An earth-air heat exchanger under installation

Geothermal Earth Heat Exchanger

Raji Panicker Senior Design Lead Mechanical, CH2M, Mumbai

Abstract

An earth to air heat exchanger (EAHE) utilizes the thermal mass of the soil surrounding or beneath the building in order to pre-heat or pre-cool incoming ventilation air. With the ground's large thermal capacity and relatively stable temperature, outdoor temperature variations are dampened and ventilation heating and cooling loads are reduced. This study emphasises earth-air heat exchangers, which are a promising technology for passive heating/cooling of buildings. Several research papers have been published in which sophisticated design equations are given, which cannot be easily implemented. This study presents a simplified analysis of design equations that has been validated with Computational Fluid Dynamics (CFD) at an early stage of EAHE design, and can be implemented through a spreadsheet. The equation allows calculation of undistributed ground temperature throughout the year, length of the tube required for heat transfer effectiveness, and pressure drop and temperature of air exiting the tubes. The location – Bangalore – has been considered in this study due to its high temperature amplitude.

About the Author

Raji Panicker has 17 years of experience in HVAC Design, Construction and Project Management, and is currently working with CH2M as Senior Design Lead Mechanical. He is a LEED AP BD+C professional from Green Building Certification Institute (GBCI), CEng (UK) and a member of USGBC and MIET.

Nomenclature

P = Air fan power (W)
Cp = Specific heat of air (J/kg-K)
d = Depth of tube (m)
f = Fluid flow friction factor
h_c = Convective heat transfer coefficient from air to tube wall (W/m²-K)
K_t = Thermal conductivity of tube (W/m-K)
K = Thermal conductivity of air (W/m-K)
L = Length of tube
m = Mass flow rate of air (kg/s)
NTU = Number of heat transfer unit
n = Number of parallel tube
Nu = Nusselt number
Δp = Pressure loss (pascal)
Re = Reynolds number
r_i, r_o = Inlet and outlet diameter of tube (m)
U_t = Overall heat transfer coefficient (W/m²-K)
v = Velocity of air (m/s)
V = Total volume flow of air (m³/s)
ε = Effectiveness of EAHE system
ρ = Density of air (kg/m³)
μ = Dynamic viscosity (N-s/m²)

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Introduction

Since the industrial revolution, the rate of growth of human population and the associated annual per capita energy consumption have been exponential (Glassley, 2010). Geothermal energy is a versatile and near inexhaustible resource capable of satisfying these needs. Geothermal energy can be used for provision of heating, ventilation and air conditioning (HVAC) in residential, commercial and industrial buildings as well as for power generation (de Moel et al., 2010, Johnston et al., 2011, Glassley, 2010).

The earth heat capacity for air conditioning buildings is improved in regions where there is a huge temperature amplitude along a day period or seasonally. The ground is regarded as a large reserve of solar energy. Its heat capacity is so high that the diurnal variations of the surface soil temperature do not penetrate more than 1m, and the annual fluctuation of the earth temperature extends to a depth of 9 to 10 meters. Beyond this depth, the temperature of the ground remains constant.

In summer, with a depth of a few meters, the temperature of the ground is always below the average ambient temperature, and is particularly below the temperature of the air. As a result, the soil has the potential to serve as a cooling source for buildings. Further, it is possible by very simple means to lower the temperature of the earth well below its normal temperature. The cooling surface, where the temperature of the soil surface is lowered, induces a significant reduction in the temperature of the mass of earth which is below the surface.

