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DESIGN OF A LOW COST HOUSE USING LOCAL MATERIAL COUPLED TO MECHANICAL -EARTH TUBE VENTILATION SYSTEM

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Abstract. The building sector accounts for 50% of the total worldwide energy consumption. This percentage is expected to increase with the population growth and climate change compounding the problem of dwindling in energy resources. One means of mitigating the increase in energy consumption is by relying on natural ventilation systems for thermal comfort purposes and on the applications of natural (as compared to processed and manufactured) and recycled materials in building construction. Nonetheless, the use of natural ventilation systems with energy efficient construction materials and building envelope cannot always ensure thermal comfort conditions throughout the whole year. Additional systems are sometimes necessary to aid in providing continuous thermal comfort, year round. One such system, the Earth to Air Heat Exchanger (EAHE), has been found to have the potential of providing indoor comfort at reduced energy cost. In this paper, different scenarios for natural building materials coupled with an earth tube heat exchanger are investigated with the aim of reducing the operational energy of a typical house in Lebanon. It is found that use of an optimal wall configuration when coupled with the EAHE results in 76.7% energy savings compared to reference case

Key words

Earth tube heat exchanger; thermal comfort; ventilation and optimized operation of the mechanical system

1. Introduction

For a building to be regarded as truly “Green”, attention should be given not only to its energy consumption, but also to other sustainability aspects such as impact on environment, natural resources, and society using indicators such as embodied energy, Scheuer and Keolian [1].

The embodied energy can be defined as the energy content of all materials, building components, and systems incorporated in the building starting from its design phase till the end of its service life, Reddy and Jagadish [2]. Aspects covered in embodied energy include but are not limited to energy consumed in: material extraction, production, transportation, placement, replacement, disposal and salvage. The challenge in the research of reducing a building energy life cycle is the use of techniques and procedures that reduce the building’s operating energy without negatively affecting the embodied energy. An example of a potentially successful strategy is the use of an earth tube heat exchanger ventilation system that moderates the indoor air temperature during winter and summer periods. Such a system can reduce the dependency on mechanical air conditioning system and can, therefore, achieve indoor air quality and thermal comfort at lower energy cost.

Kusuda et al. [3], Labs [4] and Krarti [5] have reported that the ground temperature often significantly differs from the ambient temperature in extreme weather conditions. This is due to the fact that the temperature fluctuations at the surface of the ground diminish as the depth to the subsurface layers increases. This phenomenon is made possible due to the high thermal inertia of the soil. Hence, an Earth to Air Heat Exchanger (EAHE) system consisting of a buried pipe with access to open air can utilize the soil as a heat source/sink to moderate the open air. The performance of an EAHE depends on pipe length and diameter, the pipe burial depth, outside air velocity, the air flow rate inside the pipe, and soil properties.

As such, the proposed research will consider the simultaneous lowering of operational energy and embodied energy of typical apartments in Lebanon by conducting research that considers both the building envelope material and a mechanical earth tube heat exchanger ventilation system.

2. Mathematical Formulation

The earth tube heat exchanger draws air through a pipe that is buried in soil to moderate its temperature to conserve energy and achieve thermal comfort for the larger period of the time during the year. The house is divided into two thermal zones, the living zone and the bedroom zone. Different wall material can be used for each zone. For a set of indoor and outdoor conditions and for a preselected building material properties, the ventilation controller determines the amount of flow rate

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needed to temperate the indoor air temperature and to minimize the discomfort hours. The assessment of the building materials energy efficiency is based on their effect on indoor comfort and energy consumption. The overall model and its formulation are described in the following sections.

Space Model

The developed space model is applicable for each of the two house zones that constitute the case study. The transient one-dimensional heat conduction equation for a multilayered wall of thickness *L* consisting of *N* parallel layers is given by:

$$\rho_{i,j} c_{i,j} \frac{\partial T_{i,j}(t,x)}{\partial t} = k_{i,j} \frac{\partial^2 T_{i,j}(t,x)}{\partial t^2} \qquad (1)$$

Where: *i* represents building element (wall, ceiling, or floor), *j* represents the j^{th} layer within the element *i*, *t* and *x* are the time and spatial coordinates respectively, $T_{i,j}$ is the temperature, whereas *k*, ρ, and *c* are the thermal conductivity, density, and thermal capacity respectively.

