Thermal performance of dome shaped adobe house-Case study for moderate climatic zone of India

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ABSTRACT

In this paper, the performance of a dome shaped adobe house has been analysed in terms of monthly heating/cooling potentials and hourly room air temperatures. The heating/cooling potential has been evaluated on the basis of energy balance under quasi-steady state condition by incorporating the effect of ventilation/earth-air heat exchanger (EAHE). The study has been carried out for moderate climate of Bangalore. A thermal model of dome shaped building integrated with EAHE/ventilation is developed and solved in Matlab computational environment. The study provides an idea of the climatic zone of India, where it is beneficial to use a ventilation/EAHE for heating and cooling purposes. The annual heating and cooling potential is found to be 16.89 x 10^7 kWhr and 8.87 x 10^7 kWhr respectively. The performance of adobe house was found satisfactory in both winter and summer.

Keywords - **Adobe house, Earth-air heat exchanger, Heating-cooling potential, Ventilation**

I. INTRODUCTION

Buildings are one of the major consumers of energy and are the third largest consumers of energy, after industry and agriculture. Buildings annually consume more than 20% of electricity used in India.

The potential for energy savings is 40 – 50% in buildings, if energy efficiency measures are incorporated at the design stage. For existing buildings, the potential can be as high as 20-25% which can be achieved by implementing housekeeping and retrofitting measures.

One area where energy can be saved is to provide comfort conditions in buildings. Before invention of mechanical means to provide comfort conditions, people used to make their dwellings in a way, which were comfortable to live in, and were dependent on natural means [1]. In buildings built during the Mughal period, extensive use of thick mud bricks (known as adobe) walls, high ceilings, domed tops, shading of external surfaces, water channels etc. can be found [2].

Also, reduction of energy use to provide comfort conditions in buildings can be achieved by using passive comfort techniques as suggested by various researchers like [3], [4], [5], [6] and [7].

The use of energy stored in the ground for heating/cooling of buildings and greenhouses has been received an increasing importance [8], [9], [10], [11] and [12]. The constant temperature under the earth's crust at about 12 m from the surface is a point of attraction for many researches. Several methods have been suggested by various researchers to assess the contribution of EAHE/ ventilation for reducing energy consumption in a building. The studies suggest that, energy use for providing comfort conditions in buildings can be significantly reduced by using passive comfort techniques. Thus, it is beneficial to use passive energy techniques like earth-air heat exchanger/ventilation for providing comfort.

II. CLIMATE OF BANGALORE

Latitude: 18º54'N, Longitude: 72º49'E, Elevation: 11 m above m.s.l.

Bangalore experiences a tropical savanna climate with distinct wet and dry seasons. Due to its high elevation, Bangalore usually enjoys a more moderate climate throughout the year, although occasional heat waves can make things very uncomfortable in the summer. The coolest month is January with an average low temperature of 15.1 °C and the hottest month is April with an average high temperature of 33.6 °C. Winter temperatures rarely drop below 12°C, and summer temperatures seldom exceed 34–35°C. Bangalore receives rainfall from both the northeast and the south-west monsoons and the wettest months are September, October and August, in that order. The summer heat is moderated by fairly frequent thunderstorms, which occasionally cause power outages and local flooding.

III. METEOROLOGICAL DATA

The solar radiation data have been collected for the period of 1991-2001from India Meteorology Department (IMD) Pune, India. Climate of Bangalore has been classified into following four weather conditions depending upon sunshine hours and ratio of diffuse to global radiation.

(a) Clear day (blue sky): If diffuse radiation is less than or equal to 25 % of global radiation and sunshine hour is more than or equal to 9 hours.

(b) Hazy day (fully): If diffuse radiation is less than 50 % or more than 25 % of global radiation and sunshine hour is between 7 to 9 hours.

(c) Hazy and cloudy (partially): If diffuse radiation is less than 75% or more than 50 % of global radiation and sunshine hour is between 5 to 7 hours.

(d) Cloudy day (fully): If diffuse radiation is more than 75 % of global radiation and sunshine hour is less than 5 hours.

