Enhancement Of Indoor Temperature For Human Thermal Comfort Using Variable Glazing Area For Cold Stations Of India

Nikhil Jindal, Ranjana Jha, Sarita Baghel

Abstract: This study is to enhance and to ensure the thermal comfort inside a building (i.e. room temperature 20 ± 2°C) by using variable glazing area on south wall of the building for two different kinds of climatic zones i.e. cold-sunny (Leh, -14°C to -2.8°C) and cold-cloudy (Shimla, 1.9°C to 8.5°C, Shillong, 3.6°C to 15.5°C and Ootacamund, 5.1°C to 19.9°C). In this study, single zone isolated house, having dimension 4m × 4m × 3m, has been analyzed. The periodic solution of the heat conduction equation describing heat transmission through the different building components, floor, walls and roof has been adopted. Ambient temperature and total solar radiation received by the building envelope have been represented through Fourier series. Traditional construction with 220 mm Burnt Clay Brick wall (BCB), plastered 15 mm on both sides and the other construction of same dimensions, but insulated with 10 cm of expanded polystyrene insulation on four walls and roof have been analyzed. It is found that for the four stations considered, the traditional building is not able to ensure thermal comfort with different glazing areas. To enhance the indoor temperature for thermal comfort for an insulated building, different glazing areas are required for different stations under consideration. It has been observed that for insulated building, 10%, 15%, 20% and 40% glazed area is required for Ootacamund, Shillong, Shimla and Leh respectively.

Keywords: Glazing area; Insulation; U- value; Climatic zones.

1. INTRODUCTION

In order to improve the thermal performance of buildings, the aspect of energy conservation plays an important role. Under the consideration of Kyoto protocol, the Governments world wide are trying to reduce the green house gas emission by reducing the energy use in the buildings by implementing various policies in various countries. Windows and glazed areas in a building are useful in reducing energy consumption in a building to provide indoor thermal comfort. People, nowadays, due to Changing lifestyle spend a lot of time in indoor built environment. Lot of energy is required to maintain the comfortable indoor temperature [1]. In India, Energy Conservation Building Code (ECBC-2007) has been propagated and the basic idea behind it, is to save the heating and cooling energy in built environment. Specific values of thermal transmittance of walls, roof and glazing area have been mentioned in the code. In the present study, an attempt has been made to keep a building thermally comfortable by using suitable amount of glazed area in the south wall and insulation on the external surface of walls n roof. Balcomb [2] worked on the concept of direct solar gain through south facing windows. He used insulated building and a large thermal mass behind the south window to solar energy during day time and releasing the same during night.

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Wray [3] applied the monthly load ratio method to analyze the performance of heavy buildings with direct gain, and the effect of the storage on the performance of the direct gain solar-heated building in detail. Several authors [4-6] have also worked rigorously on the energy performance of glazing and windows considering various parameters like window size, the thermal transmittance (U-value) and total solar energy transmittance (g-value) etc. The effect of the thickness of insulation on the external surface of walls and roof for energy saving has also been analyzed [7-9]. In this study, with the help of the periodic solution of heat conduction equation, the explicit expressions for time variation of the room air temperature inside a building have been obtained. Glazing on the south wall has been taken to allow direct solar gain. As the expression completely depends on an exact energy balance, they can be used in any kind of climatic zone for any building. The calculations are performed for two types of climatic zones i.e. cold-sunny and cold-cloudy. The amount of glazing area is calculated to ensure the thermal comfort inside the building for each of two climates.

2. MATHEMATICAL MODELING

A single zone isolated house, having dimension 4m × 4m × 3m, has been analyzed in this study. The heat flows through fours walls, roof and ground by conduction. The inside room air exchanges the heat by convection with the internal surfaces of the room. There is a direct gain of heat via window i.e. glazed area. The heat exchange between the inside room air and the ambient air is in the form of ventilation and infiltration. The heat flux which contributes towards room temperature by each mode is calculated and summed over all the modes. The rate of increase in internal energy of the room air is equal to the sum over all the modes of heat gain. This results in an energy balance equation in terms of a Fourier series of harmonics for each variable.

