Design and Transient Analysis of Earth-Air Heat Exchanger

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Abstract

The temperature of the earth at a depth of about 3 to 4m (Brum, et al, 2013) remains almost constant throughout the year due to high thermal capacity of soil. This constant temperature of earth, called undisturbed temperature shows negligible temperature fluctuation at this depth which is close to annual average air temperature. Thus, the temperature here is higher than atmospheric or ambient temperature in winter and lower than the atmospheric or ambient temperature in summer. This temperature difference is used to warm or cool insides of a room by blowing air through pipe which acts like a heat exchanger.

An implicit model based on transient analysis using computational fluid dynamics is developed to predict the heat exchange performance and cooling capability of earth-air heat exchanger system. Also, a mathematical model is developed using MATLAB for comparative analysis and validation purpose. The output temperature is measure of effectiveness of this system, affected majorly by the inner radius of heat exchanger, its thickness, the conductivity of material, length of pipe and depth at which the heat exchanger is laid. These parameters are evaluated in this paper.

Keywords: Earth Air Heat Exchanger, Renewable Energy, Air Conditioning, Green Building, Passive Cooling

1. Introduction

Approximately 20% of the total power generated in India is consumed just for cooling purposes. Considering the current environmental situation, and increasing rate of global warming, an alternate cooling system was needed to be developed which avoids the use of ozone depleting HCFC's. Efforts are made on various levels to create awareness about the emissions and its effects. Using renewable energy sources like solar, wind, hydroelectric, geothermal has become the need of hour. Non-conventional methods are being researched and incorporated to minimize the carbon emission.

Thus, to utilize the geothermal energy for cooling purposes, a passive cooling system termed as Earth-Air-Heat-Exchanger is to be designed. Effects of varying design parameters like length, material, diameter of pipe and depth are to be studied, optimized, and the results of this designed model are to be validated with the actual onsite data. Also, to obtain the desired output from the earth air heat exchanger a controller is to be designed. Controlling the output temperature by adjusting operational parameters will be the ultimate aim of this project.

The earth air heat exchanger (EAHE) system is a series of pipes laid below the earth surface at sufficient depth. The two ends of the pipe are extended above the ground. A blower is connected to the input and the output is extended to a distribution system. The distribution system is a network of ducts supplying air throughout the building. Temperature sensors are installed at various lengths inside the pipe to monitor the temperature variation.

The surface temperature varies by various modes like direct sunlight, conduction, perspiration, winds, surface cover, etc. This heat is further conducted to the lower layers of soil, affecting its temperature. Less heat is transferred to the lower layers due to thermal capacity of soil. The temperature of soil varies over time according to the air temperature. Due to thermal inertia, the fluctuations decrease with increasing depth. At around 3m (9feet 10inches) from surface (Brum, *et al,* 2013), the temperature of soil remains constant which is approximately the average air temperature.

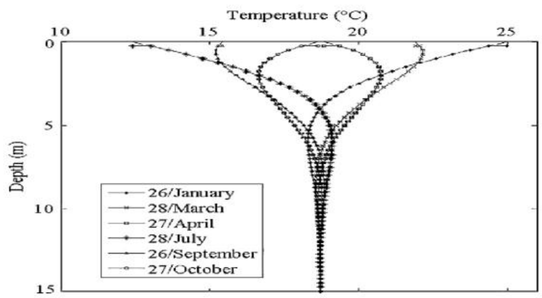

Figure 1 Variation of temperature over depth (Brum, 2013)

In tropical countries, up to certain depth below 3m, the temperature of soil is much less than the ambient temperature during day. The ambient hot air is sent into the pipes which are buried deep in the earths crest. When air flows in the earth–airpipes, heat energy is transferred from the air to the soil. The temperature of the air drops as it flows through the pipes. As a result, the air temperature at the outlet of the tubes is much lower than that of the ambient.

