Design of earth-air heat exchanger for air colling

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1 INTRODUCTION

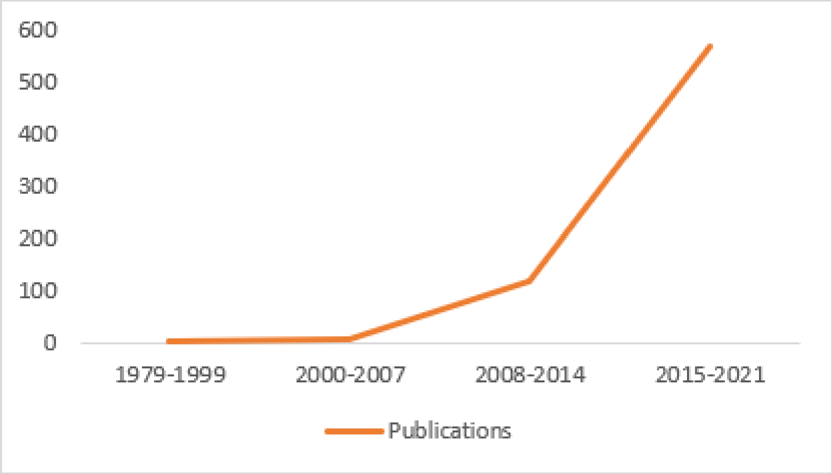
The steady increase in environmental degradation and the future exhaustion of non-renewable energy sources drive the search for clean energy production and improved conversion efficiency. Renewable energy resources are water, solar, wind, biomass, geothermal, ocean, and hydrogen. These sources are also called "clean sources", as they emit fewer greenhouse gases and are the best alternatives to the environment compared to non-renewable counterparts.

Geothermal energy comes from the heat generated inside the planet Earth or the quasi-stable temperature of the solid throughout the year. Geothermal systems have a wide range of applications, especially for the cooling and heating of buildings. It can be used in all seasons of the year and anywhere in the world (Kalogirou, 2016).

An earth-air heat exchanger (EAHE) is a specific application of geothermal systems, accomplished by passing hot/cold air through tubes buried deep in the ground (Mihalakakou et al., 2022). The EAHE system transfers heat between the ground and the air that circulates through the buried pipes, thus using the relative low/high ground temperatures for heating or cooling. The EAHE system is normally installed using 30-60m of horizontal pipe buried at 2-4m ground level (Ascione et. al, 2011). The tubes are slightly angled to remove water condensation during operation.

Geothermal exchanger systems have been studied since the 1970s, with the first publication found in 1979. When analyzing the number of publications in the Scopus database, it is noted that this area of research has remained stagnant and almost non-existent for almost 30 years. It is notorious for its growth in the last 14 years, with the period between 2015 and 2021 responsible for most of the publications.

Figure 1. Publications about geothermal systems



Most of the studies deal with the cooling and heating of buildings, automated or integrated with other forms of energy transformation. Alibaba et. al (2020) carried out a technical-economic analysis of a hybrid Geothermal-Solar cycle for the air conditioning of a building. Another application was investigated by Hegazi et. al (2021), who integrated the geothermal system into an HVAC for building thermal comfort. Bansal et al (2009, 2010) evaluated the performance of the EAHE system for summer and winter climatic conditions such as in western India. Lakzini et. al (2015) modeled and designed an air-to-ground heat exchanger and evaluated the savings in energy consumption, in Moroccan meteorological conditions, applied to poultry sheds. Studies have proven the efficiency of the EAHE system in reducing electricity consumption and the emission of harmful gases into the atmosphere.

In this study, the air-cooling potential was evaluated through metallic tubes buried in the ground. Applying heat transfer relations, it is possible to estimate the viable length and the exit air temperature of the system. The heat transfer equation was solved using the Engineering Equation Solver platform.

2 METHODOLOGY

Ground temperature

The solar radiation, upon reaching the planet's surface is also absorbed by the ground, which heats up during exposure and releases heat into the atmosphere at night. However, due to its large amount of mass, this process is slow and is called thermal inertia. The purpose of the EAHE system is to delay temperature peaks and insufflate air with a temperature closer to that of the ground, which can be cooler or hotter than the environment.

