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Heating/cooling potential and carbon credit earned for dome shaped house

M. Jamil Ahmad[1], G.N. Tiwari[1], Anil Kumar Singh[2], Manisha Sharma[2], H.N. Singh[3]

[1] Center for Energy Studies, Indian Institute of Technology, Hauz Khas, New Delhi-16, India
[2] Energy Research Applications, 211B, Pkt-C, Siddhartha Extension, New Delhi-14, India
[3] Department of Physics, R.S.S.P.G. College, Pilkhuwa, Ghaziabad, U.P. India

Abstract
In this article, the heating/cooling potential of a dome shaped house has been evaluated on the basis of energy balance under quasi-steady state condition by incorporating the effect of ventilation/earth-air heat exchanger. The study has been carried out for composite climate of New Delhi. Effect of parameters of earth-air heat exchanger (radius of pipe, length of pipe and velocity of air) on heating/cooling potential has also been studied. Analysis of energy saving by using day lighting and CO_2 credit earned has also been carried out. It is observed that an over all 732 kWh energy can be saved per year by using day lighting which corresponds to 1.49 tones/year carbon credits earned.

Keywords: Adobe house, Carbon credit, Earth air heat exchanger, Heating/cooling potential.

1. Introduction

The consumption of energy in buildings for cooling and heating purpose has increased considerably. The passive heating as well as cooling technique in which either heat is removed or given to buildings from a natural heat sink like earth has become popular today. In the operation of an earth–air heat exchanger, freely available energy, stored inside the earth has been used for heating and cooling purposes. Thus, less amount of conventional energy is required, which leads to a decrease in the mitigation of CO_2 in the environment. An earth–air heat exchanger can be operated by using solar energy in remote areas, where no electricity is available. Even a layman can carry out the operation and maintenance of an earth–air heat exchanger; thus, no skilled labour is required. Thus, an earth–air heat exchanger might prove a low cost, low maintenance and environmental friendly option for heating and cooling of buildings. The always stable temperature of the earth at a depth of 4m is a point of attraction for researchers to use the earth for passive heating or cooling purpose [1, 2 and 3]. This temperature of the earth is equal to the mean annual temperature of any place [1, 4]. The temperature of the earth is higher in winter and lower in summer compared with the ambient air temperature. The comfort conditions in buildings are affected by large fluctuations in ambient air temperature. Using the nearly constant temperature of the earth, we can reduce these temperature fluctuations. The earth can be used as a natural sink for round the year use. Thus, the earth provides a low-cost alternative source of energy for heating and cooling purposes. During winter heat is retrieved from the ground to buildings and during summer excess heat is transferred from buildings to the ground. This results in reducing the heating as well as the cooling load.
Most investigators [5, 6, 7, 8, 9 and 10] have studied the conditioning of air as it flows through buried pipes. As observed by Thanu et al. [11], when the tunnels (heat exchangers with bigger radii of buried

pipes) are used for heating and cooling purposes, a special arrangement for the removal of water due to seepage into the tunnel ought to be made. The water or moisture inside the tunnel can cause the foul smell of air and the growth of mosquitoes. Such a big tunnel always requires high maintenance and a high capacity blower, which ultimately needs more electricity. On the other hand an earth–air heat exchanger having a smaller radius is free from such drawbacks. Several methods have been suggested by researchers to increase the heating and cooling potentials of an earth–air heat exchanger [10, 12 and 13]. So it is more beneficial to use an earth–air heat exchanger in place of an earth–air tunnel. Various simplified and detailed models have been proposed to describe the thermal performance of an earth–air heat exchanger [3, 12]. However, for a large number of applications, it is necessary to know the energy potential of the system under real climatic conditions, as well as the impact of the main design parameter on the thermal behaviour of an earth–air heat exchanger.

In this paper, the heating/cooling potential of dome shaped house has been evaluated on the basis of energy balance under quasi-steady state condition by incorporating the effect of ventilation/earth air heat exchanger. The study has been carried out for composite climate of New Delhi. The performance of the system has been analysed in terms of monthly heating and cooling potentials. Effect of parameters of earth-air heat exchanger (radius of pipe, length of pipe and velocity of air) on heating/cooling potential has also been studied. The study has also provided an idea of the climatic zone of India, where it is beneficial to use an earth–air heat exchanger for heating and cooling purposes.

2. Location and climatic conditions

New Delhi is located in Northern part of India, a latitude 28.58^o N and a longitude of 77.02^o E and at an altitude of 216m above M.S.L. The climate of Delhi is a monsoon-influenced humid subtropical climate (Koppen climate classification Cwa) with high variation between summer and winter temperatures and precipitation. Summers start in early April and peak in May, with average temperatures near 32^{o}C (90^{o}F), although occasional heat waves can result in highs close to 45^{o}C (114^{o}F) on some days. The monsoon starts in late June and lasts until mid-September, with about 714 mm (28.1 inches) of rain. The average temperatures are around 29^{o}C (85^{o}F), although they can vary from around 25^{o}C (78^{o}F) on rainy days to 32^{o}C (90^{o}F) during dry spells. The monsoons recede in late September, and the post-monsoon season continues till late October, with average temperatures sliding from 29^{o}C (85F) to 21^{o}C (71^{o}C). Winter starts in November and peaks in January, with average temperatures around 12-13^{o}C (54-55^{o}F). Although winters are generally mild, Delhi's proximity to the Himalayas results in cold waves that regularly dip temperatures below freezing. Delhi is notorious for its heavy fog during the winter season. In December, reduced visibility leads to disruption of road, air and rail traffic. They end in early February, and are followed by a short spring till the onset of the summer. Extreme temperatures have ranged from −0.6 °C (30.9 °F) to 47 °C (116.6 °F).

3. Meteorological data

The solar radiation data have been collected for the period of 1991-2001 from India Meteorology Department (IMD) Pune, India. Climate of New Delhi 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

4. Design of dome shaped house

An adobe house has been designed for serving mid day meal in a government school at New Delhi. 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 windows, door, roof and floor are shown in Figure 1(a). Figure 1(b) shows details of drawing of adobe house. Figure 1(c) shows sectional front view of adobe house. Figure 1(d) shows sectional side view of adobe house.