2.1 Heat flux through walls and roof

The well known conduction equation for heat flow through a solid is given as

$$k\frac{\partial^2 T}{\partial x^2} = \rho c \frac{\partial T}{\partial t} \tag{1}$$

As the room temperature is determined by the solar radiation and ambient temperature, at that time both the components are varying periodically and are expressible in terms of Fourier coefficients, so the room temperature is also varying periodically with the same frequency for a day. By using the appropriate boundary conditions, the solution of Eq. (1) can be written in matrix form as

$$\begin{bmatrix} T_{in} \\ \dot{q}_{in} \end{bmatrix} = \begin{bmatrix} A_n & B_n \\ D_n & A_n \end{bmatrix} \begin{bmatrix} T_{on} \\ \dot{q}_{on} \end{bmatrix}$$

The values of matrix elements A, B and D, are dependent upon the thermophysical properties of the building components and are determined as:

$$A_n = \cosh(\alpha_n L)$$

$$B_n = \frac{-\sinh(\alpha_n L)}{k\alpha_n}$$

$$D_n = -k\alpha_n \sinh(\alpha_n L)$$

Where $\alpha_n = \sqrt{\frac{in\omega\rho c}{k}}$

If the fabric is multilayered, Eq. (1) gets modified to

$$\begin{bmatrix} T_{in} \\ \dot{q}_{in} \end{bmatrix} = \begin{bmatrix} P_n & Q_n \\ R_n & S_n \end{bmatrix} \begin{bmatrix} T_{on} \\ \dot{q}_{on} \end{bmatrix} \tag{2}$$

Where

$$\begin{bmatrix} P_n & Q_n \\ R_n & S_n \end{bmatrix} = \begin{bmatrix} 1 & -1/h_i \\ 0 & 1 \end{bmatrix} \begin{bmatrix} A_n^1 & B_n^1 \\ D_n^1 & A_n^1 \end{bmatrix}$$

$$\times \begin{bmatrix} A_n^2 & B_n^2 \\ D_n^2 & A_n^2 \end{bmatrix} \begin{bmatrix} A_n^3 & B_n^3 \\ D_n^3 & A_n^3 \end{bmatrix} \begin{bmatrix} 1 & -1/h_o \\ 0 & 1 \end{bmatrix} \tag{3}$$

Here P, Q, R and S are again dependent upon thermophysical properties of different layers, and the order in which various layers are arranged in the direction in which the heat flows. The value of $\dot{Q}_{in}$ is obtained by solving Eq. (2) for $\dot{q}_{in}$ and is

$$\dot{Q}_{in} = A\frac{S_n T_{in} - T_{on}}{Q_n} \tag{4}$$

When the solar radiation falls on the inner surface as well as on the outer surface of the fabric specially in the case of direct solar gain, the boundary conditions applied to Eq.(1) get modified and one finds an expression for q_{in}, similar to Eq. (4), here the respective temperature are replaced by their corresponding solar values with an additional term, i.e.

$$\dot{Q}_{in} = A\frac{S_n\left(T_{in} + \frac{\alpha_i I_{in}}{h_i}\right) - \left(T_{on} + \frac{\alpha_o I_{on}}{h_o}\right)}{Q_n} + A\alpha_i I_{in} \tag{5}$$

2.2 Heat flux through the floor

The floor has been treated as a semi-infinite medium, the solution of Eq. (1) with suitable boundary conditions for the floor gives the expression for the heat flux, i.e.

$$\dot{Q}_{in} = A_F \frac{S_n\left(T_{in} + \frac{\alpha_i I_{in}}{h_i}\right)}{Q_n} + A_F \alpha_i I_{in} \tag{6}$$

Where, for n ≠0, S_n =1.0, and $Q_n = -\frac{1}{h_i} + \frac{1}{k\alpha_n}$

And for n = 0, i.e. steady condition, $\frac{S_n}{Q_n} = 0.0$.

The heat flux through each mode has been calculated. Solar radiation and ambient temperature which are time varying function can be expressed in terms of a Fourier series, i.e.

$$f(t) = \sum_{n=-\infty}^{+\infty} f_n \exp(in\omega t) \tag{7}$$

As discussed above, the heat flux transmitted through the walls and roof can be expressed as

$$\dot{Q} = A\sum_{n=-\infty}^{+\infty} \frac{S_n\left(T_{rn} + \frac{\alpha_i I_{iwn}}{h_i}\right) - \left(T_{an} + \frac{\alpha_o I_{on}}{h_o}\right)}{Q_n}$$

$$\times \exp(in\omega t) + A\sum_{n=-\infty}^{+\infty} (\alpha_i I_{iwn}) \exp(in\omega t) \tag{8}$$

Where S_n and Q_n are dependent upon the thermophysical properties of walls and roof material. The energy flux through the floor is obtained as

$$\dot{Q} = A_F \sum_{n=-\infty}^{+\infty} \frac{S_n\left(T_{rn} + \dfrac{\alpha_i I_{ifn}}{h_i}\right)}{Q_n} \exp(in\omega t)$$

$$+ A_F \sum_{n=-\infty}^{+\infty} (\alpha_i I_{ifn}) \exp(in\omega t) \qquad (9)$$

Hourly calculations have been done for the direct gain through the glazing. The effect of direct gain has been found hourly by assuming that floor is absorbing 60% of radiation and 8% is absorbed by each of the four walls and ceiling.

