

A MATHEMATICAL MODEL FEATURING TIME LAG AND DECREMENT FACTOR TO ASSESS INDOOR THERMAL CONDITIONS IN LOW-INCOME-GROUP HOUSE

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ABSTRACT

Raipur, capital of Chhattisgarh state, India, is located at (21.18° N and 81.78° E). During summer season, the city experiences maximum temperature of 46 °C. Residents resort to external cooling sources almost throughout the year for achieving thermal comfort. Therefore, thermal performance analysis of house is important to assess the temperature inside the house at different season. In present work, mathematical model of hourly temperature distribution in each room of the Low Income Group (LIG) house has been developed using time lag and decrement factor. A system of differential equations is derived and solved. The results obtained are validated with data collected onsite. The study is reported for three major seasons realized in Raipur. Deviation of room temperature from predefined thermal comfort has been calculated and reported for different season. The report reveals the lack of thermal comfort from the sets standards in post-monsoon and summer season.

Keywords: *Thermal Performance, Time Lag, Decrement Factor, Thermal Comfort*

INTRODUCTION

On the account of (i) modernized ambiance, (ii) readily available comfort enhancing devices and (iii) tendency to optimize space, most housing layouts and constructions neglect the possibility of providing comfortable environment naturally. Dependency on external cooling sources has been increasing day by day resulting in increase in energy consumption. Investigation of thermal performance of buildings help in ascertaining the lack of thermal comfort in modern buildings and the studies allow for avenues of incorporating thermal comfort in a cost effective manner. Raipur city experiences post-monsoon, winter and extreme summer seasons throughout the year. Summer prevails during March-July followed by post-monsoon during August-October and winter during November-February. In the month of May, summer is at peak with solar radiation at its maximum. The average maximum and minimum ambient temperature during summer is 46 °C and 25 °C. In September, the city attains an average maximum and minimum ambient temperature of around 32 °C and 24 °C. During winter, the mean maximum and minimum ambient temperature attained is 30 °C and 12 °C. The National Building Code of India defines the two indoor temperature ranges for summer (23–26 °C) and winter (21–23 °C) for all region based on ASHRAE. Hence, as per the standards, the indoor temperature to define thermal comfort ranges around 23 °C to 26 °C. Designing residential buildings to provide the thermal comfort in contrast to the extreme outdoor conditions is, therefore, an interesting research problem and thermal performance analysis of residences is important to assess the temperature inside the house in different season and critically assess the building design.

Literature review indicates that researchers have conducted thermal comfort analysis of houses at specific locations of the country and pointed out the need of thermal comfort analysis for different regions to re-define the building design regulations. Many researchers have determined the thermal performance of house based on experimental, simulation and very few are based on mathematical analysis. [1-5] have reported experimental and simulation method to assess the indoor temperature of house for different region of the world. Room air temperature analysis has been investigated for different height of house using Agros2D numerical simulation [6]. Researchers have also worked on effect of roof structure on thermal performance of building, since roof is the major source of heat transfer in building. Finite element model has been used [7] to determine the indoor air temperature of house.

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Comparative study has been done for vault roof house and flat roof house and results shows that houses with vault roofs are more comfortable than the flat roof ones. In [8], the effect of orientation and insulation on indoor air temperature of house is studied using mathematical and experimental techniques for a house located in Algeria. It is found that changing orientation of houses in hot season is not helpful to improve thermal comfort. But providing insulation on walls/roof will reduce the heat transfer thereby reducing the indoor temperature.

A mathematical model using energy balance equation has been reported to determine the thermal performance of mud houses at IIT Delhi, India. It is observed that a mud house provides good thermal comfort in all seasons [9-10]. Comparison has been done of different roof shapes; dome shape and inverted U-shape. It is found out that the dome shape rooms has higher indoor temperature as compared to inverted U-shaped rooms due to the higher surface area of the dome shape room exposed to sun as compared to inverted U-shape rooms [10]. Effect of time lag and decrement factor has been reported by [11-14]. Room air temperature of building depends on the thermal performance of wall and heat flux transfer through the wall and directly effects the energy consumption of building.