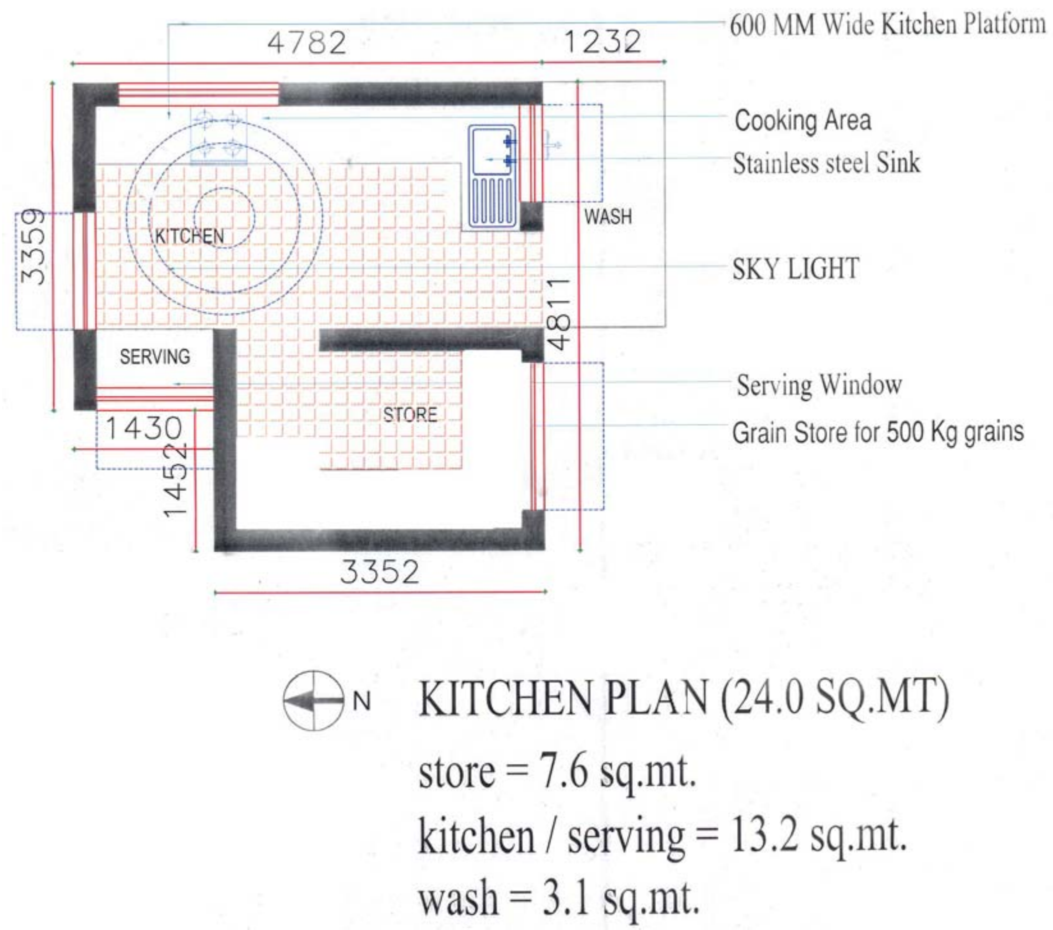

Figure 1. (a) Top view of adobe house

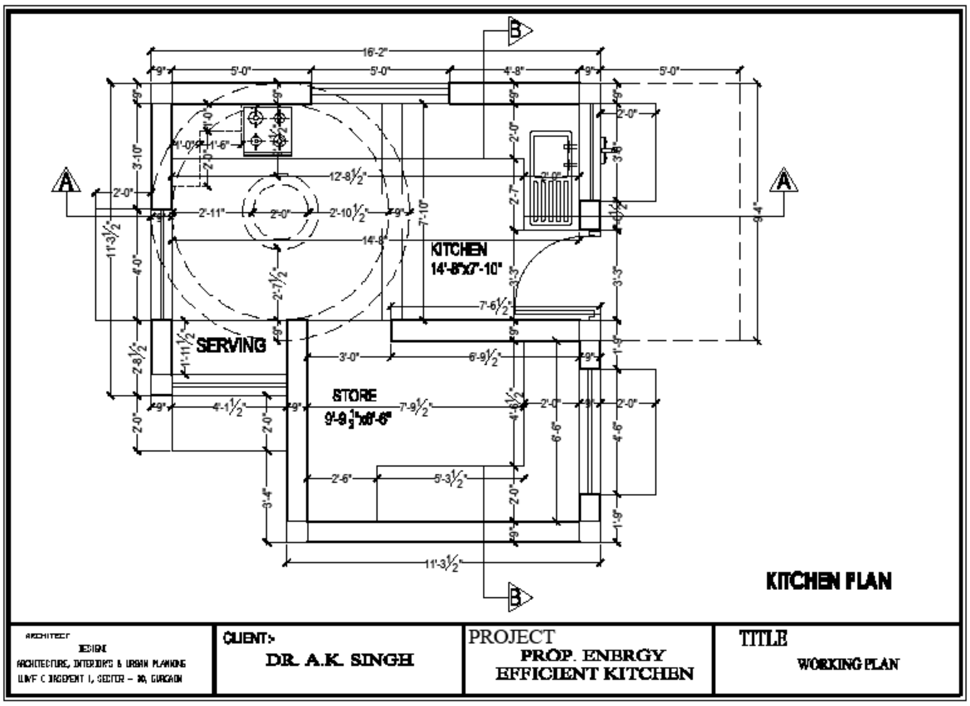

Figure 1. (b) Detailed top view of adobe house

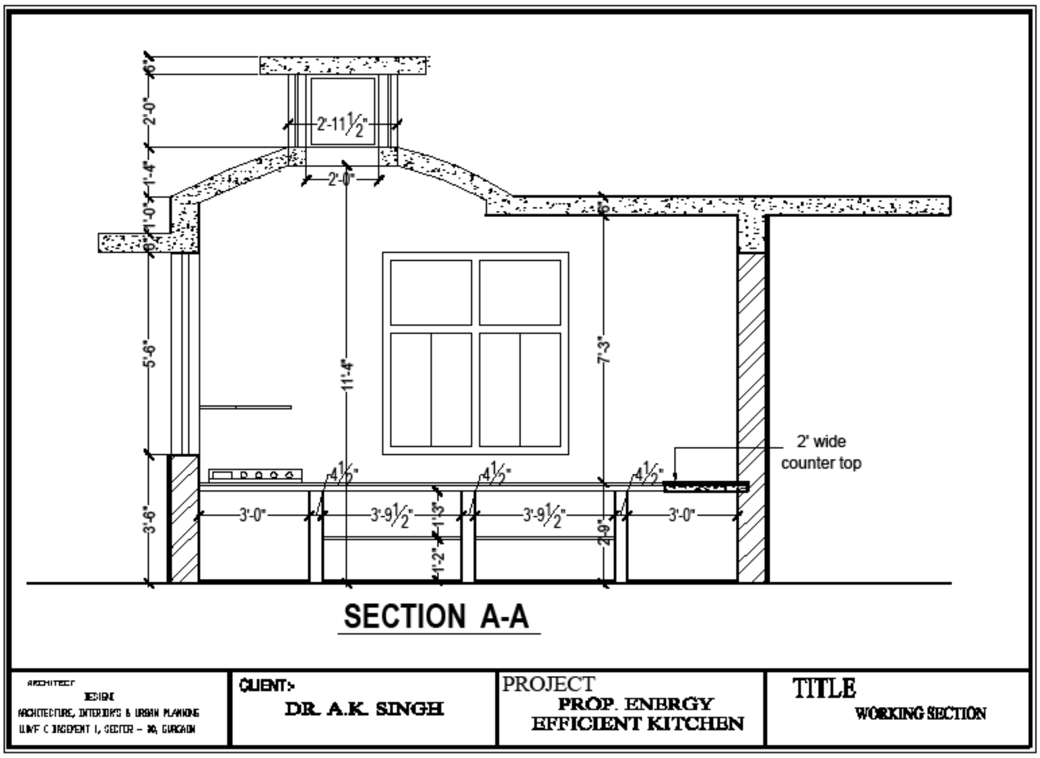

Figure 1. (c) Sectional front view of adobe house

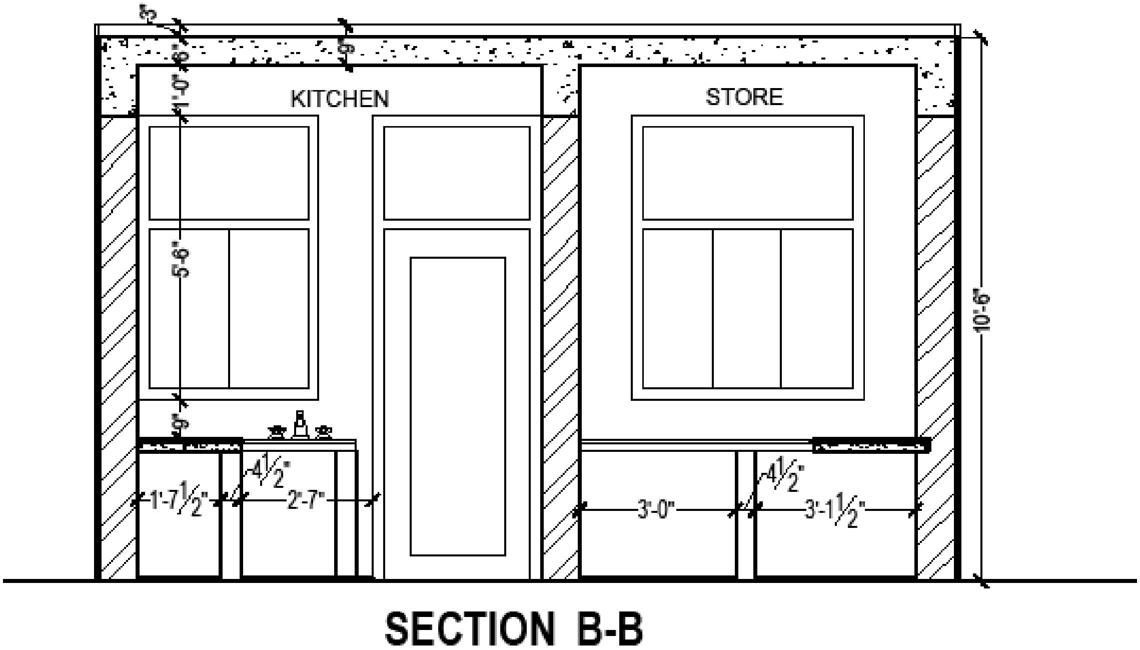

Figure 1. (d) Sectional side view of adobe house

Design parameters used for thermal modelling are given in Table 1(a). Design parameters of Earth Air Heat Exchanger (EAHE) 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 modeling

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 structure of the house

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

Table 3. U-value of building components

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

5. Mathematical formulation

Following assumptions have been made while writing energy balance equation.

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.

5.1 General energy balance equation for non-air-conditioned room air

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

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

M_a is isothermal mass (kg), C_a is specific heat of air (J/kg ^{0}C), T_r is room temperature (^{0}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).

$$Q_{gain} = Q_{wall} + Q_{roof} + Q_{window} + Q_{door} + Q_{floor} \tag{2}$$

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).

$$Q_{loss} = Q_{ventilation} \tag{3}$$

$Q_{ventilation}$ 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;

$$Q_{wall} = (UA)_{wall}\left(T_{sol,wall} - T_r\right) \tag{4}$$

U is overall heat transfer coefficient, A is area (m^2), $T_{sol,wall}$ is sol-air temperature of wall (^{0}C), T_r is room temperature (^{0}C).

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