Ventilation

An EAHE takes advantage of the high subterranean thermal capacity to obtain more comfortable temperatures, close to annual average temperature of the region. This is not a new technology and was used in the 1st century in the Middle East (Oleson, 2008), where air was cooled in *qanats* used to transport water. The ground heat exchanger (GHE) consists of a length of pipe buried at reasonable depth below the ground surface, and uses the earth as a heat source (in the winter) or a heat sink (in the summer). This design takes advantage of the moderate temperatures in the ground to boost efficiency and reduce the operational costs of heating and cooling systems. Ground-source heat exchangers provide a new and clean way of heating buildings. They make use of renewable energy stored in the ground, providing one of the most energy efficient ways of heating/cooling a building. Vast research has been conducted in the past to develop methods to analyze EAHE. Software like TRNSYS, Energy Plus and CFD are recommended to analyze the suitability of EAHE for buildings, but these are time consuming. Instead, using simplified design equations that help inform the technology potential and determine basic component sizing can be used.

There are two types of EAHE systems: (1) open loop system in which ambient air is drawn and sent to a specified location after the heat exchange process, and (2) close loop system in which room air is recirculated for heat exchange. There are several parameters that affect the design and performance of the EAHE system: (1) design parameters (tube depth, length of tube, diameter of tube, flow velocity of air, tube material, etc.); (2) climate condition (relative humidity, ambient air temperature, undisturbed soil temperature, etc.); (3) soil properties (thermal diffusivity, thermal capacity, etc.); and (4) convective heat transfer coefficient. Heat transfer between soil and air also depends on surface area of tube, and is affected by thermal resistance of tube diameter. We include the most recently developed correlation to find effective length of tube, tube diameter, pressure drop and effectiveness of EAHE system. The simple EAHE diagram is shown in *Figure 1*.

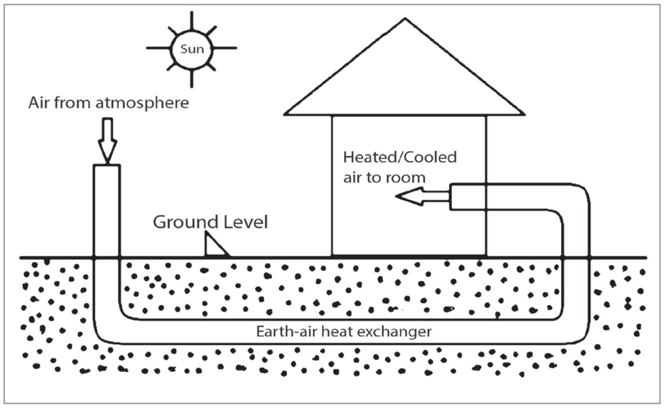

Figure 1: Earth heat exchanger

Design Parameter Modeling

Development

In the case of EAHE system, we have decided that we will consider the location as known, which means the outside air temperatures throughout the year and the basic soil conditions are known. We assume the designer has selected an air volume flow rate through the EAHE. This choice would usually be dictated by the ventilation requirements of the building. We further assume that the designer has selected a basic tube size and material for use in the EAHE; this selection sets the inner and outer radius of the tube, as well as its thermal properties. Although tube diameter could have been allowed to be a design variable, in most cases designers will be selecting from a fairly fixed set of tube sizes, so the tube size is considered a fixed input. In addition, the number of tubes used in the system is also a fixed input. Selecting the best combination of tube diameter and number of tubes may involve a little trial and error on the part of the designer; however, because the number of combinations is limited, we think the choice of inputs is still well suited to preliminary design.

Assumptions

To simplify the design equations, the following assumptions are made:

- Temperature of surrounding soil of tube is constant (uniform temperature in axial direction); earth ground temperature (EGT) is constant along the length of tube.

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- Turbulent flow of air throughout the tube so that entrance length is small in the small size tube.
- Surface temperature of the ground is taken as ambient air temperature, which is equal to inlet air temperature.
- Thermal resistance of pipe is negligible.
- Temperature on surface of tube taken as uniform in axial direction, equal to earth's undisturbed temperature.
- Uniform cross-section of tube with smooth surface on inner side.
- Thermo-physical properties (density, viscosity, thermal conductivity and specific heat capacity, etc.) of air and soil are constant.

