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Performance evaluation and life cycle cost analysis of earth to air heat exchanger integrated with adobe building for New Delhi composite climate

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ABSTRACT

This paper aims to develop thermal model of a vault roof building integrated with earth to air heat exchanger (EAHE). The building under consideration is made of brick vault and adobe (or mud) structures. The methodology adopted for developing thermal model of this building with six interconnected rooms is presented in this paper. The energy balance equations were solved simultaneously using fourth order Runge–Kutta numerical technique. The results from the thermal model were validated using experimental observed data. Experimental results showed that the room air temperature during winter was found 5–15 °C higher as compared to ambient air temperature while lower during summer months. The results show that annual energy saving potential of the building before and after integration of EAHE were 4946 kWh/year and 10321 kWh/year respectively. The seasonal energy efficiency ratio (SEER) for EAHE was determined as 2–3. This considerable increase in annual energy savings potential of building due to EAHE leads to mitigation of CO_2 emissions about 16 tons/year and the corresponding annual carbon credit of building was estimated as € 340/year. The life cycle cost (LCC) analysis shows that the payback period is less than 2 years for the investment on EAHE system.

1. Introduction

An adobe building is an example of passive building because it can maintain natural thermal comfort throughout the year as reported by Eben [1]. Hence, these structures are common in Middle East countries and other hot and dry climatic regions all over the world [1]. The adobe house constructions have natural air conditioning effect since the temperature of rooms tend to be cool during daytime and warm during nighttime as reported by Eben [1]. The most common passive solar building architecture comprises of massive walls to reduce the temperature fluctuations inside a building. This is known as the thermal flywheel effect [1]. The adobe (or mud) houses in Yemen utilize this effect for thermal conditioning of room air [1]. The engineers have realized the special properties of mud [1]. The progress in the use of mud as construction material had a good potential in hot and dry places because of its distinct advantages like its suitability for different weather and geographical conditions as the temperature remains temperate throughout the year inside the adobe house [1]. The comparison of thermal behavior of adobe house with modern concrete house in Yemen showed the potential of mud as construction material for energy saving in houses [2]. Bahadori and Haghighat [3] explained the importance of dome roof structures for passive cooling in hot arid regions in developing countries. The inside air and the mean radiant temperatures of two buildings, one built of brick having a flat roof and the other built of lightweight adobe and having a dome shape roof, were estimated through a thermal network analysis by Bahadori and Haghighat [4]. A finite element model was developed to investigate thermal performance of non-air-conditioned buildings with vault and flat roof structures by Tang et al. [5]. The results show that vault roof buildings had lower indoor air temperatures as compared to those with a flat roof [5] because such roofs dissipate more heat than a flat roof by convection and thermal radiation at night due to the enlarged curved surfaces.

The indirect heating/cooling of building using earth to air heat exchanger (EAHE) is basically achieved by ventilating outdoor air through a buried duct exploiting temperature gradients between

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Abbreviations: EAHE, Earth air heat exchanger; IMD, Indian Meteorological Department, Pune; LCC, Life cycle cost analysis; SEER, Seasonal energy efficiency ratio.

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Nomenclature

A_{Roof}	area of roof (m^2)
A_{Wall}	area of wall (m^2)
A_{Window}	area of window (m^2)
C_a	specific heat of room air (J/kg K)
CF	annual net cash flow (rupees)
e	root mean square percentage deviation (%)
h	time interval (h)
h_i	inside heat transfer coefficient of wall/roof surface (W/m^2 K)
h_o	outside heat transfer coefficient of wall/roof surface (W/m^2 K)
I_d	diffuse solar radiation available on horizontal surface (W/m^2)
I_g	global solar radiation available on horizontal surface (W/m^2)
I_T	solar radiation available on inclined surface (W/m^2)
K	thermal conductivity of material (W/m K)
L	thickness of material layer (m)
M	annual cash outflow for operation and maintenance (rupees)
M_a	mass of room air (kg)
$\dot{m}_a$	mass flow rate through EAHE pipe (kg/s)
N	number of air change per hour (h^{-1})
n_p	discounted payback period
P	initial investment (rupees)
Q_{Base}	maximum heating/cooling load of adobe house (kWh/year)
Q_{Load}	actual heating/cooling load of adobe house (kWh/year)
Q_{Saving}	heating/cooling energy saving of adobe house (kWh/year)
R	annual cash inflow (rupees)
r^2	coefficient of correlation
t	time interval (h)
T_a	ambient air temperature (°C)
T_o	earth temperature at depth of 1.5 m (°C)
T_{rExpt}	experimental room air temperature of adobe house (°C)
T_{rPred}	predicted room air temperature of adobe house (°C)
T_{Sol}	sol–air temperature of the Sun exposed surfaces (°C)
U	overall heat transfer coefficient of wall/roof structure (W/m^2 K)
υ_a	volume of room air (m^3)