h_o is outside convective heat transfer coefficient (W/m^2 ^{0}C), L is thickness of the layer (m), K is thermal conductivity (W/ m ^{0}C), h_i is inside convective heat transfer coefficient (W/m^2 ^{0}C).

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

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

where T_{sol} is the sol–air temperature of bare roof surface (^{0}C), T_a is ambient temperature (^{0}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.

$$\Delta R = 60 \;\; W/m^2 \text{ for horizontal roof surface}$$
$$\Delta R = 0 \quad \text{for vertical surface} \tag{7}$$
$$\Delta R = \left[\frac{\cos\beta}{\sin\beta}\times 60\right] \; W/m^2 \text{ for surface inclined at angle } \beta$$

The rate of heat gain through roof is

$$Q_{roof} = (UA)_{roof}\left(T_{sol,roof} - T_r\right) \tag{8}$$

The rate of heat gain through window is

$$Q_{window} = A_{window}\times\tau\times I + (UA)_{window}\left(T_{sol,window} - T_r\right) \tag{9}$$

The rate of heat gain through door is

$$Q_{door} = (UA)_{door}\left(T_{sol,door} - T_r\right) \tag{10}$$

The rate of heat gain/loss through ground is

$$Q_{floor} = (UA)_{floor}(T_r - T_0) \tag{11}$$

where T_0 is base temperature (^{0}C), T_0=25 ^{0}C

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

$$Q_{ventilation} = \frac{\rho_a v_a C_a N(T_r - T_a)}{3600} = 0.33 N v_a (T_r - T_a) \tag{12}$$

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;

$$Q_{EAHE} = F_R m_a C_a (T_0 - T_r) \tag{13}$$

where T_0=25^{0}C, Q_{EAHE} is rate of thermal energy gained by air through Earth Air Heat Exchanger (J/s), $\dot{m}_a$ is mass flow rate of air (kg/s).

$$F_R = 1 - \exp\left(-\frac{2\pi r h_{ca}}{m_a C_a} L_{pipe}\right) \tag{14}$$

h_{ca} is convective heat transfer coefficient between surface and ambient (W/m^{2} ^{0}C), L_{pipe} is length of PVC pipe (m), r is radius of PVC pipe (m).

Based on Equations (1)– (14), the heat balance equation for room of the house was written as follows.