Earth Ground Temperature

Soil temperature undergoes a daily cycle, and an associated cycle with the weather variations in addition to an annual cycle. These variations are restricted to the layers close to the surface. To evaluate the temperature of the ground, the soil is regarded as a semi-infinite solid. It is expressed according to depth and time. When surface temperatures are known, the soil temperature to a given depth can be estimated. The following equation from ASHRAE District Cooling Guide has been used to calculate the temperature at depth z and time t for homogeneous soil of constant thermal diffusivity:

$$T_G = T_m + A_s exp^{-z\sqrt{\frac{\pi}{365\alpha_s}}} sin \frac{\left(2\pi(t - t_{lag}\right)}{365} - z\sqrt{\frac{\pi}{365\alpha_s}} \quad (1)$$

T_G is the mean annual surface temperature at time t (s) and depth z (m), T_m is the average soil surface temperature (°C), A_s is the amplitude of soil surface variation (°C), α_s is the soil thermal diffusivity (m^2/day), t is the time elapsed from beginning of the calendar year (day), and t_{lag} is the phase constant of soil surface (days). Values for the climatic constants T_z, t, A_s, and t_{lag} are available from ASHRAE Handbook – Fundamentals, Climatic Data or Appendix B, 'Climatic Constant' can be referred from ASHRAE District Heating Guide.

It is very difficult to accurately calculate the value of earth's undisturbed temperature because the soil parameters are often unknown. Additionally, it is defined for mean soil properties. Hence, earth's undisturbed temperature is a hypothetical value that can be taken equal to annual average soil surface temperature of a particular locality. The soil surface temperature is assumed equal to the ambient air temperature.

Air Flow

The geometric parameters of an EAHE include the tube diameter (D), tube length (L) and number of tubes in parallel (n) in the heat exchanger. First we select an arbitrary size (D) of tube and then with the help of the known volume flow rate (V), the number of tubes (n) in parallel and mass flow rate are calculated. We have to select the optimum combination of size and number of tubes to meet EAHE performance. For a tube radius (r_i), air density (ρ), air flow velocity (v) and number of parallel tubes (n), the mean velocity of the air in one of the heat exchange tubes v will be:

$$\text{v} = \frac{V}{n\pi {r_i}^2} \quad (2)$$

and the mass flow rate in one of the tubes, m will be:m

$$m = \rho \text{v} \pi {r_i}^2 \quad (3)$$

Heat Transfer

If the dimensions of EAHE system are known, calculation of the heat transfer rate can be done either by using the log mean temperature difference (LMTD) method or the ε–number of transfer units (NTU) method. In this article, the ε–NTU method is used. The outlet temperature of air was determined by using effectiveness of EAHE (ε), which is a function of NTU.

The equation can be referred back to ASHRAE Fundamentals 2013 or BS EN 15241:2007.

The overall heat transfer coefficient per unit length from the soil to the air in the tube, U_t, is given by

$$U_t = \frac{1}{\left(\frac{1}{h_c} + \frac{1}{2\pi k_t}\ln\frac{r_o}{r_i}\right)} \quad (4)$$

Where k_t is the thermal conductivity of the tube, r_o and r_i are the outer and inner radii of the tube, and h_c is the convective heat transfer coefficient from the inside of the tube to the air. This equation assumes that the thermal resistance between the soil at temperature T_G and the tube is negligible.

To find h_c, we use the standard form for forced convection heat transfer coefficient, where Nu is the Nusselt number, K is the thermal conductivity of the air and D the hydraulic diameter of cross section:

$$h_c = \frac{Nu\,K}{D} \quad (5)$$

For this work, we compute Nu using ASHRAE 2013 Fundamentals 2013 – heat transfer forced convection correlation, which gives:

$$Nu = \left(\frac{\frac{fs}{8}(Re - 1000)Pr}{1 + 12.7\sqrt{\frac{f}{8}}\left(Pr^{\frac{2}{3}} - 1\right)}\right) \quad (6)$$

For turbulent flow, Re > 2300,

Laminar flow Nu = 3.66 for Re < 2300.

Where Re is the Reynolds number for air flow in tube, Pr is the Prandlt number of air and f is the friction factor.