2.3 Heat gain due to infiltration and ventilation

The heat gain due to infiltration of air from ambient into room has been calculated from the expression

$$\dot{Q} = C_{inf} \sum_{n=-\infty}^{+\infty} (T_{an} - T_{rn}) \exp(in\omega t) \qquad (10)$$

The expression for ventilation heat gain is given as

$$\dot{Q} = \sum_{n=-\infty}^{+\infty} C_v (T_{an} - T_{rn}) \exp(in\omega t)$$

$$= \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} C_{vm} (T_{an} - T_{rn}) \times \exp\{i(n+m)\omega t\} \qquad (11)$$

Where it has been assumed that the ventilation term C_v is time varying factor and it is expressed in terms of Fourier coefficient as

$$C_v = \sum_{m=-\infty}^{+\infty} C_{vm} \exp(im\omega t)$$

2.4 Heat conduction through glazing and door

Heat conduction through the glazing and the door has been expressed in terms of their respective U-values, i.e.

$$\dot{Q} = AU \sum_{n=-\infty}^{+\infty} (T_{an} - T_{rn}) \exp(in\omega t) \qquad (12)$$

Room air temperature has been calculated by the net amount of heat gain/loss by the room air through all its components. It has been expressed in the form of energy balance equation as

$$M_r \frac{d}{dt}\left[\sum_{n=-\infty}^{+\infty} T_{rn} \exp(in\omega t)\right] = \sum_{j=2}^{6} Q_j \qquad (13)$$

Where *j* corresponds to Equations (8) to (12). Considering the harmonics from n = −6 to n = +6 only, and by comparing coefficients of different harmonic frequencies, Eq. (13) gives 13 Equations which can be written in the form of a matrix equation as

$$[X]_{13\times13}[T_{rn}]_{13\times1} = [Y]_{13\times1}$$

or

$$[T_{rn}]_{13\times1} = [X]^{-1}_{13\times13}[Y]_{13\times1} \qquad (14)$$

Solution of Eq. (14) determines the different harmonic components of the room air temperature, and these can be combined together to give the hourly variation of room temperature, i.e.

$$T(t) = \sum_{n=-6}^{+6} T_{rn} \exp(in\omega t) \qquad (15)$$

3. INPUT DATA

The structure of walls and roof used in this study has been given in Fig.1 and Fig.2 respectively. 10 cm of RCC has been considered on floor. And 10 cm of expanded polystyrene has been provided on the external surfaces of all walls and roof to account for the effect of insulation on the room temperature. Glazing area has been expressed as a percentage of floor area and it has been provided on the south wall only. Table 1 is showing the standard values of thermophysical properties of the materials used in this particular problem for simulation. Other related parameters used in the thermal analysis have been provided below.

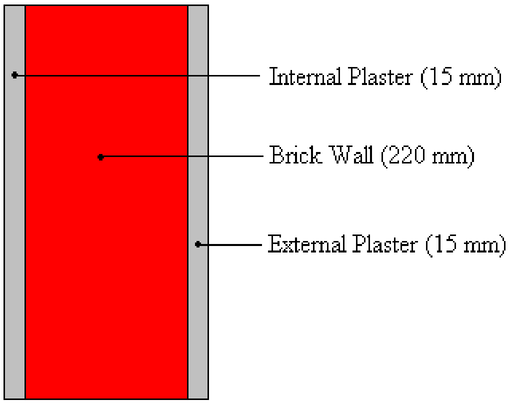

Fig. 1 Structure of the External Wall.

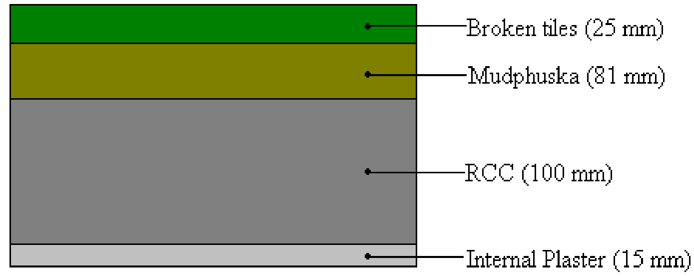

Fig. 2 Structure of the Roof.

Table1. Thermo-physical properties of the building material used in this study

S. No.	Material	Specific Heat ($J\ kg^{-1}\ K^{-1}$)	Density ($kg\ m^{-3}$)	Conductivity ($W\ m^{-1}\ K^{-1}$)
1.	Brick	880	1820	0.81
2.	RCC	880	2280	1.58
3.	Plaster	840	1762	0.72
4.	Broken Tiles	880	1820	0.81
5.	Mudphuska	880	1622	0.52
6.	Insulation (Expanded Polystyrene)	1340	34	0.035

1. **Heat transfer coefficients** ($W\ m^{-2}\ K^{-1}$)