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5.2 Heat balance equation

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

$$\frac{dT_r}{dt} = -\left[\frac{\sum_i^4 (UA)_{wall,i} + \sum_j^4 (UA)_{window,j} + (UA)_{door} + (UA)_{roof} + (UA)_{floor} - 0.33Nv_a + F_R m_a C_a}{M_a C_a}\right] T_r$$
$$+\left[\begin{array}{l}\sum_i^4 (UA)_{wall,i} T_{sol,wall,i} + \sum_j^4 (UA)_{window,j} T_{sol,window,j} + (UA)_{door} T_{sol,door} + (UA)_{roof} T_{sol,roof} \\ +(UA)_{floor} T_0 - 0.33Nv_a T_a + F_R m_a C_a T_0\end{array}\right] / M_a C_a \tag{15}$$

or

$$\frac{dT_r}{dt} = f(T_r, g(t)) \text{ or } \frac{dT_r}{dt} = aT_r + g(t) \tag{16}$$

The constant ‘a’ is the coefficients of room air temperature. The term g(t) represents the function of time ‘t’ in Eq. (16) 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 (16) is;

$$T_r = \bar{g}(t)/a\left[1 - \exp(-at)\right] + T_{r0}\exp(-at) \tag{17}$$

where $\bar{g}(t)$ is average of g(t) over time interval 0 to t.

The values of initial room air temperature (T_{ro}) of room for each month of the year were obtained from the experimental results. Based on these initial values, the next hour room air temperatures of room can be evaluated.

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

$$Q = \sum \dot{m}_a C_a (T_r - T_a)\Delta t \tag{18}$$

Q is heating or cooling potential (J), $\dot{m}_a$ is mass flow rate of air (kg/s)

6. Results
Using Equation (17) room air temperatures for 24 hours have been computed. Figure 2 shows the variation of room temperature with time at different number of air change per hour (N) in the month of June at New Delhi. Variation of atmospheric temperature (29.6^{0}C to 38.5^{0}C) with time has also been shown in Figure 2. Effect of earth air heat exchanger on room temperature has also been shown in Figure 2. At N=0, room temperatures are very high in the range of 44.1^{0}C - 52.7^{0}C. At N=10, room temperatures fall and varies from 34.3^{0}C to 44.2^{0}C. At N=20, room temperatures again fall and varies from 32.0^{0}C to 42.6^{0}C. At N=30, room temperatures again fall and varies from 31.0^{0}C to 41.9^{0}C. At N=40, room temperature varies from 30.5^{0}C to 41.4^{0}C. At N=50, room temperature varies from 30.3^{0}C to 41.1^{0}C. When the room is integrated with earth air heat exchanger (length of PVC pipe=78 m, air

velocity=3m/s), room temperature falls and varies from 25.9^0C to 31.8^0C. Maximum difference between atmospheric temperature and room temperature is 14.5^0C if there is no ventilation (N=0). With ventilation at N=10, 20 and 30, maximum temperature difference falls to 5.7^0C, 4.1^0C and 3.4^0C respectively. At N=40, maximum temperature difference is less than 3^0C. Therefore ventilation is optimized as N=30. Use of earth air heat exchanger improves cooling of the room air. With earth air heat exchanger, room temperature becomes lower than atmospheric temperature by 3.7^0C to 6.7^0C.

Figure 3 shows the variation of room temperature with time in the month of January with and without earth air heat exchanger at New Delhi. Variation of atmospheric temperature (8.6^0C to19.7^0 C) with time has also been shown in Figure 3. The room air temperatures are in the range of 24.1^0 C –34.8^0 C without earth air heat exchanger and 22.6^0 C - 30.0^0 C with earth air heat exchanger. Difference between atmospheric temperature and room temperature lies between 15.1 ^{0}C and 15.5^0C, if there is no ventilation (N=0). Using earth air heat exchanger does not improve heating of the room air. This is because the difference in base temperature T_0 and room temperature at N=0 is very less. Therefore use of earth air heat exchanger is not advisable in winter.

Some investigators [14, 15 and 16] have reported room air temperature of adobe house to be constant in composite climate of New Delhi because of high isothermal mass of the adobe house. Present study proves that room air temperature of adobe house is not constant in composite climate of New Delhi, because isothermal mass of the adobe house is not as high as earth up to 4 m depth.

The thermal comfortable room air temperature range in both winter and summer months were observed as 14^0C –18^0C and 24^0C –28^0C, respectively. The performance of dome shaped house was found satisfactory in both winter and summer for above mentioned room air temperature range. Hence, this case study provides real insight of actual performance of dome shaped house in New Delhi climatic condition. 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 the desert (hot and dry climate) and remote mountains (cold and sunny climate) places. Few deaths have been recorded in India because of heat waves in summer and cold climate in winter. Hence, 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.

Using Equation (18), monthly heating potential for four weather types of dome shaped house were computed and shown in Figure 4. In November and January, ‘b’ type weather yields maximum heating potential because of maximum number of days contained by ‘b’ type weather. In December and February, ‘c’ type weather dominates and hence produces maximum heating potential. Monthly cooling potential for four weather types of dome shaped house were estimated and shown in Figure 5. In March, April, May, June and September, ‘c’ type weather dominates and hence produces maximum cooling potential. In July and August, ‘d’ type weather dominates and hence produces maximum cooling potential. Total monthly heating /cooling potential of dome shaped house were estimated and shown in Figure 6. Although heating is required for four months only, magnitude of monthly heating potential is more than monthly cooling potential. This is due to the fact that difference between room temperature and atmospheric temperature is more in winter than in summer. In January the temperature difference is 15.5^0C and in June it is only 3.4^0C.

Effect of air flow velocity through heat exchanger, length of heat exchanger and radius of pipe on yearly heating and cooling potential have been studied for New Delhi climatic condition. It is observed that heating and cooling potentials have no effect on change in air flow velocity after 3 m/s for 50m length of heat exchanger (Figure 7). It is observed that heating and cooling potentials have no effect on change in length after 50 m the length of heat exchanger for 3m/s air flow velocity (Figure 8). It is observed that heating and cooling potentials have no effect on change in radius of the pipe after 3m for 50m length of heat exchanger and 3m/s air flow velocity (Figure 9).It has been found that when length of the pipe is more than the optimum length there is no change in heating and cooling potentials of an earth–air heat exchanger with change in air flow velocity.

