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Simulation Modeling for Earth to Air Heat Exchanger System by Using MATLAB

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ABSTRACT

A MATLAB model was built for the preparation of initial designs for the establishment of an EAHE system for the purpose of heating and cooling buildings. The purpose of creating this model is to save time and effort by creating a new model capable of providing us and specialized designers with initial perceptions of the size of the appropriate system for the functional requirements for the purpose of cooling and heating buildings. A parametric analysis was then performed to evaluate and investigate the factors affecting the efficiency of the EAHE system. It was found that the pipe diameter is directly proportional to the pipe length, and inversely to the airflow velocity, pressure losses, and AFP. Airflow velocity reduced from 77.05 m/s to 0.1926 m/s, and AFP decreased from 9223 W to 0.058 W when diameter increased from 0.1 m to 2 m. The inlet air temperature affects the length of the pipe in four phases, it is inversely proportional in the first and third phases and directly in the second and fourth phases. These phases depend on the values of soil, inlet, and outlet temperature. This paper presents new equations to determine these phases to determine excluded range which is recommended should not use an inlet air temperature value through this range. The pipe number is directly proportional to pipe length. Pipe length increased from 57.16 m to 344.9 m when the pipe number increased from 1 to 10 pipes. The number of pipes has no influence on the overall airflow velocity or total heat transfer. The length of the pipe is directly proportional to the soil temperature in the first and third phases and inversely proportional in the second and fourth phases. Designers could get an idea of this range by utilizing the equations presented in this paper. There is no direct effect between the soil temperature and power, but rather it affects it through the length of the pipe, as it is directly proportional to pipe length.

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1. Introduction

The ever-increasing number of people living across the globe is directly responsible for the rising demand for energy (S. F. Ahmed, Khan, Rasul, et al., 2014; Azad et al., 2014). This upward trend can be attributed to a number of factors, including economic and industrialization advances, social processes, changes in climate, and requirements for thermal comfort (Azad et al., 2014; Shi et al., 2016). The majority of this expansion can be attributed to developing countries that are not members of the Organization for Economic Cooperation and Development (Shahsavari & Akbari, 2018; Ahasan et al., 2014). The construction industry is responsible for the consumption of more than forty percent of the world's total energy (Yüksek & Karadayi, 2017; S. F. Ahmed et al., 2015a). Because of climate change and environmental degradation in built environments, the implementation of sustainable indicators, energy conservation measures, and renewable energy systems is absolutely necessary (G. Liu et al., 2013; G. Liu et al., 2012; Baniyounes et al., 2012; Rahman et al., 2010; Chowdhury et al., 2008; Baniyounes et al., 2013). The majority of the energy that is used in the construction industry goes toward heating and cooling the buildings that are being built (Ürge-Vorsatz et al., 2015; Siddique et al., n.d.). The use of technologies that are efficient in terms of energy production allows for the reduction of heating and cooling loads, making new building designs very appealing. It is possible to reduce these loads using a passive method by implementing a strategy known as the earth-air heat exchanger (EAHE) (A.-S. F. Ahmed et al., 2014). It is possible to use it to either heat or cool a location in a way that is kind to the environment. The EAHE system makes use of one or more underground pipes that perform the function of a heat exchanger. This enables the intake air to be heated or cooled by exchanging heat with the soil that is located nearby (S. F. Ahmed et al., 2018). After that, the air is heated or cooled as it travels through the pipe and into the vacuum of space beyond it via the output. An exhaust fan that is mounted at the outlet assists in drawing in the intake air so that it can be utilized. Fig. 1 is a depiction of the schematic diagram for the EAHE.

An underground heat pump also supports the EAHE. Subsurface chambers provide protection from noise, dust, storm, and air penetration (S. F. Ahmed, Khan, Amanullah, et al., 2014). EAHE can cool and warm industrial, agricultural, and residential structures using the ground's steady temperature. Winter ground temperatures are higher than summer ones (Whalen & Dykhuizen, 2012). With increasing subterranean depth, the earth can be a source or drain of heat. EAHE uses ground or surface water as a heat sink and supply. There are two types of EAHE closed- and open-loop setups. In open-loop systems, the air is continually supplied into the building from underground pipes and evacuated by ventilation (Sivasakthivel et al., 2014; Fazlikhani et al., 2017). Open systems are less efficient since air is recirculated through underground pipes. Open-loop cooling doesn't operate since exhaust air is cooler than external air during cooling hours.

An EAHE's heating and cooling potential must be evaluated experimentally and numerically before it can be put to use in a particular climate. In the summer, an experiment was conducted to assess the vertical EAHE performance (Z. Liu et al., 2019; Ali et al., 2021). Air temperatures below 5 meters below the ground were found to be significantly cooler than the air that was released. The economic viability of the system was examined using a payback time of 8.2 years. In order to evaluate the EAHE cooling capability of buildings, several thermal models (S. F. Ahmed et al., 2015b; Belatrache et al., 2017; Yang et al., 2016; Rosa et al., 2020; Bansal et al., 2010; De Paepe & Willems, 2001), incorporating experimental and numerical research were created. Two separate piping systems were used to test the EAHE's performance in Queensland, Australia's subtropical zone in the summer.

The model's 'excess fluctuating temperature' includes harmonic signals from the pipe entrance and the ground surface. EAHE air temperature amplitude dampening and phase shifting are detailed explicitly. Calculations confirm analytic results. Used in hot/cold climates. A deep-buried EAHE pipe can cool the air by 7°C. Those are the peak cooling and heating seasons. It can cool or heat 3000 W (Rosa et al., 2020). Ansys Fluent was used to create an EAHE thermal model based on the k - ε turbulence model. To ensure the accuracy of the models, they were tested against actual data. For a 27.23 m^3 room, a temperature drop of 1-2 degrees Celsius was achieved in these trials. A total of 241.90 \$ was saved by cutting back on the use of 866.54 kWh of electricity per year. Temperatures in South Algeria are hot and dry, thus EAHE's cooling capacity was also figured out (Yang et al., 2016).