IV. DESIGN OF DOME SHAPED HOUSE

An adobe house has been designed which is proposed for serving mid-day meal in a government school. There are two parts of the house, kitchen cum serving and store room. Only kitchen cum serving part has been studied for heating and cooling potential, because occupants are not supposed to stay in store room. Orientation and dimensions of walls, windows, door, roof and floor are shown in Fig.1.

Kitchen Plan = 24.0 m^2, Kitchen/Serving = 13.2 m^2, Store = 7.6 m^2, Wash= 3.1 m^2

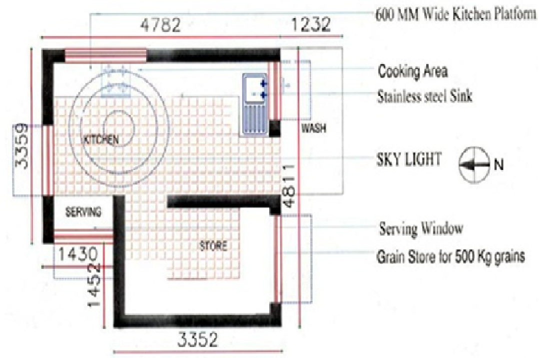

Figure 1.Plan of adobe house

V. DESIGN PARAMETERS

Design parameters used for thermal modeling are given in Table 1(a). Design parameters of earth-air heat exchanger are given in Table 1(b).Construction details of roof structure of the house are given in Table 2. U-value of building components are given in Table 3.

Table 1(a) Design parameters used for thermal modelling

Parameters for house	Value
h_o	9.5 W/m^2 K
h_i	2.8 W/m^2 K
K value of soil (or mud)	0.446 W/m K
K value of brick	0.84 W/m K
K value of bamboo	0.17 W/m K
K value of Khapra	1.28W/m K
K value of wood (door)	0.14 W/m K
Air density	1.2 kg/m^3
Emissivity of roof surface	0.9
Absorptivity of roof surface	0.4
Absorptivity of wall surface	0.4
Absorptivity of door surface	0.6
Transmissivity of glass	0.9
Air change per hour	10-50
Volume of room	58 m^3
Floor area of room	16 m^2

Table 1(b) Design parameters of EAHE

EAHE parameters	Value
Depth of PVC pipe	1.5 m
Radius of PVC pipe	0.3 m
Length of PVC pipe	78 m
Air Velocity at pipe outlet	1-3 m/s
h_{ca} inside pipe of EAHE	5.7 W/m^2
Specific heat of room air	1006 J/kg K

Table (2) Construction details of roof

Roof material layers (From inside to outside)	Thickness [mm]
Bamboo	4
Mud	4
Khapra	5

Table (3) U-value of building component

Building components	U [W/m^2 K]
Wall (brick)	1.36
Door (wood)	1.48
Window (glass)	2.15
Roof	2.0
Ground	0.44

VI. MATHEMATICAL MODELLING

Following assumptions have been made while writing energy balance equation for the dome shaped adobe house.

1. The heat transfer through roof and walls occurs in one direction along the thickness.

2. There is quasi-steady state heat transfer across the roof and wall.

3. The wall and roof structures are made of homogeneous material layers.

4. The ambient and room air temperatures are assumed constant for 1 hour.

5. Average solar intensity for 1 hour has been considered.

6. The values of parameters like air change per hour and inside (h_i) and outside (h_o) convective heat transfer coefficients are assumed constant.

7. All thermal properties of building materials e.g. thermal conductivity and specific heat are assumed constant.

A. General Heat balance equation for non-air conditioned room air

The general energy balance equations for room air can be written as follows:

$$M_a C_a \frac{dT_r}{dt} = \sum Q_{gain} - Q_{loss} \qquad (1)$$

M_a is isothermal mass (kg), C_a is specific heat of air (J/kg ˚C), T_r is room temperature (˚C), t is time (second), Q_{gain} is rate of thermal energy gained by air (J/s), Q_{loss} is rate of thermal energy lost by air (J/s).

$$Q_{gain} = Q_{wall} + Q_{roof} + Q_{window} + Q_{door} + Q_{floor} \qquad (2)$$

Q_{wall} is rate of thermal energy gained by air through wall (J/s), Q_{roof} is rate of thermal energy gained by air through roof (J/s), Q_{window} is rate of thermal energy gained by air through window (J/s), Q_{door} is rate of thermal energy gained by air through door (J/s), Q_{floor} is rate of thermal energy gained by air through floor (J/s).

$$Q_{loss} = Q_{ventilation} \qquad (3)$$

$Q_{ventilation}$ is rate of thermal energy gained by air through ventilation (J/s).

