gain and play a role in ventilation (Krishnan et al. 2001). Greater the perimeter to area and surface area to volume ratio greater the radiant heat gain during the day and heat loss at night. Similarly, smaller the perimeter to area and surface area to volume ratio lesser will be the heat gain or loss. The building orientation determines the amount of radiation it receives. Although solar heat gain is the main consideration in the selection of optimum orientation of buildings, other factors like the direction of wind, rainfall and site conditions cannot be overlooked in the final choice of the orientation. The optimum shape loses minimum amount of heat and gains maximum solar heat in winter and retains minimum amount of solar heat in summer [IS-7662 (Part I):1974 (Bureau of Indian Standards 1974)].

1.4.3 Openings and sunshades design

Area, shape, location and relative positions of openings affect air movement, daylight and glare indoors. They play a vital role in the direct gain of sun inside the buildings. In northern hemisphere windows on south facade should be designed with great care as these windows result in direct solar entry inside the building most of the time in the day. Besides reducing the lighting load, it allows sunlight to heat up the building interiors. It is necessary to have proper shading over windows to maximise solar heat gain in winter and minimise it in summer (Ralegaonkar 2004).

1.4.4 Design of building elements

Techniques for designing energy efficient buildings vary according to the site and climate. Various designs for walls and roofs like cavity wall, roof pond, hollow roof, solar chimney etc can be effectively used to alter solar heat gain and thus indoor air temperature.

Advanced passive heating or cooling techniques can be integrated in the building by using appropriate techniques for building elements like walls and roofs. For example: numerical computations have shown that incoming flux entering through walls can be reduced by air cavity (Tiwari et al., 1994).

1.4.5 Construction materials

Construction sector in India emits about 22% of the total annual emission of carbon dioxide (CO_2) generated by the Indian economy. Out of the emissions from the construction sector, 80% result mainly from the products/industrial processes of energy intensive building materials (Dakwale et al. 2011). Construction materials lower initial and lifetime environmental impact. The life cycle of a material is the most appropriate platform to analyze and assess the environmental impacts of building materials (Institut Catala d'Energia 2004). Thermal properties of building materials like conductivity, transmittance, specific heat are important factors to be considered in the appropriate choice of energy efficient building materials.

1.4.6 Finishes

Heat loss or gain by a building can be controlled to some extent by using appropriate finishes. For example, a smooth and light color surface reflects more light and heat in comparison to a dark color surface. Lighter color surfaces have higher emmisivity and should be ideally used for warm climates (Ministry of Non-conventional Energy Sources and Tata Energy Research Institute 2001).

1.4.7 Energy use

Heating, cooling and lighting in buildings can be done using natural, renewable energy sources, particularly solar energy that utilizes abundantly available solar radiation from the sun. Solar thermal driven heating technologies utilize passive or active solar energy to collect solar radiation and transform the energy into usable heat. The passive relates to building envelope design whereas the active relates to the use of solar collector to heat a fluid. The passive solar technologies for space heating and cooling rely on working mechanisms of buoyancy and evaporative effects. Many facades designs have applied the former mechanisms while the latter is relatively more common for roof designs (Chan et al. 2010).

1.5 Structure of thesis

The thesis is organized as follows:

Chapter 2 deals with an overview of literature on whole building performance, static sunshade, energy efficient walls, roofs and night ventilation. Experimental, simulation, numerical/ mathematical studies on the design and thermal performance evaluation of walls and roofs, their limitations have been discussed. Moreover, objectives of the present research work have also been presented.

Chapter 3 deals with fundamentals of passive solar architecture. The influence of climate on design of energy efficient buildings, requirements of thermal comfort, solar geometry, solar radiation calculation and computation of sun angles has been discussed.

Chapter 4 deals with the detailed methodology used for the design development of the proposed static sunshade, ventilated brick cavity wall with brick projections and hollow roof. The detailed room design with the material specifications has been discussed.

Chapter 5 deals with the comparison of thermal performance of the rooms using steady state method. The steady state method has been elaborated and the room performance has been analyzed. Available solar radiation at considered geographical location has also been calculated.

Chapter 6 describes the experimental methodology used for comparison of thermal performance of the building elements and night ventilation (independently and combined with each other).

In Chapter 7 thermal performance of rooms using experimental study has been presented. Results of various studies that compare the individual and combined effect of the proposed static sunshade, ventilated brick cavity wall with brick projections, hollow roof and night ventilation on indoor air temperature have been presented and discussed.

Chapter 8 gives the summary of the thesis along with important conclusions. Based upon findings of research work, appropriateness of individual or combination of the designed passive elements for the composite climate zone have been proposed.

In Chapter 9 future scope of work has been presented.

Chapter 2

Literature Review

2.1 Introduction

The adaptation of building to environment and climate has been a continuous problem for man since ancient times. This can be achieved by designing the building envelope responsive to climatic needs considering the seasonal variations, to provide thermally comfortable indoor environment for the occupants. The building envelope includes all the building components that separate the indoors from outdoors. It consists of the exterior walls, the roof, floors, windows and doors. The envelope must withstand the stresses to which it is exposed and also must protect the enclosed space against the local climate and also act as a climate moderator. Designs have evolved slowly, keeping pace with gradual changes in social and economic patterns and environmental requirements (Clements-Croome 2004; Hutcheon 1963). Today, with dynamic architecture and many new materials, components and construction techniques available, a large number of new designs are possible. Unfortunately, some are being adopted without adequate consideration of their long term impact on the environment, and evaluation by the slow “trial by use” methods of the past is no longer adequate (John et al. 2005).

The amount of heat transmitted into or lost from a building varies with the change from day to night time temperatures and changes through fluctuating weather, i.e. heating by sunshine and cooling by wind or rain (Ralegaonkar and Gupta 2010). The proper design and selection of a building envelope and its components are an efficient means to reduce the space heating–cooling loads (Kaynakli 2012). The main design parameters that need to be considered for design of energy efficient buildings are walls, roof, placement and size of openings, ratio of window/wall area and provision of proper shading devices. These elements have been discussed at length in previous chapter. A detailed literature review of studies reported on the performance of energy efficient building as a whole, static sunshade, wall, roof and night ventilation has been done in this chapter. The literature reports have been classified in a tabular form according to the building technologies used, climate zone and methodology (experimental, simulation, numerical, analytical).

2.2 Whole building performance

The energy consumption of a building can be affected simultaneously by many building design factors related to its main architectural features, building elements and materials. The relationship between the building design data and energy consumption data of houses can be identified (Su 2011). The indoor thermal environment in a building is a result of the collective heat transfer through various elements. It is thus necessary to understand the combined effect of various elements on the energy consumption and thermal performance of a building in different climate zones. Various studies reported on thermal performance of whole buildings in different climate zones have been presented in Table 2.1.

A number of research studies related to thermal performance and energy efficiency of buildings have focused on thermal mass, double glazing, insulation to improve indoor thermal comfort in various climate zones (Filippin et al. 2008; Shaviv 1998). Some have developed an international database of low-energy homes and the low energy techniques applied to them (Hamada et al. 2003) while others have proposed that development of passive house design guidelines could be based on the actual energy consumption data and real design data of local houses (Su 2011). Computer simulation has also been used as a design tool (Fazio et al. 2007) along with experimental data (Ghrab-Morcos et al. 1993; Shaviv 1998; Filippin et al. 2008). Heat, air and moisture processes collectively influence air quality and energy consumption in buildings. Woloszyn and Rode (2008) have done a review of the tools for performance simulation of heat, air and moisture conditions of whole buildings. Kim and Todorovic (2013) presented a review of the multi-criteria sustainability analysis methods (intrinsic thermodynamic based on energy, exergy, sustainability index, analytic hierarchy process, etc.)

Experimental and simulation methods were used to analyze the design, technology, thermal behaviour, and energy consumption of a conventional and a refurbished dwelling in temperate-cold climate in Argentina. To reduce the heating and cooling loads, the dwelling was refurbished (by including passive solar heating, shading, and an insulated envelope) and its thermal behaviour was studied through a computer simulation. This resulted in energy savings of 66% and 52% for winter and summer, respectively (Filippin et al. 2008). In another study, an integrated framework was developed, which applied information technology and the international standard Industry Foundation Classes (IFC) to ensure that the building envelope satisfied energy requirements, moisture needs and thermal performance, concurrently. The framework was designed to extract geometric and material layers data of a house from Computer-Aided Design (CAD) drawings in IFC data model, link to performance evaluation applications and compare evaluation results with a set of criteria (Fazio et al. 2007).

A study was done by Su (2011) on the impact of a number of major design features on extra winter energy consumption in 200 sample houses. The design data included the ratio of building surface to building volume, total window area to total wall area, total window area to indoor space volume, total window area to total floor area, north window area to north wall area, north wall area to indoor space volume, north wall area to total wall area, roof area to indoor space volume, roof space volume to indoor space volume (Su 2011). A mathematical method was developed by Manioglu and Yilmaz (2006) for the determination of the most convenient building envelope-operation period combination in relation to the life cycle cost and climatic comfort.

The effects of fly ash on brick properties, thermal comfort analysis and the impact of the ventilation components on the indoor environment of a low-cost energy efficient passive solar house were evaluated (Makaka et al. 2008). The passive solar house was found to be thermally comfortable for 66% of the period monitored in summer and 79% in winter. Windows were found to have a higher impact on the ventilation rates than doors (Makaka et al. 2008). In another study, experimental and simulation results demonstrated that in Tunisian conditions, direct gain element had a higher efficiency, while Trombe wall resulted in appreciable energy gains at evening. It was also found that thermal insulation was decisive for the average room temperature, but thermal capacity resulted in high temperature stability (Ghrab-Morcos et al. 1993). A building energy performance index (BEPI) reflecting the total amount of energy consumption for heating, cooling, ventilation and lighting used**,** per square meter of floor area was computed for different design options of a building in Israel (Shaviv 1998). Thermal modeling for the different design alternatives was carried out. The building was monitored for one year, and the measured values were found to be close to the predictions. With the proposed series of design elements (insulation, cooling the thermal mass by night ventilation, adding ceiling vents, a greenhouse on the upper roof, careful design of the windows' glazing shading system) it was possible to reduce the electricity consumption for lighting, heating and cooling by 60% (Shaviv 1998).

The total building performance (TBP)-based diagnostic, if properly adopted, provides a full picture of the building under consideration, identifying systematically the causes and adverse effects of poor building performance (Oyedele et al. 2012). It provides an excellent basis for developing solutions, such as the impacts of a building environment on health and productivity, cost of maintenance and operation of buildings. The performance of an existing office building in Singapore was assessed with TBP evaluation and diagnostic. Objective measurements and observations (walkthrough) coupled with occupant survey (subjective measurement) were conducted. The analysis demonstrated that there was concurrence between the objective and subjective measures, and that the holistic approach of TBP elicited the interrelationships between the performance's mandates and constituted a sound basis for diagnostics and sustainability improvement (Oyedele et al. 2012).

2.3 Static sunshade

Windows are an important source of heat gain in a building. Shading devices must be carefully designed and oriented in relation to the fenestration to maximize shading during the summer months to minimize heat gain while still letting direct sun into the interiors during the winter season to maximize heat gain (Kapur 2004). An ideal shading device is expected to exclude solar radiation during over-heated periods and admit it during under-heated periods **(**Gupta and Ralegaonkar 2006**)**. Location, latitude and orientation contribute to the design of an effective sunshade. The design procedure has been mentioned by Cowan (1980) along with several case studies of external static sunshades. Simulation studies (Kabre 1999; Hiller et al. 2000; Hellstrom et al. 2007), mathematical methods (Garg and Bansal 1986) and shading mask graphical approach (El-Refaie 1987; Etzion 1992) for design and evaluation of shading devices have been reported in literature. The use of photovoltaic modules as sunshades over windows has also been reported in literature (Yoo and Lee 2002; Davidsson et al. 2012). Various studies reported in literature related to different aspects of static sunshade have been stated in Table 2.2.

Kischkoweit-Lopin (2002) presented an overview of various existing sunshades with illustrative sketches and detailed descriptions to choose the right system for a given condition. Christoffers (1996) designed prismatic panes, which are shading responsive to sun's position for different seasons throughout the year. Jorge et al. (1993) presented a nomogram for the use in regions with Mediterranean climate to optimize the design of sunshades. This graphical approach leads to an error of about 10%. Dubois (2000) presented a simple chart to design sunshades that is complementary to existing solar path diagrams and provides additional information about the window's solar angle dependent properties and its geometrical relationship with sunbeam. Chandra (1996) gave the design of external louvres in relation to different building facades taking diurnal and seasonal variations in sun's positions. The study was limited to basic types of external sunshades like horizontal, vertical, inclined and eggcrate.

El-Refaie (1987) studied the performance of basic vertical and horizontal external sunshades. He derived mathematical formulae to express cutoff angles in terms of geometrical parameters. Yener (1999) presented a mathematical model for the design of fixed sunshade from two aspects i.e. climatic and visual. The study was restricted to horizontal and vertical sunshades only. Kassem et al. (1999) developed the computational procedure for evaluating solar heat gain to a space having a vertical cylindrical glass envelope, which can be made useful for proper selection of sunshade. Kabre (1999) developed WINSHADE, an integrated computer tool for the design of passive solar control through building fenestrations. In another study, simulated solar transmittance values obtained with ParaSol version 3.0 were compared with measured values for windows with different types of solar shadings viz. screens and venetian blinds, mounted internally and between two clear glass panes (Hellstrom et al. 2007).

Kapur (2004) investigated the impact of radiant heat transfer from the window sunshades on the glazing it shades. This was studied using sunshades made of three different materials. Experimental values were compared with simulation values obtained using RADTHERM (a simulation tool used to simulate the experiment). The shading devices were found to be effective in reducing the direct solar heat gain, but at the same time the re-radiation (long-wave radiant heat exchange) and reflection of incident solar radiation from their surfaces had a considerable effect on the glass surface temperatures (Kapur 2004).

The performance of a designed static sunshade over window on south wall was studied experimentally and found to be better as compared to a horizontal sunshade by constructing small scale models at Pilani, India (Ralegaonkar 2004). The static sunshade was designed by considering solar angles at the considered geographical location such that there was maximum entry of sunlight through the window in winter and minimum entry of sunlight in summer. This methodology for design of static sunshade has been used for design of static sunshade in present work as it considers solar path and has been found to be effective in composite climate. Moreover, application of the sunshade in actual buildings can give a better understanding of the effect of static sunshade on building's thermal performance.

2.4 Energy efficient walls

It is possible, with the aid of building science to identify the factors affecting performance of walls and to analyse wall designs in terms of their probable performance and varied requirements. With this capability, it would be possible to discriminate between various designs for particular uses and to provide a basis for the development of improved designs. The over-all function of an exterior wall, along with roof and floors, is to moderate solar radiation, temperature extremes, moisture (as vapour or liquid), dust and wind. It may be required to transmit light through a window, while contributing suitably to the form and aesthetics of the building generally. All of this must be achieved at an acceptable life time cost. Determination of the outdoor environment and establishment of that desired indoors is essential first step in exterior wall design. Only when these factors are known it is possible to assess the overall performance requirements of the wall (John et al. 2005). Thermal performance of walls depends on various parameters like the wall type or wall design, material, presence of thermal mass, surface finish and insulation and varies according to climate zones. Studies reported on these aspects of wall performance have been elaborated and presented in tabular form in this section.

2.4.1 Wall design

There are various types of advanced building wall designs that are applied to improve the energy efficiency and comfort levels in buildings. The thermophysical properties of external walls have an important effect on the energy consumption of buildings (Zhang et al. 2013). Various studies reported on thermal performance of different wall designs in different climate zones have been presented in Table 2.3. A number of research studies related to thermal performance and energy efficiency of walls have focused on difference in heat transfer behaviour of walls due to difference in design techniques in various climate zones (Zalewski et al. 2002; Pulselli et al. 2009). Ventilated walls and facades if well designed, can help to reduce considerably the summer thermal loads due to direct solar radiation (Afonso and Oliveira 2000; Balocco 2002; Ciampi et al. 2003).

Typically used in cold climates, the walls that trap and transmit solar energy efficiently into the building are called passive solar walls (Sadineni et al. 2011). The classical Trombe wall is a massive wall covered by an exterior glazing with an air channel in between. The massive wall absorbs and stores the solar energy through the glazing as shown in Fig. 2.1. Part of the energy is transferred through the wall into the room by conduction. Meanwhile, the low temperature air enters the channel from the room through the lower vent of the wall, is heated up by the wall and flows upward due to buoyancy effect. The heated air then returns to the room through the upper vent of the wall (Chan et al. 2010). Studies have been carried out to improve the classical Trombe wall design. The improvement can be classified into three aspects, i.e. inlet and outlet air openings control, thermal insulation designs, and air channel designs. By installing adjustable dampers at the glazing and adjustable vents on the wall, the classical Trombe wall can be beneficial for winter heating and summer cooling (Gan 1998; Jie et al. 2007).

Composite Trombe–Michel wall (with an insulating wall at the back of the massive wall) has also been studied to overcome the heat loss from the building as shown in Fig. 2.2 (Shen et al. 2007). During non-sunny days, winter or at nights, the vents in the insulating wall are closed. Hence, due to greater thermal resistance of this design, the heat loss is reduced. A transwall (as shown in Fig. 2.3) is a transparent modular wall that provides both heating and illumination of the dwelling space. These walls are comprised of water enclosed between two parallel glass panes supported in a metal frame with a semi-transparent glass absorbing plate at the center of the parallel glass panes. The incident solar radiation is partially absorbed by the water and semitransparent glass plate, the rest of the transmitted radiation causes both heating and illumination that are required indoors (Nayak 1987). A solar chimney is based on natural convective air movement stemming from the variation in density of indoor air currents. In those cases in which the chimney is attached to the building wall, it operates similarly to the Trombe wall, and also provides benefits in the summer. Despite its positive results, the use of a solar chimney is not always feasible for aesthetic reasons (Chan et al. 2010). Depending on the distribution and opening of air vents, the solar chimney can act as a natural ventilation system, passive heating method, or thermal insulation device, as shown in Fig. 2.4.

Saadatian et al. (2012) have discussed different types of Trombe walls. A comparative study was conducted on four different kinds of solar wall configurations - unventilated solar wall, Trombe wall, insulated Trombe wall and composite solar wall- using numerical simulations (Zalewski et al. 2002). All of these walls, transfer heat to the indoors both by conduction through wall and convection through circulating air, except the unventilated solar wall that transfers heat exclusively through conduction (Zalewski et al. 2002). In another study the thermal performance of a passive solar bank building at Shimla, was evaluated that had a heat collecting wall on the southern face and other passive solar building elements. It consisted of a massive concrete wall of thickness 0.23m glazed with 6-mm-thick toughened glass with gray-colored tiles fixed on the outer side of the wall. Four vents, each of 0.5 m^2 area, were provided at the top and bottom of the wall for circulation of air inside the building. It was able to reduce the heat loss by 11%. The estimated heat gain from the wall was found to be 755.6 kW while on actual monitoring the heat load was 762.05 kW (Chandel and Aggarwal 2008).

A solar facade is composed of metal sheet with holes, as shown in Fig. 2.5. The outside metal cladding receives solar radiation, and the air that enters (with the help of a fan) through the holes to the inside of the building is thus heated. The heated air is then ducted into the building via a connection to the heating system (Pacheco et al. 2012). Experimental results indicated that this system can provide savings in energy consumption of up to 1 MWh/m^2/year, with an effectiveness of up to 63–68% (Chan et al. 2010). It is also more economical to build than the Trombe wall.

It is possible to control the air movement in magnitude and direction to obtain wall components with varying thermal resistance. Such a system can be used for mild heating in winter and summer cooling for composite climate as in Delhi (Sharma et al. 2003). The flow of air can be controlled into the room or to the ambient by providing proper vents in the interior wall. During the summer daytime, the wall provides effective air insulation and during the night, the cool ambient air comes in contact with the warm brick wall and gets heated, establishing a natural flow of air. This air movement helps in quick removal of the heat flux. During winter, the vents may be opened during the day for supplying warm air into the room and all vents may be kept closed during the night time, thus providing an air insulation which minimizes heat losses to the ambient. Vary therm wall (that derives its name from the variable resistance) has been reported by Sharma et al. (2003). This wall can be operated in three modes:

i. No flow of air in the gap thus effectively reducing the system to an air gap within the wall
ii. Continuous flow of air into the room or to the atmosphere maintained by natural or forced convection and
iii. No air flow during the day or night and creating an air flow by opening the vents during night or day time depending on the weather conditions (Sharma et al. 2003).

He and Hoyano (2011) developed a passive evaporative cooling wall (PECW) constructed of porous ceramics. These ceramics enabled their vertical surfaces to be wet up to a level higher than 100 cm when their lower end is placed in water. Air passing through the PECW unit was cooled, and its temperature could be reduced by around 2 °C during summer daytime. In another study, three identically sized and oriented houses were compared experimentally and using TRACE-700 simulation (a dynamic cooling/heating load hourly calculation program). Two of the homes were identically constructed using wood frame/stucco construction while the third used a wall of sandwiched styrofoam in between

concrete layers. It was found that the concrete house on the average consumed about 15% less for HVAC operation than the wood frame houses (Moujaes and Madeja 2006).
Finite element method (FEM) was used for studying heat transfer equation for five different light concrete hollow brick walls (Del Coz Diaz et al. 2007). In another study, an analysis was developed for the evaluation of the daily quasi steady state energy losses from composite walls under the effect of time-varying meteorological driving forces, when heating at the room side was intermittent (Tsilingiris 2006). Becker (1993) investigated the local and global thermal resistance of masonry walls composed of multicore hollow concrete blocks by comparing results obtained by the two computational methods with those derived from a more-accurate three-dimensional finite-difference thermal analysis. A prefabricated and panelized brick veneer, with a steel framework backup wall system, was developed at the Pennsylvania State University with a combined cavity insulation and exterior insulation (Liang and Memari 2011). Calculations showed that thermal resistance of all four systems exceeded the code required value (which is either 3.35 or 3.70 $K \cdot m^2/W$), depending on the location.

A double skin façade is a building envelope formed by two layers (internal facade and external facade) of different glazing materials that are separated by a ventilated air cavity (channel). The external facade layer provides protection against the weather. In normal use shading devices such as blinds are installed in the cavity to protect the rooms from high cooling loads caused by solar radiation. The ventilated cavity is used to collect or evacuate the solar radiation that is absorbed by the facade. In cold weather, the double skin facade acts as a heat exchanger when sunlit, so that the internal glass facade temperature nearly equals the room air temperature, which improves the thermal comfort. In hot summer, double skin facade can have a very low shading coefficient if the shading devices are appropriately placed, since the majority of solar gains are removed from the window (Zhou and Chen 2010). Photovoltaic ventilated facades are double facade constructions which combine the advantages of cooling the photovoltaic modules using ambient air with the potential to use the hot air so produced for heating and cooling of the building. Steady state analysis for calculating the thermal impact of an integrated ventilated photovoltaic façade on building performance was done and validated against detailed temperature measurements for the calculation of winter heating and summer cooling loads (Infield et al. 2006).

A methodology for determining the thermal performance of a complex ventilated glazed facade system, through desktop analysis and computer simulation was developed by

Dagnall et al. (2011). The results showed that a double cavity façade significantly improved solar heat gain coefficient performance when the cavity was well ventilated. In another study, computational fluid dynamic (CFD) analysis and experimental study was carried out to investigate the effect of blind and thermal mass concrete on the thermal performance of a double-skin façade by El-Sadi et al. (2010). The dynamic buffer zone (DBZ) concept consists of ventilating a cavity within a wall to control heat movement and moisture migration across the assembly. During winter operation, the DBZ typically introduces heated outside air containing little moisture into an interstitial cavity within the wall assembly. Using analytical modelling, Richman and Pressnail (2009) showed that solar dynamic buffer zone (SDBZ) curtain wall is a sustainable option for traditional curtain wall assemblies.

Energy Analysis (EA) and an Emergy Evaluation (EE) were performed to assess environmental costs and benefits of plus-insulated wall, ventilated wall, traditional air cavity wall (Pulselli et al. 2009). The passive ventilation inside the external air-cavity of a ventilated wall (in months with a mean temperature of more than 21^0C) was found to have a positive effect relative to the intensity of solar irradiation. Moreover, when ventilation was avoided, the external air-cavity, behind brick panels, worked like a wool covering and enhanced thermal resistance. Therefore, according to thermal analysis, plus-insulated and ventilated walls were found to have a higher thermal efficiency than a traditional air-cavity wall corresponding to an improvement of about 44% and 54%, respectively and were found to achieve better results in locations with extreme weather conditions such as Berlin and Palermo (Pulselli et al. 2009).

An experimental and theoretical study was done to evaluate the thermal behaviour of the alveolar brick construction system, which was compared with a traditional Mediterranean brick system with insulation in four real house-like cubicles. The thermal transmittance in steady-state (U-value) was calculated theoretically and experimentally for each cubicle, presenting the insulated cubicles as the best construction system, with differences of around 45% in comparison to the alveolar one. On the other hand, experimental results showed significantly smaller differences on the energy consumption between the alveolar and insulated construction systems during summer period (around 13% higher for the alveolar cubicle). Thus the alveolar brick construction system was found to have higher thermal inertia than the insulated one justifying the low measured energy consumption (De Gracia et al. 2011).

Various numerical, simulation and experimental studies on thermal behavior of cavity walls have been reported in literature as stated in Table 2.4. Numerical computations showed that incoming flux entering through walls can be reduced by air cavity (Tiwari et al., 1994) and application of a thin layer of cow dung slurry inside the wall cavity (Kumar et al., 1994). Analytical solutions were obtained defining transient and periodic heat flow through walls of cavity construction composed of two layers of materials of dissimilar thermal properties separated by a sealed airspace (Pratt 1965). Finite element analyses using COMSOL were carried out to study the heat transfer behavior and storing capacity of concrete walls with air cavities (Zhang and Wachenfeldt 2009).

Case study dwellings in England were monitored either before or after (or both) the introduction of energy efficiency retrofit measures such as cavity wall insulation, loft insulation, draught stripping and energy efficient heating system. Cavity wall and loft insulation were found to reduce space heating fuel consumption by 45 - 49% theoretically, while on monitoring in actual dwellings, the reduction was only 10 -17% (Hong et al. 2006). An experimental investigation of heat transfer through a variable aspect ratio cavity wall was conducted with the aid of a guarded hot box. A block and brick cavity wall measuring $1.2 \times 1.2\ m^2$ was tested at cavity depths of 78, 60 and 40 mm. The experimental results showed that with increasing aspect ratio, flow magnitude and circulation intensity reduced and the thermal resistance of the air cavity thereby increased (Aviram et al. 2001).

The microclimates in wall cavities of brick-veneer houses in tropical (Darwin), subtropical (Brisbane) and temperate (Melbourne) zones of Australia were recorded over a complete year. Relative humidity and temperature in wall cavities of two different orientations and in the house interior were measured every 20 minutes. Diagrams defining the exceedences of the climatic variables on a seasonal basis were made for the assessment of material durability and life prediction (Cole 1994). An experimental study was conducted for open rain screen walls with capillary cracks and vent hole on the outer wythe and capillary cracks on the inner wythe (Fazio and Kontopidis 1988). A mathematical model was developed to correlate cavity pressure, wind pressure and openings. From this relationship and experimental results, it was found that the cavity pressure equals the average wind pressure around the building for cases where the outer wythe has only cracks and no vent hole. While cavity pressure was not equal with average wind pressure for uniformly distributed openings on the outer wythe (Fazio and Kontopidis 1988).

2.4.2 Wall material, thermal mass, surface finish

Recycled or renewable materials may be an alternative to conventional construction materials such as concrete or steel to reduce carbon emission and to save energy for manufacturing (Goodhew et al. 2004). Strawbale is one such material that showed good thermal resistance and delayed heat-transfer from inside to outside (Elias-Ozkan et al. 2006). Thermal mass refers to the high heat capacity materials that can absorb heat, store it and release it later (Sadineni et al. 2011). It helps in the regulation of indoor temperature by absorbing and progressively releasing the heat gained through both external and internal means. This leads to delaying/reducing the peak indoor loads and decreasing the mean radiant temperature (Antinucci et al. 1992; Balaras 1996). For thermal storage to be effective, the diurnal ambient temperature variation should exceed 10 K. Heat gain or loss from a building depends on the nature of surface finish. Highly textured walls have portions of their surfaces in the shade. The radiation absorbing area of such a textured surface is less than its radiation emitting area and therefore it will be cooler than a flat surface (Sharma et al. 2003). Various studies reported on thermal performance of wall material, thermal mass, surface finish have been summarized in Table 2.5 and elaborated in this section.

Thermal mass has been used to regulate indoor air temperature in extreme climates in traditional buildings in Jaisalmer (Krishnan et al. 1996) and Diyarbakir (Sozen and Gedik 2007). The effect of thermal mass was studied experimentally in hot humid climate by Cheng et al. (2005), while it is being used for school buildings in Israel (Capeluto et al. 2004). Shaviv et al. (2001) and Granja and Labaki (2003) have reported that walls with substantial thermal inertia are suitable for use in constructions built in regions with hot and humid climate, in conjunction with nocturnal ventilation.

In Jaisalmer, due to thick stone walls that have a large thermal capacity and offer thermal lag, outside conditions are attenuated to provide comfort conditions inside. Heat flux entering the building is also controlled by the use of textures organized at three levels (Krishnan et al. 1996). At the habitat scale the buildings are of unequal height with parapets and high walls, creating sky lines and desired shading of each other. Building facades have a large number of projections like *jharokas* and *chajjas* which provide shade on facades. The front facades which remain exposed are controlled by creating deeply carved patterns. This device minimizes the heat gain in day time by providing shading due to textured surface; they reduce heat gain by increased convective heat loss due to increased surface area. In the evening when ambient conditions are cool the increased surface area helps in cooling faster (Krishnan et al. 1996). The thickness of the outer walls of the old buildings in Diyarbakir, Turkey are between 0.5 and 0.8m and made of porous basalt stone (Sozen and Gedik 2007). Coefficient of heat transmission of basalt stone is 0.5 W/mK and density is 1600 kg/m^3. The transmission time of outside temperature to inner surface temperature of the walls is thus long (Sozen and Gedik 2007).

An experimental study, on the effect of envelope colour and thermal mass on indoor temperatures was done using test cells in hot humid climate of Hong Kong (Cheng et al. 2005). The result of this study revealed that with high solar radiation and light building color, the building performance is more sensitive to envelope color. Addition of thermal mass also cuts down indoor maxima, brings up indoor minima and causes delay in the occurrence of peak indoor temperature for several hours. This time lag depends on heat storage properties of thermal mass (Cheng et al. 2005).

Vernacular buildings in north east India were found to be fairly thermally comfortable in presummer, summer and pre-winter periods (Singh et al. 2010). These buildings had brick, cement and sand walls (in warm and humid climate zone), processed mud and woven bamboo walls (in cool and humid climate zone) and rock slab, cement and sand walls (in cold and cloudy zone) along with other passive features (Singh et al. 2009).

Researchers have demonstrated use of alternative materials like strawbales (Elias- Ozkan et al. 2008) and rice-husk (Milani and Labaki 2012) in buildings. Autoclaved aerated concrete (AAC) is a type of light weight concrete produced by introducing aluminum powder to generate miniscule air bubbles. It has superior thermal resistance than other types of light weight concrete (Sadineni et al. 2011). Thermal performance analysis was done of three buildings constructed with different types of walls viz. strawbales rendered with mud plaster, AAC blocks and cement plaster, strawbales rendered with mud plaster inside and a layer of thin AAC blocks on the outside. The measured data charts showed strawbale to be the warmest building, followed by AAC, while the strawbale-cum-AAC building was the coolest (Elias-Ozkan et al. 2008). Milani and Labaki (2012) studied the physical, mechanical, and thermal performance of cement-stabilized rammed earth–rice husk ash walls. A thermal inertia of approximately 4 hours was observed both for a typical summer and winter day. The results showed that because of the thermal inertia and dampening, thermal gains of the prototype building occurred in the afternoon and thermal losses occurred in the morning (Milani and Labaki 2012).

A 1-D transient model developed by Moujaes and Brickman (2003), was used to study the thermal performance of a highly reflective paint applied sequentially to the outer walls and roof of a simulated residence in a hot and arid region. This simulation showed that a reduction of 33.6% (cooling load) on the average is achieved when the outer surface of the roof and walls are painted over the base case where no reflective paint is used. A study that investigated the impact of ceiling and wall reflectance values on Leadership in Energy and Environment Design (LEED) credits showed that increasing the ceiling reflectance has more impact on the daylight factor than increasing the wall reflectance (Yoon and Moeck 2005)

2.4.3 Insulation

Thermal insulation is an important means to achieving energy conservation in buildings (Al-Homoud 2005). Thus, many studies have been reported on determining the type of thermal insulation material and the economic thickness of the material used in the building envelope (Kaynakli 2012). The concept of economic thermal insulation thickness considers the initial cost of the insulation system plus the ongoing value of energy savings over the expected service lifetime of the insulation. The optimum economic thickness is the value that provides the minimum total life-cycle cost. The thickness is a function of the following: the building type, function, shape, orientation, construction materials, climatic conditions, insulation material and cost, energy type and cost, and the type and efficiency of air-conditioning system (Al-Homoud 2005).

A proper amount of thermal insulation in the building envelope helps to reduce the cooling and heating energy demands of a building and its associated carbon dioxide (CO_2) and sulphur dioxide (SO_2) emissions into the atmosphere as demonstrated by Comakli and Yuksel (2004), Dombayci (2007), Mahlia and Iqbal (2010). Thermal insulation helps in saving energy by reducing the rate of heat transfer. Numerous studies have been reported in different climate conditions to estimate the optimum thickness of thermal insulation used in external walls (Kaynakli 2008; Ucar and Balo 2009; Daouas et al. 2010) where some of the works considered both annual heating and cooling loads (Bolatturk 2008; Yu et al. 2009; Ucar and Balo 2010). Sodha et al. (1979), Al-Sallal (2003), Ozel and Pihtili (2007) investigated the most suitable location to apply insulation for the roof and/or walls. Properties of thermal insulation materials have also been studied (Al-Homoud 2005; Papadopoulos and Giama 2007; Anastaselos et al. 2009). Kaynakli (2012) has done a review of various studies on insulation materials like extruded polystyrene, fibreglass, expanded polystyrene, rock wool, foamed polyurethane, perlite, foamed polyvinyl chloride, polyethylene foam, styrofoam. Various studies reported in literature on thermal performance of walls due to application of insulation have been presented in Table 2.6.

2.5 Energy efficient roofs

The heat transmission into buildings through the roof directly contributes towards increasing internal surfaces temperatures, resulting in a higher radiant heat, as well as higher consumption of energy for cooling (Aboulnaga 1998). The roofs are the most important component that contribute significantly to the quality of the indoor thermal comfort and are responsible for as much as 50% heating and cooling load of the buildings (Florides et al. 2002). The thermal performance of roofs depends on the design, surface reflectance, roof treatment. Various studies reported on these aspects have been stated in this section.

2.5.1 Roof design

Interaction of the building envelope with the surrounding climatic conditions is responsible for the indoor comfort conditions (Givoni 1969). The roof has been found to be the most important structural element of buildings in a hot environment by modeling and simulation of energy flows in modern houses (Caren et al. 2008). Researchers have studied various types of roofs like naturally ventilated cavity roof (Susanti et al. 2008), cool ceiling with roof solar chimney (Chungloo and Limmeechokchai 2009), filler slab roof (Reddy 2004) as stated in Table 2.7.

The ventilated roof systems are essentially two slabs delimiting a duct through which air flows. This air gap/air flow diminishes the heat transfer across the roof into the building (Sadineni et al. 2011). Ventilated roofs can be either a passive type, with stack effect driving the air flow, or an active type, with fan induced ventilation. They are more popular in hot climatic conditions and are particularly useful in moderate height and wide roof area buildings. Solar roof ventilation may perform better than Trombe wall design in climates where the solar altitude is large as roof collectors provide larger surface area to collect the solar energy and hence higher air exit temperature (Awbi Hazim 1998). However, Khedari et al. (2000) observed that with only roof solar collector system, there is little potential to satisfy room thermal comfort. Roof integrated water solar collector made of several layers of glass followed by water chamber and metallic sheet at the bottom was developed by Juanico (2008) and could be used for domestic heating and cooling systems. Various numerical studies have been done on ventilated lightweight low sloped roof (Cerne and

Medved 2007), ventilated roof without thermal insulation (Maneewan et al. 2005) and air temperature variation along ventilated cavity (Hirunlabh et al. 2001). Numerical calculations showed that energy saving exceeding 30% can be achieved by using ventilated roofs in summer, compared to the same non-ventilated structure (Ciampi et al. 2005). Naturally ventilated cavity roof was found to be superior to the single roof in lowering the operative temperature by about 4.4^0C in a factory. When the factory was air conditioned, the cooling load reduction reached approximately 50% during the summer to maintain an operative temperature of 26^0C (Susanti et al. 2008, 2010, 2011).

A venturi-shaped roof can drive the natural ventilation of the building zones. The integration of this roof concept into a larger framework of sustainable building design has been discussed by Bronsema (2010). Different design configurations of the venturishaped roof were analysed: without guiding vanes, with guiding vanes at every 90^0 interval and with guiding vanes at every 10^0interval with focus on the under pressure in the narrowest roof section (contraction) by Van Hooff et al (2011). Adding guiding vanes strongly increased the flow resistance, which caused a larger part of the approaching wind flow to flow over and around the roof, rather than being forced through it (Van Hooff et al 2011). In another study numerical analysis showed that a passive building component cooled with evaporation is an effective protection against solar gains (Manzan and Saro 2002). Buoyancy-driven turbulent ventilation in attic space under a gable roof under winter conditions was simulated in terms of a CFD model (Wang et al. 2012). The numerical study showed that increasing vent size results in higher ventilation air flow rate but barely affects the attic heating load, and that both sufficient ventilation and insulation are needed to ensure the proper functions of the attic and its energy efficiency (Wang et al. 2012).

A solar chimney in roof is simply constructed by providing a small air gap under the roof and hot air in the room is removed by routing the air through the air gap due to the developed thermal buoyancy. The applications and modification of solar chimney on roof have been studied. The modifications include increasing the area of solar chimney per volume of the room, utilizing different materials for solar chimney (Khedari et al. 2000; Waewsak et al. 2003), increasing the number of openings (Hirunlabh et al. 2001) and increasing the temperature difference by adding a heater at the outlet of the solar chimney (Gan and Riffat 1998). Aboulnaga (1998) presented a parameteric analytical study of roof solar chimney coupled with wind cooled cavity using spread-sheet computer program. In another study, the application of cool ceiling and solar chimney was found to reduce the ceiling temperature by 2–4^{0}C, increase the circulation in the upper and lower regions of the room and reduce the air temperature in the room by 0.5–0.7^{0}C, thus increasing the comfort opportunity (Chungloo and Limmeechokchai 2009).

Filler slab roofs are basically solid reinforced concrete slabs with partial replacement of the concrete in the tension zone by a filler material (Reddy 2004). The filler material could be cheaper or cheaper and lighter like brick or brick panel, Mangalore tile, stabilized mud block, hollow concrete block, hollow clay tile/block, etc. Quantity of concrete in the tension zone of the slab that can be replaced by a filler material depends upon the shape of the filler material and the thickness of the solid slab. For example in a solid concrete slab of 125 mm thickness, a filler block of 60–70 mm thickness can be easily accommodated. In a typical situation, by using a stabilized mud block, 25% of the concrete can be replaced by a material, which costs one third the cost of concrete. This means that 15–20% of the cost of concrete can be saved by this operation (Reddy 2004). Burned clay pots were used as fillers in a RCC slab to increase the effective depth and thereby save steel, while also reducing the volume of concrete. These pots are useful for creating floor slabs and also act as insulators. The pots required no plastering and could be integrated with inexpensive shuttering planks. This resulted in 60% saving in steel and 30% saving in cost (Auroville 2000). Hourdi's blocks produced by the Auroville Earth Institute (2010) can rest on either reinforced concrete T-beams or on ferrocement channels to create roofs which are more comfortable in a hot climate (Fig. 2.6a-b).

Some researchers have done numerical studies on comparative thermal performance of different roof types (Nayak et al. 1982; Dutt et al. 1987; Sodha et al. 1981). The different roof systems were roof shading by plants, use of removable canvas, evaporative cooling, a roof garden and use of earthen pots over the roof. For optimum thermal load levelling and least average heat flux into the room, a shaded roof (due to a vegetable pergola) with a water film was found to be the best choice (Nayak et al. 1982). In another study, roof configuration consisting of a network of pipes buried in the roof with a blackened and glazed upper surface to absorb the solar energy incident on it and to reduce the convective heat loss to the ambient air from it was analyzed numerically. Comparative thermal performance of a roof under different conditions, viz., bare, glazed, glazed with movable insulation and glazed with a thermal trap sheet on the roof was studied. The use of the thermal trap material resulted in almost the same performance as movable insulation, while it eliminated the manually operated components, unlike movable insulation (Dutt et al.

1987). A study on the effect of placing a reflecting sheet in an air gap on the thermal performance of single hollow, double hollow and insulated hollow walls and roofs showed that the use of a reflecting sheet in single hollow and double hollow roofs is more economical and gives a better performance than water film system (Sodha et al. 1981).

Theoretical analysis of thermal performance of hollow-cored concrete slabs showed that heat flux entering the room through roof, is independent of the location of the air cavity within the depth of slab (Gandhidasan and Ramamurthy 1985). A new concept wherein hollow clay tiles (HCT) are laid over RCC instead of weathering course, was proposed. The energy savings obtained with the use of HCT roof was found to be 38–63% when compared with conventional weathering course roof. With air flow through the hollow passages, almost uniform roof bottom surface temperature was attained (Vijaykumar et al. 2007).

Detailed finite element modeling of vaulted roof and flat roof in various climatic conditions showed that vaulted roofs are only suitable for hot and dry climates, due to the presence of larger beam component of the solar radiation which is effectively reflected by the curved roof surface, and not so much for hot and humid climates (Tang et al. 2006). In hot and arid climatic conditions (Middle East) vaulted and domed roofs are quite popular in the vernacular architecture (Sadineni et al. 2011). Although vaulted roofs absorb more heat during the daytime than flat roofs, they also dissipate more heat through natural convection and re-radiation especially during night times in typical desert climate that experiences colder ambient temperatures. High thermal stratification occurs inside vaulted roof buildings, with almost 75% of the stratification taking place in the volume under the vault, keeping the lower part of the building space cool. The hot air can be exhausted near the top of the gable walls of vaults (Tang et al. 2006).

2.5.2 Cool roof

Cool roofs are defined as those with a surface that is both highly reflective and emissive. Reflectivity, or albedo, is the amount of total sunlight striking the roof surface that gets reflected back into the atmosphere, and emissivity is the ability of a roof surface to emit residual heat during cool evening hours. Cool roof systems use certain light-colour membranes or coatings to achieve these characteristics (Cavanaugh 2008). For cool roofs the combined effect of the three parameters that define heat gain and loss from a roof, namely solar albedo, thermal emittance and sub-roof resistance value, must be considered

(Gentle et al. 2011). Various studies reported in literature on thermal performance of cool roofs are stated in Table 2.8.

2.5.3 Green roof

Green roof most commonly refers to vegetative roof systems that contain live plants atop the roof membrane. Vegetative roofs are classified as either intensive or extensive, based on planting medium depth. Intensive vegetative roofs are the more substantial roof-garden variety and accommodate the growth of trees and shrubs. They require a planting medium of at least 1 foot in depth and can reach up to 3 feet in depth. Extensive vegetative green roofs are thinner, lighter systems using vegetation of grasses or sedums that have shallower root structures (Cavanaugh 2008). Green roofs have been vastly investigated in the last decades in many cities around the world as a tool to solve many problems in the urban environment, such as storm water runoff management (Mentens et al. 2006), mitigation of urban heat island effects (Takebayashi and Moriyama 2007) and increase of roof materials durability (Teemusk and Mander 2009). With an insulation role (Ekaterini and Aravantinos 1998) associated with evaporative cooling (Lazzarin et al. 2005) and better capturing of the solar radiation by the phenomena of inter reflections within the foliage, green roofs have a very positive impact on the energy performance of buildings (Spala et al. 2008). The climate did not seem to have a significant impact on the planted roofs' performance as examined by Kanellopoulou (2008). The green roofs presented a similar picture regarding their summer surface temperatures in hot and humid and hot and dry climates. A thermal performance metric for vegetated roof systems was also developed (Moody and Sailor 2013). Another study on life-cycle assessment of green roofs suggested that they are currently not cost effective on a private cost basis, but multifamily and commercial building green roofs are competitive when social benefits are included (Blackhurst et al. 2010). Various studies reported in literature on green roofs have been stated in Table 2.9.

2.5.4 Roof treatments

Extreme summertime weather conditions (Frank 2005; Christenson et al. 2006), higher internal and solar heat gains and increased comfort expectations give rise to an increase in building cooling demand. The roof is most exposed to impacts of solar radiation, as it receives sunlight for practically the whole day. Heat gain through roof elevates ceiling surface temperature and causes radiant heat load on the occupants. The term 'roof' includes the roof structure, the outer covering, and layers of insulating materials or membranes and the ceiling (Kabre 2010). Insulating material (Yu et al. 2011), roof pond (Kharrufa and Adil

2008), multi-reflective radiant barrier (Miranville et al. 2012) have been used to reduce the heat flow through the roof. Various studies reported on such different roof treatments are stated in Table 2.10.

The effect of a roof pond, which was ventilated mechanically for summer cooling was tested experimentally by Kharrufa and Adil (2008). Thermal measurements were taken for the room in normal conditions without a pond, with pond and no mechanical ventilation, and with pond and mechanically forced ventilation. The results showed a reduction of 6.5^{0}C between room without the roof pond and with a ventilated one. In another study, on the night-cooling roof-pond method, system optimization of pond-water depth (to achieve the target equilibrium temperature) and the optimization of cool-room dimensions for best cost/performance of the required volume of interior storage space were done (Chu and Boon-long 1992). Spanaki et al. (2011) presented a summary of comparative characteristics of roof pond variants: covered/uncovered pond with/without sprays, skytherm, energy roof, coolroof, walkable pond, wet gunny bags, cool-pool shaded and ventilated pond. A detailed comparison in terms of effectiveness and cooling demand reduction was also done. Dhiman et al. (1982) discussed the thermal modelling of the technique for cooling buildings by means of open evaporation of water over the roof. A comparative study of cooling by means of a roof pond, a water spray and moving water over the roof was done. The influences of parameters such as wind speed, relative humidity and water flow velocity on the performance of the system were numerically examined (Dhiman et al. 1982).

The experimental evaluation of a roof-mounted multi-reflective radiant barrier, on a dedicated test cell was done (Miranville et al. 2012). Several experimental sequences were conducted to determine the thermal resistance of the roof according to parameters like seasonal effects and the rate of ventilation of the upper air layer of the assembly. Determination of the thermal indicator was done using building simulation code. In another study, different passive techniques like painting of roof with white cement, pieces of glass, clay layer and one without any material over concrete roof were used for cooling the environment inside test structure. The structure with clay on top of the concrete was found to be the most efficient structure for cooling purpose. It was found that the cooling efficiency of the clay structure increased with thickness up to 0.05 m, beyond which the inside temperature remained constant (Hamdan et al. 2012).

Analysis of different configurations for a roof showed that when using one small layer of insulation in a wall/roof, the best thermal performance in an intermittent air conditioned cooled or heated room is achieved by placing it at the exterior side (Barrios et al. 2012). A study on the estimation of average roof insulation requirements in modern cold storage buildings based on economic and environmental considerations showed that there is a need to design more efficient, sustainable cold storage buildings (Richman et al. 2009). Life cycle cost analysis of four different insulation materials showed that depending on different cities, insulation materials and roof surface colors, optimum insulation thicknesses of a typical roof varied from 0.065 to 0.187 m and payback periods varied from 0.9 to 2.3 years for 24-h operation of cooling and heating equipments (Yu et al. 2011).

A laboratory test was carried out in the context of a weatherization program, which considers the feasibility of insulating flat roofs, which are often uninsulated in the Montreal area (Derome and Fazio 2000). This program represents potential annual energy savings of over 100 GWh for the province of Quebec. It was proposed that cellulose insulation should be installed at a high density to reduce air movement to a level that would avoid condensation problems. The results of the lab test showed that there was no sign of accumulated moisture after one cycle on the tested assemblies (Derome and Fazio 2000). The influence of local insulated roofing materials used in Burkina Faso on air conditioning loads of typical individual houses located in dry tropical climates was investigated (Toguyeni et al. 2012). The walls were of a composite clay–straw mixture whereas the insulation materials were red wood, white wood, and two assembled insulated panels. The thermophysical properties of the insulating materials as well as the clay–straw composite were studied, using an experimental apparatus based on the hot plate method. Simulation using TRNSYS showed that the clay–straw mixture reduced the air conditioning load by about 8% compared to clay walled houses. Analysis of the influence of roof insulation on the air conditioning load showed that a 1.5 cm thick insulator made of red wood induced energy saving of about 6.2%, while insulation panel made of natural fiber and a lime–cement mixture led to energy saving of 12.1% (Toguyeni et al. 2012).

2.6 Night ventilation

Suitable planning of energy-efficient buildings requires a balance between the thermal performance of the building and the appropriate selection of techniques for heating and cooling. It also necessitates thermal comfort which comes from an adequate quality of the indoor climate. Utilizing natural ventilation for maintaining satisfactory air quality in the interior is dependent on the supply of fresh air (Hughes et al. 2011). It is possible to reduce the increasing energy requirements in buildings by the passive cooling of buildings by night time ventilation. The basic idea of the concept is to ventilate a building during the night with relatively cold outdoor air. In the simplest case this can be done by opening windows or, if necessary, by using a mechanical ventilation system (Artmann et al. 2010).

Night ventilation works by using natural or mechanical ventilation to cool the surfaces of the building\fabric at night. Night ventilation is particularly suited to office buildings because these are usually not occupied during the night (Kolokotroni and Aronis 1999). Night ventilation can affect internal conditions during the day in four ways:

- reducing peak air-temperatures
- reducing air temperatures throughout the day, in particular during the morning hours
- reducing slab temperatures
- creating a time lag between the occurrence of external and internal maximum temperatures (Kolokotroni and Aronis 1999).

Despite the simplicity of the concept, the effectiveness of night time cooling is affected by many parameters, which makes predictions uncertain (Artmann et al. 2008). Various studies reported in literature on night ventilation have been stated in Table 2.11.

The climatic ambient conditions and the air flow rate during night-time ventilation mode were identified to have the most significant effect. However, building construction (thermal mass) and heat gains also have a considerable effect on thermal comfort in summer. Therefore, as much thermal mass as possible should be placed in contact with the room air (e.g. avoidance of suspended ceilings) and heat gains should be limited by applying energy-efficient office equipment, daylight utilisation, and the installation of an effective sun protection system (Artmann et al. 2010).

A hybrid cooling system, utilizing wind-driven cross ventilation and radiational panel cooling in an office setting was investigated. The system was devised with an energy-saving strategy, which utilized stratified room air with a vertical temperature gradient. The cooled air settled down within the lower part of the room, while the hot and humid air passed through the upper region of the room, sweeping out the heat and contaminants generated indoors. This strategy was found to be quite energy-efficient in the intermediate seasons of spring and autumn in Japan. Even under hot and humid outdoor conditions, the hybrid system coupled with radiational cooling brought significant energy savings compared with a hybrid system coupled with underfloor air-conditioning (Song and Kato 2004). Using an hourly simulation model, Shaviv et al. (2001) analysed the maximum indoor temperature in a residential building in the hot humid climate of Israel as a function of night ventilation air change rate, thermal mass and daily temperature difference. In a heavy mass building, the maximum indoor temperature was found to be reduced by 3–6^{0}C compared to the outdoor maximum temperature.

Comparative studies on different ventilation strategies have also been reported in literature. Four ventilation strategies, night time-only ventilation, daytime-only ventilation, full-day ventilation and no ventilation were evaluated for hot-humid climate according to the number of thermal discomfort hours in the whole typical year on the basis of simulations (Liping and Hien 2007). The results indicated that full-day ventilation is better than the other three ventilation strategies for indoor thermal comfort. In another study, comparison of room with an earth-air heat exchanger, untreated room and room with cross ventilation in an adobe house was done in Delhi. During off sunshine hours in summers, temperature of room with cross ventilation was found to be significantly lower in comparison with other rooms, so cross ventilation is a good option for cooling of room (Shukla et al. 2008). Becker and Paciuk (2002) studied various ventilation and precooling strategies and its overall effect on the energy utilization and thermal performance to reduce the energy demands in buildings. The results showed that concentrated night pre-cooling is extremely efficient cooling technique for buildings with high internal heat loads.

Geros et al. (2005) carried out a study on the impact of urban environment on night ventilation energy performance in ten urban canyons in Greece. The results confirmed that the energy conservation caused by night ventilation in air-conditioned buildings can be reduced by up to 90%. This is due to urban canyon geometry that leads to higher ambient temperature in the canyon than outside one during night. Wang et al. (2009) investigated the feasibility of operating night ventilation for office buildings in China. The results showed that the efficiency of using this passive cooling technique is higher when the active cooling time is almost equal to the ventilation operation time. The study concluded that the mean radiant temperature of the interiors was reduced up to 3.9^{0}C.

2.7 Important findings from the literature review

The building envelope (roof, walls, doors, and windows) and the operation period of the heating system are the factors that have the greatest impact on the total energy consumption of the building (Manioglu and Yilmaz 2006). The envelope determines interior climate conditions, and thus, the additional energy demand for heating and cooling. Actions on the elements that make up the building envelope can have a positive impact on certain energy requirements and have a negative effect on others. Consequently, it is necessary to evaluate the performance of the building as a whole (Radhi 2008). Design of various building elements like static sunshade, wall, roof play a major role in the overall heat gain or loss by the building. Cavity walls and hollow roof have been found to be effective in regulating energy requirements in buildings in regions with hot summer and cold winter. Extensive work has been done on energy efficient buildings as a whole, static sunshades, walls, roofs and night ventilation. From the literature review it is observed that various studies have been done on wall and roof treatments to reduce energy consumption in buildings. But there is scope to design a new wall and roof specific to a climate zone based on the characteristics of that climate zone. Studies have not been done on combined effect of different aspects like static sunshades, walls, roofs and night ventilation. There is a need to design, implement and evaluate passive design elements in a single building in specific climate zone. The detailed thermal performance and interaction of actual buildings are not clearly understood. Many simulations, mathematical and analytical studies have been done, but there is a need to study the thermal performance of energy efficient building elements in rooms of habitable dimensions to verify their actual thermal performance that has been proven using mathematical or simulation methods. The fundamental requirement is a greater understanding of the total nature of the physical environment in buildings, how it is created and what role is played by the building envelope in creating this environment. Thus comparative experimental studies that evaluate the performance of different passive design elements like static sunshade, wall, roof, night ventilation (independently and combined with each other) need to be done.