Pipe diameter, length, pipe materials, thickness, airflow, and pipe depth are all factors that affect the EAHE's performance. In order to maximize the EAHE's performance, a large number of studies were conducted on parametric analysis (Serageldin et al., 2016; Lee & Strand, 2008; Wu et al., 2007; Ghosal & Tiwari, 2006; Mihalakakou et al., 1994; S. F. Ahmed et al., 2016; Hanby et al., 2005; Li et al., 2019; Benrachi et al., 2020; Zhao et al., 2019; Zhou et al., 2020). EAHE thermal performance was evaluated in Egyptian climates by a computational and experimental investigation (Serageldin et al., 2016). Ansys Fluent used the standard k - ε turbulence model for constructing a numerical model. Using the numerical model, effective parametric research was carried out by taking into account the characteristics of inlet velocity, length, diameter, and space, as well as the material of the piping. The diameter, length, and velocity of the EAHE had a significant impact on its performance, but the material did not. For predicting the thermal performance of earth heat exchangers in various situations, Lee and Strand (Wu et al., 2007) evaluated the impact of a few influential parameters. The simulation tool Energy Plus was used to create a model of an earth heat exchanger and measure the effects of the various factors. It was decided to perform the parametric analysis by taking into account variables such as pipe diameter and length as well as depth. The heating and cooling rates of the pipes are influenced by the length and depth of the tubes, while the tube diameter and airflow velocity influence the temperature of the air entering the pipes. Southern China (Ghosal & Tiwari, 2006) examined the effect of these variables on EAHE cooling performance. Computational Fluid Dynamics (CFD) software PHOENICS was used to construct an implicit and transient model to evaluate their influence. As the airflow rate increased, so did the temperature of the output air. Energy savings of up to 74.6 kWh a day can be achieved by employing EAHE system. There is evidence from EAHE studies that the pipe outlet temperature decreases as the pipe length, radius, and depth are all increased up to a maximum of 4 meters (Mihalakakou et al., 1994).

A variety of cooling and heating speeds can be achieved using an EAHE system with pipes of varying sizes. In the research carried out by Mihlakakou et al. (S. F. Ahmed et al., 2016). the effectiveness of the pipes' cooling capabilities was evaluated based on their radii of 0.125, 0.180, and 0.250 meters. In this particular investigation, a larger pipe radius resulted in a greater air exit temperature. Another study (Mihalakakou et al., 1994) discovered statements that were very similar to these, and it was reported that reducing the pipe radius led to a decrease in the air outlet temperature. This is due to the fact that the air that travels through the buried pipe is able to transmit heat quickly to the soil for a short pipe radius (S. F. Ahmed et al., 2016). This occurs because the center of the buried pipe is getting closer to the outside soil. The length of the buried pipe is one of the most important factors that determines EAHE performance. It has been demonstrated in a number of studies that an extended period of burial for a pipe results in a decrease in the pipe outlet temperature. Because the pipe is so lengthy, the air has more time to circulate and therefore more time to heat up. However, the length of the underground pipe is sometimes limited to make it more cost-effective, and as a result, the pipes for an effective cooling system should not be expensive. In a warm and arid zone of Kuwait, the costeffectiveness of the EAHE system was examined by analyzing its payback period (Li et al., 2019). 7.24 years was determined to be the payback period for the ideal setup of EAHE. In a separate study (S. F. Ahmed et al., 2016), the researchers evaluated how the performance of the EAHE was affected by using pipes of varying depths. In order to investigate the pipe outlet temperature, the pipes were installed at depths of 1.2, 2, and 3 meters below the earth. The results showed that the temperature range was lowest at the depth of 3 meters. They also conducted the same kind of investigation using pipes of varying depths, including 2.5 meters, quite a bit less than 4 meters, and 4 meters. In addition, the findings of the study were comparable to those of earlier studies.

The speed at which air is circulated throughout the system is yet another essential component that determines EAHE performance. When the water moves through the pipe at a faster rate, there is less time for the water to absorb heat from the ground below it, which results in the pipe outlet reaching a higher temperature. During the summer, a number of different air velocities were used in an effort to assess the EAHE cooling performance (Benrachi et al., 2020). As a result of the higher air velocity that was entering through the inlet, the temperature that was measured at the outflow was significantly higher than the typical value. This was demonstrated in previous studies (Hanby et al., 2005). When Benrachi et al. (Zhao et al., 2019) conducted their parametric study, they made sure to take into account the varying air velocities that were present at the EAHE intake. The input velocity was increased from 2 meters per second to 2.5 meters per second, which resulted in a decrease in the average cooling efficiency of the EAHE from (60-33)%. In the parametric research carried out by Zhao et al. (Zhou et al., 2020), the EAHE performance suffered whenever the input velocity was increased. The performance of EAHE is also affected by the material that the pipe is made of. The pipe's excess heat is released into the soil during the warm summer months, but during the colder months, the flow of heat is in the opposite direction. The rate at which heat is transferred is proportional to a material's thermal conductivity; therefore, the material with the greatest conductivity will experience the greatest rate of transfer. When it came to EAHE performance, stainless steel pipes performed significantly better than polyethylene (PE) or PVC pipes, as stated in the research carried out by Liu et al. (Benrachi et al., 2020). These materials contribute to the reduction in the temperature of the airflow thanks to the superior thermal conductivity that they possess.

Zhou et al. (Lee & Strand, 2008) carried out a series of studies with the purpose of analyzing the effects of using different pipe materials. There was no discernible effect that the material had on EAHE performance. However, the vast majority of parametric studies did not take into account all of the significant EAHE factors, which is something that has an effect on the actual performance of the system.

According to the previous literature, not enough studies have been done to develop a new model to examine the characteristics of EAHEs and their power output by using Matlab/Simulink. This paper aims to create a Matlab/Simulink model and observations to be helpful in preliminary plant design by proposing a simple approach for evaluating the properties of EAHE and the specification.