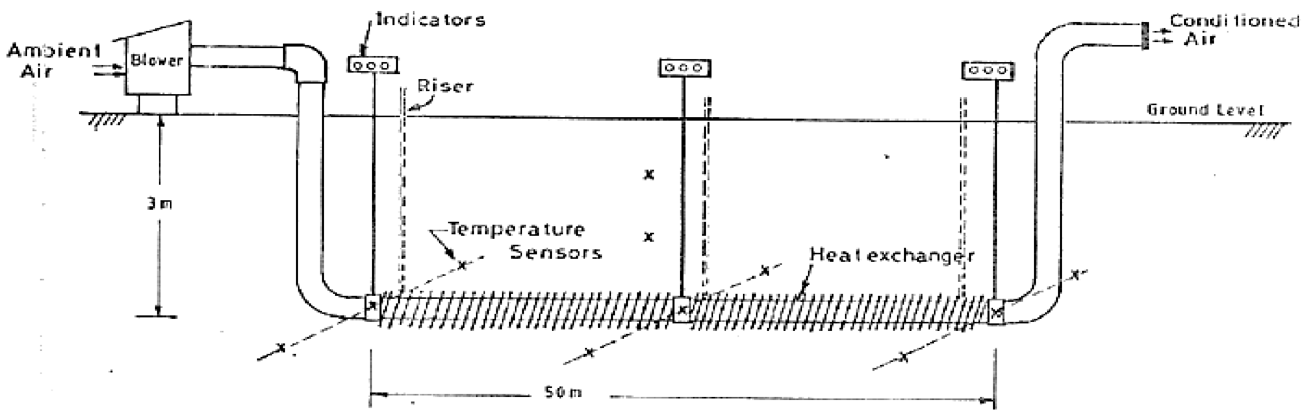

Figure SEQ Figure * ARABIC 2 Schematic diagram of EAHE

The outlet air from these tubes can be directly used for space cooling since its temperature is low enough. Alternatively, in colder regions, cold outdoor air is sent into the tubes that are buried in the ground. When air flows in the earth–air– tubes, heat is transferred from the soil to the air. As a result, the air temperature at the outlet of the tubes is much higher than that of the ambient. The outlet air from these tubes can be directly used for space heating in winters since ambient air temperatures are extremely low.

1.1. The global scenario of EAHE

Since 1950's number of researchers and scientists have studied the potential of cooling pipesburied in earth soil. With the growing awareness regarding the need of passive cooling system, Germany currently has more than 1000 such heat exchangers installed. Many countries in Europe have adapted this system in houses, commercial buildings, factories with over 5000 systems already installed. Although these systems are implemented in European countries on a wide scale, there are a limited number of models in developing countries like India.

Advantage of EAHE is its simplicity, high cooling, low operational costs, saving fossil fuels and zero emissions. (Pfafferott Jens, *et al,* 2003)

Tzaferis et al. studied eight ground coupled earth air heat exchanger models, complying with the actual measurements. His results show that a one dimensional steady state model is sufficient to characterize the behavior of EAHE. (Tzaferis A, *et al,* 1992)

Wu et al. has developed a transient implicit model in computational fluid dynamics (CFD) and then implemented it to evaluate effects of operating parameters like pipe radius, length, depth, air flow rate on the thermal performance and cooling capacity of EAHE. (Wu H, *et al,*2007)

Mihalakakou et al. executed a parametric analysis to evaluate the effect of pipe radius pipe length, air flow rate and pipe depth on the overall performance during winters. The paper concluded that the pipe length and pipe depth affected overall cooling rate, whereas air flow rate affected inner temperature of the EAHE. (Mihalakakou G, *et al,*1955)

Ozgener and Ozgener determined the best possible design for a closed loop EAHE. The results obtained show that the losses in blower and earth air heat exchanger are mainly responsible for exergy destructions in the system. The COP of system was found to be 10.51 and the energy efficiency of 89.25% was determined. Using simple thermo-economic optimization methodologies contribute for best design calculations. (OnderOzgener, *et al,* 2011)