2.8 Objectives of present research work

Based on the extensive literature review and gaps in existing research, present research work aimed at the following objectives:

1. Design passive building elements like static sunshade, wall, roof responsive to climate for energy efficiency in buildings

2. Analyze the thermal performance of rooms with different combination of building elements in various months and on representative days
3. Implement the designed elements in actual buildings to assess their impact on thermal performance of a building
4. Study the individual and combined effect of the designed building elements in all the seasons throughout the year
5. Compare the thermal performance of the whole building having the designed passive building elements with a conventional building
6. Study impact of night ventilation on energy efficient and conventional building

Table 2.1 Review of studies on thermal performance of whole building

Place/ Climate zone	Building performance parameters	Methodology*	References
Montreal, Canada	building envelope, moisture, thermal performance	Si	Fazio et al. 2007
Argentina, Temperate-Cold	insulation, hermetic double glazing and night protection for windows, increase of the north area for direct solar gain	Si, Ex	Filippin et al. 2008
New Zealand, Temperate	building surface, volume, window area, wall area, indoor volume	Ex	Su 2011
Istanbul, Temperate-humid	materials of the envelope, heating system, economic cost	Ma	Manioglu and Yilmaz 2006
South Africa, Subtropical	fly ash bricks, thermal comfort, ventilation	Ex	Makaka et al. 2008
Tunisia, Hot- Humid	Trombe wall, thermal insulation, thermal capacity, direct gain element, double glazing	Ex, Si	Ghrab-Morcos et al. 1993
Rehovot, Israel, Hot-Humid	insulation, night ventilation, thermal mass, ceiling vents, greenhouse on the upper roof, windows glazing shading system	Si, Ex	Shaviv 1998
Singapore	spatial, acoustic, visual, thermal, indoor air quality, building integrity using total building performance (TBP)	An	Oyedele et al. 2012

***** An-analytical; Ex-experimental; Ma-mathematical; Si-simulation

Table 2.2 Review of studies on static sunshades

Place/ Climate zone	Study	Methodology*	Authors
India, Singapore, Australia	Design of sunshade using software	Si	Kabre 1999
	Design of sunshade using software	Si	Hellstrom et al. 2007
New Delhi, India, Composite	Appropriate size of overhangs	Ma	Garg and Bansal 1986
	Analysis of sunshades using shading mask	Ma	El-Refaie 1987
	Tool for sunshade design	Ma	Etzion 1992
Korea	Efficiency of photovoltaic modules as sunshades	Ex	Yoo and Lee 2002
Sweden	Analysis of photovoltaic hybrid solar window	Ex, Si	Davidsson et al. 2012
	Overview of daylight systems		Kischkoweit-Lopin 2002
	Analysis of prismatic panes	Ex	Christoffers 1996
	Mathematical tool for sunshade design	Ma	Jorge et al. 1993
	Chart to design sunshades		Dubois 2000
	Design principles of sunshades		Chandra 1996
	Radiant effect of sunshade on glass surface temperature	Ex, Si	Kapur 2004
Pilani, India, Composite	Design of sunshade considering solar angles	Ex	Ralegaoankar 2004
	Mathematical model to design sunshades	Ma	Yener 1999
	Computational procedure for solar heat gain to select sunshade	Si	Kassem et al. 1999

***** Ex-experimental; Ma-mathematical; Si-simulation

Table 2.3 Review of studies on thermal performance of different wall types

Place/ Climate zone	Wall type	Methodology*	Authors
Shimla, India, Cold	solar heat collecting wall	Ex, Ma	Chandel and Aggarwal 2008
Srinagar, India, Cold	transwall	Ma	Nayak 1987
Delhi, India, Composite	vary therm wall	An	Sharma et al. 2003
	Trombe Michel wall	Ma	Shen et al. 2007
North China	Water thermal storage wall	Ex, Si	Wang et al. 2013
Various	unventilated solar wall, Trombe wall, insulated Trombe wall, composite solar wall	Ma, Ex	Zalewski et al. 2002
	passive evaporative cooling wall	Ex	He and Hoyano, 2011
Munich, Germany	double-skin façade	Ma, Si, Ex	El-Sadi et al. 2010
Brisbane, Australia	double skin facade	Si	Dagnall et al. 2011
Mataro, Spain Stuttgart, Germany	ventilated photovoltaic facade	Ex, Ma	Infield et al. 2006
	ventilated façade	An, Ma	Ciampi et al. 2003
Berlin, Germany Barcelona , Spain Palermo, Italy	air-cavity wall, plus-insulated wall, ventilated wall	Ma	Pulselli et al. 2009
	light concrete hollow brick walls	Ma	Del Coz Dıaz et al. 2007
	masonry walls of multicore hollow concrete blocks	Ex, Ma	Becker 1993
Las Vegas, USA, Hot-Dry	sandwiched styrofoam in between concrete layers	Ex, Si	Moujaes and Madeja 2006
Mediterranean	composite wall	An	Tsilingiris 2006
	alveolar brick construction system	Ex, Ma	De Gracia et al. 2011

***** An-analytical; Ex-experimental; Ma-mathematical; Si-simulation

Table2.4 Review of studies on thermal performance of cavity walls

Place/ Climate zone	Methodology*	Authors
Delhi, India, Composite	Ma	Tiwari et al. 1994
Jodhpur, India, Hot-Dry	Ma	Kumar et al. 1994
	A	Pratt 1965
	Si	Zhang and Wachenfeldt 2009
England, Various	Ma, Ex	Hong et al. 2006
	Ex	Aviram et al. 2001
Darwin, Australia, Tropical Brisbane, Australia, Subtropical Melbourne, Australia, Temperate	Ex	Cole 1994
	Ma, Ex	Fazio and Kontopidis 1988
Delhi, India, Composite	Ma	Verma et al. 1986

***** An-analytical; Ex-experimental; Ma-mathematical; Si-simulation

Table 2.5 Review of studies on thermal performance of materials, thermal mass, surface finish of walls

Place/ Climate zone	Wall parameter	Methodology*	Authors
Jaisalmer, India, Hot-Dry	thermal mass, deeply carved patterns	Ex	Krishnan et al.1996
Cold climate	Thermal storage capacity	Si	Karlsson et al. 2013
Hong Kong, Hot-Humid	thermal mass, envelope colour	Ex, Ma	Cheng et al. 2005
Diyarbakir, Turkey, Hot-Dry	porous basalt stone thick walls	Ex	Sozen and Gedık 2007
	AAC blocks, strawbales	Ex, Si	Elias-Ozkan et al. 2008
	reinforced plastered straw bale composite sandwich walls	Ex	Kim et al. 2012
Brazil, Tropical	cement-stabilized rammed earth–rice husk ash walls	Ex	Milani and Labaki 2012
	coal fly ash and scrap tire fiber insulation	Ex	Van de Lindt et al. 2008
Northeast India, Warm-Humid, Cool-Humid, Cold-Cloudy	processed mud and woven bamboo walls	Ex	Singh et al. 2009, 2010
United States of America, Hot-Arid	highly reflective paint	Ma	Moujaes and Brickman 2003
	ceiling and wall reflectance	Si	Yoon and Moeck 2005

***** Ex-experimental; Ma-mathematical; Si-simulation

Table 2.6 Review of studies on thermal performance of insulation materials in walls

Place/ Climate zone	Type of study	Methodology*	Results	Authors
Turkey, Warm	optimum insulation thickness	Ma	cooling degree-hours is more significant for energy savings	Bolatturk 2008
Greece, Mild	insulation in double brick wall	Si	30% higher heating requirements by taking thermal bridge effects into account	Theodosiou and Papadopoulos 2008
Dubai, Hot-Humid	thermal bridging, insulation	Si, Ex	30% energy savings	Freiss et al. 2012
Turkey, Various	optimum insulation thickness	An	energy saving:13.996-63.071 $/m^2, payback period:1.346-2.023 years	Ozkan and Onan 2011
Quebec	insulation	Ex	vapour-tight insulation board caused longer exposure to moisture	Derome and Desmarais 2006
	vacuum insulation panels	Ex, Ma	thermal improvement of 95% by adding 60 mm insulation boards (with 40 mm vacuum insulation panels)	Nussbaumer et al. 2006

***** An-analytical; Ex-experimental; Ma-mathematical; Si-simulation

Table 2.7 Review of studies on thermal performance of roof technologies

Place/ Climate zone	Roof type	Methodology*	Authors
Toyohashi City, Japan, Hot-Humid	naturally ventilated cavity roof	Ma, Ex	Susanti et al. 2008, 2010, 2011
Pittsburg, USA	Roof integrated solar chimney	Si, Ma	Deblois et al. 2013
	ventilated roof	Ma	Ciampi et al. 2005
Al-ain city, UAE, Hot-Arid	solar chimney with wind cooling cavity	Ma	Aboulnaga 1998
	low sloped roof with forced ventilated cavity	Ma, Ex	Cerne and Medved 2007
	passive building component cooled with evaporation	Ma	Manzan and Saro 2002
Thailand, Hot-Humid	cool ceiling with roof solar chimney	Ex, Ma	Chungloo and Limmeechokchai 2009
	venturi-shaped roof	Ex, Ma	Hooff et al. 2011
New Delhi, India, Composite	earthen pots over roof	Ma	Nayak et al. 1982
Auroville, India, Hot-Humid	filler slab with clay pots	Ex	Auroville 2000
	filler slab roof		Reddy 2004
New Delhi, India, Composite	hollow roof with reflecting sheet in air gap	Ma	Sodha et al. 1981
India, Tropical	hollow clay tile roof	Ma	Vijaykumar et al. 2007
New Delhi, India, Composite	hollow-cored concrete slab	Ma	Gandhidasan and Ramamurthy 1985
Jodhpur, India, Hot-Dry	evaporative cooling with air cavity roof	Ma	Kumar et al. 1994
	roof with pipes buried	Ma	Dutt et al. 1987
	air and water flow over roof	Ma	Kumar and Tiwari 1994

***** Ex-experimental; Ma-mathematical

Table 2.8 Review of studies on thermal performance of cool roofs

Place/ Climate zone	Methodology*	Results	Authors
Sydney, Australia, Temperate	Si	no dominant influence on average winter heating needs	Gentle et al. 2011
Various	Si	reduction in cooling loads by 18–93% and peak cooling demand in air-conditioned buildings by 11–27%	Synnefa et al. 2007
California, Various	Si, Ex	reduction in daily peak roof surface temperature by 33–42 K	Akbari et al. 2005
London, United Kingdom, Moderate	Si, Ex	cooling demand is reduced, heating demand is increased and total energy savings vary between 1 and 8.5%	Kolokotroni et al. 2011
North America, Various	Si	improvement in moisture performance; energy efficiency and environmental benefits	Moghaddaszadeh Ahrab and Akbari 2012
Tropical areas with latitude angle 23.5^0 or less, Warm/ Hot	Ma	significant reduction in downward heat flow by using a light or reflective roof colour instead of a dark one	Suehrcke et al. 2008
Oregon, USA, Various	Ex, Ma	increased albedo of white roofs reduces their surface temperature and decreases sensible flux into the urban atmospheric system	Scherba et al. 2011
Turkey	Ex	decrease in the solar reflectance of roof covering due to weathering	Kultur and Turkeri 2012

***** Ex-experimental; Ma-mathematical; Si-simulation

Table 2.9 Review of studies on thermal performance of green roofs

Place/ Climate zone	Methodology*	Results	Authors
Taiwan, Tropical, Subtropical	Ex	for achieving thermal reduction a greater coverage ratio means a smaller total leaf thickness is required	Fang 2008
Florianopolis, Brazil, Temperate	Ex	Reduction in heat gain by 92–97% and enhancement of the heat loss to 49% and 20% in warm period	Parizotto and Lamberts 2011
La Rochelle, France	Ma, Ex	green roof improves thermal comfort since it lowers soil temperature	Ouldboukhitine et al. 2011
Reunion Island, Tropical Humid	Ex	decrease in temperature fluctuations between green roof surface and the green roof at the depth of 120 mm (6.7±0.1°C)	Morau et al. 2012
Hong Kong, Tropical Humid	Ex	Capability of green roof to reduce temperature was relatively inefficient compared to temperate region counterparts	Jim and Tsang 2011
Mediterranean area, Mild	Ma	well wet green roof has good cooling performance, dryer the roof the lower is heating demand	Zinzi and Agnoli 2011
Taiwan, Tropical	Ex	Irrigation twice a week has the best thermal reduction percentage of heat amplitude (91.6%)	Lin and Lin 2011

***** Ex-experimental; Ma-mathematical

Table 2.10 Review of studies on thermal performance of roof treatments

Place/ Climate zone	Roof type/ Treatment	Methodology*	Authors
Baghdad, Iraq, Hot and Dry	roof pond	Ex, Si	Kharrufa and Adil 2008
	roof pond variant	An	Spanaki et al. 2011
Thailand, Tropical	roof pond	Ma	Chu and Boon-long 1992
New Delhi, India, Composite	open evaporation of water over the roof	Ma	Dhiman et al. 1982
	evaporative cooling	Ma	Tiwari et al. 1994; Kumar et al. 1994
Papua New Guinea	air and water flow in roof cavity and over the roof	Ma	Kumar and Tiwari 1994
	reflective underlay on pitched roofs	Ex, Si	Roels and Deurinck 2011
Reunion Island, Tropical, Humid	multi-reflective radiant barrier	Ex	Miranville et al. 2012
China, Hot, Cold	optimum insulation thickness	Ma	Yu et al. 2011
	Insulation		Barrios et al. 2012
Jordan	white cement, glass pieces and clay layer over roof	Ex	Hamdan et al. 2012
Burkina Faso, Dry Tropical	insulation materials: red wood, white wood, two assembled insulated panels	Ex, Si	Toguyeni et al. 2012
Tampa, Milwaukee, USA, Hot, Cold	optimum insulation thickness	Si	Richman et al. 2009
Switzerland	vacuum insulation panels	Ex	Brunner and Simmler 2008
Hong Kong	insulation	Ex, Ma	Ho 1995
Brazil	porous sandy roof	Ma	dos Santos and Mendes 2013

***** An-analytical; Ex-experimental; Ma-mathematical; Si-simulation

Table 2.11 Review of studies on thermal performance of night ventilation

Place/ Climate zone	Building type	Methodology*	Authors
Various	office	Si	Artmann et al. 2010
Belgium	office	Ma	Leenknegt et al. 2013
United Kingdom, moderate	office	Si	Kolokotroni et al. 1998
England	air-conditioned offices	Si	Kolokotroni and Aronis 1999
China	office	Si	Wang et al. 2009
Japan	office	Si	Song and Kato 2004
Ireland, moderate maritime	library	Si	Finn et al. 2007
United States	non residential	Si	Zhao and Jones 2007
Singapore, hot-humid	residential	Si	Liping and Hien 2007
Israel, hot humid	heavy mass building	Si	Shaviv et al. 2001
Delhi, India, composite	adobe structure	Ex	Shukla et al. 2008
Greece	single-zone room	Ex	Geros et al. 2005

* Ex-experimental; Ma-Mathematical; Si-simulation

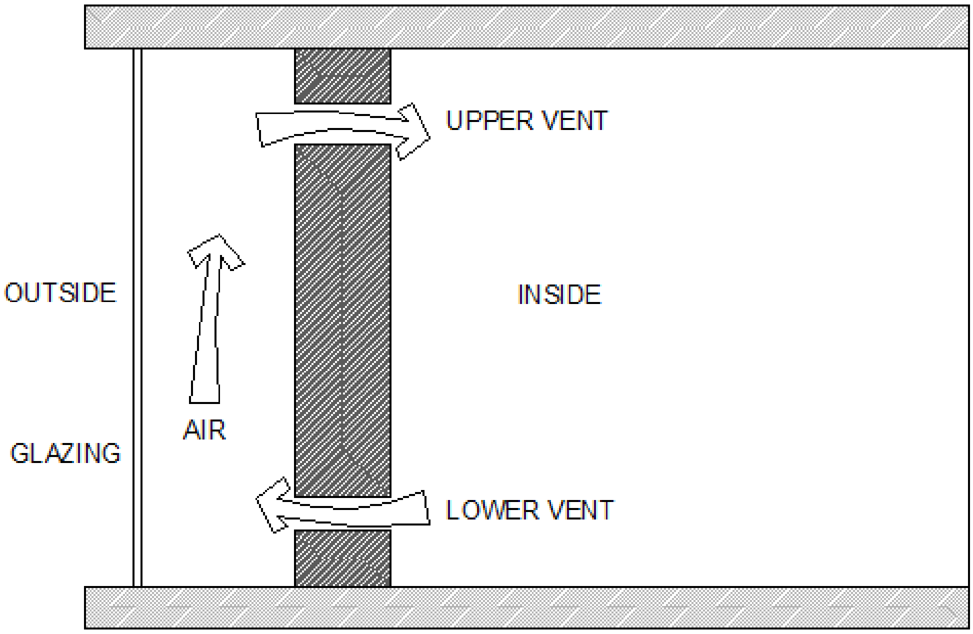


Fig. 2.1 Schematic diagram of classical Trombe wall (without dampers)
(Source: Chan et al. 2010)

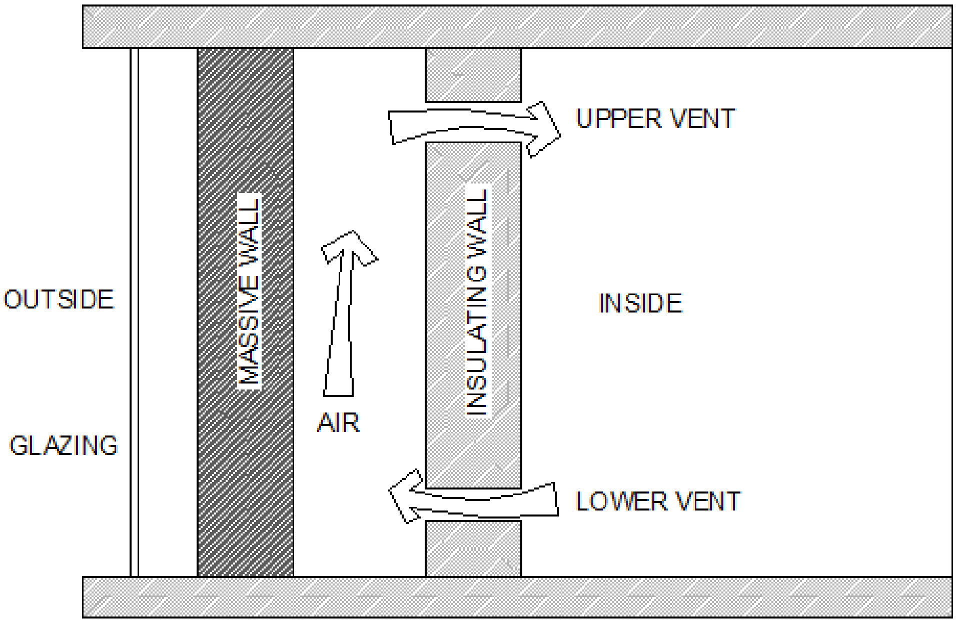


Fig. 2.2 Schematic diagram of composite Trombe-Michel wall
(Source: Chan et al. 2010)

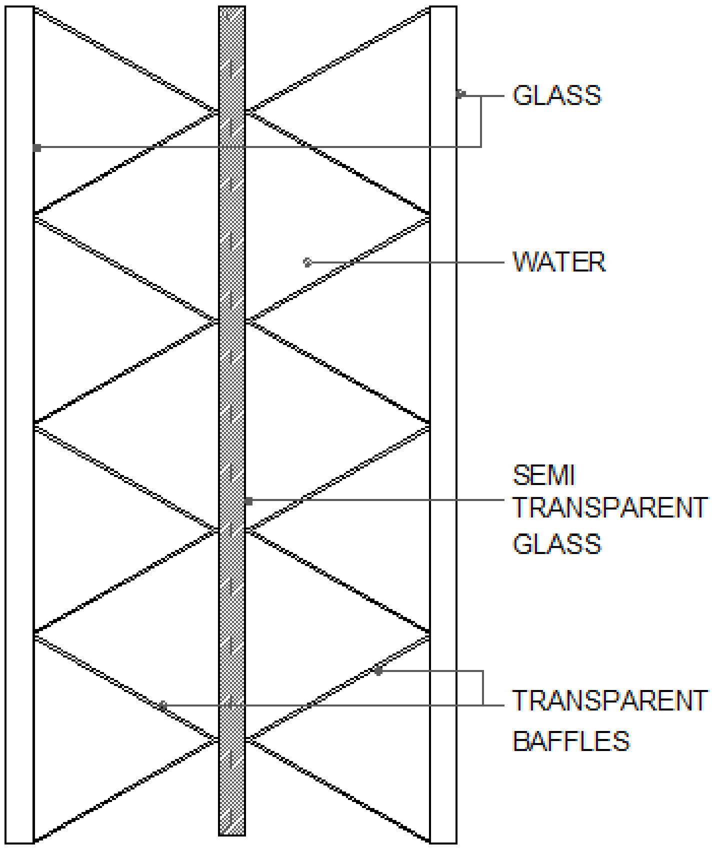


Fig. 2.3 Schematic diagram of transwall system (Source: Nayak 1987)

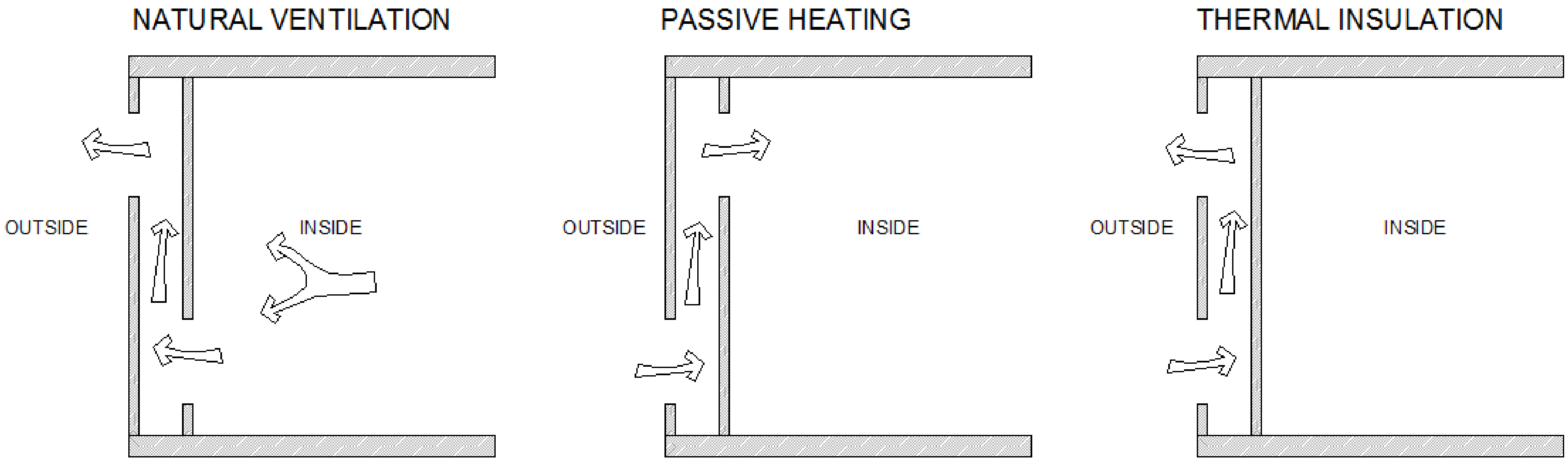


Fig. 2.4 Solar chimney models (Source: Pacheco et al. 2012)

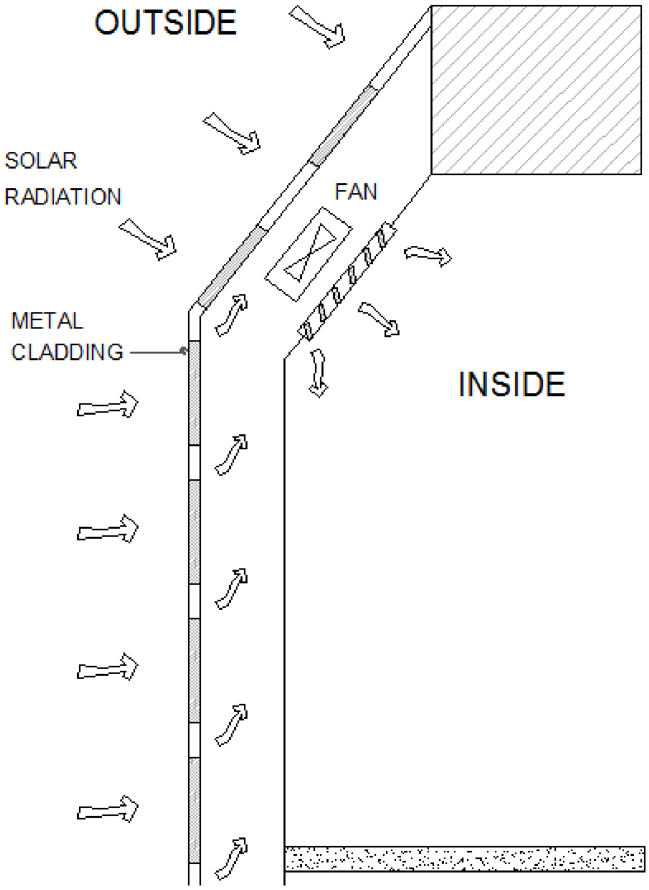


Fig. 2.5 Solar facade (Source: Pacheco et al. 2012)

(a)

(b)

Fig. 2.6 Roof/ floor with hourdi blocks (a) Roof with hourdi blocks and T beams (b) Floor with hourdi blocks and ferrocement channels (Source: Auroville Earth Institute 2010)

Chapter 3

Fundamentals of Passive Solar Architecture

3.1 Background

Ever since human beings started constructing buildings for their protection, they have tried to modify the climatic influences through proper design and form of the structure. It is possible to reduce investments and running cost for the heating and cooling equipment in a building by considering climatic influences like air circulation, solar radiation in building design. Thus, climatically responsive architecture is always energy conscious construction. Solar radiation is the most abundant renewable energy source that sustains life on earth. It is the driving energy of our ecosystem and precipitation cycle. The term "passive solar building" is a qualitative term describing a building that significantly utilizes solar gains to reduce heating and cooling energy consumption based on natural energy flows - radiation, conduction and convection; forced convection based on mechanical means such as pumps and fans is not expected to play a major role in the heat transfer process. The ultimate design objective is minimization of energy costs (heating, cooling, electricity) while maintaining good interior thermal comfort (Athienitis and Santamouris 2002). For this it is necessary to optimize buildings as systems which act as natural selective filters between the indoor and outdoor environments, which admit desirable influences (like daylight, winter sun etc.), exclude undesirable ones, while maximizing utilization of solar energy (Szokolay 2001). Thus the climatic factors those affect building design, difference in building design due to difference in climate parameters and the sun's movement throughout the year need to be considered for design of climate responsive buildings. This chapter deals with climate parameters affecting building design and solar geometry.

3.2 Climate and architecture

Climate is an integration in time of the physical states of the atmospheric environment and characteristics of a certain geographical location while weather is the momentary state of the atmospheric environment at a certain location (Koenigsberger et al. 1973). The interaction of solar radiation with the atmosphere and the gravitational forces, together with the distribution of land and sea masses, produce a wide variety of climates. However, certain zones and belts of approximately uniform climates can be distinguished. Familiarity with the character and location of these zones is essential as they are indicative of the climatic problems encountered in the building design process. The classification of climate for types of building is an aid to the functional design of buildings [SP-41:1987 (Bureau of Indian Standards 1987)]. One zone merges gradually and imperceptibly into the next and so boundaries of climatic zones cannot be accurately mapped. It is nevertheless easy to identify the zone or transition area between two zones to which a particular settlement belongs.

For a climatically responsive design of buildings in any climatic zone consideration of those aspects of climate which affect human comfort as also the use of buildings is essential. They include sun path (to identify desirable or undesirable radiation), averages, changes and extremes of temperature, the temperature differences between night and day (diurnal range), humidity, sky conditions, rainfall and its distribution and air movements (Willkomm 2001). Analysis of this climatic information needs to be done to present it in a form that helps to identify features that are beneficial or harmful to the future occupants of the building. Then certain general guidelines for zones of a specific climate type can be followed and modified for the special conditions of a particular building (Koenigsberger et al. 1973).

3.2.1 Factors affecting climate

Both weather and climate are characterised by certain variables known as climatic factors (Bansal and Minke 1988). They are solar radiation, ambient temperature, air humidity, precipitation, wind, sky condition.

i. *Solar radiation:* Solar radiation is the most important weather variable that determines whether a place experiences high temperatures or is predominantly cold. It is the intensity of sunrays falling per unit time per unit area and is usually expressed in watts per square metre (W/m^2). It is the radiant energy received from the sun. The radiation incident on a surface varies depending on its geographic location (latitude and longitude of the place), orientation, season, time of day and atmospheric conditions. Average daily amounts of solar radiation (MJ/m^2day) for each month of the year would give a fair indication of climatic conditions, including seasonal variations (Koenigsberger et al. 1973).

ii. *Ambient temperature:* The temperature of the air in a shaded (but well ventilated) enclosure is known as the ambient temperature; it is generally expressed in degree Celsius (^{0}C). Temperature at a given site depends on wind as well as local factors such as shading, presence of water body, sunny condition, etc. When the wind speed is low, local factors strongly influence temperature of air close to the ground. With higher wind speeds, the temperature of the incoming air is less affected by the local factors (Nayak and Prajapati 2006).

iii. *Air humidity:* Air humidity, which represents the amount of moisture present in the air, is usually expressed in terms of 'relative humidity'. Relative humidity is defined as the ratio of the actual amount of moisture present, to the amount of moisture the air could hold at the given temperature and is expressed as percentage (Koenigsberger et al. 1973). It varies considerably, tending to be the highest close to dawn when the air temperature is at its lowest, and decreasing as the air temperature rises. The decrease in the relative humidity towards midday tends to be the largest in summer. In areas with high humidity levels, the transmission of solar radiation is reduced because of atmospheric absorption and scattering. High humidity reduces evaporation of water and sweat. Consequently, high humidity accompanied by high ambient temperature causes a lot of discomfort (Nayak and Prajapati 2006).

iv. *Precipitation:* Precipitation is the collective term used for rain, snow, hail, dew or frost i.e. all forms of water precipitated from the atmosphere. It is usually measured in millimeters (mm) by using a rain gauge (Koenigsberger et al. 1973).

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

vi. *Sky condition:* Sky conditions are usually described in terms of presence or absence of clouds. Under clear sky conditions, the intensity of solar radiation increases; whereas it reduces in monsoon due to cloud cover. The re-radiation losses from the external surfaces of buildings increase when facing clear skies than covered skies. On an average two observations are made per day, when the proportion of sky covered by cloud is expressed as a percentage or in octets. For example, 50% or four-eights would indicate that half of the sky hemisphere is covered by cloud (Koenigsberger et al. 1973).

3.2.2 Climate classification

Tropical climates are those where heat is the dominant problem, where for greater part of the year buildings serve to keep the occupants cool rather than warm, where the annual mean temperature is not less than 20^0C (Koenigsberger et al. 1973). Tropical climate is characterized by significant hourly and large diurnal variations in temperature and sunshine that also vary considerably over the year. Classification of climate in respect of building design means zoning the country into regions in such a way that the differences in climate from region to region are reflected in the building design, warranting some special provisions for each region. India has tropical climatic conditions and based on these criteria, there are five major climatic zones viz. hot-dry, warm-humid, temperate, cold and composite as stated in Table 3.1 [National Building Code of India:2005 (Bureau of Indian Standards 2005)]. Each climate zone does not have the same climate for the whole year; it has a particular season for more than six months and may experience other seasons for the remaining period. A climate zone that does not have any season for more than six months may be called as composite zone. A map of India depicting various climate zones is shown in Fig. 3.1

i. *Hot and dry:* The hot and dry zone lies in the western and the central part of India. Due to intense solar radiation (values as high as 800-950 W/m^2), the ground and the surroundings of this region are heated up very quickly during day time. In summer, the maximum ambient temperatures are as high as 40–45^{0}C during the day and 20–30 ^{0}C at night. In winter, the values are 5-25^{0}C during the day and 0-10^{0}C at night. The diurnal variation in temperature is quite high, (more than 10^{0}C). Jaisalmer, Jodhpur and Sholapur are some of the towns that experience this type of climate. The climate is described as dry because of a low relative humidity (25-40%) due to less vegetation, fewer surface water bodies and less rainfall - the annual precipitation being less than 500 mm. Hot winds blow during the day in summers and sand storms are also experienced. The night is usually cool and pleasant. A generally clear sky, with high solar radiation causing an uncomfortable glare, is typical of this zone. As the sky is clear at night, the heat absorbed by the ground during the day is quickly dissipated to the atmosphere. Hence, the air is much cooler at night than during the day.

ii. *Warm and humid:* The warm and humid zone covers the coastal parts of the country. The diffuse fraction of solar radiation is quite high due to cloud cover, and the radiation can be intense on clear days. The dissipation of the accumulated heat from the earth to the night sky is generally marginal due to the presence of clouds. Hence, the diurnal variation in temperature is quite low. In summer, temperatures can reach as high as 30-35 ^{0}C during the day and 25-30^{0}C at night. In winter, the maximum temperature is between 25-30^{0}C during the day and 20-25^{0}C at night. Although the temperatures are not excessive, the high humidity causes discomfort. Some cities that fall under this zone are Mumbai, Chennai and Kolkata. An important characteristic of this region is the relative humidity, which is generally very high, about 70-90 % throughout the year. Precipitation is also high, being about 1200 mm per year, or even more. Hence, the provision for quick drainage of water is essential in this zone. The wind is generally from one or two prevailing directions with speeds ranging from extremely low to very high. Wind is desirable in this climate, as it can cause sensible cooling of the body.

iii. *Temperate:* Areas having a temperate climate are generally located on hilly or high-plateau regions with fairly abundant vegetation. The solar radiation in this region is more or less the same throughout the year. Being located at relatively higher elevations, these places experience lower temperatures than hot and dry regions. The temperatures are neither too hot nor too cold. In summers, the temperature reaches 30-34^{0}C during the day and 17-24^{0}C at night. In winter, the maximum temperature is between 27-33^{0}C during the day and 16-18^{0}C at night. Pune and Bangalore are examples of cities that fall under this climatic zone. The relative humidity is low in winters and summers, varying from 20-55%, and going upto 55-90% during monsoons. The total rainfall usually exceeds 1000 mm per year. Winters are dry in this zone. Winds are generally high during summer. Their speed and direction depend mainly upon the topography. The sky is mostly clear with occasional presence of low, dense clouds during summers.

iv. *Cold:* Generally, the northern part of India experiences this type of climate. The mean monthly maximum temperature is below 25^{0}C. Places with all values of relative humidity are included in this zone. Most cold regions are situated at high altitudes. Ootacamund, Shimla, Shillong, Srinagar, Mahabaleshwar, Leh are examples of places belonging to this climatic zone. Summers are quite pleasant while winters are chilly.

v. *Composite:* The composite zone covers the central part of India. Some cities that experience this type of climate are New Delhi, Kanpur and Allahabad. The intensity of solar radiation is very high in summer with diffuse radiation amounting to a small fraction of the total. In monsoons, the intensity is low with predominantly diffuse radiation. The maximum daytime temperature in summers is in the range of 32-43^{0}C, and night time values are from 27-32^{0}C. In winter, the values are between 10-25^{0}C during the day and 4-10^{0}C at night. The relative humidity is about 20-25 % in dry periods and 55-95 % in wet periods. The presence of high humidity during monsoon months is one of the reasons why places like New Delhi and Nagpur are grouped under the composite and not hot and dry climate. Precipitation in this zone varies between 500-1300 mm per year. This region receives strong winds during monsoons from the south-east and dry cold winds from the north-east. In summer, the winds are hot and dusty. The sky is overcast and dull in the monsoon, clear in winter and frequently hazy in summer.

3.2.3 Thermal comfort

The characteristics of each climate differ and accordingly the comfort requirements vary from one climatic zone to another. The primary purpose of building design and choice of materials is the creation of an indoor thermal environment which is conducive to the well being of the occupants. The main challenge in building design is to strive towards the optimum of total comfort, the criteria for which depend upon human senses. The most important physiological requirement of human health and general well-being is the ability of the human body to maintain a constant internal temperature [SP-41:1987 (Bureau of Indian Standards 1987)]. To maintain body temperature at a steady level, all surplus heat must be dissipated to the environment including any simultaneous heat gain from the environment. The body exchanges heat with the surroundings through convection, radiation, evaporation and to a lesser extent by conduction (Koenigsberger et al. 1973). The conditions under which thermal balance is achieved and the state of the body when it is in thermal equilibrium with the surroundings depend on many factors, significant ones being the environmental factors. The heat exchange of the body can be considerably modified by these factors [SP-41:1987 (Bureau of Indian Standards 1987)]. The heat balance of the body with the surroundings is governed by the following equation (Eqn. 3.1):

$$M_h - W_m = \pm R_h \pm C_h + E_h \pm S \qquad \ldots 3.1$$

where,

M_h: metabolic heat generation rate

W_m: work rate of mechanical energy leaving the body

R_h: rate of heat loss or gain by radiation

C_h: rate of heat loss or gain by convection

E_h: rate of evaporative heat loss

S : rate at which heat is being stored within the body, + ve sign denoting chilling of the body.

R, C and E_h are functions of the external environment, skin temperature and vapour pressure. The distribution of the total heat loss into the radiative, evaporative and convective components depends upon the level of environmental factors like air temperature, vapour pressure, radiation and air movement. For instance, the evaporative loss of a clothed person at 20^0C air temperature may be only 20 percent of the total heat loss from the body whereas at 40^0C it may rise to as high as 50 percent for low relative humidity conditions. The radiative loss is high at low ambient temperature but decreases as the temperature of the bounding surfaces approaches the skin temperature. At temperatures of the surrounding surfaces higher than the skin temperature, the radiative heat loss turns into radiative heat gain. Similarly, the convective heat loss is high at low air temperatures and decreases with increasing air temperatures, turning into gain when air temperature rises above skin temperature [SP-41:1987 (Bureau of Indian Standards 1987)]. There are four environmental factors which essentially determine the heat exchange of the human body. These are air temperature, mean radiant temperature, relative humidity or water vapour pressure of air and air movement. These can vary independently of each other and can influence one or more modes of heat transfer at a time (Szokolay 2004).

The environmental factors vary independently of each other but act simultaneously on the human body. It is not possible to express the thermal response of the human body in terms of any single factor as the influence of any one depends upon the level of others. Many attempts have been made to integrate the effect of two or more environmental factors and to express the thermal response in terms of the integrated parameter. These attempts have resulted in formulae or nomograms on theoretical or experimental grounds which can estimate the thermal stress due to a wide range of climatic conditions. Such a combination of influencing environmental factors into a single parameter is called 'Index of Thermal Comfort' or simply comfort [SP-41:1987 (Bureau of Indian Standards 1987)].

Many thermal indices have been developed in various countries throughout the world, but none of them appears to be universally satisfactory over the entire range of environmental conditions. For an index to be valid, its functions must correlate well with the thermal sensation of people engaged in their normal life routine. The divergence appears to be mainly on physiological grounds; partly due to the rapid and complex adjustments the body continually makes to counter environmental changes, partly to the fact that thermally equivalent conditions produce different subjective sensations and partly to the individual variations in adaptation to a given environment. Air movement affects body cooling. It does not decrease the temperature but causes a cooling sensation due to heat loss by convection and due to increased evaporation from the body. As velocity of air movement increases, the upper comfort limit is raised. However, this rise slows as higher temperatures are reached. The effects of climatic elements were assembled in a single chart called as the bioclimatic chart (Olgyay and Olgyay 1963). The chart has the comfort zone in the centre with the climatic elements shown around it by curves which indicate the nature of corrective measures necessary to restore the feeling of comfort at any point outside the comfort zone (Olgyay and Olgyay 1963).

3.2.4 Implications of climate for building design

Design of functional and energy efficient buildings involve designing buildings that would function in conformity with climate. This involves identification of the climate at the building site in question, determination of the comfort requirements of the relevant climate and selection of appropriate architectural features including space planning, orientation, location and size of fenestration, shading devices, treatment of building envelope (Mathur and Chand 2003). Building design involves creating an indoor environment that is thermally comfortable. Comfort requirements change with the climate zone and hence the building design would also be different for different climate zones. The comfort requirements for each climate zone and their physical manifestation for buildings are stated in the following paragraphs (Nayak and Prajapati 2006; Szokolay 2004).

i. *Hot and dry:* In such a climate, it is imperative to control solar radiation and movement of hot winds. The design criteria should therefore aim at resisting heat gain by providing shading, reducing exposed area, controlling and scheduling ventilation, and increasing thermal capacity. The aim of building design in hot and dry climate zone is to reduce heat gain and maximize heat loss. Heat gain can be reduced by decreased exposed surface area, increased thermal resistance and thermal capacity (time lag), introduction of buffer spaces like verandahs and increased shading by providing fins (Nayak and Prajapati 2006). Massive walls and roof with high thermal capacity are an important characteristic. Building surfaces should be white, which would act as a reflective surface. This is important for roofs exposed to the night sky. The radiant cooling effect can help to dissipate the heat stored during the day (Szokolay 2004). An inward looking courtyard is a good solution to protect the building from the harsh hot and dusty outdoor environment. Air mass in the courtyard enclosed by the building is cooler than the environment and thus heavier. It would thus settle down and can be used to ventilate habitable spaces surrounding the courtyard. This air can be further cooled by a pond or vegetation in the courtyard. Ventilation during the daytime, beyond the small fresh air supply from the courtyard, is undesirable as the outdoor air is hot and dusty. Heat loss can be maximized by increasing humidity levels by introducing trees, waterpond, increasing night ventilation with courtyards, wind towers and appropriate arrangement of openings (Nayak and Prajapati 2006).

ii. *Warm and humid:* The main design criteria in the warm and humid region are to reduce heat gain by providing shading, and promote heat loss by maximising cross ventilation. Dissipation of humidity is also essential to reduce discomfort. Heat gains can be minimized by providing buffer spaces like verandahs, using a reflective roof surface, having a separate ceiling, forming an attic space and ensuring its adequate ventilation, using resistive insulation on the ceiling, using a reflective surface for the underside of the roof. Walls facing the east and west should have no windows, to avoid heat input from a low-angle sun, and should be reflective and insulated. In order to ensure maximum cross ventilation, the major openings should face within 45^0 of the prevailing wind direction and taking care to minimize heat gain.

iii. *Temperate:* The design criteria in the temperate zone are to reduce heat gain by providing shading, and to promote heat loss by ventilation. In most temperate climates the nighttime temperatures are too low even in the summer. For this reason a heavy construction (capacitive insulation) may be preferable. Overhanging eaves or other horizontal shading devices may ensure summer shading but allow winter entry of solar radiation. As air temperatures are not too high, unwanted heat can be dissipated to maximize heat loss by natural ventilation which may be provided with courtyards, openings and facilities for fresh air supply without any special provisions. Heat gain can be minimized by protecting glazed surfaces with overhangs, fins and decreasing exposed surface area by proper orientation and shape of the building.

iv. *Cold:* The main criteria for design are aimed at resisting heat loss by insulation and infiltration, and promoting heat gain by directly admitting and trapping solar radiation within the living space. In cold climates the main concern is to minimize heat loss, which can be achieved by a compact building form, small windows with double glazing, insulation in walls and roof, increasing thermal capacity with thick walls, air tight building envelope, increasing surface absorptivity with dark colors. Heat gain can be maximized by reduced shading and trapping heat with sunspaces and trombe walls.

v. *Composite:* Generally, composite regions experience higher humidity levels during monsoons than hot and dry zones. Thus, the design criteria are more or less the same as for hot and dry climate except that maximizing cross ventilation is desirable in the monsoon period. Heat gain can be resisted in summer and heat loss can be resisted in winter by decreasing exposed surface area, increasing thermal resistance of walls and roofs, increasing thermal capacity, increasing shading with fins and overhangs, increasing surface reflectivity by using pale, reflective colors. Heat loss can be promoted in summer and monsoon by promoting ventilation with courtyards, wind towers, openings and increasing humidity levels in dry summer.

3.3 Solar radiation

The sun is a sphere of intensely hot gaseous matter, about 1.39 x 10^6 km in diameter and its average distance from the earth is 1.496 x 10^8 km. The heat is generated by various kinds of fusion reactions. As the solar disc subtends a very small angle of 32' at any point on the earth's surface, the radiation received from the sun directly on the earth's surface can be considered parallel for all practical purposes. The energy flux received from the sun outside the earth's atmosphere is of nearly constant value and is termed as the Solar Constant (I_{sc}). It is defined as the energy received outside the atmosphere, per second, by a unit surface area normal to the direction of sun's rays at the mean sun-earth distance; its value is accepted as 1367 W/m^2 (Nayak and Prajapati 2006). The earth revolves round the sun in an elliptical orbit with the sun as one of the foci. Thus, there is a variation in the extraterrestrial radiation. Hence, the intensity of extraterrestrial radiation (I_{ext}) on a plane normal to sun's rays on any day is given by (Eqn. 3.2):

$$I_{ext} = I_{sc}[1.0 + 0.033\ cos(360n/365)] \qquad ...3.2$$

The climate of earth is driven by the energy input from the sun. Thus it is essential to understand the apparent movement of the sun (the solar geometry) and the energy flows from the sun and how to exclude it or make use of it (Szokolay 2004). The amount of energy received from the sun depends on the location on earth's surface, position of the sun and time of the year. Knowledge of solar angles is helpful in the design of passive solar buildings, especially for placing openings on the walls for solar access and overhangs for shading the walls and windows at certain times of the year.

3.3.1 Sun's apparent motions

The distance between earth and sun changes every day and throughout the year due to the earth's rotation and revolution. The earth makes one rotation about its axis every 24 hours and one revolution about the sun in a period of about 365 days. The amount of radiation received on the earth's surface depends on the length of atmosphere passed by the solar radiation. The earth’s equatorial plane is tilted at an angle of about 23.5^0 with respect to its orbital plane. The earth’s rotation is responsible for day and night, while its tilt is responsible for change of seasons [Refrigeration and air conditioning (National Programme on Technology Enhanced Learning 2013)]. Fig. 3.2 shows the position of the earth at the start of each season as it revolves in its orbit around the sun. During summer solstice (June 21st) the sun's rays strike the northern hemisphere more directly than the southern hemisphere. As a result, the northern hemisphere experiences summer while the southern hemisphere experiences winter during this time (Goswami et al. 2000). The reverse happens during winter solstice (December 22nd). On the equinoxes i.e. March 23rd and September 23rd, the sun is directly above the equator with day and night of practically equal duration throughout the world.

If the sky is conceived as a hemispherical shell completely covering the plane on which we stand, for an observer on the earth's surface, the sun will appear to move on its daily paths along the arc of a circle and such parallel circular paths on different days that are slightly different throughout the year (Fig. 3.3). On its daily paths, the sun will appear to move along the arc of a circle symmetrical about a vertical plane running through north and south as shown in Fig. 3.3. At solar noon the sun lies in this vertical plane and occupies highest angular position above the horizon for the day. This is due to the earth's rotation about its axis. The earth's revolution around the sun, causes a relative shift of the sun to the north and south of equator as in its orbital movement, the earth's axis is always oriented in the same direction as shown in Fig. 3.2. Thus on different days throughout the year the sun traces circular paths that are parallel to each other but slightly different. Thus to an observer during the course of a year, the sun will appear to trace out patterns of daily paths, with shortest and lowest corresponding to the day of winter solstice and longest and highest corresponding to the day of summer solstice as shown in Fig. 3.3. Each pathway lying between these extremes will be followed by the sun on two days in a year. These days will be equally spaced before and after a solstice. Due to the earth's shape, complete pattern of parallel sun-paths will be same for all places having same latitude, but will differ from those having other latitude. This difference depends upon the difference in latitude (Ralegaonkar 2004). Some important parameters on which solar angles depend are discussed in this section (Goswami et al. 2000).

i. *Declination (δ):* The angle between the earth-sun line and equatorial plane is called the declination angle. Declination changes with the date and is independent of the location on earth's surface. The declination is 0 on the equinoxes i.e. sun is directly overhead and it is 23.45^0 on summer solstice (21st June) and -23.45^0 on winter solstice (22nd December). The declination on any particular day can be calculated as follows (Eqn. 3.3):

$$Declination\ \delta = 23.45 sin\left[\frac{360 \times (284+n)}{365}\right] \quad ...3.3$$

where,

n: day of the year and can be obtained as shown in Table 3.2.

ii. *Latitude (L):* Latitude is the angular distance measured along a meridian from the equator, north or south, to a point on the earth's surface. Any location towards the north is considered having positive latitude and towards the south as negative latitude. Thus the latitude along with the longitude indicates the position of any point on earth and it varies from 0^o at equator to 90^o at the poles.

iii. *Hour angle (H):* The hour angle is the angular distance that the earth has rotated in a day. It is the angle through which the earth must turn to bring the meridian of the point directly in line with the sun's rays. The hour angle is a measure of the time of the day with respect to solar noon. Thus at solar noon the hour angle is zero and accounts for 15^o for each hour from solar noon with negative sign for forenoon and positive sign for afternoon.

iv. *Solar time:* Time as measured by the apparent diurnal motion of the sun is called Solar time. Solar time is the time used in all sun-angle relationships and it does not coincide with local civil time. Due to the elliptical shape of the earth's orbit and increase in velocity at the perihelicon, the length of the apparent solar day i.e. interval between two successive passages of the sun through the meridian is not constant. Local civil time may deviate from true solar time by as much as 4.5^0 because even if the length of any apparent solar day and its corresponding mean solar day differs a little, the effect is cumulative (Rai 1989). The time kept in each zone is the local civil time of a selected meridian near centre of the zone. Such time is called standard time. The difference between local solar time (*LST*) and local civil time (*LCT*) is called the equation of time (*E*). Local civil time is derived from standard time with the help of equations (Eqn. 3.4 - Eqn. 3.6):

$$E = LST - LCT \quad ...3.4$$

$$LCT = ST \pm (L_{st} - \theta) \times 4 \quad ...3.5$$

Local solar time is derived from the following equation (Eqn. 3.4):

$$LST = ST + E \pm (L_{st} - \theta) \times 4 \quad ...3.6$$

(+ve sign for west and -ve for east)

where,

E: equation of time in minutes and is determined from Fig. 3.4

ST: standard time

L_{st}: standard meridian for the local time zone

θ: longitude of the location (in degrees west or east)

3.3.2 Derived solar angles

The sun's position in the sky changes every hour throughout the year. The sun's position in the sky can be defined by two solar angles: solar zenith angle (θ_z) and solar azimuth angle (β) (Duffie and Beckman 1991). The zenith angle (θ_z) is the vertical angle between the sun's rays and a line perpendicular to the horizontal plane through the point. Solar altitude angle (α) is the angle between the sun's rays and the projection of sun's rays onto a horizontal plane. Solar azimuth angle (β) is the angle between local meridian and the projection of line of sight of the sun onto the horizontal plane. Solar altitude angle is measured up from the horizontal, solar azimuth is measured from north as shown in Fig. 3.5. The altitude angle is a complement of the zenith angle as given by Eqn. 3.7:

$$\theta_z = \frac{\pi}{2} - \alpha \qquad \text{… 3.7}$$

The calculation of solar angles depends upon three variables (Goswami et al. 2000)**:** latitude (L), declination (δ), and hour angle (H). Latitude can be read from any standard map. Declination, a measure of how far north or south of the equator the sun has moved, varies with month. Solar time is based on solar noon when the sun is highest in the sky.

The hour angle depends on local solar time (Eqn. 3.8):

$$H = 0.25 \times (M) \qquad \text{… 3.8}$$

where,

M: number of minutes from local solar noon.

Knowing latitude, declination, hour angle, the solar altitude and azimuth angles can be computed as (Eqn. 3.9- Eqn. 3.10):

$$sin\alpha = cosLcos\delta cosH + sinLsin\delta \qquad \text{… 3.9}$$

$$sin\beta = \frac{cos\delta sinH}{cos\alpha} \qquad \text{…3.10}$$

For shading calculations horizontal shadow angle (a) and vertical shadow angle (γ) is computed. Horizontal shadow angle is difference between the solar azimuth and the wall azimuth (angle ABC in Fig. 3.6). Vertical shadow angle is angle between normal to a surface and projection of sun's rays on a plane normal to same surface (angle DEF in Fig. 3.6). It is used in sizing shading devices, and given by (Eqn. 3.11):

$$tan\gamma = \frac{tan\alpha}{cosa} \qquad \ldots 3.11$$

Solar angles on a particular day at a desired time can be calculated with the help of above-mentioned equations (Eqn 3.7 - Eqn. 3.11).

Surface azimuth angle (ξ) is the angle between the normal to the wall and south (Fig. 3.5) [Refrigeration and air conditioning (National Programme on Technology Enhanced Learning 2013)]. Thus when the wall is facing south, then the surface azimuth angle is zero and when it faces west, then the surface azimuth angle is 90^0. The angle is taken as +ve if the normal to the surface is to the west of south and –ve if it is to the east of south. It is given by (Eqn. 3.12):

$$a = [\pi - (\beta + \xi)].\mathrm{F} \qquad \ldots 3.12$$

where,

The factor F is -1 for forenoon and +1 for afternoon.

Angle of incidence (*i*) of sun's rays is the angle between the sun's rays and the normal to the surface under consideration (Fig. 3.5). It depends on solar geometry and also the orientation of the surface. For horizontal surfaces, the angle of incidence (i_{hor}) is equal to the zenith angle (Eqn. 3.13):

$$i_{hor} = \theta_z = \frac{\pi}{2} - \alpha \qquad \ldots 3.13$$

For vertical surfaces, the angle of incidence (i_{ver}) depends on orientation of the wall (Fig. 3.5) and is given by (Eqn. 3.14):

$$i_{ver} = \cos^{-1}(cos\alpha.cosa) \qquad \ldots 3.14$$

3.3.3 Calculation of solar radiation

Solar radiation is received on the earth's surface after undergoing various mechanisms of attenuation, reflection and scattering in the earth's atmosphere. In order to calculate the building heat gain due to solar radiation, one has to know the amount of solar radiation incident on various surfaces of the building. The rate at which solar radiation is striking a surface per unit area of the surface is called as the total solar irradiation (I_t) on the surface

(National Programme on Technology Enhanced Learning 2013)]. This is given by (Eqn. 3.15):

$$I_t = I_{DN} cos.i + I_d + I_r \quad ...3.15$$

where,

I_{DN}: direct radiation from sun, W/m^2

I_d: diffuse radiation from sky, W/m^2

I_r: shortwave radiation reflected from other surfaces, W/m^2

The term I_{DN} cos.i is the contribution of direct normal radiation to total irradiation. On a clear, cloudless day, it constitutes about 85 percent of the total solar radiation incident on a surface. However, on cloudy days the percentage of diffuse and reflected radiation components is higher. The objective of solar radiation calculations is to estimate the direct, diffuse and reflected radiations incident on a given surface. These radiations and the angle of incidence are affected by solar geometry.

According to the ASHRAE model (ASHRAE 1999) for calculation of solar radiation, the direct radiation I_{DN} is given by (Eqn. 3.16 - Eqn. 3.18):

$$I_{DN} = A.exp\left(-\frac{B}{\sin\alpha}\right) \quad ...3.16$$

where,

A: apparent solar irradiation in W/m^2 (Baghzouz 2012) given by:

$$A = 1160 + 75sin\left[\frac{360}{365}(n - 275)\right] \quad ...3.17$$

B: atmospheric extinction co-efficient in W/m^2 given by:

$$B = 0.174 + 0.035sin\left[\frac{360}{365}(n - 100)\right] \quad ...3.18$$

According to the ASHRAE model, the diffuse radiation I_d from a cloudless sky is given by (Eqn. 3.19 - Eqn. 3.20):

$$I_d = C.I_{DN}.F_{WS} \quad ...3.19$$

where,

C: constant given by

$$C = 0.095 + 0.04sin\left[\frac{360}{365}(n - 100)\right] \quad ...3.20$$

F_{WS}: view factor or configuration factor and is equal to the fraction of the diffuse radiation that is incident on the surface. Its value is 1 for horizontal surfaces and 0.5 for vertical surfaces.

The amount of solar radiation reflected from the ground (I_r) onto a surface is given by (Eqn. 3.21):

$$I_r = (I_{DN} + I_d)\rho F_{WG} \quad ...3.21$$

where,

ρ: reflectivity of the ground or a horizontal surface from where the solar radiation is reflected on to a given surface

F_{WG}: view factor from ground to the surface. This factor is equal to zero for horizontal surfaces and 0.5 for vertical surfaces.

When there is a sunshade over a window, due to the shadow, the radiation received by the surface will be affected (Nayak and Prajapati 2006). Hourly solar radiation on a shaded window I_w can be written as (Eqn. 3.22- Eqn. 3.28):

$$I_w = I_t . w \quad ...3.22$$

$$w = \left(1 - \frac{I_d}{I_t}\right) r_b f_i + \frac{I_d}{I_t} F_{r-s} + 0.5\rho_g \quad ...3.23$$

where,

f_i: fraction of unshaded area

F_{r-s}: view factor of the window for radiation from the sky

ρ_g: reflectivity of ground surface

$$f_i = \frac{A_i}{l d_h} \quad ...3.24$$

where,

A_i: unshaded area of the window

l: width of the window

d_h: height of the window

$$A_i = l . d_h - A_{shade} \quad ...3.25$$

where,

A_{shade}: shaded area of window

$$A_{shade} = [l - 0.5D_s tan(\beta - \xi)]D_s.tan(90 - \theta_z).\sec(\beta - \xi)$$

…3.26

where,

D_s: depth of overhang or sunshade over the window

$$r_b = \frac{\cos\varphi}{\cos\theta_z} \quad \text{…3.27}$$

$$\cos\varphi = \sin L\,(\sin\delta\cos\mu + \cos\delta\cos\xi\cos H\sin\mu) + \cos L\,(\cos\delta\cos H\cos\mu - \sin\delta\cos\xi\sin\mu) + \cos\delta\sin\xi\sin H\sin\mu$$

…3.28

where,

μ: angle made by the plane surface with the horizontal

F_{r-s} for a window of relative width r_w (=l/d_h) and relative projection r_p (=D_s/d_h) is presented in Table 3.3.

3.3.4 Sun-path diagram

The relative position of the sun at different times of the day and year is represented graphically by constructing circular sun-path diagrams (Goswami et al. 2000). The projection of the sun's rays on a horizontal plane is called the sun-path diagram. The sun path diagram represents the position of the sun based on the altitude and the azimuth. This diagram is the stereographic projection of the sun path (view of the sky on a horizontal plane). From these graphs, it is possible to find out the position of the sun at any time and day for a given location. Such diagrams are useful in determining shading phenomena associated with solar collector, windows, and sunshades. As represented in Eqns. 3.9-3.10, the solar angles i.e. solar azimuth and altitude angles depend upon the hour angle, declination and latitude. Since only two of these variables are plotted on a two-dimensional graph, the usual method is to prepare a different sun-path diagram for each latitude with variations of hour angle and declination shown for full year.

General steps for construction of sun-path diagram are as follows (Ralegaonkar 2004):

i. Concentric circles projecting from centre towards outer side are used to represent altitude angle.

ii. Radial lines are used to represent azimuth angle.

iii. For a particular location, sunrise and sunset positions are well known. For example in northern hemisphere, at equinoxes (23^{rd} March and 23^{rd} September, $\delta = 0$), sunrise is due east and sunset is due west.

iv. With specific latitude, for equinoxes the highest altitude position is determined using the following equation (Eqn. 3.29):

$$\alpha_{noon} = 90^0 - L + \delta \qquad \text{...3.29}$$

Thus an arc is generated using starting point (sunrise), end point (sunset) and highest altitude point (solar noon).

v. Similarly arcs are generated for summer solstice (21^{st} June, $\delta = +23.45^0$) and winter solstice (22^{nd} December, $\delta = -23.45^0$). Sunrise and sunset points are obtained by determining azimuths of sunrise and sunset as given in Eqn 3.30.

$$\beta_{\alpha=0} = cos^{-1}\left(\frac{-sin\delta}{cosL}\right) \qquad \text{...3.30}$$

The obtained angular value is plotted with respect to south direction.

vi. Like wise with desired declination values, several arcs are plotted.

vii. Solar time lines i.e. hour lines always cross the sun-paths at 90^0. At equinoxes for sunrise and sunset, the hour lines pass through the horizon line due east and due west respectively. The intermediate hour lines may be positioned on the basis of spacing them equally between the noon and sunrise-sunset lines.

A complete constructed sun-path diagram is represented in Fig. 3.7. Sun-path diagrams for given latitude are used by entering appropriate values of declination (d) and hour angle (*H*). The point at the intersection of corresponding d and *H* lines represents instantaneous location of the sun. The solar altitude angle (α) is then read from the concentric circles in the diagram and the azimuth (β) from the scale around the circumference of the diagram.

For the design of passive solar buildings, first the climate of the place needs to be considered. Based on this, the comfort requirements of the climate need to be identified. Then the building elements need to be designed to function in conformity to the climate. The aspects of building like orientation, sunshades, ratio of window area to wall area should be designed by considering the sun path at the considered geographical location. Thus the study of the climate and sun path helps to determine the period of year that requires shading and solar entry inside the building to attain thermal comfort. It also helps to design buildings to maximize solar heat gain in winter and minimize it in summer.

Table 3.1 Classification of climate

Climatic zone	Mean monthly maximum temperature (^oC)	Mean monthly relative humidity (%)
Hot-Dry	Above 30	Below 55
Warm-Humid	Above 30	Above 55
	Above 25	Above 75
Temperate	Between 25-30	below 75
Cold	Below 25	All values
Composite	-	-

Source: National Building Code of India: 2005 (Bureau of Indian Standards 2005)

Table 3.2 Recommended average days

Month	Date (i)	n for i^{th} day of month	n, day of year	Declination
January	17	i	17	-20.9
February	16	31+i	47	-13.0
March	16	59+i	75	-2.4
April	15	90+i	105	9.4
May	15	120+i	135	18.8
June	11	151+i	162	23.1
July	17	181+i	198	21.2
August	16	212+i	228	13.5
September	15	243+i	258	2.2
October	15	273+i	288	-9.6
November	14	304+i	318	-18.9
December	10	334+i	344	-23

Source: Duffie and Beckman 1991

Table 3.3 Window radiation view factor for the sky, $F_{r\text{-}s}$

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

Source: Nayak and Prajapati 2006

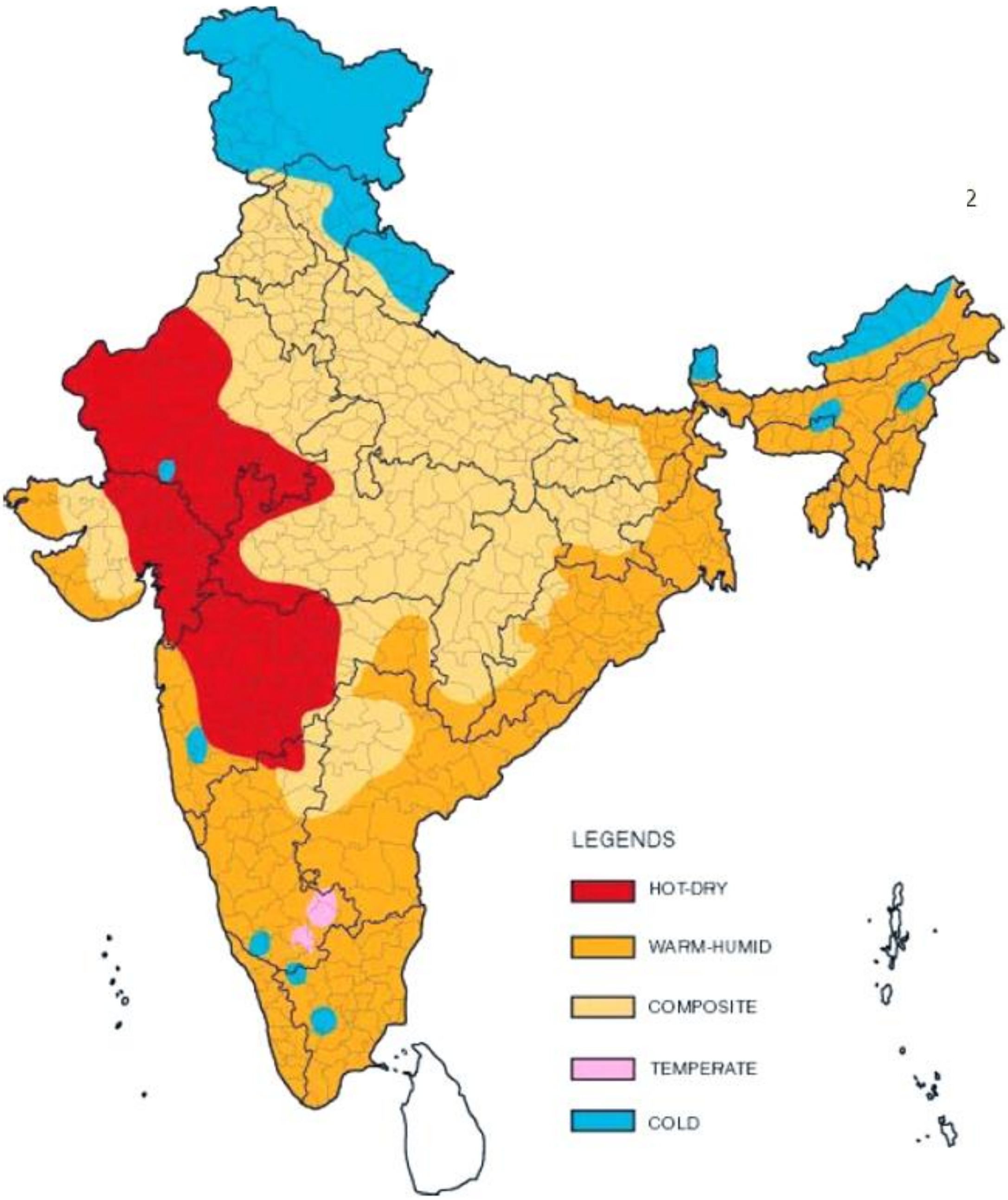


Fig. 3.1 Map of India showing climate zones

Source: National Building Code of India:2005 (Bureau of Indian Standards 2005)

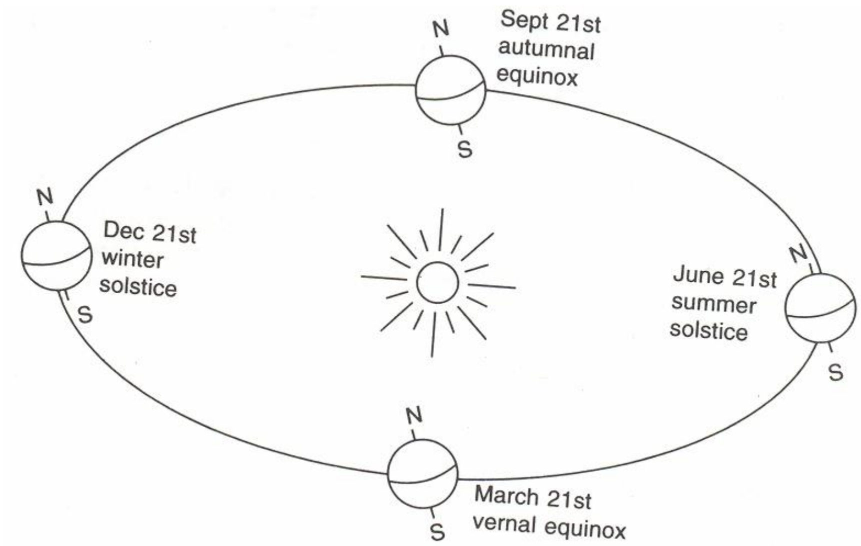


Fig. 3.2 Position of earth with respect to sun for different seasons

Source: Refrigeration and air conditioning (National Programme on Technology Enhanced Learning 2013)

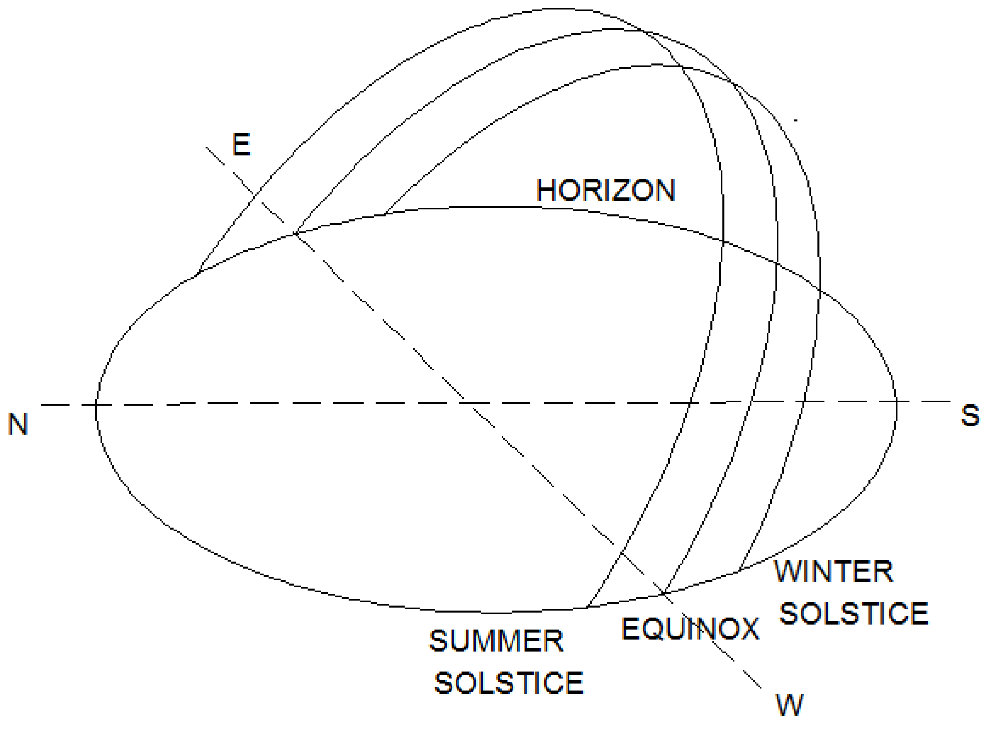


Fig. 3.3 Schematic illustration of daily and yearly movement of the sun

Adopted from: Szokolay 2004

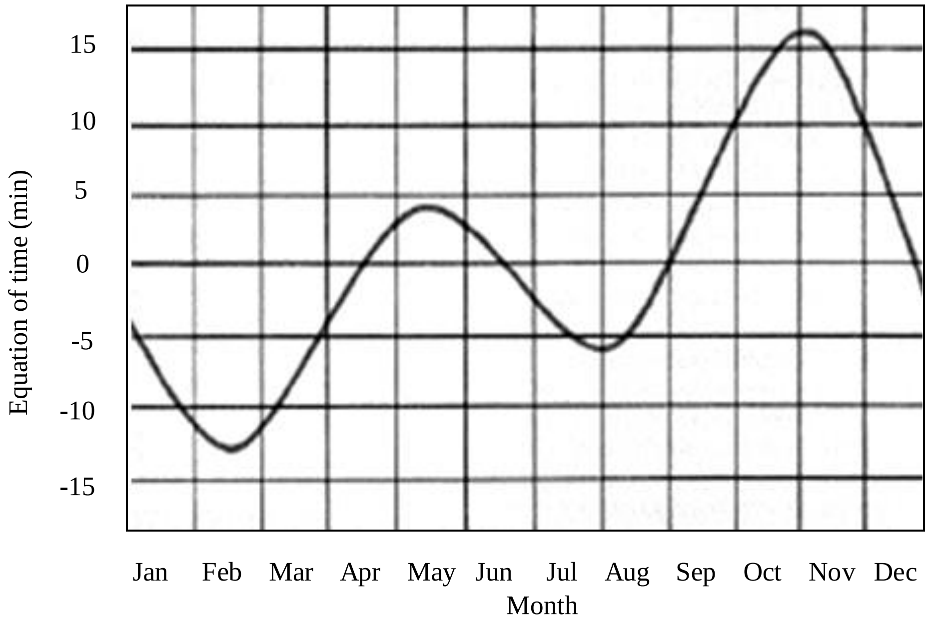


Fig. 3.4 Equation of time correction

Adopted from: Duffie and Beckman 1991

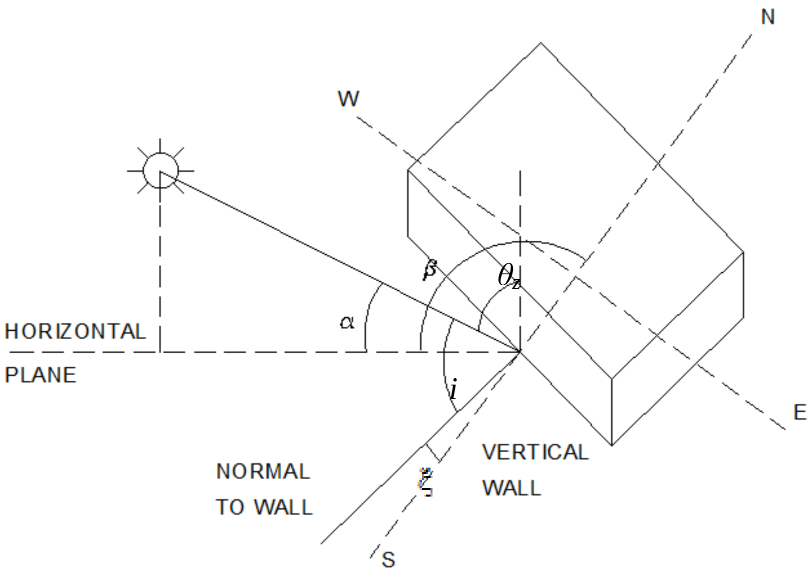


Fig. 3.5 Solar angles

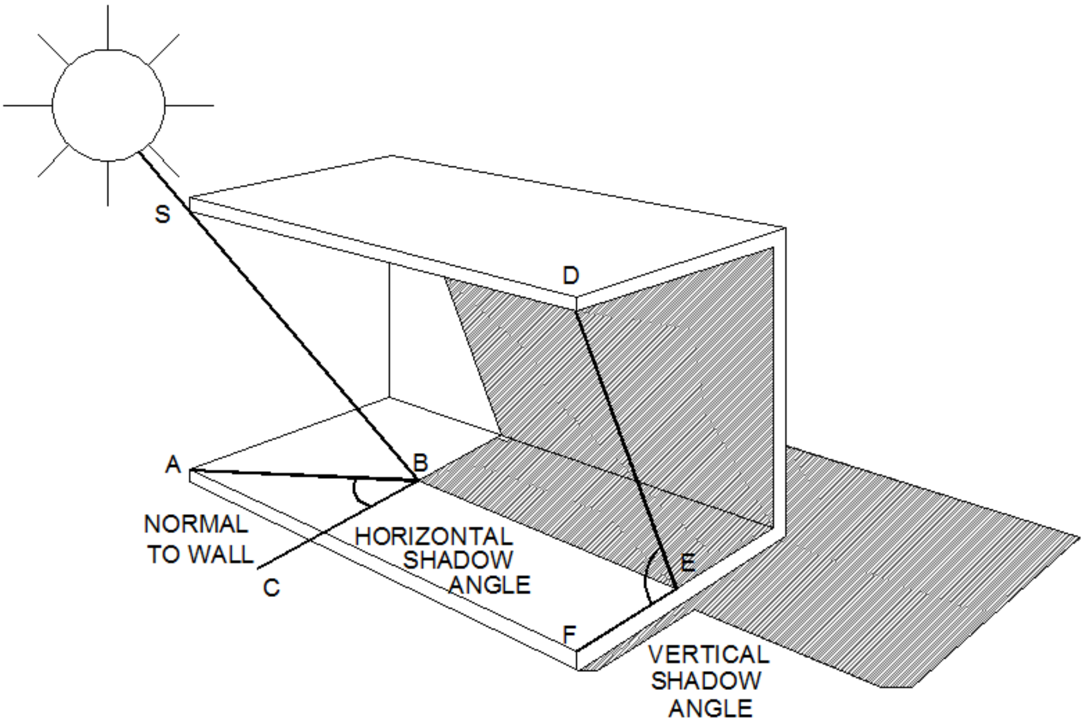


Fig. 3.6 Horizontal shadow angle and vertical shadow angle

Adopted from: Pilkington sun angle calculator instruction manual (Pilkington North America 2001)

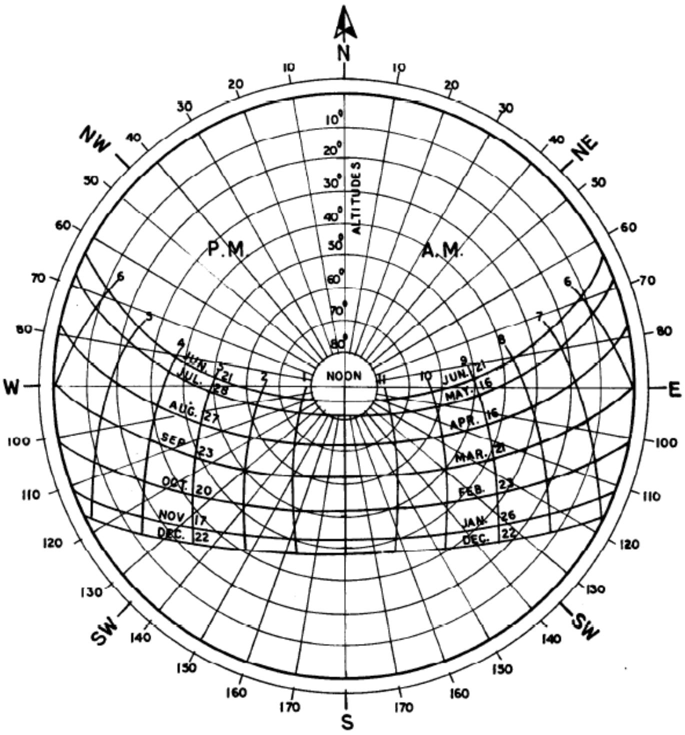


Fig. 3.7 Sun-path diagram for 29^0N latitude

Source: [SP-41:1987 (Bureau of Indian Standards 1987)]

Chapter 4

Design and Room Description

4.1 Introduction

A building design based on energy-saving criteria reduces economic costs throughout the useful life of the building because of its lower energy consumption, and this more than compensates for the greater initial investment (Pacheco et al. 2012). Consequently, it is necessary to identify the design variables that are directly related to heat transfer processes. A building envelope separates the indoor and outdoor environments of the structure. Various components such as walls, fenestration, roof, foundation, thermal insulation, thermal mass, external shading devices etc. make up the related important parts of any building (Sadineni et al. 2011). The properties of the building's envelope and its various elements may vary according to the internal and external climate in order to provide thermal comfort without disturbing the occupants (Shaviv 1998). The conceptual design phase of a building is the best time to integrate sustainable strategies. When these mechanisms are put into action at the very beginning of the construction phase, they reduce implementation costs as compared to when they are installed in subsequent stages of construction (Wang et al. 2006).