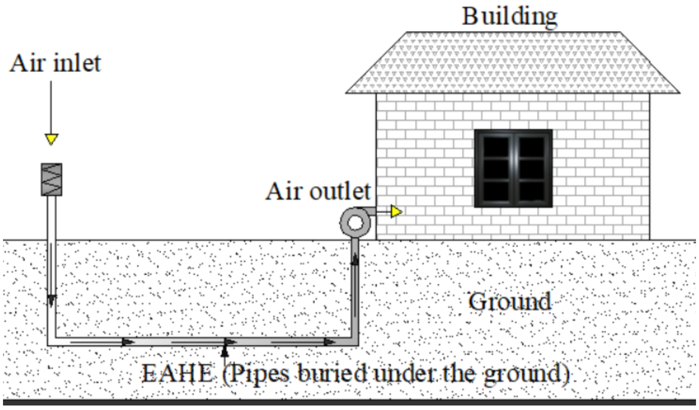

Fig. 1. EAHE schematic diagram

2. Methodology

2.1. Mathematical model

A common situation facing a lot of engineers is a heat transfer to or from the fluid flowing through the tube. This can occur in the heat exchangers and evaporators, heaters, condensers and a host of equipment to complete this process. Thus, it is very useful to know how the process is done. The pipe (PVC) is buried at a certain depth to be determined based on information and sources documented. The desired length of the tube and the area of land required to bury the pipe can be determined via using the scheme based on the needed performance which is aiming to design based on it. Below we enumerate the most important equations used and methods to extract the required data to complete the earth-air heat exchanger design (Ali et al., 2021).

Boundary conditions: At the outlet of the EAHE pipe, the relative pressure was equal to zero atm. (Subsonic flow regime). At the inlet of the EAHE pipe, the static temperature of the inlet air, T_{in} (°C), and velocity of airflow value to be defined. The specific heat capacity, density, thermal conductivity, and dynamic viscosity of air to be defined at a static temperature of the inlet air (Thermodynamic and transport properties) (Muehleisen, 2012; Bisoniya, 2015). The temperature of the pipe surface (wall) was defined as equal to earth's temperature at a specific depth and was uniformly in axial direction. The depth of pipe to bury the pipe which is specific as the design aim according to earth's temperature distribution.

- Mass flow rate of air.

$$\dot{m} = N_p \frac{\pi}{4} D^2 \rho v_a \quad (1)$$

- Heat exchanger design and effectiveness.

The total heat transferred to the air when flowing through a buried pipe is given by:

$$Q = \dot{m} C_p (T_{in} - T_{out}) \quad (2)$$

Heat can also be transferred from the source to the area via convection, which occurs when air moves past a wall, which is given by

$$Q = h A_{surf.} \Delta T_{lm} \quad (3)$$

$$\Delta T_{lm} = \frac{T_{in} - T_{out}}{ln \frac{T_{in} - T_{wall}}{T_{out} - T_{wall}}} \quad (4)$$

The internal surface area of the pipe is a function to both of diameter (D_{pipe}), and length (L_{pipe}) of EAHE.

$$A_{surf.} = \pi\, D_{pipe}\, L_{pipe} \quad (5)$$

The convective heat transfer coefficient (CHTC) during the pipe is characterized by:

$$h = \frac{Nu\, K}{D} \quad (6)$$

The EAHE system that was investigated for this study is made up of PVC cylindrical pipes with an inner diameter of D_{pipe} and an overall burial length of L_{pipe}. These pipes are buried at various depths. If we make the assumption that the inside of the PVC pipes that are a part of the EAHE system has a smooth surface, then the Nu correlations that are provided by (De Paepe & Janssens, 2003) would be used to simulate how well the system will work.

$$Nu = \frac{\left(\frac{f}{8}\right)(Re - 1000)Pr}{1 + 12.7\sqrt{\frac{f}{8}}\left(Pr^{\frac{2}{3}} - 1\right)} \quad (7)$$

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

If $2300 \leq Re < 5 \times 10^6$ and $0.5 < Pr < 10^6$

The Reynolds number is related to the average air velocity and diameter:

$$Re = \frac{\rho v_{a\,D}}{\mu} \quad (9)$$

The Prandtl number is given by:

$$Pr = \frac{\mu\, C_p}{k} \quad (10)$$

The pressure drop in a smooth pipe is given by:

$$\Delta p = f\, \frac{L}{D}\, \rho\, \frac{{v_a}^2}{2} \quad (11)$$

and the EAHE efficiency, η, as:

$$\eta = 1 - e^{-\left(\frac{hA}{\dot{m}\, C_p}\right)} = \frac{T_{out} - T_{in}}{T_{wall} - T_{in}} \quad (12)$$

To calculate the pressure drop in the pipe as a result of bends in the pipe:

$$\Delta p_{loss} = C_{loss}\, \rho \frac{v_a^2}{2} \quad (13)$$

Where C_{loss} is the bend loss coefficient can be gotten from fitting the measured data introduced in the ASHRAE Handbook (ASHRAE, 2009) to a quadratic condition. The results got are:

$$C_{loss} = 0.09057 - 0.001439 D_{pipe} + 0.001294 D_{pipe}^2 \quad (14)$$

Then, the total drop pressure in EAHE system (Δp_T) given by:

$$\Delta p_T = \Delta p + \Delta p_{loss} \quad (15)$$

The air fan power (AFP) required to move the volume of air (m^3/s) over the total pressure drop Δp_T is then computed as:

$$AFP = V_{air} \ \Delta p_T \qquad (16)$$

Where: N_p is the number of parallel pipes (-), ρ: air density (m^3/kg), v_a : air flow velocity (m/s), C_p: is the specific heat of air (J/kg-K), T_{out}: is the temperature of air at outlet of EAHE pipe (°C), ΔT_{lm}: The logarithmic average temperature difference (-), $T_{wall}=T_{soil}$ at a certain depth, Nu: is Nusselt number, K: is the thermal conductivity (W/m-K), f: is the friction factor for smooth pipes and μ: the dynamic viscosity of air (kg/m-s).

2.2. Solution process

The design of earth-to-air heat exchanger needs to determine the length, diameter, and type of tube material that is preferred to be used, as well as the total heat transferred to the air to be provided, the airflow velocity of the supplied air suitable for the space to be conditioned, and the power needed to circulate this air by determining the expected incoming air temperature, the required mass flow rate, and the required outlet air temperature.

The Matlab/Simulink model (shown in Figure 2) was developed using the equations of the previous section (1-16) and the mathematical and programmatic linkage between all of them. This model can calculate density, thermal conductivity, dynamic viscosity, heat capacity, Prandtl number, air velocity, Reynold number, friction factor, nesult number, convective heat transfer coefficient, pressure drop pipe length, the total heat transferred to the air, and AFP. They can get it by selecting the inlet air temperature, pipe diameter, soil temperature, mass flow rate, number of parallel pipes, and outlet temperature. This makes the model suitable to be helpful in preliminary plant design by proposing a simple approach for evaluating the properties of EAHE and its specification.

