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Earth-to-air Heat Exchanger for Cooling Applications in a Hot and Dry Climate: Numerical and Experimental Study

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A B S T R A C T

Shallow geothermal energy, by an earth-to-air heat exchanger (EAHE), is utilized to cool buildings with minimal energy usage. Significant parameters affecting the heat exchanger's performance must be investigated to obtain a suitable design. Shallow geothermal energy, by an earth-to-air heat exchanger (EAHE), is utilized to cool buildings with minimal energy usage. Significant parameters affecting the heat exchanger's performance must be investigated to obtain a suitable design. This article numerically and experimentally investigates the effect of pipe diameter, pipe length, inlet air temperature, soil temperature, airflow velocity, and soil thermal conductivity on the performance of the heat exchanger under hot and dry climate conditions. The soil temperature distribution was measured from the surface to a depth of 7 m in the city of Karbala (center of Iraq) in the summer season. The experimental test for EAHE was carried out in water-saturated soil and ambient air temperatures of 41 ºC, 45 ºC, and 49.5 ºC at four different velocities. The percentage drop in the EAHE outlet air temperature at 9 m/s was 28.3%, 25.5%, and 19.5%, respectively. Also, the three-dimensional model was created, and the simulation results were compared with the experimental results, which were in good agreement. An equation for the outlet air temperature was found as a function of pipe diameter and length, ambient air temperature, soil temperature around the pipe, and soil thermal conductivity. The resulted equation were compared with the current experimental results and experimental results of reported data inliterature. As a result, a very good agreement was observed. The results showed that the parameter L (length of the pipe) causes the strongest nonlinear behavior in the equation. For the cases considered, at diameters 75 and 100 mm, an approximate linear behavior for the length required to achieve a specific outlet temperature was observed. It can be concluded from the results that changing the soil type from dry one (k=0.5 W/m K) to saturated one (case of Karbala city, k=1.5 W/m K) resulted about 25% reduction in the length of the pipe. Also, the results showed that at an air velocity of 7m/s, the length required to obtain 26 ºC at the outlet of EAHE is 62.1 m which is 55% higher than the case of 29 ºC (39.9m).

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1. INTRODUCTION

In recent years, humanity has realized the danger of climate change to the continuation of life and that global warming has reached to dangerous levels that threaten environmental disasters. The main reason for climate change is the large consumption of energy, especially the power generated by burning fossil fuels. Most consumption takes place in cities, which is equal to 73% of the global energy consumption, and the most considerable amount of energy usage is consumption on cooling and heating operations [1]. Using traditional cooling systems in residential areas significantly contributes to increasing the heat in these areas, indirectly through large energy consumption and directly by exposing heat through the condenser to the neighboring regions [2]. Therefore, it is necessary to think of alternative ways to reduce the use of traditional

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cooling systems and take advantage of sustainable natural energy sources. Since ancient times, people have benefited from the heat stored in the ground for cooling and heating purposes, as the temperature of the subsurface soil at a depth of between 1-4 m is lower than the ambient air temperature in the summer and higher than the ambient air temperature in the winter [3].

Geothermal energy was used to cool residential buildings and greenhouses, using pipes buried horizontally or vertically under the earth's surface. The heat exchanger can be defined as a device to help the process of heat transfer between various materials without direct mixing [4]. The earth-to-air heat exchanger (EAHE) system is considered adequate and economical in the long run [5]. Unfortunately, its use is still limited due to the relatively high initial cost and the difficulty of digging and burying pipes in residential areas. Because of the human race's significant challenges, all possible natural resources must be used to replace traditional energy with clean, renewable energy, especially in hot areas where residents need to use cooling systems all day throughout the summer. Many parameters affect the operation of the geothermal heat exchanger, including the soil's thermal characteristics and water content. Furthermore, main parameters like the depth of pipe burial, pipe length, pipe diameter, and airflow velocity inside the pipe significantly affect the performance of EAHE.

Many researchers have measured the soil temperature distribution in depths less than 20 meters, e.g., Popiel et al. [6] in Poznan in Poland, and Al-Ajmi et al. [7] in Kuwait. These studies have shown that the temperature distribution of soil depends primarily on geographical location, soil type, outdoor air temperature, ground cover, and measurement time. Also, they showed that temperature increases during the day and decreases at night. It also changes with the change of the months of the year, where the temperature fluctuation is significant at the soil surface and drops to a lower value at a depth of more than 4 meters, beyond which it remains almost constant.