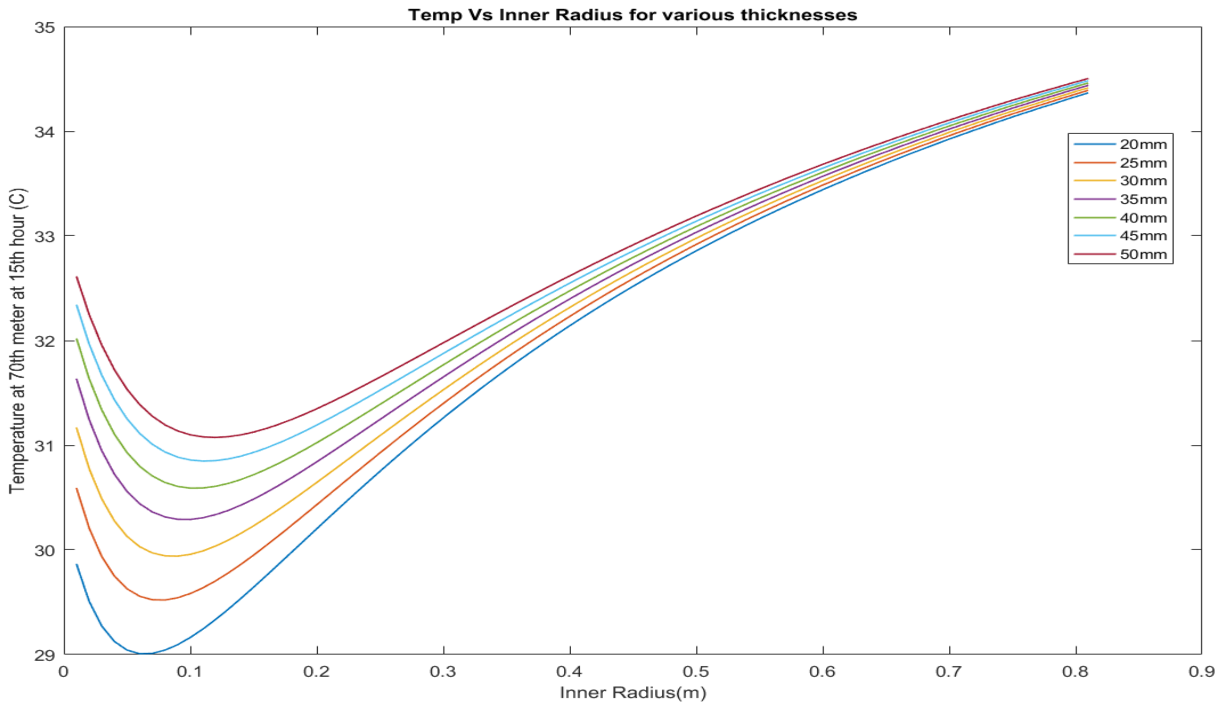

Figure SEQ Figure * ARABIC 3 Temperature Vs. Inner radius for various thicknesses

2. Design Methodology

MATLAB was used to simulate an EAHE. The design contained air model, pipe model and soil model operating over two basic heat transfer equations. The input air temperature, the design parameters and thermal as well as specific heat constants were predetermined.

The heat transfer coefficient was determined using Nusselts number as (Cengel, 2002)

$$h = (Nu \times k3)/2Ri$$

h – Heat transfer coefficient
Nu – Nusselts number
k3 – Thermal conductivity of air
Ri – Inner radius of heat exchanger

The Nusselt number for this case is given by second Putekhov equation (Cengel, 2002)

$$Nu = ((f/8)(Re - 1000)Pr)/(1 + 12.7(f/8)\text{^}0.5 (〖Pr〗\text{^}(2/3) - 1))$$

$$(0.5 \leq Pr \leq 2000\ 3 \times 〖10〗\text{^}3 < Re < 5 \times 〖10〗\text{^}6)$$

Pr – Prandtl Number
Re – Reynolds number

Where friction factor was determined using first Putekhov equation (Cengel, 2002)

$$f = (0.790 \times \square ln\ ln\ (Re) - 1.64)\text{^}(-2)$$

$$〖10〗\text{^}4 < Re < 〖10〗\text{^}6$$

The Reynolds number was calculated using velocity of air in the EAHE.

