Design of an Earth Air Heat Exchanger System for Space Cooling in Hot and Dry Climate of Pandharpur, India

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Abstract: *Earth Air Heat Exchanger (EAHE) system is a promising passive cooling technique which uses earth's potential to maintain constant temperature at certain depths throughout year to cool air during summer and vice versa in winter for space air-conditioning. EAHE systems are best suited in hot and dry climatic conditions because EAHE systems in humid areas face challenges of condensation of water and contamination by microorganisms. Commercial Heating, Ventilation and Air Conditioning (HVAC) systems are now installed everywhere because of various standards and guidelines in their installation. EAHE systems lack such standards, installations guidelines and hence have less commercialization, being in their early stages. An effort is made in this paper to design an EAHE system for a lab of SVERI's College of Engineering (Polytechnic) in hot and dry climate of Pandharpur City, India. Heat exchanger calculations are made based on NTU method and a piping layout is created for optimum space utilisation. This system is expected to reduce energy demands for space cooling in educational institutes.*

Keywords: Earth-air Heat Exchanger, Earth's Undisturbed Temperature, NTU, Nusselt number.

1. Introduction

Heat Exchangers are used in Air conditioning systems worldwide for space cooling or heating in both industrial and residential buildings. It is mainly achieved efficiently by vapour compression machines. Various heat transfer enhancement involve the use of surface vibration, change of geometry, various inserts and use of nanofluids [2,3]. Air conditioning systems are worldwide employed for space cooling or heating in both industrial and residential buildings. An earth to air heat exchanger draws ventilation supply air through buried tube .The incoming air being heated in the winter and cooled in the summer by means of earth coupling. System can be driven by natural sack ventilation, but usually require mechanical ventilation. Earth to air heat exchangers are suitable to mechanically ventilated buildings with a moderate cooling demand, located in climates with a large temperature difference between summer and winter and between day and night [4]. Earth tubes are often a viable and economical alternative to conventional central heating or air conditioning systems since there are no compressors, chemicals or burners and only blower are required to move air. These are used for either partial or full cooling and /or heating of facility ventilation air. Their use can help building meet passive house standards. Passive Cooling techniques are gaining importance being pollutant free and low cost which use natural sources and Earth–Air Heat Exchanger (EAHE) system is one of them. Uses of EAHE can contribute to reduction in energy consumption, maintenance cost and toxic pollutants

Earth's undisturbed temperature (EUT) is the temperature of earth at a depth of 3 to 4 m that remains fairly constant throughout the year. The EUT remains higher than ambient air temperature in winter and lower than ambient air temperature in summer. As shown in figure 1, the ambient air is drawn through the pipes of the EAHE buried at a particular depth, moderated to EUT, and gets heated in winter and vice versa in summer. In this way, the heating and cooling load of building can be reduced passively.EAHE require low maintenance and low operating cost.

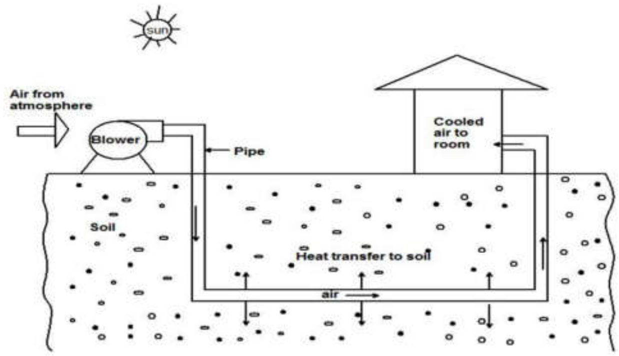

Figure 1:Two-dimensional EAHE model

Bordoloia [5] presented an apprehensible summary of the previous works on EAHE and describes of the analytical and experimental studies on the different combination of EAHE in different locations such as the hot and humid climate of Sahara, cold climate of Australia, tropical climate of Brazil, Mediterranean climate, moderate climate of India etc. EAHE systems in conjunction with the ventilation system and other cooling technique, i.e. hybrid EAHE has become very prominent in today's research as it promotes more energy saving.