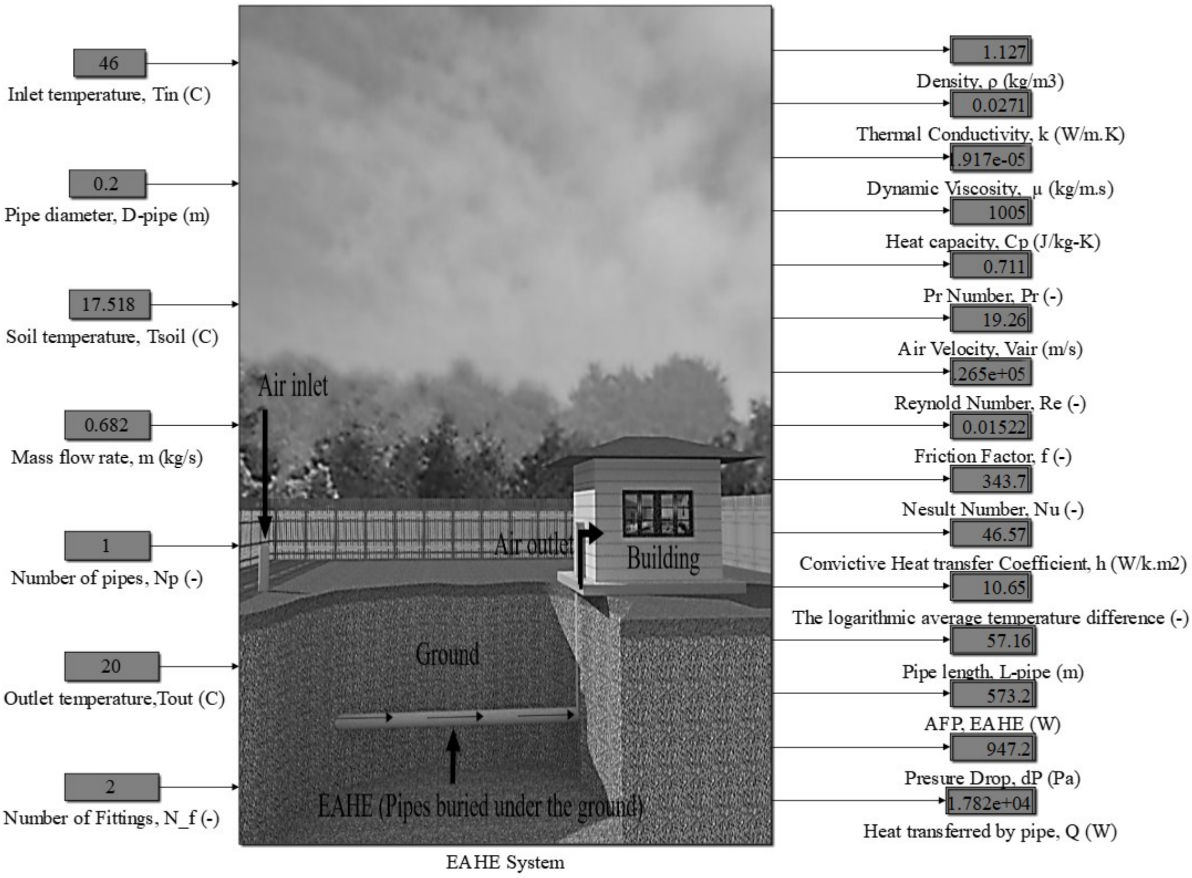

Fig. 2. Final step of the Matlab/Simulink model

3. Results and discussion

3.1. Matlab model validation

The model was validated using experimental data published by Bansal et al. (Bansal et al., 2012) at various ambient temperatures before the parametric investigation was performed. Table 1 shows the input parameters, and Table 2 shows the findings from the validation process.

The air inlet conditions in the Matlab/Simulink model were maintained at the experimental set-up for this validation session. Experiment and model data for output temperatures are shown in Table 2 to have a 2.81-9.85 percent discrepancy. As a result, we concluded that the model could be used to carry out our extensive study for every hour of the year. In order to calculate the EATHE system's hourly cooling/heating effect, a flow velocity of 5.0 m/s was used by using (1-10) equations. The mathematical modeling of EAHE's operation has also been the subject of a large number of articles (Badescu, 2007; Badescu & Isvoranu, 2011; Bojic et al., 1997; Cucumo et al., 2008; Vickers, 2017; Hollmuller & Lachal, 2001; Pfafferott, 2003; Trząski & Zawada, 2011). There are multi pipes in the EAHE system stated, which are exchanger structures that focus on the thermal performance of EAHE. According to these comparisons, the model's validity is supported by the analytical results.

Table 1.
Validation input parameters versus experimental data from Bansal et al. (Bansal et al., 2012)

Parameters	Reference value
Pipe length	23.42 m
Pipe diameter	0.15 m
Number of pipes, Np	1
Depth of buried pipe	2.7 m
Thermal conductivity of the pipe (PVC)	0.16 (W/m.K)
Air density	1.225 (kg/m3)
Air specific heat capacity	1006 (J/kg.K)
Soil Temperature	26.7 ^{o}C
Airflow velocity	5 m/s

Table 2.
Comparison of experimental and Matlab model results (for outlet temperatures)

Inlet temperature (^{o}C), both experimental and Matlab model	Outlet temperature (^{o}C)		
	Experimental data	Matlab model data	Relative error (%)
31.9	23.2	26.9	9.75
34.1	24.1	27.0	7.28
35.9	25.2	27.1	4.05
37.3	25.8	27.1	3.80
38.3	26.3	27.2	2.81
38.7	26.4	27.2	2.85
38.7	26.4	27.2	2.85
37.9	26	27.1	3.50

3.2. Performance characteristics of EAHE systems

A variety of EAHE systems of varying sizes are shown in Figures (3-11) for comparison, discussion, and conclusion purposes. The proportions of the facility have been selected so that investors may build it.

Noted from Figure 3 that the diameter of the pipe is inversely proportional to the airflow velocity inside the pipe, as the larger the diameter of the pipe, the lower the airflow velocity, which leads to lower pressure losses and therefore decrease the value of power required to circulate the air inside the pipe to its lowest values (as illustrated in Figure 4), the value of airflow velocity decreased to 0.1926 m/s after its value was equal to 77.05 m/s, and the value of power decreased to 0.058 W after its value was equal to 9223 W.