Solar energy is the most important source of heat gain through building envelope (Aboulnaga 1998). The main parameters that need to be considered for design of energy efficient buildings are walls, roof, placement and size of openings, ratio of window/wall area and provision of proper shading devices. Beam radiation penetrating through openings can be controlled using sunshades for temperature regulation (Yener 1999). Solar contribution to cooling and heating load of building can be altered by proper wall design (Charde and Gupta 2012). Hollow roof can be an effective energy saving solution. Proper static sunshade, wall and roof design can alter heating and cooling load in buildings by modifying solar heat gain and regulating indoor air temperature. Further protection from direct solar radiation can be achieved by shading the wall with optimum brick projections. Night ventilation can be an effective way for passive cooling of buildings and thus help to conserve energy. Passive solar building design aims to maximise solar heat gain in winter and avoid overheating in summer and bring the indoor air temperature near the comfort temperature zone (18 - 27^{0}C). In the composite climate zone in India, the need is to design a room that would keep the indoor air temperature more in winter and less in summer as compared to outdoor air temperature.

In the current research work, a static sunshade, brick cavity wall with brick projections and hollow roof have been designed and verified experimentally by constructing four rooms of habitable dimensions (3.0m x 4.0m x 3.0m high) and studying average hourly temperatures in various seasons throughout the year. Each room has a different combination of type of static sunshade, wall and roof. Hence the difference in indoor air temperature of the rooms will mainly be due to difference in heat transferred through these building elements. A new geometry of a static sunshade was designed and verified using small scale modeling technique at this geographical location (Ralegaonkar 2004). In the present study, the proposed static sunshade has been adopted in an actual room of habitable dimensions as per methodology described by Ralegaonkar (2004). The detailed methodology for design of proposed brick cavity wall with brick projections for the considered geographical location has been described in this chapter. The detailed calculations for the hollow roof design have been elaborated. The methodology for comparison of individual and combined effect of designed static sunshade, brick cavity wall with brick projections, hollow roof and night ventilation on indoor air temperature and room performance has also been described.

4.2 Theoretical background

Heat flow through a building depends on thermal insulation properties of building elements (Szokolay 2001). Temperature is the outward appearance of the thermal state of a body (Koenigsberger et al. 1973). For the energy efficient buildings, among several governing environmental factors, atmospheric temperature is considered to be the fundamental determinant of heat load inside the buildings (Ralegaonkar 2004). Design of shading devices by considering solar geometry and provision of insulation layers in walls and roofs can help to modify heat gain or loss in buildings. As climatic conditions in the geographical location under study are extreme, it is necessary that entry of sunlight through the window is maximum in winter and minimum in summer. Thus the static sunshades over windows on south walls of rooms R2, R3, R4 have been designed by calculating solar angles for two design dates (viz. 22nd December and 23rd March) depending on seasonal characteristics.

An open air cavity (that is not airtight) increases thermal resistance and during summer, an air stream starts moving inside following a vertical convection and helps heat dissipation (Pulselli et al. 2009). Textured wall surfaces shade the wall and reduce heat gain by increased convective heat dissipation due to increased surface area. At night when ambient conditions are cool, the increased surface area helps in faster cooling (Krishnan et al. 1996). Thus ventilated cavity walls with optimum brick projections (by considering solar angles) that can keep maximum wall area in shade in summer and minimum wall area in shade in winter have been provided in rooms R3 and R4. Alternate brick courses of the outer leaf of brick cavity wall have been projected outside the wall face to provide shade to the wall. Air vents that open in the wall cavity, with operable shutters have been provided in the cavity walls of rooms R3, R4 to facilitate ventilation of the wall cavity during summer nights and winter daytime. The air in the wall cavity can be cooled or heated by outdoor air as per seasonal requirements by keeping these air vents open or closed. During daytime in summer, when outdoor air temperature is high, shutters of the air vents can be kept closed to insulate the room. At night when the outdoor air temperature decreases, these shutters of air vents can be opened to facilitate ventilation of air in the wall cavity, to help in faster heat dissipation from the room. Whereas, in winter the air vents may be kept open throughout the day when outdoor air temperature is higher (as compared to that at night) to facilitate ventilation of air in wall cavity and help in faster heat gain. These shutters may be kept closed at night when outdoor air temperature decreases to insulate the room and slow down the heat loss. This would help to regulate the indoor air temperature.

Air has a low conductivity (0.026W/m K) and hence is a good insulator (Szokolay 2001). So hollow roof can be an effective energy saving solution in regions with hot summer and cold winter conditions. Filler slab roofs with filler material like clay tiles (Kabre 2010) and earthen pots (Auroville 2000) have been found to perform better thermally and consume less energy as compared to conventional reinforced concrete slabs. Use of earthen pots to provide an insulating cover of still air over roof has also been reported in literature (Sharma et al. 2003; Nayak et al. 1982). Although this system is thermally efficient, it suffers from practical difficulties as the roof becomes unusable and its maintenance is difficult. Hence in this study, hollow pipes have been used to introduce an air cavity in the roof. A hollow earthen pipe 2 feet long was made by the local potter. But the cost of 2 feet long earthen pipe was Rs. 60, while the cost of 2 feet long hollow stoneware pipe was Rs. 35. Thus, air cavity has been introduced in the roof of room R4 by integrating hollow stoneware pipes that are readily available. The combined effect of hollow roof, brick cavity wall with brick projections and static sunshade would help to maximise solar heat gain in winter, minimize it in summer and bring the indoor air temperature near the comfort temperature zone (18^0C - 27^0C). Night ventilation can be effective in reducing peak indoor air temperature, creating a time lag between the occurrence of external and internal maximum temperature and reducing indoor air temperature throughout the day (Kolokotroni and Aronis 1999). This can be done in the simplest case by opening windows (Artmann et al. 2010). Thus in the extreme summer months, night ventilation has been used for passive cooling of the rooms by opening windows at night.

4.3 Room description

The four test rooms for the experimentation are located at Birla Institute of Technology and Science (BITS), Pilani, Rajasthan (India). It is desirable that the building is oriented with longer walls facing north and south, so that only short walls face east and west. Thus only the smallest wall areas are exposed to intense morning and evening sun (Sharma et al. 2003). Hence all the rooms are oriented with their longer axis along east west. They have the same orientation and are exposed to similar conditions. The relative position of the rooms is such that there is minimum shading of the rooms by each other (Fig. 4.1-4.2). Room R1 (Fig. 4.3-4.5) has a horizontal static sunshade over window on south wall, solid brick walls 338mm thick and solid RCC roof 100mm thick. Room R2 (Fig. 4.6-4.8) has the designed static sunshade over window on south wall, solid brick walls 338mm thick and solid RCC roof 100mm thick. Room R3 (Fig. 4.9-4.14) has the designed static sunshade over window on south wall, designed brick cavity walls with brick projections on east, west, south faces, a brick cavity wall on north face and solid RCC roof 100mm thick. Room R4 (Fig. 4.15-4.19) has the designed static sunshade over window on south wall, designed brick cavity walls with brick projections on east, west, south faces, a brick cavity wall on north face and the designed hollow roof with stoneware pipes. The details of various building elements of the four rooms are stated in Table 4.1 (with differences in rooms shown in bold).

Rooms R2, R3, R4 have the designed static sunshade over window on the south wall, designed by calculating solar angles for two design dates, which depends on seasonal characteristics as per methodology described by Gupta and Ralegaonkar (2006**)**. The static sunshade has been designed such that entry of sunlight through the window is maximum in winter and minimum in summer. Rooms R3 and R4 have the designed brick cavity walls with brick projections on east, west, south faces as per methodology described by Charde and Gupta (2013). Alternate brick courses of the outer leaf of brick cavity wall have been projected outside the wall face to provide shade to the wall. Optimum brick projections have been provided by considering solar angles at the geographical location in India such that maximum area of the wall is in shade in summer and minimum area is in shade in winter. The north wall will be in shade for most part of the year as duration of sunshine on it throughout the year for considered geographical location is less as compared to the other three walls. Hence the north wall is a brick cavity wall without brick projections. The cavity walls have an effective thickness of 338mm with outer and inner brick leaf 112.5mm each separated by an air cavity of 113mm. Rectangular mild steel wall ties have been used to provide a connection between the outer and inner brick leaf of the brick cavity wall. The spacing of the wall ties has been done as per Technical notes-44B (The Brick Industry Association 2003) as shown in Fig. 4.10. The plan of alternate courses of the brick cavity wall with brick projections are shown in Fig. 4.11. The various stages in its construction are shown in Fig. 4.12-4.13. Air vents with operable shutters have been provided on all the cavity walls of rooms R3, R4 to ventilate the air in wall cavity as per seasonal requirements. During daytime in summer, when outdoor air temperature is high, shutters of the air vents can be kept closed to insulate the room. At night when the outdoor air temperature decreases, these shutters of air vents can be opened to facilitate ventilation of air in the wall cavity, to help in faster heat dissipation from the room. While in winter, the vents can be kept open during the day to help in faster heat gain and closed at night to insulate the room. Room R4 has the proposed hollow roof with hollow stoneware pipes of 100mm diameter. Hollow stoneware pipes cut in half have been integrated in the RCC roof to reduce the total slab depth and provide an air cavity that would help to insulate room interiors which would in turn regulate room temperature and hence be useful for energy conservation inside the building. Fig. 4.16 shows the details of the hollow roof. Various stages in its construction are shown in Fig. 4.17-4.18.

4.4 Design development of static sunshade

The sun's position in the sky changes every hour during the day throughout the year. The sun is higher in the sky in summer than in winter. In the northern hemisphere the sun rises south of east in winter and north of east in summer. The sun's position must be defined in order to plan for the most effective use of shading (Ralegaonkar and Gupta 2005). Knowing latitude, declination, hour angle, the solar altitude and azimuth angles can be computed. For shading calculations horizontal shadow angle and vertical shadow angle is computed and is used in sizing shading devices. A design procedure enables a free form line in plan to be projected into a position in three dimensional space such that the line represents the outer extremity of the sunshade and will shade the window for the specified period. Alternatively a particular geometric form may be superimposed over the window and the redundancy plotted upon that form. The redundant part may then be removed and the developed surface of the remaining portion drawn. The appropriateness of geometry selected as a basis for the design will be a function of facade orientation (Harkness 1980).

Stepwise methodology for the static sunshade development (Ralegaonkar 2004) over window on south wall of rooms R2, R3, R4 is as follows:

i. For a given facade orientation for which a static sunshade is to be designed, a decision as to the design day and period of time on that design day during which the window is to be shaded is made. For example, in view of the climatic conditions at the considered location (Pilani), 22nd December is selected as the first design day for which total exposure of the window is desired and 23rd March is selected as the second design day, for which complete shading is desired throughout the day.

ii. The corresponding horizontal and vertical shadow angles (which define the movement of sun relative to a normal projection from the face of facade) are computed at close intervals of time for accurate geometry of desired sunshade.

iii. A decision about the maximum projection of the sunshade from the face of the facade and also its extension beyond each side and above the window is made.

iv. Then the sun's movement relative to the building facade and window position is plotted to obtain the desired geometry of static sunshade.

Thus using horizontal shadow angles, the sun's position relative to normal to the wall is plotted in the plan. The sun's morning and afternoon movement is plotted from the western-most lower edge and eastern-most lower edge of the window. The obtained intersection points in plan are projected in side view with the vertical shadow angles from the lower edge of the window. These points are then projected onto the elevation. Practical design of the obtained geometry of sunshade is important.

For the considered location (Pilani, Rajasthan, India) geographical location details are as, Latitude: 28.25^0N Longitude: 75.65^0E. Studying the atmospheric data from previous years it can be inferred that the climatic condition over the region is extreme. With reference to solar chart (Duffie and Beckman 1991) and comfort temperature zone (18-27^0C) design dates were chosen for the development of proposed static sunshade. On 22^{nd} December, the sun is at lowest position in the sky and from climatic point of view it lies in extreme winter. Thus on 22nd December there should be maximum entry of sunlight through the window. 23^{rd} March onwards, when the sun is appreciably high in the sky, there should be no direct entry of sunlight inside the room. From climatic point of view the second cutoff date lies, where the season changes from moderate winter to moderate summer. Assumption made for the design development of proposed static sunshade is that the sun’s entry will be between 8 a.m. to 4 p.m. solar time from south facade window inside the room. Using the described methodology, proposed geometry of the static sunshade for the considered dates can be obtained. Considering the problem of accumulation of rainwater at the interface between sunshade and wall surface, minimum amount of drop-down is made at the end of the sunshade. The surface is generated using RCC. For practical application and ease of construction, the geometry of designed static sunshade has been modified so that it can be adopted easily in any building without compromising on the sunlight entry requirements on the design dates as shown in Fig. 4.7.

4.5 Design development of brick cavity wall with brick projections

As discussed in section 4.5, solar angles have been used for the decision of optimum brick projections from the wall face of the brick cavity wall with brick projections. Stepwise methodology used for the decision of optimum brick projections from the outer brick leaf of the brick cavity wall of rooms R3 and R4 is as follows:

i. The cut off dates were considered depending upon seasonal requirements.

ii. The desired sun angles at a fixed time (every one hour) interval were computed.

iii. The corresponding horizontal shadow angle and vertical shadow angle (which define the movement of sun relative to a normal projection from the face of facade) were calculated.

iv. The shaded area on the wall due to brick projections on the desired dates at different time intervals was obtained. Based on these, a decision was made regarding the optimum brick projection from wall face that would keep maximum area of wall in shade in summer and minimum wall area in shade in winter.

On 22nd December, the sun is at lowest position in the sky and from climatic point of view it lies in extreme winter. Thus on 22nd December there should be minimum shadow of brick projections on the wall to maximize heat gain. 23rd March onwards, when the sun is appreciably high in the sky, there should be maximum shadow of brick projections on the wall, to minimize heat gain. From climatic point of view the second cutoff date lies, where the season changes from moderate winter to moderate summer. As the solar angles are different for east and south walls, the length of brick projections is different. For west wall, the solar angles are same as that of east wall with only difference being the sun is to the east of south in morning and west of south in evening. Hence the length of brick projections is same for east and west walls. The optimum brick projection that would keep maximum area of wall in shade in summer and minimum wall area in shade in winter was decided by studying shadow area obtained on wall surface on design dates. Shaded area of wall due to brick projections on the desired dates at different times of the day for south wall are shown in Fig. 4.20-4.21 and east wall are shown in Fig. 4.22-4.23. Using the described methodology the proposed cavity wall with brick projections for east, west and south faces of room R3 have been obtained. Rectangular mild steel wall ties have been used to provide a connection between outer and inner brick leaf of the brick cavity wall as per Technical Notes-44B (The Brick Industry Association 2003) as shown in Fig. 4.10.

4.6 Design development of hollow roof

The hollow roof has been made up of RCC and hollow stoneware pipes. Hollow stoneware pipes of 100mm diameter were cut in half and then integrated in the roof to introduce an air cavity. The air cavity would help to insulate room interiors. The pipes were cut in half to reduce the slab depth. The detailed calculations for the design of the RCC hollow roof (Pillai and Menon 2003) are presented in this section.

Internal room dimensions: $4000\ mm \times 3000\ mm$

Surrounding brick walls: $338\ mm\ thick$

Live load: $1.5\ kN/m^2$

Finish load: $2\ kN/m^2$

Density of concrete = $25\ kN/m^3$

Weight of 1 half cut pipe = $3.325\ kg = \frac{3.325}{101.97}\ kN = 0.0326\ kN$

Characteristic strength of concrete $f_{ck} = 20\ MPa$

Specified yield strength of reinforcing steel $f_y = 500\ MPa$

With reference to Fig. 4.16, considering the hollow pipes and assuming 8mm diameter bars overall thickness of slab

$D = 75mm + 85mm + 16mm = 176mm$

Effective depth (short span) $d_x = 176 - 25 - 4 = 147mm$

Effective depth (long span) $d_y = 147 - 8 = 139mm$

Effective short span $l_x = 3000 + 147 = 3147mm$

Effective long span $l_y = 4000 + 139 = 4139mm$

Aspect ratio $r = \frac{l_y}{l_x} = \frac{4139}{3147} = 1.315$

Note: effective span is taken as (clear span + *d*) as this is less than centre-to-centre span between supports.

Volume of concrete (Fig. 4.24):

a. $[(4.676 \times 0.488 \times 2) + (2.7 \times 0.488 \times 2)] \times 0.176 = 1.267m^3$

b. $2.7 \times 3.7 \times 0.066 = 0.659m^3$

c. $2.7 \times 3.7 \times 0.025 = 0.25m^3$

d. total concrete in pipe area = concrete volume in pipe area - total pipe volume

concrete volume in pipe area = $2.7 \times 3.7 \times 0.085 = 0.849m^3$

total pipe volume = $0.4122m^3$

total concrete in pipe area = $0.849 - 0.4122 = 0.437m^3$

e. total volume of concrete in slab = $1.267 + 0.659 + 0.25 + 0.437 = 2.613m^3$

Self weight of slab = weight of concrete + weight of pipes

= (density x volume) of concrete + (number of pipes x weight of 1 pipe)

= $(25 \times 2.613) + (95 \times 0.0326)$

= $68.42\ kN$

Self weight of slab per unit area = $\frac{68.42}{4.676 \times 3.676} = 3.981kN/m^2$

Loads on slab

Self weight of slab per unit area = $3.981\ kN/m^2$

Finishes = $2\ kN/m^2$

Live loads = $1.5\ kN/m^2$

Total load on slab $w = 7.481\ kN/m^2$

Factored load $w_u = 7.397 \times 1.5 = 11.221\ kN/m^2$

Design moments (for strips at midspan, 1m wide in each direction)

Assuming the slab corners to be torsionally unrestrained, the Rankine-Grashoff method may be applied:

Maximum short span factored moment (per unit width): $M_{ux} = \alpha_x w_u l_x^2$

Maximum long span factored moment (per unit width): $M_{uy} = \alpha_y w_u l_x^2$

where

Moment coefficient (short span)

$$\alpha_x = \frac{1}{8}\left[\frac{r^4}{1+r^4}\right] = \frac{1}{8}\left[\frac{1.315^4}{1+1.315^4}\right] = 0.0937$$

Moment coefficient (long span)

$$\alpha_y = \frac{1}{8}\left[\frac{r^2}{1+r^4}\right] = \frac{1}{8}\left[\frac{1.315^2}{1+1.315^4}\right] = 0.0542$$

$$M_{ux} = \alpha_x w_u l_x^2 = 0.0937 \times 11.221 \times 3.147^2 = 10.411\ kNm/m$$

$$M_{uy} = \alpha_y w_u l_x^2 = 0.0542 \times 11.221 \times 3.147^2 = 6.019\ kNm/m$$

Design of reinforcement

Constant (short span) $R_x = \frac{M_{ux}}{b\,d_x^2} = \frac{10.411\ x\ 10^6}{1000\ x\ 147^2} = 0.482\ MPa$

Constant (long span) $R_y = \frac{M_{uy}}{b d_y^2} = \frac{6.019\ x\ 10^6}{1000\ x\ 139^2} = 0.312\ MPa$

where

b = width

Percentage tension reinforcement required

$$\frac{(P_t)_{reqd}}{100} = \frac{(A_{st})_{reqd}}{bd} = \frac{f_{ck}}{2f_y}\left[1 - \sqrt{1 - 4.589R/f_{ck}}\right]$$

Percentage tension reinforcement required (short span)

$$\frac{(P_t)_{x,reqd}}{100} = \frac{20}{2 \times 500}\left[1 - \sqrt{1 - (4.589 \times 0.482)/20}\right] = 0.0011$$

$$\frac{(A_{st})_{reqd}}{bd} = 0.0011$$

$$(A_{st})_{x,reqd} = 0.0011 \times 1000 \times 147 = 167.269\ mm^2/m$$

Required spacing of 8mm diameter bars = $\frac{1000\ x\ 50.24}{167.269} = 300.354mm$

$$\frac{(P_t)_{y,reqd}}{100} = \frac{20}{2 \times 500}\left[1 - \sqrt{1 - (4.589 \times 0.312)/20}\right] = 0.000728$$

$$\frac{(A_{st})_{reqd}}{bd} = 0.000728$$

$$(A_{st})_{y,reqd} = 0.000728 \times 1000 \times 139 = 101.196\ mm^2/m$$

Required spacing of 8mm diameter bars = $\frac{1000 \times 50.24}{101.196} = 496.461\ mm$

Reinforcement provided:

Short span: 8mm diameter bars at 300mm c/c i.e $(A_{st})_{x,reqd} = 167.46\ mm^2/m$

Long span: 8mm diameter bars at 300mm c/c i.e. $(A_{st})_{y,reqd} = 167.46\ mm^2/m$

Check for deflection

$$P_{t,x} = \frac{(A_{st})_x}{bd} \times 100 = 0.1139$$

$$f_s = \frac{0.58 \times 500 \times 167.269}{167.46} = 289.657\ MPa$$

modification factor $k_t = 1.4$

$$\left(\frac{l}{d}\right)_{max} = 20 \times 1.4 = 28$$

$$\left(\frac{l}{d}\right)_{provided} = \frac{3147}{147} = 21.408 < 28\ \ Hence\ OK$$

The static sunshade, south, east, west walls and roof of room R4 were designed using the methodology described in the previous sections. The performance of conventional room R1, room R2 with designed static sunshade, room R3 with designed static sunshade, brick cavity walls with brick projections and energy efficient room R4 with all three designed passive elements was compared with each other to study the individual and combined effect of the designed passive elements.

Table 4.1 Details of building elements of rooms R1, R2, R3, R4

Building element	Room R1	Room R2	Room R3	Room R4
Foundation	PCC 1:3:6 Random rubble stone masonry (sandstone), mortar 1:6	PCC 1:3:6 Random rubble stone masonry (sandstone), mortar 1:6	PCC 1:3:6 Random rubble stone masonry (sandstone), mortar 1:6	PCC 1:3:6 Random rubble stone masonry (sandstone), mortar 1:6
Plinth slab	RCC 1:2:4	RCC 1:2:4	RCC 1:2:4	RCC 1:2:4
Walls	338mm thick load bearing brick walls, mortar 1:6	338mm thick load bearing brick walls, mortar 1:6	Double leaf brick cavity walls, mortar 1:4 Inner leaf 112.5mm thick, cavity 113mm thick, outer leaf 112.5mm thick	Double leaf brick cavity walls, mortar 1:4 Inner leaf 112.5mm thick, cavity 113mm thick, outer leaf 112.5mm thick
Roof	100mm thick RCC (1:1.5:3)	100mm thick RCC (1:1.5:3)	100mm thick RCC (1:1.5:3)	176mm thick RCC (1:1.5:3) with hollow stoneware pipes
Plaster	Mortar 1:4	Mortar 1:4	Mortar 1:4	Mortar 1:4
Kota stone flooring	Mortar 1:6	Mortar 1:6	Mortar 1:6	Mortar 1:6

Legend: PCC-plain cement concrete; RCC-reinforced cement concrete; MS-mild steel

Table 4.1 (Cont.) Details of building elements of rooms R1, R2, R3, R4

Building element	Room R1	Room R2	Room R3	Room R4
Kota stone skirting	Mortar 1:4	Mortar 1:4	Mortar 1:4	Mortar 1:4
Water proofing terrace	PCC 1:1.5:3 Base plaster 1:4 Ceramic vitreous tiles in neat cement 1:4	PCC 1:1.5:3 Base plaster 1:4 Ceramic vitreous tiles in neat cement 1:4	PCC 1:1.5:3 Base plaster 1:4 Ceramic vitreous tiles in neat cement 1:4	PCC 1:1.5:3 Base plaster 1:4 Ceramic vitreous tiles in neat cement 1:4
Openings	1000 x 1200mm MS window frame and shutter	1000 x 1200mm MS window frame and shutter	1000 x 1200mm MS window frame and shutter	1000 x 1200mm MS window frame and shutter
Static sunshade	RCC 1:1.5:3	Designed static sunshade, RCC 1:1.5:3	Designed static sunshade, RCC 1:1.5:3	Designed static sunshade, RCC 1:1.5:3
Door	1000mm x 2100 mm MS frame with wooden shutter	1000mm x 2100 mm MS frame with wooden shutter	1000mm x 2100 mm MS frame with wooden shutter	1000mm x 2100 mm MS frame with wooden shutter

Legend: PCC-plain cement concrete; RCC-reinforced cement concrete; MS-mild steel

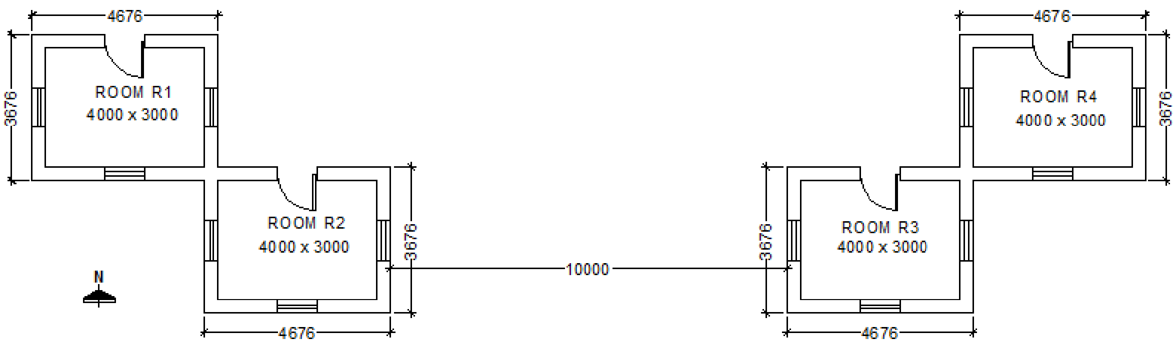


Fig. 4.1 Key plan showing position of rooms (Note: all dimensions are in mm)

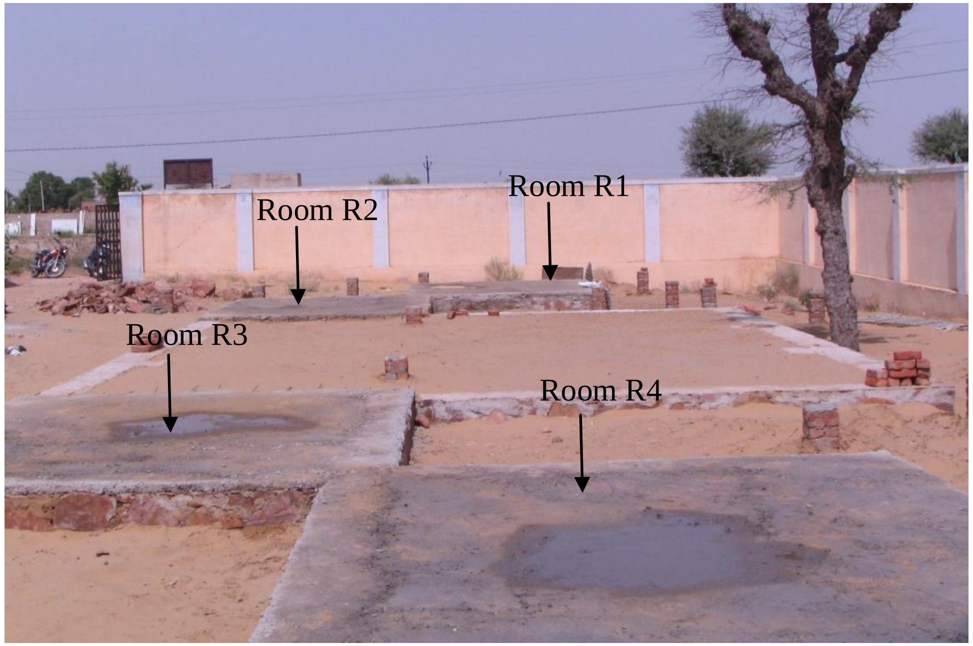


Fig. 4.2 Photograph showing rooms under construction (upto plinth level)

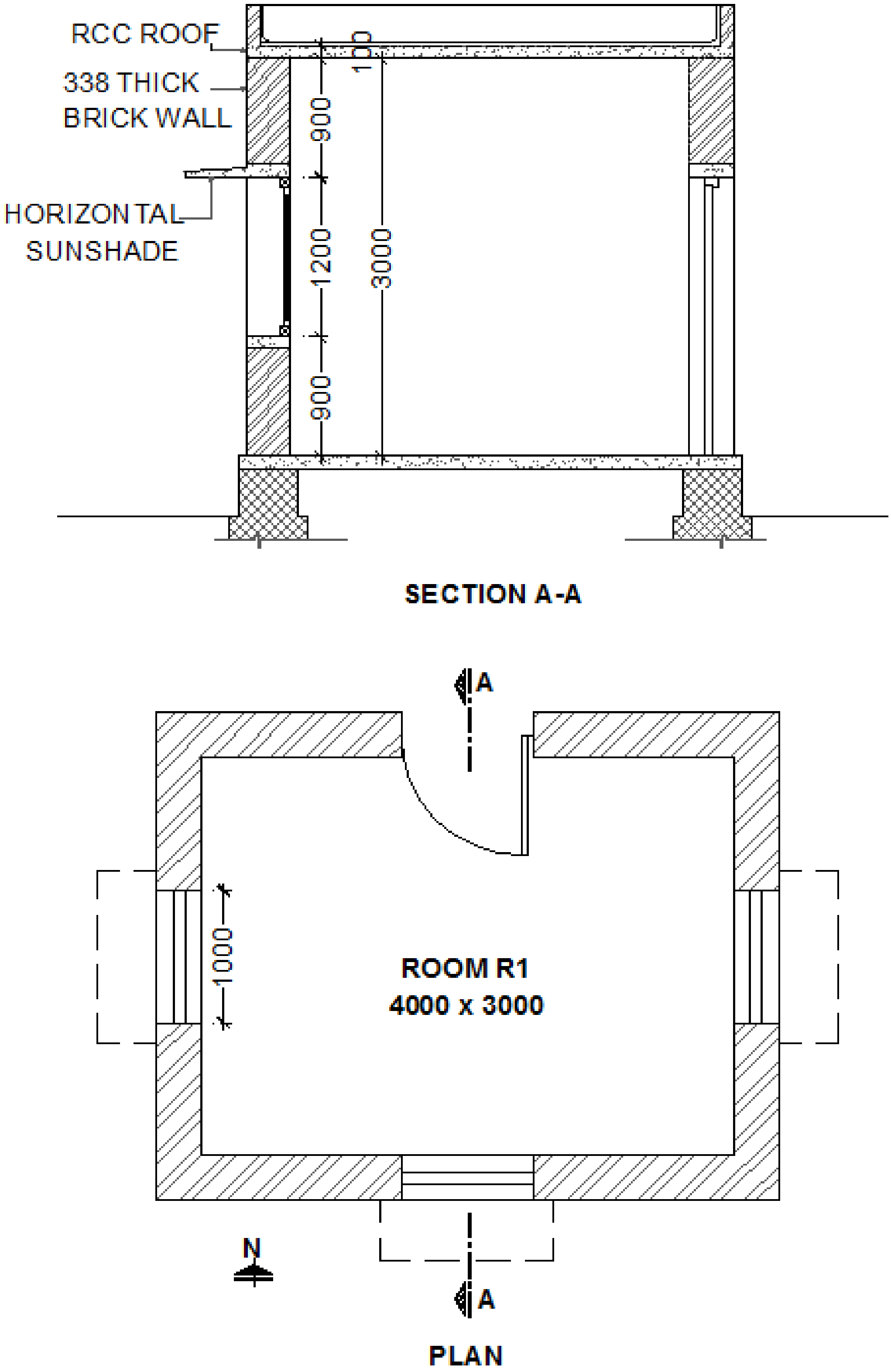


Fig. 4.3 Plan and section of room R1 (Note: all dimensions are in mm)

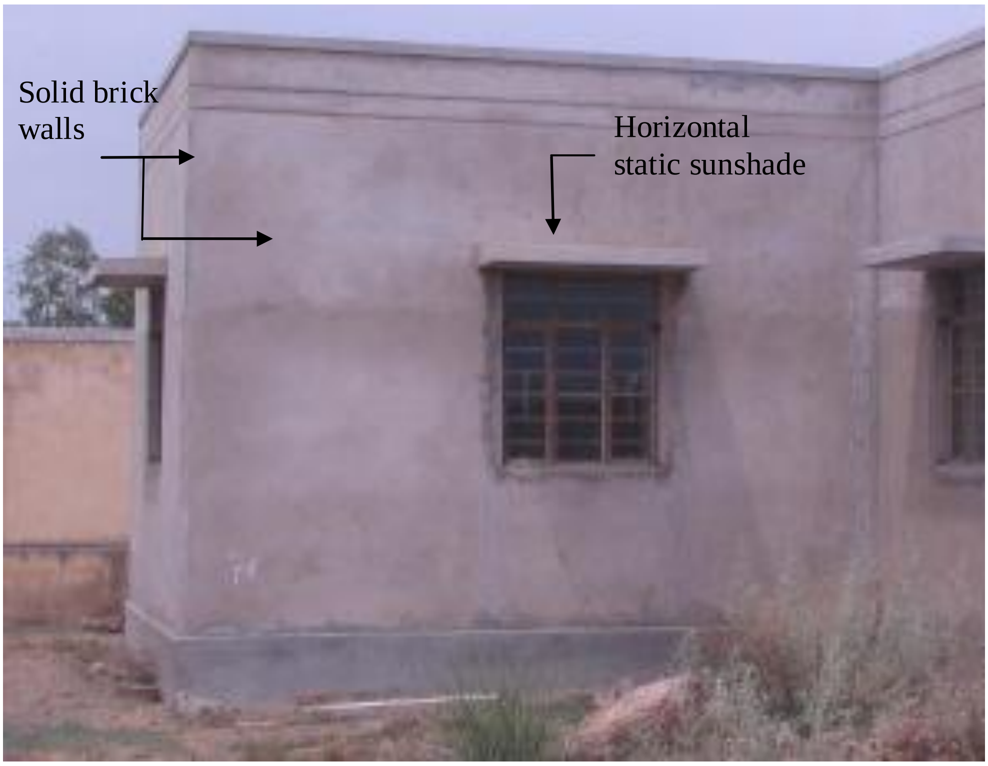


Fig. 4.4 View of room R1

Fig. 4.5 View of rooms R1 and R2

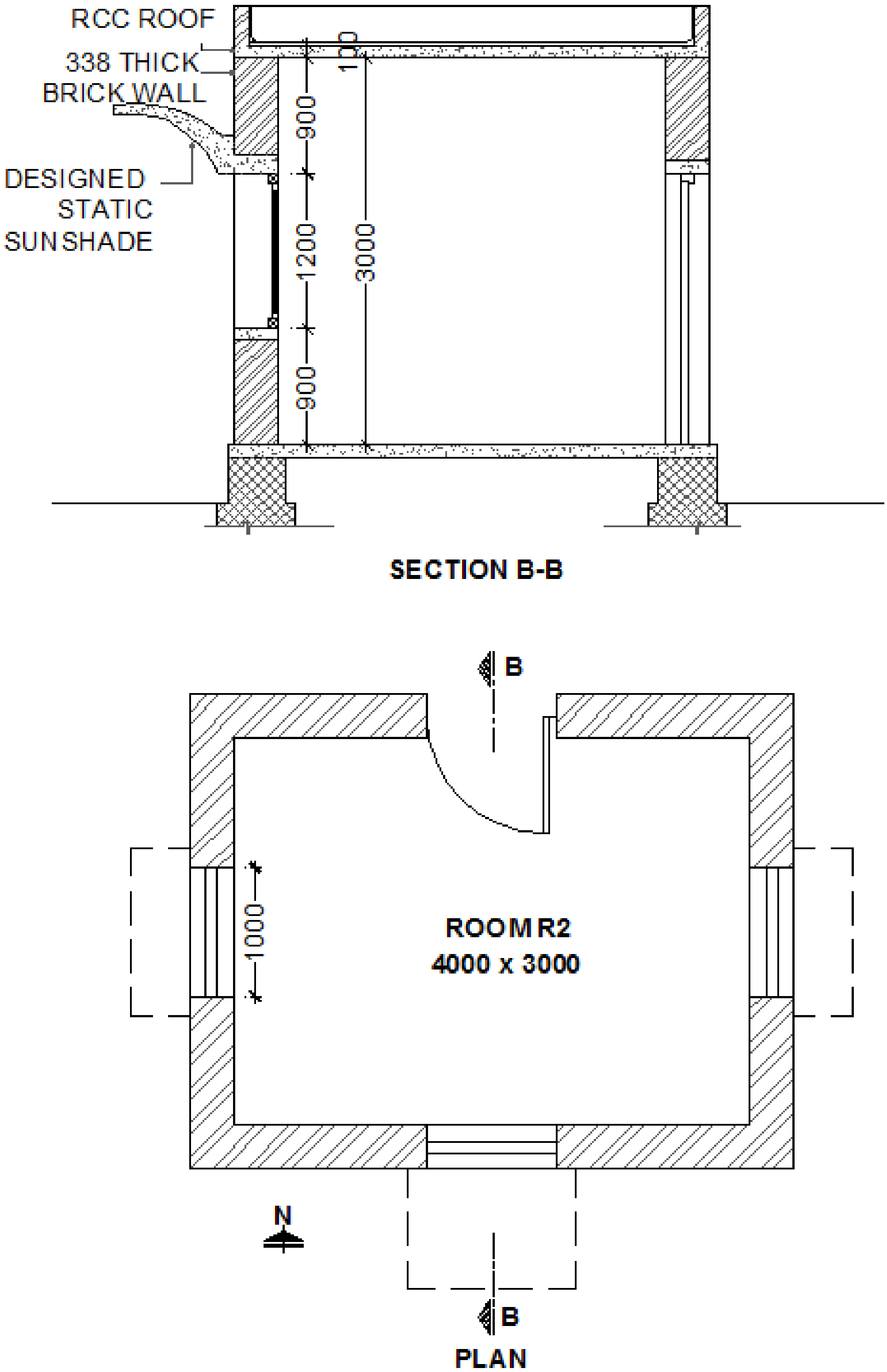


Fig. 4.6 Plan and section of room R2 (Note: all dimensions are in mm)

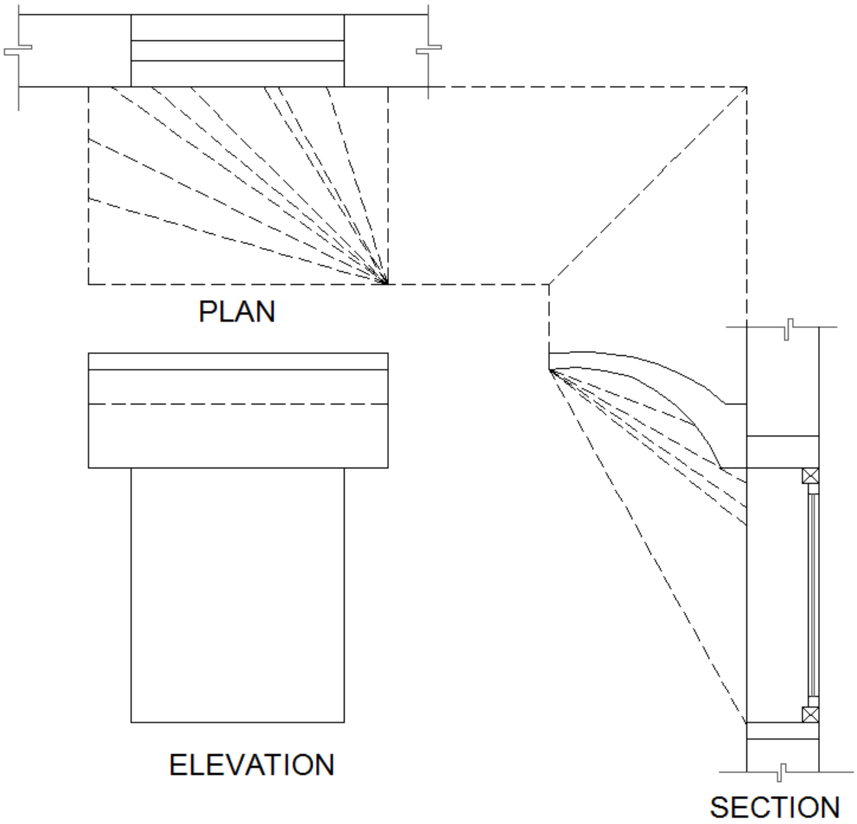


Fig. 4.7 Details of designed static sunshade

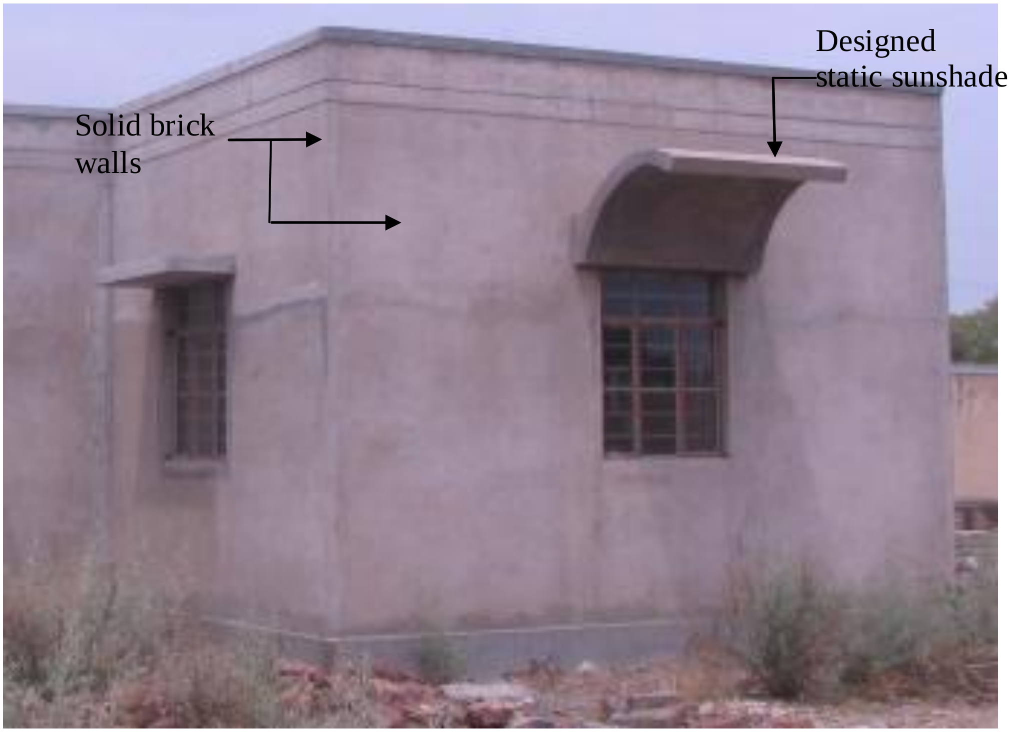


Fig. 4.8 View of room R2

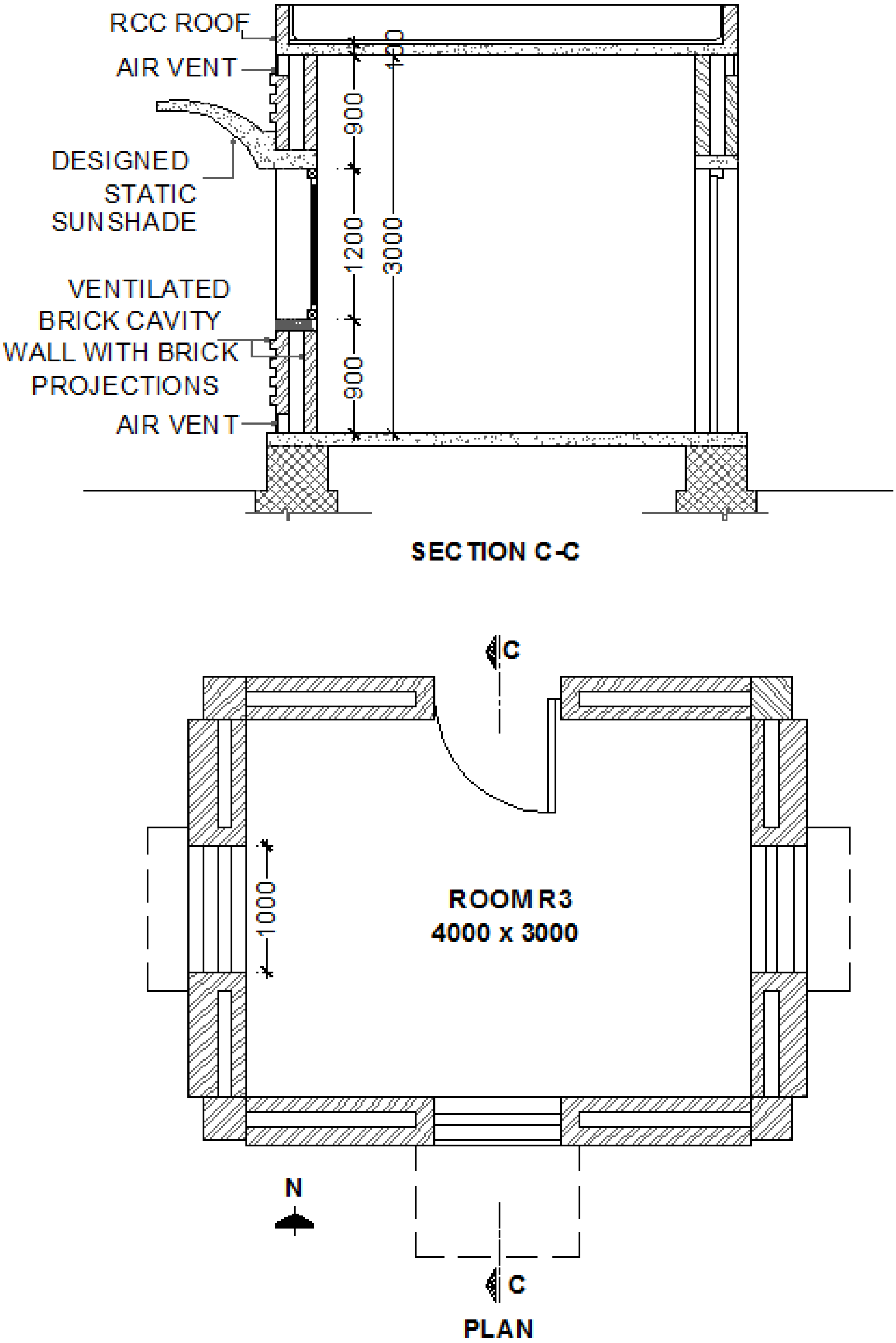
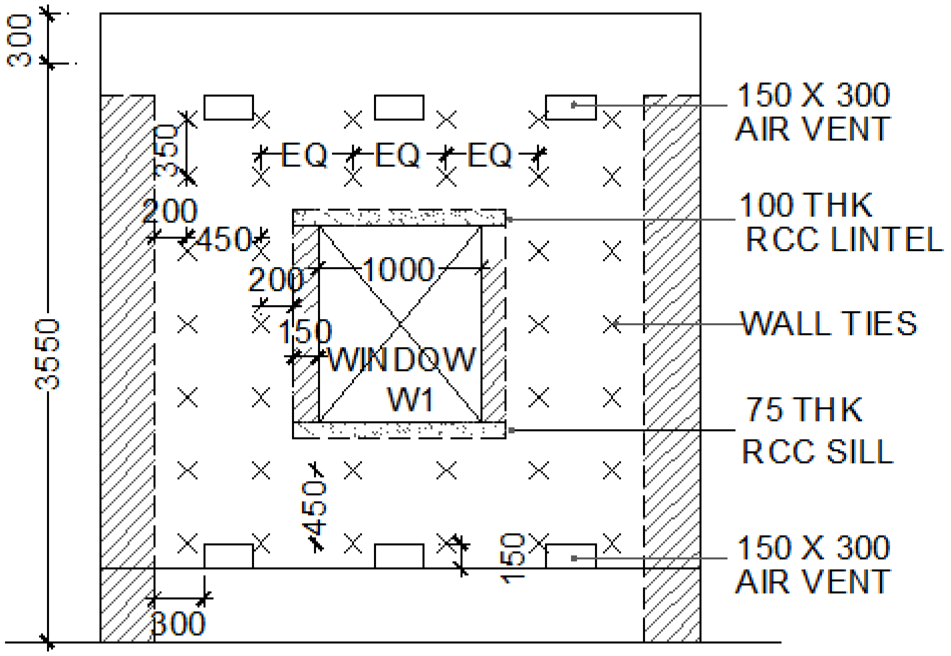
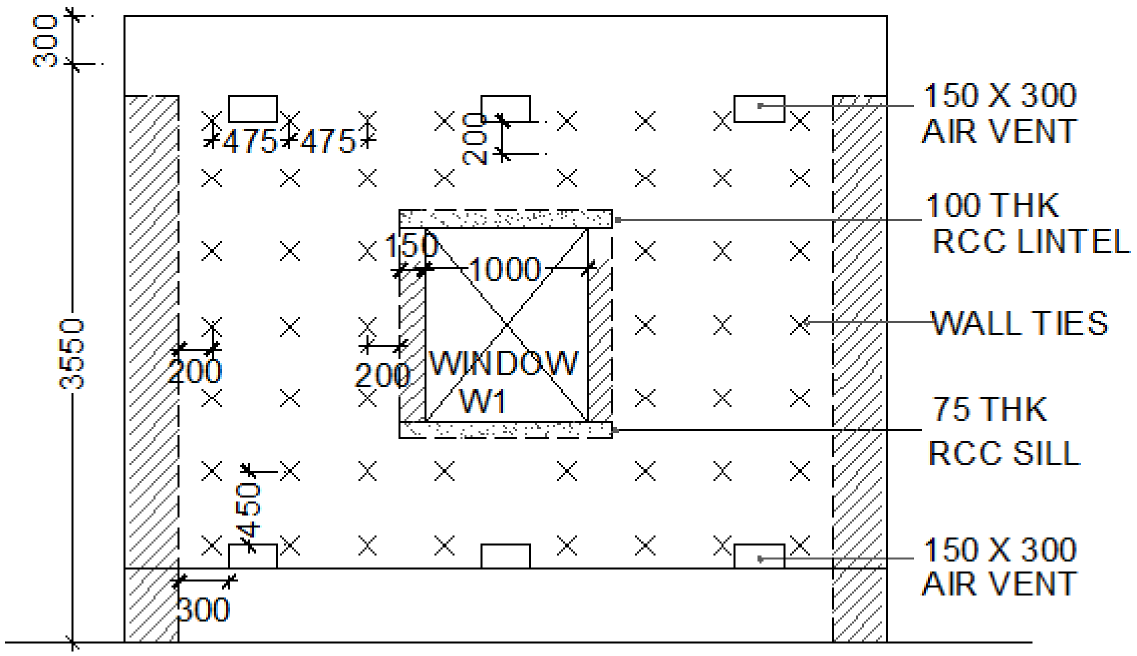


Fig. 4.9 Plan and section of room R3 (Note: all dimensions are in mm)

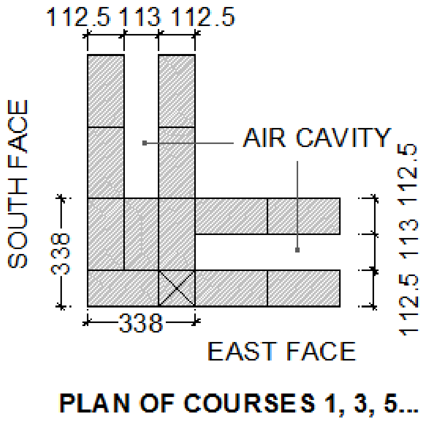


EAST/ WEST WALL ELEVATION



SOUTH WALL ELEVATION

Fig. 4.10 Elevation of walls of room R3 (Note: all dimensions are in mm)



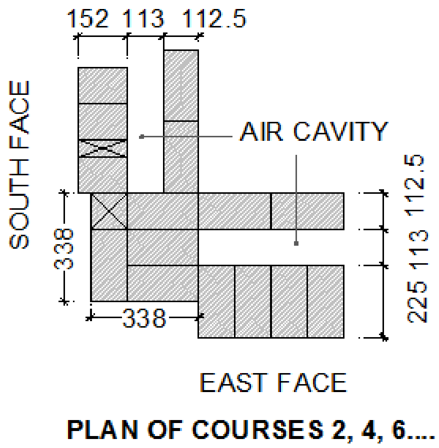


Fig. 4.11 Plan of courses (Note: all dimensions are in mm)

(a) (b)

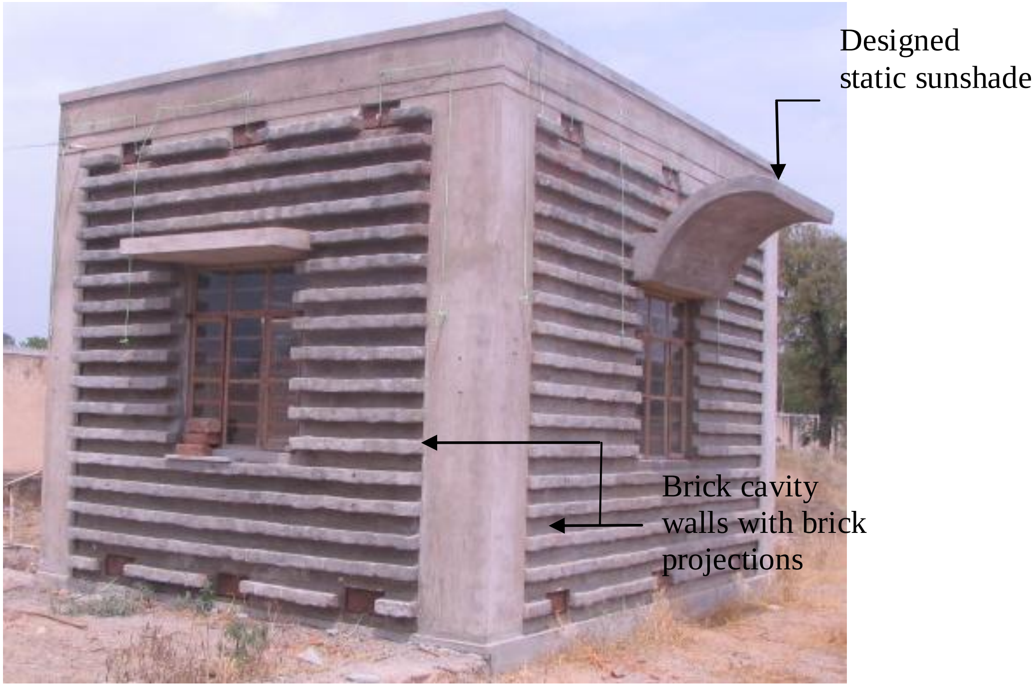
Fig. 4.12 View of courses of brick cavity wall with brick projections (a) View of first course (b) View of second course

(a)

(b)

Fig. 4.13 View of brick cavity wall with brick projections under construction (a) View of west wall and south wall (b) View of rectangular mild steel wall ties

(a)



(b)

Fig. 4.14 View of room R3 (a) View of the west and south walls (b) View of rooms R3 and R4

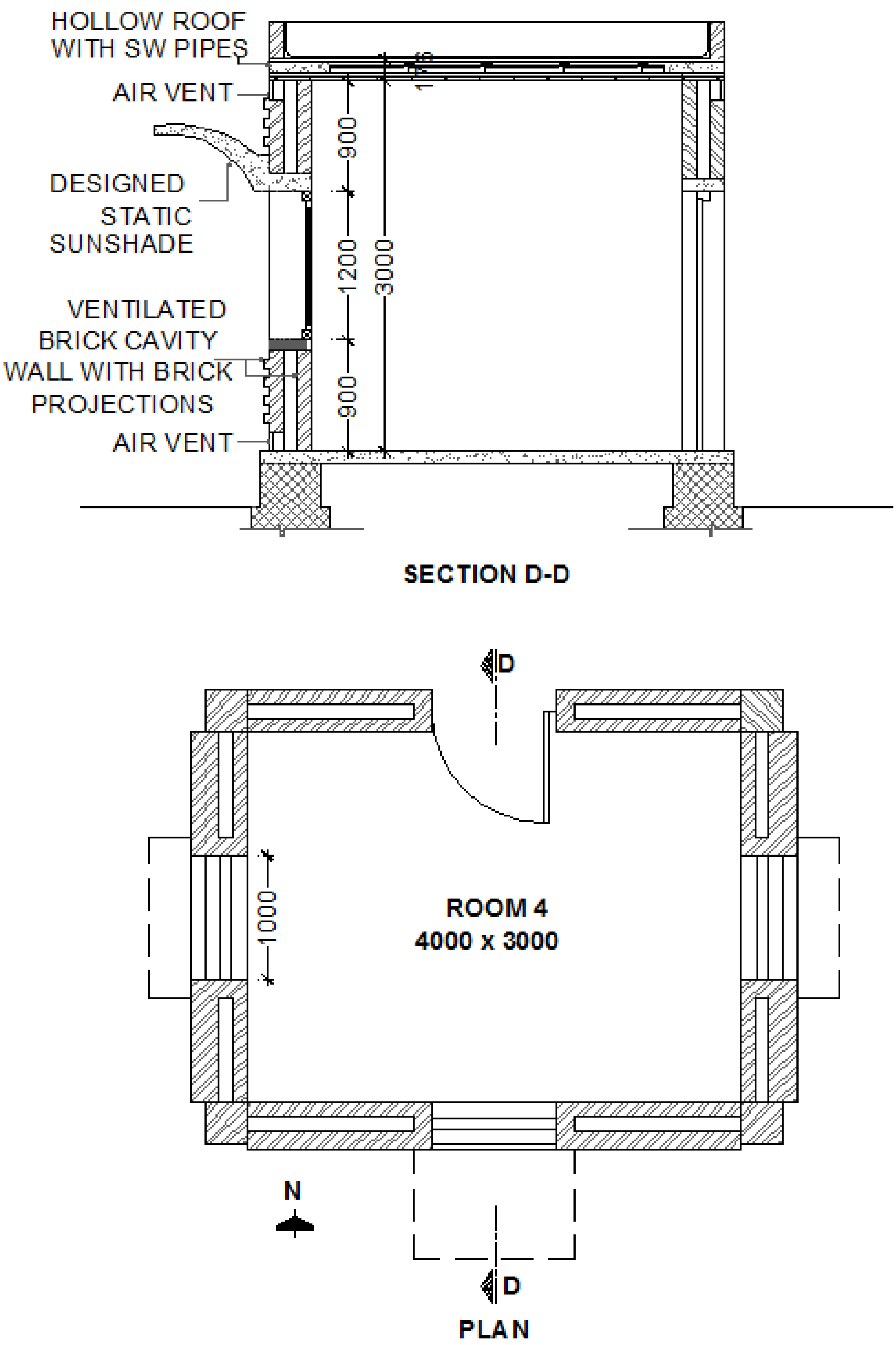


Fig. 4.15 Plan and section of room R4 (Note: all dimensions are in mm)