For heat transfer through air and pipe, hear transfer willbe in the form of convection.

$$Q\dot{}\_conv = h \times A \times \Delta T$$

For heat transfer through pipe and soil, hear transfer will be in the form of conduction.

$$Q\dot{}\_cond = k \times A \times \Delta T/\Delta x$$

The corresponding temperatures can be calculated from the heat balance equation given by

$$Q\dot{}\_out = m\dot{} \times Cp \times \Delta T + Q\dot{}\_in$$

3. Design Parameters of EAHE

Following parameters are studied by using computational fluid dynamic simulation and mathematical model.

a. Inner radius
b. Thickness
c. Length
d. Mass flow rate
e. Conductivity

3.1. Inner radius

All the parameters other than inner radius are maintained constant during simulation. The

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temperature that is recorded for every reading is taken at 70th meter of pipe when a steady state is reached. The mass flow rate of the air is considered constant for this simulation. Thus, the velocity of air is decreasing as the inner radius increases. The mass flow rate is a control parameter; thus, it was preferred to take as constant instead of velocity. i.e. the velocity is a dependent parameter and the mass flow rate is independent. (Refer Figure 3)

- The temperature drops initially with the rise in inner radius for constant thickness.
- The temperature rises logarithmically from minima.
- The plot if extrapolated, will converge and become parallel to the x axis.

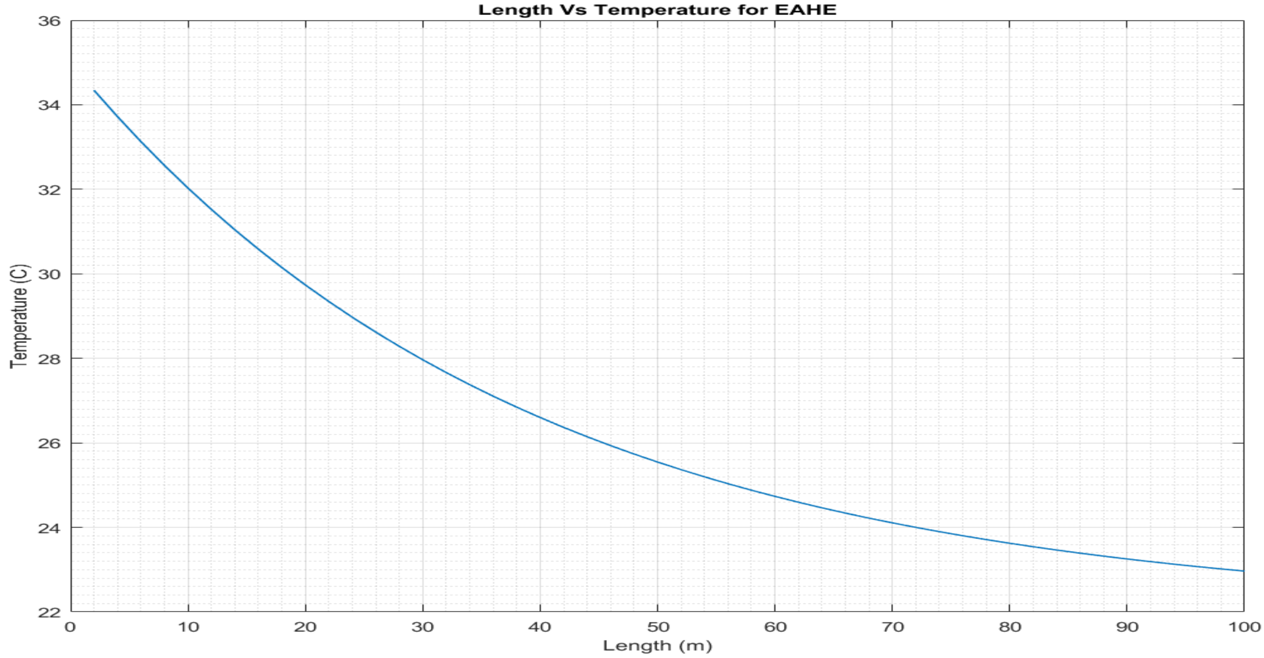

Figure SEQ Figure * ARABIC 4 Temperature Vs. Length

- Initially, due to higher velocity, the heat transfer due to convection at the pipe air boundary is very high for smaller radii.
- However, if the radii are excessively smaller (here less than around 0.1m), the air gets lesser time to exchange heat and thus, less energy is transferred.
- The minimums of the plot are breakeven points of the two conditions viz. Heat transfer due to velocity rates and time of heat exchange.