Some researchers investigated the effect of the water content in the soil on the heat transfer to the heat exchanger. Lu et al. [8] developed a numerical model that links thermal conductivity and soil water content. They validated this model using eight soil samples' measured thermal conductivity. The results showed that the thermal conductivity significantly increases with an increase in water content. Song et al. [9] studied the effect of soil density and water content on the thermal conductivity of the soil. They took seven different soil types, made a new mathematical model, and proved that the type of soil and water content significantly affect the magnitude of thermal conductivity. They concluded that heat transfer increases by an increase in the water content in the soil. The heat transfer in the soil primarily depends on soil thermal conductivity, which is improved by high thermal conductivity near soil for the EAHE system. The thermal conductivity of soil is determined mainly by the soil type, dry density, water saturation level, and particle size [10]. Agrawal et al. [11] made two similar experimental setups of the EAHE system and examined the performance of the dry and wet soil. They noticed that the thermal conductivity of the soil increased when the soil water content increased; which is resulted an enhancement in the thermal efficiency of EAHE.

Many experimental studies have been performed on the heat exchanger's design parameters, including pipe length, diameter, and burial depth. Abbaspour et al. [12], in northeast Iran, conducted 72 practical experiments. The experiment was conducted with two parallel pipes of two different materials (galvanized steel and PVC). They buried pipes at two different depths (2 and 4 m). They used a pipe diameter of 4 inches and three airflow velocities (4, 7, and 10 m/s). The experiments were conducted during the summer and winter at 36.5 ºC and 3.8ºC, respectively. In summer, the soil temperature was 20 ºC and 18 ºC at 2 m and 4 m depths. They concluded that all parameters have an important influence on the EAHE system's performance except for the pipe's material. The system performs more effectively with a galvanized pipe at a depth of 4 m and air velocity at 4 m/s.

Bisoniya et al. [13] conducted an experimental study to investigate the effectiveness of the EAHE system in hot weather in Bhopal city (India). They produced 3D models of the EAHE system and validated this model with their experimental results. Modeling and experimental results were in good agreement. They concluded that the lowest outlet air temperature was obtained at the minor diameter and lowest airflow velocity. In Marrakech (Morocco), Khabbaz et al. [14] experimented on a heat exchanger in the summer season, consisting of three parallel horizontal pipes with an inner diameter of 6 inches and a length of 72 m, buried under a depth of (2.2 and 3.2 m). They found that at an ambient air temperature of 44 ºC, the cooling capacity was 55 W/m^2, and the heat exchanger reduced the temperature inside the building to 26 ºC.

Serageldin et al. [15] studied the thermal parameters of the (EAHE) system experimentally and numerically in dry and hot weather in Egypt. The study was carried out to investigate the impact of various parameters such as length, diameter, material, pipe thickness, and airflow velocity. They have shown that all parameters have a significant effect, except for pipe materials and thickness, which have a negligible impact. Hasan et al. [16] numerically investigated the performance of the EAHE system in hot regions such as Nasiriyah city (Iraq). They found that when the inlet air temperature was 50 ºC, 50 m pipe length, and 3 m burial depth, the EAHE system with a pipe diameter of 150 mm provided the best performance.

Additional research has been conducted in the field of EAHE, mainly to identify the effective parameters of its performance. But it is known that the performance of EAHE depends on some features of the installed location, such as the type of soil, its water content, the vegetation cover, the climate of the region, and the time of the year. The goal of this article is to conduct an experimental and numerical investigation to study the effectiveness of ground cooling systems in a hot and arid area such as Karbala city in central Iraq, which has a temperature of more than 50 ºC and an average of more than 45 ºC during the summer day. The special condition of the soil in this city is so that at a depth of more than 2 m, the soil is fully saturated (full of water), which has not been reported to be studied in previous articles. Finally, based on experimental and numerical data, a correlation is developed for the air outlet temperature from EAHE as a function of different parameters such as inlet pipe temperature, pipe diameter, air velocity, burial depth, soil thermal conductivity, and pipe length. The equation estimates the effect of designing parameters on the EAHE's performance.

