Passive solar design for energy efficiency in buildings in composite climate

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Abstract. Renewable energy sources offer an unlimited supply of energy. 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 for design of building elements like static sunshade, wall and roof. To study the effect of passive building elements in composite climate zone, four rooms were designed with a different combination of type of static sunshade, wall and roof. The static sunshade and brick cavity wall with brick projections were designed using sunpath diagram and shadow angles. Air cavity was introduced in the reinforced cement concrete (RCC) roof by laying hollow stoneware pipes. This paper presents theoretical and simulation studies to compare thermal performance of the four rooms. Theoretically, the four rooms were compared by steady state method based on total heat load in every month and on representative days in different seasons throughout the year. The extreme and most frequently occurring temperature values (mode) in every season were identified by obtaining the frequency distribution of the outdoor air temperature with the software SPSS Statistics (IBM Corp. 2012). 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. This shows the effectiveness of the designed passive elements in insulating the room interiors from the extreme climatic conditions. The rooms were also simulated using software Autodesk Ecotect Analysis 2011 and their performance was compared on a typical day in each month. Results showed that this software can be helpful for preliminary design to get an idea about the room performance that can help to create thermally comfortable indoor environment for the well being of occupants.

1. Introduction

The passive solar building design 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 [1]. Energy consumption and thermal comfort in buildings are affected by weather conditions [2]. 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 [3].
Research studies related to thermal performance and energy efficiency of buildings to improve indoor thermal comfort in various climate zones have been reported [4,5]. Computer simulation has also been used as a design tool [6] and explore effectiveness of passive cooling strategies [7]. Simulation studies [8,9] and mathematical methods [10] 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 [11]. Finite element method (FEM) was used for studying heat transfer equation for five different light concrete hollow brick walls [12] while three identically sized and oriented houses were compared using TRACE-700 simulation [13]. Liang and Memari [14] calculated thermal resistance of prefabricated and panelized brick veneer, with a steel framework backup wall system. Numerical computations showed that incoming flux entering through walls can be reduced by air cavity [15] and application of a thin layer of cow dung slurry inside the wall cavity [16]. 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 [17]. Various numerical studies have been done on ventilated lightweight low sloped roof [18], ventilated roof without thermal insulation [19] and air temperature variation along ventilated cavity [20]. Numerical studies on comparative thermal performance of different roof types have been reported [21-23]. Thus many researchers have used theoretical, mathematical, analytical, simulation methods to compare performance of building elements like sunshade, wall and roof. This paper presents theoretical and simulation studies to compare thermal performance of four rooms designed with a different combination of type of sunshade, wall and roof. Theoretically, the four rooms were compared by steady state method based on total heat load in every month and on representative days in different seasons throughout the year. The rooms were also simulated using software Autodesk Ecotect Analysis 2011 and their performance was compared on a typical day in each month. In separate experimental studies individual and combined effect of the designed passive building elements on indoor air temperature has been analysed [24-28]