Time lag (TL) and decrement factor (DF) are the two important parameters to evaluate the thermal performance of wall. For improving the thermal performance of wall, one needs to choose correct building material with due consideration to the thermal conductivity, thermal capacity and thickness of wall [15]. Optimum position of insulation on walls to increase the time lag and decrease the decrement factor value has been suggested by [12]. Insulation throughout of the wall except outer surface of wall is not recommended as it results in undesired amount of time lag and decrement factor. For desirable time lag and decrement factor, half insulation should be placed at mid plane of wall and half at the outer surface of the wall. The method to determine “Equivalent Temperature Difference (ETD)” for various materials and for different time of the day is proposed in [16] where in the heat transfer through conduction is calculated by multiplying ETD to overall heat transfer coefficient of walls. In [17], time lag, decrement factor and ETD have been determined experimentally as well as theoretically for different configuration of walls and roofs and experimental and theoretical values are validated with good agreement. It is also reported that thermo physical property of material affects the time lag and decrement factor value as high heat capacity material has high decrement factor and higher ETD result in higher heat gain. Finite difference Method is used to numerically model the thermal performance of a building envelope and the effect of thermal properties and external convection coefficient on the time lag and decrement factor is reported in [18].

Dynamic simulation of the thermal performance of modern wall-constructions in Tehran has been reported in [19] where in the role of insulation materials and thermal mass on thermal performance is investigated. The role of local weather reports in dynamic simulation and performance indicators is discussed. The feasibility of post-occupancy strategies, namely ventilation strategies and adaptive occupancy patterns throughout the day during hot-dry climate in naturally ventilated residential apartments has been investigated to improve the thermal comfort in [20]. The study reports a combined improvement of around 28 % in thermal comfort due to both strategies. Thermal comfort analysis of LIG house using CFD is reported in [21], it is reported that varying the sizes of windows do not improve the thermal comfort of house. Energy requirement of building is studied in [22] and revealed that providing a insulating material on building walls and roof reduces the energy requirement of building

Many researchers [23-25] have studied the effect of thermo physical properties of material and wall thickness on time lag and decrement factor, however none of the papers have reported the effect of time lag and decrement factor for estimating room temperature of house. In present paper semi empirical method has been used for thermal performance analysis of LIG (Low Income Group) house located at Raipur, India. Mathematical model has been developed in terms of a system of differential equations to compute hourly temperature distribution inside a room using the time lag and decrement factor.

METHODOLOGY

Indoor temperature depends on many factors such as solar radiation, ambient temperature, material properties, and orientation of houses. The mathematical model developed for LIG houses in this work takes into account all such factors the model is developed assuming constant thermal properties of building materials, constant

inner and outer heat transfer coefficient and one dimensional heat flow through walls and slabs. The material properties considered for the model is reported in table 1.

The mathematical model is developed for each of the rooms of an LIG house situated in Raipur. The layout of the house is shown in Figure 1. The colony comprises of similar houses with common/shared walls as it is targeted for residents belonging to low income group.

Table 1. Material properties [26]

Thermal conductivity of brick	0.811 W/mK
Thermal conductivity of cement	0.721 W/mK
Thermal conductivity of concrete	1.10 W/mK
Thermal conductivity of plywood	0.174W/mK
Thermal conductivity of glass	0.814W/mK
Heat transfer coefficient at inner surface of wall	8.3 W/m ² K
Heat transfer coefficient at outer surface of wall	22.7 W/m ² K

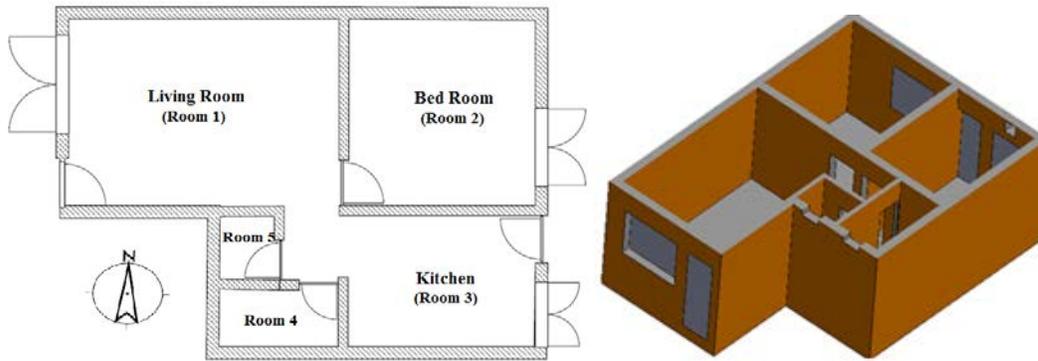


Figure 1. House plan and 3D view of LIG house located at Raipur, India

MATHEMATICAL MODEL

Applying the energy conservation for each room, the mathematical equation for heat gain and loss is expressed as [10]:

$$m_a c_a \sum \frac{dT_r}{dt} = Q_{gain} - Q_{loss} \quad (1)$$

$$Q_{gain} = Q_{wall} + Q_{roof} + Q_{window} + Q_{door} + Q_{internal} \quad (2)$$