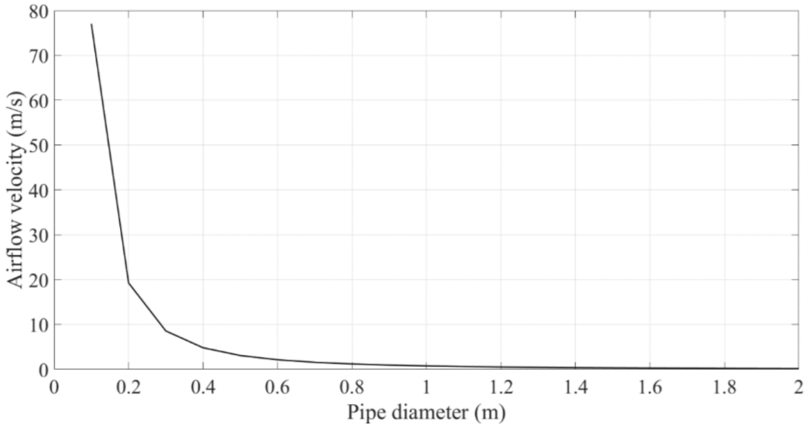

Fig. 3. Effect of pipe diameter on airflow velocity (T_{in}= 46 ºC, T_{soil}= 17.518 ºC, T_{out}= 20 ºC, ṁ= 0.682 kg/s, N_p= 1, and N_f= 2)

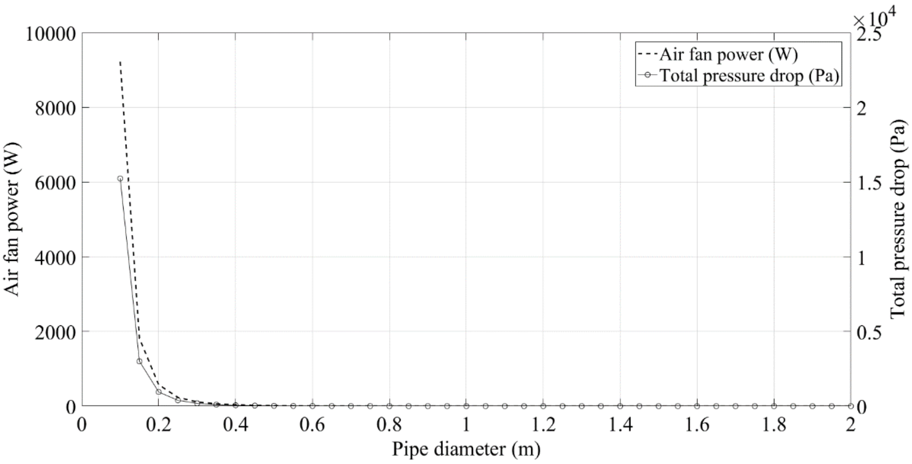

Fig. 4. Effect of pipe diameter on AFP and total pressure drop (T_{in}= 46 ºC, T_{soil}= 17.518 ºC, T_{out}= 20 ºC, ṁ= 0.682 kg/s, N_p= 1, and N_f= 2)

Figure 5 shows how the pipe diameter affects the pipe length. It is observed that the pipe length is directly proportional to the diameter of the pipe, the pipe length was 32.77 m (with 0.1 m diameter), and then its length was 344.9 m (with 2 m diameter), which means a significant increase in investment costs as a result of the large diameter of the pipe, which usually indicates the relatively high purchase costs, as well as the costs of drilling, installation, burial and other requires of the establishment of the system while there will be a significant decrease in future operational costs, due to considerable reduction in power needed as illustrated in Figure 5.

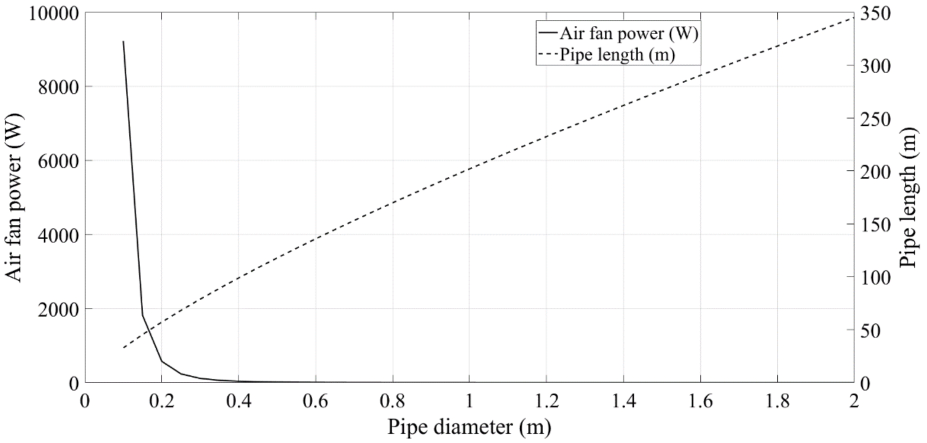

Fig. 5. Effect of pipe diameter on AFP and pipe length (T_{in}= 46 ºC, T_{soil}= 17.518 ºC, T_{out}= 20 ºC, ṁ= 0.682 kg/s, N_p= 1, and N_f= 2)

The length of the pipe required to create the system is affected by the inlet air temperature, as shown in Figure (6), and this effect goes through fourth phases. The first three phases refer to the heating process. This is due to the fact that the inlet air temperature is still lower than the required outlet air temperature during these phases of the process. In contrast, the fourth phase is referred to as the cooling process because the inlet air temperature rises over the required outlet air temperature during this phase. In the first and third phases, it was found that the length of the pipe is inversely proportional to the temperature of the inlet air. The length of the pipe in the second and fourth phases is directly proportional.