2. EXPERIMENTAL SETUP

As previously noted, the EAHE's energy performance mainly depends on climate and soil conditions. As a result, the dynamic thermal behavior of an EAHE is case-sensitive and must be investigated in the context of climate. In this paper, an EAHE system was assembled as a case study in Karbala city, located in the center of Iraq, at 32.37° north latitude and 44.02° east longitude. Karbala has a hot desert climate, with scorching, dry summers, and the average maximum temperature in the summer reaches more than 45 °C and sometimes exceeds 50 °C during July and August. The experimental portion of this study is divided into two parts:

The first stage aimed to measure the ground temperature distribution from the surface to a depth of 7m. Two temperature sensors were used to ensure good measurement accuracy, a K-type thermocouple with 0.5ºC accuracy, and the sensors connected to Multi-Channel Data Logger (Fuji phf61b11).

The second type of sensor is a waterproof sensor connected to the Arduino device. The sensors were installed in an open area, clear of vegetation directly exposed to solar radiation, and the water table at depths of 1 m. The measurement was carried out on (15-30) July 2021, the weather was sunny, and the air temperature in the middle of the day was between (45-50) °C. Table 1 summarized the types of sensors used, their depths, the total error rate for each measurement, and a comparison between some measured temperature measurements for three days in July.

TABLE 1. The temperatures along the depth of 7 m

Depth m	Thermometer type	16 July TºC	17 July TºC	19 July TºC	Total error
Ambient	TPM-10	46.5	48	47	
Surface	TPM-10	59	60	59.3	
0.05	Thermocouple	51	52	51.2	1.9
0.5	Arduino	33.1	32.9	33.1	0.6
0.5	Thermocouple	32.9	33.1	33.4	1.5
1	Arduino	30.6	30.8	30.5	1
1	Thermocouple	31	31.1	31.3	0.95
2	Arduino	27.3	27.4	27.7	1.4
2	Thermocouple	27.7	27.6	28.2	2.1
3	Arduino	25.8	25.5	25.6	1.1
3	Thermocouple	25.5	25.4	25.9	1.5
4	Arduino	23.7	24.7	24.9	4.8
5	Thermocouple	23.7	24.2	24.6	3.6
6	Arduino	23.7	24.1	24.2	2
7	Thermocouple	23.7	23.8	24.1	1.6

Figure 1 shows the distribution of temperature sensors under the ground's surface to a depth of 7 m. It can be observed at a depth of 0.5, 1, 2, and 3 m that two types of Arduino sensors and a thermocouple were installed to compare the measured temperature for both types to obtain the highest measurement accuracy.

Figure 2 shows the temperature distribution of the soil on 17th July 2021 at 14:00, when the ambient temperature was 48°C. A significant increase in surface

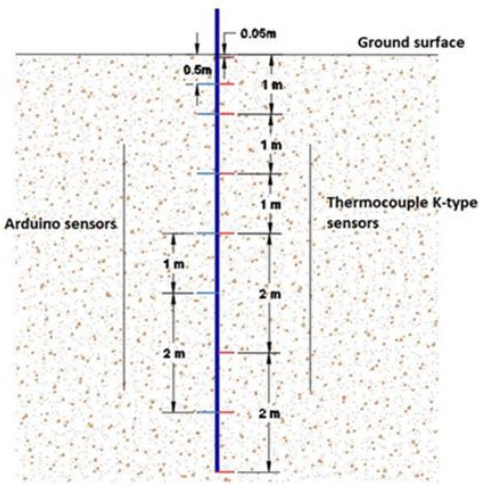

Figure 1. Distribution of temperature sensors under the ground's surface

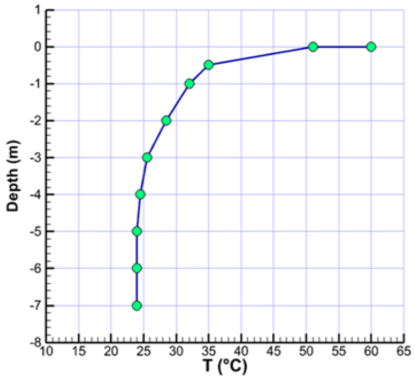

Figure 2. The ground temperature distribution and sensors on 17th July 2021 at 14:00.

temperature can be observed because of direct exposure of the earth's surface to sunlight. The surface temperature reached 60 °C, dropping dramatically from the surface to a depth of 1m to 32 °C. The temperature drops marginally until it arrives at a depth of 4m. After that, the temperature is almost constant and equal to 24°C.