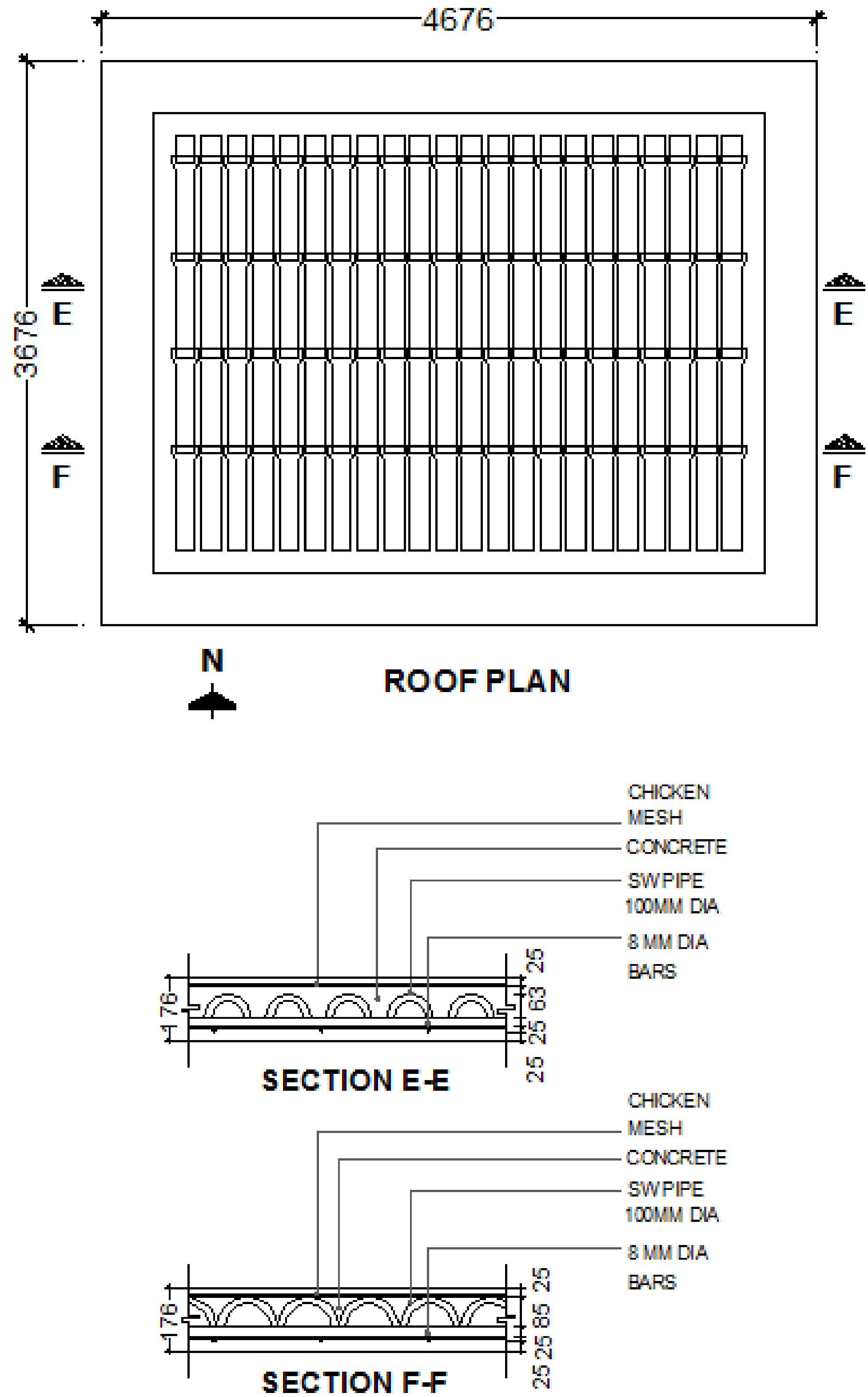


Fig. 4.16 Details of hollow roof (Note: all dimensions are in mm)

(a)

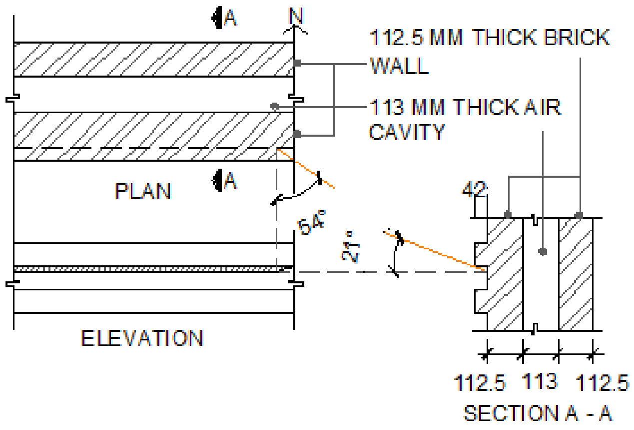
(b)

Fig. 4.17 View of hollow roof under construction (a) View of the hollow stoneware pipes (b) View of concrete layer over hollow stoneware pipes

Fig. 4.18 View of chicken wire mesh and concrete layer in hollow roof

Fig. 4.19 View of room R4

(a)



(b)

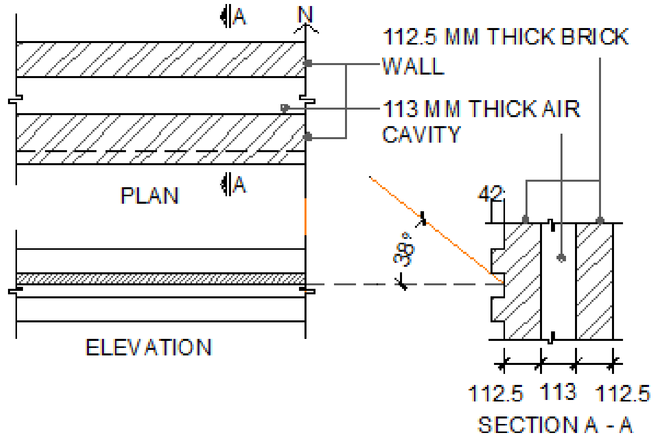
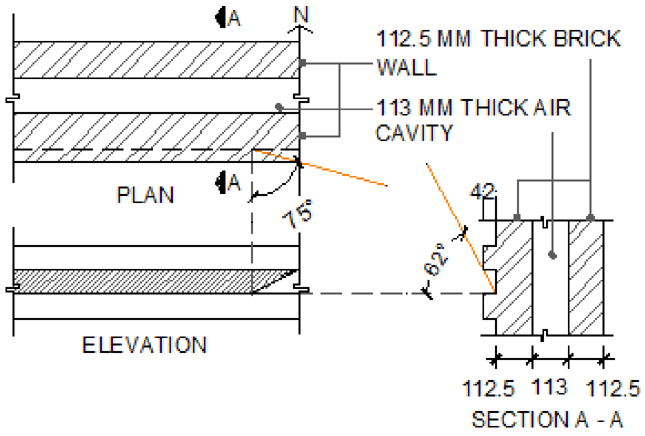


Fig. 4.20 Shaded wall area for one brick course of south wall on 22nd December (a) At 0800/ 1600 hours (b) At 1200 hours

(a)



(b)

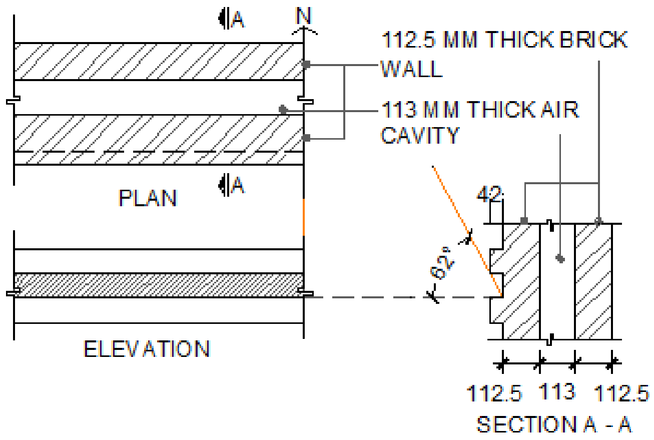


Fig. 4.21 Shaded wall area for one brick course of south wall on 23rd March (a) At 0800/ 1600 hours (b) At 1200 hours

(a) (b)

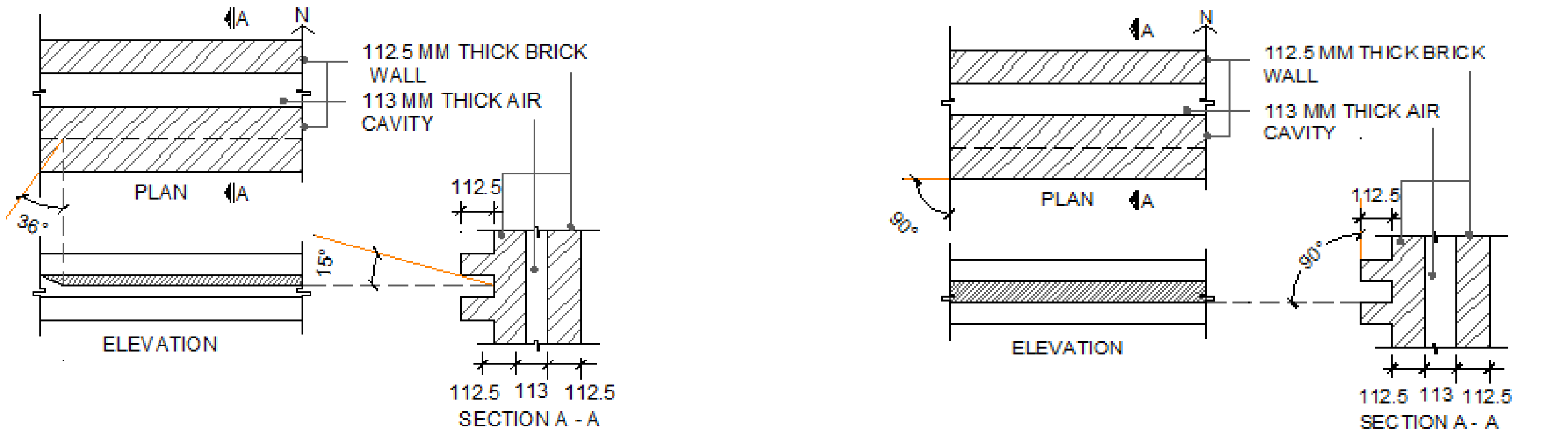


Fig. 4.22 Shaded wall area for one brick course of east wall on 22nd December (a) At 0800/ 1600 hours (b) At 1200 hours

(a) (b)

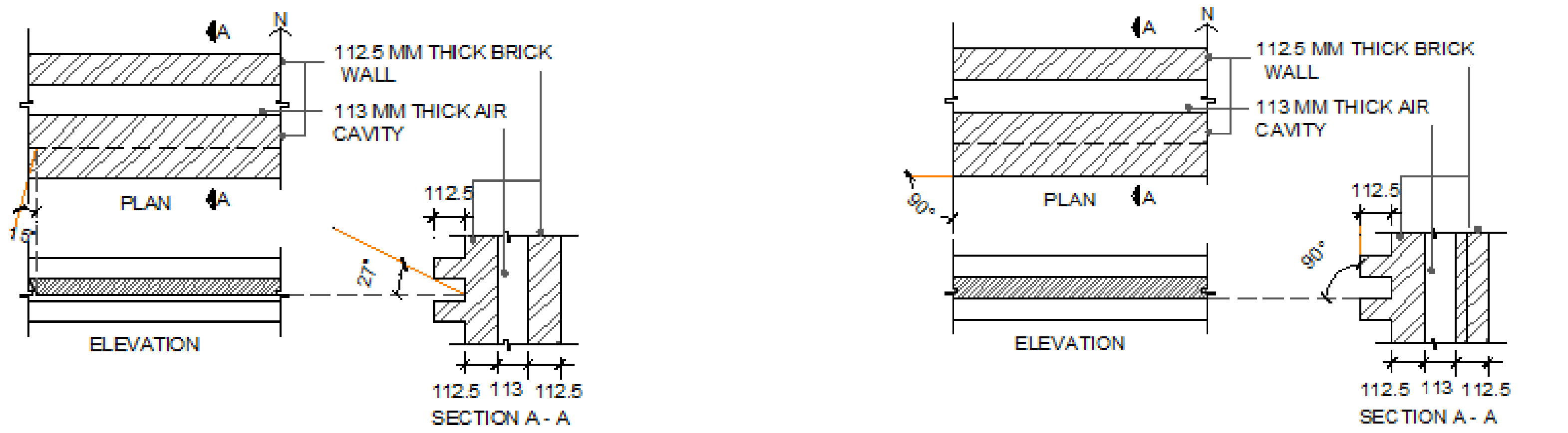


Fig. 4.23 Shaded wall area for one brick course of east wall on 23rd March (a) At 0800/ 1600 hours (b) At 1200 hours

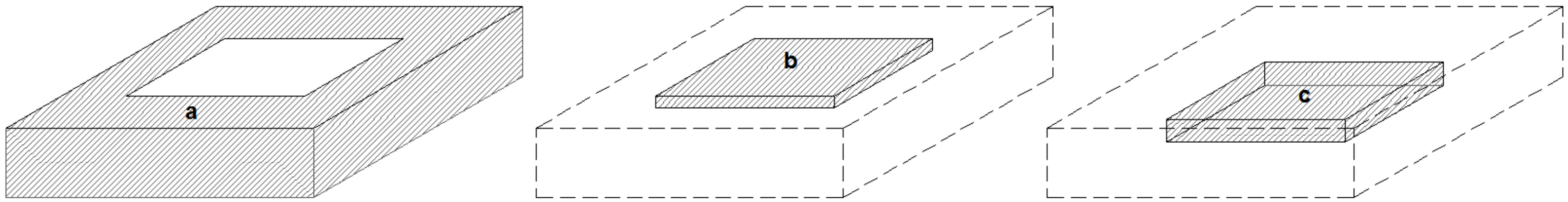


Fig. 4.24 Schematic diagram of hollow roof for calculation of concrete volume

Chapter 5

Thermal Performance Analysis

5.1 Introduction

The process of modeling the energy transfer between a building and its surroundings or thermal performance of a building helps to calculate temperature variation inside the building over a specified time and estimate the duration of uncomfortable periods. It is thus an aid to estimate the heating, cooling load and hence, the sizing and selection of HVAC equipment. These quantifications help to develop effective designs of energy efficient buildings that help to create thermally comfortable indoor environment for the well being of occupants (Nayak and Prajapati 2006). There are three aspects which require careful attention in the thermal design of buildings. Firstly, an evaluation must be made of indoor thermal condition most conducive to comfort, health and safety of the occupants. Secondly, it is necessary to describe optimum outside climatic data that must be taken into account when developing the best design to suit specific procedures. Thirdly physical properties of structural materials which can be effectively utilized to ensure the best possible control of living and working environments [SP-41:1987 (Bureau of Indian Standards 1987)]. The building can be considered as a defined unit and its heat exchange processes with the outdoor environment can be examined. The transfer of heat energy occurs as a result of a driving force called temperature difference (Koenigsberger et al. 1973). In the present chapter, the thermal performance of the four rooms has been evaluated using steady state method. The solar radiation for the considered geographical location has also been calculated.

5.2 Method for performance estimation

Various heat exchange processes are possible between a building and the external environment. Heat flows by conduction through various building elements such as walls, roof, ceiling, floor, etc. Heat transfer also takes place from different surfaces by convection and radiation. Besides, solar radiation is transmitted through transparent windows and is absorbed by the internal surfaces of the building. There may be evaporation of water resulting in a cooling effect. Heat is also added to the space due to the presence of human occupants and the use of lights and equipments. The thermal performance of a building depends on design variables, material properties, weather data and a building’s usage data (internal gains due to occupants, lighting and equipment, air exchanges, etc.) (Nayak and Prajapati 2006). The influence of these factors on the performance of a building can be studied using appropriate analytical tools. Several techniques are available for estimating the performance of buildings. Based on the fundamentals of heat transfer and solar radiation it is possible to calculate the various heat exchanges taking place in a building.

5.2.1 Conduction

The rate of heat conduction (Q_c) through any element such as roof, wall or floor under steady state can be written as (Eqn. 5.1):

$$Q_c = A_s U \Delta T \qquad ...5.1$$

where,

A_s: surface area (m^2)

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

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

The steady state method does not account for the effect of heat capacity of building materials. U is given by (Eqn. 5.2):

$$U = \frac{1}{R_T} \qquad ...5.2$$

where,

R_T is the total thermal resistance and is given by (Eqn. 5.3):

$$R_T = \frac{1}{h_i} + \left(\sum_{j=1}^{z} L_j/k_j\right) + \frac{1}{h_o} \qquad ...5.3$$

where,

h_i : inside heat transfer coefficient

h_o: outside heat transfer coefficient

L_j: thickness of the j^{th} layer

z: number of layers

k_j: thermal conductivity of its material

U indicates the total amount of heat transmitted from outdoor air to indoor air through a given wall or roof per unit area per unit time. The lower the value of U, the higher is the insulating value of the element. Thus, the U-value can be used for comparing the insulating values of various building elements. Eqn. 5.1 is solved for every external constituent element of the building i.e., each wall, window, door, roof and the floor, and the results are summed up. The heat flow rate through the building envelope by conduction (Q_c), is the sum of the area and the U-value products of all the elements of the building multiplied by the temperature difference. It is expressed as (Eqn. 5.4):

$$Q_c = \sum_{i=1}^{N_c} A_i U_i \Delta T_i \qquad ...5.4$$

where,

i: building element

N_c: number of components

If the surface is also exposed to solar radiation then, ΔT is calculated as (Eqn. 5.5):

$$\Delta T = T_{so} - T_i \quad ...5.5$$

where,

T_i: indoor temperature

T_{so}: sol-air temperature, calculated using the expression (Eqn. 5.6):

$$T_{so} = T_o + \frac{\alpha_b S_T}{h_o} - \frac{\varepsilon \Delta R}{h_o} \quad ...5.6$$

where,

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

α_b: absorptance of the surface for solar radiation

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

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

ε: emissivity of the surface

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

Values of heat transfer coefficient (h_o) at different wind speeds and orientation are presented in Table 5.1 (Nayak and Prajapati 2006). Daily average values of hourly solar radiation can be calculated from the hourly data. Global and diffuse solar radiation on a horizontal surface and vertical surfaces has been calculated in this chapter.

5.2.2 Ventilation

The heat flow rate due to ventilation (Q_v) of air between the interior of a building and the outside, depends on the rate of air exchange. It is given by (Eqn. 5.7):

$$Q_v = \rho_a V_r C_a \Delta T \quad ...5.7$$

where,

ρ_a: density of air (kg/m^3)

V_r: ventilation rate (m^3/s)

C_a: specific heat of air (J/ kg-K)

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

If the number of air changes is known, then V_r can be calculated as (Eqn. 5.8):

$$V_r = \frac{NV}{3600} \quad ...5.8$$

where,

N: number of air changes per hour

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

The minimum standards for ventilation in terms of air changes per hour (N) are presented in Table 5.2 [SP-41:1987 (Bureau of Indian Standards 1987)].

5.2.3 Solar heat gain

The solar heat gain (Q_s) through transparent elements can be written as (Eqn. 5.9):

$$Q_s = \alpha_s \sum_{i=1}^{e} a_i S_{gi} \tau_i \qquad ...5.9$$

where,

α_s : mean absorptivity of the space

a_i: area of the i^{th} transparent element (m^2)

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

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

e: number of transparent elements

5.2.4 Internal gain

The internal heat gain may be due to:

i. The heat generated by the people occupying the building. Table 5.3 shows the heat output rate of human bodies for various activities (Nayak and Prajapati 2006).

ii. The heat generated by the appliances

Thus the heat flow rate due to internal heat gain (Q_i) is given by (Eqn. 5.10):

$$Q_i = (No.of\ people\ x\ heat\ output\ rate) + Rated\ wattage\ of\ lamps + Appliance\ load \qquad ...5.10$$

5.2.5 Evaporation

The rate of cooling by evaporation (Q_e) from, say, a roof pond, fountains or human perspiration, can be written as (Eqn. 5.11):

$$Q_e = m_e L_e \qquad ...5.11$$

where,

m_e: rate of evaporation (kg/s)

L_e: latent heat of evaporation (J/kg-K)

5.2.6 Equipment gain

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

5.3 Methodology

5.3.1 Calculation of total solar radiation

The total solar radiation was calculated using the ASHRAE model (ASHRAE 1999) as discussed in section 3.3.3. The calculations were done using Excel VBA (Visual Basic for Applications) code given in Appendix A1.1. The total solar radiation on all the surfaces (roof, north, south, east and west walls) was calculated for all the 365 days of the year from sunrise to sunset. From this the daily average solar radiation for each month was calculated. The calculations were validated by comparing the calculated values of average solar radiation on horizontal surface at New Delhi (Latitude: 28.58^0N, 77.2^0E) with the measured values (Nayak and Prajapati 2006) for the month of May. Then the total solar radiation at the considered geographical location, Pilani (Latitude: 28.25^0N Longitude: 75.65^0E) on all surfaces was calculated.

5.3.2 Monthly analysis of thermal performance

Based on the concepts discussed in section 5.2, the thermal performance of the four rooms described in chapter 4 was compared. The following assumptions were made for the calculations:

i. A clear sky atmosphere was considered
ii. Outside wind speed of 12 km/h was considered
iii. As the rooms were unoccupied there will be no internal heat gains
iv. As the windows were kept closed there will not be any ventilation.
v. The only heat loads contributing to the overall heat gain are the conduction and solar heat gain.

The daily average solar radiation on all surfaces was calculated. The radiation on windows due to shading by rectangular as well as designed static sunshade for east, west and south walls was calculated using the equations for shaded surface (as discussed in section 3.3.3). The calculations were done using Excel VBA (Visual Basic for Applications) code given in Appendix A1.2-A1.3. To calculate the shaded area of window due to the designed static sunshade, the curve was approximated as made of three straight lines for simplicity of calculations. The solar heat gain of all the windows of all the four rooms was calculated (refer section 5.2.3). The product *AU* was calculated for every building component of all the four rooms. The sol-air temperature was calculated using the daily average outdoor air temperature (Appendix A2) and the daily average solar radiation on the surface for every month. Then the conduction heat load of the rooms was calculated. The sum of conduction heat load and the solar heat gain gives the total heat load on the rooms R1, R2, R3 and R4. The thermal performance analysis was done based on this total heat load for every month throughout the year.

5.3.3 Thermal performance analysis on representative dates

The thermal performance of the rooms was also compared on representative critical dates in various seasons throughout the year. The seasonal classification was done on the basis of maximum and minimum values (as shown in Fig. 5.1) of the average hourly outdoor air temperature in each month throughout the year (April 2011 to March 2012). These average temperature values were used to classify months into various seasons as represented in Table 5.4. The indoor air temperature in the four rooms and outdoor air temperature was recorded at one hour intervals throughout the day for 24 hours. The methodology of the temperature measurements has been discussed in further details in chapter 6.

For each of the four seasons, viz. moderate summer, summer, moderate winter, winter, four dates were considered on the basis of outdoor air temperature as shown in Fig. 5.2. In each season, extreme and most frequently occurring temperature values were identified during the day and night. The day time was considered from 0600 - 1800 hours where as night time was considered from 1900 - 0500 hours. In moderate summer and summer, the highest temperature was taken as the extreme value, while in moderate winter and winter, the lowest temperature was taken as the extreme value. The extreme and most frequently occurring temperature values (mode) were identified by obtaining the frequency distribution of the outdoor air temperature. This frequency distribution was obtained with the software SPSS Statistics (IBM Corp. 2012?). If there was more than one mode, the one with highest value was considered for moderate summer and summer, while lowest value was taken for moderate winter and winter. In the case of mode, the date and time for which the direct normal radiation was highest was chosen. The conduction heat load and the solar heat gain of the four rooms was calculated at each of the extreme and mode temperature values in all the seasons during the day and night. The thermal performance analysis was done based on this total heat load in every season throughout the year.

5.4 Results and discussion

5.4.1 Calculation of total solar radiation

The total solar radiation was calculated using the ASHRAE model (ASHRAE 1999). The calculations were validated by comparing the theoretical values of average hourly solar radiation on horizontal surface at New Delhi (Latitude: 28.58^0N, 77.2^0E) with the measured values (Nayak and Prajapati 2006) for the month of May. Fig. 5.3 shows the theoretical and measured solar radiation values on a horizontal surface for New Delhi. The theoretical values vary slightly from the practical values. This can be attributed to the fact that a clear sky condition was considered always in the theoretical calculations, where as that may not be the case always.

The total solar radiation on all the surfaces (roof, north, south, east and west walls) at Pilani was calculated. Fig. 5.4 shows the daily average solar radiation on each surface in different months throughout the year. It was observed that the roof and south wall received more radiation as compared to the east and west walls. This is because the considered geographical location is in the northern hemisphere. The east and west walls received same amount of solar radiation as they received direct radiation in the forenoon and afternoon respectively. The north wall received the least amount of radiation as it is in shade for most of the time. Fig. 5.5 shows the percentage of solar radiation incident on each surface in different months throughout the year. In January, 33% solar radiation was incident on south wall, while in June it reduced to 13%.

5.4.2 Monthly analysis of thermal performance

The solar heat gain due to the windows on south, east and west walls were calculated for each room taking into account the effect of sunshades and are graphically represented in Fig. 5.6. As the windows, sunshades and their orientation were same for the rooms R2, R3 and R4, the solar heat gain for these three rooms was also same. It was observed that the solar heat gain of rooms R2, R3, R4 was more than that of room R1 from November to January, while it was less than that in room R1 in February, March, September, October. This may be attributed to the designed static sunshade over window on south walls of rooms R2, R3, R4, that let in more sunlight in moderate winter and winter and less in moderate summer. From April to August, the solar heat gain of all the rooms was same as the sunpath shifted towards the north and the designed static sunshade over window on south wall did not alter sunlight entry through the window as direct sunlight was not incident upon the south wall.

The product *AU* was calculated for every building component of all the four rooms as stated in Table 5.5. The product *AU* was maximum for rooms R1, R2 (117.54 W/ K) and least for room R4 (68.46 W/ K). This was due to the designed passive elements viz. brick cavity wall with brick projections and hollow roof. The detailed calculations are given in Appendix A3 (A3.1-3.4). The sol-air temperatures for different surfaces of each room were calculated and overall conduction heat load per room was determined for each month. The results are shown in Fig. 5.7. The conduction heat load of rooms R1, R2 was same as the building elements through which conduction heat load was calculated were same for both rooms. The conduction heat load of room R4 is least, while that of room R1 is maximum due to the combined effect of the designed passive elements.

The total heat load of all the rooms is shown in Fig. 5.8. The total heat load of room R2 was more than that of room R1 in winter months due to the effect of designed static sunshade. The brick cavity wall with brick projections helped to significantly lower total heat load of room R3 than that of room R2. Due to the effect of hollow roof, the heat load of room R4 was less than that of room R3 throughout the year. Due to the combined effect of designed passive elements, the heat load of room R4 was less than that of room R1.

5.4.3 Thermal performance analysis on representative dates

The outdoor air temperature frequency distribution for the day and night in the four seasons viz. moderate summer, summer, moderate winter, winter is shown in Appendix A4.1-A4.8. From this the mode and extreme values were extracted for each season and the total heat load was calculated. The total heat load on the rooms R1, R2, R3, R4 was calculated on four representative dates in the four seasons (Fig. 5.9-5.12). There were 7 mode value instances on different dates in summer. The most frequently occurring outdoor air temperature was 35.7^{0}C. The value of solar radiation was maximum on 28th May at 1300 hours and hence it was chosen for calculating the heat load. The heat load on room R4 with designed passive elements was least (2244.47 W) while it was maximum for room R1 (3498.64 W). In summer, the maximum outdoor air temperature (45.4^{0}C) occurred on 7th June at 1500 hours. Fig. 5.10 shows the total heat load on the four rooms during day for the extreme outdoor air temperature. The heat load on room R4 was least (2820.10 W). Similarly the heat load on all rooms was calculated for most frequently occurring and extreme temperature values as shown in Fig. 5.9-5.12. The total heat load for the most frequently occurring temperature during day (25.1^{0}C) and night (23.9^{0}C) in moderate summer was not calculated as the outdoor air temperature was well within the comfort temperature zone. It was observed that room R4 with designed passive elements gained minimum heat in summer and moderate summer, while it lost minimum heat in winter and moderate winter. This shows the effectiveness of the designed passive elements in insulating the room interiors from the extreme climatic conditions.

i.

Table 5.1 Values of surface heat transfer coefficient

S. No.	Wind speed	Position of surface	Direction of heat flow	Surface heat transfer coefficient (W/m^2K)
1	Still air	Horizontal	Up	9.3
		Sloping 45^0	Up	9.1
		Vertical	Horizontal	8.3
		Sloping 45^0	Down	7.5
		Horizontal	Down	6.1
2	Moving air (12 km/h)	Any position	Any direction	22.7
	Moving air (24 km/h)	Any position	Any direction	34.1

Source: Nayak and Prajapati 2006

Table 5.2 Recommended air change rates

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

Source: SP-41:1987 (Bureau of Indian Standards 1987)

Table 5.3 Heat production rate in a human body

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

Source: Nayak and Prajapati 2006

Table 5.4 Seasonal classification

Months	Seasonal classification
April, August, September	Moderate summer
May, June, July	Summer
October, November, March	Moderate winter
December, January, February	Winter

Table 5.5 Values of *AU* of rooms R1, R2, R3, R4

Room	*AU* (W/ K)
R1	117.54
R2	117.54
R3	87.65
R4	68.46

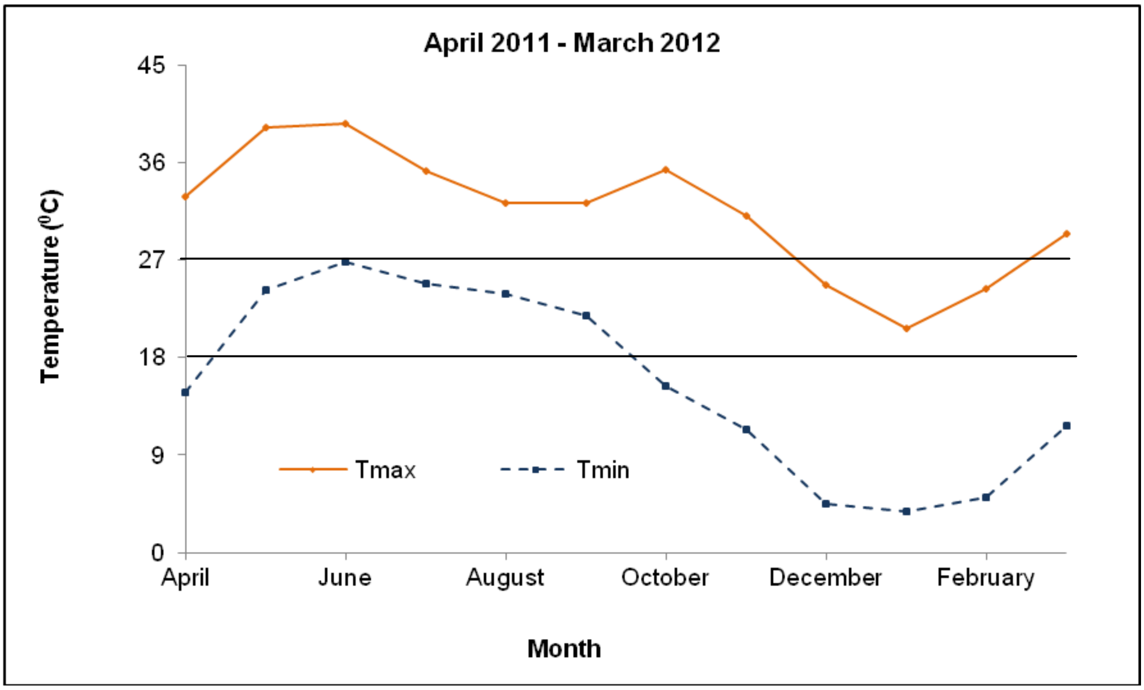


Fig. 5.1 Yearly temperature variation

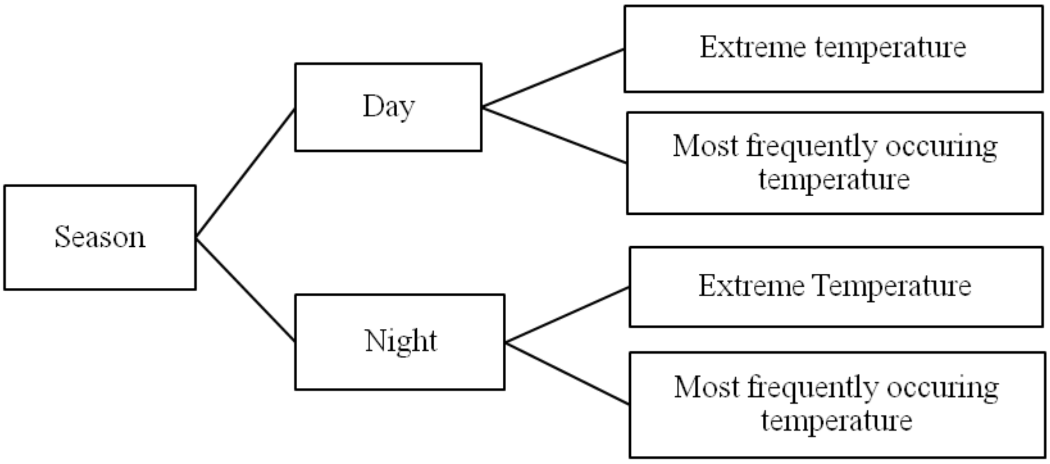


Fig. 5.2 Representative dates in every season

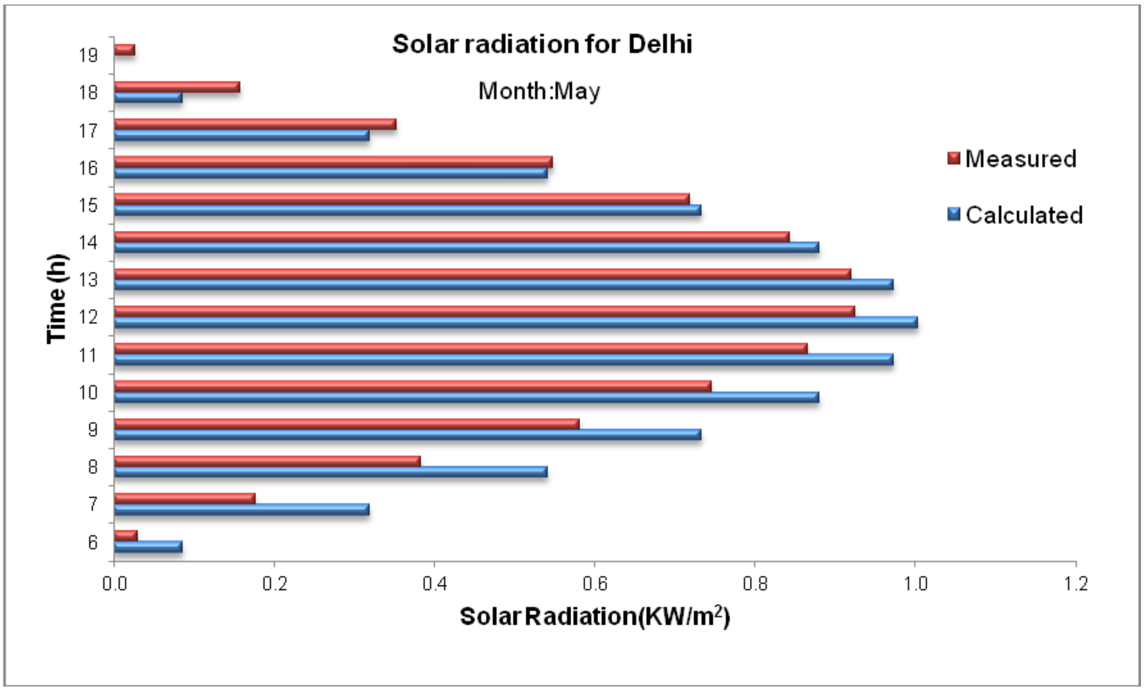


Fig. 5.3 Comparison of calculated and measured values of total solar radiation

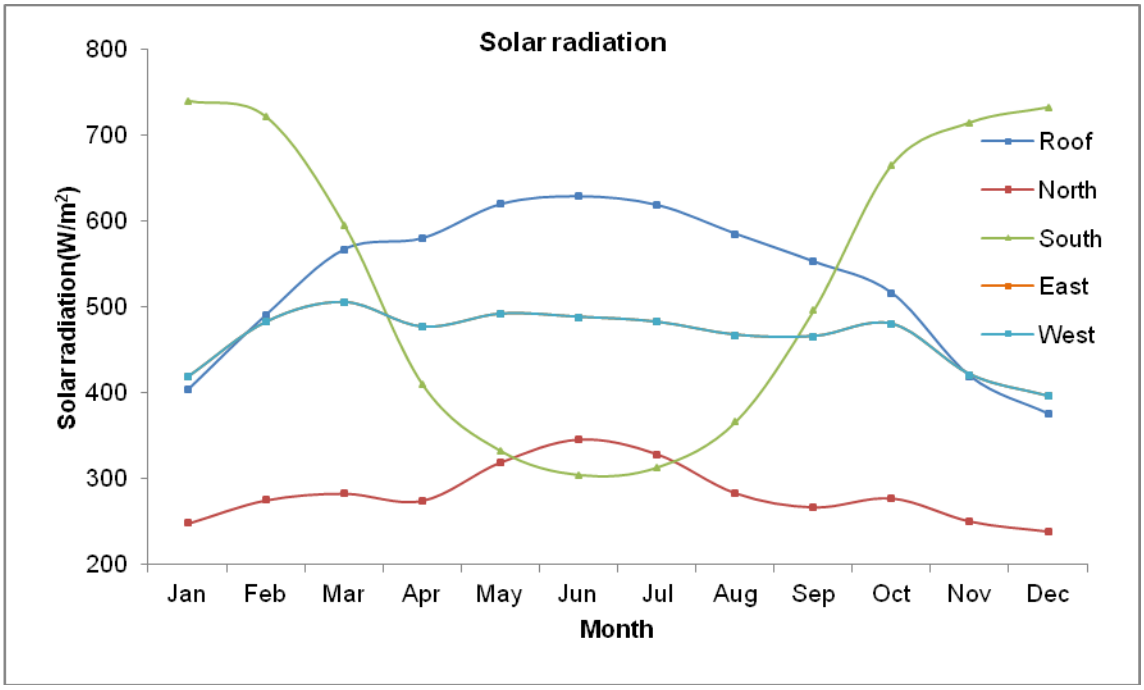


Fig. 5.4 Average solar radiation incident on different surfaces

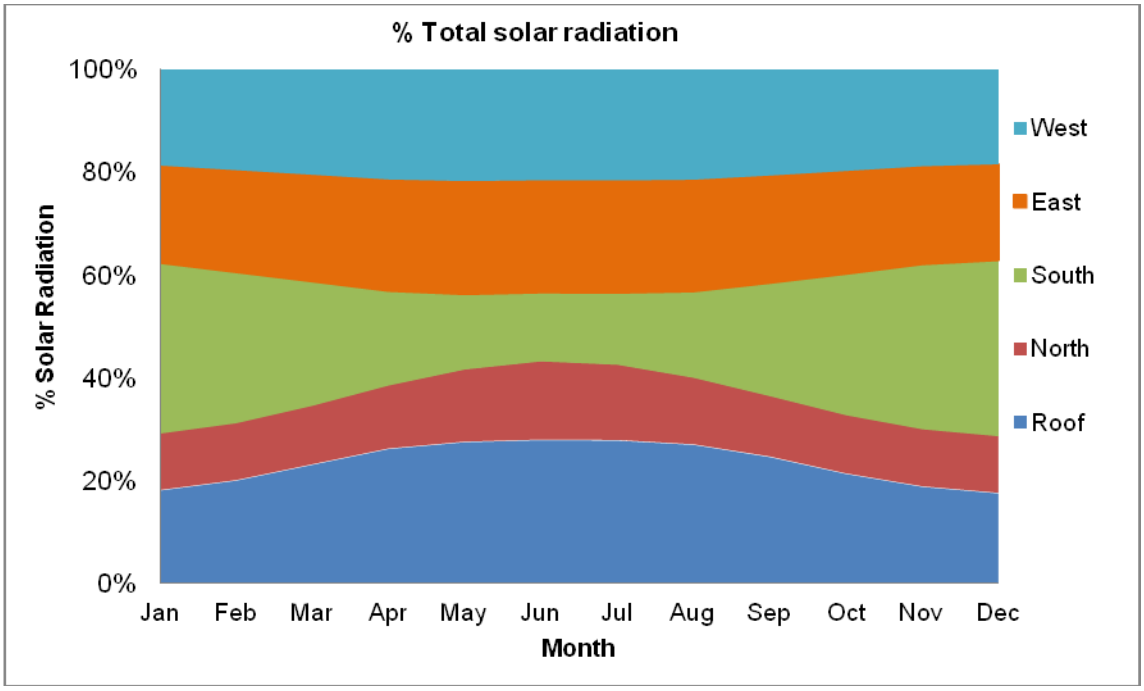


Fig. 5.5 Percentage total solar radiation incident on different surfaces

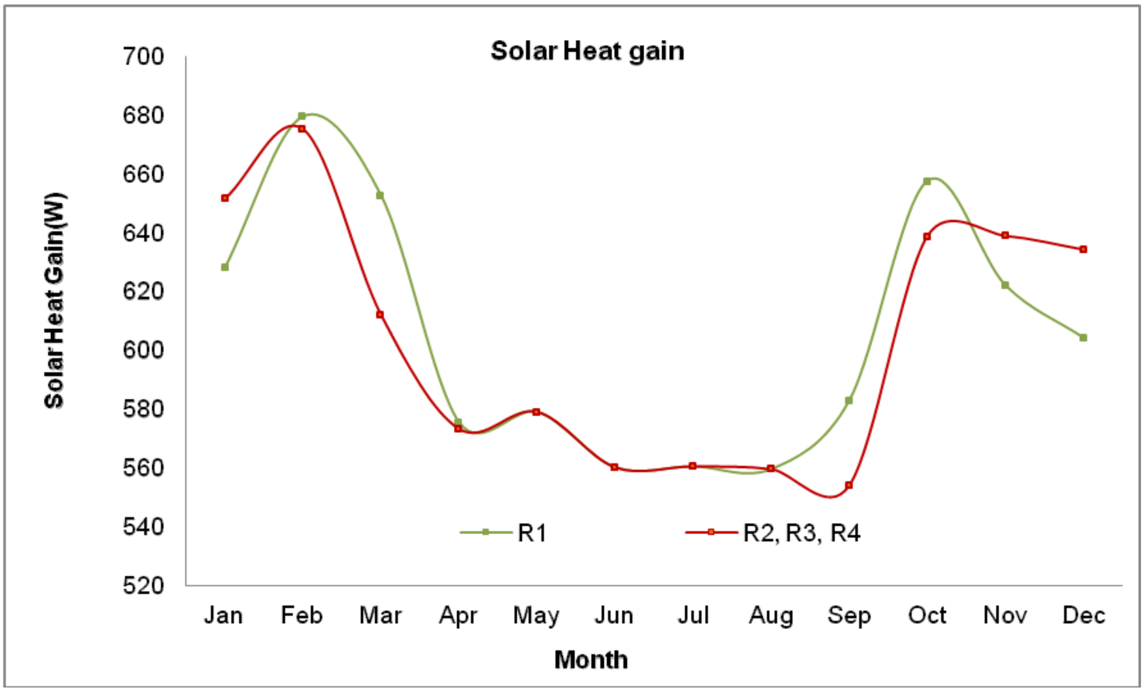


Fig. 5.6 Solar heat gain of rooms R1, R2, R3, R4

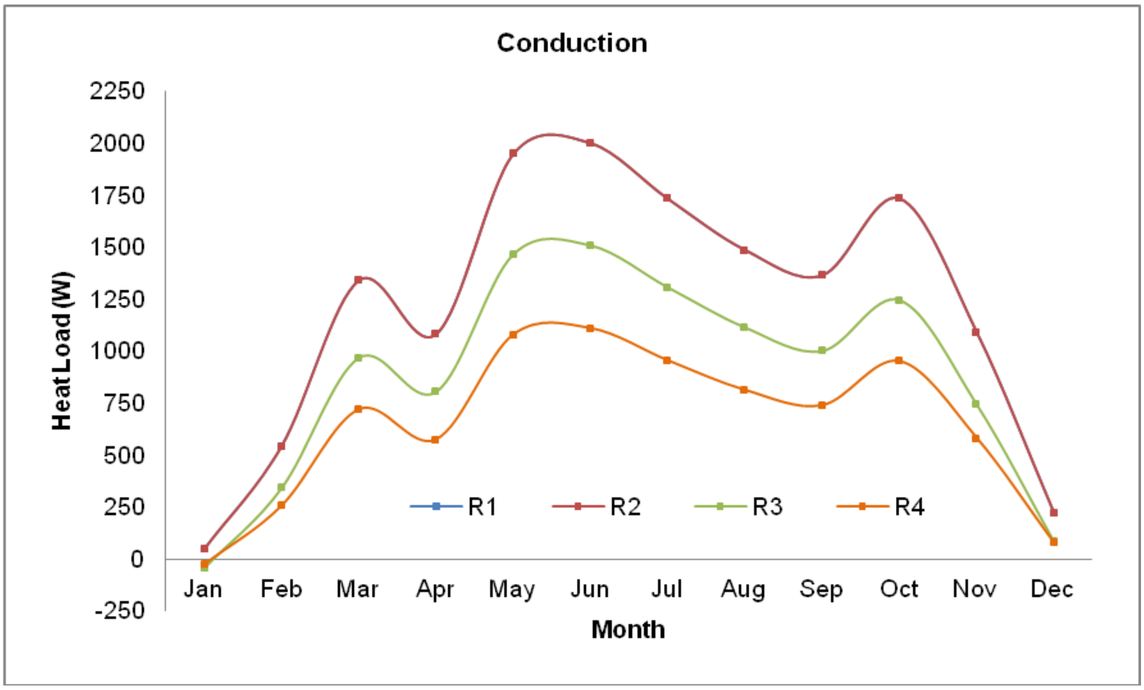


Fig. 5.7 Conduction heat load of rooms R1, R2, R3, R4

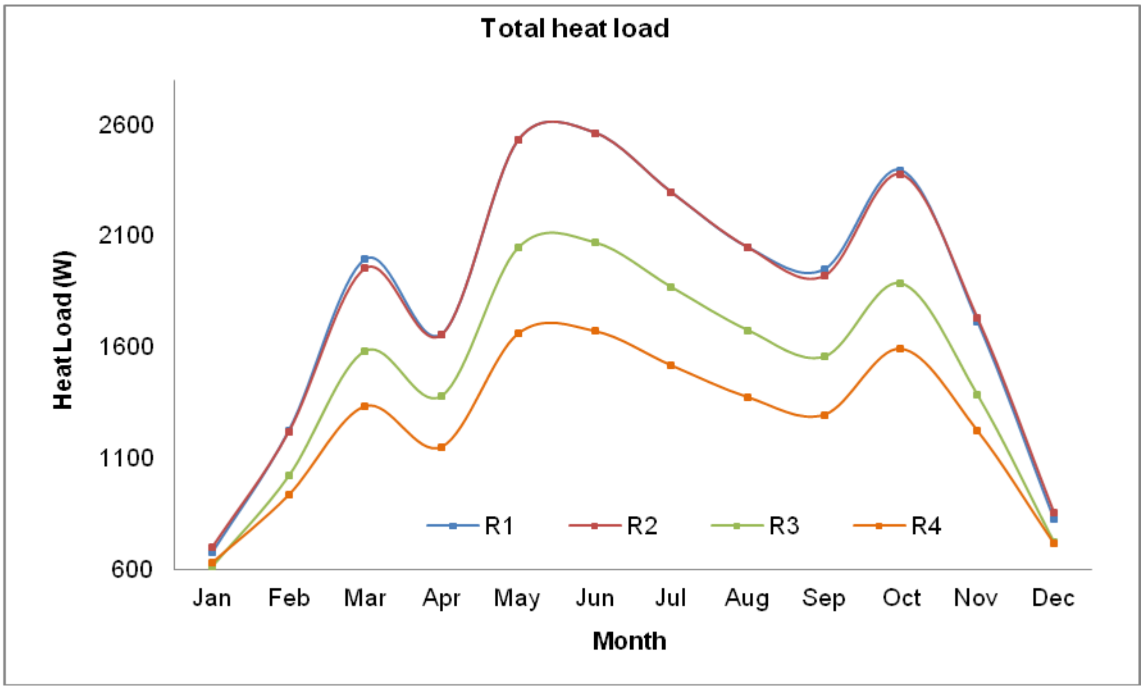


Fig. 5.8 Total heat load of rooms R1, R2, R3, R4

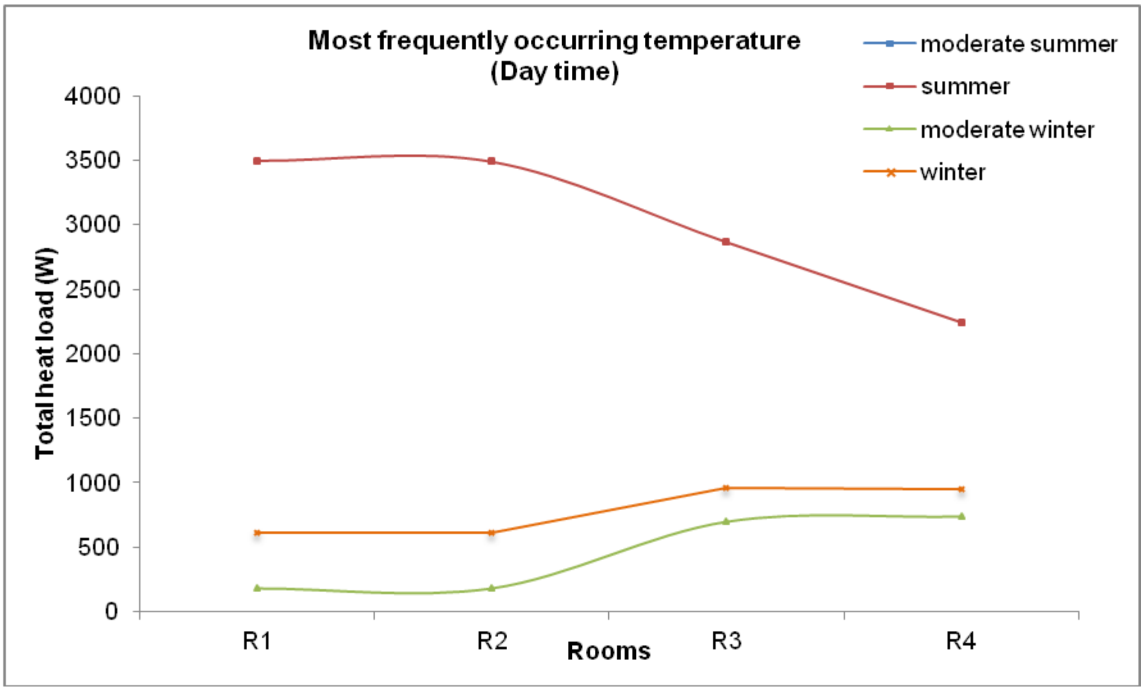


Fig. 5.9 Total heat load of rooms for most frequently occurring temperature (daytime)

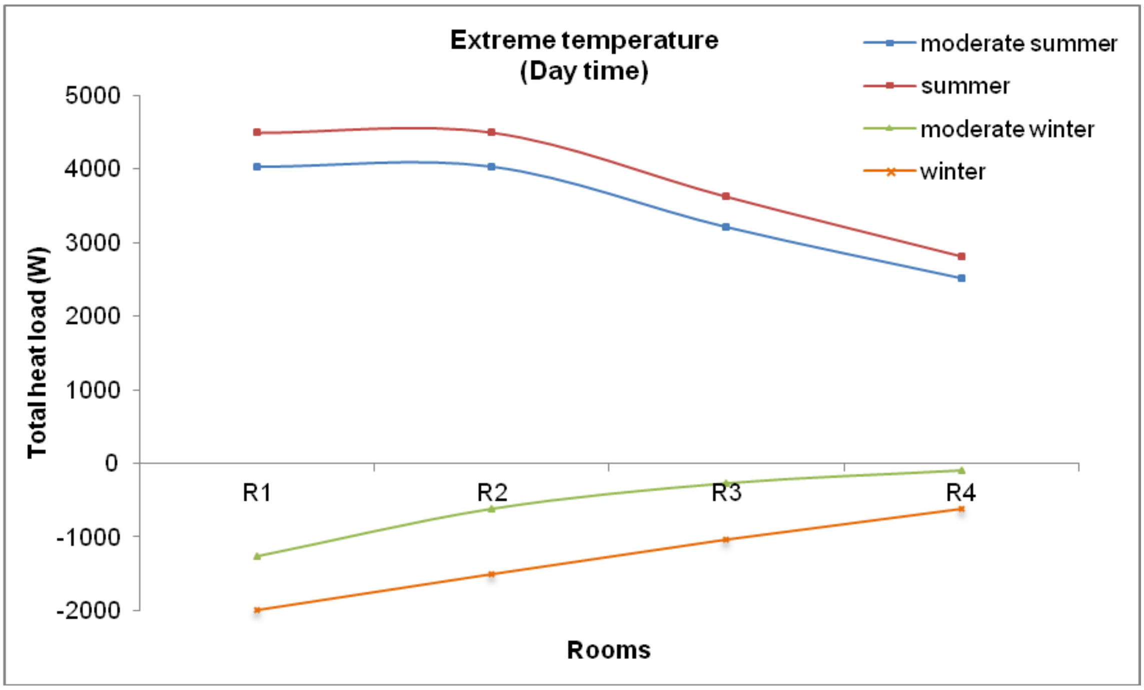


Fig. 5.10 Total heat load of rooms for extreme temperature (daytime)

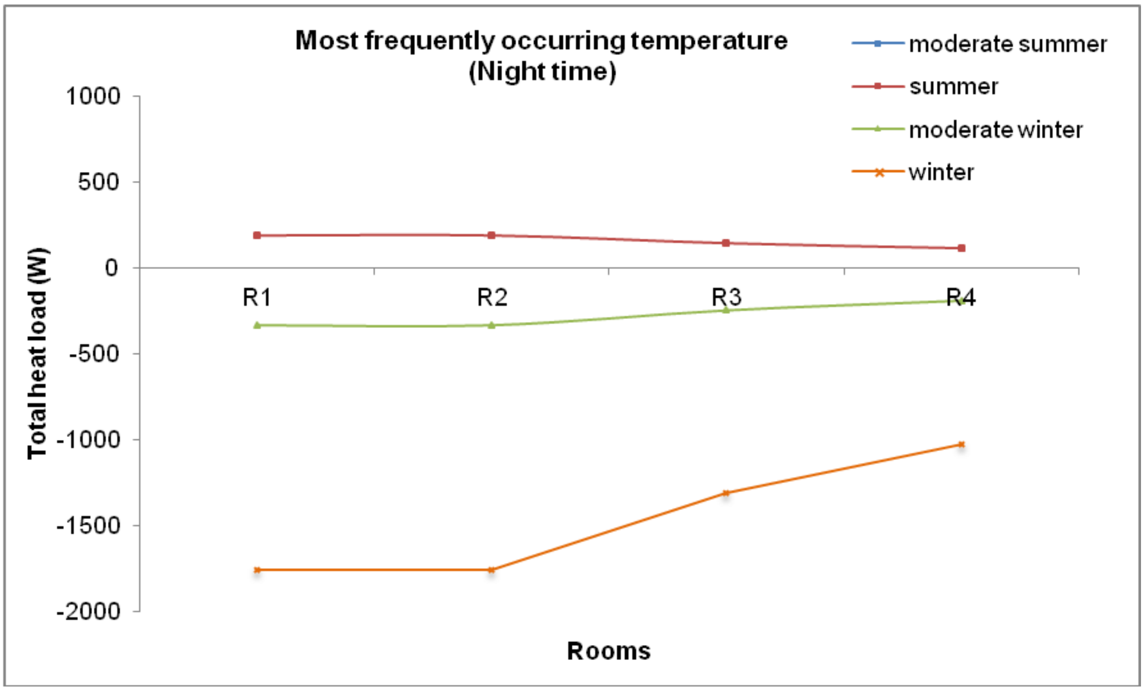


Fig. 5.11 Total heat load of rooms for most frequently occurring temperature (night time)

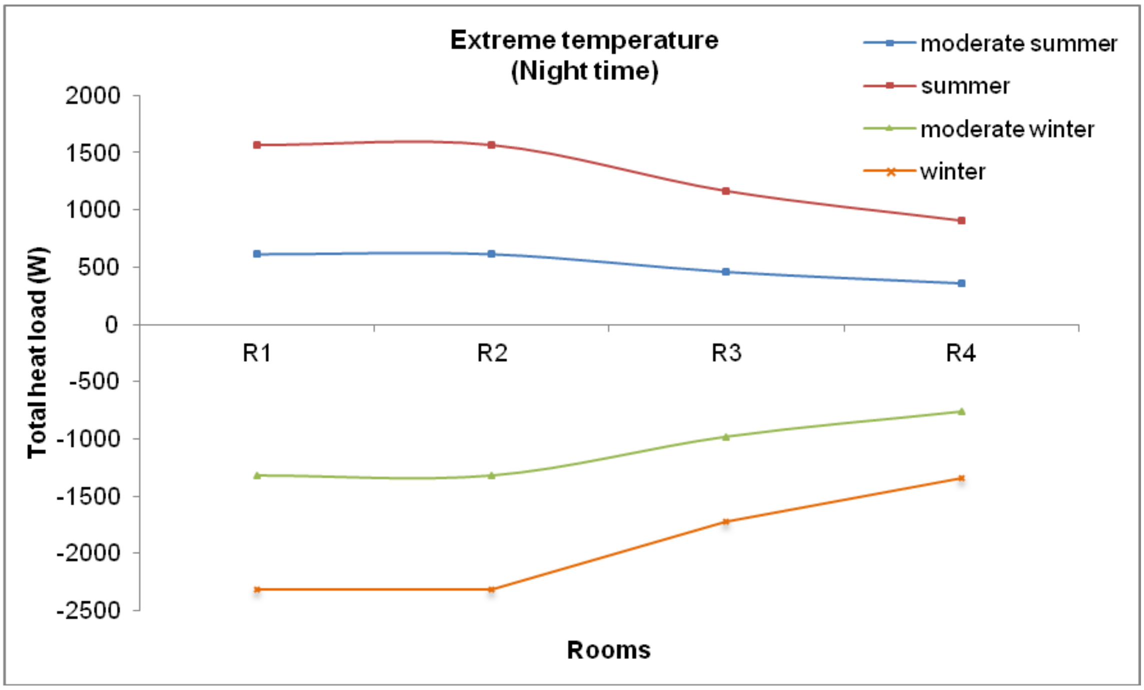


Fig. 5.12 Total heat load of rooms for extreme temperature (night time)

Chapter 6

Experimental Methodology

6.1 Introduction

The considered location for experimentation is in India, that has tropical climatic conditions and is broadly classified into five climatic zones as per National Building Code of India:2005 (Bureau of Indian Standards 2005). Tropical climate is characterized by significant hourly and large diurnal variations in temperature and sunshine that also vary considerably over the year. The experimentation has been carried out at Birla Institute of Technology and Science (BITS), Pilani (Latitude: 28.25^{0}N, Longitude: 75.65^{0}E), Rajasthan (India). It lies in the composite climate zone [National Building Code of India:2005 (Bureau of Indian Standards 2005)], which can further be classified mainly under summer and winter seasons (refer sec 3.2.2). To study the effect of designed static sunshade, brick cavity walls with brick projections and hollow roof (independently and combined with each other) on indoor air temperature, four test rooms (3.0m x 4.0m x 3.0m high) with different building elements, were constructed (as discussed in chapter 4) . The four rooms have same orientation and are exposed to similar conditions.

Room R1 has horizontal static sunshade, solid brick walls, solid reinforced cement concrete (RCC) roof, room R2 has designed static sunshade, solid brick walls, solid RCC roof, room R3 has designed static sunshade, brick cavity walls with brick projections, solid RCC roof, and room R4 has designed static sunshade, designed brick cavity walls with brick projections and hollow roof. There is a single window centrally located on each of the east, west and south walls and a centrally located door on the north wall of rooms R1, R2, R3, R4. All other design parameters for the four rooms are same. Hence the difference in indoor air temperature of the four rooms will mainly be due to difference in heat transferred through the designed static sunshade, brick cavity wall with brick projections and hollow roof.

Hourly room air temperature measurements were recorded with Global Water air temperature sensors WE700 (least count 0.1 ^{0}C) [Weather Sensor Manual, revised (Global Water Instrumentation Inc. 2009)] installed in the centre of room at the thermostat or desk level [Indoor Space Temperature Guidelines (Columbia University 2006)]. Hourly outdoor air temperature measurements were recorded with a Global Water air temperature sensor WE700 shielded from solar radiation with a solar shield WE 770 [Weather Sensor Manual, revised (Global Water Instrumentation Inc. 2009)]. All temperature sensors were connected to a Global Water GL500 data logger [GL500 Data Logger Manual (Global Water

Instrumentation Inc. 2006)] from which temperature readings were then stored on a computer.

The effect of various designed passive building elements on indoor air temperature was studied (independently and combined with each other), with and without ventilation of air cavity of the brick cavity walls with brick projections (by opening or closing air vents), with and without ventilation of all the rooms (by opening or closing windows). The methodology used for this comparison of room performance has been described in the following sections.

6.2 Room comparison without ventilation of rooms

Indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature was recorded every hour for one year from 1st April 2011 to 31st March 2012. The effectiveness of proposed static sunshade, brick cavity wall with brick projections, hollow roof (independently and combined with each other) and analysis of thermal performance has been done by studying monthly average values of hourly indoor air temperature in the four rooms, outdoor air temperature and area under curve outside comfort temperature zone (AUC_c). All readings were taken with windows and doors of the four rooms closed. Air vents in the brick cavity walls of rooms R3, R4 were kept open from April 2011 to October 2011 and they were kept closed from November 2011 to March 2012. The effectiveness of the designed static sunshade, brick cavity wall with brick projections, hollow roof have been compared with a horizontal static sunshade, solid brick wall and solid RCC roof respectively. The individual and combined effect of the designed passive building elements has been analyzed by comparing outdoor air temperature and indoor air temperature in the rooms as stated in Table 6.1.

6.3 Room comparison with ventilation of air cavity and without ventilation of rooms

Indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature was recorded every hour in summer from April 2012 to September 2012 from 1st to 15th day of every month. The effectiveness of ventilated brick cavity wall with brick projections (independently and combined with designed static sunshade and hollow roof) and analysis of thermal performance has been done by studying average values of hourly indoor air temperature in the four rooms and outdoor air temperature. Shutters of the air vents in the brick cavity walls of rooms R3, R4 were kept closed during daytime when outdoor air temperature was high to insulate the room. At night when the outdoor air temperature decreased, these shutters of vents were opened to facilitate ventilation of air in the wall cavity, to help in faster heat dissipation from the room. Comparison of outdoor air temperature and indoor air temperature in the four rooms and thermal load leveling (TLL), has been done to decide effectiveness of designed passive building elements. The thermal load leveling for a non-air conditioned room (Tiwari et al. 1994) can be expressed as (Eqn. 6.1):

$$TLL = \frac{T_{max} - T_{min}}{T_{max} + T_{min}} \quad \text{... (6.1)}$$

where,

T_{max}: maximum temperature

T_{min}: minimum temperature

The value of TLL should be minimum for the best load leveling along with reduced T_{max} and T_{min}. Effectiveness of ventilated brick cavity wall with brick projections (independently and combined with designed static sunshade and hollow roof) has been studied by comparing outdoor air temperature and indoor air temperature in the four rooms as stated in Table 6.2.

6.4 Room comparison with ventilation of air cavity and rooms

Indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature was recorded every hour in summer months from April 2012 to September 2012. The effectiveness of night ventilation and analysis of thermal performance has been done by studying average values of hourly indoor air temperature in the four rooms and outdoor air temperature. From 1st to 15th day of every month, windows and doors of the four rooms were kept closed. From 16th to 30th/31st day of every month, windows and doors of the four rooms were kept closed during the daytime when outdoor air temperature was high. At night when outdoor air temperature decreased, windows were opened to facilitate ventilation in the four rooms. Shutters of air vents in the brick cavity walls of rooms R3, R4 were kept closed during daytime and opened at night to facilitate ventilation of air in the wall cavity, and faster heat loss from the room throughout the study period from April 2012 to September 2012. Effect of night ventilation in each room has been analyzed by comparing indoor air temperature in it from 1st to 15th day of every month with indoor air temperature in the same room from 16th to 30th/31st day of that month. Thus effect of night ventilation has been studied in conventional room R1, room with designed static sunshade R2, room with designed static sunshade and brick cavity wall with brick projections R3 and room with designed static sunshade, brick cavity wall with brick projections and hollow roof R4.