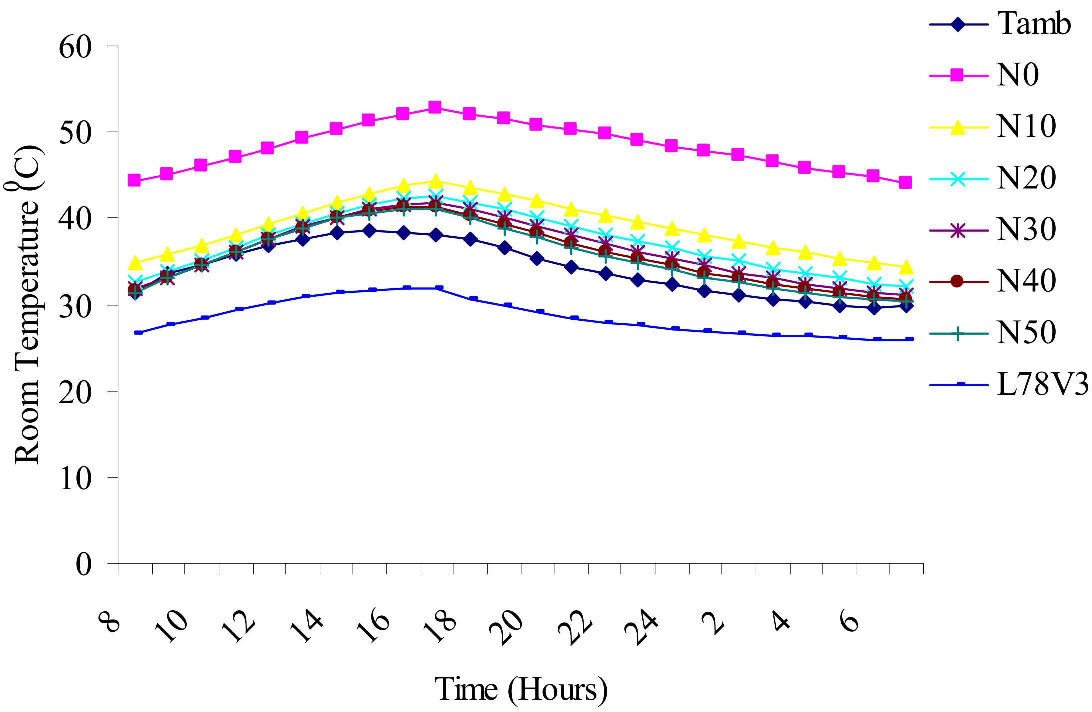

Figure 2. Variation of room temperature with time in June

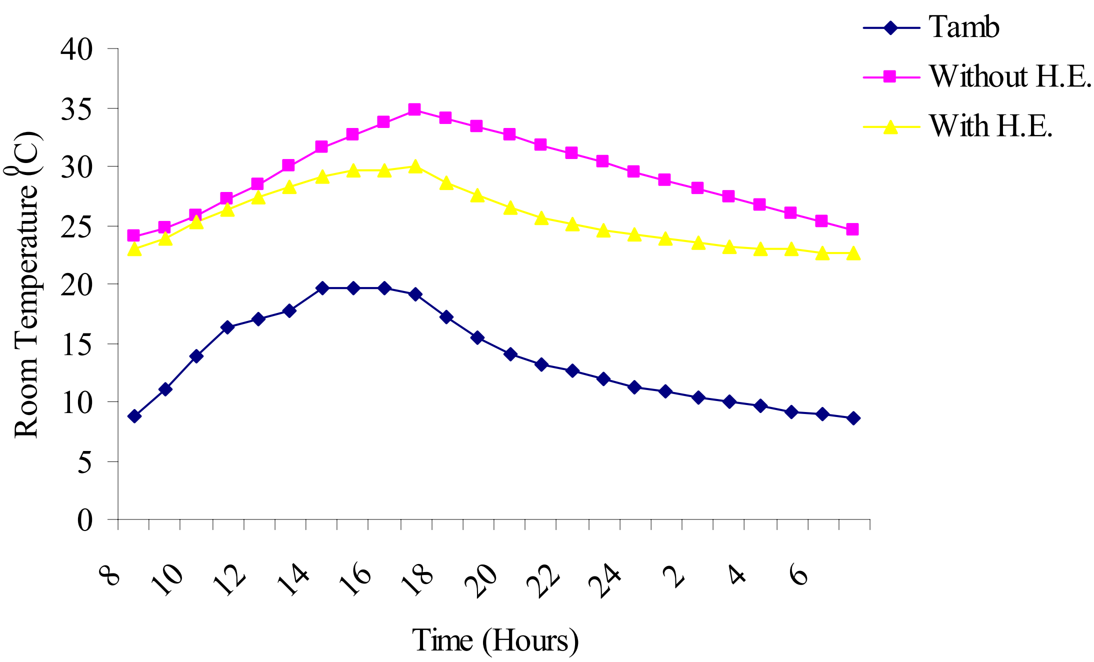

Figure 3. Variation of room temperature with time in January

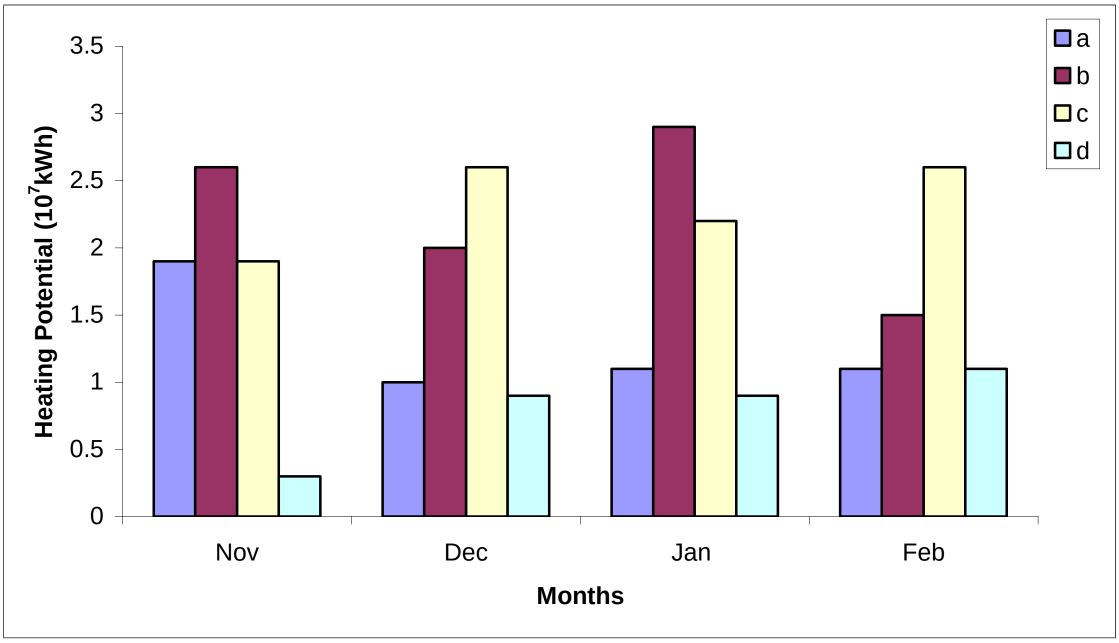

Figure 4. Heating potential in winter at New Delhi (N=0)