   Wall, External surface h_o: 20.00
   Internal surface h_i : 8.29

   Roof, External surface h_o: 23.00
   Internal surface h_i : 9.26

2. **Transmission of glazing,**
   τ for single glazed (dimensionless) : 0.85
   τ for double glazed (dimensionless) : 0.73

3. **Solar radiation absorption,** α (dimensionless)

   Wall, External surface α_o : 0.40
   Internal surface α_i : 0.08

   Roof, External surface α_o : 0.70
   Internal surface α_i : 0.08
   Floor α_i : 0.60

Leh (Latitude 34°09'N; Longitude 77°34'E; Altitude 3514m), Shillong (Latitude 25°34'N; Longitude 91°53'E; Altitude 1500m), Shimla (Latitude 31°06'N; Longitude 77°10'E; Altitude 2202m) and Ootacamund (Latitude 11°24'N; Longitude 76°44'E; Altitude 2249m) have been chosen for this study as there stations represent two different types of climatic conditions i.e. cold and sunny and cold and cloudy. Leh represents a cold and sunny climate while Shillong, Shimla and Ootacamund belong to cold and cloudy climatic conditions. January, the coldest month of India has been chosen for simulation. The Table 2 is showing the monthly mean hourly temperature, global radiation and diffuse radiation [10].

Table 2. Meteorological hourly data of the four stations used in this study

T: Ambient Temp. (°C); G: Global Radiation (kWh m^{-2}); D: Diffuse Radiation (kWh m^{-2})

Time (hr)	Leh			Shimla			Shillong			Ootacamund		
	T	G	D	T	G	D	T	G	D	T	G	D
1	-12.5			2.8			5.1			7.0		
2	-13.1			2.4			4.6			6.3		
3	-13.6			2.2			4.1			5.7		
4	-13.9			2.0			3.7			5.2		
5	-14.0			1.9			3.6			5.1		
6	-13.8	0.100	0.100	2.0	0.100	0.100	3.8	0.100	0.100	5.4	0.100	0.100
7	-13.2	0.100	0.100	2.4	0.104	0.103	4.4	0.116	0.108	6.1	0.189	0.127
8	-12.2	0.207	0.129	3.0	0.233	0.133	5.5	0.284	0.139	7.5	0.402	0.149
9	-10.8	0.362	0.146	3.8	0.396	0.149	7.1	0.457	0.153	9.4	0.596	0.163
10	-9.1	0.485	0.156	4.8	0.526	0.159	8.8	0.595	0.163	11.6	0.742	0.170
11	-7.2	0.565	0.161	5.9	0.607	0.164	10.9	0.679	0.167	14.1	0.836	0.174
12	-5.4	0.592	0.163	7.0	0.634	0.165	12.8	0.708	0.168	16.5	0.868	0.176
13	-4.0	0.565	0.161	7.8	0.607	0.164	14.2	0.679	0.167	18.3	0.836	0.174
14	-3.1	0.485	0.156	8.3	0.526	0.159	15.1	0.595	0.163	19.5	0.742	0.170
15	-2.8	0.362	0.146	8.5	0.396	0.149	15.5	0.457	0.153	19.9	0.596	0.163
16	-3.1	0.207	0.129	8.3	0.233	0.133	15.1	0.284	0.139	19.5	0.402	0.149
17	-3.9	0.100	0.100	7.8	0.104	0.103	14.3	0.116	0.108	18.4	0.189	0.127
18	-5.2	0.100	0.100	7.1	0.100	0.100	13.0	0.100	0.100	16.8	0.100	0.100
19	-6.6			6.3			11.5			14.9		
20	-8.1			5.4			9.9			12.9		
21	-9.3			4.7			8.6			11.3		
22	-10.4			4.0			7.4			9.8		
23	-11.3			3.5			6.5			8.7		
24	-12.0			3.1			5.7			7.8		

3. RESULTS AND DISCUSSION

The results have been obtained in terms of hourly variation of room temperature for a typical winter day for Leh, Shillong, Shimla and Ootacamund. The effect of glazing area upon the room temperature, for different combinations of U-values of walls and roof has been determined. The results, in terms of maximum and minimum room air temperature, for different values of glazing areas are given. The value of U_{wn} (single glazed window) for non insulated building has been taken 5.0 W m^{-2} K^{-1} and for well insulated building two different values of U_{wn} (double glazed low-e window) have been taken which are 1.5 W m^{-2} K^{-1} for day time and 0.5 W m^{-2} K^{-1} for night respectively. Night value of U_{wn} is achieved by putting a wooden shutter in front of the glazing during night time.

3.1 COLD AND SUNNY REGION

LEH

Leh is having cold and sunny climate where the ambient temperature varies from -14°C to -2.8°C in winter month (January). For human thermal comfort the room air temperature should be 20 ± 2°C. For this station, only well insulated building is considered. For the traditional building, no amount of glazed area can ensure the thermal comfort.

