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Optimization of Building Envelope to Reduce Air Conditioning

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Abstract

Background/Objectives: Air conditioning in tropical buildings constitutes a major component towards the total energy consumption. General guidelines for reducing the incident solar radiation on the building envelope are available in literature. However information on the reduction in energy requirement is not readily available. **Methods/Statistical Analysis:** Reduction in energy requirement by varying the building planform, orientation and construction materials was studied. **Findings:** A building with a planform area close to the Golden Ratio and with the broader side facing North, resulted in the least amount of solar radiation on the surface of the building envelope. Further the white coloured buildings made of rammed walls and roof material with longer phase lag decrease the heat transfer into the buildings. **Conclusion:** The building orientation and planform are crucial in reducing the incident solar radiation on the building envelope surface. Use of white colour and materials like rammed earth for walls resulted in substantial reduction of the required cooling loads to maintain the indoor thermal comfort temperature.

Keywords: Energy Consumption, Green Buildings, Solar Radiation, Sustainable Architecture

Nomenclature

I - Total Solar Flux (W/m^2)
I_d - Diffuse Solar Flux (W/m^2)
I_{dH} - Average Clear Day Diffuse Solar Flux (W/m^2)
I_D - Direct Solar Flux (W/m^2)
I_{DN} - Direct Normal Flux (W/m^2)
I_R - Reflected Solar Flux (W/m^2)
L - Length of the Wall (m)
Q - Periodic Heat Flow per Day (W)
$\mathbf{S}_T$ - Average radiation on the surface (W/m^2)
T - Ambient temperature (°C)
T_0 - Monthly Mean Outdoor Temperature (°C)
T_{avg} - Average Temperature of a Month (°C)
$T_{comfort}$ - Comfort Temperature of a Month (°C)
T_{hour} - Average Temperature of an Hour (°C)
T_{sol} - Sol-air temperature (°C)
U - Thermal Conductivity (W/m^2-K)
W - Width of the Wall (m)
θ - Angle of Incidence (degree)
μ - Decrement Factor
Φ - Phase Lag (h)
Σ - Surface Tilt Angle (degree)

1. Introduction

Solar radiation on the building envelope results in heat transfer in to the building, resulting in increased indoor temperature[1]. In the absence of air conditioning, indoor temperatures in tropical countries exceed acceptable thermal comfort levels. In[2] gives guidelines to minimize the heat transfer, by addressing issues like building plan form, orientation and construction material thermal properties. However data on percentage reduction of solar radiation on the building envelope and consequent reduction in energy consumed towards air conditioning is not available. This study addresses this limitation by providing an estimate of the reduction in energy consumed.

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Coimbatore city (11.0183°N latitude and 76.9725° E longitude) located in South India was chosen for this study. The annual solar radiation on different building surfaces for 365 days was calculated for above mentioned location. Effect of change in building planform on the incident solar radiation on the building was studied and an optimum planform obtained. Using the optimum planform, a study on the building orientation was carried out. Various combinations of building materials for a roof were then studied, to further reduce the energy consumption required for air conditioning.

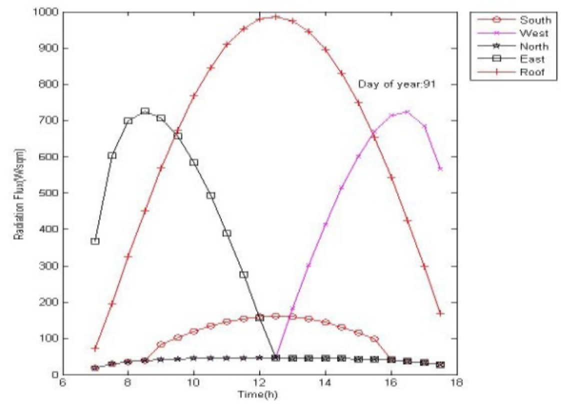

Figure 1. Radiation flux on walls and roof for 1st April.