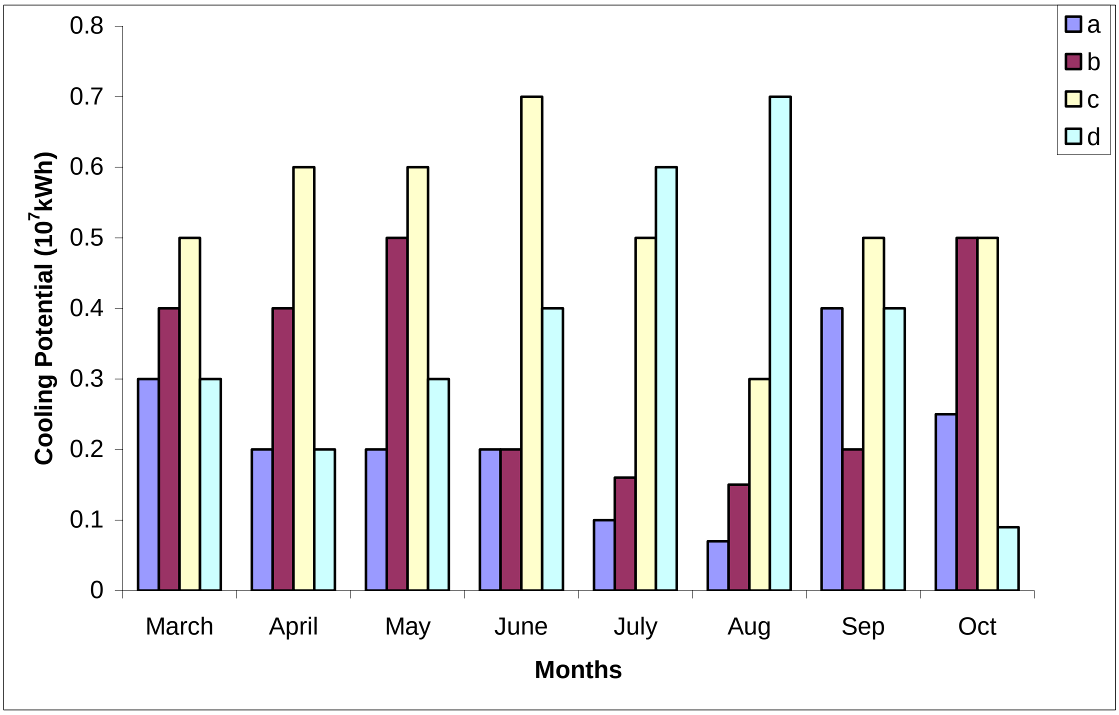

Figure 5. Cooling potential in summer at New Delhi (N=30)