The heat exchange capacity of the soil depends on its properties, such as conductivity, composition, specific heat, and thermal diffusivity. Considering that the soil thermal diffusivity constant is homogeneous, the soil temperature at a depth z and time t can be estimated using Eq. (1) (Hegazi et. al, 2021):

$$T_{ground} = T_m - A_s \, exp\left[-z\left(\frac{\pi}{365\alpha_s}\right)^{\frac{1}{2}} cos\left\{\frac{2\pi}{365}\left[t - t_0 - \frac{z}{2}\left(\frac{365}{\pi\alpha_s}\right)^{\frac{1}{2}}\right]\right\}\right] \quad (1)$$

where α_s is the thermal diffusivity of the soil (m^2/s), A_s is the thermal amplitude of the soil surface (°C), *z* represents the depth at which the tube is buried (m), t_0 is a phase constant of soil surface temperature (days) and *t* is selected day of the year.

Internal Flow

In Nellis and Klein (2009) it is possible to find a set of useful correlations for heat transfer processes. These correlations can be used to solve a wide range of engineering. For the EAHE tube the flow condition is determined by the Reynolds number (Re) based on hydraulic diameter, according to Eq. (2):

$$Re = \frac{\rho u_m D}{\mu} \quad (2)$$

where ρ is the specific mass of air (kg/m^3), one is the mean velocity of the fluid in the cross-section (m/s), D is the inner diameter of the tube (m), and the dynamic viscosity (Pa·s).

In a fully developed flow, the critical Reynolds number which corresponds to the appearance of turbulence is approximately 2300. Turbulence intensifies the thermal exchange and is the recommended regime EAHE system.

Nusselt number (Nu) is the main parameter for heat transfer process analysis. The system boundary condition for EAHE pipes is that of constant tube wall temperature, which matches that of the soil layer around the pipeline.

There are some simple correlations in the literature to calculate the Nusselt number. However, they can have errors of around 25%. These errors can be reduced to less than 10% using more complex but more precise relations, such as the modification of the second Petukhov equation (Çengel, 2008), expressed by Eq. (3), which Pr is the Prandtl number, a property related to the temperature of the fluid. Equation 3 is valid when $0.5 \leq Pr \leq 2000$ and $3x10^3 \leq Re \leq 5x10^6$.

$$Nu = \frac{\left(\frac{f}{8}\right)(Re - 1000)Pr}{1 + 12{,}7\left(\frac{f}{8}\right)^{0{,}5}\left(Pr^{\frac{2}{3}} - 1\right)} \quad (3)$$

With the Nusselt number, the mean convection coefficient ($\bar{h}$) is given according to Eq. (4), in W/m^2K, where k represents the thermal conductivity of the material (W/m·°C):

$$\bar{h} = \frac{Nu \cdot k}{D} \tag{4}$$

In turn, the energy balance defined by the first law of thermodynamics expresses that the amount of energy that leaves the tube must equal that of the input and possible heat and work interactions with the environment. In Eq. (5) $\dot{m}_{air}$ represents the air mass flow, and h_{in} and h_{out} are the enthalpies of the air at the entrance and exit of the tube:

$$\dot{Q}_{pipe} = \dot{m}_{air} \cdot (h_{out} - h_{in}) \tag{5}$$

By manipulating the energy balance equation, it is possible to obtain the air exit temperature (T_{out}), according to (Hegazi et. al, 2021):

$$T_{out} = T_{ground} + (T_{in} - T_{ground})exp\left(-\frac{L}{\dot{m}_{air} C_p R_t}\right) \tag{6}$$

when L represents the tube length, C_p is the thermal conductivity of the air, R_t is the value of the total conduction resistance, and T_{in} is the inlet temperature of the air.

In convection problems, the surface temperature of the tube is unknown, instead, the material that surrounds it. In this study, the tube wall temperature will be considered constant and equal to the surrounding soil temperature.