2. Solar Radiation on the Building Envelope

To estimate the heat transfer into the building envelope, diurnal solar radiation on exterior wall surfaces and roof is required. Solar radiation incident on these surfaces consists of direct radiation (I_D), diffuse radiation (I_d) and reflected radiation (I_r). Out of these, the reflected radiation component is very low and was neglected in this study. Diurnal radiation on the wall surfaces and roof was calculated for Coimbatore for all months using following relations given in ASHARAE[3].

$$I = I_D + I_d \tag{1}$$

$$I_D = I_{DN} * \cos(\theta) \tag{2}$$

$$I_d = I_{dH} * (1+\cos\Sigma)/2 \tag{3}$$

Where θand Σare angle of incidence and surface tilt angle respectively. Using Equations (1) to (3), it was found that the radiation was maximum during the month of April, compared to other months. The calculated diurnal variation of total solar radiation on all external surfaces for the month of April is shown in Figure 1.
Following were inferred from Figure 1

- The highest amount of solar radiation (W/m^2) on the roof is higher than other surfaces of the building envelope.
- Radiation on North and South walls are negligible.
- Radiation on East and West walls are symmetrical.

3. Building Aspect Ratio

A study was carried out on the effect of building aspect ratio (L/W) on the incident annual radiation on the building envelope. For this study, a building of rectangular plan form with a plinth area of 18.3m^2 was used. A building height of 3.3m, which is a standard value for present generation buildings, is used in this paper. The aspect ratio was varied from 0.5 to 2 with the South and East facing walls taken as length and width respectively. The annual solar radiation on the building envelope for different aspect ratios is as shown in Figure 2.
From Figure 2, following were observed:

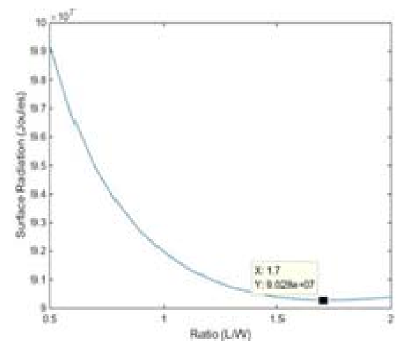

Figure 2. Radiation for different aspect ratios.

- Presently buildings are constructed with an aspect ratio of 0.59. The surface radiation can be reduced by 9.4 % if an aspect ratio of 1.6 to 1.75 is used.
- Architects use an aspect ratio of 1.618 called 'Golden ratio' for aesthetic reasons. It was found that an aspect ratio of approximately 1.618(Golden Rule), resulted in least annual surface radiation.

Based on the above mentioned inferences, an aspect ratio of 1.618 was used for subsequent studies.

4. Building Orientation

The effect of building orientation on incident annual solar radiation was then studied. The building orientation was varied from 0° (longer side facing South) to 90° (longer side facing East). The results are as shown in Figure 3. Following were inferred from Figure 3.

- Zero degree orientation resulted in least amount of annual solar radiation.
- An increase in radiation by 7.7 % for 90° when compared with that of 0° orientation.

The increase in radiation was very less from 0° to 10° orientation. Hence it offers scope for building alignments other than E-W orientation, without compromising on energy efficiency.

5. Natural Ventilation Potential

Since Coimbatore is located near a pass in the Western Ghats, wind velocity of more than 3m/s was observed throughout the year. Hence there was sufficient scope for using natural ventilation to reduce energy consumption. However, natural ventilation can be used only during those periods, when the outside temperature, is less than the inside temperature. Hence both internal temperature and diurnal variation of the outside temperature were quantified. In this study, internal temperature was estimated using the adaptive thermal comfort temperature model given by the following equation[4].

$$T_{comfort} = 13.5 + 0.54\, T_0 \quad (4)$$

The diurnal variation was calculated using the ASHRAE guidelines. The natural ventilation cooling periods are given in Figure 4 for the month of April.

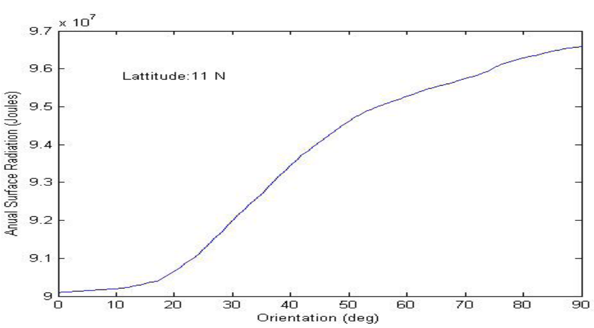

Figure 3. Solar radiation vs building orientation.