The expressions for rate of heat gain and loss from different building components for quasi-steady state heat transfer analysis is given below. The rate of heat gain through wall is:

$$Q_{wall} = (UA)_{wall}(T_{sol,wall} \quad T_r) \qquad (4)$$

U is overall heat transfer coefficient, A is area (m^2), $T_{sol,wall}$ is sol-air temperature of wall (˚C), T_r is room temperature (˚C).

$$(UA)_{wall} = \left[\frac{1}{h_o} + \frac{L_1}{K_1} + \frac{L_2}{K_2} + \cdots + \frac{1}{h_i}\right] A_{wall} \quad (5)$$

h_o is outside convective heat transfer coefficient (W/m^2 ˚C), L is thickness of the layer (m), K is thermal conductivity (W/ m ˚C), h_i is inside convective heat transfer coefficient (W/m^2 ˚C).

The expression of sol–air temperature on any inclined wall/roof surface can be written as

$$T_{sol} = \left[\frac{\alpha I}{h_o} + T_a - \frac{\varepsilon \Delta R}{h_o}\right] \quad (6)$$

where, T_{sol} is the sol–air temperature of bare roof surface (˚C), T_a is ambient temperature (˚C), I is solar radiation falling on different surfaces of dome shaped house (W/m^2) and

$$h_o = h_{ra} + h_{ca}$$

where, the terms h_{ra} and h_{ca} are radiative and convective heat transfer coefficient between surface and ambient respectively. ΔR is the long wavelength radiation exchange between surface and sky; its values for different surface orientation are as follows.

$$\Delta R = 0 \; for \; vertical \; surface$$

$$\Delta R = 60 \; W/m^2 \; for \; horizontal \; roof \; surface$$

$$\Delta R = \left[\frac{\cos\beta}{\sin\beta} * 60\right] W/m^2 \; for \; surface \; inclined \; at \; \beta$$

The rate of heat gain through roof is

$$Q_{roof} = (UA)_{roof}(T_{sol,roof} - T_r) \quad (7)$$

The rate of heat gain through window is

$$Q_{window} = A_{window}\,\tau I + (UA)_{window}(T_{sol,window} - T_r) \quad (8)$$

The rate of heat gain through door is

$$Q_{door} = (UA)_{door}(T_{sol,door} - T_r) \quad (9)$$

The rate of heat gain/loss through ground or floor is

$$Q_{floor} = (UA)_{floor}(T_r - T_0) \quad (10)$$

where, T_0 is base temperature (˚C), T_0=25 ˚C.

The equation for rate of heat loss/gain due to room air ventilation to ambient air can be expressed as follows:

$$Q_{ventilation} = \frac{\rho_a v_a C_a N (T_r - T_a)}{3600} = 0.33\, N v_a (T_r - T_a) \quad (11)$$

where, N is number of air change per hour, ρ_a is density of air; v_a is volume of air in the room.

When the building room air is integrated with recirculation type earth air heat exchanger (EAHE), the rate of heat gain in winter (or loss in summer) is given below

$$Q_{EAHA} = F_R m_a C_a (T_0 - T_r) \quad (12)$$

where, T_0=25˚C, Q_{EAHE} is rate of thermal energy gained by air through Earth Air Heat Exchanger (J/s), m_a is mass flow rate of air (kg/s).

$$F_R = 1 - exp\left(-\frac{2\pi r h_{ca}}{m_a C_a} L_{pipe}\right) \quad (13)$$

h_{ca} is convective heat transfer coefficient between surface and ambient (W/m^2 ˚C), L_{pipe} is length of PVC pipe (m), r is radius of PVC pipe (m).