In an insulated building, the inside room temperature has been calculated on hourly basis for the five different values of glazed area i.e. 10%, 20%, 30%, 35% and 40%. The results obtained for insulated building are shown in the Table 3. The Fig. 3 shows that in a well insulated building, for 10% glazed area, the room air temperature is about 0°C. As the glazed area is increased to 20%, the room temperature varies from 7.1°C to 9.0°C. For 35% glazed area, the room temperature shows variation from 17.0°C to 20.7°C and when it is 40%, the corresponding values are 20.0°C and 24.2°C. From these values, it is evident that the glazed area should lie between 35% and 40%. It is also evident that the swing in the room air temperature is about 4°C.

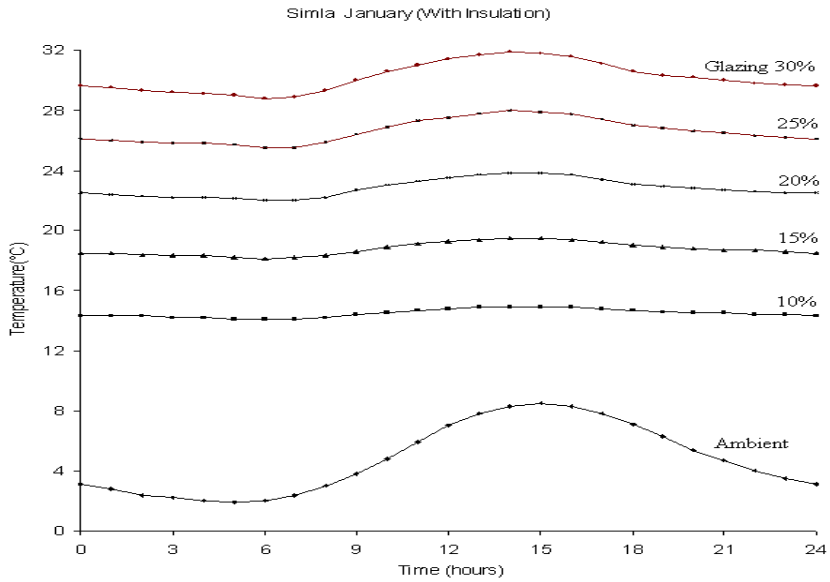

Fig. 3. Time variation of room air temperature in severe cold conditions at Leh, for different glazing areas (U= 1.5 W m^{-2} K^{-1} in day and 0.5 W m^{-2} K^{-1} in night); glazing, % of floor area, ACH=0.5;

3.2 COLD AND CLOUDY REGION

The three stations namely Ootacamund, Shimla and Shillong are having different climate than Leh i.e. cold and cloudy. Among the three Shimla is coldest one with ambient temperature ranging between 1.9°C to 8.5°C. For Shillong and Ootacamund, the ambient temperature range is 3.6°C to 15.5°C and 5.1°C to 19.9°C respectively. Here the effect of glazed area has been optimized for insulated as well as non-insulated buildings. It has been observed that glazing is beneficial for the insulated buildings only.

Shimla

Two types of buildings i.e. non insulated and insulated, have been analyzed. The results are shown in Table 4. For non insulated building, it is seen in Fig. 4 that for 50% glazed area $T_{max.}$ is 14.2°C and for 30% glazed area, the values of $T_{max.}$ is 10.7°C. In order to achieve the comfortable room air temperature one requires more than 50% of the glazed area for non insulated building. It is evident that temperature swing is also very large for such type of building. Fig. 5 is showing the results for the insulated building. It is observed that when glazed area is 10%, the inside room air temperature varies from 14.1°C to 14.9°C. As the glazed area is increased, the inside room temperature increased significantly. When the glazed area is 20%, one achieves the comfortable temperature range inside the room which is 22.0°C to 23.8°C. It is evident from the graph that the swing in the inside room air temperature is very less (less than 2°C), when the building is insulated.