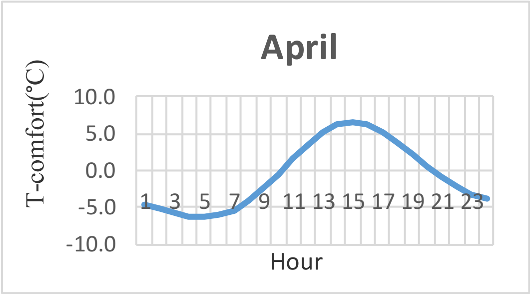

Figure 4. Natural ventilation cooling potential.

Natural ventilation was used in this study whenever outdoor temperature was less than the comfort temperature ($T_{comfort}$). For April which is the hottest month, natural ventilation was used for 15 hours (0 to 9h and then from 19 to 24h).

6. Building Materials

To further reduce the heat flow into the building the study concentrated on three thermal properties of the building envelope which are its decrement factor (μ), phase lag (Φ) and thermal Conductivity (U).

To calculate the periodic heat flow following equations[5] were used.

$$T_{sol} = T_{hour} + (0.6 * S_T/22) \quad (5)$$

$$\Delta T_{net} = (T_{avg} - T_{com}) + (\mu * (T_{sol} - T_{avg})) \quad (6)$$

$$Q = U * A * \Delta T_{net} \quad (7)$$

Different combinations of building materials, given in the Table 1 were used for estimating the heat transfer (W) for a typical day in the month of April (hottest month in a year).

The daily energy requirement (Wh) for different combinations of building materials with 200W internal load are as given in the Table 2. It was observed from the above mentioned Table that Case 4 requires minimum energy for cooling. Further it was also found that conduction through the roof was the largest component of heat transfer through the building envelope. Since conduction through the roof contributes most to the heat transfer, a hypothetical roof with different decrement factors, thermal conductivity and phase lags were studied. Results of the energy requirement after accounting for natural ventilation are as given in Table 3.

Table 1. Thermal properties of building materials

Type	Material	Time- Lag (hours)	Decrement Factor	U (W/ m^2-K)
Wall (W1)	Brick Plaster (130mm)	3	0.7	2.640
Wall (W2)	Brick Plaster (250mm)	7.6	0.33	1.830
Wall (W3)	Rammed Earth(300mm)	10.3	0.22	2.860
Roof (R1)	Concrete Roof (150mm)	7	0.58	0.896
Roof (R2)	Metal Corrugated Sheet	0	1	7.14

Table 2. Energy requirements for different combinations

Case	Material	Energy requirement (Wh)
1	W2+R1	1505
2	W1+R1	5681
3	W3+R1	**589**
4	W3(white) + R1(white)	**329**
5	W2+R2	15660

Table 3. Energy requirement for a hypothetical roof

Time Lag(h)	Decrement factor	U (W/m^2-K)	Energy requirement (Wh)
7	0.464	0.896	288
7	0.58	0.896	329
7	0.696	0.896	372
7	0.58	0.7168	294
7	0.58	0.896	329
7	0.58	1.0752	364
4	0.58	0.896	411
7	0.58	0.896	329
10	0.58	0.896	188

Following were observed:

- As decrement factor increased by 50 %, the cooling load increased by 29%.
- As thermal conductivity increased by 50%, the cooling load increased by 23%.
- An increase of 38% in phase lag, resulted in decrease of the cooling load by 54%.

It is hence felt that increase in phase lag can result in substantial saving of energy, compared to properties like decrement factor and thermal conductivity.

7. Conclusion

The solar radiation on different surfaces of a building was calculated. It was found out that a building aspect ratio close the golden rule resulted in least amount of solar radiation for a given floor area. It was also found out that the solar radiation increased by 7.7%, when the broader side of the building faced east. The radiation increased marginally up to 10°. Heat transfer in to various building materials was studied and it was found that white colored walls made of rammed earth and concrete roof resulted in least amount of energy required for cooling. A hypothetical roof was also studied by varying its thermal properties and it was found that 'thermal phase lag' has a strong influence on the energy requirement.

The result of this study can be used by practicing architects to reduce energy consumed towards air conditioning in tropical countries.

8. References

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