The second stage is aimed at studying the behavior of the Earth-Air heat exchanger. The experimental EAHE setup consists of a horizontal polyvinyl chloride pipe (PVC) with a diameter of 0.1 m and a total horizontal length of 20 m. The pipe is buried at 2 meters in water-saturated soil on a flat area in Karbala city, as shown in Figure 2. The air is blown through the pipe by a blower driven by a 550-W single-phase electric motor (maximum flow rate of 870 m^3/h and a maximum velocity of 2820 RPM) with velocity control. The inlet air temperature and the underground air temperature were measured at the pipe center using the temperature sensors, PT100, and a digital thermometer (TPM-10) with 0.5ºC accuracy, installed in every 3 meters of the pipe, as shown in Figure 3. The temperature is monitored by the Multi-Channel Data Logger (Fuji phf61b11). The airflow velocity and the air temperature at the outlet EAHE system are measured using an anemometer (RZ8901) hang the range of 0–45 m/s and a thermometer with 3% accuracy. The experiment was carried out on days 6, 8, 13, and 30 Aug 2021, when the temperature ranged between 40 and 50 °C.

3. COMPUTATIONAL FLUID DYNAMCS (CFD) MODELING

Computational Fluid Dynamics (CFD) is widely used to solve problems that involve fluid flows. The Navier-Stokes equations are the foundation of practically all CFD issues [17]. Heat transfer affects the soil layer near the EAHE pipe surface. This soil is referred to as thermally disturbed soil, as shown in Figure 4. The thickness of the disturbed soil layer depends on its thermal properties, the temperature difference between the soil and the air passing through the pipe, the airflow velocity, and the operating time of the heat exchanger [18]. According to some academics, the disturbed soil thickness should be equivalent to the pipe radius [7].

Others suggested that the thickness of the soil layer should be twice [19] or four times the pipe radius [16]. The disturbed soil thickness in this research was assumed to be three times the pipe radius.

3-D fluid flow and conjugate heat transfer analyses under temperature conditions are used to model the heat transfer produced by airflow at various temperatures. The conduction heat transfer occurs in the soil and the pipe

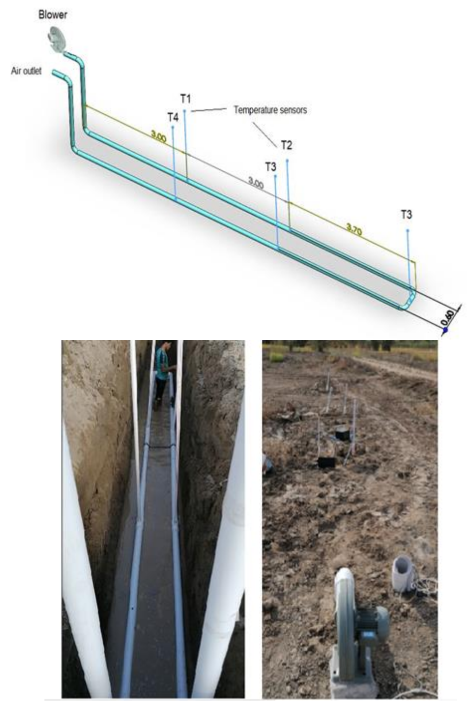

Figure 3. EAHE system layout schematic and stages of construction

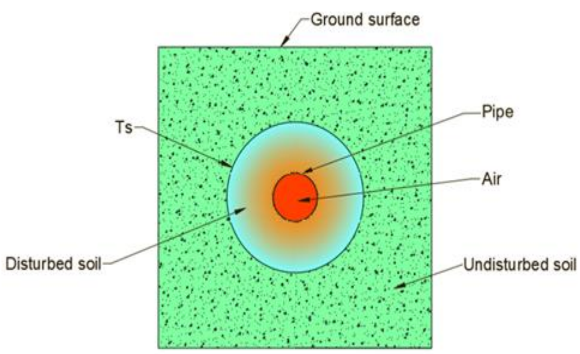

Figure 4. Cross-section showing the disturbed and undisturbed soil around the heat exchanger pipe

wall. The heat exchange between the airflow in the pipe and the pipe wall is dominated by convection heat transfer. The k-omega SST turbulence model is chosen to accurately analyze near-wall(s) conditions and boundary layer evolution [20]. The following are the transport equations [21]:

Continuity equation:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

Momentum equation:

$$\frac{\partial}{\partial x_i}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right) + \frac{\partial}{\partial x_j}\left(-\overline{\rho u_i' u_j'}\right) \tag{2}$$

$$\frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial xi}\left(\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right) + G_k - \rho\beta^* k\omega + S_k \tag{3}$$

$$\frac{\partial}{\partial x_i}(\rho \omega u_i) = \frac{\partial}{\partial x_i}\left(\left(\mu + \frac{\mu_t}{\sigma_\omega}\right)\frac{\partial k}{\partial x_i}\right) + \alpha\frac{\omega}{k}G_k - \rho\beta\omega^2 + S_\omega \tag{4}$$

$$\mu_t = \frac{\rho k}{\omega} \tag{5}$$

$$G_k = -\overline{\rho u_i' u_j'}\frac{\partial u_j}{\partial xi} \tag{6}$$

where k is the turbulence kinetic energy, ω is the specific dissipation rate, σ_ω and σ_k are the turbulent Prandtl numbers for ω and k, respectively, μ_t is the turbulent viscosity, and S_k and S_ω are introduced source terms. For incompressible flow, β^*=0.09 and $\beta = 0.075$. The energy equation for the incompressible and viscous flow of the air, soil, and pipe:

$$U_j\frac{\partial T}{\partial x_j} = \frac{1}{\rho c_p}\frac{\partial}{\partial x_j}\left(k\frac{\partial T}{\partial x_j} - \overline{u_j' T'}\right) \tag{7}$$

$$\frac{\partial}{\partial x_j}\left(k_p\frac{\partial T}{\partial x_j}\right) = 0 \tag{8}$$

$$\frac{\partial}{\partial x_j}\left(k_s\frac{\partial T}{\partial x_j}\right) = 0 \tag{9}$$

where k_p and ks are the pipe and soil thermal conductivity, respectively. The following equation is used to calculate EAHE's cooling capacity:

$$Q = \mathring{m}Cp(T_{in} - T_{out}) \tag{10}$$

$$\mathring{m} = \frac{\pi}{4}D^2\rho V \tag{11}$$

where Q is the cooling capacity of EAHE; $\mathring{m}$ is the air mass flow rate; D is pipe diameter; ρ is air density; V is airflow velocity; Cp is the specific heat of air; Tin is the inlet air temperature, and Tout is the outlet air temperature.

4. BOUNDARY CONDITION

In the CFD simulation investigation of the EAHE system, the following boundary conditions were used:

1. Inlet boundary conditions: the constant inlet air velocity and temperature (Tin) were used. The values of Tin were chosen for the summer season based on the climate conditions of Karbala city in central Iraq.
2. Wall: The conjugate heat transfer model is used to simulate the soil's temperature distribution more realistically in the disturbed region; the temperature Ts is considered constant on the outer surface and equal to the undisturbed soil temperature at that depth (Figure 4).
3. Outlet boundary conditions: The relative pressure at the outlet was assumed to be constant and equal to 0 atm.

The value 1×10^{-6} is used as the convergence criterion for momentum and energy equations.

5. VALIDATION OF THE MODEL

To simulate the process of airflow and heat transfer in the EAHE system, the 3D geometry of both the solid and liquid domains are considered, as shown in Figure 4. A structured grid for soil and the fluid domain reduces the computational time and helps to obtain the most accurate solution. CFD-based analysis was used to calculate the outlet air temperature from EAHE by using ANSYS FLUENT software.

The CFD simulation used the same thermo-physical parameters of the clayey loam soil with high water content as the experiment. Table 2 summarized the thermal properties of air and soil [22]. The soil temperature Ts is constant at the disturbed soil's outer surface and equals 31.5 ºC; it was measured at a depth of 2 m in Karbala city during the summer season. Experimental data was used to validate the numerical model in this research. Because of the high Reynolds number of the flow (2.4×10^4 -1.9×10^5), the turbulent model (k-w SST) was chosen to compute the temperature and velocity of the airflow inside the pipe and the heat transfer in the soil.