$$Q_{loss} = Q_{ventilation} + Q_{ground} \quad (3)$$

In Eq. 1, the heat gain is computed by taking into consideration heat input from walls, roof, doors and windows. Internal heat generation due to electrical sources also add to heat gain but are not considered presently as the study is carried out for an empty house. The heat gain and loss is calculated using Eq. 2 and 3. The heat gain through walls and roof takes into account time lag (ϕ) and decrement factor (λ). The heat transfer to the wall by solar radiation is partially stored in wall due to thermal capacity of wall and is partially transferred to the indoor space (Figure 2). Due to thermal energy storage of wall if wall temperature exceeds the outdoor temperature then heat will flow outside. Hence the thermal capacity of the wall introduces a decrement in heat transfer. Decrement factor (Eq. 4) decreases with increase of wall thickness and vice versa [12]. The larger is the thickness and thermal resistance, longer will be the time delay of heat flowing through outer surface to inner surface. This time delay is called time lag

(Eq. 5) which physically means the difference in time scale of the time of heat entering the outer surface and leaving the inner surface.

$$\lambda = \frac{A_r}{A_o} = \frac{T_r^{\max} - T_r^{\min}}{T_{amb}^{\max} - T_{amb}^{\min}} \quad (4)$$

$$\phi = t_{T_r, \max} - t_{T_{amb, \max}} \quad (5)$$

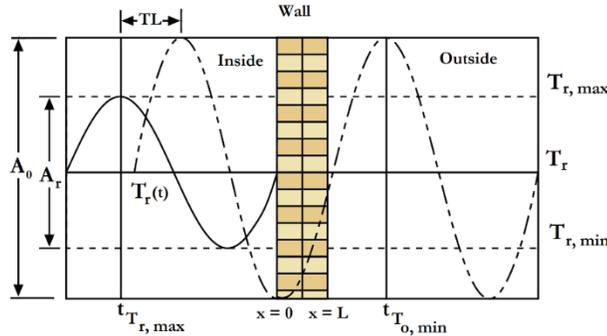


Figure 2. Definitions of time lag and decrement factor [12]

Semi empirical method combines analytical treatment along with the experimental data for solving unsteady heat transfer problem. This method is being used for solving heat transfer problem in buildings by introducing equivalent temperature difference (ETD). ETD [27] is dependent on solar radiation, ambient temperature, maximum and minimum indoor temperature. Time lag and decrement factor are important terminologies in ETD used to estimate the indoor temperature of building (Eq. 6).

$$ETD = (T_{sol-air, avg} - T_r) + \lambda (T_{sol-air, \phi} - T_{sol-air, avg}) \quad (6)$$

Sol air temperature of wall and roof can be calculated from following equation [9]:

$$T_{sol} = \left(\frac{\alpha I}{h_o} + T_{amb} - \frac{\varepsilon \Delta R}{h_o} \right) \quad (7)$$

In Eq. (7), for horizontal and vertical surface, $\varepsilon \Delta R = 60 \text{ W/m}^2$, and 0 respectively.

For inclined surface; $\varepsilon \Delta R = (\cot(\beta) \times 60) \text{ W/m}^2$

In Eq. 2 the heat gain through wall (Q_{wall}) is calculated on the basis of ETD [4] as follows:

$$Q_{wall} = (UA)_{wall} (ETD)_{wall} \quad (8)$$

In Eq. 6 and Eq. 8 the values of time lag and decrement factor for the LIG house is calculated from the field data and is taken as 4 hours and 0.111 respectively. It is to be noted that these values are independent of the season. U is the overall heat transfer coefficients of wall which is calculated for the walls having three layer as shown in Figure 3:

$$U_{wall} = \left(\frac{1}{h_i} + \frac{L_1}{K_1} + \frac{L_2}{K_2} + \frac{L_3}{K_3} + \frac{1}{h_o} \right)^{-1} \quad (9)$$

In Eq. 9, L_1, L_2, L_3 are the thickness and K_1, K_2, K_3 are thermal conductivities of wall layers respectively.