Carslaw and Jaeger [6] provided analytical solutions for heat transfer through infinite hollow cylinder and infinite line sources, respectively. The temperature field on the ground can be written as a function depending on time (*t*) and radius I around a line source with a constant heat injection rate (*q*) from a line along the vertical axis of the borehole in an infinite solid.

$$\Delta \mathrm{T} = -\frac{Q}{4\pi k}\mathrm{Ei}\left(\frac{-r2}{4\propto t}\right) \tag{1}$$

The model does not account for ground surface interaction, does not readily account for initial ground temperature gradients, and the line source is also variable along the length of the pipe due to the fluid temperature changing, so this method cannot suitably predict the behaviour along the pipe. An effort is made in studying the behaviour of soil under constant heat flux conditions beneath the ground by DigvijayRonge[1]. Soil is observed to be thermally saturated after a period of time and there is no further heat transfer in soil.

De Paepe and Janssens [7] put forwarded one-dimensional analytical method for parametric analysis of thermo-hydraulic performance of Earth-Air heat exchanger. They considered design parameters like tube length, tube diameter, and number of parallel tubes. The purpose of this model is to evaluate the balance between pressure drop and heat transfer by developing an ε-NTU correlation for the earth tube heat exchanger. A ‘specific pressure drop’ term was used to allow a designer to then calculate required lengths of parallel tubes. The specific pressure drop *J* can be defined as a measure for the pressure drop necessary to realize one unit of NTU.

$$J = \frac{\Delta P}{NTU} \tag{2}$$

De Paepe suggested that multiple smaller diameter tubes in parallel both would lower pressure drop and raise thermal performance. Al-Ajmi et al. [8] developed a theoretical model to predict the outlet air temperature and cooling potential of an EATHE in a hot and arid climate by. It was concluded that if EAHE system is used in conjunction with an air-conditioning system, the energy demands can be reduced. A transient, numerical model was presented by Mihalakakou et al. [9] that predicts the ground temperature at various depths. Kusuda et al. [10] have mathematically modelled the annual sub-surface soil temperature based on heat conduction theory applied to a semi-infinite homogenous solid. Predictions of soil temperature exhibit a sinusoidal pattern due to the annual temperature fluctuation above as shown in eq. 3.

$$T_{z,t} = T_m - A_s * \exp\left[\frac{z}{zo}\right] * \cos\left(\omega\left(t - to\right) - \frac{z}{zo}\right) \quad (3)$$

Liu [11] had established an experimental setup of EAHE in Changsha, a hot summer and cold winter area of China. The effect of different variables, including inlet air temperature, pipe length, operation time on the performance and the influence of EAHE on underground soil temperature were analysed. Thermal saturation time of five days was observed, after which the system was disabled and allowed for self-recovery.

Yusof [12] presented the performance of EAHE based on experimental studies using a laboratory simulator. The simulator system has considered inlet temperatures of air from 31°C to 35°C, ground temperatures from 23°C to 25 °C and the air flow rate ranging from 0.03 to 0.07 kg/s.This concept of design for EAHE simulator in analysing the performance of EAHE has the advantages like no excavation cost involve in digging the soil, quick respond time in changing the variable and high repeatability of the experiment at constant variable.

Bansal et al. [13] developed a new concept of “derating factor” that could relate decline in thermal performance of EATHE under transient operating conditions with respect to steady state conditions in predominantly hot and dry climate of Ajmer, India. CFD-model with experimental results, in FLUENT software were validated. Derating Factor ($\mathrm{DF}_{L,t}$) is defined as the ratio of the deterioration in thermal performance of EATHE under transient condition to the thermal performance under steady state condition.

$$\mathrm{DF}_{L,t} = 1 - \frac{(\mathrm{T_i} - \mathrm{T_o})_{\mathrm{L,t}}}{(\mathrm{T_i} - \mathrm{T_o})_{\mathrm{L,s}}} \quad (4)$$

RohitMisra[14] investigated the thermal performance of EATHE system with dry and wet soil for the climatic conditions of Ajmer (India). A parametric study was carried out to examine the influence of soil moisture variation on the thermal performance of wet soil EATHE system. The thermal performance of EATHE was improved with wet soil during the experimentation as compared to dry soil.