The room lumped air-node energy balance is given by:

$$\rho_a V_a c_{p,a} \frac{\partial T_a(t)}{\partial t} = \sum_{i=1}^{6} h_{c,a}.A_i(T_i - T_a) + \dot{m} c_{p,a}(T_{a,supplied} - T_a) + \sum q_{int} \qquad (2)$$

Where: $\rho_a, V_a, and\ c_a$ are density, volume and specific heat capacity of the room air respectively, A_i and T_i are the surface area and the temperature of the room element i, $\dot{m}\ and\ T_{supplied}$ are the mass flow rate and the temperature of the air supplied by the ventilation system. q_{int} is the internal heat load.

The simplified dynamic moisture mass balance for the space is:

$$\rho_a V_a \frac{dw_a}{dt} = G - \dot{m}(w_a - w_{a,supplied}) \qquad (3)$$

Where G is the rate of moisture generation inside the space due to latent loads, and w_∞ and w_a are the room air and supply air humidity ratios.

The predicted values of inside air temperature, internal air relative humidity and wall temperature are used in the determining the thermal sensation of occupant using the Predicted Mean Vote (*PMV*) model, Fanger [6]. The *PMV* represents the thermal sensation of people on a scale ranging from -3 (cold) to + 3 (hot). The model is simple and, widely used by researchers. The input requirements are divided into two main categories: a) environmental which include temperature, relative humidity, and air velocity, and b) personal which include clothing insulation and metabolic rate. Thermal sensation inside the space is calculated on an hourly basis, based on the hourly average room temperature, average relative humidity and air velocity for the precedent hour

Controller Model

The PID controller model of Dorf and Bishop [7] is used in the current study to regulate the air flow rate. The ultimate objective is to provide thermal comfort for as much time as possible. As the indoor air temperature deviate from the defined summer and winter set points, the controller updates at regular intervals (every 5 minutes) the ventilation air flow rate to keep the indoor air temperature as close as possible to the set point temperature

Soil & Air Heat Exchanger

The performance of the earth-air pipe ventilation system depends on: the ambient conditions (temperature, solar radiation, relative humidity and wind velocity); the dimensions of the pipe (length and cross sectional area); the depth at which it is buried; the material used for transporting the outdoor air; the temperature of soil in the vicinity of the buried pipe; soil characteristics; and the air flow rate. According to Krarti [5], the temperature of the soil at any depth z and time t can be estimated by using:

$$T_{z,t} = T_m - A_s exp\left[-z\left(\frac{\pi}{365\alpha_s}\right)^{0.5} \cos\left\{\frac{2\pi}{365}\left[t - t_0 - \frac{z}{2}\left(\frac{\pi}{365\alpha_s}\right)^{0.5}\right]\right\}\right] \qquad (4)$$

where T_m, A_s, z, and α_s are the mean annual ground surface temperature and amplitude, soil depth and thermal diffusivity. t_0 is the phase constant of air and is related to the time elapsed from the beginning of the year at which the air temperature reaches the minimum value in the year and the phase angle difference between the air and soil surface temperature

4. Numerical Simulation & Control Strategy

The case study consists of two zones: living zone and bedroom zone of a typical residential apartment. It is assumed that neither of the zones is occupied during the full time. The bedroom zone is occupied between hour 23 and hour 10 while the living zone is occupied between hour 8 and hour 23.

The ventilation controller modulates the air to be brought to the space between a lower and an upper limit to maintain an indoor air temperature as close as possible to the winter and summer set points. A set point temperature of 28 °C in summer season (June till September) results in a PMV of 0.92 for a person with a clothing factor of 0.8 clo while in winter season (October throughout May) a set point of 16 °C is defined results in a PMV of (-1.07) for a person with a clothing factor of 1.5 clo. Those are typical clothing factor for Lebanon.