2. Room design and description

Tropical climate is characterized by significant hourly and large diurnal variations in temperature and sunshine [29]. India has tropical climate and is broadly classified into five climatic zones [3]. To study the effect of static sunshade, brick cavity wall with brick projections, hollow roof and their combined effect on indoor air temperature, four test rooms (3.0m x 4.0m x 3.0m high) were designed and constructed in India at Birla Institute of Technology and Science (BITS), Pilani, Rajasthan. This lies in the composite climate zone [3]. Room R1 had a horizontal static sunshade over window on south wall, solid brick walls 338mm thick and solid RCC roof 100mm thick (Figures 1-2). Room R2 had designed static sunshade over window on south wall, solid brick walls 338mm thick and solid RCC roof 100mm thick (Figures 1-2). Room R3 had designed static sunshade over window on south wall, solid brick walls 338mm thick and solid RCC roof 100mm thick (Figures 1-2). Room R4 had designed static sunshade over window on south wall, brick cavity wall without brick projections on north face, designed brick cavity walls with brick projections on east, west, south faces, and solid RCC roof 100mm thick (Figures 1-2). Room R4 had designed static sunshade over window on south wall, brick cavity wall without brick projections on north face, designed brick cavity walls with brick projections on east, west, south faces and designed hollow roof (Figures 1-2). The four test rooms had same orientation and were exposed to similar conditions. The details of various building elements of the four rooms are stated in Table 1 (with differences in rooms shown in bold). The designed static sunshade over window on the south wall of rooms R2, R3, R4 was designed by calculating solar angles for two design dates, which depends on seasonal characteristics as per methodology described by Gupta and Ralegaonkar [29]. The designed brick cavity walls with brick projections on east, west, south faces of rooms R3 and R4 were as per methodology described by Charde and Gupta [24]. The north wall was a brick cavity wall without brick projections as it would be in shade for most part of the year at considered geographical location. Rectangular mild steel wall ties were used to provide a connection between the outer and inner brick leaf of the brick cavity walls. The spacing of the wall ties was done as per Technical notes-44B [30]. Air vents with operable shutters were provided on all the cavity walls of rooms R3, R4. Room R4 had the designed hollow roof with hollow stoneware pipes (100 mm diameter) cut in half integrated in the RCC roof to reduce the total slab depth and provide
an air cavity. Hence the difference in heat transferred through the designed static sunshade, designed brick cavity wall with brick projections and hollow roof would lead to difference in indoor air temperature of the four rooms.

Table 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 | RCC 1:2:4 |  |  |
| RCC plinth slab  | 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 |
| Walls            |  |  |  |  |
| 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 |
| Openings         | 1000 x 1200mm MS window frame and shutter |  |  |  |
| Static sunshade  | Horizontal 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             | 1000 x 2100mm MS frame with wooden shutter |  |  |  |
Figure 1. Plan of rooms R1, R2, R3, R4

Figure 2. Section of rooms R1, R2, R3, R4
3. Methodology for thermal performance estimation: Theoretical study

The thermal performance of a building depends on design variables, material properties, weather data and a building’s usage data [31]. Based on the fundamentals of heat transfer and solar radiation it is possible to calculate the various heat exchanges taking place in a building. Heat flows by conduction (through various building elements such as walls, roof, ceiling, floor, etc), 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. The presence of human occupants and the use of lights and equipments leads to addition of heat to the space. The thermal performance of the four rooms was compared based on total heat load in every month and on representative days using steady state method [31]. 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.

3.1. Monthly analysis of thermal performance

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 using the ASHRAE model [32]. 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. The calculations were done using Excel VBA (Visual Basic for Applications) code [33]. 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 [31] of all the windows of all the four rooms was calculated as shown in equation (1):

\[ Q_s = \alpha_s \sum_{i=1}^{e} q_i S_{gi} \tau_i \]

where:
- \( \alpha_s \): mean absorptivity of the space
- \( a_i \): area of the \( i \)th transparent element (m²)
- \( S_{gi} \): daily average value of solar radiation (including the effect of shading) on the \( i \)th transparent element (W/m²)
- \( \tau_i \): transmissivity of the \( i \)th transparent element
- \( e \): number of transparent elements

The product \( AU \) was calculated for every building component of all the four rooms. \( U \) 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 [31]. The steady state method does not account for the effect of heat capacity of building materials. \( U \) is given by equation (2):

\[ U = \frac{1}{R_T} \]

\( R_T \) is the total thermal resistance and is given by equation (3):

\[ R_T = \frac{1}{h_i} + \left( \sum_{j=1}^{z} L_j / k_j \right) + \frac{1}{h_o} \]

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
The sol-air temperature \((T_{so})\) was calculated using the daily average outdoor air temperature and the daily average solar radiation on the surface for every month [33] using equation (4):

\[
T_{so} = T_o + \frac{\alpha_b S_T}{h_o} - \frac{\varepsilon \Delta R}{h_o} \tag{4}
\]