Greek symbols

α	absorptivity of surface
β	slope of wall/roof surface with respect to horizontal
ε	emissivity of surface
τ_g	transmissivity of window/ventilator glass
ρ_a	density of air ($kg\,m^{-3}$)

Subscripts

a	air
r	room

outdoor air and the earth resulting in energy savings while conditioning an indoor environment [6,7]. This system has application for both heating and cooling of residential and commercial buildings and can significantly reduce the energy demand from the power grid [8]. Currently most of the studies deal with the accurate modeling [9,10], life cycle cost (LCC) analysis and feasibility comparison [11]. Esen [11] conducted a techno-economic analysis of EAHE systems for the purpose of space cooling. Similarly, Hamada et al. [12] describes an improved EAHE by developing a no-dig method to reduce the installation cost of system. The EAHE consists of underground air duct and air blower. The air blower maintains an average air velocity inside the air duct by consuming electrical energy. This energy consumption can be substantially reduced by using hybrid ventilation systems as reported by Heiselberg [13].

In this paper, a computer based thermal model was developed to predict room air temperature and energy saving potential of an adobe house with vault roof structure having six interconnected rooms. The thermal model of the house was developed based on the six quasi-steady state heat balance equations which were solved simultaneously using fourth order Runge–Kutta numerical technique. The experimental hourly measured six room air temperatures data was used for the validation of simulation results of thermal model. The input New Delhi (28.58°N, 77.20°E, 216 m) climatic data for thermal model was obtained from Indian Meteorological Data (IMD), Pune. The LCC analysis was carried out for the investment on EAHE system components. The CO_2 emissions mitigation potential and annual carbon credit of the house was also estimated.

The adobe house under study is commonly observed in village and semi-urban areas of India and Middle East countries. Hence, this study gives an insight to the energy saving potential of such houses for obtaining natural thermal comfort inside the room especially for hot and dry climatic conditions all over the world.

2. Heating/cooling of adobe house using EAHE system

The experimental setup consists of the adobe house integrated with EAHE system. The EAHE consists of air blower of rating 0.3 kW and PVC pipes of 6 cm diameter buried at depth of 1.5 m underground. The underground pipe layout is as shown in Fig. 1. When the air blower is operated, room air gets sucked inside the air duct through air filter and air is then circulated through the underground air duct system. The delivery pipe is fed inside the room which supplies hot/cool air during winter/summer month respectively. The design details of the adobe house and EAHE system are given in Table 1. The room air exchanges its heat with the ground through air duct and gets heated or cooled during winter and summer months respectively depending on the room air and earth temperature difference. The monthly average ground air temperature at a depth of 1.5 m was experimentally measured as shown in Fig. 1. These underground pipes are at stable underground temperature equal to annual average ambient air temperature at a depth of 4 m as reported by Tiwari [6]. The room air is re-circulated back into the same room after the process of heat exchange between room air and the earth. There is convective heat transfer between room air and the duct surface.

3. Adobe house design

The adobe house has a vault or inverted U-shape and dome shape roof structures designed by German architect in the year 1981. The schematic diagram of the adobe house considered for building simulation is as shown in Fig. 2(a). The floor plan of six rooms of adobe house is shown in Fig. 2(b). There are six