Table 6.1 Room comparison without ventilation of rooms

Comparison of rooms	Effect of designed passive building elements
R1 and R2	Static sunshade
R2 and R3	Brick cavity wall with brick projections
R3 and R4	Hollow roof
R1 and R3	Combined effect of static sunshade and brick cavity wall with brick projections
R2 and R4	Combined effect of brick cavity wall with brick projections and hollow roof
R1 and R4	Combined effect of static sunshade, brick cavity wall with brick projections, hollow roof

Table 6.2 Room comparison with ventilation of air cavity and without ventilation of rooms

Comparison of rooms	Effect of designed passive building elements
R3 and R2	Ventilated brick cavity wall with brick projections
R3 and R1	Ventilated brick cavity wall with brick projections and designed static sunshade
R4 and R2	Ventilated brick cavity wall with brick projections and hollow roof
R4 and R1	Ventilated brick cavity wall with brick projections, designed static sunshade and hollow roof

Chapter 7

Results and Discussion

7.1 Introduction

The indoor air temperature in the four rooms and outdoor air temperature was recorded for one year from 1st April 2011 to 31st March 2012 at one hour intervals throughout the day for 24 hours. Fig. 5.1 represents maximum and minimum values of the average hourly outdoor air temperature in each month throughout the year (April 2011 to March 2012). These average temperature values were used to classify months into various seasons as represented in Table 5.4. The effectiveness of designed passive building elements (independently and combined with each other) and analysis of thermal performance has been done by studying variation of monthly average values of hourly indoor air temperature in the rooms R1, R2, R3, R4 and monthly average values of hourly outdoor air temperature with time (Fig. 7.1–7.12). For calculating the average hourly temperature, temperature values on days on which it rained and hence were not typical days of the month in summer and winter, have been excluded. The monthly average values of hourly indoor air temperature in the rooms R1, R2, R3, R4 and monthly average values of hourly outdoor air temperature have been given in a tabular form (Table A2.1-A2.12) in Appendix A2.

7.2 Room comparison without ventilation of rooms

Analysis of performance of the designed passive building elements has been done by studying variation of monthly average values of hourly indoor air temperature in the rooms R1, R2, R3, R4 and monthly average values of hourly outdoor air temperature with time from April 2011 to March 2012 (Fig. 7.1-7.12). AUC_c outside the comfort temperature zone for the four rooms has been obtained by integrating within specific time limits, using software Origin 8 (OriginLab, Northampton, MA) as stated in Table 7.1.

In April 2011 (Fig. 7.1) the maximum and minimum outdoor air temperature occurred earlier as compared to maximum and minimum indoor air temperature in all four rooms. Thus there was a time lag. There was a large variation (18^0C) in the outdoor air temperature while variation in indoor air temperature in rooms R1, R2, R3, R4 was 3.9^0C, 3.8^0C, 4.4^0C, 3.6^0C respectively. Thus all the rooms helped to reduce diurnal temperature swing. From 0300 hours to 1500 hours indoor air temperature in room R3 was less than that in rooms R1 and R2. After that, indoor air temperature in room R3 was more than that in rooms R1 and R2. The brick cavity wall with brick projections independently and combined with designed static sunshade was effective in lowering the minimum indoor air temperature. This may be attributed to the shadow cast by brick projections on the wall and open air vents in the brick cavity wall with brick projections of room R3 which caused cooling of air in the wall cavity at night. As these open air vents also caused heating of air in the wall cavity during day, indoor air temperature in room R3 was more than that in room R2 after 1600 hours till midnight. Indoor air temperature in room R4 was less than that in room R3 from 1200 hours to 0300 hours, while it was less than that in rooms R1, R2 throughout the day. Indoor air temperature in the four rooms varied between 24.3^0C to 28.8^0C. Thus the temperature curves were partly above and partly within comfort temperature zone (18^0C to 27^0C). AUC_c of room R4 was least (3.2^0C-h) while that of rooms R3, R2, R1 was 10^0C-h, 9.5^0C-h, 7.3^0C-h respectively as stated in Table 7.1. The hollow roof independently was effective to lower indoor air temperature for a major part of the day. This may be attributed to the insulating effect of proposed hollow roof during the hotter part of day. As the night progressed, this difference in indoor air temperature decreased as the roof radiated the stored heat into the room interiors and increased the indoor air temperature in room R4 in the early morning hours. While the hollow roof in combination with brick cavity wall with brick projections and designed static sunshade helped to keep indoor air temperature in room R4 less than that in room R1 throughout the day. Indoor air temperature was lowered by the brick cavity wall with brick projections in the early morning hours and afternoon, while it was lowered by the hollow roof in the afternoon and night. Their combined effect lowered indoor air temperature in room R4 throughout the day in room R4 as compared to that in room R1. The maximum, minimum indoor air temperature and swing in indoor air temperature was least in room R4 as compared to that in rooms R3, R2, R1. This was due to the effect of hollow roof independently and combined with static sunshade and brick cavity wall with brick projections on indoor air temperature.

In May 2011 (Fig. 7.2), indoor air temperature in rooms R1 and R2 was nearly same. The designed static sunshade being on the south wall and the sun being higher in the sky in summer, the static sunshade had a lesser effect on indoor air temperature. Indoor air temperature in room R3 was less than that in rooms R1 and R2 in the early morning hours and afternoon. After 1600 hours indoor air temperature in room R3 was more than that in rooms R1 and R2. The brick cavity wall with brick projections independently and combined with static sunshade helped to lower indoor air temperature in the early morning and afternoon. Indoor air temperature in room R4 was less than that in room R3 from 1300 hours to 2300 hours, while it was less than that in room R2 from 0600 to 1700 hours and room R1 from 1000 hours to 1900 hours. The hollow roof independently and combined with brick cavity wall with brick projections lowered indoor air temperature in room R4 as compared to that in rooms R3 and R2. From Table 7.1 it can be seen that, AUC_c of room R4 was less than that of rooms R3, R2, R1 by 2%, 2.9% and 2.6% respectively. The combined effect of designed static sunshade, brick cavity wall with brick projections and hollow roof helped to keep minimum indoor air temperature and swing in indoor air temperature in room R4 less than that in room R1.

In June 2011 (Fig. 7.3), rooms R1 and R2 showed similar indoor air temperature, while indoor air temperature in room R3 was less than that in room R2 from 0400 hours to 1700 hours. After that indoor air temperature in room R3 was more than that in room R2. Indoor air temperature in room R3 was less than that in room R1 throughout the day. Indoor air temperature in room R4 was less than that in rooms R1, R2 throughout the day, while AUC_c of room R4 was least (163.8^{0}C-h) as compared to that of rooms R3(168.8^{0}C-h), R2 (174.9^{0}C-h), R1 (180.7^{0}C-h) as stated in Table 7.1. In July 2011 (Fig. 7.4), indoor air temperature in rooms R1, R2 was nearly same, while the brick cavity wall with brick projections independently and combined with designed static sunshade lowered indoor air temperature in room R3 as compared to that in rooms R2, R1 throughout the day. Indoor air temperature in room R4 was less than that in rooms R1, R2 throughout the day, while AUC_c of room R4 was less than that of rooms R3, R2, R1 by 1.5%, 14.4% and 11% respectively due to the effect of hollow roof (independently and combined with designed static sunshade and brick cavity wall with brick projections).

In August 2011 (Fig. 7.5), as the season changed from summer to moderate summer (Table 5.4) all the rooms showed distinct indoor air temperatures throughout the day, which were more nearer to the maximum outdoor air temperature as compared to that in July and September. Indoor air temperature in room R2 was more than that in room R1 due to the effect of the designed static sunshade. The brick cavity wall with brick projections independently and combined with designed static sunshade lowered indoor air temperature throughout the day. The effect of hollow roof independently and combined with brick cavity wall with brick projections and designed static sunshade kept indoor air temperature in room R4 less than that in rooms R1, R2, R3 throughout the day except from 0300 hours to 12 noon when it was either same or more than that in room R3. It can be inferred that in August 2011, AUC_c of room R4 was less than that of rooms R3, R2, R1 by 2.9%, 20.3% and 14.7% respectively (Table 7.1). In September 2011 (Fig. 7.6), indoor air temperature in room R3 was less than that in rooms R2, R1 throughout the day. Indoor air temperature in room R4 was less than that in rooms R2, R1 throughout the day, except at 1700 hours when indoor air temperature in room R4 was more than that in room R1 due to direct sunlight incident on air temperature sensor, while indoor air temperature in room R4 was less than that in room R3 for a major part of the day. The AUC_c of room R4 was least (40.7^0C-h), while that of rooms R3, R2, R1 was 41.7^0C-h, 61.3^0C-h and 49.1^0C-h respectively (Table 7.1).

There was a sudden rise in indoor air temperature in the four rooms from May to July 2011 (Fig. 7.2-7.4) at 0800 hours, in August 2011 (Fig. 7.5) at 0700 hours and 1700 hours and in September 2011 (Fig. 7.6), at 1700 hours. This was due to direct sunlight incident on the air temperature sensor through the window on east and west walls.

In the summer months from May to July (Table 5.4), indoor air temperature in rooms R1 and R2 was nearly same. Indoor air temperature in room R3 was less than that in rooms R1 and R2 in early morning hours and afternoon. This difference was maximum in the morning duration from 0800 hours to 1200 hours. This may be attributed to the shadow cast by brick projections on the wall and open air vents in the brick cavity wall with brick projections of room R3 which caused cooling of air in the wall cavity at night. As these open air vents also caused heating of air in the wall cavity during day, indoor air temperature in room R3 was more than that in room R2 after 1800 hours till midnight. Maximum difference in indoor air temperature of rooms R4 and R3 was from 1600 hours to 2200 hours. This may be attributed to the insulating effect of proposed hollow roof during the hotter part of day. As the night progressed, this difference in indoor air temperature decreased as the roof radiated the stored heat into the room interiors and increased the indoor air temperature in room R4. The maximum indoor air temperature in room R4 was less than that in room R3 while the minimum indoor air temperature was nearly same. Thus temperature swing was less due to hollow roof. The combined effect of proposed hollow roof and designed brick cavity walls with brick projections helped to keep indoor air temperature in room R4 less than that in room R2 throughout the day in June and July, and for hotter part of the day in May. The difference in indoor air temperature of the two rooms was maximum at 0800 hours in June and July. This may be ascribed to the open air vents in the designed brick cavity wall with brick projections of room R4 which caused cooling of air in the wall cavity at night. The combined effect of proposed hollow roof, designed brick cavity walls with brick projections and static sunshade helped to keep the maximum and minimum indoor air temperature in room R4 less than that in room R1. The AUC_c of room R4 (Table 7.1) was least in the summer and moderate summer months (Table 5.4) indicating that indoor air temperature in room R4 was in the comfort temperature zone for the maximum duration. In the moderate summer months of April, August, September, maximum difference in indoor air temperature of rooms R4, R3 due to hollow roof was attained in the duration from 1600 hours to 2100 hours. This may be attributed to the insulating effect of proposed hollow roof during the hotter part of day. As the night progressed, this difference in indoor air temperature decreased as the roof radiated the stored heat into the room interiors and increased the indoor air temperature in room R4. The effect of hollow roof combined with only brick cavity wall with brick projections and both designed static sunshade and brick cavity wall with brick projections kept indoor air temperature in room R4 less than that in rooms R2, R1 throughout the day in the moderate summer months.

In October 2011 (Fig. 7.7), as the season changed to moderate winter, indoor air temperature in room R2 was more than that in rooms R1, R3 throughout the day. The combined effect of designed static sunshade and brick cavity wall with brick projections kept indoor air temperature in room R3 more than that in room R1 from 1500 hours to 0200 hours. Indoor air temperature in room R4 was less than that in rooms R3, R2, R1 throughout the day except for a short duration in the evening. The AUC_c of room R4 was less than that of rooms R3, R2, R1 by 38.6%, 65.1%, 19.2% respectively. In November 2011 (Fig. 7.8), the indoor air temperature in room R1 was less than that in rooms R2 and R3 throughout the day. The minimum indoor air temperature in room R3 was less than that in room R2, while maximum indoor air temperature in both rooms was nearly same. Indoor air temperature in all the rooms varied between 21.2^{0}C and 25.2^{0}C throughout the day which was in the comfort temperature zone.

In December 2011 (Fig. 7.9), the indoor air temperature in rooms R2, R3 was more than that in room R1 throughout the day due to the effect of designed static sunshade independently and combined with brick cavity wall with brick projections. Room R3 was warmer than room R2 from 1200 hours to 0300 hours. Indoor air temperature in room R4 was less than that in rooms R3, R2 throughout the day. The combined effect of designed static sunshade, brick cavity wall with brick projections and hollow roof kept indoor air temperature in room R4 more than that in room R1 in the morning and late night. The maximum indoor air temperature in room R4 was less than that in the other three rooms. The indoor air temperature in all the rooms varied between 14.7^{0}C to 19^{0}C. The temperature curves of all the rooms were partly below and partly within comfort temperature zone. The AUC_c of room R4 was maximum (39^{0}C-h) while that of rooms R3, R2, R1 was 20.1^{0}C-h, 21.8^{0}C-h, 38.3^{0}C-h respectively.

In January 2012 (Fig. 7.10), indoor air temperature in rooms R2 and R3 was more than that in room R1 throughout the day. The minimum indoor air temperature in room R3 was less than that in room R2, while maximum indoor air temperature in both rooms was nearly same. Room R4 had the least swing (2.4^0C) in indoor air temperature as compared to rooms R3, R2, R1. TheAUC_c of room R4 was 97.6^0C-h while that of rooms R3, R2, R1 was 77.2^0C-h, 79^0C-h, 95.2^0C-h respectively. In February 2012 (Fig. 7.11), the designed static sunshade independently and combined with brick cavity wall with brick projections kept indoor air temperature in rooms R2 and R3 more than that in room R1 throughout the day. Indoor air temperature in room R3 was more than that in room R2 from 1900 to 0200 hours. Indoor air temperature in room R4 was more than that in room R1 in the morning from 0800 hours to 1100 hours and from 2100 hours to midnight, while it was less than that in rooms R3, R2 throughout the day. TheAUC_c of room R4 was 35.8^0C-h while that of rooms R3, R2, R1 was 21.8^0C-h, 19.2^0C-h, 34.7^0C-h respectively. In March 2012 (Fig. 7.12), indoor air temperature in all the rooms varied between 20.9^0C and 26.8^0C which is in the comfort temperature zone, while outdoor air temperature varied between 11.7^0C to 30.5^0C.

Due to direct sunlight incident on the air temperature sensor through the window on west wall, there was a sudden rise in indoor air temperature in the four rooms at 1700 hours in October 2011 (Fig. 7.7), February 2012 (Fig. 7.11) and March 2012 (Fig. 7.12).

In the winter months (Table 5.4) from December to February, indoor air temperatures in the four rooms differed distinctly from each other from 1300 hours to 1800 hours. This shows that there was difference in response of the designed passive building elements when outdoor air temperature was maximum. In the winter months, indoor air temperature in room R1 was less than that in rooms R2 and R3 throughout the day. With closed air vents in the brick cavity wall with brick projections, room R3 was warmer than room R2 in the afternoon and late night. Maximum difference in indoor air temperature of rooms R2 and R3 was reached in the night duration from 2000 hours to 2100 hours. Although, room R3 had lower minimum indoor air temperature than that in room R2, the maximum indoor air temperature in room R3 was more i.e. room R3 was able to gain more heat as compared to room R2. Room R3 was warmer than room R1 throughout the day. This difference in indoor air temperature of rooms R1 and R3 was maximum in the night duration from 2000 hours to 2100 hours. The maximum and minimum indoor air temperature in room R4 was less than that in rooms R3, R2, R1 in all the winter months. Room R4 had the least swing in indoor air temperature as compared to rooms R3, R2 and R1. The proposed hollow roof independently and in combination with designed brick cavity wall with brick projections and static sunshade provided insulation to the room interiors, thereby resulting in lower indoor air temperature and reduced temperature swing in room R4. The combined effect of proposed hollow roof and designed brick cavity walls with brick projections kept indoor air temperature in room R4 less than that in room R2 throughout the day. The combined effect of proposed hollow roof, designed brick cavity walls with brick projections and static sunshade helped to keep the indoor air temperature in room R4 more than that in room R1in the morning duration from 0800 hours to noon and at night from 2100 hours to midnight. This may be ascribed to the designed static sunshade that let in the low early morning and late evening sunlight indoors. In the afternoon with the sun higher in the sky, the designed static sunshade played a lesser role in regulating indoor air temperature. Rooms R2, R3 had less AUC_c as compared to rooms R4, R1. Thus designed static sunshade and brick cavity wall with brick projections were effective in increasing indoor air temperature in winter. The AUC_c of room R4 was maximum in the winter months indicating that indoor air temperature in room R4 was below comfort temperature zone for the maximum duration. In the moderate winter months (Table 5.4) maximum difference in indoor air temperature of room R4 and rooms R3, R2, R1 was attained in the duration from 1400 hours to 1800 hours when outdoor air temperature was maximum. The relative performance of the designed passive building elements independently and combined with each other from April 2011 to March 2012 is presented in Table 7.2. They have been ranked according to their thermal performance with 1 being best. Performance of room R4 is best from April to October, performance of room R3 is best in December and January, while room R2 is best in February. In November and March indoor air temperature in all the rooms was in the comfort temperature zone and hence performance wise all have been classified as best.

7.3 Room comparison with ventilation of air cavity and without ventilation of rooms

The effectiveness of ventilated brick cavity wall with brick projections (independently and combined with designed static sunshade and hollow roof) and analysis of thermal performance has been done by studying variation of average values (for fifteen days of every month) of hourly indoor air temperature in the rooms R1, R2, R3, R4 and average values (for fifteen days of every month) of hourly outdoor air temperature with time (Fig. 7.13-7.18). These values are given in a tabular form in Appendix A2 (Table A2.13-A2.18). The values of TLL of the four rooms and outdoor air have been calculated using Eqn. 6.1 and are given in Table 7.3.

In April 2012 (Fig. 7.13) there was a large variation (17^0C) in the outdoor air temperature while variation in indoor air temperature in rooms R1, R2, R3, R4 was 3.7^0C, 3.7^0C, 4.7^0C, 3.6^0C respectively. The swing in indoor air temperature in room R3 was maximum as compared to the other three rooms R1, R2, R4. Indoor air temperature in room R3 was less than that in room R2 from 0100 to 1600 hours, while it was less than that in room R1 from 0800 to 1500 hours. The ventilated brick cavity wall with brick projections was effective to lower indoor air temperature after some time when the vents were opened in the evening and for a longer duration when vents were closed in the morning. When it was combined with static sunshade, it was effective to keep indoor air temperature lower for a part of the day when outdoor air temperature was high. Indoor air temperature in room R4 was less than that in rooms R2, R1 throughout the day. The ventilated brick cavity wall with brick projections in combination only with hollow roof and both static sunshade and hollow roof helped to keep indoor air temperature less throughout the day. The TLL for rooms R4 and R2 was minimum as shown in Table 7.3.

In May 2012 (Fig. 7.14), indoor air temperature in rooms R3, R4 was less than that in room R2 throughout the day. Indoor air temperature in room R3 was less than that in room R1 from 0400 to 1600 hours, while indoor air temperature in room R4 was less than that in room R1 from 0600 to 2000 hours. The ventilated brick cavity wall combined with designed static sunshade and hollow roof was effective in keeping indoor air temperature less for a longer time. The values of TLL for rooms R1, R2, R3, R4 were 0.043, 0.042, 0.051, 0.040 respectively. In June 2012 (Fig. 7.15), indoor air temperature in rooms R3, R4 was less than that in rooms R2, R1 for a lesser duration as compared to that in May 2012. The TLL was minimum for room R4 and maximum for room R1. In July 2012 (Fig. 7.16), indoor air temperature in rooms R3, R4 was less than that in rooms R2, R1 throughout the day except for two hours in the morning. The TLL was minimum for room R4 and maximum for room R3.

In August 2012 (Fig. 7.17), all the rooms showed distinct indoor air temperature throughout the day. The TLL was minimum for room R4. In September 2012 (Fig. 7.18), indoor air temperature in rooms R3, R4 was less than that in room R2 throughout the day. Indoor air temperature in room R3 was less than that in room R1 throughout the day except from 1900 to 2300 hours and at 0800 hours, while indoor air temperature in room R4 was less than that in room R1 throughout the day except at 0800 hours. The values of TLL for rooms R1, R2, R3, R4 were 0.052, 0.053, 0.054, 0.048 respectively. There was a sudden rise in indoor air temperature in the rooms from April to September 2012 in the morning (Fig. 7.13-7.18) and in April 2012 (Fig. 7.13) and September 2012 (Fig. 7.18) in the evening. This was due to direct sunlight incident on the air temperature sensor through the windows on east and west walls.

Indoor air temperature in room R3 was less than that in room R2 from 0100 to 1600 hours from April to June, and throughout the day from July to September, the difference being maximum in morning duration from 0700 to 1000 hours and minimum in the evening duration from 1800 to 0200 hours. This may be ascribed to the open air vents in the ventilated brick cavity wall with brick projections at night which caused cooling of air in the wall cavity. From April to June, indoor air temperature in room R3 was more (or same) than that in room R2 from 1700 to 0100 hours, when there was a larger difference (as compared to that from July to September) between the average indoor air temperature and minimum (or maximum) outdoor air temperature. At night when the outdoor air temperature decreased, heat loss in room R3 was slower than that in room R2. The maximum and minimum indoor air temperature in room R3 was less than that in room R2 throughout the study period except in April, when maximum indoor air temperature in room R2 was less than that in room R3 due to a sudden rise in indoor air temperature caused by direct sunlight incident on the air temperature sensor. The swing in indoor air temperature in room R3 was more than that in room R2 throughout summer. This may be ascribed to the open air vents in the ventilated brick cavity wall with brick projections at night which caused cooling of air in the wall cavity and also lowered the maximum and minimum indoor air temperature in room R3; the effect being more on the minimum rather than maximum indoor air temperature. TLL for room R3 was more than that of room R2 throughout the study period. Hence it cannot be exclusively used to judge thermal comfort inside.

The ventilated brick cavity wall with brick projections combined with static sunshade helped to keep indoor air temperature in room R3 less than that in room R1 for hotter part of the day in the study period and also at night from July to September. The ventilated brick cavity wall with brick projections combined with hollow roof was effective in keeping indoor air temperature in room R4 less than that in room R2 throughout the day in study period except in June nights when indoor air temperature in both rooms was nearly same. Their combined effect also kept maximum, minimum indoor air temperature and the swing in indoor air temperature in room R4 less than that in R2 throughout summer. The difference in indoor air temperature of the two rooms was maximum in the morning duration from 0700 to 0800 hours in April, May while it was maximum from 1200 to 1700 hours from June to September. The ventilated brick cavity wall with brick projections helped to lower the indoor air temperature in room R4 in the morning, while in the later months the hollow roof lowered the indoor air temperature when outdoor air temperature was maximum. The combined effect of ventilated brick cavity wall with brick projections, designed static sunshade and hollow roof helped to keep indoor air temperature in room R4 less than that in room R1 for hotter part of the day throughout the study period and also at night in April and from July to September. This difference was maximum in the afternoon duration from 1300 to 1800 hours. It also helped to keep maximum and minimum indoor air temperature in room R4 less than that in room R1 throughout the study period except in June when minimum indoor air temperature in room R1 was less than that in room R4. In June, as the outdoor air temperature was high, heat loss in room R4 was slower than that in room R1 and led to higher indoor air temperature in room R4 at nights. TLL of room R4 was less (shown in bold in Table 7.3) than that of rooms R1, R2, R3 throughout the study period indicating that combined effect of ventilated brick cavity wall with brick projections, designed static sunshade and hollow roof gave best load levelling and thermal comfort indoors. Due to the combined effect of the designed passive building elements, the swing in indoor air temperature in room R4 was less than that in room R1 throughout the study period in summer although there was a large variation in outdoor air temperature. The relative performance of the designed passive building elements independently and combined with each other from April 2012 to September 2012 is stated in Table 7.4. They have been ranked according to their thermal performance with 1 being best.

7.4 Room comparison with ventilation of air cavity and rooms

The effectiveness of night ventilation in conventional room, room with designed static sunshade, room with designed static sunshade and brick cavity wall with brick projections, room with designed static sunshade, brick cavity wall with brick projections and hollow roof and analysis of thermal performance was done by studying variation of average hourly indoor air temperature and average hourly outdoor air temperature. Average values of first fifteen days of every month of hourly indoor air temperature and average values of last fifteen days of the same month of hourly indoor air temperature in each room were studied with average values (separately for first and last fifteen days of every month) of hourly outdoor air temperature. The average values (for last fifteen days) of hourly indoor air temperature in the rooms R1, R2, R3, R4 and average values (for last fifteen days) of hourly outdoor air temperature have been given in a tabular form in Appendix A2 (Table A2.19-A2.24).

Fig. 7.19 shows average (for first fifteen days) hourly indoor air temperature [T(R1)] in conventional room R1 without night ventilation and average (for first fifteen days) hourly outdoor air temperature [T(Out)] in April 2012. These values are compared with average (for last fifteen days) hourly indoor air temperature [T(R1v)] in conventional room R1 with night ventilation and average (for last fifteen days) hourly outdoor air temperature [T(Outv)] denoted in the same Fig. 7.19. The indoor air temperature in conventional room with night ventilation was less than that in conventional room without night ventilation throughout the day. This difference in indoor air temperature of room with and without night ventilation was more at night when windows of the room were opened to facilitate night ventilation than during the daytime. This difference was maximum when the outdoor air temperature was minimum i.e. in the early morning from 0600 – 0700 hours. The variation in indoor air temperature in room without night ventilation was 3.7^0C, while that in room with night ventilation was 4.9^0C. There was a rapid decrease in the indoor air temperature in the room (with night ventilation) in evening when the windows were opened to facilitate night ventilation. Thus night ventilation was effective in increasing the heat loss from the room. Similarly when the windows were closed in the morning, there was a sudden rise in indoor air temperature. This was due to ventilation being stopped and an increase in the outdoor air temperature. The maximum and minimum indoor air temperature in room with night ventilation was less than that in room without night ventilation.

Fig. 7.20 shows average (for first fifteen days) hourly indoor air temperature [T(R2)] in room with designed static sunshade R2 without night ventilation and average (for last fifteen days) hourly indoor air temperature [T(R2v)] in the same room with night ventilation in April 2012. The maximum and minimum indoor air temperature in room with night ventilation was less than that in room without night ventilation. The swing in indoor air temperature in room with night ventilation was more than that in room without night ventilation. Similarly in room R3 (with designed static sunshade and ventilated brick cavity walls with brick projections) with night ventilation, the maximum and minimum indoor air temperature was less than that in same room without night ventilation in April 2012 as shown in Fig. 7.21. The swing in indoor air temperature in room with night ventilation was more than that in room without night ventilation. Same effect on indoor air temperature was also observed in room with designed static sunshade, ventilated brick cavity wall with brick projections and hollow roof R4 with night ventilation in April 2012 as shown in Fig. 7.22.

Comparison of the four rooms with each other along with effect of night ventilation (Table A2.19, Appendix A2) showed that individually, the designed passive building elements were able to reduce indoor air temperature in the rooms for a part of the day. Their combined effect was able to keep indoor air temperature in room R4 less than that in rooms R2 and R1 for the whole day in April 2012 (Fig. 7.19-7.22).

In May 2012 (Fig. 7.23-7.26), indoor air temperature in all rooms R1, R2, R3, R4 without night ventilation was less than that in the same rooms with night ventilation throughout the day. This may be ascribed to the maximum and minimum outdoor air temperature during the later part of the month that was higher (when windows of the four rooms were kept open at night to facilitate night ventilation) than that in first half of the month. This difference in indoor air temperature of the rooms reduced at night when night ventilation was facilitated, even though the difference in outdoor air temperature was more. In room R4, due to the combined effect of designed static sunshade, ventilated brick cavity wall with brick projections, hollow roof with night ventilation, the maximum indoor air temperature and swing in indoor air temperature was least as compared to that in rooms R3, R2, R1 with night ventilation (Table A2.20, Appendix A2).

In June 2012 (Fig. 7.27-7.30), indoor air temperature in all rooms R1, R2, R3, R4 without night ventilation was less than that in the same rooms with night ventilation during daytime. This may be ascribed to the higher outdoor air temperature during the later part of the month. However at night when the windows of the rooms were opened, the indoor air temperature in rooms with night ventilation was less than that in rooms without night ventilation. Amongst the four rooms with night ventilation (Table A2.21, Appendix A2), swing in indoor air temperature and maximum indoor air temperature was least in room R4 as compared to that in rooms R3, R2, R1.

In July 2012, indoor air temperature in all rooms with night ventilation was less than that in the same rooms without night ventilation (Fig. 7.31-7.34). This difference in indoor air temperature of room with and without night ventilation was more at night when windows of the rooms were opened to facilitate night ventilation than during the daytime. This difference was maximum when the outdoor air temperature was minimum i.e. in the early morning from 0600 – 0700 hours. In room R4, due to the combined effect of designed static sunshade, ventilated brick cavity wall with brick projections, hollow roof with night ventilation, the maximum indoor air temperature and swing in indoor air temperature was least as compared to that in rooms R3, R2, R1 with night ventilation (Table A2.22, Appendix A2).

In August 2012 (Fig. 7.35-7.38) as the outdoor air temperature reduced as compared to that in June, July, the difference in indoor air temperature of rooms with and without night ventilation increased. The maximum and minimum indoor air temperature in rooms with night ventilation was less than that in the same rooms without night ventilation. This may be ascribed to the maximum and minimum outdoor air temperature during the later part of the month that was lower (when windows of the four rooms were kept open at night to facilitate night ventilation) than that in first half of the month. Amongst the four rooms with night ventilation (Table A2.23, Appendix A2), swing in indoor air temperature and maximum indoor air temperature was least in room R4 as compared to that in rooms R3, R2, R1.

In September 2012, variations in outdoor air temperature in the later part of the month (when windows of the four rooms were opened to facilitate night ventilation) were more than those in the first part of the month (Fig. 7.39-7.42). The average maximum outdoor air temperature in the last fifteen days was more while average minimum outdoor air temperature was less than that during the first fifteen days of the month. Due to this the difference in indoor air temperature of rooms with and without night ventilation was less as compared to that in August 2012 (Fig. 7.35-7.38). This difference was maximum in the early morning hours when outdoor air temperature was minimum. As the outdoor air temperature increased, this difference reduced, and increased again in the evening after windows were opened to facilitate night ventilation. Amongst the four rooms with night ventilation (Table A2.24, Appendix A2), swing in indoor air temperature was minimum in room R1 and maximum and minimum indoor air temperature were least in room R3. There was a sudden rise in indoor air temperature in the rooms from April to July (Fig. 7.19-7.34) in the morning and in September (Fig. 7.39-7.42) in the evening. This was due to direct sunlight falling on the temperature sensors through windows on east and west walls.

In Table 7.5, summary of room performance with and without night ventilation in summer from April to September 2012 is given. It can be inferred that night ventilation was a good proposition in moderate summer months. While in the summer months, when the outdoor air temperature was high night ventilation was effective in reducing indoor air temperature at night. Effect of night ventilation on indoor air temperature in any room depends upon outdoor air temperature. Night ventilation was equally effective in all the rooms except in the moderate months of April and September 2012 when the effect of night ventilation was less in conventional room R1. The maximum indoor air temperature and swing in indoor air temperature was least in room R4 due to the combined effect of designed static sunshade, ventilated brick cavity wall with brick projections and hollow roof with night ventilation from May to August. In September and April, the swing in indoor air temperature was least in room R1. Maximum and minimum indoor air temperature was least in room R4 in April, while they were least in room R3 in September.

7.5 Design guidelines

Buildings are characterized by the climate in which they are located. Building envelopes provide the thermal divide between indoor and outdoor environment and play an important role in determining how effectively the building can utilize natural lighting, ventilation, heating and cooling resources. Thus, configuration and moulding of the built form and its surroundings can considerably minimize the level of discomfort inside a building, and reduce the consumption of energy required to maintain comfortable conditions (Nayak and Prajapati 2006). In the present study, performance of designed passive building elements like static sunshade, brick cavity wall with brick projections, hollow roof (independently and combined with each other) was analyzed. This section deals with the important findings of the work to propose guidelines vis-a-vis existing ones mentioned in Handbook on functional requirements of buildings [SP-41:1987 (Bureau of Indian Standards 1987)].

Exclusion of sun during day time is required. Sunlight penetration is desirable during winter. Adequate provision for air change and comfort ventilation in monsoon period is required. Building axis (that is, axis parallel to the longer side of the building) should fall East-West to minimize heat gains through walls in summer and maximize the same in winter. Location of rooms should be judiciously determined. Performance of horizontal, vertical, egg-crate and inclined louvers for different facades have been discussed in detail in the Handbook on functional requirements of buildings. Fenestrations having 15 to 20 percent of floor area should be used for ventilation and daylighting. Shutters, if used, should be capable of being closed tightly during summer days or winter nights. Shutters should be made of steel, aluminium or treated timber. Windows should be protected by external louvers, sun-breakers, etc. Internal shading like curtains, heat resistant glasses, double and painted glasses can also be used to avoid excessive solar heat penetration [SP-41:1987 (Bureau of Indian Standards 1987)]. *In the present study, the designed static sunshade over window on south wall was found to be effective in winter as compared to a horizontal sunshade. In summer due to higher altitude angle of the sun, it did not play a significant role in regulating indoor air temperature. Thus sunshade over window on south wall may be designed using solar angles to maximize solar entry in winter and thus increase heat gain. The generalized methodology may be used at any geographical location by selecting suitable cut off dates as per seasonal requirements.*

Walls should be constructed of bricks or similar locally available materials. The thickness of external wall should not be less than 22.5 cm. Heavy massive structures with thick walls and roof are preferred as compared to thin concrete walls and asbestos cement roof. The building materials used should satisfy the requirements of strength, water absorption and durability as prescribed in relevant Indian Standards. Cavity walls, hollow block can also be used. The empty air space can be filled with loose insulating materials to improve the thermal performance. Unexposed walls should be constructed of suitable building materials and their thickness should not be less than 11.15 cm. Precast concrete panels; hollow blocks and lightweight cellular concrete blocks can also be used. Partition walls should be constructed of brick or other suitable materials. Structural and noise reduction requirements should be given due consideration [SP-41:1987 (Bureau of Indian Standards 1987)]. *In the present study, the brick cavity wall with brick projections was found to be effective in lowering minimum indoor air temperature in summer and raising it in winter evening and night as compared to a heavy massive wall of the same thickness. Shading of the wall with optimum brick projections is an additional design aspect that can help to reduce heat gain in summer and also minimize shading in winter. Ventilation of the wall cavity in summer helped to lower maximum and minimum indoor air temperature in summer. Operable vents that can be opened to ventilate the air cavity (to help in faster heat loss in summer) or closed to stop the ventilation (and insulate the room interiors) can be effectively used as per seasonal requirements. In winter, the vents can be opened during daytime to ventilate the air cavity to help in faster heat gain and closed at night to insulate the room.*

Roof may be either a flat roof or sloping with asbestos cement. It should be of 10 cm RCC or reinforced brick cement (RBC) over which 7.5 cm thick mud phuska or cinder or any other equivalent insulting material is laid. It should be waterproofed with 7.5 cm of lime concrete or 5.9 cm of brick tiles or with 2 layers of tar felt according to relevant Indian

Standard. Sloping roof may be of either 6.0 mm asbestos cement sheets or of thatch or brick tile according to Indian Standards. In the asbestos cement sheets roof, false-ceiling should be provided to improve thermal performance. For false ceiling, 2.5 cm of wood-wool board or other equivalent insulating materials should be used. [SP-41:1987 (Bureau of Indian Standards 1987)]. *In the present study the hollow roof with stoneware pipes was effective in lowering maximum indoor air temperature and swing in indoor air temperature. Air cavity can be thus introduced in the roof with the hollow stoneware pipes to insulate the room interiors.*

The main problem in summer is to provide protection from sun's heat during day so as to keep the indoor temperature lower than that outside under the sun and for this purpose windows and other openings are generally kept closed and only minimum ventilation is provided for the control of odors or for removal of products of combustion [SP-41:1987 (Bureau of Indian Standards 1987)]. *In the present study night ventilation was found to be effective in lowering indoor air temperature throughout the day in moderate summer months. In the summer months, when the outdoor air temperature was high, night ventilation was effective in reducing indoor air temperature at night.*

The designed passive building elements may also be used in combination with each other, to obtain the additive effect of these building elements when used independently. The optimum combination may be chosen based on the seasonal requirements at the geographical location under consideration.

Other special needs like outdoor sleeping areas for summer nights are essential. Cooling of building during summer months by spraying water on roofs, white washing and shading is needed. Use of ceiling fans is most desirable. Desert coolers, should be used in summer, if required. Unit type room heaters are also needed during winter months.

Table 7.1 AUC_c of rooms R1, R2, R3, R4 from April 2011 to March 2012

Month	AUC_c (^{0}C-h)*			
	Room R1	**Room R2**	**Room R3**	**Room R4**
April 2011	7.3	9.5	10.0	3.2
May 2011	147.4	147.8	146.4	143.5
June 2011	180.7	174.9	168.8	163.8
July 2011	122.2	127.1	110.5	108.8
August 2011	75.3	80.6	66.1	64.2
September 2011	49.1	61.3	41.7	40.7
October 2011	13.0	30.1	17.1	10.5
November 2011	111.2	129.8	129.2	110.9
December 2011	38.3	21.8	20.1	39.0
January 2012	95.2	79.0	77.2	97.6
February 2012	34.7	19.2	21.8	35.8
March 2012	95.0	111.2	111.2	100.7

*AUC_c-Area under curve outside comfort temperature zone (18-27^{0}C)

Table 7.2 Relative performance* of designed passive building elements from April 2011 to March 2012

Month	Designed static sunshade (R2 and R1)	Brick cavity wall with brick projections (R3 and R2)	Hollow roof (R4 and R3)	Designed static sunshade + brick cavity wall with brick projections (R3 and R1)	Brick cavity wall with brick projections + hollow roof (R4 and R2)	Designed static sunshade + brick cavity wall with brick projections + hollow roof (R4 and R1)
April 2011	5	3	3	4	1	2
May 2011	5	3	3	4	2	1
June 2011	4	6	5	3	2	1
July 2011	6	2	5	4	1	3
August 2011	6	2	5	4	1	3
September 2011	6	1	5	3	1	2
October 2011	6	2	3	5	1	4
November 2011	-	-	-	-	-	-
December 2011	2	3	6	1	5	4
January 2012	2	3	6	1	5	4
February 2012	1	2	4	1	4	3
March 2012	-	-	-	-	-	-

***** The designed passive building elements have been ranked according to their thermal performance with 1 being best.

-Indoor air temperature in all rooms was in the comfort temperature zone and hence all the designed passive building elements created a thermally comfortable indoor environment

Table 7.3 Thermal load leveling of rooms R1, R2, R3, R4 and outdoor air

Month		Room R1	Room R2	Room R3	Room R4	Outdoor air
April 2012	T_{max} (^{0}C)	31.7	32.1	32.6	31.3	36.3
	T_{min} (^{0}C)	28.0	28.4	27.9	27.8	19.3
	TLL	0.062	0.061	0.077	**0.061**	0.306
May 2012	T_{max} (^{0}C)	32.7	32.9	32.8	32.4	38.5
	T_{min} (^{0}C)	30.0	30.3	29.7	29.9	22.5
	TLL	0.043	0.042	0.051	**0.040**	0.261
June 2012	T_{max} (^{0}C)	37.4	37.5	37.3	37.0	40.6
	T_{min} (^{0}C)	33.4	34.4	33.9	34.3	26.7
	TLL	0.056	0.043	0.048	**0.038**	0.206
July 2012	T_{max} (^{0}C)	36.0	36.0	35.7	35.4	37.0
	T_{min} (^{0}C)	33.7	33.8	33.2	33.6	27.1
	TLL	0.033	0.031	0.036	**0.026**	0.155
August 2012	T_{max} (^{0}C)	32.8	32.9	32.6	32.1	33.5
	T_{min} (^{0}C)	30.4	30.6	30.1	30.2	24.8
	TLL	0.038	0.036	0.040	**0.031**	0.148
September 2012	T_{max} (^{0}C)	31.8	32.3	31.5	31.1	31.3
	T_{min} (^{0}C)	28.7	29.0	28.3	28.3	23.7
	TLL	0.052	0.053	0.054	**0.048**	0.138

Legend: T_{max}-Maximum temperature; T_{min}-Minimum temperature; TLL-Thermal load levelling; values in bold indicate lowest TLL values for each month

Table 7.4 Relative performance of designed passive building elements from April 2012 to September 2012

Month	Ventilated brick cavity wall with brick projections (R3 and R2)	Ventilated brick cavity wall with brick projections + designed static sunshade (R3 and R2)	Ventilated brick cavity wall with brick projections + hollow roof (R4 and R2)	Ventilated brick cavity wall with brick projections + designed static sunshade + hollow roof (R4 and R1)
April 2012	3	4	1	2
May 2012	2	3	1	4
June 2012	2	3	1	3
July 2012	1	2	3	4
August 2012	3	4	1	2
September 2012	2	4	1	3

* The designed passive building elements have been numbered in the ascending order according to their performance with 1 denoting the best room in terms of thermal comfort

Table 7.5 Summary of room performance with and without night ventilation from April 2012 to September 2012

Month	Room R1		Room R2		Room R3		Room R4	
	WNV	NV	WNV	NV	WNV	NV	WNV	NV
April 2012		√		√		√		√
May 2012	√		√		√		√	
June 2012	√	√	√	√	√	√	√	√
July 2012		√		√		√		√
August 2012		√		√		√		√
September 2012		√		√		√		√

Legend: WNV-without night ventilation; NV-with night ventilation; √-room is better