B. *Heat balance equation*

Based on the above described equations (1) to (13), the heat balance equation for room of the house is written as follows:

$$M_a C_a \frac{dT_r}{dt} = \sum_i^4 (UA)_{wall,i}(T_{sol,wall,i} - T_r) + \sum_j^4 (UA)_{window,j}(T_{sol,window,j} - T_r) + (UA)_{door}(T_{sol,door} - T_r) + (UA)_{roof}(T_{sol,roof} - T_r) + (UA)_{floor}(T_r - T_0) - 0.33 N v_a (T_r - T_a) + F_R m_a C_a (T_0 - T_r)$$

or,

$$\frac{dT_r}{dt} = -\left[\frac{\sum_i^4 (UA)_{wall,i} + \sum_j^4 (UA)_{window,j} + (UA)_{door} + (UA)_{roof} + (UA)_{floor} - 0.33 N v_a + F_r m_a C_a}{M_a C_a}\right] T_r + \left[\sum_i^4 (UA)_{wall,i} T_{sol,wall,i} \sum_j^4 (UA)_{window,j} T_{sol,window,j} + (UA)_{door} T_{sol,door} + (UA)_{roof} T_{sol,roof} + (UA)_{floor} T_{sol,floor} - 0.33 N v_a T_a + F_r m_a C_a T_0\right] / M_a C_a$$

or,

$$\frac{dT_r}{dt} = f(T_r, g(t)) \; or \; \frac{dT_r}{dt} = aT_r + g(t) \quad (14)$$

The constant 'a' is the coefficients of room air temperature. The term g(t) represents the function of time 't' in above equation and comprises of the time dependent terms like sol–air surface temperature (T_{sol}), ambient air temperature (T_a) and solar radiation on surface (I). The exact solution of the above first-order linear differential equations (14) is

$$T_r = \left[\frac{\bar{g}(t)}{a}\right](1 - exp(-at)) + T_{r0}\, exp(-at) \qquad (15)$$

where, □(*t*) is average of g(t) over time interval 0 to t.

Based on the above equation, the room air temperatures of for 24 hours were evaluated.

C. *Heating Cooling Potential*

Monthly heating and cooling potential obtained for a dome shaped house is obtained as

$$Q = \sum m_a C_a (T_r - T_a)\, \Delta t \qquad (16)$$

Q is heating or cooling potential (J), m_a is mass flow rate of air (kg/s).

VII. Results and Discussions

The room air temperatures for the moderate climate of Bangalore have been computed by the use of equation (15). Fig.2 shows the resulting hourly variation of room temperature during the month of January with and without earth-air heat exchanger. Ventilation is not studied during the month of January as it causes the necessary heating potential to rise. Thus figure shows only the variation of room temperature with and without earth-air heat exchanger. The variation of atmospheric temperature lies between 13.0ºC to 25.0ºC as shown in Fig.2.The room air temperatures are in the range of 20.1ºC to 28.8ºC without earth-air heat exchanger and 24.6ºC to 28.3ºC with earth-air heat exchanger. Difference between atmospheric temperature and room temperature lies between 1.8 °C and 8.7ºC for the case of no ventilation (i.e. N=0).

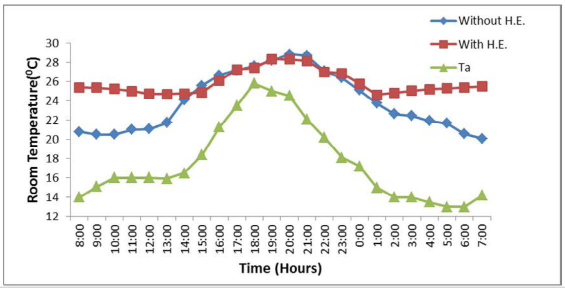

Figure 2.Variation of room temperature with time in January

The use of earth-air heat exchanger does not substantially improve the heating of the house but, it is beneficial to use it use it during the early day and late night hours to improve room air temperature. For the rest of the hours the temperature is itself maintained in the comfort zone by the adobe house.