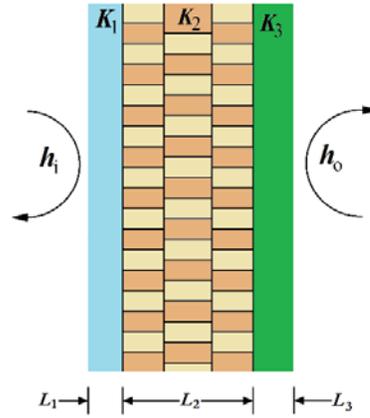


Figure 3. Configuration of building wall

Similarly, Heat gain through roof (Q_{roof}) is calculated using Eq. 10:

$$Q_{roof} = (UA)_{roof} (ETD)_{roof} \quad (10)$$

Heat transfer through doors and windows are calculated using Eq. 11 and 12 respectively.

$$Q_{door} = (UA)_{door} (T_{sol,door} - T_{r1}) \quad (11)$$

$$Q_{win} = [A_{win} U_{win} (T_{sol,win} - T_r) + A_{win} \tau I] \quad (12)$$

Heat loss takes place through ground and ventilation. The heat losses through ground (Q_{ground}) is:

$$Q_{ground} = (UA)_{ground} (T_r - T_o) \quad (13)$$

And heat loss through ventilation is:

$$Q_{vent} = \frac{\rho V C_a N (T_r - T_{amb})}{3600} \quad (14)$$

The calculation of total solar radiation incident (I) on horizontal and vertical surfaces, reported by [28] is used in present work and is as follows.

$$I = I_d * \cos(\theta) + I_{diff} * \frac{(1 + \cos\beta)}{2} + \rho_{ref} * (I_d + I_{diff}) * \frac{(1 - \cos\beta)}{2} \quad (15)$$

In Eq. 15, I_d is direct radiation, I_{diff} is diffused solar radiation, β is wall inclination angle from horizontal, ρ_{ref} is ground reflectance (usually 0.2 for normal condition) and θ is the solar incident angle.

$$\theta = \cos^{-1} \left(\begin{aligned} &\sin \delta \sin \varphi \cos \beta - \sin \delta \cos \varphi \sin \beta \cos \gamma + \cos \delta \cos \varphi \cos \beta \cos \omega \\ &+ \cos \delta \sin \varphi \sin \beta \cos \gamma \cos \omega + \cos \delta \sin \beta \sin \gamma \sin \omega \end{aligned} \right) \quad (16)$$

In Eq. 16, Declination (δ) is calculated as follows:

$$\delta = 23.45 \sin\left(360 \frac{284+n}{365}\right) \quad (17)$$

Here, n is the day of year, ϕ is the latitude, γ is Surface azimuth angle ($-180^\circ \leq \gamma \leq 180^\circ$) and ω is hour angle. The model suggested by [10] is modified using time lag and decrement factor, and applied to LIG house at Raipur to yield the indoor temperature at the center of room (Eq. 18). Energy balance equation for room-1 is written as:

$$(m_a c_a)_1 \frac{dT_{r1}}{dt} = \sum_{i=1}^4 (UA)_{wall} (ETD)_{wall} + (UA)_{roof} (ETD)_{roof} + [A_{win} U_{win} (T_{sol} - T_{r1}) + A_{win} \tau I_T] + (UA)_{door} (T_{sol} - T_{r1}) + Q_{internal} - \frac{\rho V C N (T_{r1} - T_a)}{3600} - (UA)_{ground} (T_{r1} - T_o) \quad (18)$$

Since the house under study has five interconnected rooms, energy balance equations for each of the five rooms are derived. These Eqs. (19-23) are obtained as a system of ordinary differential equations and solved numerically using ODE45 in MATLAB. The room temperature is then calculated and reported on hourly basis. For room-1, energy balance equation reduces to

$$\frac{dT_{r1}}{dt} = f(T_{r1}, T_{r2}, T_{r3}, T_{r4}, T_{r5}, g_1(t)) \quad (19)$$

Similarly, Energy balance equation for room-2:

$$\frac{dT_{r2}}{dt} = f(T_{r1}, T_{r2}, T_{r3}, T_{r4}, T_{r5}, g_2(t)) \quad (20)$$

Energy balance equation for room-3:

$$\frac{dT_{r3}}{dt} = f(T_{r1}, T_{r2}, T_{r3}, T_{r4}, T_{r5}, g_3(t)) \quad (21)$$

Energy balance equation for room-4

$$\frac{dT_{r4}}{dt} = f(T_{r1}, T_{r2}, T_{r3}, T_{r4}, T_{r5}, g_4(t)) \quad (22)$$

Energy balance equation for room-5

$$\frac{dT_{r5}}{dt} = f(T_{r1}, T_{r2}, T_{r3}, T_{r4}, T_{r5}, g_5(t)) \quad (23)$$

To validate the results obtained through mathematical model, Eqs. (19-23), on-field data collection has been carried out.