\(T_o\): daily average value of hourly ambient temperature (K)
\(\alpha_b\): 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)
\(\varepsilon\): emissivity of the surface
\(\Delta R\): 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

Then the conduction heat load of the rooms was calculated. 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 [31]. It is expressed as in equation (5):

\[
Q_c = \sum_{i=1}^{N_i} A_i U_i \Delta T_i \tag{5}
\]

\(i\): building element
\(N_i\): number of components

If the surface is also exposed to solar radiation then, \(\Delta T\) is calculated as in equation (6):

\[
\Delta T = T_{so} - T_i \tag{6}
\]

\(T_i\): indoor temperature
\(T_{so}\): sol-air temperature

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.

3.2. Thermal performance analysis on representative dates

The thermal performance of the rooms was compared on representative critical dates in various seasons throughout the year. The indoor air temperature in the four rooms and outdoor air temperature was recorded at one hour intervals throughout the day for 24 hours [33]. The seasonal classification was done on the basis of maximum and minimum values (as shown in figure 3) 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 2.

![Figure 3. Yearly temperature variation](image-url)
Table 2. Seasonal classification

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

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 figure 4. 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 [33]. 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.

![Figure 4. Representative dates in every season](image)

4. Results and Discussion

4.1. Monthly analysis of thermal performance

Based on methodology described in section 3.1, the solar heat gain due to windows and conduction heat load of all four rooms was calculated. 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 figure 5. 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. The product $AU$ was maximum for rooms R1, R2 (117.54 W/ K) while it was 87.65 W/K for room R3 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 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 figure 6. 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 figure 7. 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.

4.2. 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 was obtained [33]. 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 (Figures 8-11). There were 7 mode value instances on different dates in summer. The most frequently occurring outdoor air temperature was 35.7°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°C) occurred on 7th June at 1500 hours. Figure 9 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 figures 8-11. The total heat load for the most frequently occurring temperature during day (25.1°C) and night (23.9°C) in moderate summer was not calculated as the outdoor air temperature was well within the comfort temperature zone.

**Figure 8.** Total heat load of rooms for most frequently occurring temperature (daytime)

**Figure 9.** Total heat load of rooms for extreme temperature (daytime)

**Figure 10.** Total heat load of rooms for most frequently occurring temperature (night time)

**Figure 11.** Total heat load of rooms for extreme temperature (night time)

5. **Simulation Analysis**

Software Autodesk Ecotect Analysis 2011 was used to simulate and compare the rooms. *Autodesk Ecotect Analysis 2011* uses the Chartered Institute of Building Services Engineers (CIBSE) Admittance Method to determine internal temperatures and heat loads. Thermal models in *Autodesk Ecotect Analysis 2011* are based on the spatial arrangement of discrete zones. The climatic variables used in the simulation weather file were obtained from the U.S. Department of Energy website [34] for the weather station nearest to the experimental setup.

The limitations and assumptions associated with modelling of the rooms are listed below:
1. Thermal properties of shades were neglected as they were assigned non-thermal zones.
2. Metal frame in windows and vents were not modelled due to limitations of the modelling tools.
3. Thermal mass of the brick projections on the walls of room R3 was assumed to be distributed uniformly over the whole wall.
4. The vents opening in the wall cavities of the walls of room R3 were modelled as windows with custom material having air as outer layer and brick as inner layer.
5. The hollow roof of room R4 was modelled by replacing the stoneware pipes as a single layer of stoneware material
6. The required weather information, not collected due to limitations of the experiment, was acquired from an external source (U.S. Department of Energy) [34].