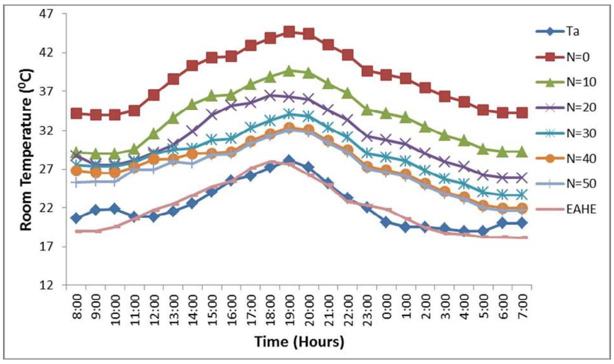

Figure 3.Variation of room temperature with time in June

The hourly variation of room temperature at different rate of ventilation (or number of air change per hour, N), in the month of June at Bangalore is shown in Fig.3.The Atmospheric temperature variation from 19.0 ºC to 28.1ºC has also been shown in Fig.3. The variation of room temperature when the room is integrated with an earth air heat exchanger has also been shown. At N=0, room temperatures are in the range of 33.9ºC to 44.6ºC. At N=10, room temperatures falls considerably and lies in the range 28.9ºC to 39.6ºC. At N=20, room temperatures again fall and varies from 25.8ºC to 36.4ºC. At N=30, room temperatures falls in the range of 23.6ºC to 34.0ºC. At N=40, room temperature varies from 21.9ºC to 32.3ºC. At N=50, room temperature varies from 21.6ºC to 32.0ºC. With the earth air heat exchanger (length of PVC pipe=78 m, air velocity=3m/s) integrated to the room, the hourly room temperature falls varies from 18.1ºC to 27.9ºC. Maximum difference between atmospheric temperature and room temperature is 13.5ºC if there is no ventilation (N=0). With ventilation at N=10, 20 and 30, maximum temperature difference falls to 5.0ºC, 4.2ºC and 3.4ºC respectively. At N=40 and 50 maximum temperature difference is 2.2ºC and 1.6ºC, i.e., no significant reduction in room temperature is further observed. Therefore ventilation is optimized as N=30. The use of ventilation thus recommended to lowers the temperature in such climate.

Use of earth air heat exchanger does not improve the cooling of the room air. With earth-air heat exchanger, the room temperature closely follows the atmospheric temperature. The maximum difference in atmospheric temperature and room temperature (with EAHE) is found to be 1.8 ºC. Thus the use of earth air heat exchanger in summer for the moderate climate of Bangalore is not recommended.

The room air temperature (with earth-air heat exchanger incorporated) of adobe house is not constant instead it is varying as confirmed by other researchers [13].

Using Equation (16), heating/cooling potential for four weather types of dome shaped house was computed for each month.

It was observed that for the climate of Bangalore heating requirement occurs in the five months of January, February, October, November and December.

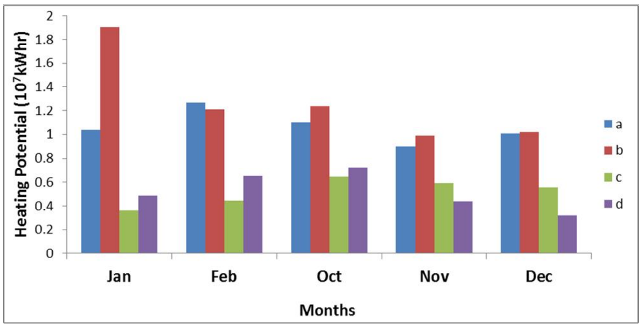

Figure 4. Heating potential in winter at Bangalore (N=0)

Fig.4 shows the heating potential during winter for the four weather types (a-d). In February, ‘a’ type weather yield the maximum heating potential. While for rest of the winter months i.e. January, October, November and December ‘b’ type weather dominates and produces maximum heating potential owing to the maximum number of days in a month falling in that category.