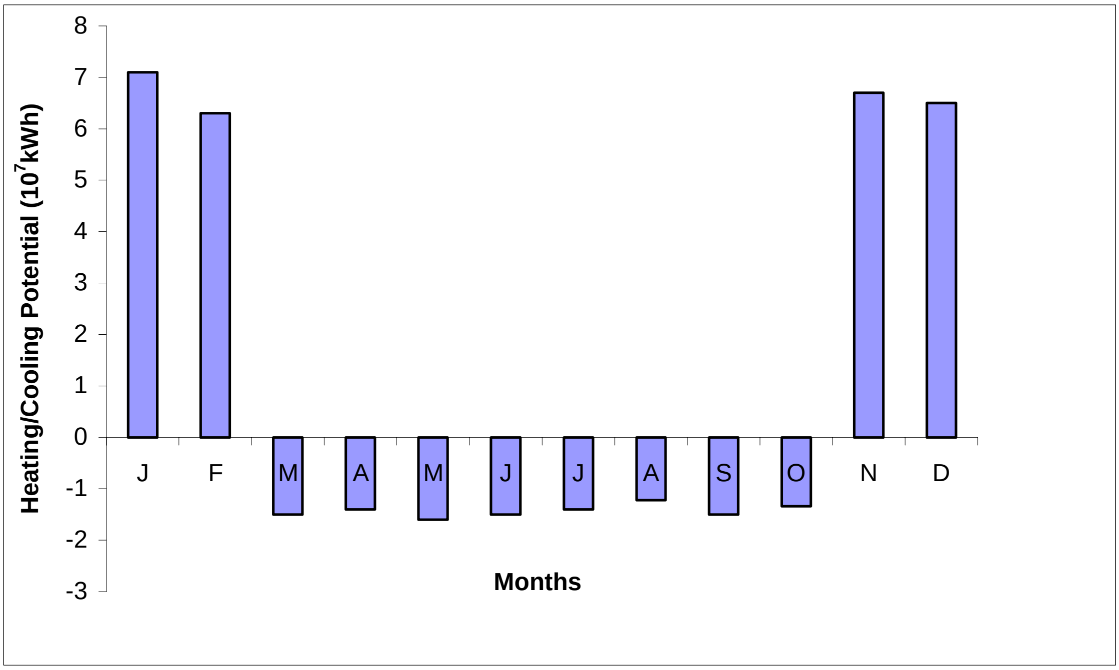

Figure 6. Monthly heating/cooling potential at New Delhi

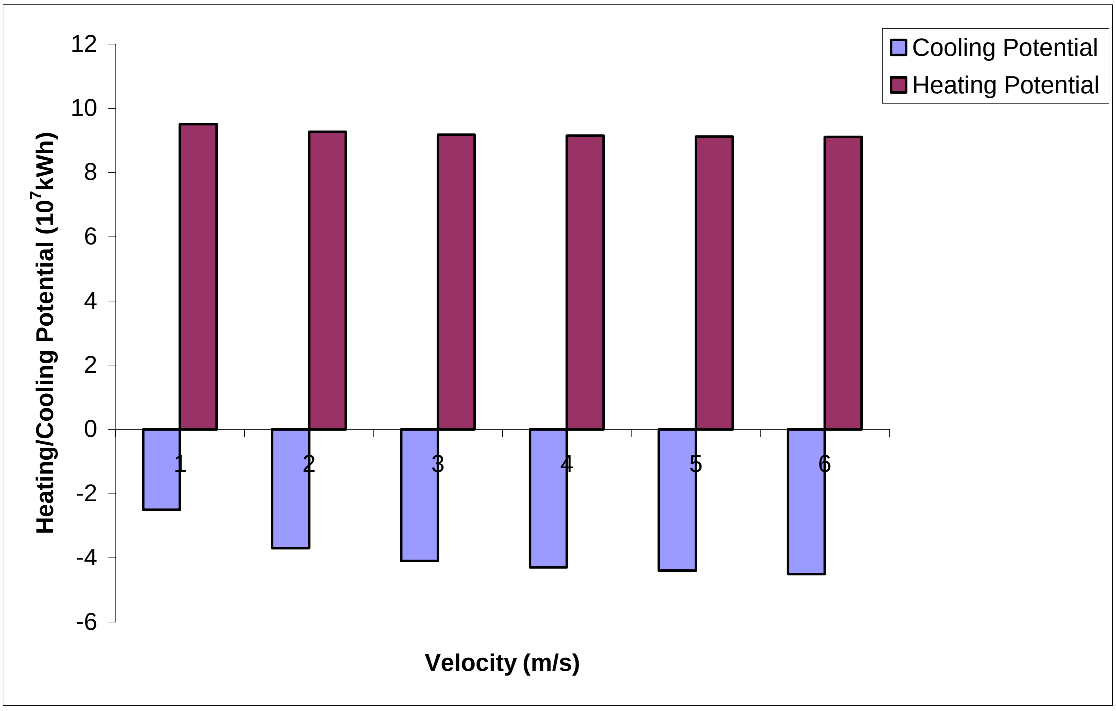

Figure 7. Variation of heating/cooling potential with air velocity of EAHE

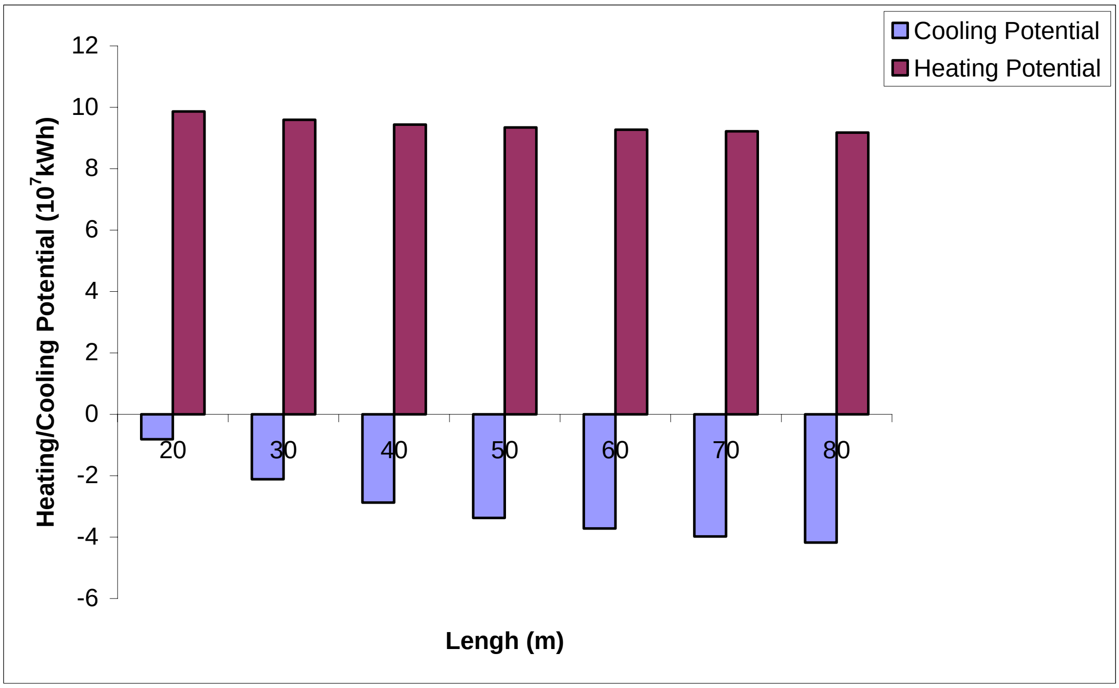

Figure 8. Variation of heating/cooling potential with pipe length of EAHE

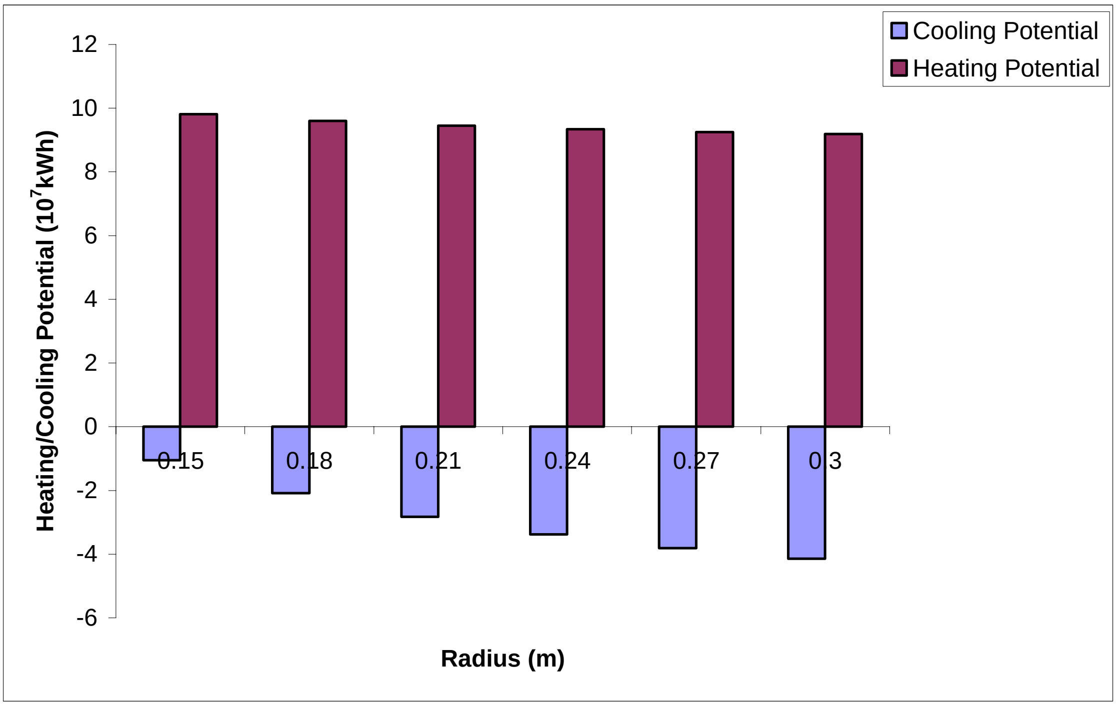

Figure 9. Variation of heating/cooling potential with pipe radius of EAHE

7. CO_2 emission mitigation and carbon credit earned

The application of day lighting in this dome shaped house can best be illustrated with worked example. This can also give a feel for the likely magnitude of energy savings when using day lighting schemes in New Delhi. The example is based on above mentioned house of size 4.8 m × 3.35 m with the following assumptions:

1. A light transmittance of 0.3 and a shading coefficient of 0.4 for typical reflective glass used in commercial buildings in New Delhi;
2. An area-weighted mean reflectance of 0.5 for the internal surfaces;
3. No external obstruction;
4. An indoor design illuminance of 500 lux with a typical installed lighting load of 20 W/m^2 of floor area;
5. A 10-h working day (08:00-18:00) and a 5.5 day working week.