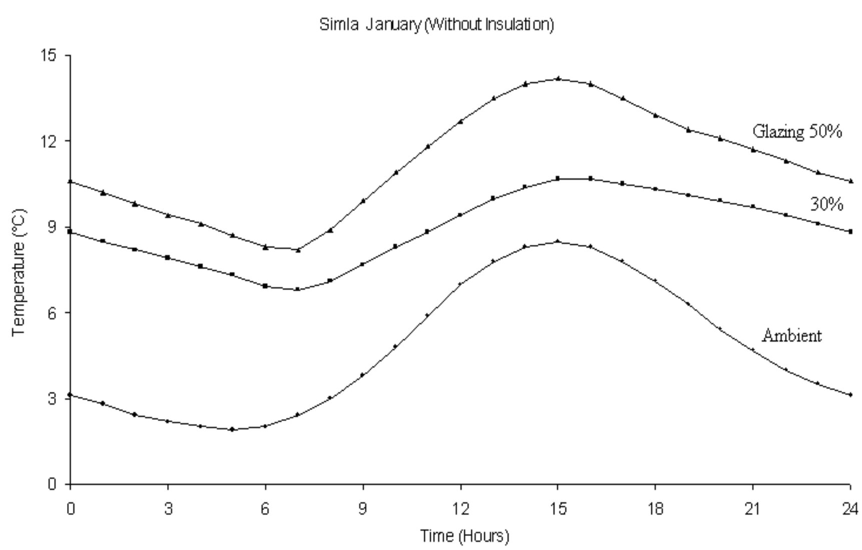

Fig. 4. Time variation of room air temperature for a non-insulated building at Shimla, for different glazing areas (U= 5.0 W m^{-2} K^{-1}); glazing, % of floor area, ACH=1.0;

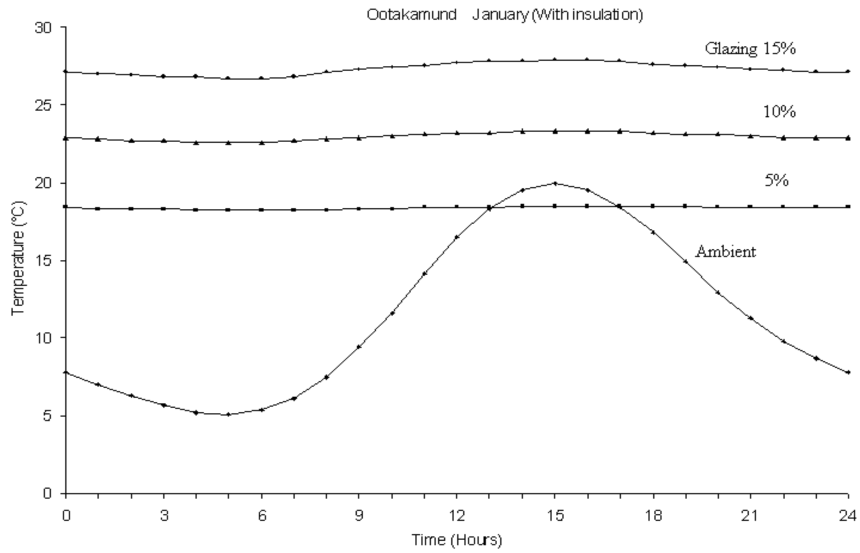

Fig. 5. Time variation of room air temperature for an insulated building at Shimla, for different glazing areas (U= 1.5 W m^{-2} K^{-1} in day and 0.5 W m^{-2} K^{-1} in night); glazing, % of floor area, ACH= 0.5;

Ootacamund

The climatic condition of Ootacamund is not very cold in comparison to Shimla. The difference in max. and min. ambient temperature is around 15°C in the month of January. The calculations have been done for a non insulated as well as insulated building. The results are shown in Table 5. For a non insulated building, five different values of glazed area have been taken for the computation of comfortable inside room air temperature. The results are shown in Table 5 and Fig. 6. It can be seen that when the glazed area is 10%, the value of $T_{max.}$ is 16.2°C and when glazed area is increased to 20%, 30% and 40%, the value of $T_{max.}$ increases to 17.5°C, 19.1°C and 20.8°C respectively. When the glazed area is 50%, the inside room temperature varies from 16°C to 22.4°C. In order to achieve the comfortable room air temperature, more than 50% glazed area is required whish is not advisable for the building even aesthetically it is not advisable. It is also evident that the temperature swing is very high for such a building. The results for an insulated building are shown in Fig. 7. It is observed that when glazed area is 5%, the inside room air temperature varies from 18.2°C to 18.5°C. When the glazed area is increased to 10%, one achieves the comfortable room air temperature which is 22.6°C to 23.3°C. It is evident from the graph that the swing in the room air temperature is very less (less than 1°C) for such type of building.