Cooling potential for the seven months of March to September for four weather types of dome shaped house were also estimated and is shown in Fig. 5. For March, April, June and September type ‘a’ weather yields maximum cooling potential. For the months of May, July and August ‘b’ type weather dominates and hence produces maximum cooling potential.

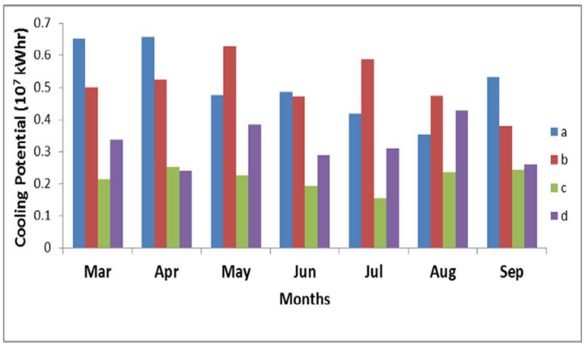

Figure 5.Cooling potential in summer at Bangalore (N=30)

Total monthly heating /cooling potential of dome shaped house were estimated and shown in Fig.6. During winter, the month of January shows maximum heating potential of 3.78×10^7 kWhr and during summer May shows maximum cooling potential of 1.45×10^7 kWhr. The magnitude of monthly heating potentials for the months of winter and monthly cooling potential for summer directly depends on the difference between room temperature and atmospheric temperature. Therefore, magnitude of monthly heating potential for winter is larger than that of monthly cooling potential ought to the larger difference in room temperature and ambient temperature in winters.

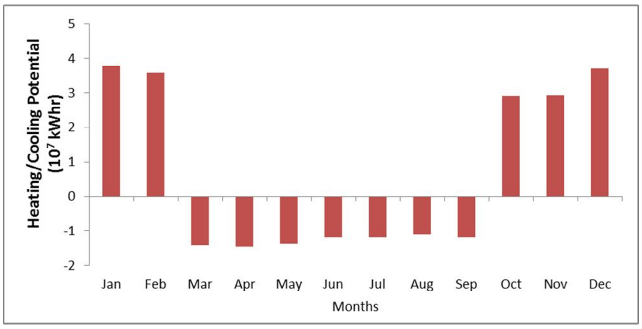

Figure 6. Monthly heating/cooling potential at Bangalore

VIII. CONCLUSION

- The performance of dome shaped house is, thus, found satisfactory in both summer and winter for the moderate climate of Bangalore. Hence, the adobe house under study can provide natural thermal comfort in moderate climate. An adobe building may attain thermal comfort without the use of mechanical means and thus have energy saving potential just by applying passive heating/cooling techniques.

- In the moderate climatic zone (Bangalore), cooling period is larger than the heating period. Heating is required for the five months of October to February while cooling is required for March to September.
- During winter, incorporation of earth-air heat exchanger improves the heating of the room air. For summer, ventilation is found to be a good option for cooling. Ventilation is optimized at N=30 and the room air temperatures are in the range 23.6°C-34.0°C. Earth-air heat exchanger could not improve the cooling of room air and is not recommended for use in summer.
- Yearly heating potential for winters was estimated to be 16.89×10^{7} kWhr while yearly cooling potential was estimated as 8.87×10^{7} kWhr.

Thus, the performance of dome shaped house was found satisfactory in both winter and summer for the location considered in moderate climatic zone. Also, adobe house was found to temperate the room air temperature, thus significantly reducing temperature fluctuations.

Few deaths have been recorded in India because of heat waves in summer and cold climate in winter. This naturally comfortable mud-house building is one of the solutions not only in India but also all over the world like Middle East countries for both rural and urban population. Hence, the adobe house under study is promising solution for obtaining natural thermal comfort.

Hence, this case study provides real insight of actual performance of dome shaped house in climatic condition of India. Thermal comfortable room air temperature range for person living in Indian villages is also same as that of actual performance of dome shaped house. Hence, such dome shaped house/ home/shelters can easily provide naturally thermal comfortable zone for poor people residing in various climatic zones.

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