During the occupancy period in the winter, the controller is activated whenever the indoor air temperature is lower than the winter set point temperature of 16°C ($T_{room} < T_{setpoint}$) provided exchanger can moderate the indoor air temperature ($T_{outlet} > T_{room}$). While in the summer time if the indoor air temperature is lower than the set point temperature ($T_{room}<T_{setpoint}$), the amount of fresh air entering the space is set to the minimum amount of fresh air requirement recommended by ASHRAE [8]. The controller is activated whenever the indoor air temperature is higher than the set point temperature ($T_{room}>T_{setpoint}$) provided that the outlet air temperature can moderate the indoor air temperature ($T_{outlet}<T_{room}$) and T_{outlet} is the outlet air temperature from the earth tube heat exchanger**.**

5. Case Study

As mentioned earlier, a typical apartment in the Bekaa - an inland region of Lebanon - is considered as a reference case in this paper. The apartment has a floor area of 160 m^2 and a height of 3m. The apartment is divided into two zones: a living zone consisting of dining and living rooms and a bedroom zone consisting of three bedrooms. The living zone has three 30 m^2 external walls on the North, South and West sides and has a floor area of 100 m^2. Similarly, the bedroom zone has three 30 m^2 exposed walls oriented to the north and south in addition to an 18 m^2 wall resulting in a total floor area of 60 m^2. The external walls consist of 15cm concrete masonry blocks with 1.5cm of mortar cement plaster on the internal and external sides of the wall resulting in an overall heat transfer coefficient of 2.36 W/m^2·K, while the internal partition wall has an overall heat transfer coefficient of 3.63 W/m^2·K. This configuration is typical for urban residential apartments in Lebanon.

6. RESULTS AND DISCUSSION

To attain the objective of identifying building configurations which may optimize, energy requirements, different wall configurations were tested. These include increasing the insulation beyond the reference case for the living zone and increasing and decreasing the wall thickness for the external walls in the living and bedroom zones resulting in seventy-two simulations (six simulations for each month). To attain the objective of identifying building materials which can help further reduce building's energy requirements, the use of natural materials (e.g. hemp, straw) was also considered. Hempcrete, which has lower thermal conductivity, higher thermal capacitance (C_p=1430 J/kg·K) and lower embodied energy as compared to the conventional hollow concrete block, is selected. Also straw is used as an insulation layer in the different configurations since it has a high thermal capacitance (C_p=2000 J/kg·K). The investigated walls in this study are: Wall 1 and Wall 2 for the living zone, and Wall 3 and Wall 4 for the bedroom zone. Wall 1 consists of 3cm of straw sandwiched between 2 × 6cm of Hempcrete, whereas Wall 2 consists of 5cm of straw sandwiched between 2 × 10cm of Hempcrete. Wall 3 consists of 10cm of Hempcrete, and Wall 4 is made of 10cm of Hempcrete and 5cm of straw board placed on the internal side.

Figure 1 represents the indoor temperature and mass flow rate inside the living zone. The EAHE is activated for 3 hours (between hours 8 and 10 and between 17 and 18) for the reference case compared to 1 hour (between hours 8 and 9) for Wall 1 and Wall 2 cases. In the reference case (Fig 1(a)), the EAHE was disabled at hour 18 since the outlet temperature from the earth tube heat exchanger becomes lower than the indoor air temperature; whereas for Wall 1, the EAHE was disabled at hour 22.