The friction factor we use here is the newly developed correlation of Ghanbari et. al. (Ghanbari et al., 2011), which gives f as:

$$f = \left(-1.52log\left(\left(\frac{\epsilon/D}{7.12}\right)^{1.042} + \left(\frac{2.731}{Re}\right)^{0.9152}\right)\right)^{-2.619} \quad (7)$$

where ϵ is the roughess factor, which can be significant as f, Nu and h_c can change by a factor if the design changes from smooth PVC to rough concrete tubes.

The Reynolds number is calculated using the average air flow velocity (v) and diameter D of the tube:

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$$Re = \frac{\rho v D}{\mu} \quad (8)$$

The Prandtl number is defined as:

$$Pr = \frac{\mu\, C_p}{K} \quad (9)$$

where C_p is the specific heat of air.

Once U_t has been computed, the outlet temperature of the air leaving the EAHE system can be estimated as a function of tube wall temperature and inlet air temperature using the equation:

$$T_L = T_G + (T_{in} - T_G)e^{-\frac{h\,A}{m\,C_p}} \quad (10)$$

The monthly average, T_L can be obtained by using monthly average temperatures in *Equation 10*. The instantaneous rate of heat transfer from the ground to the air in each tube, Q_t, is then given as:

$$Q_t = m\, C_p(T_{in} - T_L) \quad (11)$$

Non-dimensional heat transfer unit, NTU is defined as,

$$NTU = \frac{h_c A}{m\, C_p} \quad (12)$$

where $A = 2\pi r_i L$.

The efficiency of EAHE is defined as

$$\varepsilon = \frac{T_L - T_{in}}{T_G - T_{in}} = 1 - e^{-NTU} \quad (13)$$

Finally, the pressure drop, Δp, at the end of the tube will be

$$\Delta p = \rho\, f \frac{v^2}{4 r_i} L \quad (14)$$

Because tubes will also have bends, the pressure drop from the bends is not included. However, the designer can include this in the estimate, which can be for a right angle. The fitting equivalent length can be obtained from ASHRAE Fundamentals.

Design Equation

Design equations are derived from the above relations. For estimating the length of tube and pressure drop across the tube, we know the value of total volume flow rate, size of tube, depth at which tubes are placed and number of parallel tubes.

Equation 13 is easily inverted:

$$NTU = -\ln(1 - e) \quad (15)$$

The effectiveness of the heat exchanger is determined by the dimensional unit NTU. *Figure 2* shows the effect of NTU on effectiveness. Increase in NTU increases the effectiveness though the rapid curve flattens; after NTU > 3, the relative gain is small.

The required length of tube can be determined from the derived value of NTU using the relation:

$$L = \frac{m\, C_p}{2\pi\, r_i\, U_t} \quad (16)$$

The pressure drop is computed from Equation 14, and the fan power required to move V volume of air across the total pressure drop is calculated as:

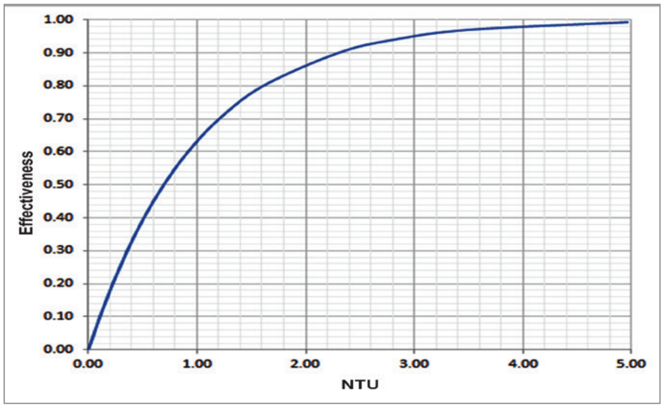

Figure 2: NTU v/s effectiveness

$$P = V\Delta p \quad (17)$$

Example

In *Figure 3*, Bangalore has been selected to show the undistributed ground temperature calculated as per the above equations. The graph generated in *Figure 3* is for temperature versus Julian days at different depths ranging from 1.5m to 9m. It is apparent from the data that the amplitude of the temperature swing drops with depth.