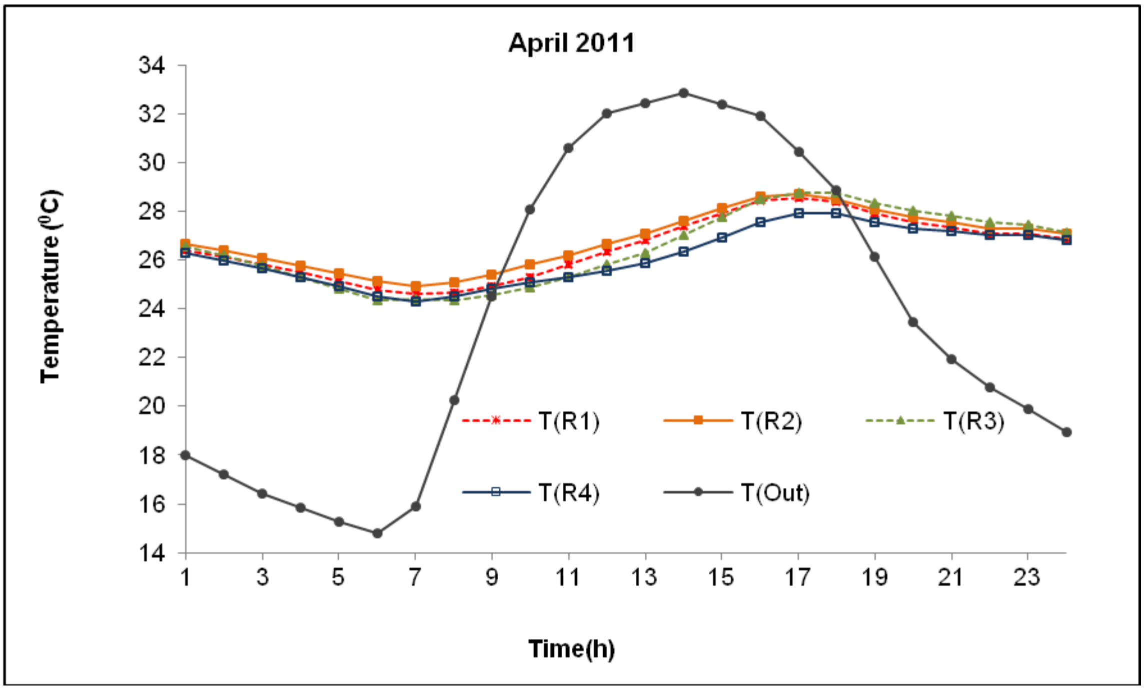


Fig. 7.1 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in April 2011

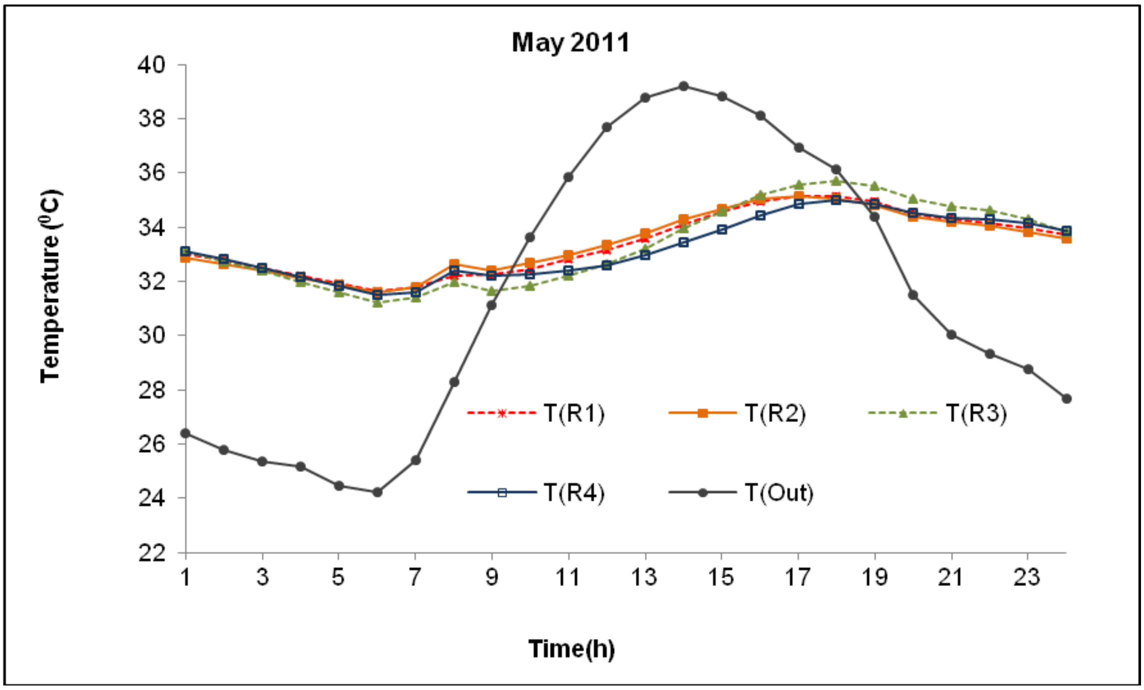


Fig. 7.2 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in May 2011

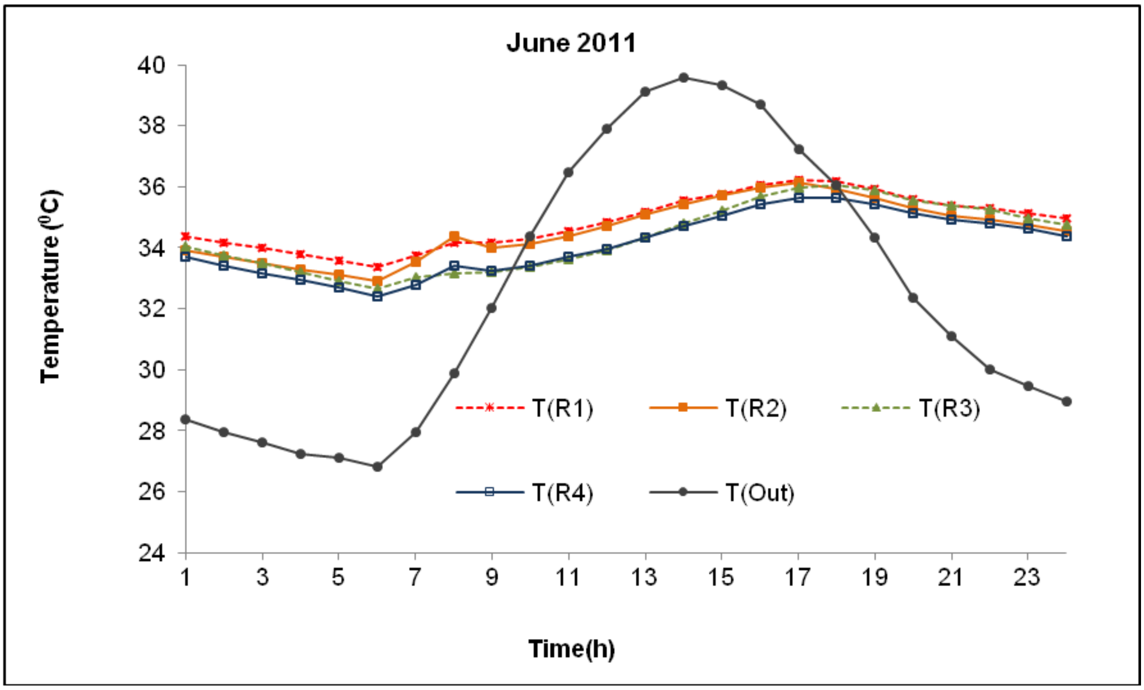


Fig. 7.3 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in June 2011

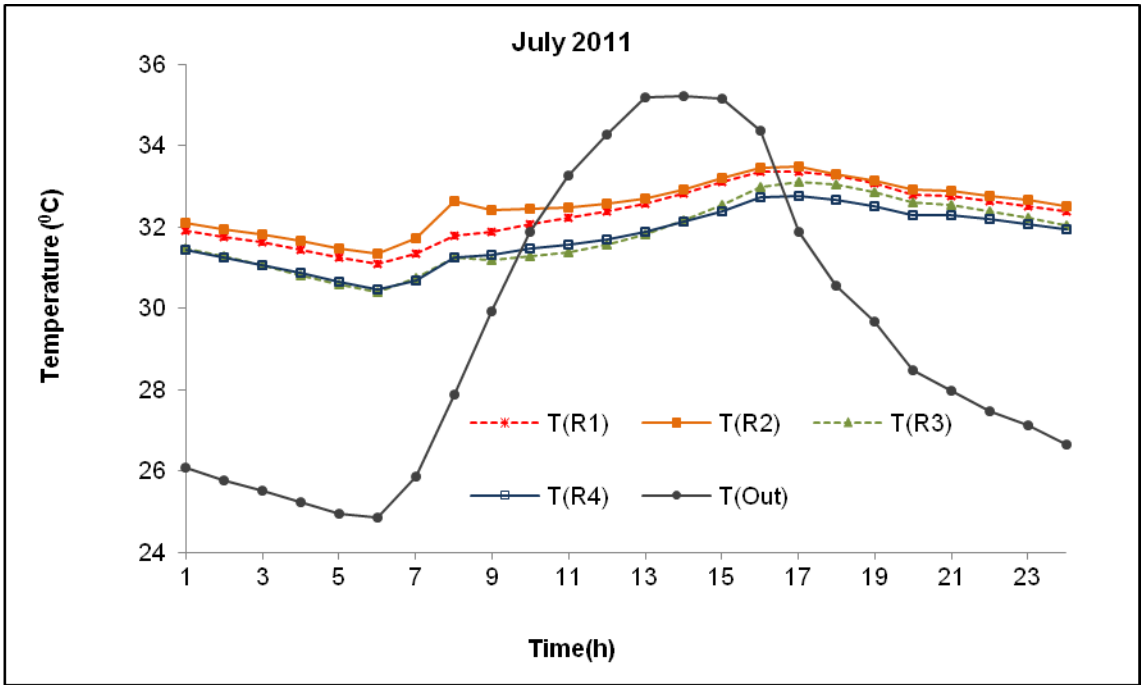


Fig. 7.4 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in July 2011

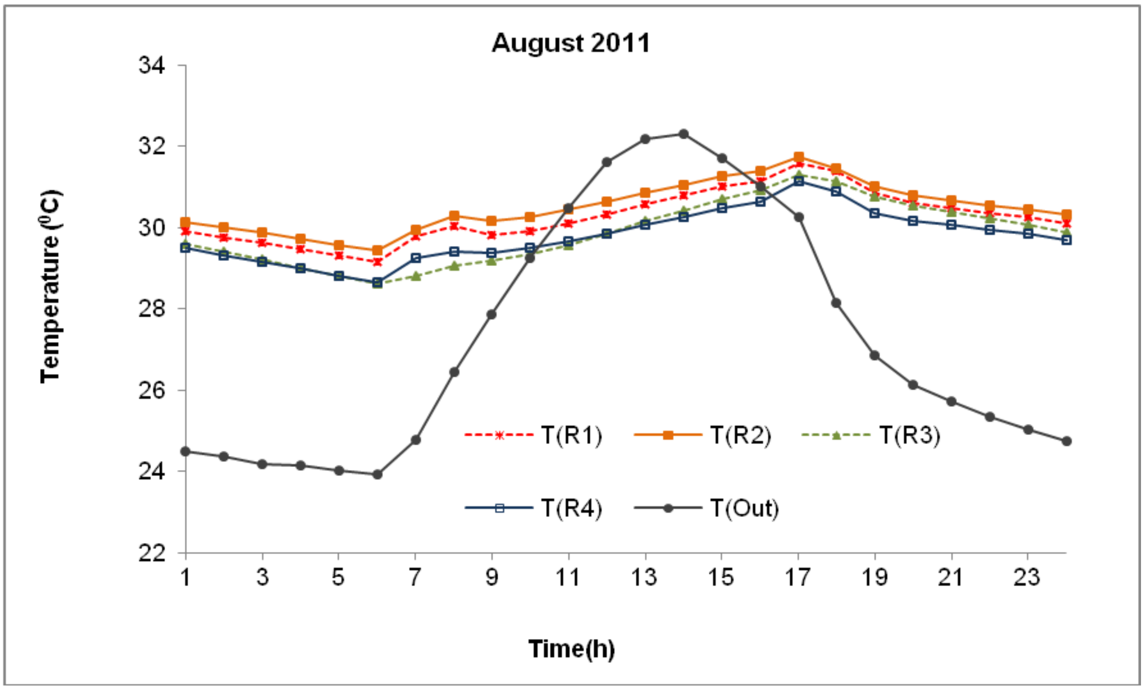


Fig. 7.5 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in August 2011

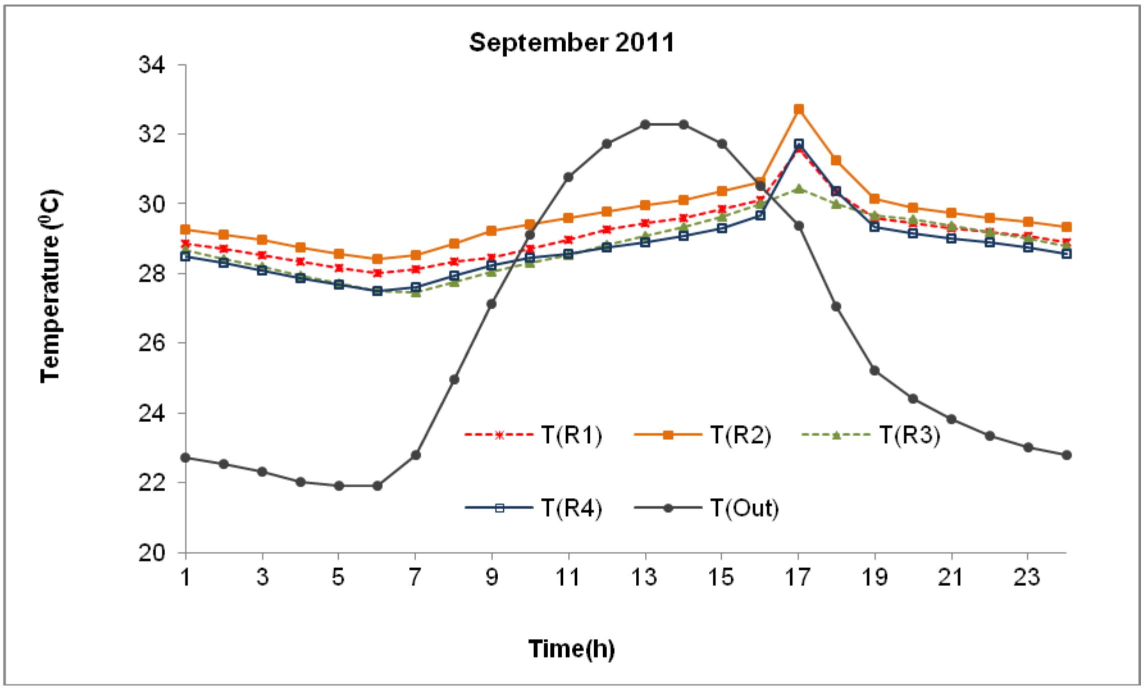


Fig. 7.6 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in September 2011

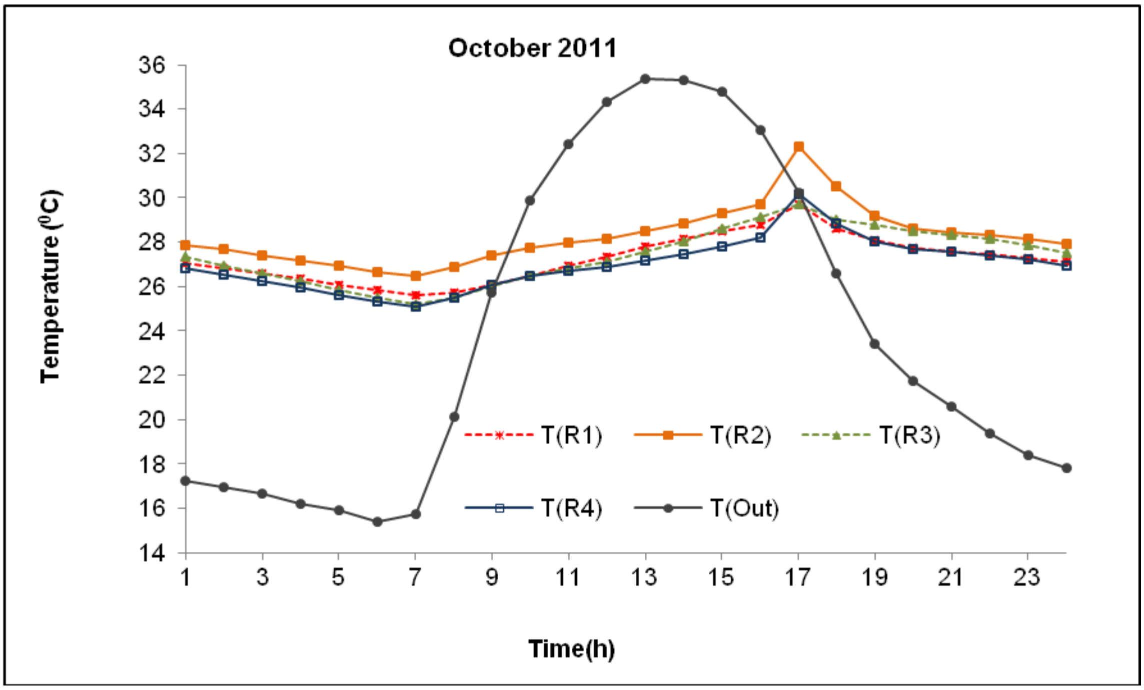


Fig. 7.7 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in October 2011

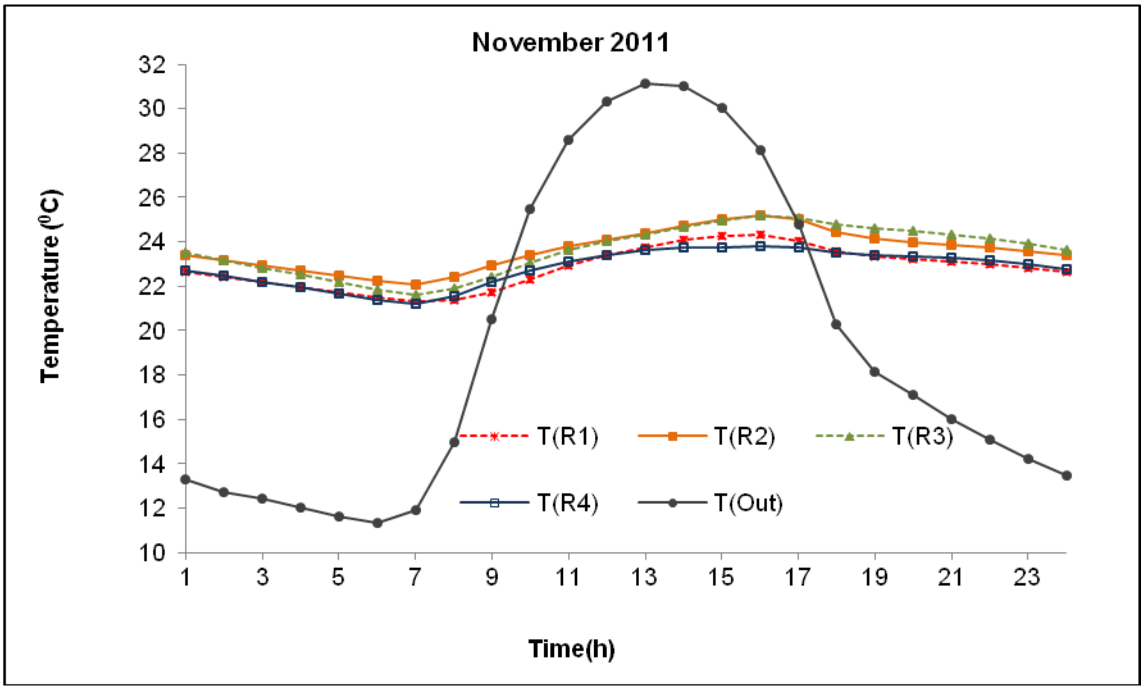


Fig. 7.8 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in November 2011

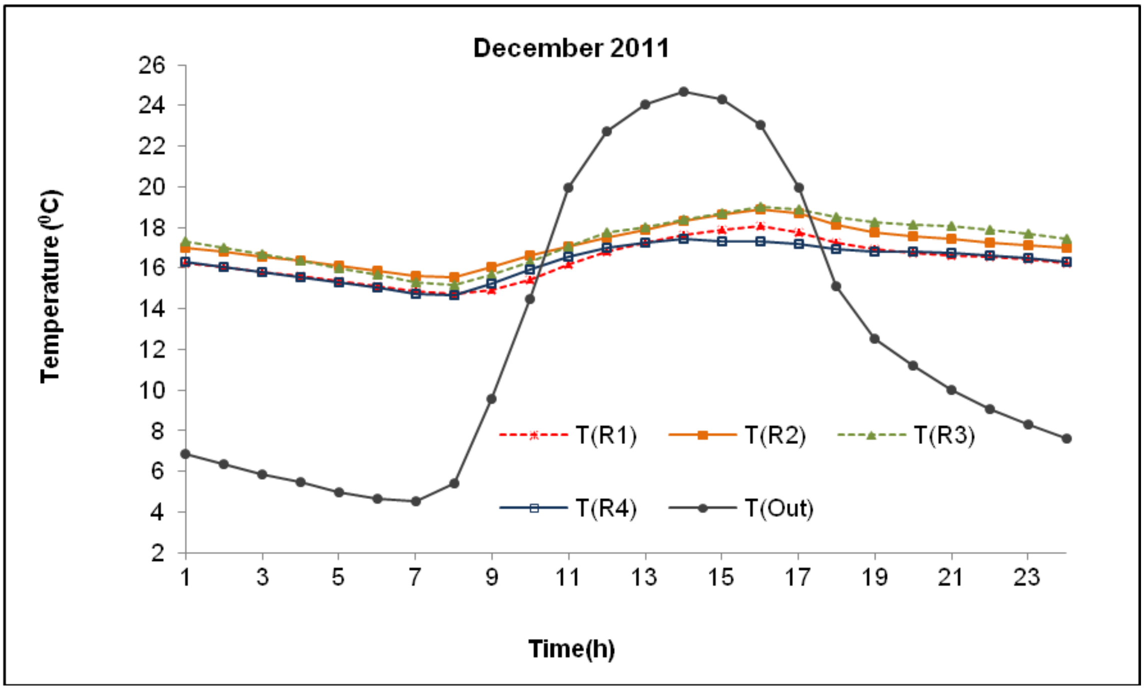


Fig. 7.9 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in December 2011

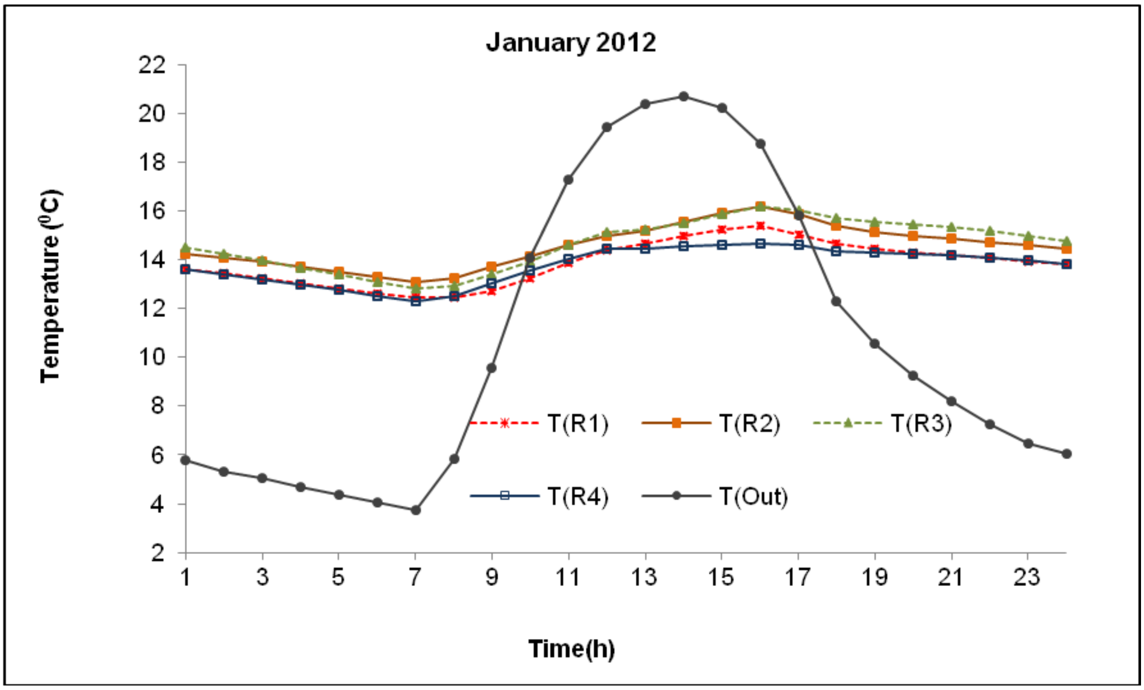


Fig. 7.10 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in January 2012

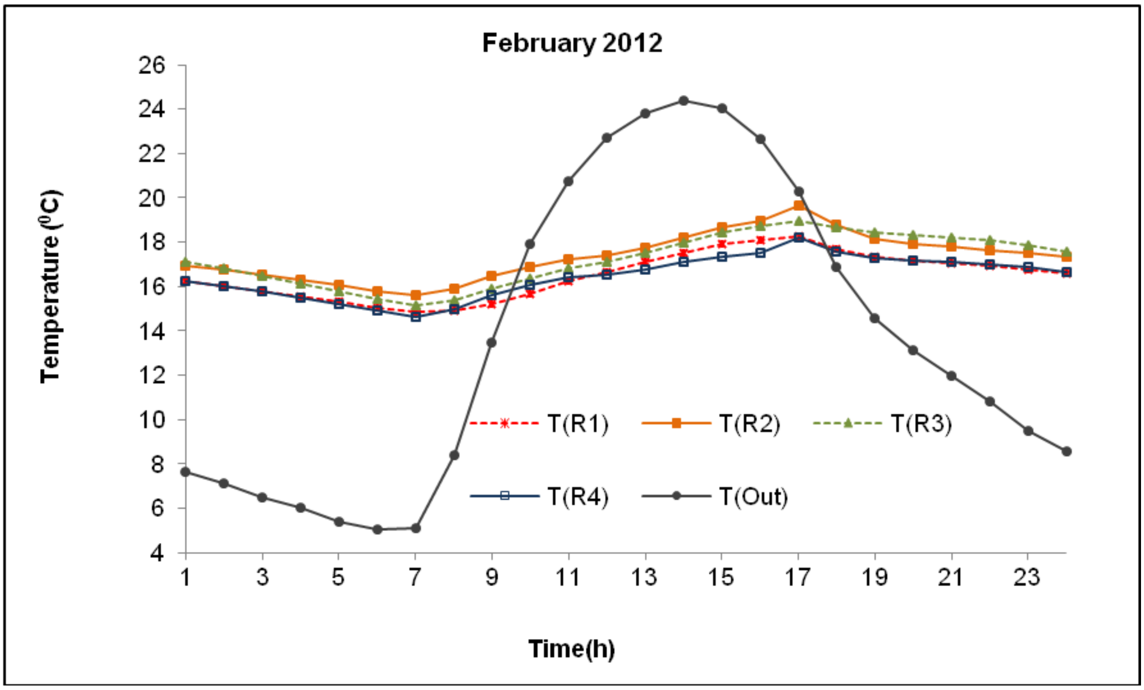


Fig. 7.11 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in February 2012

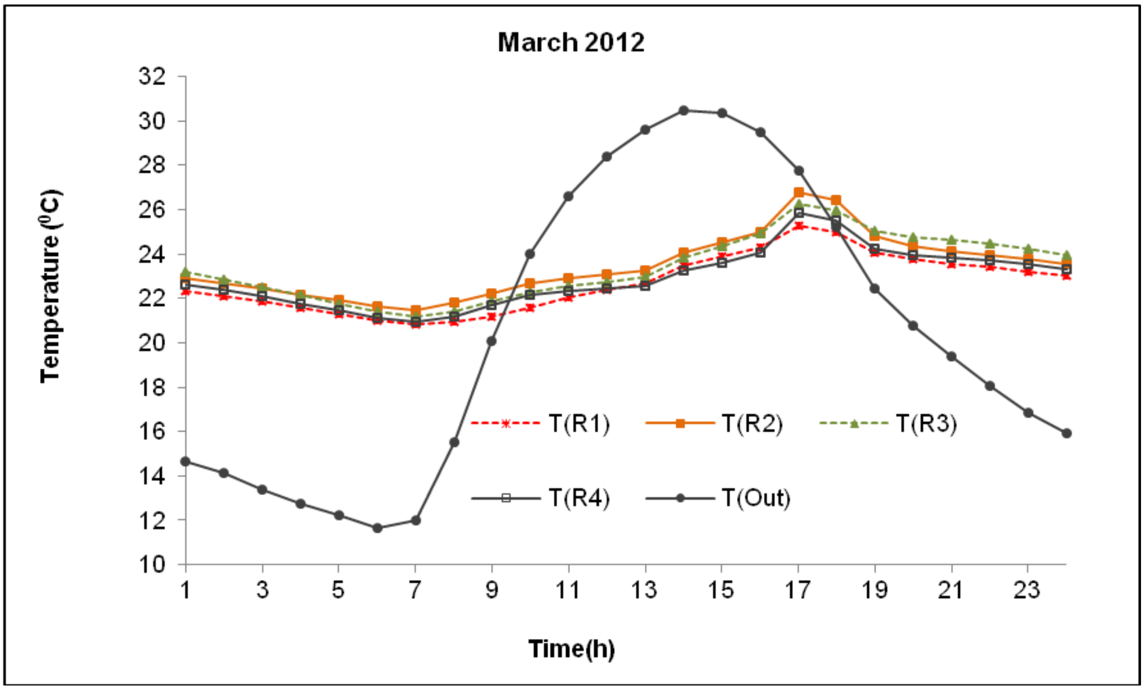


Fig. 7.12 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in March 2012

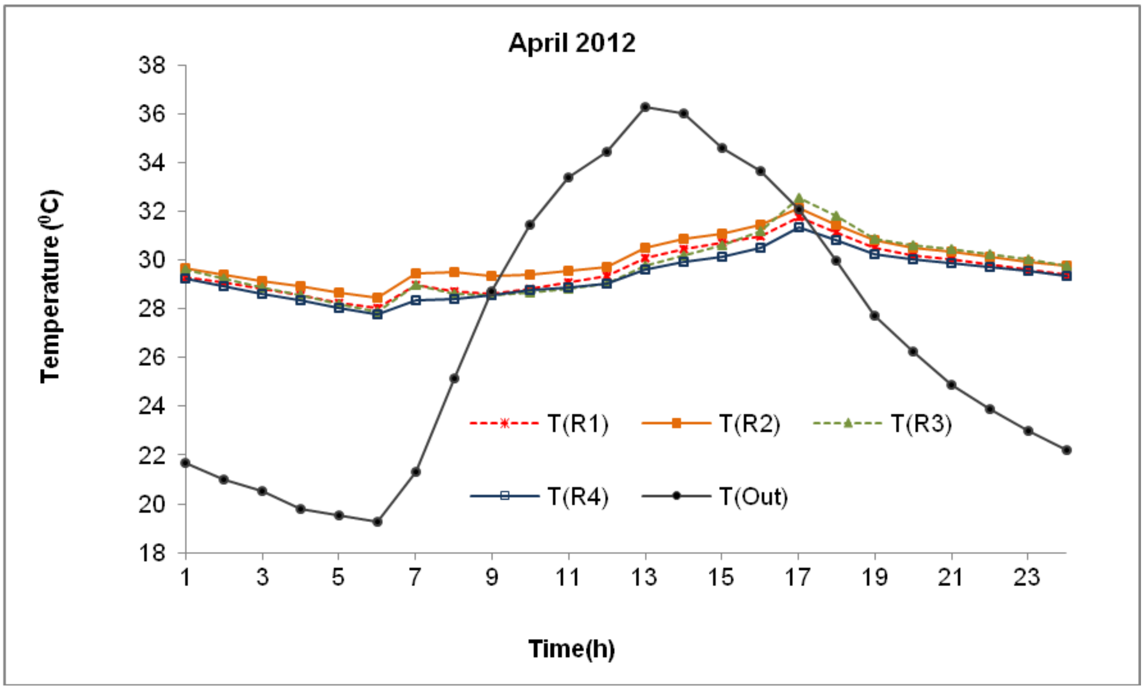


Fig. 7.13 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in April 2012

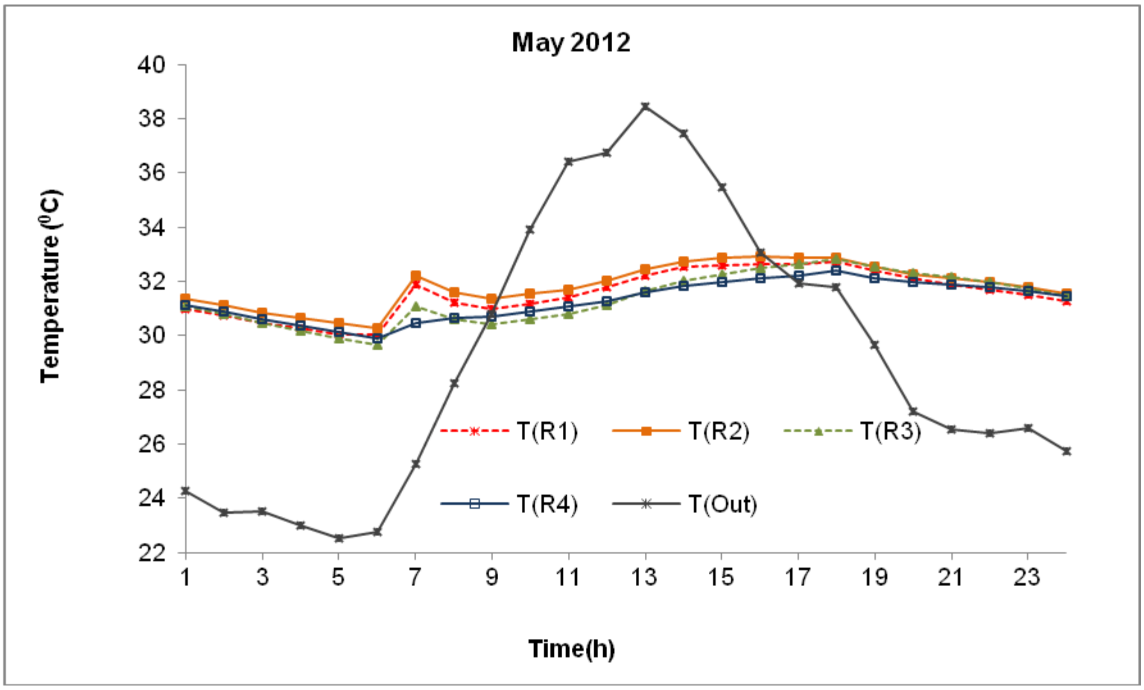


Fig. 7.14 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in May 2012

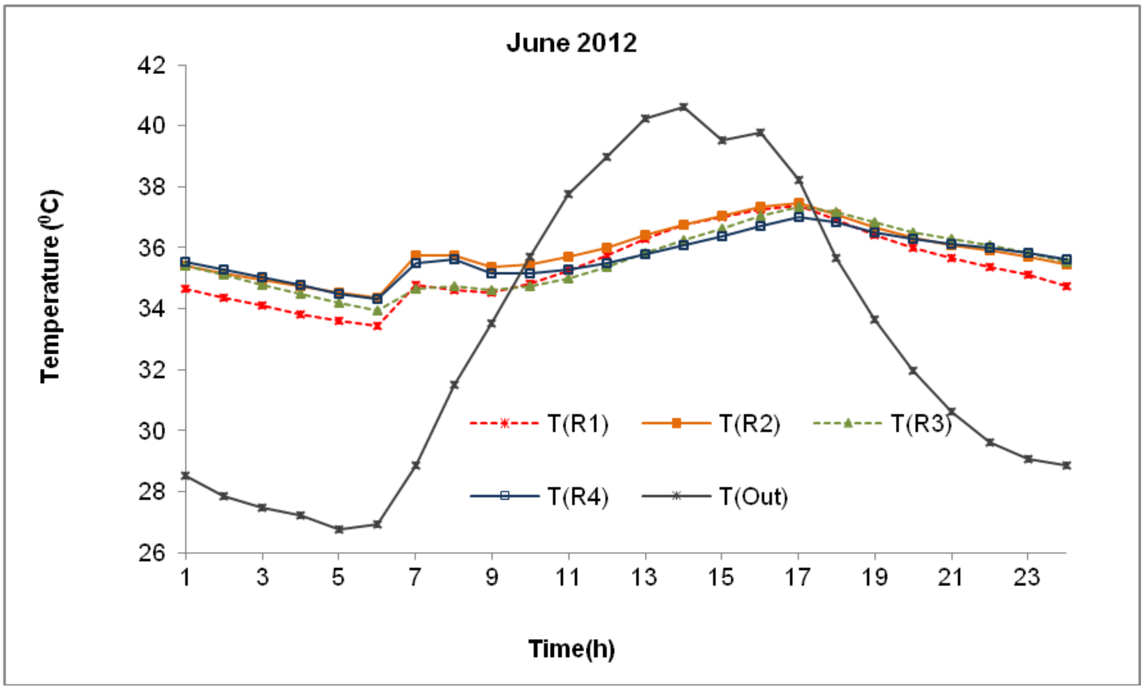


Fig. 7.15 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in June 2012

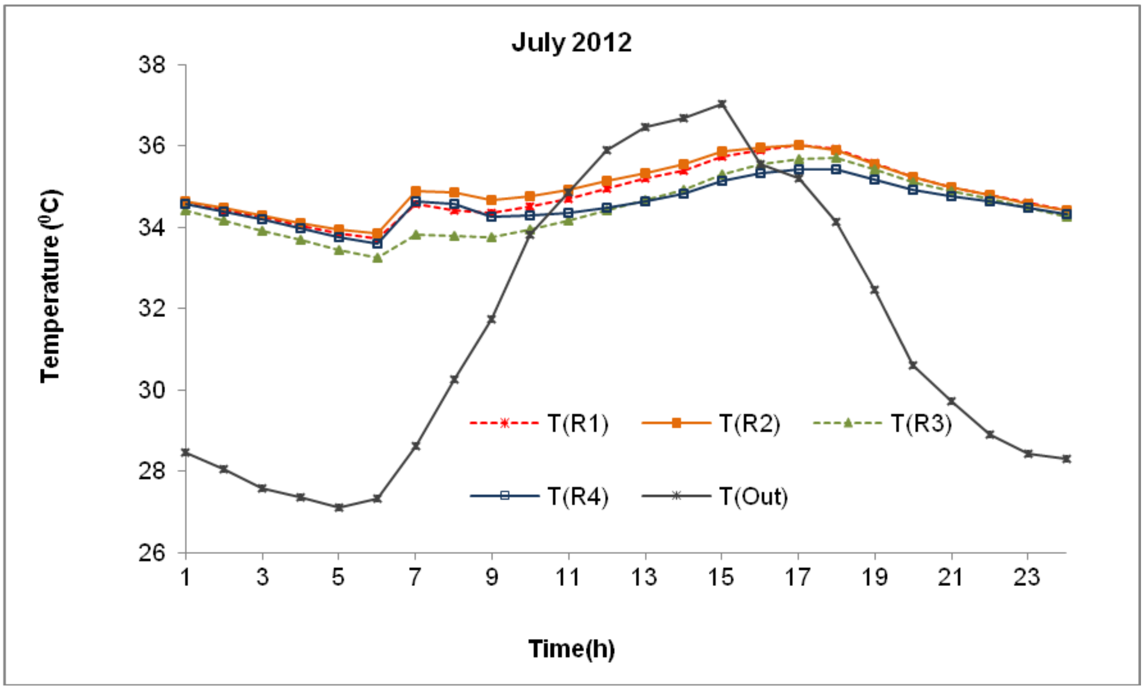


Fig. 7.16 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in July 2012

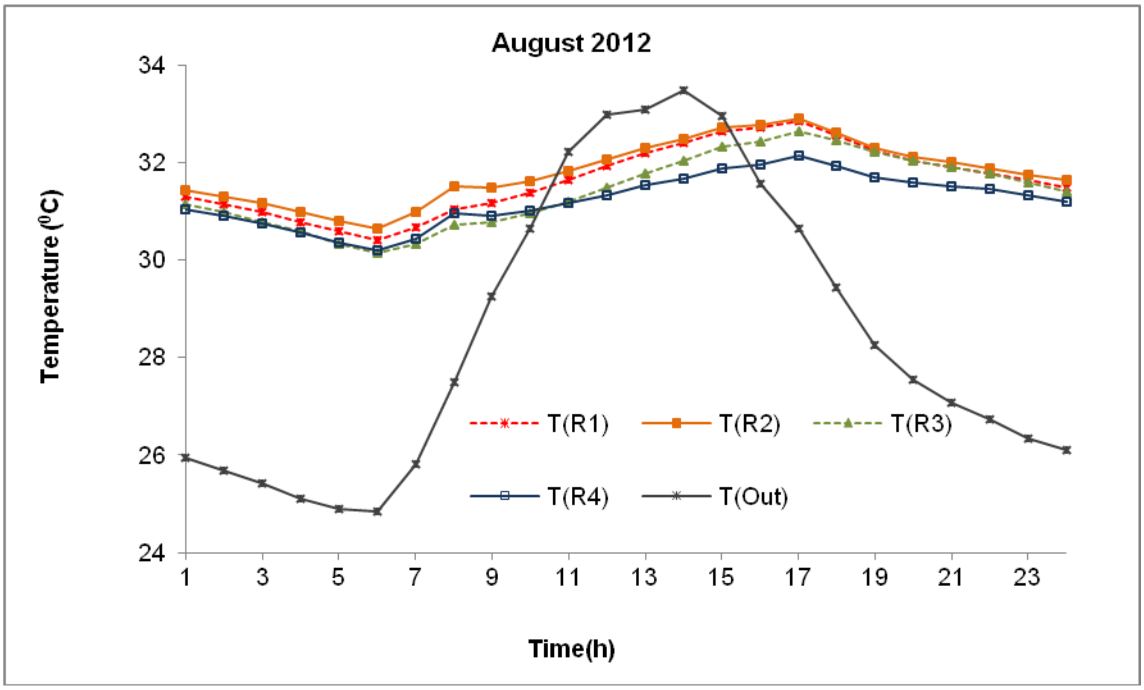


Fig. 7.17 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in August 2012

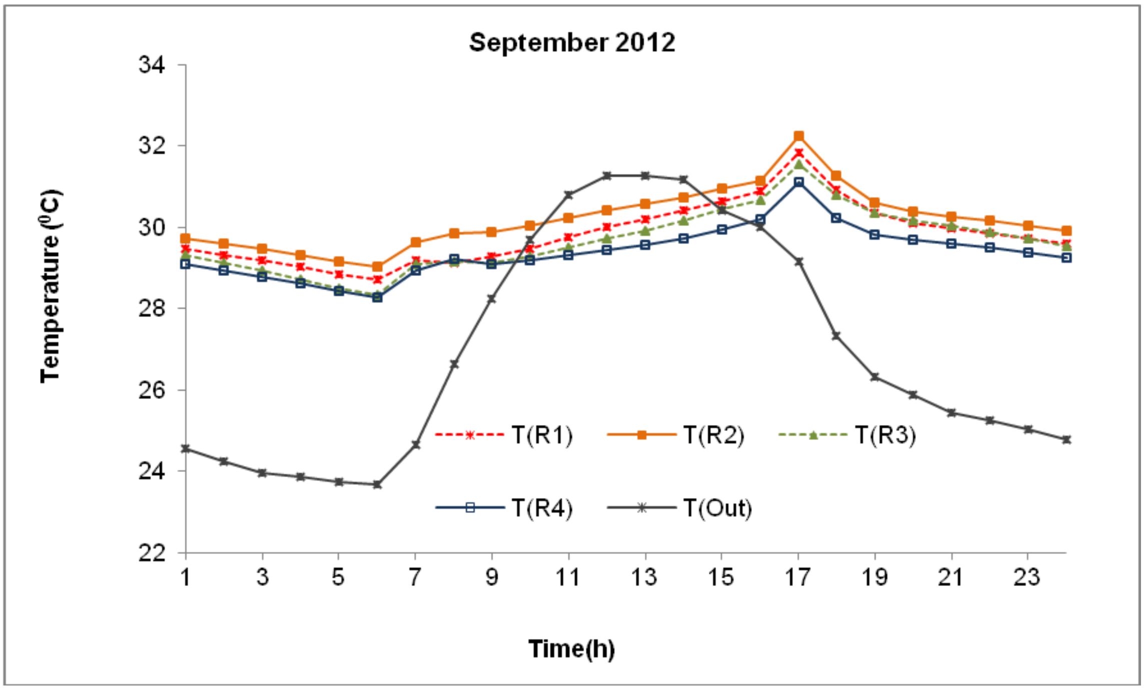


Fig. 7.18 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in September 2012

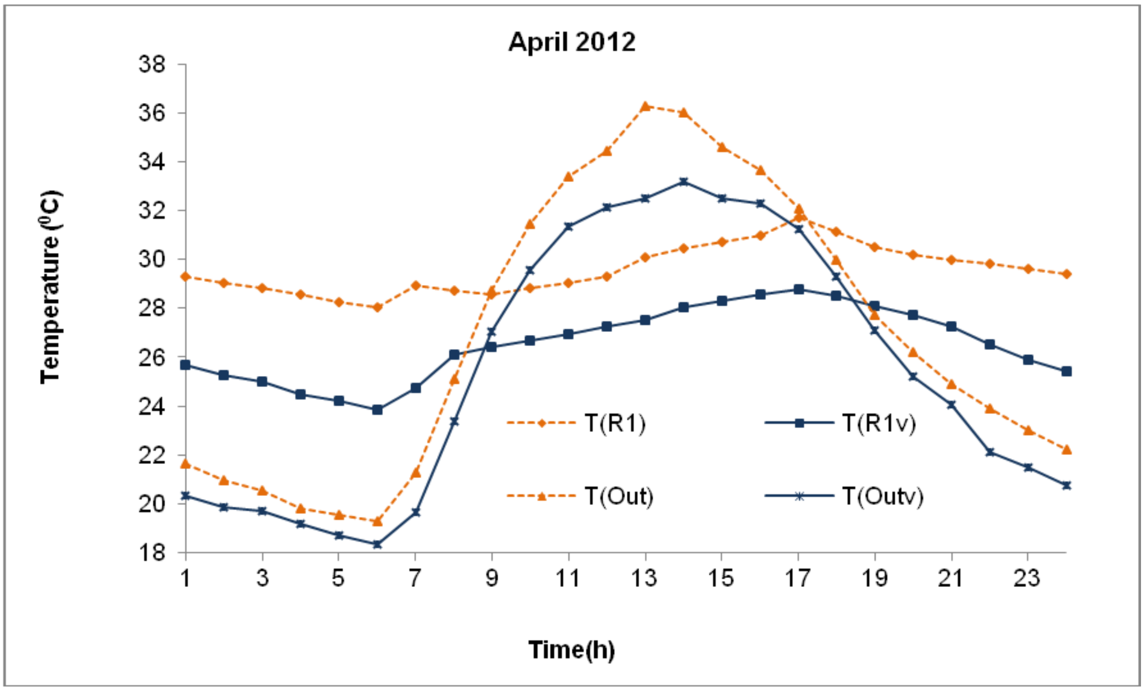


Fig. 7.19 Average hourly indoor air temperature in room R1 (with and without night ventilation) and outdoor air temperature in April 2012

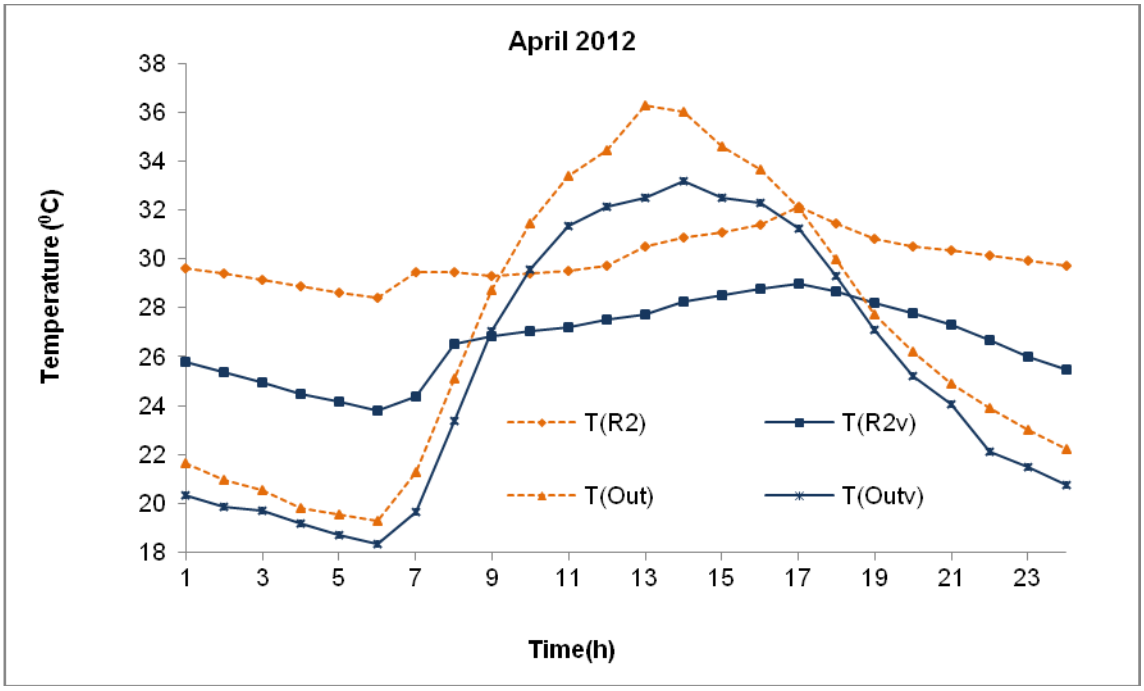


Fig. 7.20 Average hourly indoor air temperature in room R2 (with and without night ventilation) and outdoor air temperature in April 2012

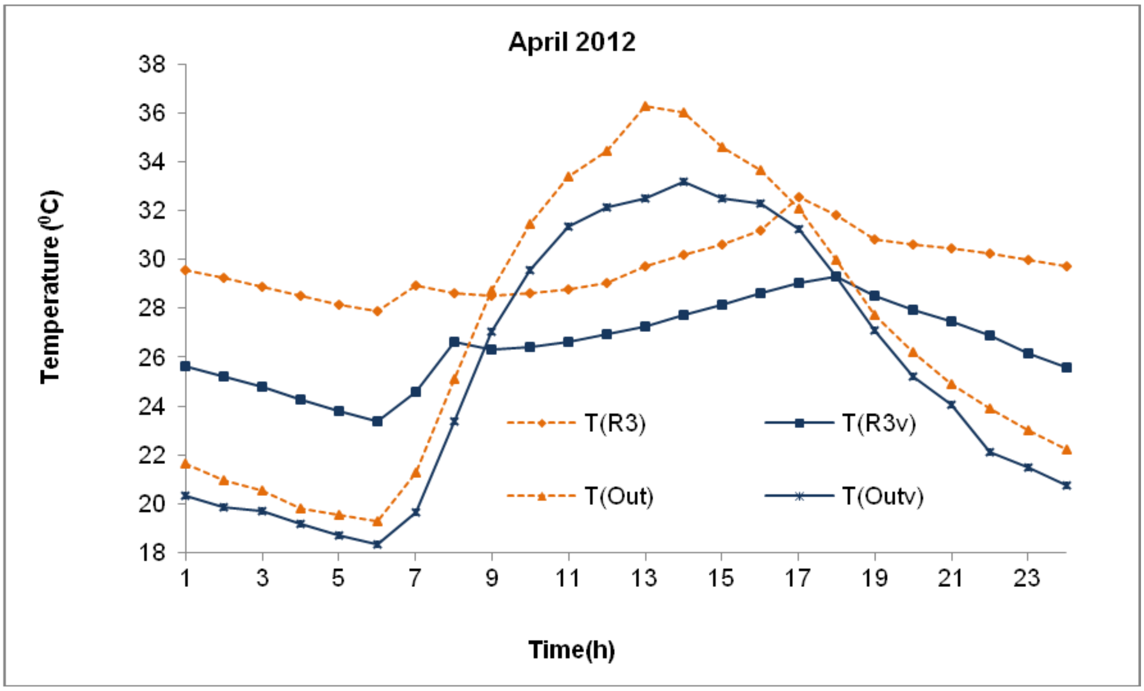


Fig. 7.21 Average hourly indoor air temperature in room R3 (with and without night ventilation) and outdoor air temperature in April 2012

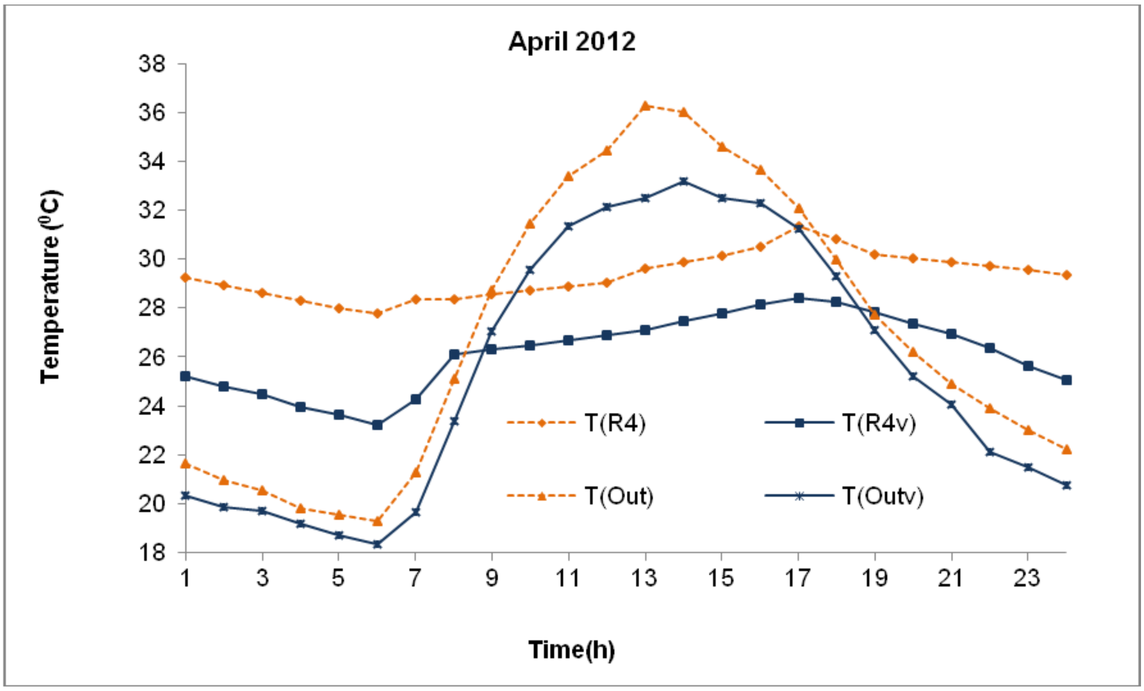


Fig. 7.22 Average hourly indoor air temperature in room R4 (with and without night ventilation) and outdoor air temperature in April 2012

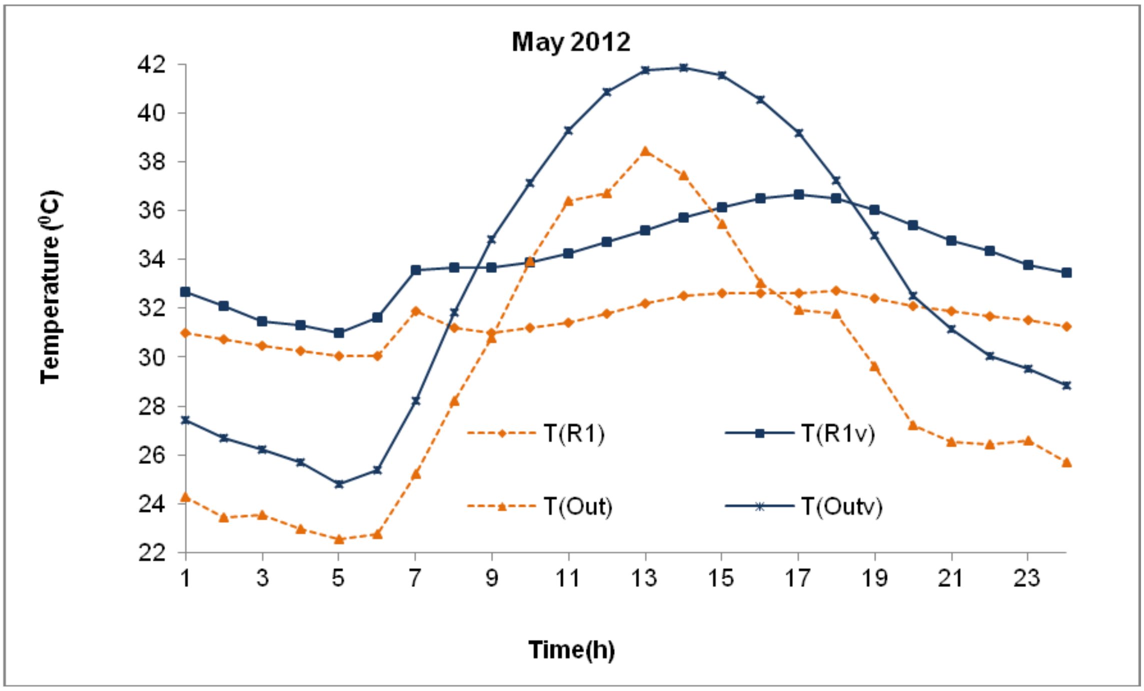


Fig. 7.23 Average hourly indoor air temperature in room R1 (with and without night ventilation) and outdoor air temperature in May 2012

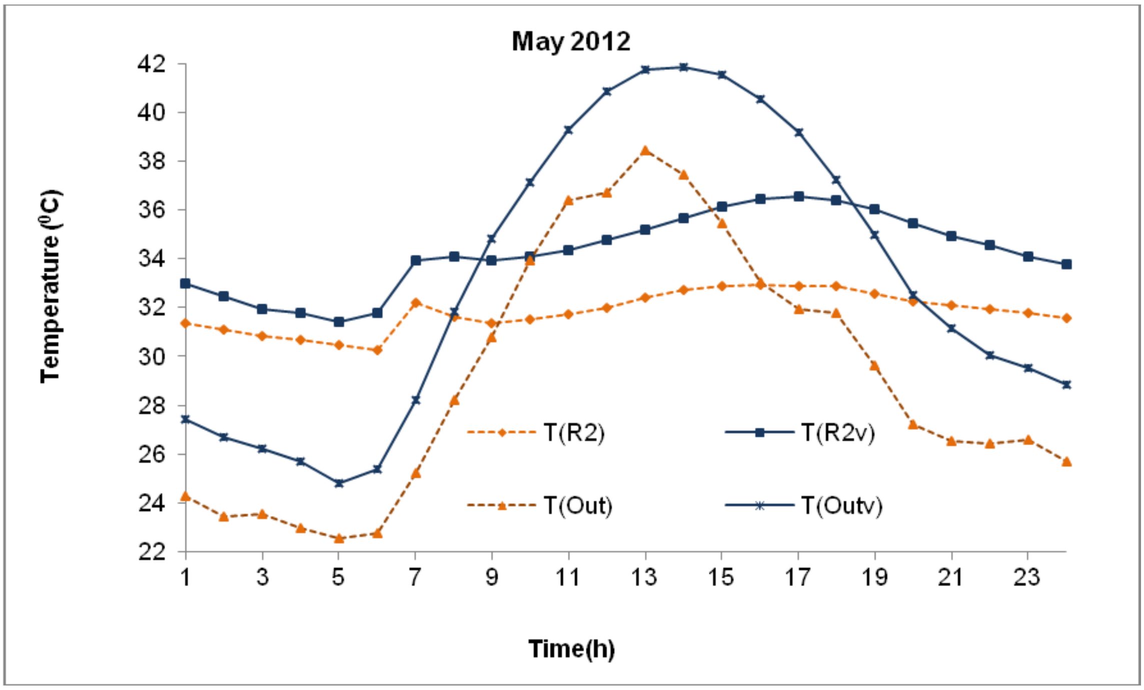


Fig. 7.24 Average hourly indoor air temperature in room R2 (with and without night ventilation) and outdoor air temperature in May 2012

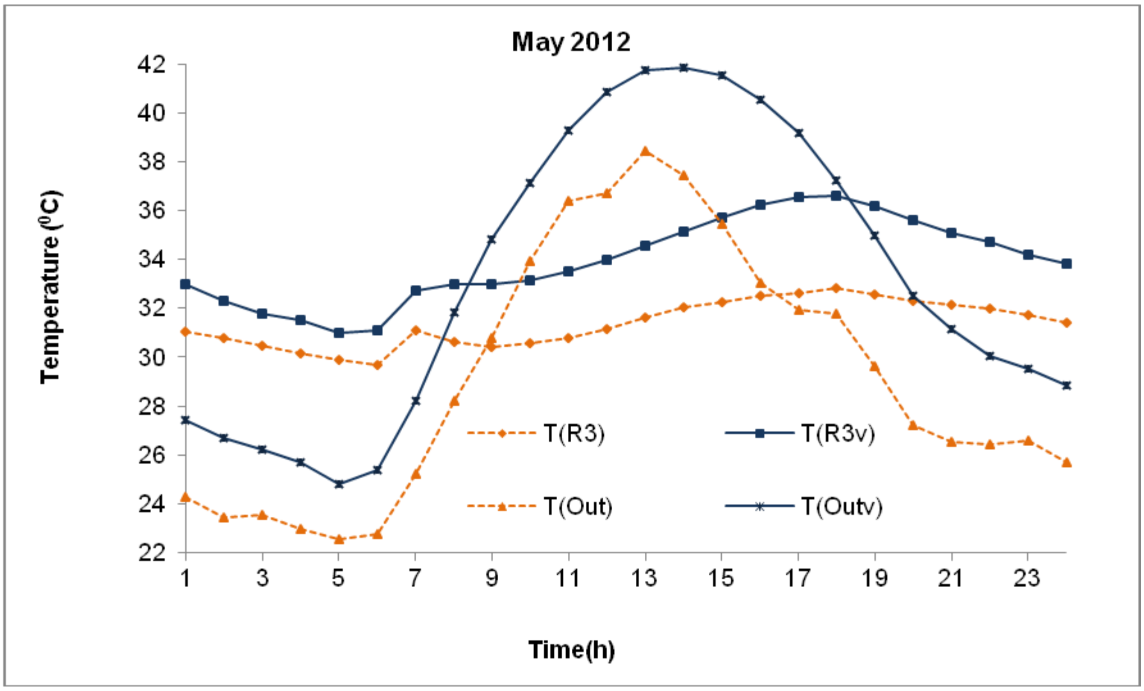


Fig. 7.25 Average hourly indoor air temperature in room R3 (with and without night ventilation) and outdoor air temperature in May 2012

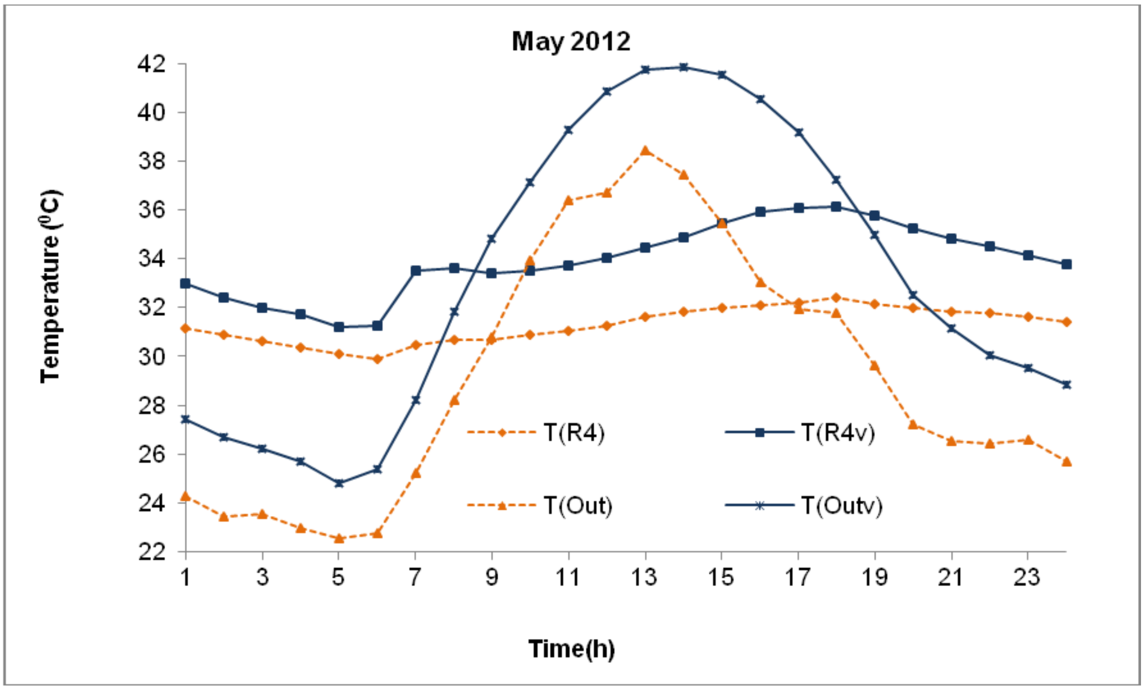


Fig. 7.26 Average hourly indoor air temperature in room R4 (with and without night ventilation) and outdoor air temperature in May 2012

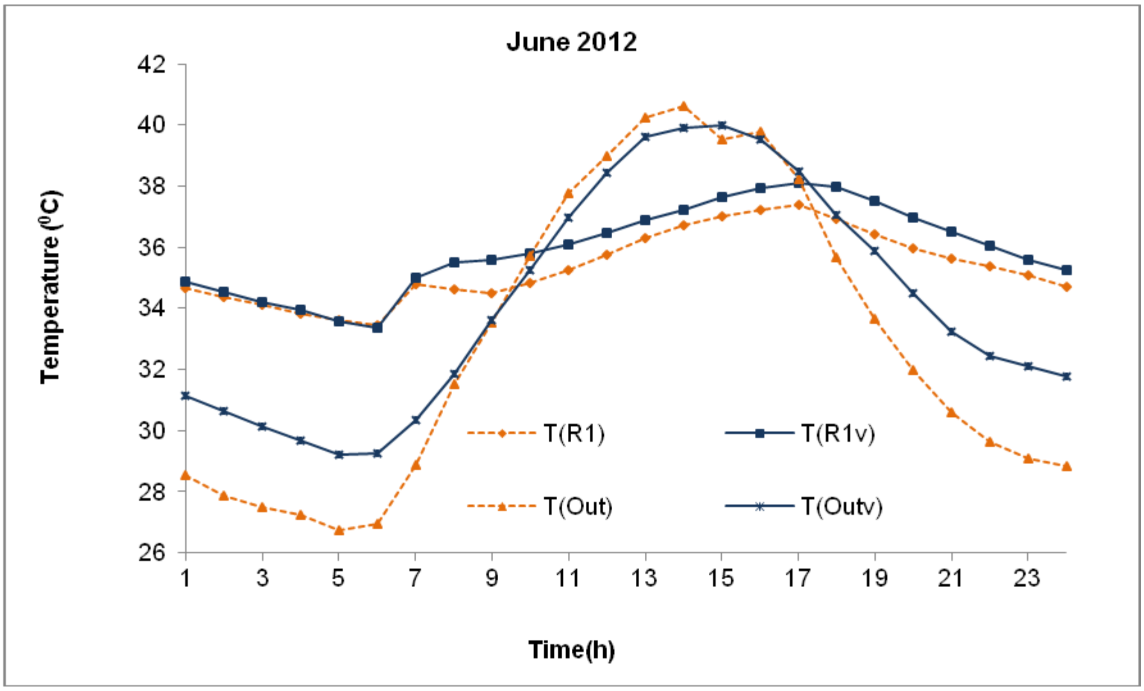


Fig. 7.27 Average hourly indoor air temperature in room R1 (with and without night ventilation) and outdoor air temperature in June 2012

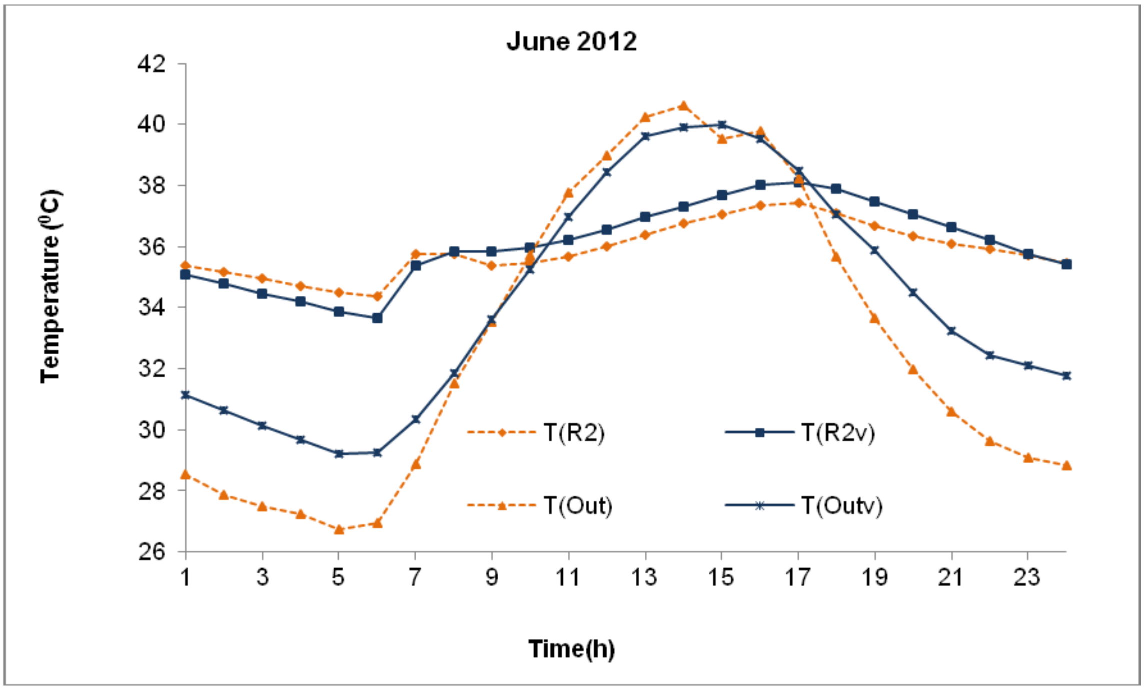


Fig. 7.28 Average hourly indoor air temperature in room R2 (with and without night ventilation) and outdoor air temperature in June 2012

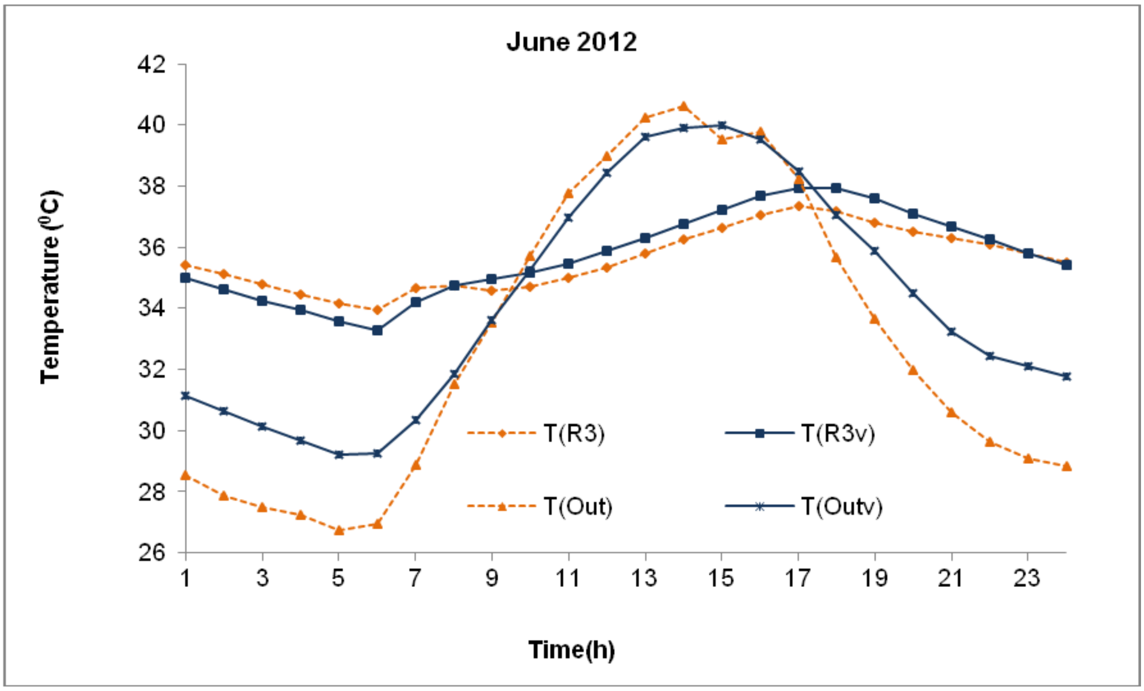


Fig. 7.29 Average hourly indoor air temperature in room R3 (with and without night ventilation) and outdoor air temperature in June 2012

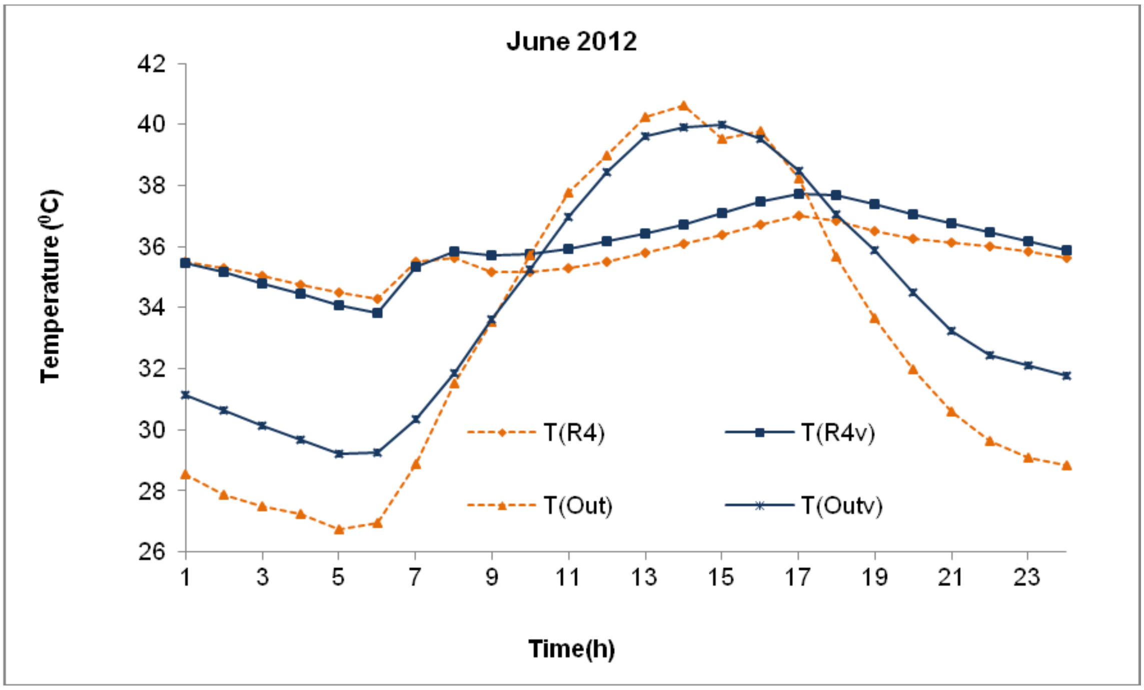


Fig. 7.30 Average hourly indoor air temperature in room R4 (with and without night ventilation) and outdoor air temperature in June 2012

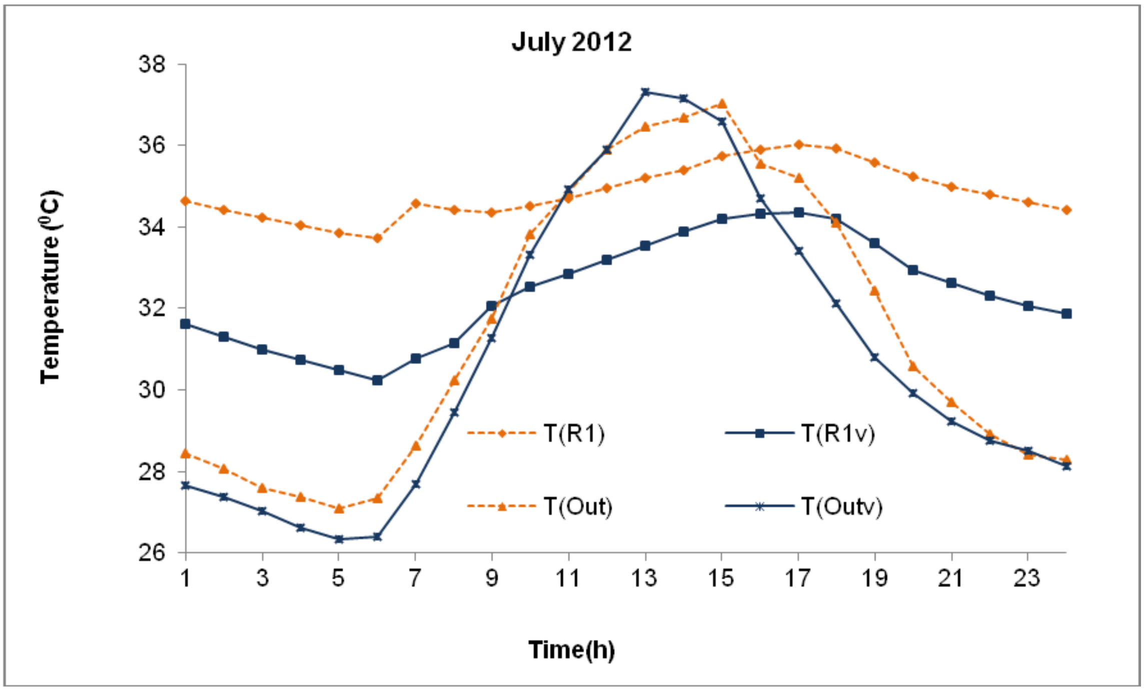


Fig. 7.31 Average hourly indoor air temperature in room R1 (with and without night ventilation) and outdoor air temperature in July 2012

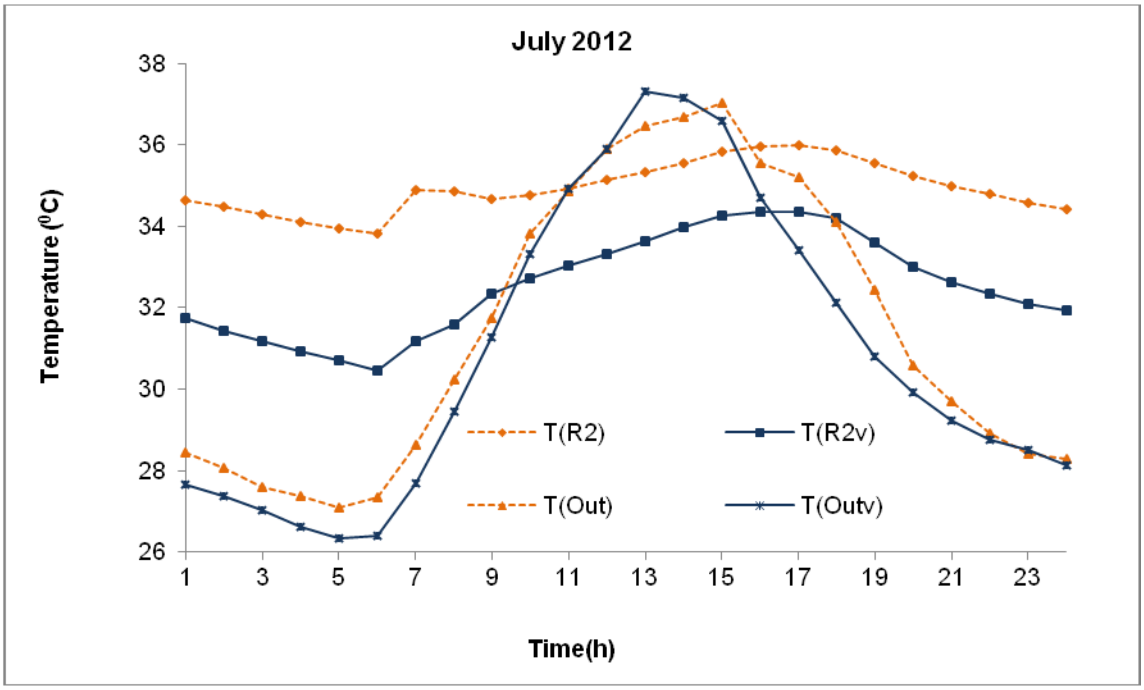


Fig. 7.32 Average hourly indoor air temperature in room R2 (with and without night ventilation) and outdoor air temperature in July 2012

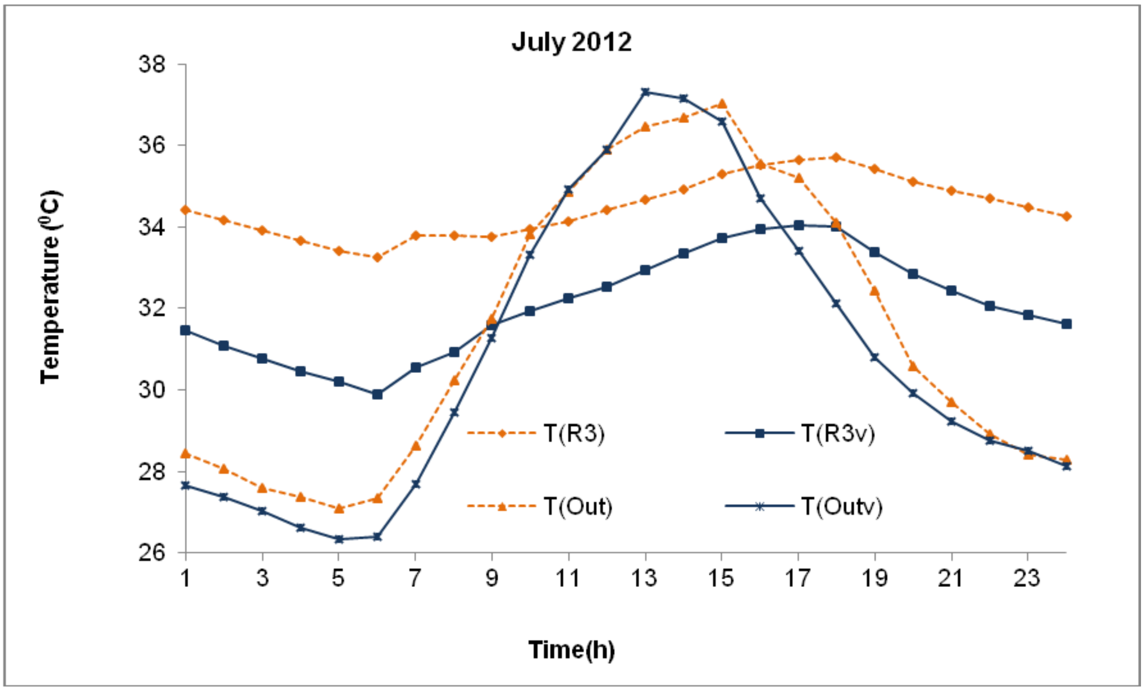


Fig. 7.33 Average hourly indoor air temperature in room R3 (with and without night ventilation) and outdoor air temperature in July 2012

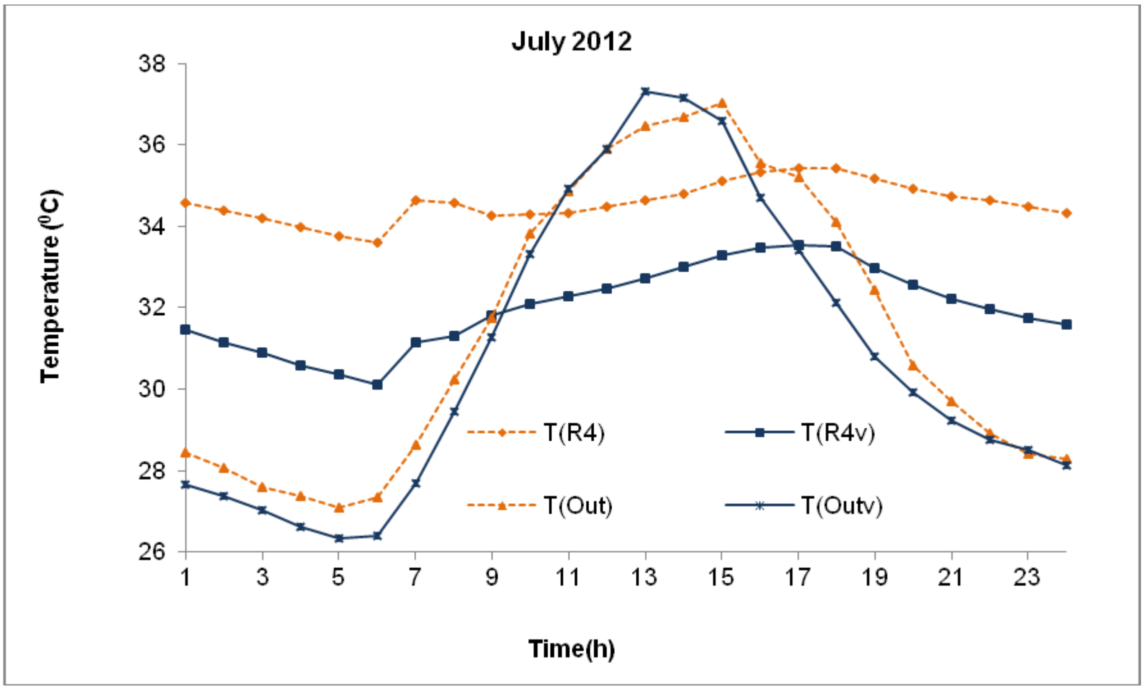


Fig. 7.34 Average hourly indoor air temperature in room R4 (with and without night ventilation) and outdoor air temperature in July 2012