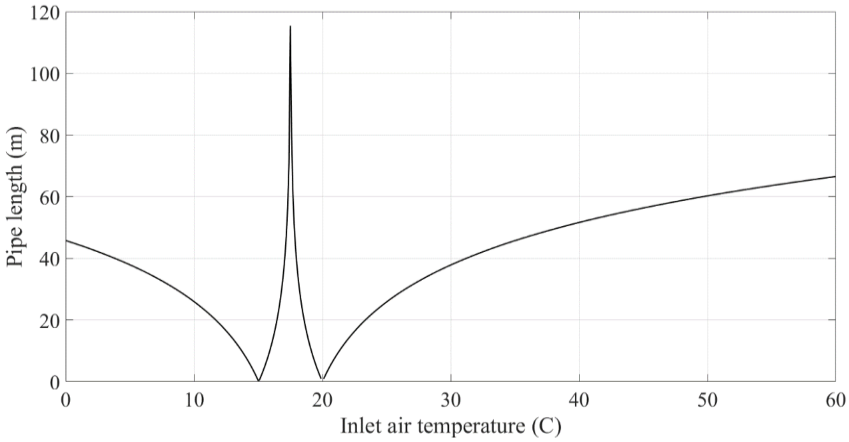

Fig. 6. Effect of inlet air temperature on pipe length (T_{in}= 46 ºC, T_{soil}= 17.518 ºC, T_{out}= 20 ºC, ṁ= 0.682 kg/s, N_p= 1, and N_f= 2)

The second and third phases are confined between specified inlet air temperature (named inlet air temperature phase ($T_{in\text{-}phase}$) which is known in the Eq. (17), this equation considered as an innovative equation within this research) and the outlet temperature (T_{out}). If ($T_{in\text{-}phase}$ - $T_{in\text{-}min}$ > $T_{in\text{-}max}$ - T_{out}) that is means the main purpose from the system is for heating uses and must depend on first phase to select the suitable length of pipe to design this system, and if ($T_{in\text{-}max}$ - T_{out} > $T_{in\text{-}phase}$ - $T_{in\text{-}min}$) that is means the main purpose from the system is cooling uses and must depend on fourth phase to select the suitable length of pipe to design this system.

$$T_{in\text{-}phase} = 2T_{soil} - T_{out} \quad (17)$$

Concerning the temperatures range between $T_{in\text{-}phase}$ and T_{out}, based on the results of this research and analysis, it is not recommended for designers to use the values of the pipe length within this range. Since the system is exposed to inverse and direct influences resulting from being affected by temperatures (T_{in}, T_{out}, and T_{soil}), these temperatures are in close values. The design of the EAHE system within this range will be less accurate and thus affect its efficiency, as it will be of the best accuracy in the first and fourth phases. This range can be determined using the Eq. (17) assigned to extract the value of Tin-phase and the value T_{out} specified by the designer.

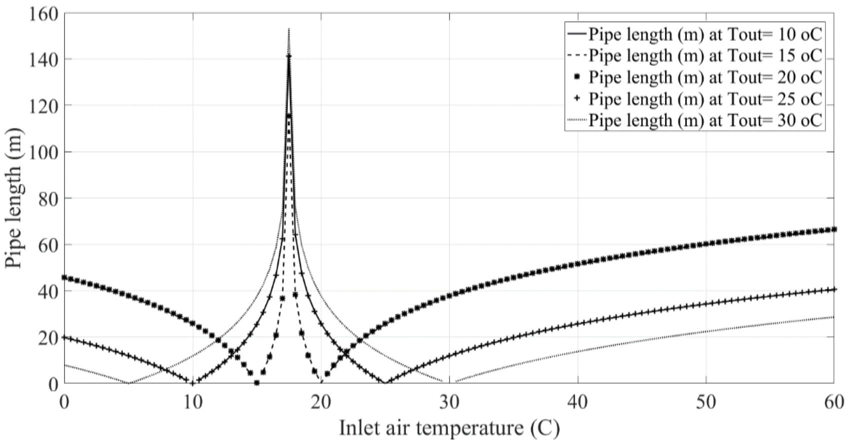

Fig. 7. Effect of inlet air temperature on pipe length (T_{in}= 46 ºC, T_{soil}= 17.518 ºC, T_{out}= 20 ºC, $\dot{m}$= 0.682 kg/s, N_p= 1, and N_f= 2)

Figure (7) shows the relationship between the temperature of the inlet air and the length of the pipe at different required outlet air temperatures; in this Figure, the outlet air temperatures are (10, 15, 20, 25, and 30 ºC). We notice through this figure that the pipe length values at various inlet air temperatures confined between (T_{out}) and ($T_{in\text{-}phase}$) and the various outlet air temperatures it is subjected to apparent fluctuations. The higher the required outlet air temperatures, the wider the difference between T_{out} and $T_{in\text{-}phase}$, which leads to greater fluctuations in the amount of tube length. Therefore, recommended through this research to avoid using values of inlet air temperature equal to one of the temperature values within the range between T_{out} and $T_{in\text{-}phase}$ when designing an EAHE via the designers (which can be called the excluded range). The use of results within this range leads to a defect in the design data obtained, which negatively affects the system's data in general. It thus causes losses, including the high costs of construction and/or operating costs, and consequently the inability to found this system's entire objective.

It seems that at outlet air temperatures of 15 and 20 °C, the design outcomes are comparable, as shown in Figure 7, while at outlet air temperatures of 10 to 25 °C, there is a similar scenario. The disparity between the outlet air temperatures and the soil temperature utilized in this study (T_{soil}=17.5 ºC) is the possible source, according to our investigations. Using T_{out} as an example, T_{out} is equal to 15 and 20 ºC; the difference between T_{soil} and T_{out} is equal to 2.5 ºC, and when T_{out} is equal to 10 and 25 ºC; the difference between T_{soil} and T_{out} is equal to 7.5 ºC, which means that the temperature of the soil and the temperature of the outlet air directly affects the amount of the excluded range. To get an idea of this range, suggest the following equation (Eq. 18):

$$T_{in\text{-}range} = T_{out} - T_{in\text{-}phase} \tag{18}$$

Eq. (17) can also be substituted into Eq. (18) to get the following equation:

$$T_{in\text{-}range} = T_{out} - (2T_{soil} - T_{out}) \tag{19}$$

Therefore, the equation can be expressed as follows:

$$T_{in\text{-}range} = 2\ (T_{out} - T_{soil}) \qquad (20)$$

There is a direct correlation between the number of pipes and the length of the pipes, and the AFP in Figure (8). It's worth noting, though, that while there is a decrease in pipe length, there is an increase in the overall length of the pipe because of this. It measured 57.16 meters in length while using a single pipe. For several pipes (multi-lines), the pipe length decreased to 34.49 m/line, leading to a total pipe length of 344.9 m in this scenario. If it were a single pipe, it would be six times longer, which indicates that the investment expenditures would be six times higher, but the operating expenses would be just one percent lower since 573.2 W was needed for a single pipe, while 0.575 W was needed for ten pipes.