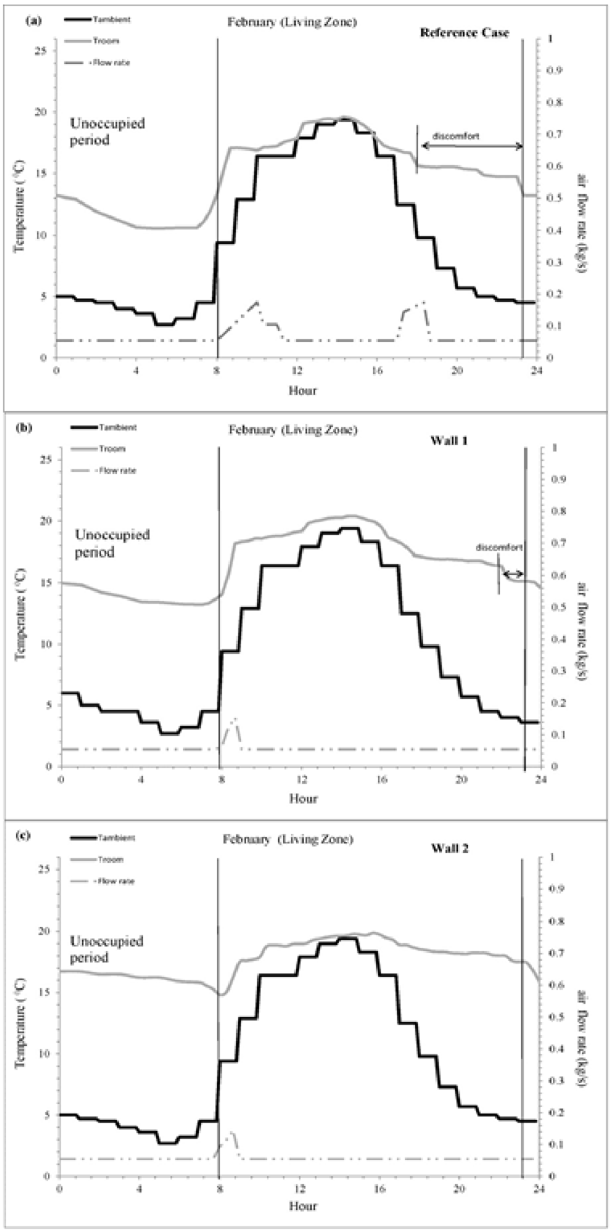

Fig. 1: Temperature and mass flow rate in the living zone during February for a) reference case, b) Wall 1, and c) Wall 2.

The reference case (Fig.1 (a)) is characterized by lower thermal capacitance and, therefore, shows an indoor air temperature profile which responds to the outdoor temperature variation much more than the two other configurations. This is due to higher amount of heat losses from the space to the outdoor resulting in 5 discomfort hours occurring between hour 18 and 23, as compared to 1 discomfort hours for Wall 1 taking place between hour 22 and 23 and 0 discomfort hours for Wall 2 type. Wall 2 configuration (Fig. 1(c)) is characterized by high thermal capacitance and, therefore, tends to store the temperature inside the space resulting in a higher indoor air temperature. The fan consumption is equal to 1.43 kWh in the reference case, 1.24 kWh for Wall 1 configuration and 1.18 kWh for Wall 2 configuration.

In the bedroom zone, since the outlet temperature from the tube at the minimal value of flow rate is lower than the room temperature (ranging between 12 °C to 14 °C), the system was set to the deactivation mode resulting in equal fan consumption across the three different cases (1.13 kWh). However, due to a higher amount of heat loss between the indoor and the outdoor spaces, Wall 4 (Fig. 2(c)) seems to have better conditions in the winter season since it has 9 discomfort hours (hours 23 to 7) as compared to 10 in the reference case (hours 23 to 8) and 11 in Wall 3(hours 23 to 9). The wall with the lowest insulation, i.e. Wall 3 (Fig. 2(b)), corresponds to the lowest air temperature as shown in Fig. 2(b).