The individual models of the rooms is shown in Figure 12. Thermal zone for room R1 was a simple rectangular zone created with zone tool. Windows and door were inserted on appropriate locations. Separate non-thermal zones were created for the sunshades and plinth. 100 mm thick concrete slab was used as floor material, while 100mm thick RCC covered with 25 mm thick concrete stone, 5 mm thick plaster and 20 mm thick ceramic tiles was used for roof. Room R2 was modelled in same way as room R1 except for the sunshade on south wall. Only lower surface of the shade was modelled. For room R3, a new material made up of 113 mm thick air gap sandwiched between 112.5 brick masonry was created for the cavity walls. To account for the additional shading and thermal mass due to brick projections on the west, east and south wall, the projections were modelled as non-thermal zones and their thermal mass was distributed uniformly over the main walls. So the thickness of the outer layer was increased for all three walls depending on the dimensions of the brick projections. The vents opening in the wall cavity were simulated as windows made up of a material consisting of air gap as outer layer and 112.5 mm thick brick masonry as inner layer. This is a simplification and it might have caused some deviation from the actual results. Room R4 was modelled in a similar way as room R3. Basic assumption in modelling the hollow roof of room R4 roof was that the distribution of air cavities and pipe material will not significantly change the thermal performance of the roof. So the stoneware pipes were modelled as a continuous mass in a single layer. Similarly the air cavities were added up to form another layer.

![Figure 12. Individual models of rooms R1, R2, R3, R4 in Autodesk Ecotect Analysis 2011](image)

A day was selected from each month which had temperatures closest to the average temperature of the month. Thermal analysis was then performed for these days. The days selected were: 17 January, 14 February, 15 March, 15 April, 13 May, 15 June, 15 July, 14 August, 15 September, 15 October, 15 November and 19 December. Figures 13-16 show the indoor air temperature in rooms R1, R2, R3, R4 obtained after simulation in software *Autodesk Ecotect Analysis 2011* and outdoor air temperature in various seasons.

In summer and moderate summer months (Table 2), due to effect of designed passive building elements room R4 has least maximum indoor air temperature while minimum indoor air temperature is least in room R3 (figure 13-14). Rooms R1 and R2 have nearly same indoor air temperature throughout the day. In summer months indoor air temperature is least in room R4 during hotter part of the day from 1100 hours to 1800 hours. In moderate summer and summer months indoor air temperature was more in room R4 than that in rooms R1, R2, R3 from 0300 hours to 0800 hours i.e. when outdoor air temperatures are lower. This may be attributed to insulating effect of the brick cavity wall with brick projections and hollow roof that caused a delay in heat dissipation thus stabilising indoor air temperature in room R4. In winter and moderate winter months (Table 2), minimum indoor air temperature is least in rooms R1, R2 while it is maximum in room R4 (figure 15-16). The swing in indoor air temperature in room R4 from October to March was 4.3°C, 3.5°C, 3.3°C, 2.8°C, 3.3°C, 4.3°C respectively. This swing
was least in room R4 amongst the four rooms throughout this period. Due to combined effect of designed passive building elements indoor air temperature was least in room R4 in summer while it was maximum in winter.

Figure 13. Simulated indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in moderate summer

Figure 14. Simulated indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in summer

Figure 15. Simulated indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in moderate winter

Figure 16. Simulated indoor air temperature in rooms R1, R2, R3, R4 and outdoor air temperature in winter

6. Conclusion

In India (composite climate zone) the need is to design a room that would keep indoor air temperature less in summer and more in winter as compared to outdoor air temperature. In present paper four rooms with a different combination of type of sunshade, wall, roof were compared using theoretical and simulation studies. The monthly analysis of thermal performance of the four rooms by steady state method showed maximum reduction of heat load due to combined effect of designed passive elements in room R4 was 53.31% in summer month of June. Thermal performance analysis on representative days showed 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. The comparison of thermal performance of the four rooms using software Autodesk Ecotect Analysis 2011 showed that room R4 with designed passive building elements helped to lower indoor air temperature in summer during hotter part of day and raise it in winter during night. From the theoretical and simulation study it can be concluded that the combined effect of designed passive building elements is suitable for energy conservation in buildings in composite climate as per seasonal needs.

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