Three types of meshes were tested to obtain a precise solution in the proper time. Figure 5(a) compares the experimental and numerical results of the air temperature

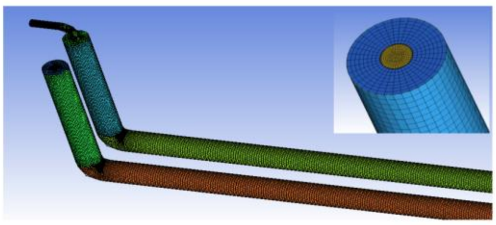

Figure 5. Modeling geometry and mesh of the EAHE

along the EAHE pipe at the air velocity of 5 m/s and the inlet temperature of 49.5 ºC. It can be seen that at the mesh size of 850000, a good agreement between the numerical and experimental results is obtained. Table 3 compares the experimental and numerical results for different air velocities. Figure 5(b) represents compare between the results of the present model and the experimental results of Misra et al. [18]. It can be seen that the current numerical model is in good agreement with the experimental results, and the maximum percentage of error was 3.42%. It can investigate the impact of various parameters on the EAHE system's overall performance.

6. RESULTS AND DISCUSSION

The numerical analysis was carried out to determine the impact of five essential parameters: pipe length, pipe diameter, airflow velocity, soil thermal conductivity, soil temperature, and inlet air temperature of the EAHE system. Because the average temperature in the summer is 45ºC and the in the winter it is 18ºC. The EAHE system has a larger capacity for summer cooling than winter heating under the climatic circumstances of Karbala City [13]. As a result, only summer cooling was considered in the study. The previous heat exchanger design will be studied, but with a 60m pipe length and a distance between the parallel pipes of 1 m. The amount of air exiting the heat exchanger must be sufficient to obtain good cooling capacity in the area at the minimal possible temperature. The EAHE system's performance is improved by increasing the pipes' total surface, which can be enhanced by increasing pipe length and diameter. As a result, the cost rises, so the pipe length should be kept in a proper range. So, we investigate the impact of the previous parameters listed out in Table 4 and the cases to be studied on the outlet air temperature as a function of the pipe length.

TABLE 2. Thermo-physical properties of air and soil

Material	Density (kg/m^3)	Specific heat capacity (J/kg K)	Thermal conductivity (W/m-K)
Soil	2050	1840	1.5
Air	1.225	1006.5	0.0242

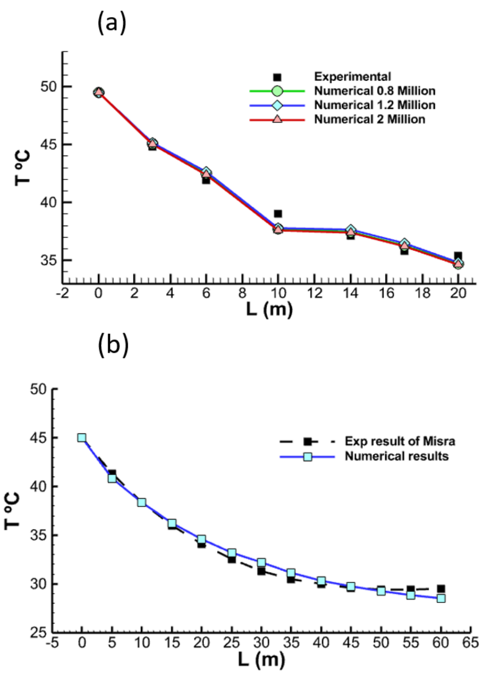

Figure 6. Compares the experimental and numerical results for (a) present experimental for different mesh numbers. (b) Experimental result of (Misra et al.) [18]

Figure 7(a) shows the temperature distribution of air, and adjacent soil layers in the inlet section of the EAHE pipe in the longitudinal plane, with 100 mm pipe diameter, inlet air temperature of 50°C, airflow velocity of 5 m/s, the thermal conductivity coefficient is 1.5 (w/m.k), and soil temperature T_s is 31.5°C. It can be seen that the temperature of the soil adjacent to the pipe increases due to the heat transfer from the hot air passing inside the pipe. In return, the air temperature decreases gradually in the flow direction. The heat transfer in the first meters is significant due to the temperature difference between the air and the soil, and the heat transfer gradually decreases along the length of the pipe. Figure 7(b) shows the air and soil temperature distribution in a radial direction at pipe lengths of 3 m and 17 m, where the temperature in the center of the pipe was 45 and 36 °C, respectively. It is also noted that the temperature of the soil around the pipe at a length of 3 m increased sharply compared to the soil at a pipe length of 17 m. The temperature drop per unit length can be obtained from the following equation:

$$TD = \frac{\Delta T}{\Delta L} = \frac{T_1 - T_2}{L_2 - L_1} \quad (12)$$

Figure 8 depicts the variation in air temperature along the length for pipe diameters 75, 100, 150, and 200 mm V=5m/s, k=1.5 w/m.K, and Ts=25.5°C). It can be observed that the reduction in air temperature is significant at the first 15m for all pipes diameter. The TD value in the first five meters is high, e.g. (3.34, 2.27, 1.6, 1.07) ºC/m for pipe diameters 75, 100, 150, and 200mm, respectively, because the temperature difference between air and soil is significant (24.5°C), which reduces as the length increases. It can also be seen that as the diameter of the pipe increases, the outlet air temperature increases. For a pipe with a diameter of 75 mm, the outlet temperature became 27 °C, and the temperature drop TD was 0.11°C/m at the pipe length of 25 m. The temperature drop can be considered as the criterion for the required length of the EAHE pipe because increasing the length means increasing the EAHE; the length should be as small as possible; for example, it can be regarded that a temperature drops less than 0.15 °C/m may be sufficient to ensure the efficient operation of EAHE. As shown in Figure 8, for D=100 mm, the length of 30 m can be considered sufficient where Tout = 27.8°C and TD=0.15 °C/m. In other words, to achieve a slight enhancement in outlet temperature from this value (27.8°C), a much longer EAHE is needed. For pipe diameters 150 and 200 mm, TD<0.15°C/m when the pipe length is 45 m and 55 m, respectively. So, these lengths are recommended for the conditions mentioned above in Karbala.

TABLE 3. Comparison between the experimental and numerical results for different air velocities

Location	V=5 m/s			6.5 m/s			9 m/s					
	T_{Expe}	T_{Num}	T_{diff}	T_{Expe}	T_{Num}	T_{diff}	T_{Expe}	T_{Num}	T_{diff}	T_{Expe}	T_{Num}	T_{diff}
T_{inlet}°C	49.5	49.5	0	49	49	0	48.5	48.5	0	45	45	0
T1 (3m)°C	44.8	45.1	-0.3	45.1	45.19	-0.09	45.3	45.5	-0.2	43	43.06	-0.06
T2 (6m)°C	41.9	42.49	-0.59	42.8	42.92	-0.12	43.3	43.6	-0.3	41.3	41.87	-0.57
T3 (10m)°C	38.6	37.72	0.88	39.2	38.45	0.75	39.6	39.52	0.08	37.8	39.05	-1.25
T4 (14m)°C	37.1	37.48	-0.38	38.1	38.24	-0.14	38.9	39.37	-0.47	37.1	38.96	-1.86
T5 (17m)°C	35.4	36.29	-0.89	36.6	37.06	-0.46	37.1	38.22	-1.12	35.5	38.1	-2.6
T_{out}°C	35.4	34.7	0.7	35.2	35.39	-0.19	35.5	36.5	-1	35	36.73	-1.73

TABLE 4. EAHE system variable at different levels

Location	Symbol	Level											
		1	2	3	4	5	6	7	8	9	10	11	12
Diameter of EAHE pipe (mm)	D	75	100	150	200								
Airflow velocity (m/s)	V	5	7.5	10	15								
Thermal conductivity of soil (W/m K)	Ks	0.5	1	1.5									
Inlet air temperature (ºC)	Tin	35	40	45	50								
Soil temperature (ºC)	Ts	25.5	30										
pipe length (m)	L	5	10	15	20	25	30	35	40	45	50	55	60

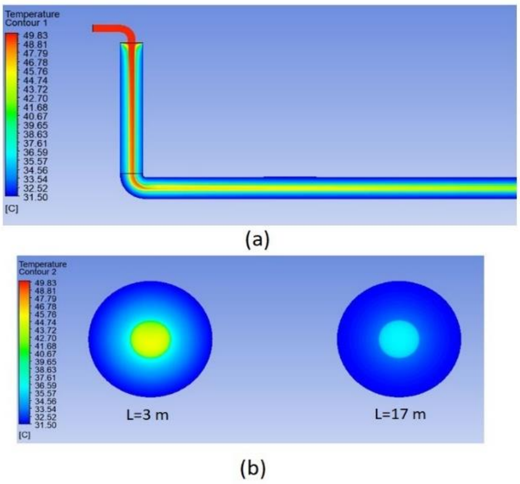

Figure 7. Temperature contours of EAHE pipe for air and disturbed e (a) longitudinal plane at the Inlet section (b) Perpendicular plan to the airflow at horizontal lengths 3m and 17m