FIELD DATA COLLECTION

An experimental investigation for determining the room temperature of LIG house has been carried out at each of the three seasons of the year; in summer 2016, post-monsoon 2016 and winter 2016. Wi-Fi enabled temperature data logging sensor, has been used to measure the indoor temperature. Eight temperature sensors were placed at the center of bed room at different heights of 0.6 m, 0.9 m, 1.2 m, 1.5 m, 1.8 m, 2.1 m, 2.4 m and 2.7 m to continuously measure the indoor temperature of room throughout a day as shown in Figure 4(d). Temperature

sensors were connected with TP Link wireless system (Figure 4. (b)) for storing the data. Plan view of experimental setup of Wi-Fi-enabled data logger system is shown in Figure 4(c). Temperature at the centre of room (1.5 m) is used for validation of mathematical model, being a representative indoor temperature. The data collection has been carried out over a period of three continuous days during each study in the seasons mentioned. The closeness of numerical results and experimental data are established in terms of root mean square of percent deviation, e (Eq. 24)

$$e = \sqrt{\frac{\sum \left(\frac{T_{\text{num}(i)} - T_{\text{exp}(i)}}{T_{\text{num}(i)}} \times 100 \right)^2}{n}} \quad (24)$$

where $i = 1$ to n (no of data).

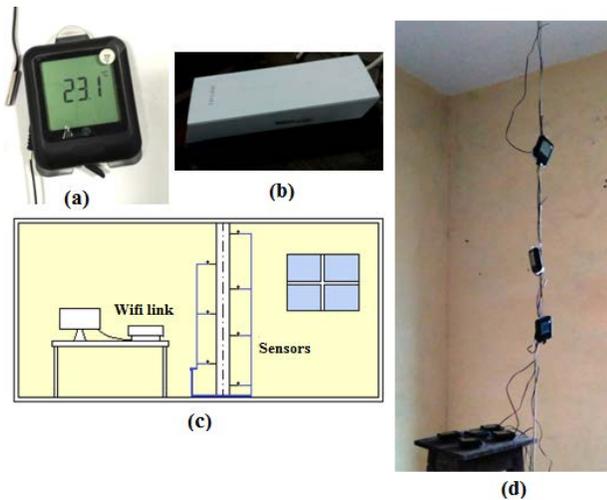


Figure 4. Experimental setup (a) Temperature sensor (b) Wi-Fi sensor (c) Scheme of arrangement of thermocouple (d) on-site photograph

RESULTS AND DISCUSSION

Based on the mathematical model, results of room temperature in different seasons incorporating solar radiation values, time lag and decrement factor are determined, validated and are reported for further analysis.

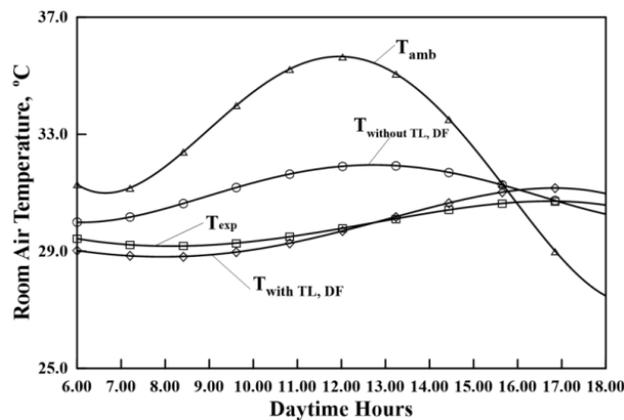


Figure 5. Room air temperatures with and without incorporating TL and DF on September 3, 2016 for room-2

Figure 5, Shows the effect of TL and DF in estimating the room air temperature. It indicates the estimation of indoor temperature without incorporating the time lag and decrement factor is an unfitting approach as the deviation from the field value is significant. It is observed that the result obtained by incorporating time lag and decrement factor in the mathematical model gives a very good agreement with the experimental/field values thus establishing the correctness of the mathematical model.

Post-Monsoon Season

August-October is the post-monsoon season in Raipur, where the day time outdoor temperature variation observed is from 27.5 °C to 36.5 °C during September, 2016. The temperature data at different heights, inside LIG house during post-monsoon season has been collected on September 1 to 3, 2016 from 6:00 hours to 18:00 hours. Figure 6 shows the validation of numerical results with experiment data with an e value of 2.4. Eight temperature sensors were placed at the center of bed room at different heights of 0.6 m, 0.9 m, 1.2 m, 1.5 m, 1.8 m, 2.1 m, 2.4 m and 2.7 m to continuously measure the indoor temperature of room throughout a day and the collected data is shown in Figure 7. Figure 8 plots the numerical solution of room temperature for all five rooms.