3.2. Thickness

All the parameters other than thicknessare maintained constant during simulation.The temperature is recorded for every reading is taken at 70th meter of pipe at various thickness when a steady state is reached. The mass flow rate of the air is considered constant for this simulation. (Refer Figure 3)

- The effect of thickness is significant when inner radius is between 0.05m and 0.3m.
- The minimum shifts towards right as the thickness increases.
- The temperature decreases as the thickness decreases for any constant inner radius.
- The effect of thickness is negligible when inner radius is approximately more than 0.3m.

- The plot if extrapolated, will converge and become parallel to the x axis.

3.3. Length

The following plot is prepared from the simulation in which all the parameters are held constant. The temperature of air is calculated from the heat transfer equations. The heat transfer is between the soil and air via pipe. This simulation is performed at constant mass flow rate. The temperatures are as recorded after reaching the steady state. The soil temperature in this case is 25oC. The temperature of air falls exponentially as the air passes through the pipe. But this drop-in temperature decreases with length. The temperature drop converges and becomes parallel to the x axis.
This decrease in temperature drop can be justified by decrease in temperature difference between the air and the soil/pipe surface. (Refer Figure 4)

- As length increases, air get mode time and surface area for heat transfer.
- As length increase, the air temp reaches close to soil temp and rate of heat transfer decreases.
- So, the length of the pipe is the trade off between the effectiveness and cost of the system.

3.4. Mass flow rate

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The Model is simulated to see how the mass flow rate of air affect the outlet air temperature. All the parameters of the model are kept constant except the mass flow rate and the parametric simulation is done.

From the simulation results we can see that as we increase the mass flow rate, the air gets less time for heat transfer with the soil and as a result the overall cooling/heating effect decreases.

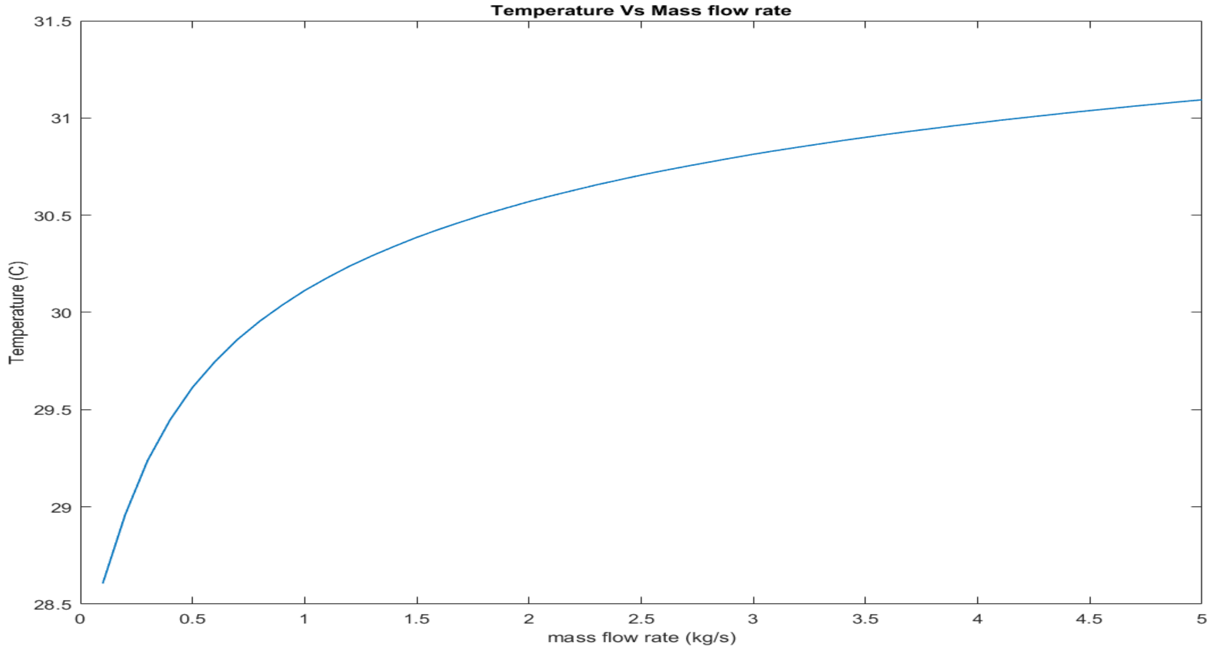


Figure SEQ Figure * ARABIC 6 Transient Analysis of EAHE

Mass flow rate the only parameter which we can control after the complete design of the system, so it serves as control parameter. (Refer Figure 5)