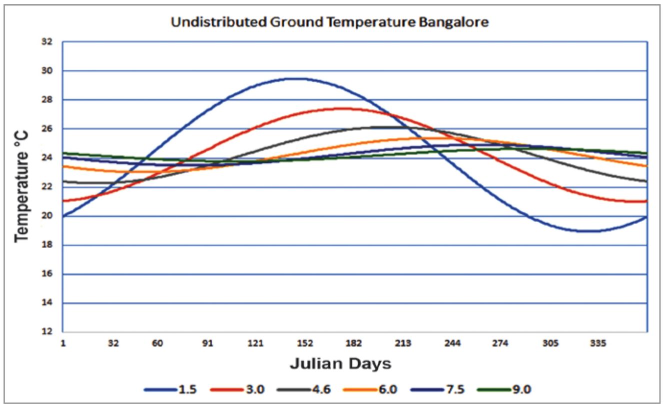

Figure 3: Plot for soil temperature swing at depths d = 1.5m to d = 9m for Bangalore

Figure 4 is an output of EAHE at 9m depth, length 42m with a radius of 400mm, when the material used is concrete pipe with an NTU of 1.6 and 85% effectiveness. The concrete pipe has a thicker wall but has a higher thermal conductivity and increased surface roughness, which result in a slightly higher overall friction, Nusselt and overall heat transfer coefficient, resulting in lower length as compared to other materials.

It is well known that a CFD solution includes detailed information of the flow variables at each grid. It provides numerical solutions of partial differential equations governing fluid flow and heat transfer in a discretized form. In this study, to examine the airflow leaving temperature and heat transfer processes in an EAHE system, CFD was used to validate the output of design result. In CFD analysis

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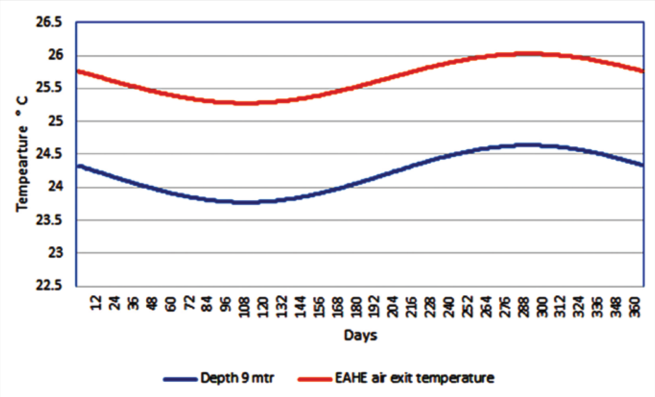

Figure 4: Analysis of ground temperature with respect to air leaving EAHE at 9m depth

it was assumed that the ground temperature is uniform along the axial length, the ground is homogenous and maintains constant temperature at 25°C with a flow rate 1 m³/s. Other parameters remain as given above. The outputs of the analyses, which have been done along the length of the tube for pressure (pascal), velocity (m/s) and temperature (°C), are shown in *Figure 5, 6,* and *7*.