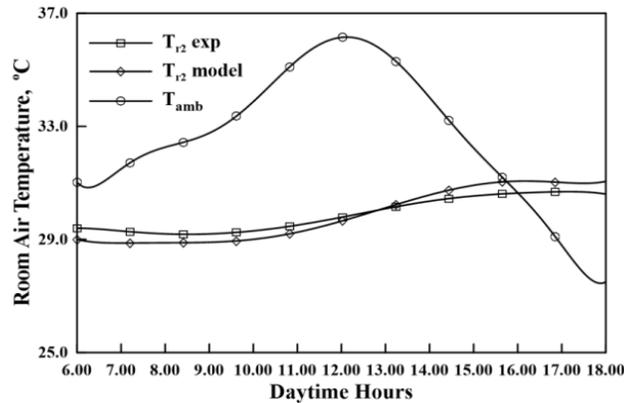


Figure 6. Comparison of numerical results with on-site data on September 3, 2016 for room-2

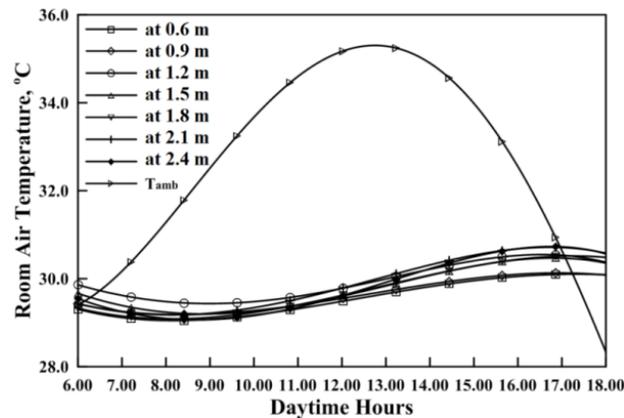


Figure 7. Room temperature of room-2 collected on-site at different heights on September 3, 2016

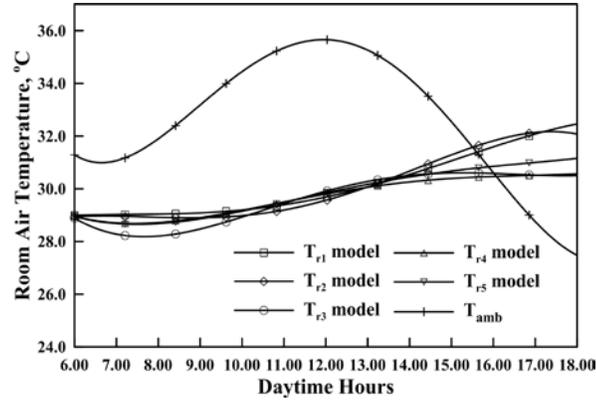


Figure 8. Indoor temperature of the rooms on September 3, 2016 based on numerical model

Winter Season

November-February is the winter season in Raipur, where the day time outdoor temperature variation observed ranges from 16.5 °C to 29.5 °C in the month of December. The temperature data at different heights, inside LIG house on a winter day has been collected on December 22 to 24, 2016 from 6:00 hours to 18:00 hours. Figure 9 reports the validation of numerical results with experiment data with an e value of 2.4. Six temperature sensors were placed at the center of bedroom at different heights of 0.9 m, 1.2 m, 1.5 m, 1.8 m, 2.1 m and 2.4 m to continuously measure the indoor temperature of room throughout a day as shown in Figure 9. The results reported in Figure 10 are for December 23, 2016. In Figure 11, the numerical results of room air temperature for all the five rooms are plotted.

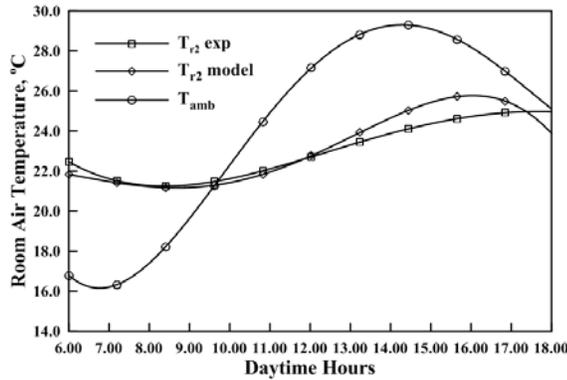


Figure 9. Comparison of numerical results with on-site data on December 23, 2016 for room-2