Łukasz [15] validate the EAHE flow performance numerical model prepared by means of CFD software Ansys Fluent by using experimentally obtained flow characteristics of multi-pipe earth-to-air heat exchangers (EAHEs). CFD model of multi-pipe EAHE validated in this paper can be used for simulation of the flow performance of multi-pipe earth-to-air heat exchangers in the process of designing and optimization of the EAHE structures.

N. Rosa [16] numerically assessed the influence of three parameters on the overall thermal performance of an EAHE system for residential buildings in warm-summer Mediterranean climate: spacing between pipes, pipes diameter and air velocity. ANSYS-CFX® was used to simulate the EAHE transient behaviour during heating and cooling operation modes. A validated numerical model was used to perform a parametric study on the effect of three different pipe diameters operating with different air velocities, and the effect of three distances between adjacent pipes, operating with different air velocities and pipe diameters.

Thermal saturation and self-recovery ability of soil under continuous and intermittent operation modes was compared by A. Mathur et al. [17]. Campbell [18] measured thermal conductivity of nine soil minerals samples and studied variation in thermal conductivity caused by temperature, bulk density and soil moisture content. The thermal conductivities increased with increase in temperature, moisture content and bulk density and decrease in porosity. A laboratory experiment was conducted by P. Pramanik and P. Aggarwal[19] with three texturally different soils, compared the thermal properties as influenced by texture, compaction and mineralogical composition of soils. As revealed from their study, thermal properties were highest for black soil followed by alluvial soil and lowest for red soil.

Review of literature shows the experimental and numerical models have proven the EAHE system to be reducing energy requirements for space cooling. Unlike HVAC design process, these reviewed literatures lack design procedure which will guide architectures for including an EAHE system in Building planning and installation of the same. The effect of increased temperature of soil, surrounding the pipes, on EAHE performance is not considered in design calculations which are crucial in determining number of working hours and distance between adjacent pipes. Standard installation guidelines are needed for commercial success of EAHE systems which will help the contractors.

2. Problem Definition

For the present study, the Power Plant Engineering lab of floor area (9.8*6.6) 64.68m^2 and ceiling height 3m, generally occupied by 30 people in SVERI's College of Engineering (Polytechnic) at ground level is selected. The college is situated in Pandharpur city, Maharashtra, India where summer temperatures reach up to 43 °C and 16% relative humidity. The physical and thermal properties for different materials in this study are as illustrated in table 1[13, 19].

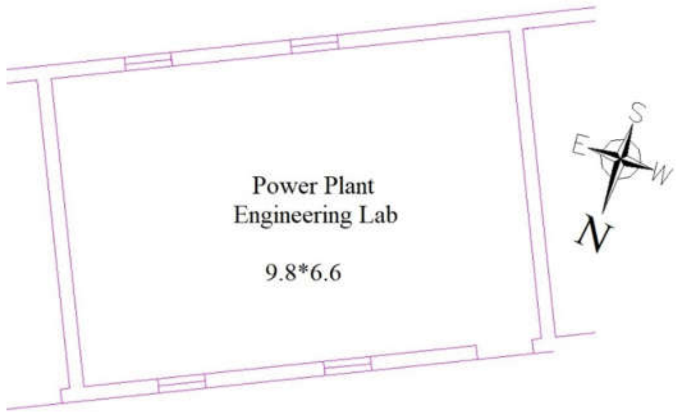

Figure 2: Classroom sketch under EAHE analysis

Table 1. Thermo-physical properties of materials

Material	Density (kg/m^3)	Specific heat capacity (J/kgK)	Thermal conductivity(W/mK)
Air	1.225	1006	0.024
Soil (SL3)	2050	1840	4
PVC	1380	900	1.16

2.1 Calculation of Parameters:

From ASHRAE climate data 2017 [23], for mean Temperature, T_{mean} = 28°C and design conditions (for 1% Peak condition) DBT = 40°C, MCWB = 22.8°C, a room condition of DBT = 30°C is selected.