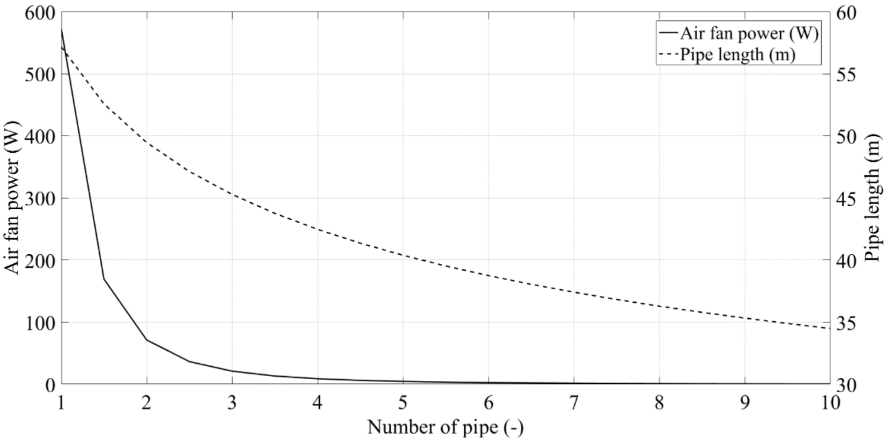

Fig. 8. Effect of number of pipes on pipe length and AFP (T_{in}= 46 ºC, T_{soil}= 17.518 ºC, T_{out}= 20 ºC, $\dot{m}$= 0.682 kg/s, D_{pipe}= 0.2 m, and N_f= 2)

As shown in Figure (9), the values of airflow velocity and total heat transferred are inversely related to the number of pipes. But what should be noted is that the airflow velocity and total heat transferred will decrease to be divided by the number of multiple pipes. The airflow velocity and total heat transferred in the case of a single pipe were 19.26 m/s and 17820 W respectively, while their values became 1.926 m/s and 1780 W in the case of multiple pipes (10 pipes) respectively, it is due to the mass flow rate divided to 10 parts. That means there is no effect of the number of pipes on the total values of the airflow velocity and total heat transferred.

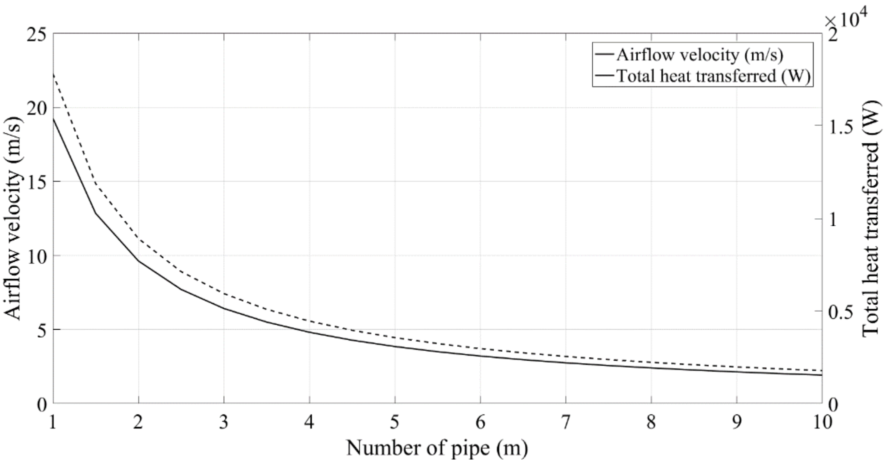

Fig. 9. Effect of number of pipes on airflow velocity and total heat transferred (T_{in}= 46 ºC, T_{soil}= 17.518 ºC, T_{out}= 20 ºC, $\dot{m}$= 0.682 kg/s, D_{pipe}= 0.2 m, and N_f= 2)

The length of the pipe required to install the EAHE system according to the specified dimensions, data, and its relation to the soil temperature is clear in Figure (10). Where it was noted that the length of the pipe is affected by the soil temperature in an M-shape in four phases, as it is directly proportional during the first and third phases and inversely during the second and fourth phases.

- In the first phase, it was noticed that as the soil temperature increased, the length of the required pipe increased to be longer (77.21 ºC) until the soil temperature was equal to the outlet air temperature, which means it may be directly proportional to it.
- In the second phase, it was observed that as the soil temperature increases, the length of the required pipe decreases to be shorter. As this phase ends until the soil temperature is equal to $T_{soil\text{-}phase}$ (it can be calculated through Eq. (21)), it means it has been inversely proportional.
- In the third phase, it was observed that as the soil temperature increased, the length of the required pipe increased to be longer (75.4 m) until the soil temperature was equal to the inlet air temperature, meaning that it may be directly proportional to it.
- In the fourth phase, it was observed that as the soil temperature increases, the length of the required pipe decreases to be shorter, as this phase ends at the maximum soil temperature, which may be inversely proportional to it.

As for AFP, there is no direct effect between the temperature of the soil and AFP required to circulate the air inside the pipe, but rather it affects it through the length of the pipe, as it is directly proportional to pipe length which represents clearly in Fig. 11-left and Fig. 11-Right. The required power can be obtained through the Eq. (22), which fits with the case study referred to in this research.