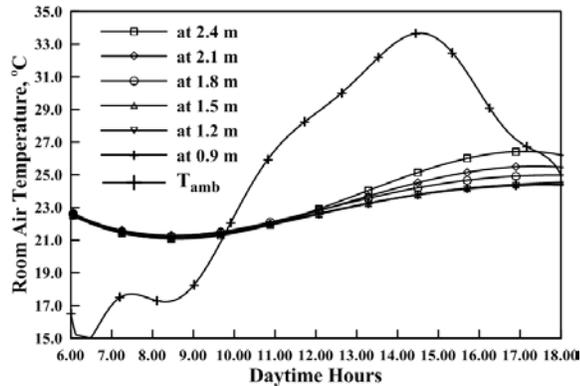


Figure 10. Room temperature of room-2 collected on-site at different heights on December 23, 2016

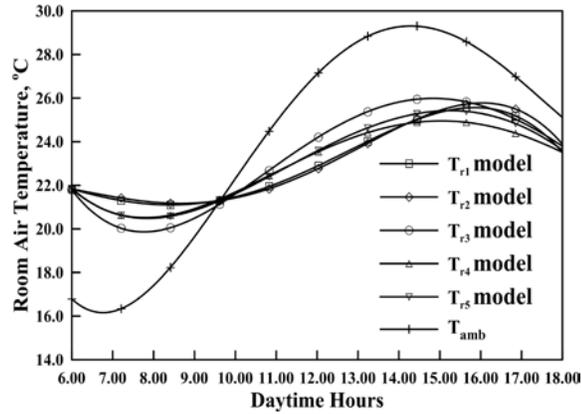


Figure 11. Indoor temperature of the rooms on December 23, 2016 based on numerical model

Summer Season

March-July is the summer season in Raipur where summer peaks in the month of May, the maximum outdoor temperature reaches to 48 °C. The temperature data at different heights inside LIG house on a summer day has been collected on May 20 to 22, 2016 from 9:30 hours to 17:30 hours. Also the room temperature has been compared with numerical solution and plotted in Figure 12 with a root mean square deviation of 2.8. Room air temperature has been collected at height of 0.9 m, 1.5 m and 2.1 m during 9:30 hours to 17:30 hours as shown in Figure 13. In Figure 14 the numerical results of room air temperature is reported for all five rooms.

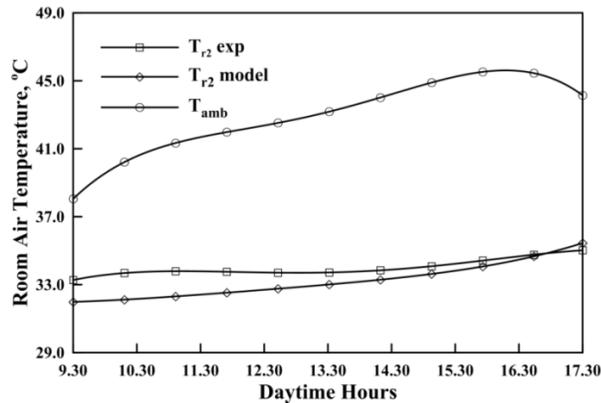


Figure 12. Comparison of numerical results with on-site data on May 20, 2016 for room-2

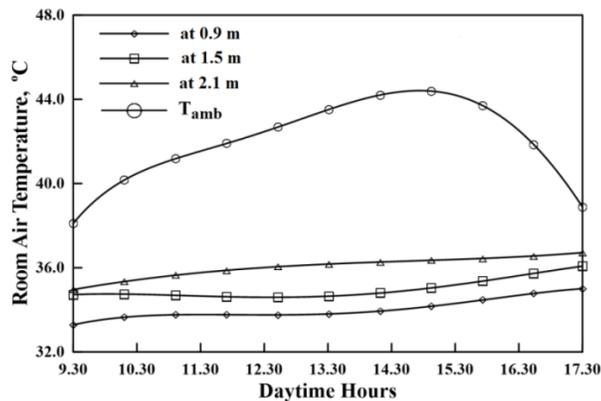


Figure 13. Room temperature of room-2 collected on-site at different heights on May 20, 2016

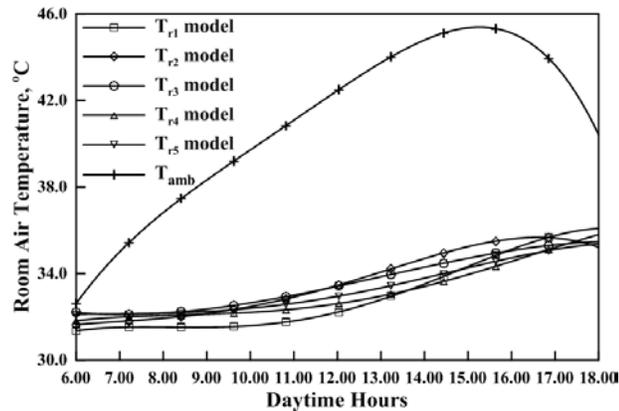


Figure 14. Indoor temperature of the rooms on May 20, 2016 based on numerical model