A pipe of diameter 150mm and thickness 7mm (STD schedule of pipes for 6in) is selected for carrying air at velocity of 4 m/s. The other parameters such as heat transfer coefficient (h), length of pipe (L), etc. are calculated with NTU method for heat exchangers [7, 21].

2.2 Selection of Pitch (P):

The distance between centers of two adjacent pipes, as we've referred as Pitch (P), is taken 1 meter with reference to the EAHE model of R. Mishra [12].

2.3 Selection of depth:

Temperature variation with depth (z) underground is given by [10]

$$T_{z,t} = T_m - A_s * \exp\left[\frac{z}{zo}\right] * \cos\left(\omega\left(t - to\right) - \frac{z}{zo}\right) \quad (5)$$

Where:

i. $T_m = T_{mean}$ = Mean surface temperature = 28°C (ASHRAE climate data [19])
ii. A_s = Maximum Annual Amplitude of surface temperature = 8°C (Average temp in the month of May = 33.1°C [ ])
iii. α_s = Thermal diffusivity of the ground (soil) = 0.203 m^2 /day
iv. Day of min temperature, t_o = 10^{th} Jan
v. t = current time (day) in hours = 141 (21^{th}March 2017)
vi. Angular frequency , $\omega = \frac{2\pi}{365}$; Damping depth , $z_o = \sqrt{\frac{2\alpha_s}{\omega}}$

With given parameters, following table 3 illustrates temperature variation with depth for the selected date of the year in Pandharpur city.

Table 2. Temperature variation with depth

Depth (m)	Underground Temperature (°C)
1	30.3
2	28.7
3	27.6
4	26.8
5	26.3

As we have assumed $T_{wall} = T_{mean}$, a depth of 3 - 4meters can be selected.

2.4 Calculation for Length (L) based on NTU method [8][9]:

i. Design conditions:

$T_{air,out}$= Room DBT= 30°C; $T_{air,in}$ = Outdoor DBT= 40°C; T_{wall}= T_{mean}= 28°C
D = 150 mm, v = 4 m/s

Here, the kinematic viscosity of air (ν) is calculated [8] using Eq. (8):

$$\nu = 10^{-4}(0.1335 + 0.000925T_a) \quad (6)$$

Here, $\nu = 1.7e\text{-}5\ m^2/s$

ii. Reynolds's no.,

$$R_e = \frac{VD}{vair} \quad (7)$$

=35294.11

Friction factor,

$$f = (1.82*\log Re - 1.64)^{-2} \quad (8)$$

= 0.0227

iii. Nusselt number

$$N_u = \frac{\frac{f}{8}*(R_e - 1000)*P_r}{1+12.7*\sqrt{\frac{f}{8}}*(P_r^{\frac{2}{3}}-1)} \quad (9)$$

= 69.60 for P_r= 0.71

iv. Heat transfer coefficient (h):

$$Nu = \frac{hD}{k_{air}} \quad (10)$$

➔h = 11.13 W/m^2K

v. NTU calculation:

$$\varepsilon = 1 - e^{(-NTU)} = \frac{T_{air,out} - T_{air,in}}{T_{wall} - T_{air,in}} \quad (11)$$

= 0.833

Therefore, NTU = 1.79

vi. Calculation for overall heat transfer coefficient (U):

Radius of soil domain (r_2) is assumed as twice of radius of pipe [8] and pipe thickness is neglected.

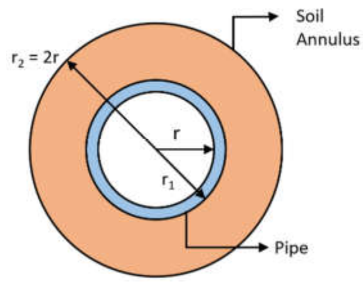

Figure 3: Earth–air heat exchanger (EAHE) system with the layers is shown in cross-section.

$$\text{Thermal resistance, } R_{th} = \frac{1}{h} + \frac{r ln\left(\frac{r1}{r}\right)}{k_{pipe}} + \frac{r_1 ln\left(\frac{r_2}{r_1}\right)}{k_{soil}} \quad (12)$$