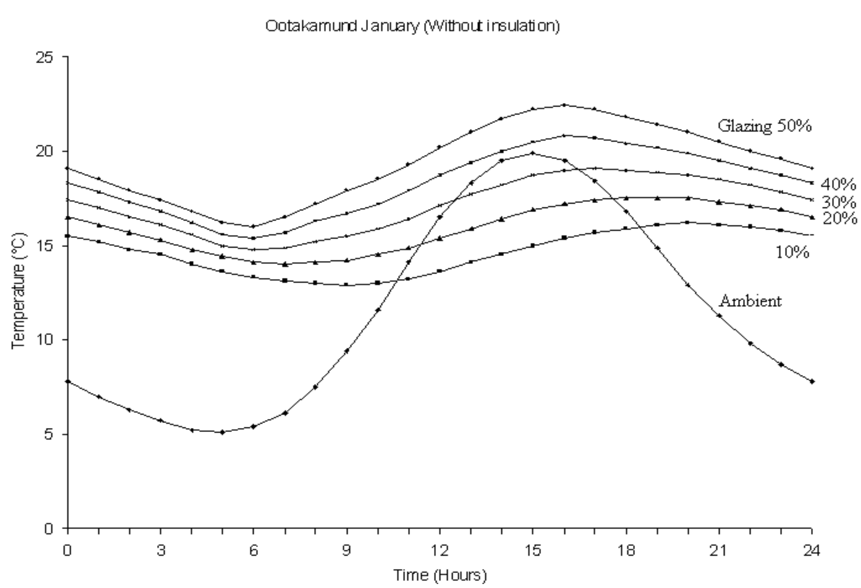

Fig. 6. Time variation of room air temperature for a non-insulated building at Ootacamund, for different glazing areas (U= 5.0 W m^{-2} K^{-1}); glazing, % of floor area, ACH=1.0;

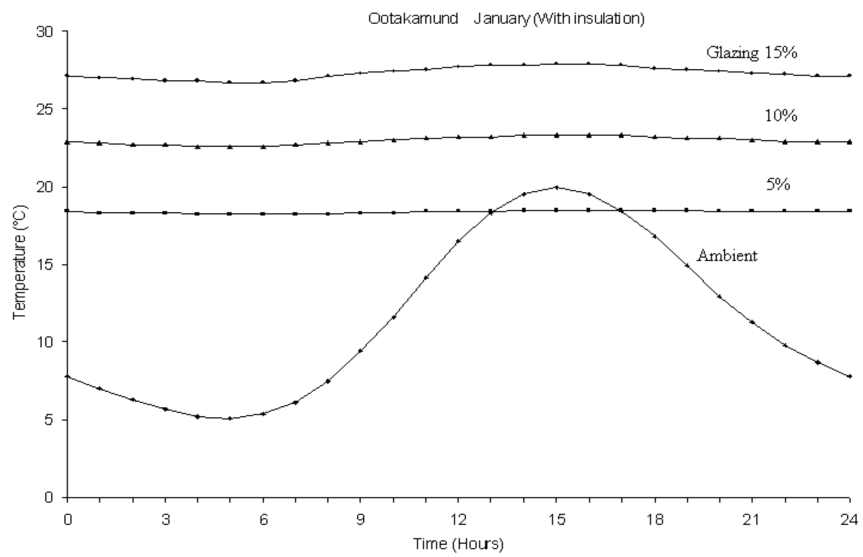

Fig. 7. Time variation of room air temperature for an insulated building at Ootacamund, for different glazing areas (U= 1.5 W m^{-2} K^{-1} in day and 0.5 W m^{-2} K^{-1} in night); glazing, % of floor area, ACH= 0.5;

Shillong

Non insulated as well as insulated buildings have been analyzed for this station. For a non insulated building, the inside room air temperature has been calculated for 30% and 50 % glazed area. It is observed from Fig. 8 that for 30% glazed area, the inside room air temperature varies from 10.9°C to 15.2°C.When glazed area is increased to 50%, the variation in room air temperature is from 12.2°C to 18.6°C. To ensure the thermal comfort inside the building, more than 50% glazed area is required for a non insulated building. It is evident that the temperature swing is also very high (more than 6°C) for such a building. For a well insulated building, four different values of glazed area have been used to decide the optimum area of glazed surface to get the comfortable room air temperature. As shown in Fig. 9, it has been observed that when glazed area is 10%, the inside room air temperature varies from 18.4°C to 19.3°C. As the glazed area is increased, the inside room temperature increased significantly. When the glazed area increased to 15%, one achieves the comfortable room air temperature range which is 22.4°C to 23.8°C. And the temperature swing in the room air temperature is less than 2°C such a building.