COMFORT ANALYSIS

Temperature defining thermal comfort is the temperature at which occupant feels comfortable. Considering 25 °C as comfort temperature for residential buildings, deviation of room air temperature from thermal comfort has been computed and shown in Figure 15. ΔT , plotted along the ordinate, is the difference between room air temperature and thermal comfort temperature and larger is ΔT larger is the discomfort. Results show during summer thermal discomfort is highest followed by post-monsoon and winter with recorded maximum ΔT of 11.7, 5.7 and 4.1 respectively.

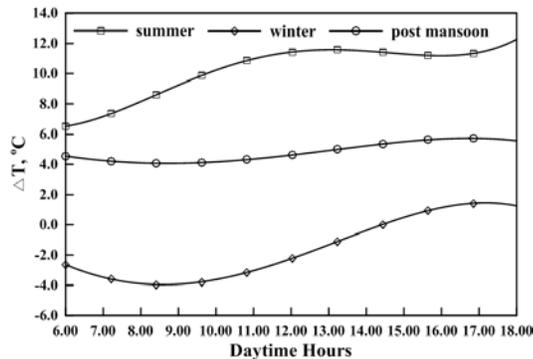


Figure 15. Hourly deviation of room temperature from thermal comfort, ΔT

CONCLUSIONS

For analysing thermal comfort, the models reported so far have not taken time lag decrement factor into account. In this work a mathematical model incorporating time lag and decrement factor has been proposed, for thermal performance analysis of LIG house which is validated and shows good agreement with experiment results with e value of 2.4, 2.4 and 2.8 for the season post monsoon, winter and summer respectively. The incorporation of time lag decrement factor in the model provides a realistic picture of the indoor thermal condition, once solved. The mathematical model obtained is a system of differential algebraic equations of first order. The solution of the equations provides the indoor temperatures which are plotted for ready reference.

Room 2 and 3 has maximum indoor temperature irrespective of season as shown in Figs. 8, 11, and 14. Room 2 and 3 are east facing and receives maximum solar radiation in all seasons. Also, the room has two glass windows; glass being highly thermally conductive with low thickness allows maximum solar radiation in the house. Figs. 7, 10 and 13 shows the temperature distribution at different heights of house for the room-2 which corroborates that room temperature increases with height of house. The daily variation of temperature in summer,

post monsoon and winter is 4°C, 3°C and 3.7 °C. In winter season, the temperature inside the house is within comfortable range and in summer, discomfort is at highest. For the present LIG housing plan, the materials used highlights the incapability of LIG house in providing a comfortable stay during summer and post-monsoon.

NOMECLATURE

A	Area (m ²)
C _a	Specific heat of air (J/KgK)
h _i	Inside heat transfer coefficient (W/m ² K)
h _o	Outside heat transfer coefficient (W/m ² K)
I	Total solar Radiation (W/m ²)
I _d	Direct radiation (W/m ²)
I _{diff}	Diffused solar radiation (W/m ²)
k	Thermal conductivity (W/mK)
l	Thickness of material layer (m)
M _a	Air mass (kg)
N	Air change rate (h ⁻¹)
Q	Heat transfer (J)
t	Time (Sec)
T _{amb}	Ambient temperature (K)
T _{amb, max}	Maximum ambient temperature (K)
T _{amb, min}	Minimum ambient temperature (K)
T _O	Earth temperature at depth of 1.5 m (K)
T _r	Room temperature (K)
T _{r, max}	Maximum room temperature (K)
T _{r, min}	Minimum room temperature (K)
T _{sol}	Sol-air temperature (K)
T _{sol-air, avg}	Averaged daily sol-air temperature (K)
T _{sol-air, φ}	Sol-air temperature φ hours before (K)
U	Overall heat transfer coefficient (W/m ² K)
V	Volume (m ³)

Greek Symbols

α	Solar absorbtivity
β	Wall inclination angle
δ	Declination
ε	Emissivity
θ	Solar incident angle
φ	Time lag (hours)
λ	Decrement factor
ρ	Density (kg/m ³)
ρ _{ref}	Ground reflectivity
τ	Transmissivity
ω	Hour angle
φ	Latitude
γ	Surface azimuth angle
n	Day of year

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