Energy savings (Wh) in electric lighting per year [17]

$$ES = L.A_f.H_a.F \tag{19}$$

where

L = Installed lighting power density = 20 W/m^2 for indoor design illuminance of 500 lux
A_f = Floor area =16 m^2
H_a = Annual operating hours of the electric lighting system = 10 x 5.5 x 52
F= factor for type of glass and indoor design illuminance = 0.8
Substituting these values in Eq. (19),
ES= 732 kWh

The average carbon dioxide equivalent intensity for electricity generation from coal is approximately 0.982 kg of carbon dioxide per kilowatt hour at source [18, 19]. However, 40% is transmission and distribution losses and 20% loss is due to the inefficient electric equipment used are considered. Then the total figure comes to be 2.04 kg of carbon dioxide per kilowatt hour. So
CO_2 emission reduction =1493 kg
= 1.493 ton per year
If CO_2 emission reduction at present being traded @Euro 21per ton, then CO_2 emission reduction by day lighting = Euro 31.35 which corresponds to Carbon credit earned= Rs.2038 per year.

8. Conclusion

In the climatic zone of New Delhi, the cooling period is larger than the heating period. Cooling is required for eight months. In rest of months, heating is required. During summer, cross ventilation is a good option for cooling of the house. The temperature of the room with an earth air heat exchanger decreases significantly (6.8^o C) in comparison with that of the untreated room during June. EAHE is more economical for heating the house in winter and cooling in summer. However monthly heating potential in winter is more than monthly cooling potential in summer.

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M. Jamil Ahmad, born at Ballia (UP), graduated in Mechanical Engineering from Aligarh Muslim University, Aligarh in 1991. He did his M.Sc.Engg from Aligarh Muslim University, Aligarh in 1993.
He is working as a Senior Lecturer in Department of Mechanical Engineering at Aligarh Muslim University, Aligarh.
Presently he is pursuing his Ph.D. program under supervision of Prof. G.N.Tiwari at Centre for Energy Studies, Indian Institute of Technology Delhi. His research interest is in the field of solar radiation and daylighting and its application.
E-mail address: jamil.amu@gmail.com

G.N. Tiwari born on July 01, 1951 at Adarsh Nagar, Sagerpali, Ballia (UP), India. He had received postgraduate and doctoral degrees in 1972 and 1976, respectively, from Banaras Hindu University (B.H.U.). Over several years since 1977, he has been actively involved in the teaching programme at Centre for Energy Studies, IIT Delhi. His research interests are Solar distillation(water purification), Water/air heating system , Greenhouse technology for agriculture, aquaculture and crop drying, Earth to air heat exchanger , Passive building design and Hybrid photovoltaic thermal systems for greenhouse, solar house and drying. He has guided about 60 Ph.D. students and published over 400 research papers in journals of repute. He has authored twenty books associated with reputed publishers namely Pergaman Press UK, CRC Press USA, Royal Society of Chemistry (RSC), UK, Pira International, UK, Alpha Science, UK, Narosa Publishing House, Anamaya Publisher, New Delhi etc. He is a co-recipient of 'Hariom Ashram Prerit S.S. Bhatnagar' Award in 1982. He has been recognized both at national and international levels. His contribution for successful implementation of hot water system in the IIT campus has been highly appreciated. He had been to the University of Papua, New Guinea in 1987-1989 as Energy and Environment Expert. He was also a

recipient of European Fellow in 1997. He had been to the University of Ulster (U.K.) in 1993. Besides, he had been nominated for IDEA award in the past. He is responsible for development of "Solar Energy Park" at IIT Delhi and Energy Laboratory at University of Papua, New Guinea, Port Moresby. He has organized many QIP (Quality Improvement Program) at IIT Delhi.
Professor Tiwari had visited many countries namely Italy, Canada, USA, UK, Australia, Greece, Thailand, Singapore, Sweden, Hong Kong, PNG and Taiwan etc. for invited talks, chairing international conferences, expert in renewable energy, presenting research papers etc. He has successfully co-coordinated various research projects on Solar distillation, water heating system, Greenhouse technology, hybrid photovoltaic thermal (HPVT) etc. funded by Govt. of India in past. He is an Associate Editor Solar Energy Journal (SEJ), USA (2006- Present) and Int. J. Agricultural Research, USA (2006- Present) and Editorial board member of Int. J. of Energy Research, Canada (2006- Present) and The Open Environment Journal (2007-present). He was organizing secretary 3rd International conference on Solar Radiation and Day Lighting “SOLARIS 2007”, at IIT Delhi during February 07 to 09, 2007.
Professor Tiwari has also been conferred “Vigyan Ratna” award by Government of Uttar Pradesh in the year 2007 on his work in the area of SOLAR ENERGY APPLICATIONS. Currently he is President of Bag Energy Research Society (BERS-2007) (www.bers.in) form to disseminate energy education in rural areas.
E-mail address: gntiwari@ces.iitd.ac.in

Anil Kumar Singh is the President and Director of ERA. Dr. Singh has 15 years of experience in the field conditions after having his Master of Technology and Ph. D. degrees in renewable energy technologies from Indian Institute of Technology (IIT) Delhi in 1989 & 1993 respectively. Department of Science & Technology, Government of India has awarded him BOYSCAST fellowship in 1994. He has been visiting scientist at Ben-Gurion University of Negev, Israel. He has two patents and more than 30 scientific papers in national & international journals. He has executed about fifty projects on energy and efficiency funded by Government of India and UNDP.
E-mail address: energyresapp@sify.com

Manisha Sharma is an architect with variety of architectural projects which includes hospitality projects, office complexes, educational institutions, infrastructural projects and residences etc. Ms Manisha Sharma is the Principal/Partner of DESIGN and graduated with B Arch from School of Architecture, Indore. She has done her Masters in Urban Planning from NIT, Bhopal.
E-mail address: ar.manisha@gmail.com

H.N. Singh, after graduating in science from Allahabad University, completed his master’s degree in Physics and Ph. D. degree in the field of Solar Energy, both from Indian Institute of Technology, Delhi at New Delhi, India. He is the recipient of Neeraj Shrivastva Memorial Award which is conferred by I.I.T. Delhi to the topper in M. Sc. Physics. His research involvement has been in the field of Solar Radiation Estimation and Solar Thermal Applications. His research work has been published in the journals of international repute, namely, Solar Energy, Energy, Energy Conversion and Management, Desalination and Ambient Energy. He has keen research interest in the field of Solar Radiation Estimation, Day lighting, Solar Thermal Applications and Optical Meteorology. Presently, he is the faculty and Head of the Department of Physics in Rana Shiksha Shivir Post Graduate College, under C.C.S. University, at Pilkhuwa, Ghaziabad, U. P. India.
E-mail address: hnsinghsolar@rediffmail.com