= 0.1053

$$U = \frac{1}{R_{th}} = 9.49 \text{ W}/m^2K$$

vii. Calculation of Length

$$\text{NTU} = \frac{U * A_s}{\dot{m}_{air} * c_{p,air}}; \quad (13)$$

$$\text{Surface area, } A_s = \pi D L \quad (14)$$

$$\text{Mass flow rate, } \dot{m}_{air} = \rho_{air} * A * V \quad (15)$$

Therefore L = 34.86 ~ 35 m

2.5 Pressure drop (Δp)

The pressure difference and the power required to pump the air through the earth air heat exchanger is given by [20]

$$\Delta p = f * \left(\frac{\dot{m}_{air}}{\rho_{air}}\right) * \left(\frac{L}{D}\right)^3 \quad (16)$$

= 20383.96 Pa

This pressure drop often increases due to contamination of dust and other particles, pipe bends, fittings, blower outlet, filters, supply diffuser outlet, etc.

Considering all these losses as 15% of Δp, Total Δp_{tot} ~ 23441.5 Pa

2.6 Air Fan Power (AFV)

The fan energy consumed in blowing air through a pipe is additional energy expenditure in the EAHE system. The fan air power is given by [20]

$$P_f = \frac{\Delta p_{tot} * q}{\eta_{fan}} \quad (17)$$

Where Δp_{tot} is the fan total pressure difference, q is volumetric flow rate and η_{fan} is fan total efficiency which may be expressed as the ratio of total air power to the shaft power input.

Assuming 85% fan efficiency (η_{fan}), P_f = 1949.39W ≈ 2kW

This power will be consumed to overcome pressure losses. Hence Fresh air blower for introducing fresh air into EAHE system is selected for flow rate of 148 CFM and power of 2kW. A Variable Frequency Drive (VFD) can be installed along with blower for controlling air flow according to requirement.

2.8 Trench sizing:

For a given length of pipes and pitch value and with allowance for installation, a trench of (6x6)m size and 4m deep underground should be made nearer to the lab for ease of installation.

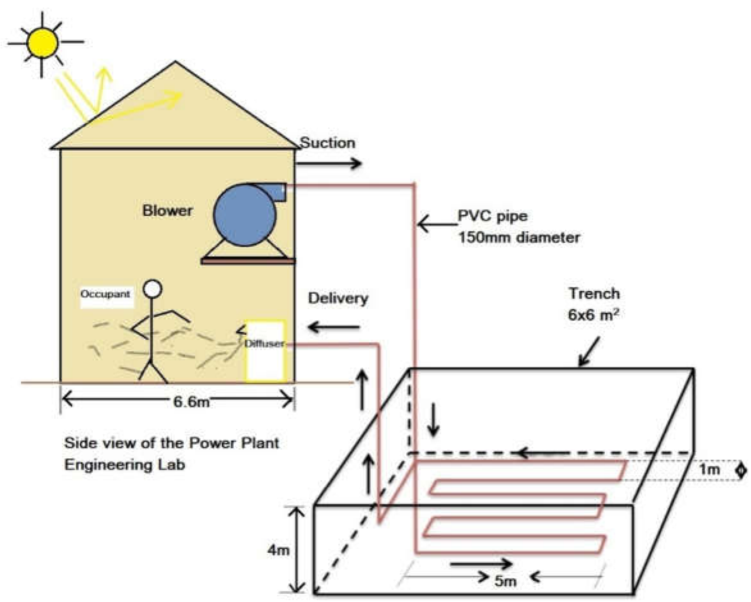

Figure 4: Planned schematic of EAHE system for the lab

3. Conclusion

In this paper the authors have reported the design parameters and the calculations useful for design of EAHE systems. These calculations are applied to hot and dry climate of Pandharpur city. With assessment of ASHRAE weather data and NTU method of heat exchangers, we were successful in designing the system of PVC pipe of 100 mm diameter of 35 m length placed in serpentine manner and air blown at 4m/s. The same system can work in winter conditions space heating, when the T_{mean} will be greater than $T_{air,in}$. Such

EAHE systems will provide alternative to commercial HVAC systems and make most of natural resources for space cooling.

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