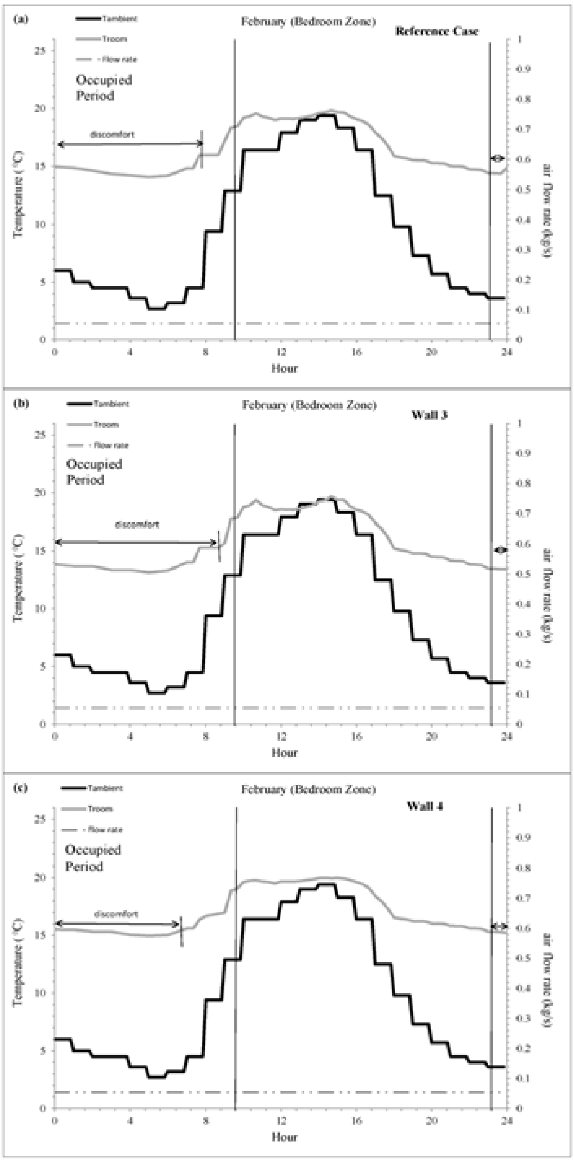

Fig. **2:** Temperature and mass flow rate in the bedroom zone during February for a) reference case, b) Wall 3, and c) Wall 4.

As mentioned earlier, seventy two simulations were carried out for the representative day of each month of the year. The monthly data are acquired by multiplying the results of the simulation by the number of days in each month. It was shown that using a double wall consisting of 5cm of straw sandwiched between 2 × 10 cm of Hempcrete, wall 2, in the living zone has the lowest operational energy and lowest number of discomfort hours (total of 62) during the whole year as compared to the other living zone wall configurations. These hours occur during the months of January and December. As for the bedroom zone, wall 4 (10 cm of Hempcrete and 5 cm of straw board) resulted in the lowest number of discomfort hour inside the space with 1,635 hour compared to 1,908 hour for the reference case and 2,089 hour for Wall 3. During winter, the earth tube cannot moderate the room temperature enough, and thus the ventilation controller is set to its minimal values. In the summer period, the temperature inside the space is within the comfort range, thus the ventilation controller set the flow rate to its minimal value.

In order to assess the savings of the earth tube heat exchanger, the cooling and heating load for a typical building were calculated for an equal set point temperature using a commercially available software, TRNSYS which was calibrated for the real conditions of Lebanon. The space requires a yearly electrical load of 35 kWh/m^2 to achieve an indoor temperature of 28 °C in summer and 16 °C in winter compared to 9.86 kWh/m^2 in the reference case with an EAHE. The earth tube heat exchanger can save 71.8% of the electrical power consumption used for mechanical cooling and heating system. The discomfort hours resulting from the use of *EAHE* in the reference case constitutes 28.3% of the total hours of the year. The optimal building wall configuration leads to a reduction of 31.5% in discomfort hours and 17.5% in the fan power consumption compared to the reference case with an earth tube heat exchanger.

7. Conclusion

This paper presents an integrated space, comfort, and controller model. The model helps investigate design features that can reduce the energy consumed in attaining appropriate thermal comfort levels in typical residential buildings. In particular, the model was used to simulate and evaluate various scenarios of building wall layouts and materials. Different wall configurations were assumed for each of the living zone and the bedroom zone of a typical residential house located in an inland region of Lebanon.

The simulation results revealed an optimal envelope configuration comprised of 1) a massive wall made of a 5cm layer of straw sandwiched between 2×10cm of Hempcrete in the living zone, and 2) a 10cm wall made out of Hempcrete with 5cm of insulation in the bedroom zone.

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