3 CONCLUSION

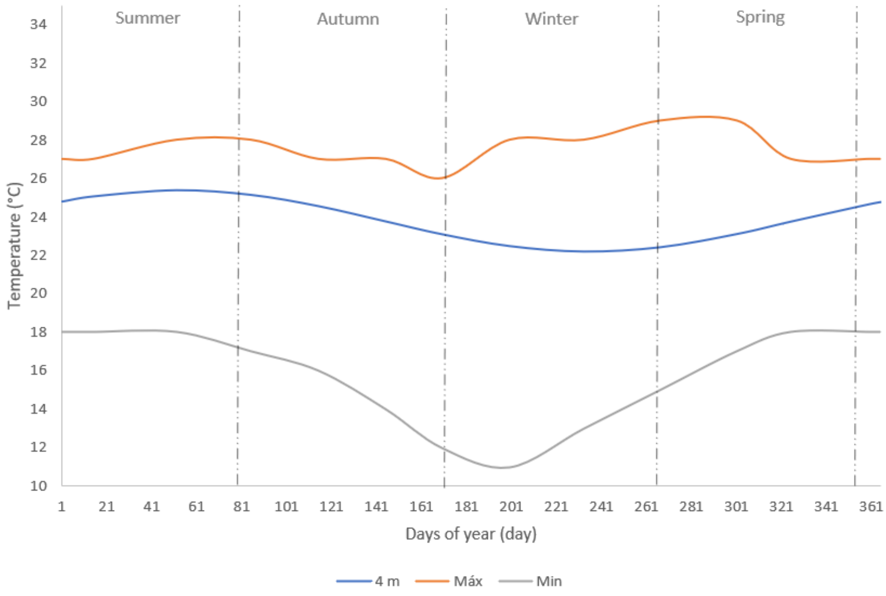
The aim is to simulate the cooling mode of an EAHE installed in Brasília-DF, in the center-west region of Brazil. This system consists of a long metallic tube. The nominal diameter of the pipe is 0,2 m and the wall thickness is 3 mm. It is buried at a depth of 4 m below the surface. The annual average soil temperature at this depth is 23,8°C. The temperature of inlet air is 33°C.

Soil Temperature Profile

The surface layers are the first to heat and cool, this makes the temperature variation very large. As the depth increases, the inertia becomes greater and the thermal exchange becomes slower, which causes the temperature at depth to be “delayed” about the surface (Oliveira and Monteiro, 2008).

In Figure 2, it is possible to analyze the soil temperature profile, at a depth of 4m, compared with the monthly averages of maximum and minimum temperature in the region of Brasíia/DF (National Centers for Environmental Information, 2022), throughout the year and its seasons. It is remarkable that even in seasons with large temperature variations, the soil temperature remains constant and varies by approximately only 3°C throughout the year.

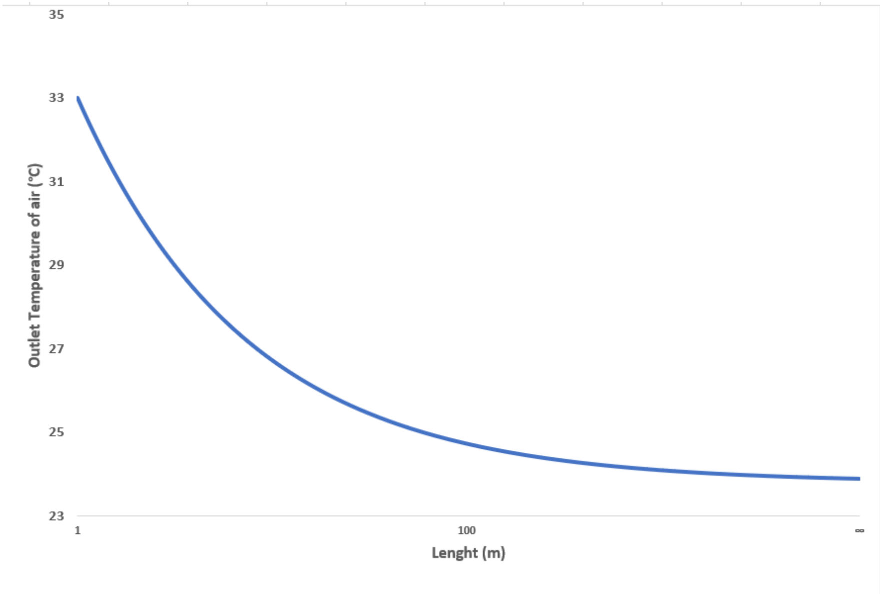
Figure 2. Comparison of ambient and soil temperatures during the year