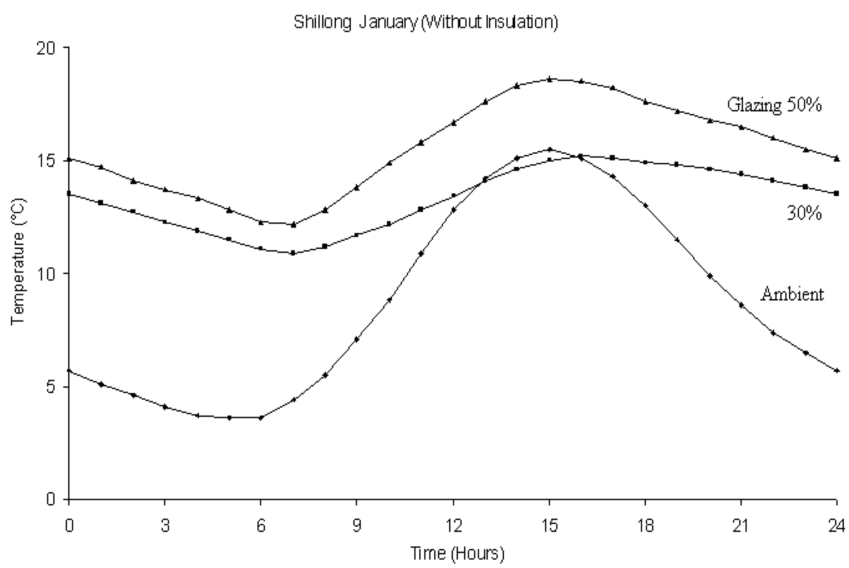

Fig. 8. Time variation of room air temperature for a non-insulated building at Shillong, for different glazing areas (U= 5.0 W m^{-2} K^{-1}); glazing, % of floor area, ACH=1.0;

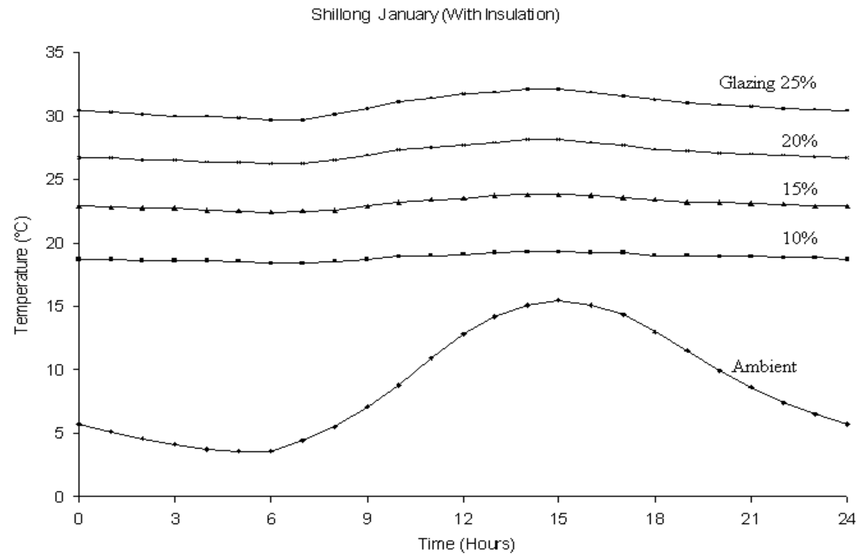

Fig. 9. Time variation of room air temperature for an insulated building at Shillong, for different glazing areas (U= 1.5 W m^{-2} K^{-1} in day and 0.5 W m^{-2} K^{-1} in night); glazing, % of floor area, ACH= 0.5;

4. Conclusions

The insulation on the outside surface of walls is having significant effect on room air temperature as well as on the swing of this temperature. The temperature swing is about 3°C to 4°C. For all the four stations considered here, if the building is non insulated, the amount of glazed area which ensures thermal comfort becomes too large and hence impracticable. With insulation on the external surface of the building it has been observed that

a) For Leh, 40% of the glazing area gives a comfortable room air temperature where the climatic condition is cold and sunny.
b) For Ootacamund, 10% of the glazing area gives a comfortable temperature zone with minimum fluctuation in room temperature.
c) For cold *and* cloudy station like Shimla, 20% of the glazing area provides the adequate condition to achieve a comfortable temperature zone inside the room.
d) For Shillong where the climate is same as that of Shimla and Ootacamund but the difference in max. and min. ambient temperature is about 10°C, 15% of the glazed area is advised to use for the building.

NOMENCLATURE

A	area of the fabric (m^2)
A_F	area of the floor (m^2)
C	heat transfer coefficient for air exchange (W K^{-1})
C_{inf}	infiltration coefficient
C_v	ventilation coefficient
c	specific heat (J kg^{-1} K^{-1})
h	convective heat transfer coefficient (W m^{-2} K^{-1})
I	radiation flux (W m^{-2})
L	thickness (m)
k	thermal conductivity (W m^{-1} K^{-1})
M	thermal mass (J K^{-1})
N	number of air exchanges per hour
$\dot{Q}$	rate of heat flow across any fabric surface (W)
$\dot{q}$	rate of heat flow across any surface per unit area (W m^{-2})
T	temperature (°C)
t	time (sec)
ACH	Air changes per hour
Q, S	as defined by Eq (3) (see mathematical modeling)
U	conduction transmittance (W m^{-2} K^{-1})
V	volume of room (m^3)
X	coefficient matrix of order 13×13
Y	column matrix of order 13×1

Greek letters

ρ	density (kg m^{-3})
α	absorptivity (dimensionless)
ω	angular frequency, w = 2π/86,400 rad s^{-1}

Subscripts

a	air
d	door
f	floor
i	inside surface
n	nth harmonic
o	outside surface
r	room
v	ventilation
w	wall
WN	window

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