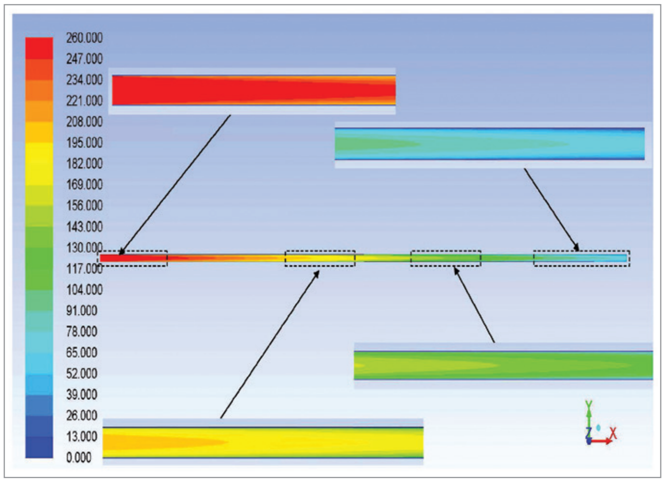

Figure 5: Contours of total pressure drop across the tube

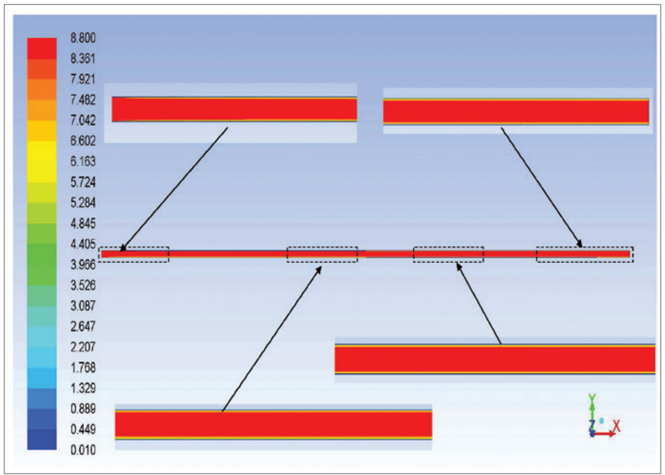

Figure 6: Contours of velocity profile across the concrete tube

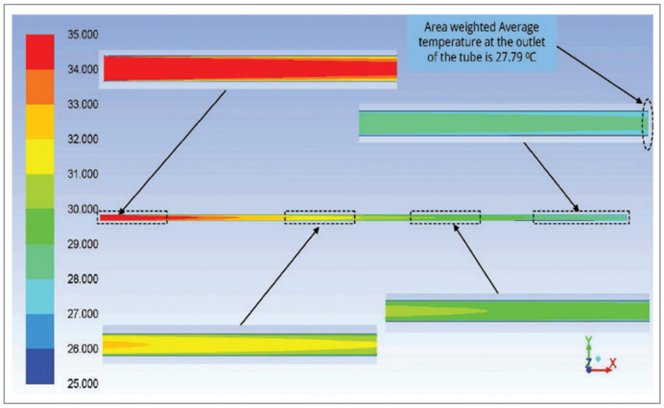

Figure 7: Contours of internal temperature across the concrete tube

The comparison chart for CFD with respect to calculation are given in *Table 1*.

Table 1: CFD versus calculated parameters

Parameter	CFD	Calculated
EAHE air leaving temperature from the tube	27.79°C	27°C
Total pressure	209 Pascal	196 Pascal
Heat transfer from soil to air	8778 watt	9849 watt

Conclusion

A set of simplified equations has been shown, which can be implemented through a spreadsheet for earth-air heat exchangers (EAHE). Heat transfer rate has been captured by the equation from the side of the tube, and a recent correlation of friction and Nusselt number has been used. The results of the equation, when implemented through an excel sheet, are shown in the charts. The designer can carry out a set of calculations as per the equations shown.

The modeling design analysis predicts the monthly average and instantaneous heat transfer performance, the system pressure drop and the required air fan power once a tube length has been selected. The importance of including heat transfer through the sides of the tube and heat transfer correlations that include surface roughness was shown in this simplified method, which will impact the performance of heat exchanger.

The results obtained in CFD analysis for velocity, total pressure, temperature and total heat transfer from air to tube were compared in *Table 1*. It can be seen that the difference in parameters is between 10 and 15%. In CFD the length has been kept constant; however in the above equation the length is calculated. The number of tubes can also be in parallel to reduce the length once the desired output temperature has been achieved.

Hence, geothermal heat exchange for ventilation presents a significant opportunity to reduce the growing energy demand and its impact on the environment.

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