Tube length

In Figure 3 can be seen that the temperature decay about the length of the tube occurs exponentially. This behavior is due to the logarithmic difference in temperature between the fluid and the surface, requiring long meters of pipe to reach the temperature of the pipe wall, in this case, the soil temperature.

Figure 3. Relation between outlet air temperature and tube length



One way to analyze heat exchangers is through the effective method and NTU – Number of Transfer Units (Çengel, 2008), a dimensionless parameter relative to $-h\pi DL/\dot{m}_{air}C_p$. The relation between effectiveness (ε) and NTU is defined by:

$$\varepsilon = 1 - \exp(-NTU) \tag{7}$$

By this method, it is estimated that a length between 31.3 and 47m has a transfer effectiveness between 86.4 and 95%.

The outlet temperature of the air

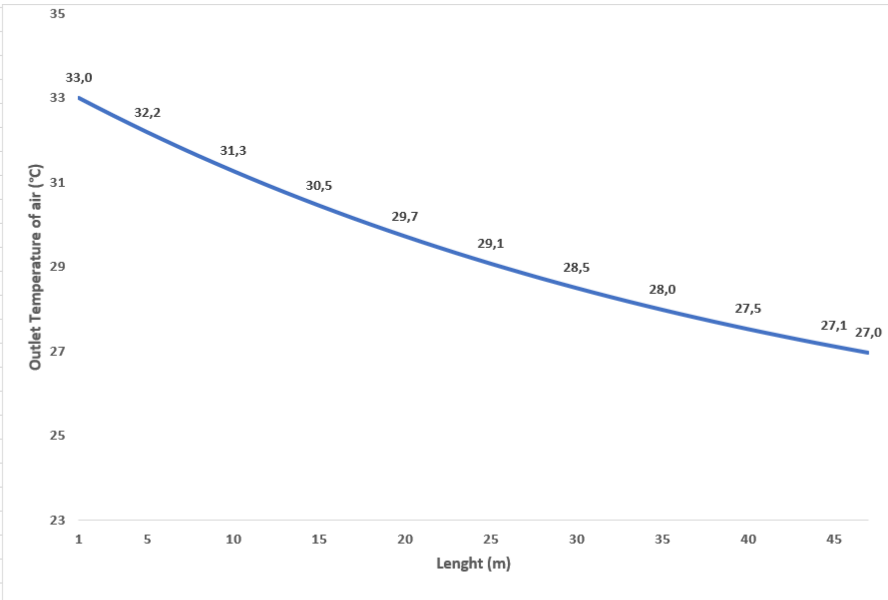
The parameters expressed in Table 1 were used to estimate the system outlet temperature.

Table 1. Sizing of EAHE

Length (m)	32-47
Depth (m)	4
Diameter (m)	0,2
Fluid Inlet Temperature (ºC)	33
Soil Temperature (ºC)	22,8

Below, you can view the temperature decay graph. With a length of 32m, the air exits the system at a temperature of 28.3°C, decaying to 27°C if the length is extended to 47m. It is noticed that it is necessary to add another 15m, almost half of the initial length, to reduce 1.3°C, which in the cost-benefit analysis may not be so advantageous. Thus, the final length of 32m was chosen.

Figure 4. Outlet air temperature decay



From the results obtained, it can be concluded that the geothermal air cooling system is viable for applying air conditioning in buildings or integrating with other cooling systems. The proposed system has the potential to reduce the air temperature by up to 6°C. This reduction may imply considerable reductions in spending on electricity with air conditioning systems, and consequently, reduce the levels of CO_2 emissions into the atmosphere.

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