- Mass flow rate can be easily changed by changing the speed of blower after the complete design of EAHE.
- Mass flow rate can be used to remotely change the outlet temperature depending on the comfort level.

3.5. Conductivity

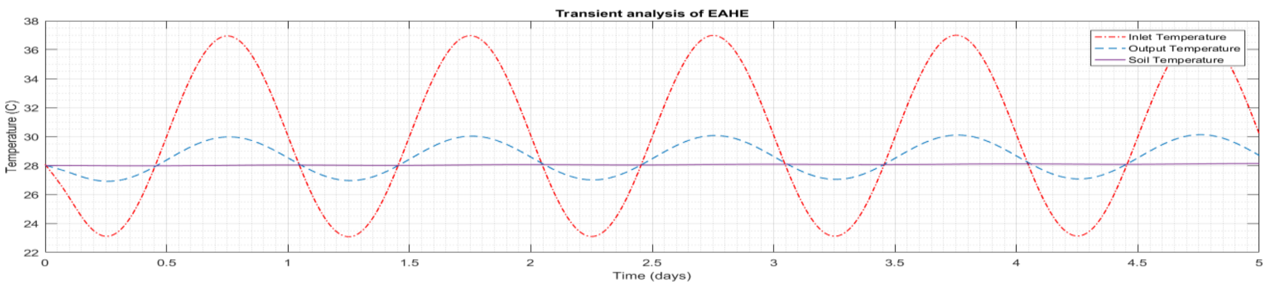
Being an important parameter, the limiting conductivity is that of soil. The effect of heat transfer depends on the equivalent resistance of the soil and the pipe. But as the soil is in infinitely large amounts (by mass and volume) as compared to the pipe, the material of pipe plays a significant role in heat transfer.

Better the conductivity of pipe, lower the resistance for the heat transfer, better the heat transfer and less the temperature at the output.

The difference in conductivities of Iron and steel is significantly high, yet the temperature at output is hardly changing. This is due to the limiting conductivity of soil as said above. The effect of conductivity, thus is only significant in the lower range of conductivities, around 0 to 10 W/mK.

3.6. Transient analysis of EAHE

In transient analysis, the EAHE of length 70m was simulated. The system was modelled with 0.6m diameter cement pipe and 4m diameter soil elements. The daily air variation was assumed sinusoidal with minimum 22^{0}C and maximum 35^{0}C. The model was simulated for 4 days and following results were obtained.



In summer days, the soil temperature increases during the day and this increased temperature can be compensated during the night time when the air temperature is less than the soil temperature.

From the simulation results we can see that the maximum difference between the air inlet temperature and air outlet temperature is 7^{0}C. The temperature of soil increases by 0.02^{0}C per day. (Refer Figure 6)

Conclusions

The air that is flowing through the EAHE, exchange heat with the soil via convection and radiation modes of heat transfer. The direction of heat transfer clearly depends on the temperatures. The temperature at the output is lower than the ambient air temperature in summer and higher than the ambient in winter. The temperature drops(summer)/increases(winter) as the air moves forward along the pipe, though the rate of heat transfer reduces.

Lower radii show better effectiveness with thin pipe (Ri is minimum at ~0.1m). The thickness affects the output significantly for lower values of inner radii (Ri < 0.3m).

The effectiveness increases at lower mass flow rates. Better cooling can be achieved at expense of flow velocity.

Lower thermal conductivities (upto 2W/mK) have significant effect on effectiveness. Higher thermal conductivities don't make much difference.

The soil temperature is affected 0.02^{0}C per day which may change the output over a longer period of time.

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