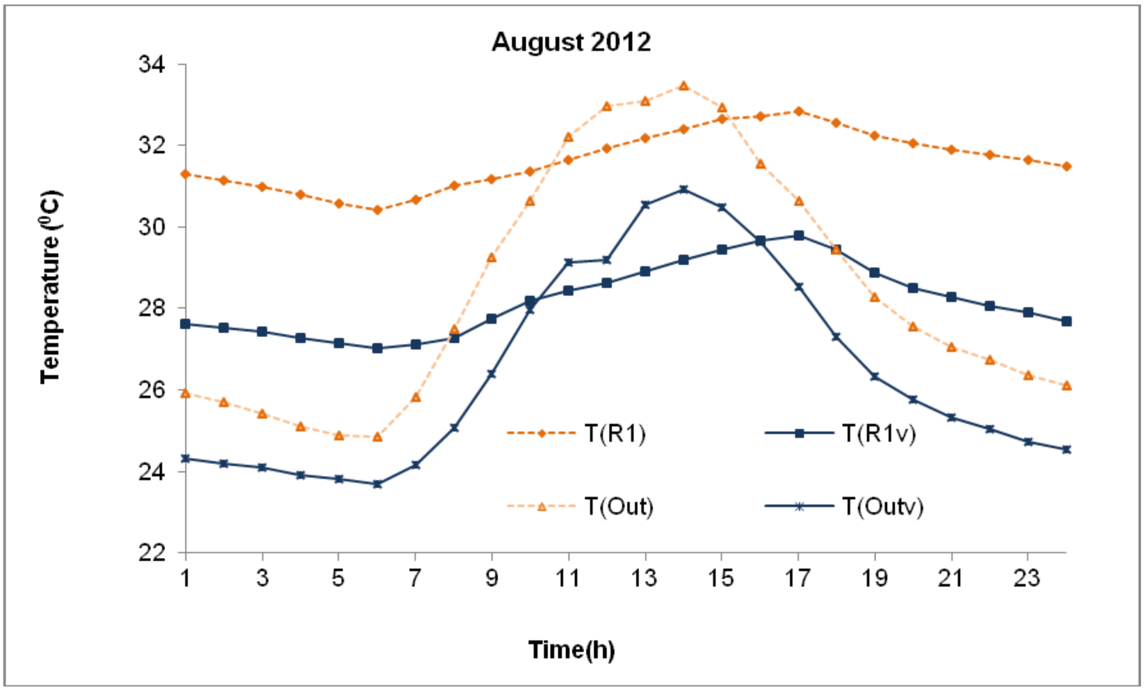


Fig. 7.35 Average hourly indoor air temperature in room R1 (with and without night ventilation) and outdoor air temperature in August 2012

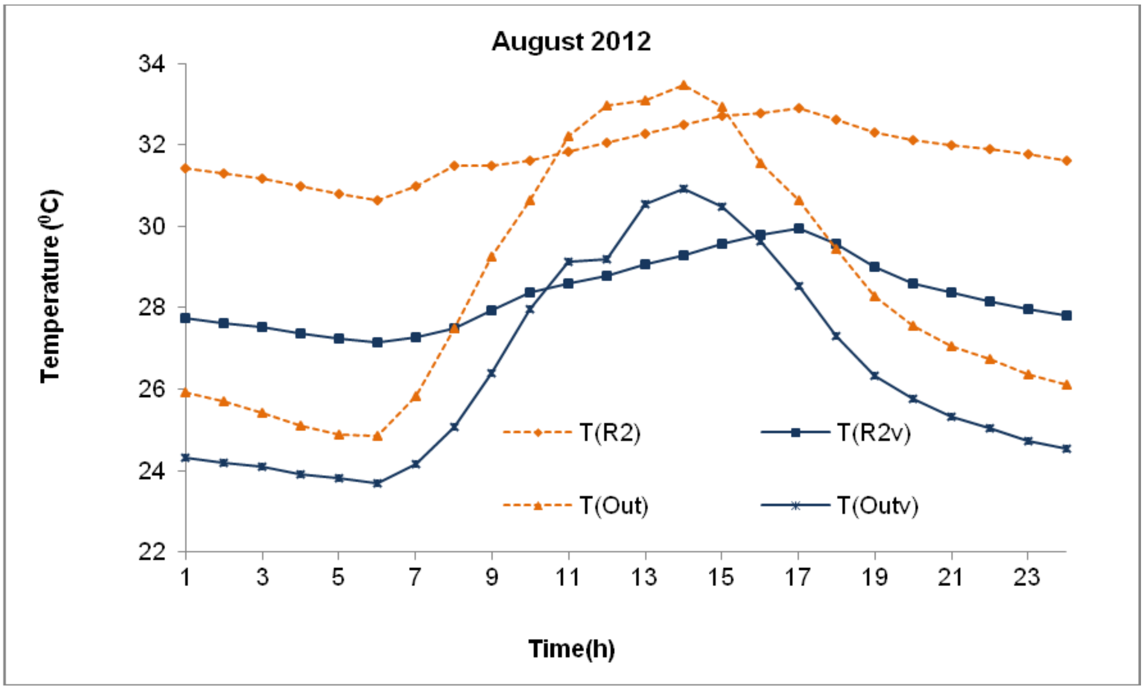


Fig. 7.36 Average hourly indoor air temperature in room R2 (with and without night ventilation) and outdoor air temperature in August 2012

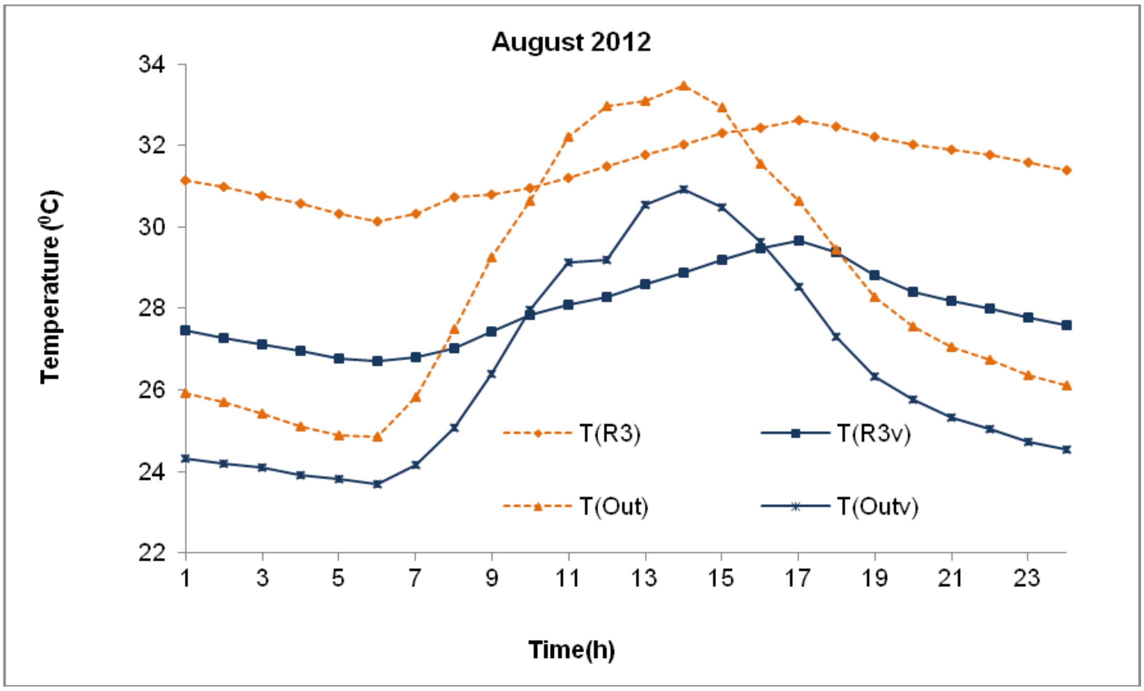


Fig. 7.37 Average hourly indoor air temperature in room R3 (with and without night ventilation) and outdoor air temperature in August 2012

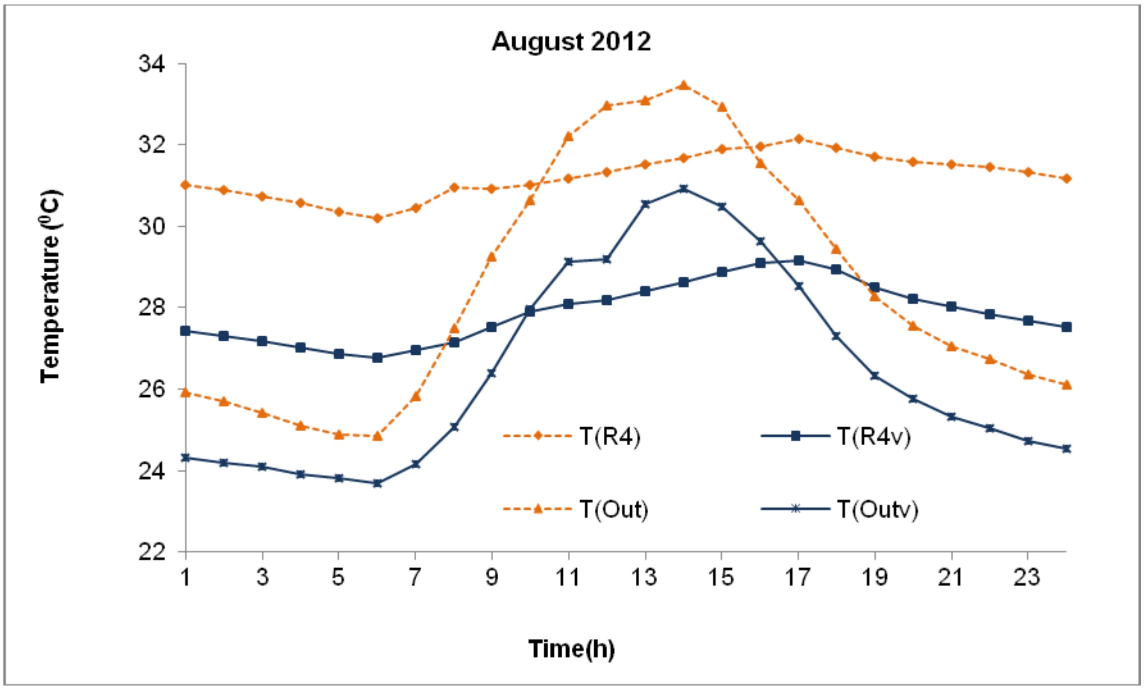


Fig. 7.38 Average hourly indoor air temperature in room R4 (with and without night ventilation) and outdoor air temperature in August 2012

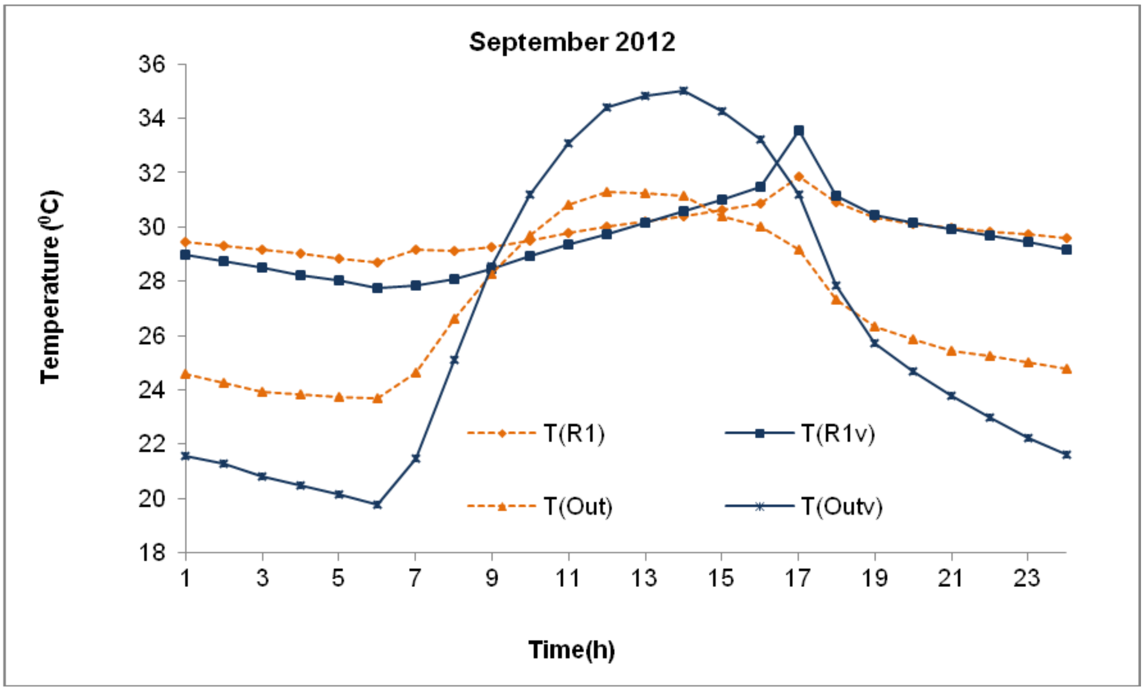


Fig. 7.39 Average hourly indoor air temperature in room R1 (with and without night ventilation) and outdoor air temperature in September 2012

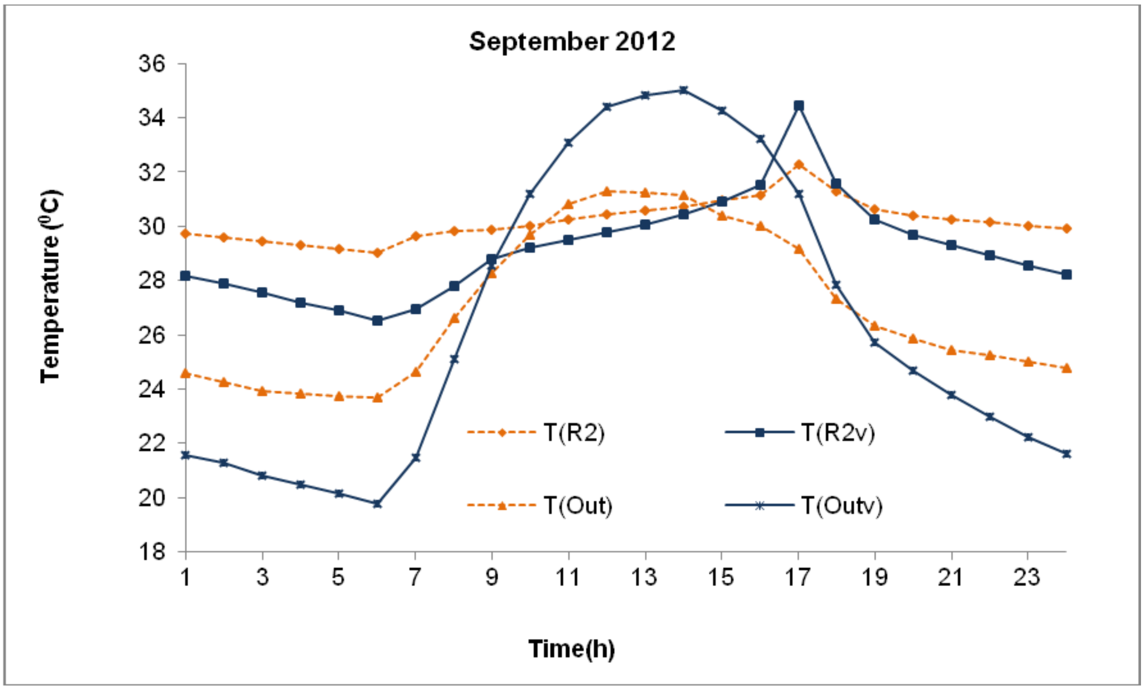


Fig. 7.40 Average hourly indoor air temperature in room R2 (with and without night ventilation) and outdoor air temperature in September 2012

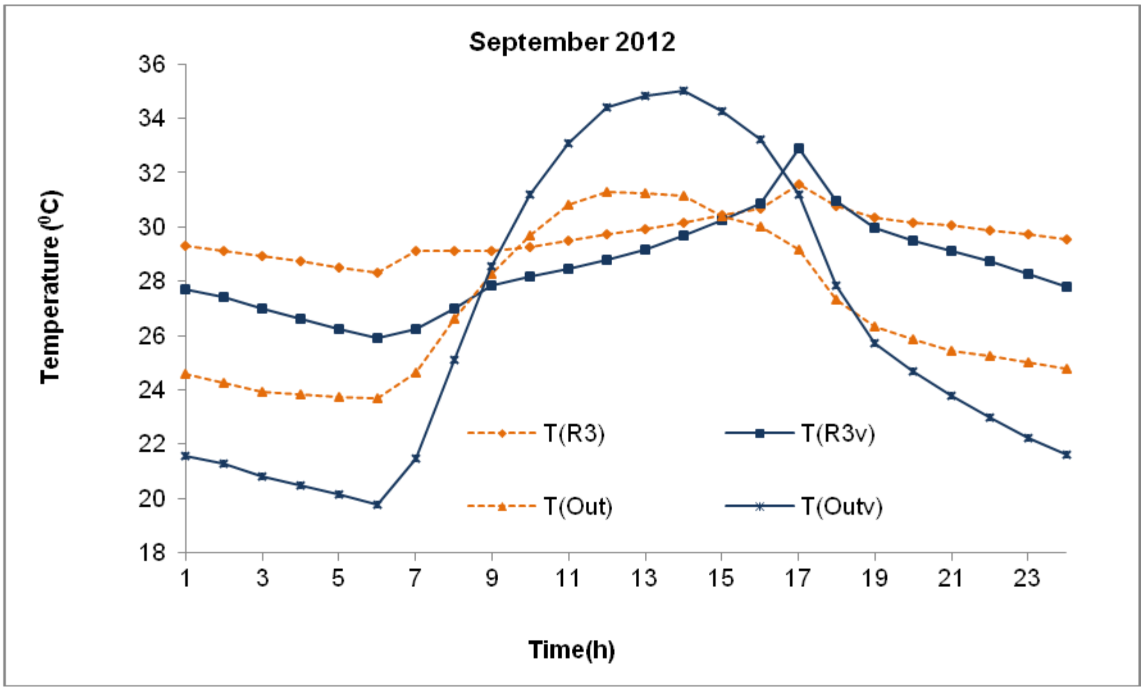


Fig. 7.41 Average hourly indoor air temperature in room R3 (with and without night ventilation) and outdoor air temperature in September 2012

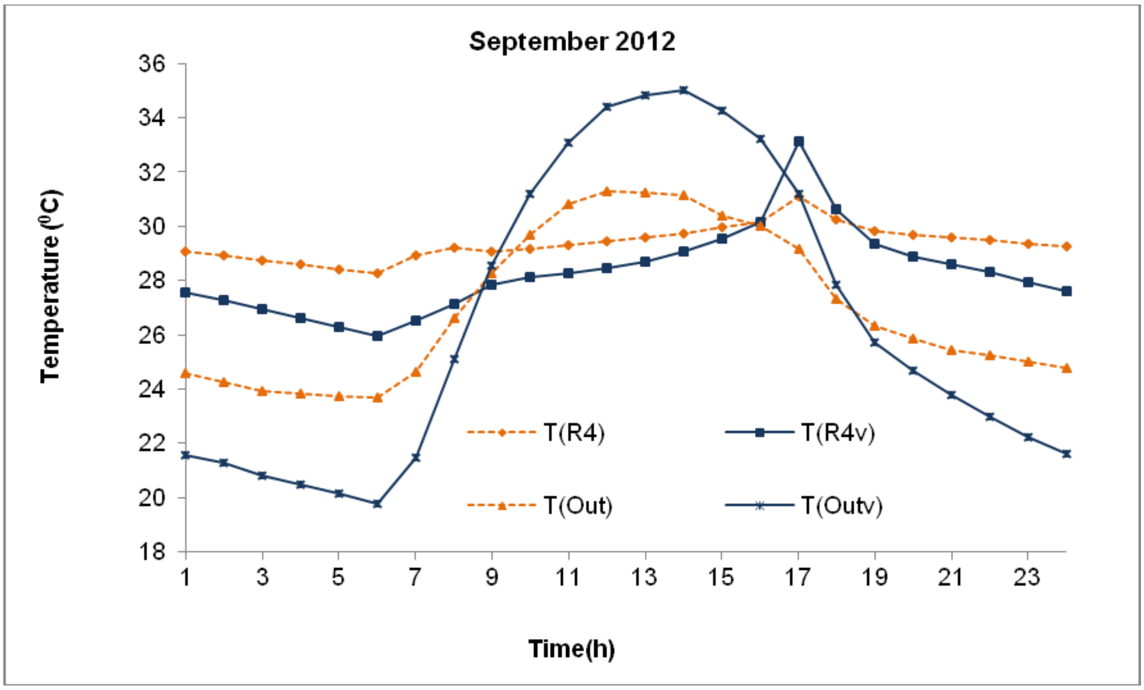


Fig. 7.42 Average hourly indoor air temperature in room R4 (with and without night ventilation) and outdoor air temperature in September 2012

Chapter 8

Summary and Conclusions

The objective of climate responsive architecture is to maximize heat gain in cold winter months and minimize heat gain in hot summer months, to optimize energy needs in buildings. It is thus necessary to analyze climatic elements and design the building suitable to specific climate of the place. The need is to validate the performance of designed passive elements in actual buildings and verify whether they actually behave in the way they are meant to and respond to the variations in climate. In the present study, designed passive elements viz. static sunshade, brick cavity wall with brick projections and hollow roof, were implemented in actual rooms of habitable dimensions to study their effect on indoor air temperature. The static sunshade was designed using sunpath diagram and shadow angles by selecting two cutoff dates as per seasonal requirements. The brick cavity wall with brick projections was designed by considering solar angles such maximum area of wall is in shade in summer and minimum wall area is in shade in winter. Vents with operable shutters were also provided to cool or heat the air in the wall cavity by outdoor air as per seasonal requirements. Air cavity was introduced in the roof by laying stoneware pipes to provide insulation to the room.

8.1 General observations from the study

The monthly analysis of thermal performance of the four rooms showed maximum reduction of heat load due to combined effect of designed passive elements was 53.31% in summer month of June. The designed static sunshade had less solar heat gain in moderate summer months and more in winter months as compared to a horizontal sunshade. Among the individual building elements, the brick cavity wall with brick projections led to maximum reduction of heat load (492.76 W in June). The heat load reduction due to hollow roof was significant. On representative days, the heat gain of room with designed passive elements was more in winter and less in summer as compared to the other three rooms as per seasonal requirements at the considered geographical location.

From this experimental study, it can be inferred that in actual rooms of habitable dimensions, designed static sunshade was effective in increasing the indoor air temperature in winter while its effect on indoor air temperature in summer was not significant due to the higher altitude angle of the sun. The difference in indoor air temperature due to the designed static sunshade in actual rooms of habitable dimensions was less as compared to the one obtained in small scale models (Ralegaonkar 2004). This was due to the effect of the other building elements viz. walls, roof, more number of windows and larger room volume, where the effect of the single static sunshade on the indoor air temperature was less. The brick cavity wall with brick projections was effective in lowering the minimum indoor air temperature in summer. In winter, it was effective in increasing the indoor air temperature in the evening and night. The hollow roof was effective in lowering the maximum indoor air temperature and the temperature swing in summer as it insulated the room interiors during hotter part of the day. In winter, the hollow roof provided insulation to the room interiors, thereby resulting in lower indoor air temperature and reduced temperature swing.

When the designed passive building elements were used in combination, their effect on indoor air temperature was equivalent to additive effect of these elements when used independently. The combined effect of the three passive building elements was less than the effect of individual element in a particular season. The designed static sunshade and brick cavity wall with brick projections together lowered indoor air temperature in summer mornings and increased it during winter evenings and nights. The maximum difference in AUC_c due to their combined effect was 18.2^0C-h in December. The brick cavity wall with brick projections and hollow roof together lowered indoor air temperature throughout the year. The maximum difference in AUC_c due to their combined effect was 20.6^0C-h in September. The combined effect of all the designed passive elements lowered the maximum, minimum indoor air temperature in summer and winter. In winter, their combined effect raised the indoor air temperature in mornings and nights. The AUC_c of room with all designed passive elements was least in summer indicating that due to their combined effect, indoor air temperature was in the comfort temperature zone for the maximum duration. During this period, the maximum difference in AUC_c of conventional room and room with all designed passive elements was maximum (16.9^0C-h) in June, minimum (3.9^0C-h) in May, while the average difference was 9.6^0C-h.

The ventilated brick cavity wall with brick projections helped to lower maximum and minimum indoor air temperature for five months in summer. When it was combined with designed static sunshade, it lowered indoor air temperature for hotter part of the day. The ventilated brick cavity wall with brick projections combined with hollow roof lowered indoor air temperature throughout the day (except in June nights when difference in indoor air temperature was not significant). They also lowered maximum, minimum indoor air temperature and temperature swing in summer. The combined effect of all the designed passive elements lowered maximum and minimum indoor air temperature and temperature swing in summer. It also led to least TLL (as compared to other rooms) throughout summer indicating that their combined effect gave best load leveling and thermal comfort indoors.

The maximum difference in TLL of conventional room and room with all designed passive elements was 47.37% while minimum was 1.64%.

From the study of the effect of night ventilation, it can be inferred that night ventilation was effective in moderate summer month to maintain indoor air temperature at a lower value throughout the day. While in the summer months, when the outdoor air temperature was high, night ventilation was effective in reducing indoor air temperature only at night. Night ventilation was equally effective in all the rooms.

8.2 Conclusions

This study in actual rooms of habitable dimensions has been useful in rightly showing the effect of individual building elements like static sunshade, brick cavity wall with brick projections and hollow roof and their combined effect on indoor air temperature and thus thermal comfort. Considering the composite climate of the location in the present study, the building elements that respond to the varied climatic needs in summer and winter can be selected as the optimum solution for energy conservation. The following conclusions can be drawn:

- Designed static sunshade may be used when it is desirable to raise indoor air temperature in winter
- Brick cavity wall with brick projections may be used in summer to lower minimum indoor air temperature and in winter to raise indoor air temperature
- Hollow roof may be used in summer when it is desirable to lower indoor air temperature
- Designed static sunshade and brick cavity wall with brick projections may be used in summer to lower indoor air temperature and in winter to raise indoor air temperature
- Brick cavity wall with brick projections and hollow roof may be used in summer to lower indoor air temperature
- All the building elements may be used in combination in summer to lower maximum and minimum indoor air temperature and in winter to raise it in morning and night
- Ventilated brick cavity wall with brick projections may be used in summer to lower maximum and minimum indoor air temperature
- Ventilated brick cavity wall with brick projections and designed static sunshade may be used in summer to lower indoor air temperature during hotter part of the day

- Ventilated brick cavity wall with brick projections and hollow roof may be used in summer to lower indoor air temperature throughout the day. It may also be used to lower maximum, minimum indoor air temperature and reduce temperature swing
- Ventilated brick cavity wall with brick projections, designed static sunshade and hollow roof may be used in summer to lower maximum, minimum indoor air temperature and reduce temperature swing
- Night ventilation may be used effectively in moderate summer months to lower indoor air temperature throughout the day and it would be equally effective in all rooms

The room with designed static sunshade, brick cavity wall with brick projections and hollow roof lowered indoor air temperature in summer and raised it in winter mornings and nights. The combined effect of these building elements is thus useful for energy conservation in buildings in composite climate as per seasonal needs.

Chapter 9

Future Scope of Work

The future scope of this study on designed passive elements has been presented in this chapter.

9.1 Mathematical modeling using linear graph theory

Modeling of the rooms can be done using mathematical approach to predict the room performance due to the building elements which could help in designing new buildings in the climate zone. Developing suitable computational tools capable of being applied to all stages of a design process to help designers to generate alternative proposals and choose between them are important tasks. Due to numerical approximation and high computation time, manual methods are cumbersome and inefficient. The simulation technique could be a useful tool to achieve an optimum thermal performance of buildings under given thermal environment considering the dynamic outdoor air temperature and dynamic response of the building elements. One of the simple ways to simulate the thermal performance of the building is to consider scaled one-room passive solar house design (Ralegaonkar 2004). Linear graph theory, which is a systematic methodology for modeling of systems with exact number of independent equations in terms of state variables was used to model the thermal performance of room R1 and predict the indoor air temperature. An analogy between building elements and electrical elements was developed whose values were computed using heat transfer mechanism. The algorithm for the generated software was coded in MATLAB (Hanselman and Littlefield 1996) the room performance was compared with the experimental results for a period of 7 days in May. It was assumed that the ambient air temperature was the same on all sides of the room. The model was idealized taking into consideration that the window glass temperature and the corresponding wall temperature are the same. The linear graph was drawn by taking a separate reference node, at ambient temperature and connected to all the nodes of the system. A node represents temperature at salient point either on the wall or inside the room. These nodes were connected by the line-segments that represent the heat flow rate between two nodes. It was found that the simulated indoor air temperature values maintained the same trend as that of the experimental indoor air temperature values i.e, sinusoidal form. But the amplitude was significantly less than the experimental values. The maximum difference between experimental and simulated values was about 5^0C. The variation may be due to the fact that the radiation was not considered in modeling this system. The future scope of this study would be to model all the rooms considering solar radiation and obtain further accuracy in prediction of indoor air temperature.

9.2 Computer simulation using Autodesk Ecotect Analysis 2011

The thermal performance of buildings can also be compared with the aid of computer based tools known as building simulation tools. These tools can estimate the performances of different designs of the building for a given environmental condition. It is possible to consider variation of outside air temperature and solar radiation with time, self shading and thermal capacity of the building that are factors that also actually affect the performance of a building on site. Hence, the thermal performance of the four rooms R1, R2, R3, R4 was compared using the software Autodesk Ecotect Analysis 2011 (Autodesk Inc. 2011). The analysis was done for an average day of every month throughout the year.

The limitations and assumptions associated with modelling of the rooms are listed below:

i. Thermal properties of shades were neglected as they were assigned non-thermal zones.
ii. Metal frame in windows and vents were not modelled due to limitations of the modelling tools.
iii. Thermal mass of the brick projections on the walls of room R3 was assumed to be distributed uniformly over the whole wall.
iv. The vents opening in the wall cavities of the walls of room R3 and room R4 were modelled as windows with custom material having air as outer layer and brick as inner layer.
v. The required weather information, not collected due to limitations of the experiment, was acquired from an external source (U.S. Department of Energy 2005).

The simulation of the rooms with software Autodesk Ecotect Analysis 2011 showed that there were certain differences in the experimental and simulation results. This may be attributed to the available weather file, in which the climatic variables (not available from the experiment) were input from a weather station closest to the experimental setup. Limitations in modelling the brick cavity wall with brick projections and hollow roof exactly like the experimental case may have led to the difference in experimental and simulation results. The future scope of this study would be to model all the rooms to obtain further accuracy in prediction of indoor air temperature. Other available computer simulation softwares may also be used to predict room performance.

9.3 Inclusion of more parameters for analysis

The thickness of wall and air cavity can be optimized to maximize thermal comfort. The thickness of the roof along with the air cavity can also be optimized. The static sunshade can be analyzed by inclusion of more parameters like more number of openings on particular wall facade, multiple rooms and multiple floors. This can be done by studying the effect of the designed passive elements on variations of all climatic variables like solar radiation, relative humidity, wind speed.

9.4 Extension of the study to other climate zones

The same study can also be extended to other climate zones. This would involve a detailed analysis of the climate and thermal comfort requirements of the particular climate zone, study of the effectiveness of existing passive building elements in that climate zone and design of new building elements responsive to climate

Thus the work carried out in this study can be extended further in diverse areas to maximize thermal comfort and attain energy efficiency by using passive building elements.

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Appendix

A1.1 Excel VBA code for calculating the total solar radiation

```
Sub Total_Radiation1()
'
'Activating the worksheet
Worksheets("SolarRadiation").Activate
'
'Declaring a constant
'Const pi = 3.14159
'
'Calculation of Declination angle
'Assigning values for A,B and  C
'
Dim a, b, c
d = Range("A2").Value
m = Range("B2").Value
Select Case m
Case 1
n = d
Case 2
n = 31 + d
Case 3
n = 59 + d
Case 4
n = 90 + d
Case 5
n = 120 + d
Case 6
n = 151 + d
Case 7
n = 181 + d
Case 8
n = 212 + d
Case 9
n = 243 + d
Case 10
n = 273 + d
Case 11
n = 304 + d
Case 12
n = 334 + d
End Select
g = 360 * (n - 275) / 365
gr = Application.WorksheetFunction.Radians(g)
h = 360 * (n - 100) / 365
hr = Application.WorksheetFunction.Radians(h)
```

```
a = 1160 + (75 * Sin(gr))
b = 0.175 + (0.035 * Sin(hr))
c = 0.095 + (0.04 * Sin(hr))
Range("I2").Value = a
Range("J2").Value = b
Range("K2").Value = c
x = (284 + n) * 360 / 365
xr = Application.WorksheetFunction.Radians(x)
decl = 23.45 * Sin(xr)
decl = Application.WorksheetFunction.Round(decl, 2)
Range("F2").Value = decl
declr = Application.WorksheetFunction.Radians(decl)
'
'Calculation of Equation of Time and solar time
'
LT = Range("C2").Value
'ang = (360 * (n - 81)) / 365
'angr=Application.Worksheetfunction.Radians(ang)
'E = ((9.87 * Sin(2 * angr)) - (7.53 * round(Cos(angr),12)) - (1.5 * Sin(angr))) / 60
'ST = LT + ((77.3833 - 75.6) / 15) + E
Range("D2").Value = LT
'
'Calculation of Hour Angle
'
t = Range("D2").Value
If t > 12 Then
w = 15 * (t - 12)
F = 1
Else
w = 15 * (12 + t)
F = -1
End If
Range("E2").Value = w
wr = Application.WorksheetFunction.Radians(w)
'
'Calculation of Sin(Altitude Angle)
'
l = 28.25
lr = Application.WorksheetFunction.Radians(l)
alpha = (Sin(declr) * Sin(lr)) + (Round(Cos(declr), 12) * Round(Cos(lr), 12) * Round(Cos(wr), 12))
Range("G2").Value = alpha
alti = Application.Asin(alpha)
altid = Application.WorksheetFunction.Degrees(alti)
'
'Fws and Fwg values
'
E = Range("H2").Value
```

```
If E = "Roof" Then
fws = 1
Range("L2").Value = fws
fwg = 0
Range("M2").Value = fwg
Else
fws = 0.5
Range("L2").Value = fws
fwg = 0.5
Range("M2").Value = fwg
End If
'
'Calculation of direct radiation
'
If altid = 0 Then
idn = 0
Else
idn = a * Exp(-b / alpha)
End If
Range("O2").Value = idn
'
'Calculation of diffuse radiation
'
ID = c * idn * fws
Range("P2").Value = ID
'
'Calculation of reflected radiation
'
R = Range("N2").Value
Ir = (idn + ID) * R * fwg
Range("Q2").Value = Ir
'
'Calculation of angle of incidence
'
If t = 12 Then
  If l < decl Then
   gamma1 = 0
  Else
   gamma1 = 180
  End If
Else
 If Range("H2").Value = "East Wall" Or Range("H2").Value = "West Wall" Then
   gamma1 = Application.Asin(Round(Cos(declr), 12) * Sin(wr) / Round(Cos(alti), 12))
 Else
   gamma1 = ((Round(Cos(lr), 12) * Sin(declr)) - (Round(Cos(declr), 12) * Round(Cos(wr), 12) * Sin(lr))) /
Round(Cos(alti), 12)
   gamma1 = Application.Acos(gamma1)
```

```
 End If
gamma1 = Application.WorksheetFunction.Degrees(gamma1)
End If
'gamma1 = 180 - (gamma1)
gamma1r = Application.WorksheetFunction.Radians(gamma1)
Build = Range("H2").Value
Select Case Build
Case "Roof"
theta = Application.WorksheetFunction.Radians(90 - altid)
inc = Round(Cos(theta), 12)
Case "North Wall"
surf = 180
azi = Application.WorksheetFunction.Radians((180 - (gamma1 + surf)) * F)
inc = Round(Cos(alti), 12) * Round(Cos(azi), 12)
Case "South Wall"
surf = 0
azi = Application.WorksheetFunction.Radians((180 - (gamma1 + surf)) * F)
inc = Round(Cos(alti), 12) * Round(Cos(azi), 12)
Case "East Wall"
surf = -90
azi = Application.WorksheetFunction.Radians((180 - (gamma1 + surf)) * F)
inc = Round(Cos(alti), 12) * Round(Cos(azi), 12)
Case "West Wall"
surf = 90
azi = Application.WorksheetFunction.Radians((180 - (gamma1 + surf)) * F)
inc = Round(Cos(alti), 12) * Round(Cos(azi), 12)
End Select
'
'Calculation of total radiation
'
If inc >= 0 And inc <= 1 Then
direct = idn * inc
Else
direct = 0
End If
It = direct + ID + Ir
Range("R2").Value = It
'
'Answer = MsgBox("Total Solar Radiation in W/m2 is" & It, vbOKOnly, "Radiation Value")
'If Answer = vbOK Then
'Exit Sub
End Sub
```

A1.2 Excel VBA code for calculating the total solar radiation on a window due to shading by rectangular sunshade

```
Sub Daily_radiation()
'
'Calculation of daily average of hourly solar radiation
'
'
'Const pi = 3.14159
'
'
For n = 1 To 365
Range("C2").Select
m = n - 1
ActiveCell.Offset(m, 0).Select
ActiveCell.Value = n
a = 360 * (284 + n) / 365
ar = Application.WorksheetFunction.Radians(a)
d = 23.45 * Sin(ar)
d = Application.WorksheetFunction.Round(d, 2)
'ActiveCell.Offset(0, 1).Value = d
dr = Application.WorksheetFunction.Radians(d)
lr = Application.WorksheetFunction.Radians(28.25)
h = Application.Acos(-Round(Tan(dr), 12) * Round(Tan(lr), 12))
h = Application.WorksheetFunction.Degrees(h)
sr = 12 - (h / 15)
'ActiveCell.Offset(0, 2).Value = sr
ss = 12 + (h / 15)
'ActiveCell.Offset(0, 3).Value = ss
Sum = 0
a = 0
Range("C2").Select
  For x = 4 To 19
  If (x >= sr And x <= ss) Then
  j = ActiveCell.Offset(m, -1).Value
  d = ActiveCell.Offset(m, -2).Value
  Worksheets("Sheet1").Range("A2").Value = d
  Worksheets("Sheet1").Range("B2").Value = j
  Worksheets("Sheet1").Range("C2").Value = x
  Worksheets("Sheet1").Range("D2").Value = "South Wall"
  Call SolarHeatGain1
  tot = Worksheets("Sheet1").Range("M2").Value
  Worksheets("sw2").Activate
  Range("C2").Select
  y = x - 4
  ActiveCell.Offset(m, y) = tot
```

```
  Sum = Sum + tot
  a = a + 1
  Else
  'ActiveCell.Offset(m, x).Value = 0
  End If
  Next x
  avg = Sum / a
Range("C2").Select
ActiveCell.Offset(m, 16).Value = avg

Next n
End Sub
```

A1.3 Excel VBA code for calculating the total solar radiation on a window due to shading by designed static sunshade

```
Sub Daily_radiation()
'
'Calculation of daily average of hourly solar radiation
'
'
'Const pi = 3.14159
'
'
For n = 1 To 365
Range("C2").Select
m = n - 1
ActiveCell.Offset(m, 0).Select
ActiveCell.Value = n
a = 360 * (284 + n) / 365
ar = Application.WorksheetFunction.Radians(a)
d = 23.45 * Sin(ar)
d = Application.WorksheetFunction.Round(d, 2)
'ActiveCell.Offset(0, 1).Value = d
dr = Application.WorksheetFunction.Radians(d)
lr = Application.WorksheetFunction.Radians(28.25)
h = Application.Acos(-Round(Tan(dr), 12) * Round(Tan(lr), 12))
h = Application.WorksheetFunction.Degrees(h)
sr = 12 - (h / 15)
'ActiveCell.Offset(0, 2).Value = sr
ss = 12 + (h / 15)
'ActiveCell.Offset(0, 3).Value = ss
Sum = 0
a = 0
Range("C2").Select
  For x = 4 To 19
  If (x >= sr And x <= ss) Then
  j = ActiveCell.Offset(m, -1).Value
  d = ActiveCell.Offset(m, -2).Value
  Worksheets("Sheet1").Range("A2").Value = d
  Worksheets("Sheet1").Range("B2").Value = j
  Worksheets("Sheet1").Range("C2").Value = x
  Worksheets("Sheet1").Range("D2").Value = "South Wall"
  Call SolarHeatGaindesg
  tot = Worksheets("Sheet1").Range("M2").Value
  Worksheets("Sheet2").Activate
  Range("C2").Select
  y = x - 4
  ActiveCell.Offset(m, y) = tot
```

```
  Sum = Sum + tot
  a = a + 1
  Else
  'ActiveCell.Offset(m, x).Value = 0
  End If
  Next x
  avg = Sum / a
Range("C2").Select
ActiveCell.Offset(m, 16).Value = avg

Next n
End Sub
```

Table A2.1 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in April 2011

Hour (h)	Temperature (^{0}C)				
	Room R1	**Room R2**	**Room R3**	**Room R4**	**Outdoor air**
1	**26.4**	**26.6**	**26.6**	**26.3**	**18.0**
2	**26.1**	**26.4**	**26.2**	**26.0**	**17.2**
3	**25.8**	**26.1**	**25.8**	**25.7**	**16.4**
4	**25.5**	**25.8**	**25.3**	**25.3**	**15.8**
5	**25.2**	**25.4**	**24.8**	**24.9**	**15.3**
6	**24.8**	**25.1**	**24.4**	**24.5**	**14.8**
7	**24.6**	**24.9**	**24.4**	**24.3**	**15.9**
8	**24.7**	**25.1**	**24.4**	**24.5**	**20.3**
9	**24.9**	**25.4**	**24.6**	**24.8**	**24.5**
10	**25.3**	**25.8**	**24.9**	**25.1**	**28.1**
11	**25.8**	**26.2**	**25.3**	**25.3**	**30.6**
12	**26.3**	**26.6**	**25.8**	**25.6**	**32.0**
13	**26.8**	**27.1**	**26.3**	**25.9**	**32.5**
14	**27.4**	**27.6**	**27.0**	**26.3**	**32.8**
15	**27.9**	**28.1**	**27.8**	**26.9**	**32.4**
16	**28.4**	**28.6**	**28.5**	**27.5**	**31.9**
17	**28.5**	**28.7**	**28.8**	**27.9**	**30.4**
18	**28.4**	**28.5**	**28.8**	**27.9**	**28.9**
19	**27.9**	**28.1**	**28.3**	**27.6**	**26.2**
20	**27.5**	**27.7**	**28.0**	**27.3**	**23.4**
21	**27.3**	**27.5**	**27.8**	**27.2**	**21.9**
22	**27.1**	**27.3**	**27.6**	**27.0**	**20.8**
23	**27.1**	**27.3**	**27.5**	**27.0**	**19.9**
24	**26.9**	**27.1**	**27.2**	**26.8**	**18.9**
Average	**26.5**	**26.8**	**26.5**	**26.2**	**23.7**
Maximum	**28.5**	**28.7**	**28.8**	**27.9**	**32.8**
Minimum	**24.6**	**24.9**	**24.4**	**24.3**	**14.8**

Table A2.2 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in May 2011

Hour (h)	**Temperature (^{0}C)**				
	Room R1	**Room R2**	**Room R3**	**Room R4**	**Outdoor air**
1	**33.0**	**32.9**	**33.1**	**33.1**	**26.4**
2	**32.8**	**32.6**	**32.7**	**32.8**	**25.8**
3	**32.5**	**32.4**	**32.4**	**32.5**	**25.4**
4	**32.2**	**32.1**	**32.0**	**32.2**	**25.2**
5	**31.9**	**31.9**	**31.6**	**31.8**	**24.5**
6	**31.7**	**31.6**	**31.2**	**31.5**	**24.2**
7	**31.8**	**31.8**	**31.4**	**31.6**	**25.4**
8	**32.2**	**32.6**	**31.9**	**32.4**	**28.3**
9	**32.2**	**32.4**	**31.7**	**32.2**	**31.1**
10	**32.5**	**32.7**	**31.8**	**32.3**	**33.6**
11	**32.8**	**33.0**	**32.2**	**32.4**	**35.9**
12	**33.1**	**33.3**	**32.6**	**32.6**	**37.7**
13	**33.6**	**33.7**	**33.2**	**32.9**	**38.8**
14	**34.1**	**34.3**	**33.9**	**33.4**	**39.2**
15	**34.5**	**34.7**	**34.5**	**33.9**	**38.8**
16	**34.9**	**35.0**	**35.2**	**34.4**	**38.1**
17	**35.1**	**35.2**	**35.6**	**34.9**	**36.9**
18	**35.2**	**35.0**	**35.7**	**35.0**	**36.1**
19	**34.9**	**34.8**	**35.5**	**34.9**	**34.4**
20	**34.5**	**34.4**	**35.0**	**34.5**	**31.5**
21	**34.3**	**34.2**	**34.8**	**34.4**	**30.0**
22	**34.2**	**34.0**	**34.6**	**34.3**	**29.3**
23	**34.0**	**33.8**	**34.3**	**34.1**	**28.7**
24	**33.7**	**33.6**	**33.8**	**33.9**	**27.7**
Average	**33.4**	**33.4**	**33.4**	**33.3**	**31.4**
Maximum	**35.2**	**35.2**	**35.7**	**35.0**	**39.2**
Minimum	**31.7**	**31.6**	**31.2**	**31.5**	**24.2**

Table A2.3 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in June 2011

Hour (h)	**Temperature (^{0}C)**				
	Room R1	**Room R2**	**Room R3**	**Room R4**	**Outdoor air**
1	**34.4**	**33.9**	**34.0**	**33.7**	**28.4**
2	**34.2**	**33.7**	**33.8**	**33.4**	**28.0**
3	**34.0**	**33.5**	**33.5**	**33.2**	**27.6**
4	**33.8**	**33.3**	**33.2**	**32.9**	**27.2**
5	**33.6**	**33.1**	**32.9**	**32.7**	**27.1**
6	**33.4**	**32.9**	**32.7**	**32.4**	**26.8**
7	**33.7**	**33.5**	**33.0**	**32.8**	**27.9**
8	**34.2**	**34.4**	**33.2**	**33.4**	**29.9**
9	**34.2**	**34.0**	**33.2**	**33.3**	**32.0**
10	**34.3**	**34.1**	**33.4**	**33.4**	**34.4**
11	**34.6**	**34.4**	**33.6**	**33.7**	**36.5**
12	**34.9**	**34.7**	**33.9**	**34.0**	**37.9**
13	**35.2**	**35.1**	**34.3**	**34.3**	**39.1**
14	**35.5**	**35.4**	**34.8**	**34.7**	**39.6**
15	**35.8**	**35.7**	**35.2**	**35.0**	**39.3**
16	**36.1**	**36.0**	**35.7**	**35.4**	**38.7**
17	**36.2**	**36.1**	**36.0**	**35.6**	**37.3**
18	**36.2**	**35.9**	**36.1**	**35.6**	**36.1**
19	**35.9**	**35.6**	**35.9**	**35.4**	**34.4**
20	**35.6**	**35.3**	**35.6**	**35.1**	**32.4**
21	**35.4**	**35.1**	**35.4**	**34.9**	**31.1**
22	**35.3**	**34.9**	**35.2**	**34.8**	**30.0**
23	**35.1**	**34.8**	**35.0**	**34.6**	**29.5**
24	**35.0**	**34.5**	**34.8**	**34.4**	**28.9**
Average	**34.8**	**34.6**	**34.3**	**34.1**	**32.5**
Maximum	**36.2**	**36.1**	**36.1**	**35.6**	**39.6**
Minimum	**33.4**	**32.9**	**32.7**	**32.4**	**26.8**

Table A2.4 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in July 2011

Hour (h)	Temperature (^{0}C)				
	Room R1	**Room R2**	**Room R3**	**Room R4**	**Outdoor air**
1	**31.9**	**32.1**	**31.5**	**31.4**	**26.1**
2	**31.8**	**32.0**	**31.3**	**31.2**	**25.8**
3	**31.6**	**31.8**	**31.1**	**31.1**	**25.5**
4	**31.4**	**31.6**	**30.8**	**30.9**	**25.2**
5	**31.3**	**31.5**	**30.6**	**30.7**	**25.0**
6	**31.1**	**31.3**	**30.4**	**30.5**	**24.9**
7	**31.3**	**31.7**	**30.7**	**30.7**	**25.9**
8	**31.8**	**32.6**	**31.2**	**31.2**	**27.9**
9	**31.9**	**32.4**	**31.2**	**31.3**	**29.9**
10	**32.1**	**32.5**	**31.3**	**31.5**	**31.9**
11	**32.2**	**32.5**	**31.4**	**31.6**	**33.3**
12	**32.4**	**32.6**	**31.6**	**31.7**	**34.3**
13	**32.6**	**32.7**	**31.8**	**31.9**	**35.2**
14	**32.8**	**32.9**	**32.2**	**32.1**	**35.2**
15	**33.1**	**33.2**	**32.6**	**32.4**	**35.2**
16	**33.4**	**33.5**	**33.0**	**32.7**	**34.4**
17	**33.4**	**33.5**	**33.1**	**32.8**	**31.9**
18	**33.3**	**33.3**	**33.0**	**32.7**	**30.6**
19	**33.1**	**33.1**	**32.9**	**32.5**	**29.7**
20	**32.8**	**32.9**	**32.6**	**32.3**	**28.5**
21	**32.8**	**32.9**	**32.5**	**32.3**	**28.0**
22	**32.6**	**32.8**	**32.4**	**32.2**	**27.5**
23	**32.5**	**32.7**	**32.2**	**32.1**	**27.1**
24	**32.4**	**32.5**	**32.0**	**31.9**	**26.7**
Average	**32.3**	**32.5**	**31.8**	**31.7**	**29.4**
Maximum	**33.4**	**33.5**	**33.1**	**32.8**	**35.2**
Minimum	**31.1**	**31.3**	**30.4**	**30.5**	**24.9**

Table A2.5 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in August 2011

Hour (h)	Temperature (^{0}C)				
	Room R1	**Room R2**	**Room R3**	**Room R4**	**Outdoor air**
1	**29.9**	**30.1**	**29.6**	**29.5**	**24.5**
2	**29.8**	**30.0**	**29.4**	**29.3**	**24.4**
3	**29.6**	**29.9**	**29.2**	**29.2**	**24.2**
4	**29.5**	**29.7**	**29.0**	**29.0**	**24.2**
5	**29.3**	**29.6**	**28.8**	**28.8**	**24.0**
6	**29.2**	**29.4**	**28.6**	**28.6**	**23.9**
7	**29.8**	**29.9**	**28.8**	**29.3**	**24.8**
8	**30.0**	**30.3**	**29.1**	**29.4**	**26.5**
9	**29.8**	**30.2**	**29.2**	**29.4**	**27.9**
10	**29.9**	**30.3**	**29.4**	**29.5**	**29.3**
11	**30.1**	**30.4**	**29.6**	**29.7**	**30.5**
12	**30.3**	**30.6**	**29.9**	**29.8**	**31.6**
13	**30.6**	**30.8**	**30.2**	**30.1**	**32.2**
14	**30.8**	**31.0**	**30.4**	**30.2**	**32.3**
15	**31.0**	**31.3**	**30.7**	**30.5**	**31.7**
16	**31.2**	**31.4**	**30.9**	**30.6**	**31.0**
17	**31.6**	**31.7**	**31.3**	**31.1**	**30.3**
18	**31.4**	**31.4**	**31.1**	**30.9**	**28.2**
19	**30.8**	**31.0**	**30.8**	**30.4**	**26.9**
20	**30.6**	**30.8**	**30.5**	**30.2**	**26.1**
21	**30.5**	**30.7**	**30.4**	**30.1**	**25.7**
22	**30.4**	**30.6**	**30.2**	**29.9**	**25.3**
23	**30.2**	**30.4**	**30.1**	**29.8**	**25.0**
24	**30.1**	**30.3**	**29.9**	**29.7**	**24.8**
Average	**30.3**	**30.5**	**29.9**	**29.8**	**27.3**
Maximum	**31.6**	**31.7**	**31.3**	**31.1**	**32.3**
Minimum	**29.2**	**29.4**	**28.6**	**28.6**	**23.9**

Table A2.6 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in September 2011

Hour (h)	Temperature (^{0}C)				
	Room R1	Room R2	Room R3	Room R4	Outdoor air
1	**28.9**	**29.3**	**28.7**	**28.5**	**22.7**
2	**28.7**	**29.1**	**28.4**	**28.3**	**22.5**
3	**28.5**	**29.0**	**28.2**	**28.1**	**22.3**
4	**28.4**	**28.8**	**28.0**	**27.9**	**22.0**
5	**28.2**	**28.6**	**27.7**	**27.7**	**21.9**
6	**28.0**	**28.4**	**27.5**	**27.5**	**21.9**
7	**28.1**	**28.5**	**27.5**	**27.6**	**22.8**
8	**28.3**	**28.9**	**27.8**	**27.9**	**25.0**
9	**28.5**	**29.2**	**28.1**	**28.2**	**27.1**
10	**28.7**	**29.4**	**28.3**	**28.5**	**29.1**
11	**29.0**	**29.6**	**28.5**	**28.6**	**30.8**
12	**29.3**	**29.8**	**28.8**	**28.8**	**31.7**
13	**29.5**	**30.0**	**29.1**	**28.9**	**32.3**
14	**29.6**	**30.1**	**29.3**	**29.1**	**32.3**
15	**29.9**	**30.4**	**29.6**	**29.3**	**31.7**
16	**30.1**	**30.6**	**30.0**	**29.7**	**30.5**
17	**31.6**	**32.7**	**30.4**	**31.7**	**29.4**
18	**30.3**	**31.2**	**30.0**	**30.4**	**27.1**
19	**29.6**	**30.1**	**29.7**	**29.3**	**25.2**
20	**29.5**	**29.9**	**29.5**	**29.2**	**24.4**
21	**29.3**	**29.7**	**29.4**	**29.0**	**23.8**
22	**29.2**	**29.6**	**29.2**	**28.9**	**23.4**
23	**29.1**	**29.5**	**29.0**	**28.8**	**23.0**
24	**28.9**	**29.3**	**28.8**	**28.6**	**22.8**
Average	**29.1**	**29.7**	**28.8**	**28.8**	**26.1**
Maximum	**31.6**	**32.7**	**30.4**	**31.7**	**32.3**
Minimum	**28.0**	**28.4**	**27.5**	**27.5**	**21.9**

Table A2.7 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in October 2011

Hour (h)	Temperature (^{0}C)				
	Room R1	**Room R2**	**Room R3**	**Room R4**	**Outdoor air**
1	**27.0**	**27.9**	**27.3**	**26.8**	**17.3**
2	**26.8**	**27.7**	**27.0**	**26.5**	**17.0**
3	**26.6**	**27.4**	**26.6**	**26.2**	**16.7**
4	**26.3**	**27.2**	**26.2**	**25.9**	**16.2**
5	**26.1**	**26.9**	**25.8**	**25.6**	**15.9**
6	**25.8**	**26.7**	**25.5**	**25.3**	**15.4**
7	**25.6**	**26.5**	**25.2**	**25.1**	**15.8**
8	**25.8**	**26.9**	**25.5**	**25.5**	**20.1**
9	**26.0**	**27.4**	**26.0**	**26.1**	**25.7**
10	**26.5**	**27.8**	**26.4**	**26.5**	**29.9**
11	**27.0**	**28.0**	**26.8**	**26.7**	**32.4**
12	**27.4**	**28.1**	**27.1**	**26.9**	**34.3**
13	**27.8**	**28.5**	**27.6**	**27.2**	**35.3**
14	**28.1**	**28.9**	**28.1**	**27.5**	**35.3**
15	**28.5**	**29.3**	**28.6**	**27.8**	**34.8**
16	**28.8**	**29.7**	**29.1**	**28.2**	**33.1**
17	**29.7**	**32.3**	**29.7**	**30.2**	**30.2**
18	**28.6**	**30.5**	**29.0**	**28.8**	**26.6**
19	**28.1**	**29.2**	**28.8**	**28.0**	**23.4**
20	**27.7**	**28.6**	**28.5**	**27.7**	**21.7**
21	**27.6**	**28.5**	**28.3**	**27.6**	**20.6**
22	**27.5**	**28.3**	**28.1**	**27.4**	**19.4**
23	**27.3**	**28.1**	**27.8**	**27.2**	**18.4**
24	**27.1**	**27.9**	**27.5**	**27.0**	**17.8**
Average	**27.2**	**28.3**	**27.4**	**27.0**	**23.9**
Maximum	**29.7**	**32.3**	**29.7**	**30.2**	**35.3**
Minimum	**25.6**	**26.5**	**25.2**	**25.1**	**15.4**

Table A2.8 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in November 2011

Hour (h)	Temperature (^{0}C)				
	Room R1	**Room R2**	**Room R3**	**Room R4**	**Outdoor air**
1	**22.6**	**23.4**	**23.5**	**22.7**	**13.3**
2	**22.4**	**23.2**	**23.2**	**22.5**	**12.7**
3	**22.2**	**22.9**	**22.8**	**22.2**	**12.4**
4	**22.0**	**22.7**	**22.5**	**21.9**	**12.0**
5	**21.7**	**22.5**	**22.2**	**21.7**	**11.6**
6	**21.5**	**22.3**	**21.8**	**21.4**	**11.3**
7	**21.3**	**22.1**	**21.6**	**21.2**	**11.9**
8	**21.4**	**22.4**	**21.9**	**21.6**	**15.0**
9	**21.7**	**23.0**	**22.4**	**22.2**	**20.5**
10	**22.3**	**23.4**	**23.0**	**22.7**	**25.5**
11	**22.9**	**23.8**	**23.6**	**23.1**	**28.6**
12	**23.4**	**24.1**	**24.1**	**23.4**	**30.3**
13	**23.8**	**24.4**	**24.3**	**23.6**	**31.1**
14	**24.1**	**24.8**	**24.7**	**23.7**	**31.0**
15	**24.3**	**25.0**	**25.0**	**23.7**	**30.0**
16	**24.3**	**25.2**	**25.2**	**23.8**	**28.1**
17	**24.0**	**25.0**	**25.1**	**23.7**	**24.8**
18	**23.6**	**24.4**	**24.8**	**23.5**	**20.3**
19	**23.4**	**24.1**	**24.6**	**23.4**	**18.1**
20	**23.2**	**24.0**	**24.5**	**23.3**	**17.1**
21	**23.1**	**23.9**	**24.4**	**23.3**	**16.0**
22	**23.0**	**23.7**	**24.1**	**23.2**	**15.1**
23	**22.8**	**23.6**	**23.9**	**23.0**	**14.2**
24	**22.7**	**23.4**	**23.6**	**22.8**	**13.5**
Average	**22.8**	**23.6**	**23.6**	**22.8**	**19.4**
Maximum	**24.3**	**25.2**	**25.2**	**23.8**	**31.1**
Minimum	**21.3**	**22.1**	**21.6**	**21.2**	**11.3**

Table A2.9 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in December 2011

Hour (h)	Temperature (^0C)				
	Room R1	**Room R2**	**Room R3**	**Room R4**	**Outdoor air**
1	**16.2**	**17.0**	**17.3**	**16.3**	**6.9**
2	**16.0**	**16.8**	**17.0**	**16.0**	**6.4**
3	**15.8**	**16.6**	**16.7**	**15.8**	**5.9**
4	**15.6**	**16.3**	**16.3**	**15.6**	**5.5**
5	**15.3**	**16.1**	**16.0**	**15.3**	**5.0**
6	**15.1**	**15.9**	**15.7**	**15.0**	**4.7**
7	**14.9**	**15.6**	**15.3**	**14.8**	**4.5**
8	**14.7**	**15.5**	**15.2**	**14.7**	**5.4**
9	**14.9**	**16.0**	**15.7**	**15.3**	**9.5**
10	**15.4**	**16.6**	**16.3**	**15.9**	**14.5**
11	**16.2**	**17.1**	**17.1**	**16.6**	**20.0**
12	**16.8**	**17.5**	**17.7**	**17.0**	**22.7**
13	**17.2**	**17.9**	**18.0**	**17.2**	**24.0**
14	**17.6**	**18.3**	**18.4**	**17.4**	**24.7**
15	**17.9**	**18.6**	**18.7**	**17.3**	**24.3**
16	**18.0**	**18.9**	**19.0**	**17.3**	**23.0**
17	**17.7**	**18.7**	**18.9**	**17.2**	**20.0**
18	**17.2**	**18.1**	**18.5**	**16.9**	**15.1**
19	**16.9**	**17.7**	**18.3**	**16.8**	**12.5**
20	**16.8**	**17.6**	**18.1**	**16.8**	**11.2**
21	**16.6**	**17.4**	**18.0**	**16.7**	**10.0**
22	**16.5**	**17.3**	**17.9**	**16.6**	**9.0**
23	**16.4**	**17.1**	**17.7**	**16.5**	**8.3**
24	**16.3**	**17.0**	**17.4**	**16.3**	**7.6**
Average	**16.3**	**17.2**	**17.3**	**16.3**	**12.5**
Maximum	**18.0**	**18.9**	**19.0**	**17.4**	**24.7**
Minimum	**14.7**	**15.5**	**15.2**	**14.7**	**4.5**

Table A2.10 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in January 2012

Hour	**Temperature (^{0}C)**				
(h)	**Room R1**	**Room R2**	**Room R3**	**Room R4**	**Outdoor air**
1	**13.6**	**14.3**	**14.5**	**13.6**	**5.8**
2	**13.4**	**14.1**	**14.2**	**13.4**	**5.3**
3	**13.2**	**13.9**	**13.9**	**13.2**	**5.0**
4	**13.0**	**13.7**	**13.7**	**13.0**	**4.7**
5	**12.8**	**13.5**	**13.4**	**12.7**	**4.3**
6	**12.6**	**13.3**	**13.1**	**12.5**	**4.0**
7	**12.4**	**13.1**	**12.8**	**12.3**	**3.7**
8	**12.4**	**13.3**	**12.9**	**12.5**	**5.8**
9	**12.7**	**13.7**	**13.4**	**13.0**	**9.6**
10	**13.2**	**14.1**	**13.9**	**13.5**	**14.1**
11	**13.9**	**14.6**	**14.6**	**14.0**	**17.3**
12	**14.4**	**15.0**	**15.1**	**14.4**	**19.4**
13	**14.7**	**15.2**	**15.2**	**14.5**	**20.4**
14	**15.0**	**15.6**	**15.5**	**14.6**	**20.7**
15	**15.2**	**15.9**	**15.9**	**14.6**	**20.2**
16	**15.4**	**16.2**	**16.2**	**14.7**	**18.7**
17	**15.0**	**15.9**	**16.0**	**14.6**	**15.8**
18	**14.6**	**15.4**	**15.7**	**14.4**	**12.3**
19	**14.4**	**15.1**	**15.6**	**14.3**	**10.6**
20	**14.3**	**15.0**	**15.5**	**14.3**	**9.2**
21	**14.2**	**14.8**	**15.4**	**14.2**	**8.2**
22	**14.1**	**14.7**	**15.2**	**14.1**	**7.2**
23	**13.9**	**14.6**	**15.0**	**14.0**	**6.5**
24	**13.8**	**14.5**	**14.8**	**13.8**	**6.0**
Average	**13.9**	**14.6**	**14.6**	**13.8**	**10.6**
Maximum	**15.4**	**16.2**	**16.2**	**14.7**	**20.7**
Minimum	**12.4**	**13.1**	**12.8**	**12.3**	**3.7**

Table A2.11 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in February 2012

Hour (h)	Temperature (^{0}C)				
	Room R1	**Room R2**	**Room R3**	**Room R4**	**Outdoor air**
1	**16.2**	**17.0**	**17.1**	**16.3**	**7.7**
2	**16.0**	**16.8**	**16.8**	**16.0**	**7.1**
3	**15.8**	**16.5**	**16.5**	**15.8**	**6.5**
4	**15.6**	**16.3**	**16.1**	**15.5**	**6.0**
5	**15.3**	**16.1**	**15.8**	**15.2**	**5.4**
6	**15.1**	**15.8**	**15.4**	**14.9**	**5.0**
7	**14.8**	**15.6**	**15.1**	**14.7**	**5.1**
8	**14.9**	**15.9**	**15.4**	**15.0**	**8.4**
9	**15.2**	**16.5**	**15.9**	**15.6**	**13.5**
10	**15.7**	**16.9**	**16.4**	**16.1**	**17.9**
11	**16.2**	**17.2**	**16.8**	**16.4**	**20.7**
12	**16.7**	**17.4**	**17.1**	**16.5**	**22.7**
13	**17.1**	**17.7**	**17.5**	**16.8**	**23.8**
14	**17.5**	**18.2**	**18.0**	**17.1**	**24.4**
15	**17.9**	**18.7**	**18.5**	**17.3**	**24.1**
16	**18.1**	**18.9**	**18.8**	**17.5**	**22.7**
17	**18.3**	**19.7**	**19.0**	**18.2**	**20.3**
18	**17.7**	**18.8**	**18.7**	**17.6**	**16.9**
19	**17.3**	**18.2**	**18.4**	**17.3**	**14.6**
20	**17.2**	**17.9**	**18.3**	**17.2**	**13.1**
21	**17.0**	**17.8**	**18.2**	**17.1**	**12.0**
22	**16.9**	**17.7**	**18.1**	**17.0**	**10.8**
23	**16.8**	**17.5**	**17.9**	**16.9**	**9.5**
24	**16.6**	**17.3**	**17.6**	**16.7**	**8.5**
Average	**16.5**	**17.3**	**17.2**	**16.4**	**13.6**
Maximum	**18.3**	**19.7**	**19.0**	**18.2**	**24.4**
Minimum	**14.8**	**15.6**	**15.1**	**14.7**	**5.0**