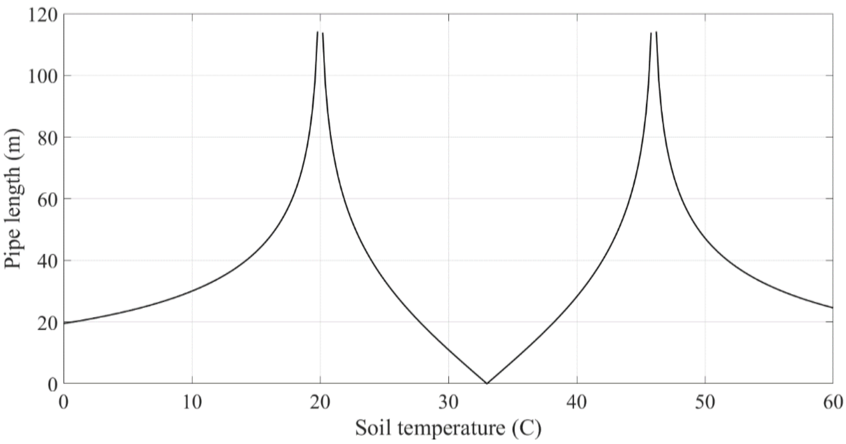

Fig. 10. Effect of soil temperature on pipe length (T_{in}= 46 ºC, D_{pipe}= 0.2 m, T_{out}= 20 ºC, $\dot{m}$= 0.682 kg/s, D_{pipe}= 0.2 m, and N_f= 2)

$$T_{soil\text{-}range} = (T_{out} + T_{in})/2 \quad (21)$$

$$AFP = 9.6Lpipe + 24 \quad (22)$$

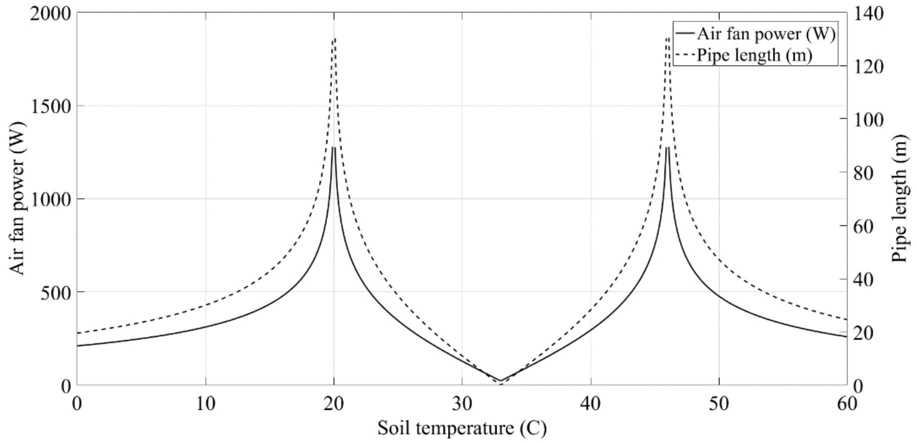

Fig. 11. Effect of soil temperature on air fan power and pipe length (T_{in}= 46 ºC, D_{pipe}= 0.2 m, T_{out}= 20 ºC, ṁ= 0.682 kg/s,, D_{pipe}= 0.2 m, and N_f= 2)

4. Conclusions

A MATLAB model was built for the preparation of initial designs for the establishment of an EAHE system for the purpose of heating and cooling buildings. The purpose of creating this model is to save time and effort by creating a new model capable of providing us and specialized designers with initial perceptions of the size of the appropriate system for the functional requirements for the purpose of cooling and heating buildings, testing and simulating them many times before starting to implement them in reality. The model developed was first validated using experimental data from the literature. A parametric analysis was then performed to evaluate, and investigate the effect of diameter, length, number of pipes, temperatures (inlet, outlet and soil), air flow velocity, total pressure losses, power required for air circulation, and the total heat transferred. The relationships between them were presented, studied, analyzed, and discussed the results obtained. The main conclusions are herein summarized.

1. The diameter of the pipe affects the airflow velocity within it: the greater the pipe diameter, the slower the airflow velocity.
2. The lower airflow velocity is directly proportional to pressure losses, leading to a decrease in the value of AFP. Airflow velocity reduced from 77.05 m/s to 0.1926 m/s, and AFP decreased from 9223 W to 0.058 W.
3. The pipe length is directly proportional to the pipe diameter. The longer pipe leads to a greater diameter, but that means a significant increase in investment costs due to the large diameter of the pipe, which usually indicates relatively high purchase costs, as well as costs of drilling, installation, burial, and other requirements of the system's establishment, while there will be a significant decrease in future operational costs due to considerable reduction of AFP needed.
4. The inlet air temperature affects the length of pipe needed to establish the system in four phases. The first three referred to heating. The fourth phase is referred to as cooling. In the first and third phases, the pipe length is inversely proportional to the inlet air temperature. The pipe length in the second and fourth phases is directly proportional.
5. The second and third phases are confined between $T_{in\text{-}phase}$ and T_{out}. Designers can calculate the $T_{in\text{-}phase}$ using Eq. 17, which this research suggests.
6. An inlet air temperature value between the T_{out} and $T_{in\text{-}phase}$ (excluded range) should not be used while developing an EAHE via the designers, according to this guide. A defect in the

design data is the outcome of using results inside this range, and this impacts the system's data in general. Consequently, it results in losses, such as expensive construction and/or operational expenses, as well as the inability to ensure the whole system goal.

7. The temperature of the soil and the temperature of the outlet air directly affect the value of the excluded range. Designers can get an idea of this range using equations (18-20), which this research suggests.
8. A clear correlation between the number of pipes, pipe length, and AFP. It's worth noting that although the pipe length decreases, the total pipe length increases. It was 57.16 meters long with a single pipe. The pipe length fell to 34.49 m/line for multiple pipes (multi-lines), for a total pipe length of 344.9 m. Using a single pipe would be six times longer, requiring six times the investment but just one percent less operational costs.
9. The number of pipes has no influence on the overall airflow velocity or total heat transfer. The airflow velocity and overall heat transfer will decrease as the number of pipes increases. The airflow velocity and total heat transfer for a single pipe were 19.26 m/s and 17820 W, respectively, but for multiple pipes (10 pipes), they were 1.926 m/s and 1780 W, owing to the mass flow rate divided by 10.
10. The length of the pipe is directly proportional to the soil temperature in the first phase ($T_{in\text{-}min} \leq T_{soil} < T_{out}$) and third ($T_{soil\text{-}phase} < T_{soil} < T_{in}$) and inversely proportional in the second phase ($T_{out} < T_{soil} < T_{soil\text{-}phase}$) and fourth phase ($T_{in} < T_{soil} \leq T_{in\text{-}max}$). Designers could get an idea of this range by utilizing equation 21.
11. There is no direct effect between the temperature of the soil and AFP required to circulate the air inside the pipe, but rather it affects it through the length of the pipe, as it is directly proportional to pipe length.

Although the numerical values reported in points 1-11 are specific to the experimental conditions, it is clear that the conclusions are general.

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