Table A2.12 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in March 2012

Hour (h)	Temperature (^{0}C)				
	Room R1	Room R2	Room R3	Room R4	Outdoor air
1	22.3	22.9	23.2	22.6	14.7
2	22.1	22.7	22.9	22.4	14.1
3	21.9	22.4	22.5	22.1	13.4
4	21.6	22.2	22.2	21.8	12.8
5	21.3	21.9	21.8	21.5	12.2
6	21.0	21.6	21.4	21.1	11.7
7	20.9	21.5	21.2	20.9	12.0
8	21.0	21.8	21.4	21.2	15.5
9	21.2	22.2	21.8	21.7	20.1
10	21.6	22.7	22.3	22.2	24.0
11	22.0	22.9	22.5	22.3	26.6
12	22.4	23.1	22.8	22.5	28.4
13	22.7	23.3	23.0	22.5	29.6
14	23.5	24.1	23.8	23.2	30.5
15	23.9	24.5	24.4	23.6	30.3
16	24.3	25.0	24.9	24.1	29.5
17	25.2	26.8	26.2	25.9	27.7
18	25.0	26.4	26.0	25.5	25.2
19	24.1	24.8	25.0	24.3	22.4
20	23.7	24.3	24.8	24.0	20.7
21	23.6	24.1	24.6	23.8	19.4
22	23.4	24.0	24.5	23.7	18.1
23	23.2	23.8	24.2	23.6	16.9
24	23.0	23.6	23.9	23.3	15.9
Average	22.7	23.4	23.4	22.9	20.5
Maximum	25.2	26.8	26.2	25.9	30.5
Minimum	20.9	21.5	21.2	20.9	11.7

Table A2.13 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature during April 1st - 15th 2012

Hour	Temperature (^{0}C)				
(h)	Room R1	Room R2	Room R3	Room R4	Outdoor air
1	**29.3**	**29.6**	**29.6**	**29.2**	**21.7**
2	**29.1**	**29.4**	**29.2**	**28.9**	**21.0**
3	**28.8**	**29.2**	**28.9**	**28.6**	**20.5**
4	**28.6**	**28.9**	**28.5**	**28.3**	**19.8**
5	**28.3**	**28.6**	**28.2**	**28.0**	**19.5**
6	**28.0**	**28.4**	**27.9**	**27.8**	**19.3**
7	**29.0**	**29.5**	**29.0**	**28.4**	**21.3**
8	**28.7**	**29.5**	**28.6**	**28.4**	**25.1**
9	**28.6**	**29.3**	**28.5**	**28.6**	**28.7**
10	**28.8**	**29.4**	**28.6**	**28.7**	**31.4**
11	**29.1**	**29.5**	**28.8**	**28.9**	**33.4**
12	**29.3**	**29.7**	**29.0**	**29.0**	**34.4**
13	**30.1**	**30.5**	**29.7**	**29.6**	**36.3**
14	**30.5**	**30.9**	**30.2**	**29.9**	**36.0**
15	**30.7**	**31.1**	**30.6**	**30.1**	**34.6**
16	**31.0**	**31.4**	**31.2**	**30.5**	**33.6**
17	**31.7**	**32.1**	**32.6**	**31.3**	**32.1**
18	**31.1**	**31.5**	**31.8**	**30.8**	**30.0**
19	**30.5**	**30.8**	**30.8**	**30.2**	**27.7**
20	**30.2**	**30.5**	**30.6**	**30.0**	**26.2**
21	**30.0**	**30.3**	**30.5**	**29.9**	**24.9**
22	**29.8**	**30.1**	**30.3**	**29.7**	**23.9**
23	**29.6**	**29.9**	**30.0**	**29.6**	**23.0**
24	**29.4**	**29.7**	**29.7**	**29.3**	**22.2**
Average	**29.6**	**30.0**	**29.7**	**29.3**	**26.9**
Maximum	**31.7**	**32.1**	**32.6**	**31.3**	**36.3**
Minimum	**28.0**	**28.4**	**27.9**	**27.8**	**19.3**

Table A2.14 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature during May 1st - 15th 2012

Hour	Temperature (^{0}C)				
(h)	Room R1	Room R2	Room R3	Room R4	Outdoor air
1	**31.0**	**31.3**	**31.1**	**31.1**	**24.3**
2	**30.7**	**31.1**	**30.8**	**30.9**	**23.5**
3	**30.5**	**30.9**	**30.4**	**30.6**	**23.5**
4	**30.3**	**30.7**	**30.2**	**30.4**	**23.0**
5	**30.1**	**30.4**	**29.9**	**30.1**	**22.5**
6	**30.0**	**30.3**	**29.7**	**29.9**	**22.7**
7	**31.9**	**32.2**	**31.1**	**30.5**	**25.2**
8	**31.2**	**31.6**	**30.6**	**30.7**	**28.2**
9	**31.0**	**31.4**	**30.4**	**30.7**	**30.8**
10	**31.2**	**31.5**	**30.6**	**30.9**	**33.9**
11	**31.4**	**31.7**	**30.8**	**31.1**	**36.4**
12	**31.8**	**32.0**	**31.1**	**31.3**	**36.7**
13	**32.2**	**32.4**	**31.6**	**31.6**	**38.5**
14	**32.5**	**32.7**	**32.0**	**31.8**	**37.4**
15	**32.6**	**32.9**	**32.3**	**32.0**	**35.5**
16	**32.6**	**32.9**	**32.5**	**32.1**	**33.0**
17	**32.6**	**32.9**	**32.6**	**32.2**	**31.9**
18	**32.7**	**32.9**	**32.8**	**32.4**	**31.8**
19	**32.4**	**32.5**	**32.5**	**32.1**	**29.7**
20	**32.1**	**32.3**	**32.3**	**32.0**	**27.2**
21	**31.9**	**32.1**	**32.1**	**31.9**	**26.5**
22	**31.7**	**32.0**	**32.0**	**31.8**	**26.4**
23	**31.5**	**31.8**	**31.7**	**31.6**	**26.6**
24	**31.3**	**31.6**	**31.4**	**31.4**	**25.7**
Average	**31.5**	**31.8**	**31.4**	**31.3**	**29.2**
Maximum	**32.7**	**32.9**	**32.8**	**32.4**	**38.5**
Minimum	**30.0**	**30.3**	**29.7**	**29.9**	**22.5**

Table A2.15 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature during June 1st - 15th 2012

Hour (h)	Temperature (^{0}C)				
	Room R1	Room R2	Room R3	Room R4	Outdoor air
1	34.6	35.4	35.4	35.5	28.5
2	34.4	35.2	35.1	35.3	27.9
3	34.1	34.9	34.8	35.0	27.5
4	33.8	34.7	34.5	34.8	27.2
5	33.6	34.5	34.2	34.5	26.7
6	33.4	34.4	33.9	34.3	26.9
7	34.8	35.8	34.7	35.5	28.9
8	34.6	35.8	34.7	35.6	31.5
9	34.5	35.4	34.6	35.2	33.5
10	34.8	35.5	34.7	35.2	35.7
11	35.3	35.7	35.0	35.3	37.8
12	35.7	36.0	35.4	35.5	39.0
13	36.3	36.4	35.8	35.8	40.2
14	36.7	36.8	36.2	36.1	40.6
15	37.0	37.0	36.6	36.4	39.5
16	37.2	37.3	37.0	36.7	39.8
17	37.4	37.5	37.3	37.0	38.2
18	36.9	37.1	37.2	36.8	35.7
19	36.4	36.7	36.8	36.5	33.6
20	36.0	36.3	36.5	36.3	32.0
21	35.6	36.1	36.3	36.1	30.6
22	35.4	35.9	36.1	36.0	29.6
23	35.1	35.7	35.8	35.8	29.1
24	34.7	35.5	35.5	35.6	28.8
Average	35.4	35.9	35.6	35.7	32.9
Maximum	37.4	37.5	37.3	37.0	40.6
Minimum	33.4	34.4	33.9	34.3	26.7

Table A2.16 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature during July 1st - 15th 2012

Hour (h)	Temperature (^{0}C)				
	Room R1	**Room R2**	**Room R3**	**Room R4**	**Outdoor air**
1	**34.6**	**34.6**	**34.4**	**34.6**	**28.4**
2	**34.4**	**34.5**	**34.2**	**34.4**	**28.1**
3	**34.2**	**34.3**	**33.9**	**34.2**	**27.6**
4	**34.0**	**34.1**	**33.7**	**34.0**	**27.4**
5	**33.8**	**33.9**	**33.4**	**33.8**	**27.1**
6	**33.7**	**33.8**	**33.2**	**33.6**	**27.3**
7	**34.6**	**34.9**	**33.8**	**34.6**	**28.6**
8	**34.4**	**34.9**	**33.8**	**34.6**	**30.2**
9	**34.3**	**34.7**	**33.8**	**34.3**	**31.7**
10	**34.5**	**34.8**	**33.9**	**34.3**	**33.8**
11	**34.7**	**34.9**	**34.1**	**34.3**	**34.8**
12	**34.9**	**35.1**	**34.4**	**34.5**	**35.9**
13	**35.2**	**35.3**	**34.7**	**34.6**	**36.5**
14	**35.4**	**35.5**	**34.9**	**34.8**	**36.7**
15	**35.7**	**35.8**	**35.3**	**35.1**	**37.0**
16	**35.9**	**36.0**	**35.5**	**35.3**	**35.6**
17	**36.0**	**36.0**	**35.7**	**35.4**	**35.2**
18	**35.9**	**35.9**	**35.7**	**35.4**	**34.1**
19	**35.6**	**35.6**	**35.4**	**35.2**	**32.4**
20	**35.2**	**35.2**	**35.1**	**34.9**	**30.6**
21	**35.0**	**35.0**	**34.9**	**34.7**	**29.7**
22	**34.8**	**34.8**	**34.7**	**34.6**	**28.9**
23	**34.6**	**34.6**	**34.5**	**34.5**	**28.4**
24	**34.4**	**34.4**	**34.3**	**34.3**	**28.3**
Average	**34.8**	**34.9**	**34.5**	**34.6**	**31.4**
Maximum	**36.0**	**36.0**	**35.7**	**35.4**	**37.0**
Minimum	**33.7**	**33.8**	**33.2**	**33.6**	**27.1**

Table A2.17 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature during August 1st - 15th 2012

Hour (h)	**Temperature (^{0}C)**				
	Room R1	**Room R2**	**Room R3**	**Room R4**	**Outdoor air**
1	**31.3**	**31.4**	**31.1**	**31.0**	**25.9**
2	**31.1**	**31.3**	**31.0**	**30.9**	**25.7**
3	**31.0**	**31.2**	**30.8**	**30.7**	**25.4**
4	**30.8**	**31.0**	**30.6**	**30.6**	**25.1**
5	**30.6**	**30.8**	**30.3**	**30.4**	**24.9**
6	**30.4**	**30.6**	**30.1**	**30.2**	**24.8**
7	**30.7**	**31.0**	**30.3**	**30.4**	**25.8**
8	**31.0**	**31.5**	**30.7**	**31.0**	**27.5**
9	**31.2**	**31.5**	**30.8**	**30.9**	**29.3**
10	**31.4**	**31.6**	**31.0**	**31.0**	**30.6**
11	**31.6**	**31.8**	**31.2**	**31.2**	**32.2**
12	**31.9**	**32.1**	**31.5**	**31.3**	**33.0**
13	**32.2**	**32.3**	**31.8**	**31.5**	**33.1**
14	**32.4**	**32.5**	**32.0**	**31.7**	**33.5**
15	**32.6**	**32.7**	**32.3**	**31.9**	**32.9**
16	**32.7**	**32.8**	**32.4**	**32.0**	**31.6**
17	**32.8**	**32.9**	**32.6**	**32.1**	**30.6**
18	**32.6**	**32.6**	**32.5**	**31.9**	**29.4**
19	**32.3**	**32.3**	**32.2**	**31.7**	**28.3**
20	**32.0**	**32.1**	**32.0**	**31.6**	**27.6**
21	**31.9**	**32.0**	**31.9**	**31.5**	**27.1**
22	**31.8**	**31.9**	**31.8**	**31.4**	**26.7**
23	**31.6**	**31.8**	**31.6**	**31.3**	**26.3**
24	**31.5**	**31.6**	**31.4**	**31.2**	**26.1**
Average	**31.6**	**31.8**	**31.4**	**31.2**	**28.5**
Maximum	**32.8**	**32.9**	**32.6**	**32.1**	**33.5**
Minimum	**30.4**	**30.6**	**30.1**	**30.2**	**24.8**

Table A2.18 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature during September 1st - 15th 2012

Hour (h)	**Temperature (^{0}C)**				
	Room R1	**Room R2**	**Room R3**	**Room R4**	**Outdoor air**
1	**29.5**	**29.7**	**29.3**	**29.1**	**24.6**
2	**29.3**	**29.6**	**29.1**	**28.9**	**24.3**
3	**29.2**	**29.5**	**28.9**	**28.8**	**23.9**
4	**29.0**	**29.3**	**28.7**	**28.6**	**23.9**
5	**28.8**	**29.2**	**28.5**	**28.4**	**23.7**
6	**28.7**	**29.0**	**28.3**	**28.3**	**23.7**
7	**29.2**	**29.6**	**29.1**	**28.9**	**24.7**
8	**29.1**	**29.8**	**29.1**	**29.2**	**26.6**
9	**29.3**	**29.9**	**29.1**	**29.1**	**28.2**
10	**29.5**	**30.0**	**29.3**	**29.2**	**29.7**
11	**29.8**	**30.2**	**29.5**	**29.3**	**30.8**
12	**30.0**	**30.4**	**29.7**	**29.4**	**31.3**
13	**30.2**	**30.6**	**29.9**	**29.6**	**31.3**
14	**30.4**	**30.7**	**30.2**	**29.7**	**31.2**
15	**30.6**	**31.0**	**30.4**	**29.9**	**30.4**
16	**30.9**	**31.1**	**30.7**	**30.2**	**30.0**
17	**31.8**	**32.3**	**31.5**	**31.1**	**29.2**
18	**30.9**	**31.3**	**30.8**	**30.2**	**27.3**
19	**30.3**	**30.6**	**30.3**	**29.8**	**26.3**
20	**30.1**	**30.4**	**30.2**	**29.7**	**25.9**
21	**30.0**	**30.3**	**30.0**	**29.6**	**25.4**
22	**29.8**	**30.1**	**29.9**	**29.5**	**25.2**
23	**29.7**	**30.0**	**29.7**	**29.4**	**25.0**
24	**29.6**	**29.9**	**29.5**	**29.3**	**24.8**
Average	**29.8**	**30.2**	**29.7**	**29.4**	**27.0**
Maximum	**31.8**	**32.3**	**31.5**	**31.1**	**31.3**
Minimum	**28.7**	**29.0**	**28.3**	**28.3**	**23.7**

Table A2.19 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature during April 16th - 30th 2012

Hour (h)	Temperature (^0C)				
	Room R1	**Room R2**	**Room R3**	**Room R4**	**Outdoor air**
1	**25.7**	**25.8**	**25.6**	**25.2**	**20.3**
2	**25.3**	**25.3**	**25.2**	**24.8**	**19.9**
3	**25.0**	**25.0**	**24.8**	**24.5**	**19.7**
4	**24.5**	**24.5**	**24.3**	**24.0**	**19.2**
5	**24.2**	**24.2**	**23.8**	**23.6**	**18.7**
6	**23.9**	**23.8**	**23.4**	**23.2**	**18.4**
7	**24.7**	**24.4**	**24.6**	**24.2**	**19.7**
8	**26.1**	**26.5**	**26.6**	**26.1**	**23.4**
9	**26.4**	**26.8**	**26.3**	**26.3**	**27.0**
10	**26.7**	**27.0**	**26.4**	**26.5**	**29.6**
11	**26.9**	**27.2**	**26.6**	**26.7**	**31.3**
12	**27.2**	**27.5**	**26.9**	**26.9**	**32.1**
13	**27.5**	**27.7**	**27.3**	**27.1**	**32.5**
14	**28.0**	**28.2**	**27.7**	**27.5**	**33.2**
15	**28.3**	**28.5**	**28.2**	**27.8**	**32.5**
16	**28.6**	**28.8**	**28.6**	**28.2**	**32.3**
17	**28.8**	**29.0**	**29.0**	**28.4**	**31.3**
18	**28.5**	**28.7**	**29.3**	**28.3**	**29.3**
19	**28.1**	**28.2**	**28.5**	**27.9**	**27.1**
20	**27.7**	**27.8**	**27.9**	**27.4**	**25.2**
21	**27.2**	**27.3**	**27.5**	**27.0**	**24.0**
22	**26.5**	**26.7**	**26.9**	**26.3**	**22.1**
23	**25.9**	**26.0**	**26.2**	**25.6**	**21.5**
24	**25.4**	**25.5**	**25.6**	**25.1**	**20.8**
Average	**26.5**	**26.7**	**26.6**	**26.2**	**25.5**
Maximum	**28.8**	**29.0**	**29.3**	**28.4**	**33.2**
Minimum	**23.9**	**23.8**	**23.4**	**23.2**	**18.4**

Table A2.20 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature during May 16th – 31st 2012

Hour (h)	**Temperature (^0C)**				
	Room R1	**Room R2**	**Room R3**	**Room R4**	**Outdoor air**
1	**32.7**	**33.0**	**33.0**	**33.0**	**27.4**
2	**32.1**	**32.5**	**32.3**	**32.4**	**26.7**
3	**31.5**	**32.0**	**31.8**	**32.0**	**26.2**
4	**31.3**	**31.8**	**31.5**	**31.7**	**25.7**
5	**31.0**	**31.4**	**31.0**	**31.2**	**24.8**
6	**31.6**	**31.8**	**31.1**	**31.3**	**25.4**
7	**33.5**	**33.9**	**32.7**	**33.5**	**28.2**
8	**33.7**	**34.1**	**33.0**	**33.6**	**31.8**
9	**33.7**	**33.9**	**33.0**	**33.4**	**34.8**
10	**33.9**	**34.1**	**33.2**	**33.5**	**37.1**
11	**34.2**	**34.4**	**33.5**	**33.7**	**39.3**
12	**34.7**	**34.8**	**34.0**	**34.0**	**40.9**
13	**35.2**	**35.2**	**34.5**	**34.4**	**41.7**
14	**35.7**	**35.7**	**35.1**	**34.9**	**41.8**
15	**36.2**	**36.1**	**35.7**	**35.4**	**41.6**
16	**36.5**	**36.5**	**36.3**	**35.9**	**40.5**
17	**36.6**	**36.5**	**36.6**	**36.1**	**39.2**
18	**36.5**	**36.4**	**36.6**	**36.1**	**37.2**
19	**36.0**	**36.0**	**36.2**	**35.8**	**35.0**
20	**35.4**	**35.5**	**35.6**	**35.2**	**32.5**
21	**34.8**	**34.9**	**35.1**	**34.8**	**31.2**
22	**34.3**	**34.6**	**34.7**	**34.5**	**30.1**
23	**33.8**	**34.1**	**34.2**	**34.2**	**29.5**
24	**33.4**	**33.8**	**33.8**	**33.8**	**28.9**
Average	**34.1**	**34.3**	**33.9**	**33.9**	**33.2**
Maximum	**36.6**	**36.5**	**36.6**	**36.1**	**41.8**
Minimum	**31.0**	**31.4**	**31.0**	**31.2**	**24.8**

Table A2.21 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature during June 16th - 30th 2012

Hour (h)	Temperature (^{0}C)				
	Room R1	Room R2	Room R3	Room R4	Outdoor air
1	**34.9**	**35.1**	**35.0**	**35.5**	**31.2**
2	**34.6**	**34.8**	**34.6**	**35.2**	**30.7**
3	**34.2**	**34.5**	**34.2**	**34.8**	**30.1**
4	**34.0**	**34.2**	**34.0**	**34.5**	**29.7**
5	**33.6**	**33.9**	**33.6**	**34.1**	**29.2**
6	**33.4**	**33.7**	**33.3**	**33.8**	**29.3**
7	**35.0**	**35.4**	**34.2**	**35.3**	**30.3**
8	**35.5**	**35.8**	**34.8**	**35.8**	**31.9**
9	**35.6**	**35.8**	**34.9**	**35.7**	**33.6**
10	**35.8**	**36.0**	**35.2**	**35.8**	**35.3**
11	**36.1**	**36.2**	**35.5**	**35.9**	**37.0**
12	**36.5**	**36.6**	**35.9**	**36.2**	**38.4**
13	**36.9**	**37.0**	**36.3**	**36.4**	**39.6**
14	**37.2**	**37.3**	**36.8**	**36.7**	**39.9**
15	**37.6**	**37.7**	**37.2**	**37.1**	**40.0**
16	**38.0**	**38.0**	**37.7**	**37.5**	**39.5**
17	**38.1**	**38.1**	**37.9**	**37.7**	**38.5**
18	**38.0**	**37.9**	**37.9**	**37.7**	**37.0**
19	**37.5**	**37.5**	**37.6**	**37.4**	**35.9**
20	**37.0**	**37.0**	**37.1**	**37.0**	**34.5**
21	**36.5**	**36.6**	**36.7**	**36.7**	**33.2**
22	**36.1**	**36.2**	**36.3**	**36.5**	**32.4**
23	**35.6**	**35.8**	**35.8**	**36.2**	**32.1**
24	**35.3**	**35.4**	**35.4**	**35.9**	**31.8**
Average	**35.9**	**36.1**	**35.7**	**36.1**	**34.2**
Maximum	**38.1**	**38.1**	**37.9**	**37.7**	**40.0**
Minimum	**33.4**	**33.7**	**33.3**	**33.8**	**29.2**

Table A2.22 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature during July 16th – 31st 2012

Hour (h)	Temperature (^{0}C)				
	Room R1	**Room R2**	**Room R3**	**Room R4**	**Outdoor air**
1	**31.6**	**31.8**	**31.5**	**31.5**	**27.6**
2	**31.3**	**31.4**	**31.1**	**31.2**	**27.4**
3	**31.0**	**31.2**	**30.8**	**30.9**	**27.0**
4	**30.7**	**30.9**	**30.5**	**30.6**	**26.6**
5	**30.5**	**30.7**	**30.2**	**30.4**	**26.3**
6	**30.2**	**30.4**	**29.9**	**30.1**	**26.4**
7	**30.8**	**31.2**	**30.5**	**31.1**	**27.7**
8	**31.1**	**31.6**	**30.9**	**31.3**	**29.4**
9	**32.1**	**32.3**	**31.6**	**31.8**	**31.3**
10	**32.5**	**32.7**	**31.9**	**32.1**	**33.3**
11	**32.9**	**33.0**	**32.2**	**32.3**	**34.9**
12	**33.2**	**33.3**	**32.5**	**32.5**	**35.9**
13	**33.5**	**33.6**	**32.9**	**32.7**	**37.3**
14	**33.9**	**34.0**	**33.3**	**33.0**	**37.2**
15	**34.2**	**34.3**	**33.7**	**33.3**	**36.6**
16	**34.3**	**34.4**	**33.9**	**33.5**	**34.7**
17	**34.3**	**34.4**	**34.0**	**33.5**	**33.4**
18	**34.2**	**34.2**	**34.0**	**33.5**	**32.1**
19	**33.6**	**33.6**	**33.4**	**33.0**	**30.8**
20	**32.9**	**33.0**	**32.8**	**32.6**	**29.9**
21	**32.6**	**32.6**	**32.4**	**32.2**	**29.2**
22	**32.3**	**32.3**	**32.1**	**32.0**	**28.7**
23	**32.0**	**32.1**	**31.8**	**31.8**	**28.5**
24	**31.9**	**31.9**	**31.6**	**31.6**	**28.1**
Average	**32.4**	**32.5**	**32.1**	**32.0**	**30.9**
Maximum	**34.3**	**34.4**	**34.0**	**33.5**	**37.3**
Minimum	**30.2**	**30.4**	**29.9**	**30.1**	**26.3**

Table A2.23 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature during August 16th – 31st 2012

Hour (h)	**Temperature (^{0}C)**				
	Room R1	**Room R2**	**Room R3**	**Room R4**	**Outdoor air**
1	**27.6**	**27.7**	**27.5**	**27.4**	**24.3**
2	**27.5**	**27.6**	**27.3**	**27.3**	**24.2**
3	**27.4**	**27.5**	**27.1**	**27.2**	**24.1**
4	**27.3**	**27.4**	**26.9**	**27.0**	**23.9**
5	**27.1**	**27.2**	**26.8**	**26.9**	**23.8**
6	**27.0**	**27.1**	**26.7**	**26.8**	**23.7**
7	**27.1**	**27.3**	**26.8**	**26.9**	**24.2**
8	**27.3**	**27.5**	**27.0**	**27.2**	**25.1**
9	**27.7**	**27.9**	**27.4**	**27.5**	**26.4**
10	**28.2**	**28.4**	**27.8**	**27.9**	**28.0**
11	**28.4**	**28.6**	**28.1**	**28.1**	**29.1**
12	**28.6**	**28.8**	**28.3**	**28.2**	**29.2**
13	**28.9**	**29.0**	**28.6**	**28.4**	**30.5**
14	**29.2**	**29.3**	**28.9**	**28.6**	**30.9**
15	**29.4**	**29.6**	**29.2**	**28.9**	**30.5**
16	**29.7**	**29.8**	**29.5**	**29.1**	**29.6**
17	**29.8**	**30.0**	**29.7**	**29.1**	**28.5**
18	**29.4**	**29.6**	**29.4**	**29.0**	**27.3**
19	**28.9**	**29.0**	**28.8**	**28.5**	**26.3**
20	**28.5**	**28.6**	**28.4**	**28.2**	**25.7**
21	**28.3**	**28.4**	**28.2**	**28.0**	**25.3**
22	**28.1**	**28.2**	**28.0**	**27.8**	**25.1**
23	**27.9**	**28.0**	**27.8**	**27.7**	**24.7**
24	**27.7**	**27.8**	**27.6**	**27.5**	**24.5**
Average	**28.2**	**28.3**	**28.0**	**27.9**	**26.5**
Maximum	**29.8**	**30.0**	**29.7**	**29.1**	**30.9**
Minimum	**27.0**	**27.1**	**26.7**	**26.8**	**23.7**

Table A2.24 Average hourly indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature during September 16th - 30th 2012

Hour	**Temperature (^{0}C)**				
(h)	**Room R1**	**Room R2**	**Room R3**	**Room R4**	**Outdoor air**
1	**29.0**	**28.1**	**27.7**	**27.6**	**21.6**
2	**28.7**	**27.9**	**27.4**	**27.3**	**21.3**
3	**28.5**	**27.6**	**27.0**	**26.9**	**20.8**
4	**28.2**	**27.2**	**26.6**	**26.6**	**20.5**
5	**28.0**	**26.9**	**26.3**	**26.3**	**20.2**
6	**27.7**	**26.5**	**25.9**	**25.9**	**19.8**
7	**27.8**	**26.9**	**26.2**	**26.5**	**21.5**
8	**28.1**	**27.8**	**27.0**	**27.1**	**25.1**
9	**28.4**	**28.8**	**27.8**	**27.9**	**28.5**
10	**28.9**	**29.2**	**28.2**	**28.1**	**31.2**
11	**29.3**	**29.5**	**28.4**	**28.3**	**33.1**
12	**29.7**	**29.8**	**28.8**	**28.5**	**34.4**
13	**30.1**	**30.1**	**29.2**	**28.7**	**34.8**
14	**30.6**	**30.5**	**29.7**	**29.1**	**35.0**
15	**31.0**	**30.9**	**30.2**	**29.5**	**34.3**
16	**31.5**	**31.5**	**30.9**	**30.2**	**33.2**
17	**33.5**	**34.4**	**32.9**	**33.1**	**31.2**
18	**31.1**	**31.6**	**30.9**	**30.6**	**27.9**
19	**30.4**	**30.3**	**30.0**	**29.3**	**25.7**
20	**30.1**	**29.7**	**29.5**	**28.9**	**24.7**
21	**29.9**	**29.3**	**29.1**	**28.6**	**23.8**
22	**29.7**	**28.9**	**28.7**	**28.3**	**23.0**
23	**29.4**	**28.5**	**28.3**	**28.0**	**22.2**
24	**29.2**	**28.2**	**27.8**	**27.6**	**21.6**
Average	**29.6**	**29.2**	**28.5**	**28.3**	**26.5**
Maximum	**33.5**	**34.4**	**32.9**	**33.1**	**35.0**
Minimum	**27.7**	**26.5**	**25.9**	**25.9**	**19.8**

A3.1 Calculation of the product *AU* of room R1

Roof			
Material	**Thickness (m)**	**Thermal conductivity (W/m-K)**	**Resistance (m^2-K/W)**
RCC	0.100	1.580	0.063
PCC	0.100	1.440	0.069
hi			0.108
ho			0.044
		Total Resistance (m^2-K/W)	0.284
		Transmittance (W/m^2-K)	3.517
		Area (m^2)	12.000
		AU (W/K)	42.207
		Total AU (W/K)	42.207
North Wall			
Material	**Thickness (m)**	**Thermal Conductivity (W/m-K)**	**Resistance (m^2-K/W)**
Brick	0.338	0.811	0.417
ho			0.044
hi			0.120
		Total Resistance (m^2-K/W)	0.581
		Transmittance (W/m^2-K)	1.720
		Area (m^2)	9.770
		AU(W/K)	16.807
RCC	0.100	1.580	0.063
ho			0.044
hi			0.120
		Total Resistance (m^2-K/W)	0.228
		Transmittance (W/m^2-K)	4.389
		Area (m^2)	0.130
		AU (W/K)	0.571
		Total AU (W/K)	17.378
East/West Wall			
Material	**Thickness (m)**	**Thermal Conductivity (W/m-K)**	**Resistance (m^2-K/W)**
Brick	0.338	0.811	0.417
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	0.581
		Transmittance (W/m^2-K)	1.720
		Area (m^2)	7.573
		AU (W/K)	13.027
RCC	0.338	1.580	0.214
hi			0.120

ho			0.044
		Total Resistance (m^2-K/W)	0.378
		Transmittance (W/m^2-K)	2.642
		Area (m^2)	0.228
		AU (W/K)	0.601
Glass	0.112	0.814	0.138
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	0.302
		Transmittance (W/m^2-K)	3.310
		Area (m^2)	1.200
		AU (W/K)	3.972
		Total AU (W/K)	17.600
South Wall			
Material	**Thickness (m)**	**Thermal Conductivity (W/m-K)**	**Resistance (m^2-K/W)**
Brick	0.338	0.811	0.417
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	0.581
		Transmittance (W/m^2-K)	1.720
		Area (m^2)	10.573
		AU (W/K)	18.188
Glass	0.112	0.814	0.138
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	0.302
		Transmittance (W/m^2-K)	3.310
		Area (m^2)	1.200
		AU (W/K)	3.972
RCC	0.338	1.580	0.214
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	0.378
		Transmittance (W/m^2-K)	2.642
		Area (m^2)	0.228
		AU (W/K)	0.601
		Total AU (W/K)	22.761
Total Ai*Ui is equal to			***117.544***

A3.2 Calculation of the product *AU* of room R2

Roof			
Material	**Thickness (m)**	**Thermal conductivity (W/m-K)**	**Resistance (m^2-K/W)**
RCC	0.100	1.580	0.063
PCC	0.100	1.440	0.069
hi			0.108
ho			0.044
		Total Resistance (m^2-K/W)	0.284
		Transmittance (W/m^2-K)	3.517
		Area (m^2)	12.000
		AU (W/K)	42.207
		Total AU (W/K)	42.207
North Wall			
Material	**Thickness (m)**	**Thermal Conductivity (W/m-K)**	**Resistance (m^2-K/W)**
Brick	0.338	0.811	0.417
ho			0.044
hi			0.120
		Total Resistance (m^2-K/W)	0.581
		Transmittance (W/m^2-K)	1.720
		Area (m^2)	9.770
		AU (W/K)	16.807
RCC	0.100	1.580	0.063
ho			0.044
hi			0.120
		Total Resistance (m^2-K/W)	0.228
		Transmittance (W/m^2-K)	4.389
		Area (m^2)	0.130
		AU (W/K)	0.571
		Total AU (W/K)	17.378
East/West Wall			
Material	**Thickness (m)**	**Thermal Conductivity (W/m-K)**	**Resistance (m^2-K/W)**
Brick	0.338	0.811	0.417
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	0.581
		Transmittance (W/m^2-K)	1.720
		Area (m^2)	7.573
		AU (W/K)	13.027
RCC	0.338	1.580	0.214
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	0.378

		Transmittance (W/m^2-K)	2.642
		Area (m^2)	0.228
		AU (W/K)	0.601
Glass	0.112	0.814	0.138
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	0.302
		Transmittance (W/m^2-K)	3.310
		Area (m^2)	1.200
		AU (W/K)	3.972
		Total AU (W/K)	17.600
South Wall			
Material	**Thickness (m)**	**Thermal Conductivity (W/m-K)**	**Resistance (m^2-K/W)**
Brick	0.338	0.811	0.417
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	0.581
		Transmittance (W/m^2-K)	1.720
		Area (m^2)	10.573
		AU (W/K)	18.188
Glass	0.112	0.814	0.138
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	0.302
		Transmittance (W/m^2-K)	3.310
		Area (m^2)	1.200
		AU (W/K)	3.972
RCC	0.338	1.580	0.214
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	0.378
		Transmittance (W/m^2-K)	2.642
		Area (m^2)	0.228
		AU (W/K)	0.601
		Total AU (W/K)	22.761
Total Ai*Ui is equal to			***117.544***

A3.3 Calculation of the product *AU* of room R3

Roof			
Material	**Thickness (m)**	**Thermal conductivity (W/m-K)**	**Resistance (m^2-K/W)**
RCC	0.100	1.580	0.063
PCC	0.100	1.440	0.069
hi			0.108
ho			0.044
		Total Resistance (m^2-K/W)	0.284
		Transmittance (W/m^2-K)	3.517
		Area (m^2)	12.000
		AU (W/K)	42.207
		Total AU (W/K)	**42.207**
North Wall			
Material	**Thickness (m)**	**Thermal Conductivity (W/m-K)**	**Resistance (m^2-K/W)**
RCC	0.338	1.580	0.214
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	0.378
		Transmittance (W/m^2-K)	2.642
		Area (m^2)	0.130
		AU (W/K)	0.343
Brick	0.113	0.811	0.139
Air	0.113	0.161	0.702
Brick	0.113	0.811	0.139
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	1.145
		Transmittance (W/m^2-K)	0.873
		Area (m^2)	4.503
		AU (W/K)	3.932
Brick	0.113	0.811	0.139
Air	0.113	0.161	0.702
brick	0.113	0.811	0.139
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	1.145
		Transmittance (W/m^2-K)	0.873
		Area (m^2)	4.503
		AU (W/K)	3.932
Steel	0.006	33.000	0.000
Air	0.113	0.161	0.702
Brick	0.113	0.811	0.139
hi			0.120
ho			0.044

		Total Resistance (m^2-K/W)	1.006
		Transmittance (W/m^2-K)	0.994
		Area (m^2)	0.068
		AU (W/K)	0.067
Steel	0.006	33.000	0.000
Air	0.113	0.161	0.702
Brick	0.113	0.811	0.139
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	1.006
		Transmittance (W/m^2-K)	0.994
		Area (m^2)	0.068
		AU (W/K)	0.067
Brick	0.338	0.811	0.417
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	0.581
		Transmittance (W/m^2-K)	1.720
		Area (m^2)	0.315
		AU (W/K)	0.542
Brick	0.378	0.811	0.466
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	0.631
		Transmittance (W/m^2-K)	1.586
		Area (m^2)	0.315
		AU (W/K)	0.500
		Total AU (W/K)	9.383
East/West Wall			
Material	**Thickness (m)**	**Thermal Conductivity (W/m-K)**	**Resistance (m^2-K/W)**
Glass	0.112	0.814	0.138
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	0.302
		Transmittance (W/m^2-K)	3.310
		Area (m^2)	1.200
		AU (W/K)	3.972
RCC	0.338	1.580	0.214
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	0.378
		Transmittance (W/m^2-K)	2.642
		Area (m^2)	0.228
		AU (W/K)	0.601
Brick	0.338	0.811	0.417
hi			0.120
ho			0.044

		Total Resistance (m^2-K/W)	0.581
		Transmittance (W/m^2-K)	1.720
		Area (m^2)	0.180
		AU (W/K)	0.310
Brick	0.501	0.811	0.618
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	0.782
		Transmittance (W/m^2-K)	1.278
		Area (m^2)	0.180
		AU (W/K)	0.230
Brick	0.113	0.811	0.139
Air	0.113	0.161	0.702
brick	0.113	0.811	0.139
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	1.145
		Transmittance (W/m^2-K)	0.873
		Area (m^2)	3.471
		AU (W/K)	3.031
Brick	0.225	0.811	0.277
Air	0.113	0.161	0.702
Brick	0.113	0.811	0.139
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	1.283
		Transmittance (W/m^2-K)	0.779
		Area (m^2)	3.471
		AU (W/K)	2.705
Steel	0.006	33.000	0.000
Air	0.113	0.161	0.702
Brick	0.113	0.811	0.139
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	1.006
		Transmittance (W/m^2-K)	0.994
		Area (m^2)	0.135
		AU (W/K)	0.134
Steel	0.006	33.000	0.000
Air	0.113	0.161	0.702
Brick	0.113	0.811	0.139
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	1.006
		Transmittance (W/m^2-K)	0.994
		Area (m^2)	0.135
		AU (W/K)	0.134
		Total AU (W/K)	11.118

South Wall			
Material	**Thickness (m)**	**Thermal Conductivity (W/m-K)**	**Resistance (m^2-K/W)**
RCC	0.338	1.580	0.214
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	0.378
		Transmittance (W/m^2-K)	2.642
		Area (m^2)	0.228
		AU (W/K)	0.601
Glass	0.112	0.814	0.138
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	0.302
		Transmittance (W/m^2-K)	3.310
		Area (m^2)	1.200
		AU (W/K)	3.972
Brick	0.338	0.811	0.417
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	0.581
		Transmittance (W/m^2-K)	1.720
		Area (m^2)	0.180
		AU (W/K)	0.310
Brick	0.378	0.811	0.466
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	0.631
		Transmittance (W/m^2-K)	1.586
		Area (m^2)	0.180
		AU (W/K)	0.285
Steel	0.006	33.000	0.000
Air	0.220	0.161	1.366
Brick	0.113	0.811	0.139
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	1.671
		Transmittance (W/m^2-K)	0.599
		Area (m^2)	0.135
		AU (W/K)	0.081
Steel	0.006	33.000	0.000
Air	0.220	0.161	1.366
Brick	0.113	0.811	0.139
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	1.671

		Transmittance (W/m^2-K)	0.599
		Area (m^2)	0.135
		AU (W/K)	0.081
Brick	0.155	0.811	0.191
Air	0.113	0.161	0.702
Brick	0.113	0.811	0.139
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	1.196
		Transmittance (W/m^2-K)	0.836
		Area (m^2)	4.971
		AU (W/K)	4.156
Brick	0.113	0.811	0.139
Air	0.113	0.161	0.702
Brick	0.113	0.811	0.139
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	1.145
		Transmittance (W/m^2-K)	0.873
		Area (m^2)	4.971
		AU (W/K)	4.341
		Total AU (W/K)	13.827
Total Ai*Ui is equal to			***87.652***

A3.4 Calculation of the product *AU* of room R4

North Wall			
Material	**Thickness (m)**	**Thermal Conductivity (W/m-K)**	**Resistance (m^2-K/W)**
RCC	0.338	1.580	0.214
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	0.378
		Transmittance (W/m^2-K)	2.642
		Area (m^2)	0.130
		AU (W/K)	0.343
Brick	0.113	0.811	0.139
Air	0.113	0.161	0.702
Brick	0.113	0.811	0.139
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	1.145
		Transmittance (W/m^2-K)	0.873
		Area (m^2)	4.503
		AU (W/K)	3.932
Brick	0.113	0.811	0.139
Air	0.113	0.161	0.702
brick	0.113	0.811	0.139
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	1.145
		Transmittance (W/m^2-K)	0.873
		Area (m^2)	4.503
		AU (W/K)	3.932
Steel	0.006	33.000	0.000
Air	0.113	0.161	0.702
Brick	0.113	0.811	0.139
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	1.006
		Transmittance (W/m^2-K)	0.994
		Area (m^2)	0.068
		AU (W/K)	0.067
Steel	0.006	33.000	0.000
Air	0.113	0.161	0.702
Brick	0.113	0.811	0.139
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	1.006
		Transmittance (W/m^2-K)	0.994
		Area (m^2)	0.068

		AU (W/K)	0.067
Brick	0.338	0.811	0.417
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	0.581
		Transmittance (W/m^2-K)	1.720
		Area (m^2)	0.315
		AU (W/K)	0.542
Brick	0.378	0.811	0.466
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	0.631
		Transmittance (W/m^2-K)	1.586
		Area (m^2)	0.315
		AU (W/K)	0.500
		Total AU (W/K)	9.383
East/West Wall			
Material	**Thickness (m)**	**Thermal Conductivity (W/m-K)**	**Resistance (m^2-K/W)**
Glass	0.112	0.814	0.138
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	0.302
		Transmittance (W/m^2-K)	3.310
		Area (m^2)	1.200
		AU (W/K)	3.972
RCC	0.338	1.580	0.214
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	0.378
		Transmittance (W/m^2-K)	2.642
		Area (m^2)	0.228
		AU (W/K)	0.601
Brick	0.338	0.811	0.417
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	0.581
		Transmittance (W/m^2-K)	1.720
		Area (m^2)	0.180
		AU (W/K)	0.310
Brick	0.501	0.811	0.618
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	0.782
		Transmittance (W/m^2-K)	1.278
		Area (m^2)	0.180
		AU (W/K)	0.230
Brick	0.113	0.811	0.139

Air	0.113	0.161	0.702
brick	0.113	0.811	0.139
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	1.145
		Transmittance (W/m^2-K)	0.873
		Area (m^2)	3.471
		AU (W/K)	3.031
Brick	0.225	0.811	0.277
Air	0.113	0.161	0.702
Brick	0.113	0.811	0.139
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	1.283
		Transmittance (W/m^2-K)	0.779
		Area (m^2)	3.471
		AU (W/K)	2.705
Steel	0.006	33.000	0.000
Air	0.113	0.161	0.702
Brick	0.113	0.811	0.139
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	1.006
		Transmittance (W/m^2-K)	0.994
		Area (m^2)	0.135
		AU (W/K)	0.134
Steel	0.006	33.000	0.000
Air	0.113	0.161	0.702
Brick	0.113	0.811	0.139
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	1.006
		Transmittance (W/m^2-K)	0.994
		Area (m^2)	0.135
		AU (W/K)	0.134
		Total AU (W/K)	11.118
South Wall			
Material	**Thickness (m)**	**Thermal Conductivity (W/m-K)**	**Resistance (m^2-K/W)**
RCC	0.338	1.580	0.214
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	0.378
		Transmittance (W/m^2-K)	2.642
		Area (m^2)	0.228
		AU (W/K)	0.601
Glass	0.112	0.814	0.138
hi			0.120

ho			0.044
		Total Resistance (m^2-K/W)	0.302
		Transmittance (W/m^2-K)	3.310
		Area (m^2)	1.200
		AU (W/K)	3.972
Brick	0.338	0.811	0.417
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	0.581
		Transmittance (W/m^2-K)	1.720
		Area (m^2)	0.180
		AU (W/K)	0.310
Brick	0.378	0.811	0.466
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	0.631
		Transmittance (W/m^2-K)	1.586
		Area (m^2)	0.180
		AU (W/K)	0.285
Steel	0.006	33.000	0.000
Air	0.220	0.161	1.366
Brick	0.113	0.811	0.139
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	1.671
		Transmittance (W/m^2-K)	0.599
		Area (m^2)	0.135
		AU (W/K)	0.081
Steel	0.006	33.000	0.000
Air	0.220	0.161	1.366
Brick	0.113	0.811	0.139
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	1.671
		Transmittance (W/m^2-K)	0.599
		Area (m^2)	0.135
		AU (W/K)	0.081
Brick	0.155	0.811	0.191
Air	0.113	0.161	0.702
Brick	0.113	0.811	0.139
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	1.196
		Transmittance (W/m^2-K)	0.836
		Area (m^2)	4.971
		AU (W/K)	4.156
Brick	0.113	0.811	0.139
Air	0.113	0.161	0.702

Brick	0.113	0.811	0.139
hi			0.120
ho			0.044
		Total Resistance (m^2-K/W)	1.145
		Transmittance (W/m^2-K)	0.873
		Area (m^2)	4.971
		AU (W/K)	4.341
		Total AU (W/K)	13.827
Roof			
Material	**Thickness (m)**	**Thermal conductivity (W/m-K)**	**Resistance (m^2-K/W)**
RCC	0.162	1.580	0.103
Air	0.042	0.161	0.261
Stoneware	0.012	1.850	0.006
ho			0.108
hi			0.044
		Total Resistance (m^2-K/W)	0.521
		Transmittance (W/m^2-K)	1.918
		Area (m^2)	12.000
		AU (W/K)	23.012
		Total AU (W/K)	23.012
Total Ai*Ui is equal to			68.458

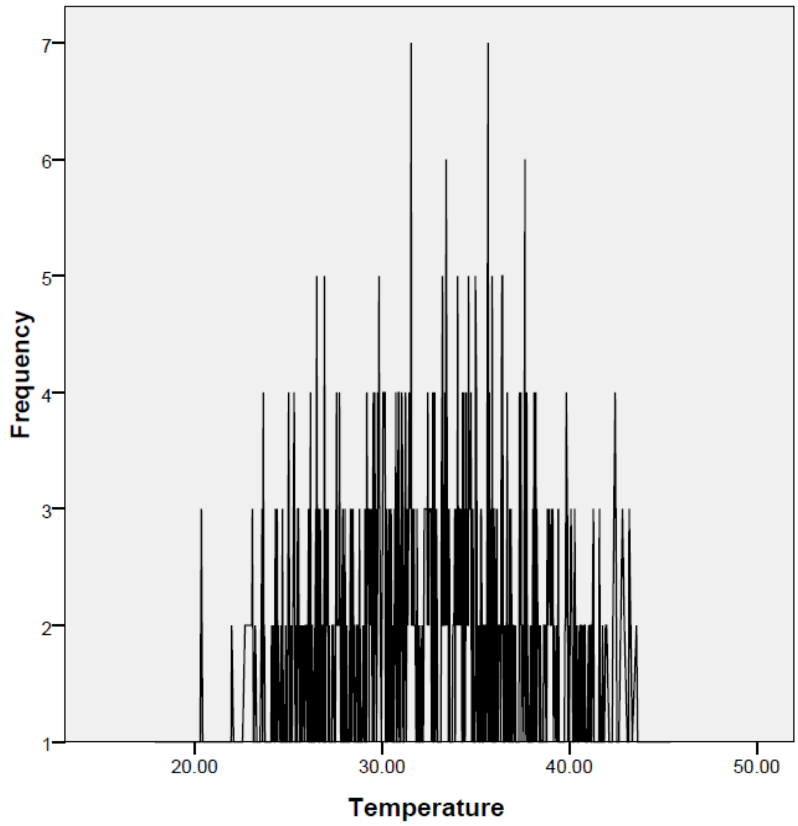

Fig. A4.1 Day time outdoor air temperature frequency distribution for summer

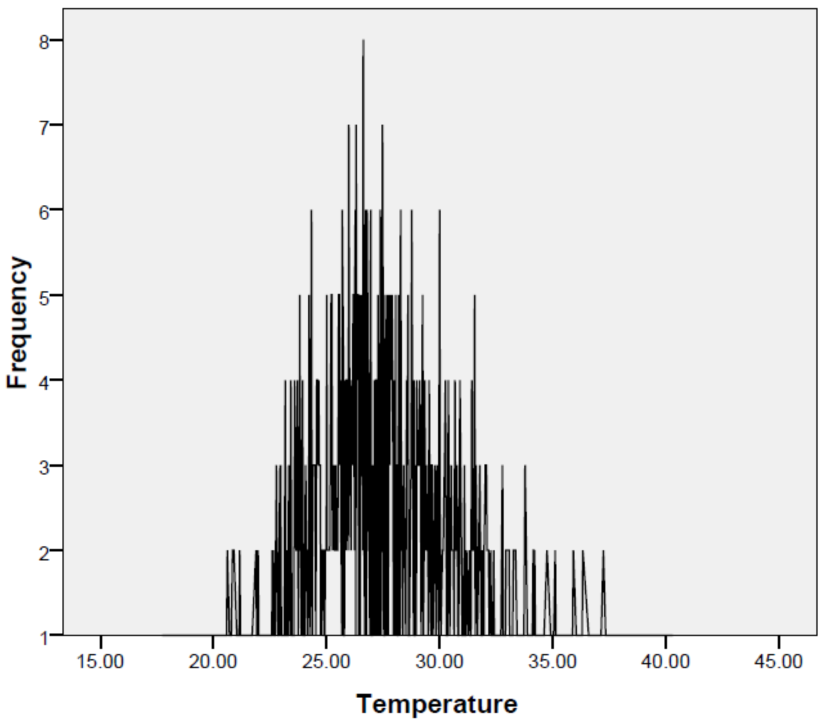

Fig. A4.2 Night time outdoor air temperature frequency distribution for summer

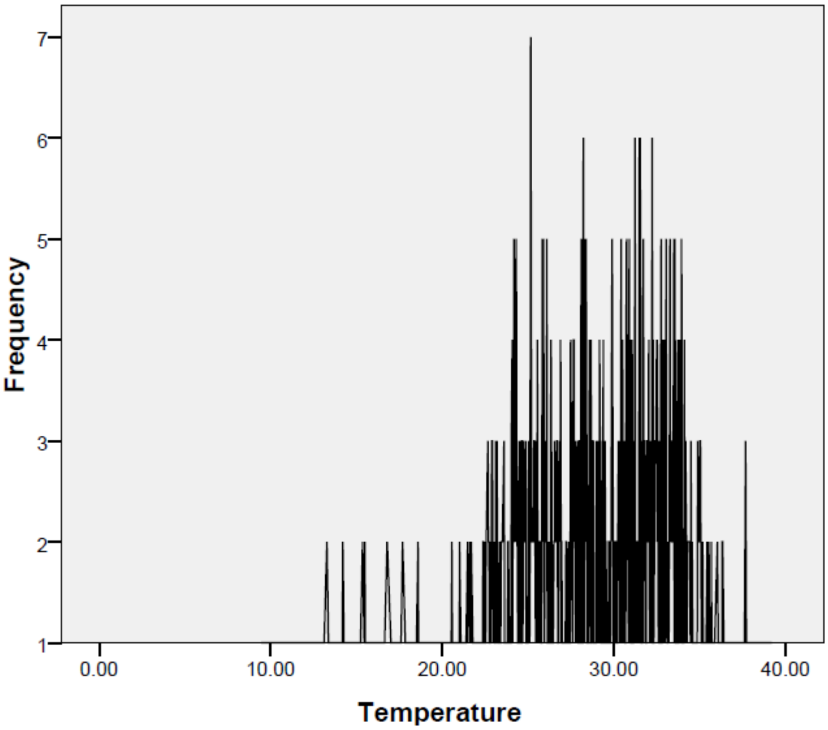

Fig. A4.3 Day time outdoor air temperature frequency distribution for moderate summer

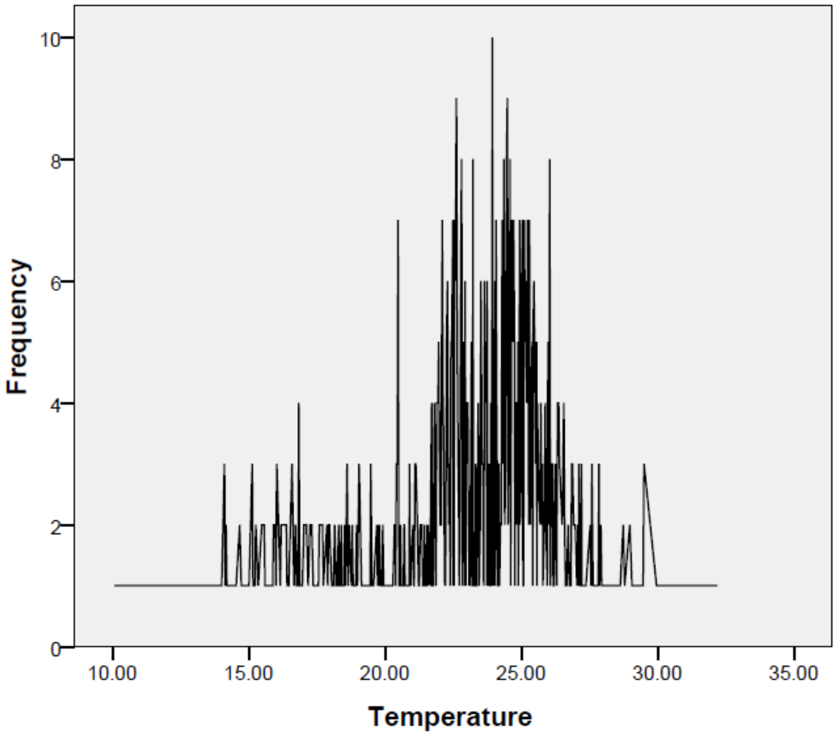

Fig. A4.4 Night time outdoor air temperature frequency distribution for moderate summer

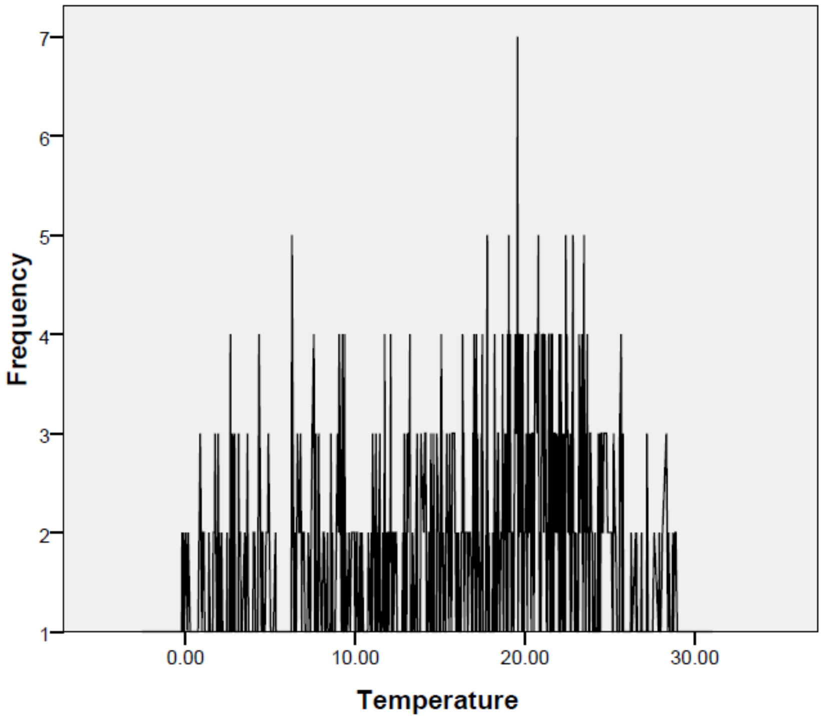

Fig. A4.5 Day time outdoor air temperature frequency distribution for winter

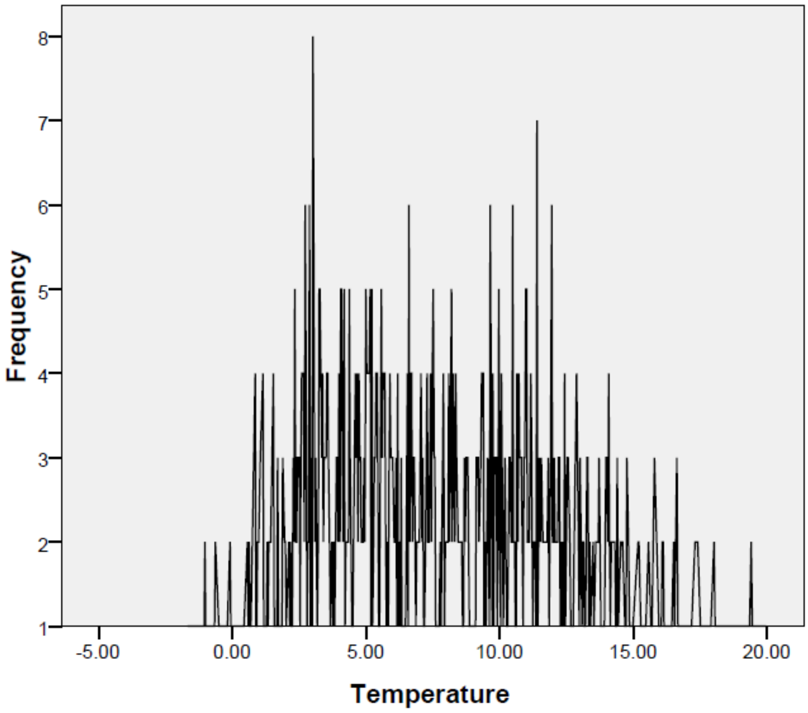

Fig. A4.6 Night time outdoor air temperature frequency distribution for winter

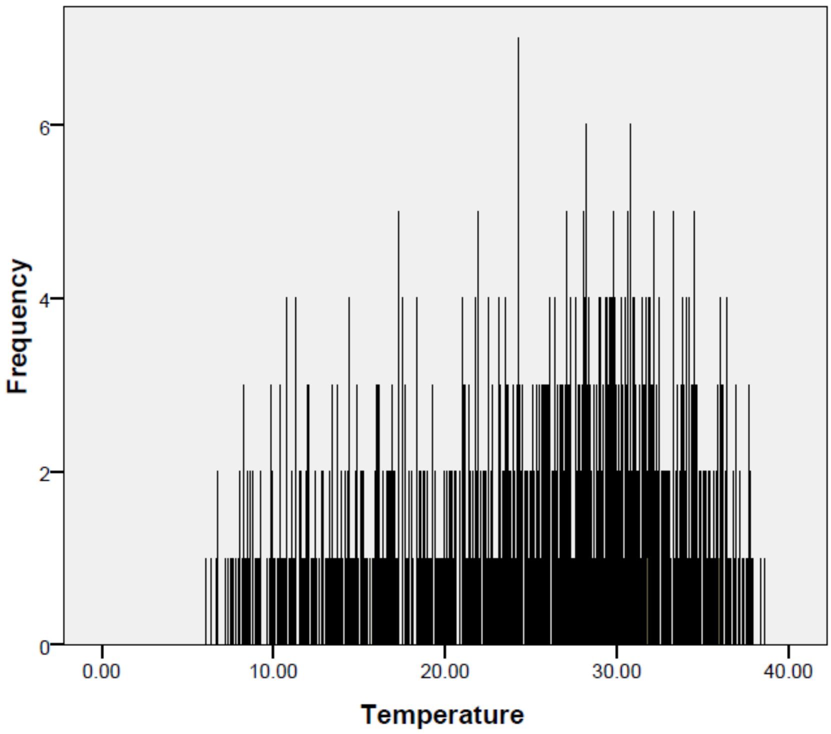

Fig. A4.7 Day time outdoor air temperature frequency distribution for moderate winter

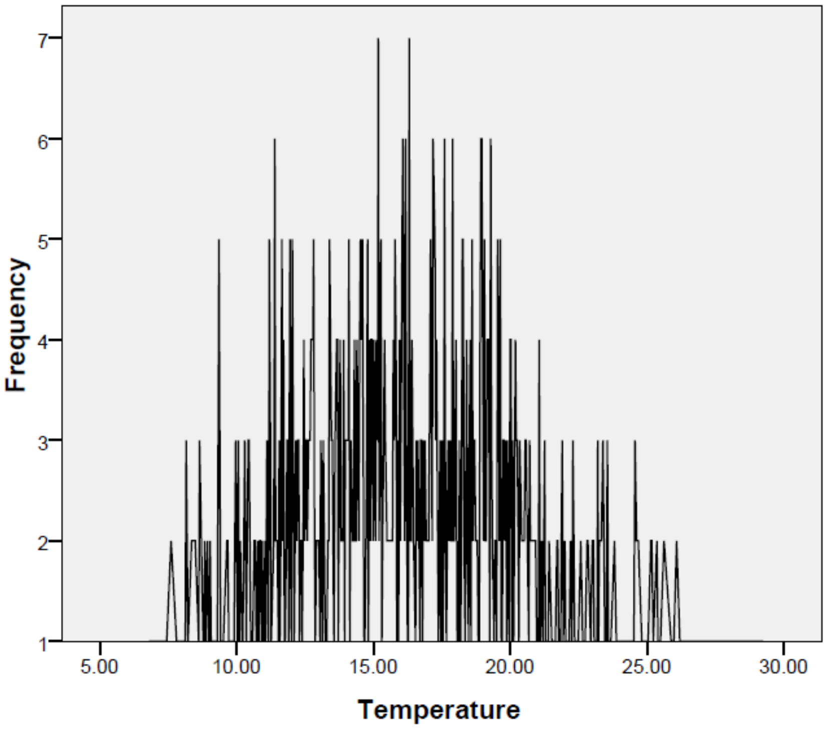

Fig. A4.8 Night time outdoor air temperature frequency distribution for moderate winter

List of Publications and Presentations

Publications

1. Charde, M., Gupta, R., 2013. Annual thermal performance of hollow roof in combination with cavity wall and static sunshade: An experimental study of energy efficient rooms, Journal of Energy Engineering ASCE, Accepted for publication.
2. Charde, M., Gupta, R., 2013. Design development and thermal performance evaluation of static sunshade and brick cavity wall: An experimental study, Energy and Buildings 60, 210-216.
3. Charde, M., Gupta, R. Effect of energy efficient building elements on summer cooling of buildings. Communicated to Energy and Buildings. Paper resubmitted after 1st review.
4. Charde M., Gupta, R. Night ventilation for passive cooling of conventional and energy efficient room: A comparative experimental study. Communicated to Architectural Science Review.

Paper Presentations at Conferences

1. Charde, M., Gupta, R., 2012. Design development and thermal performance evaluation of a brick cavity wall, Proceedings of 4th International Conference on Sustainable Energy and Environment: A paradigm shift to low carbon society, Bangkok, Thailand. 2012 February 27 - 29, 428 – 434.
2. Charde, M., Gupta, R., 2011. Thermal performance of a hollow roof: An experimental study. Proceedings of World Renewable Energy Congress, International Conference on Renewable Energy and Energy Efficiency, Bali, Indonesia. 2011 October 17 – 19, pp. 44.
3. Charde, M., Vemuri, A., Gupta, R., 2013. Analysis of brick cavity wall for energy conservation in buildings, Accepted for presentation in International Congress on Materials and Renewable Energy, Athens, Greece. 2013 July 1 – 3.
4. Charde, M., Bhati, S., Kheterpal, A., Gupta, R., 2013. Thermal performance of static sunshade and brick cavity wall in composite climate, Accepted for presentation in 8th Conference on Sustainable Development of Energy, Water and Environment Systems, Dubrovnik, Croatia. 2013 September 22 – 27.

Other Publications

1. Gupta, R., Charde, M., Ralegaonkar, R., 2007. Development of small and medium towns through disintegration of cities. Journal of Indian Buildings Congress 14, 147-151.

Biography of Rajiv Gupta

Rajiv Gupta is Professor in Civil Engineering Department at Birla Institute of Technology and Science Pilani, Pilani Campus. He completed his Ph.D. from BITS, Pilani on fluid structure interaction. He has nearly 26 years of teaching and research experience and has supervised several doctoral, postgraduate and undergraduate students. He has published research articles in renowned journals and presented papers in conferences in India and abroad. He has authored several books and course development materials. He has been awarded scientific awards for several national publications. He has successfully completed several government and consultancy projects.

Biography of Meghana Shrikant Charde

Ms. Meghana Shrikant Charde has completed her Bachelor of Architecture (B. Arch.) from Sir J. J. College of Architecture, University of Mumbai, Mumbai in the year 2004. She has been working as a faculty at BITS Pilani, Pilani Campus since 2006 and continuing her Ph.D. work. She has published research articles in renowned journals and presented papers in conferences.