When the diameter of the pipe increases, the contact surface between the pipe and the soil increases, leading to a rise in the heat transfer between the air and the soil;

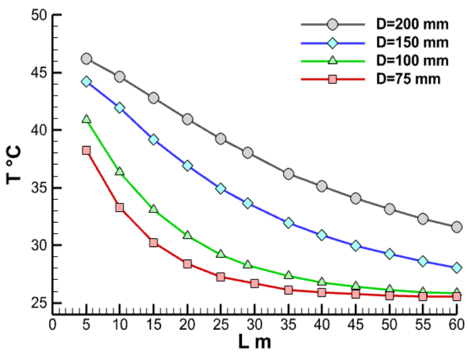

Figure 8. The temperature along pipe length for different diameters at 5 m/s airflow velocity and 50 ºC inlet air temperature

for the same airflow velocity, the volumetric flow rate inside the pipe will be greater, causing a rise in outlet air temperature (Eq. 10). In most cases, the heat transfer through the soil is not fast enough for this amount of air, which causes an increase in the outlet air temperature. Therefore, considering the economic cost, the airflow rate and pipe diameter should be optimized when designing the heat exchanger.

Figure 8 shows the effect of the soil thermal conductivity on the air temperature along the EAHE pipe of 100mm diameter at the inlet air temperature of 50 ºC and 5 m/s airflow velocity. It was observed that with increasing the soil thermal conductivity, the outlet air temperature decreases because the heat transfer rate inside the soil increases, leading to improvement in the performance of the heat exchanger. When the thermal conductivity of soil is 1 and 1.5 (W/m K), the outlet air temperature at the length of 35 m is 28.27 and 27.25°C, respectively, and the TD<0.13°C/m; this length can be considered sufficient, but when the thermal conductivity is 0.5 (W/m K), the acceptable pipe length is 45 m where the outlet air temperature is 29.4°C at this length. So changing the soil type from dry one (k=0.5 W/m K) to saturated one (case of Karbala city, k=1.5 W/m K) causes about a 25% reduction in the length of the pipe.

The influence of airflow velocity on the outlet air temperature when Tin=50 ºC and k=1.5 W/m K is shown in Figure 9. It can be seen that when the airflow velocity increases, the time that air remains in contact with the soil decreases, causing the outlet air temperature to rise. On the other hand, increased air velocity leads to a higher mass flow rate, leading to increased heat transfer between soil and air, as shown in Equation (10).

It can also be seen in the figure that TD<0.15 when the length of the pipe is 35, 36, 40, and 45 m at the airflow velocity is 5, 7.5, 10, and 15 m/s, respectively, and the outlet air temperature in these cases is 27.3, 28.5, 28.9, and 30°C, respectively.

As a result, it is recommended that the airflow velocity be optimized to get the most out of the EATHE system.

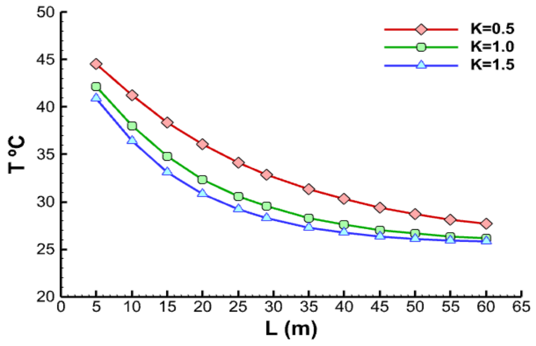

Figure 9. Air temperature distribution along the EAHE pipe at 50°C inlet temperature and 5 m/s airflow velocity for three soil thermal conductivity K (0.5,1,1.5) (W/m K)

Many parameters affect soil temperatures (Ts), such as soil type, ground surface cover, solar radiation, water content, geographical location, and depth from the ground surface. Figure 10 compares the outlet temperature for two soil temperatures (Ts), 25.5 and 30ºC, at the 5 m/s airflow velocity with 100 mm pipe diameter and 50ºC inlet air temperature. The significant effect of Ts on the EAHE system's outlet air temperature can be observed. As the soil temperature decreases, the outlet air temperature of the EAHE system decreases. TD is lower than 0.15 at a pipe length of 35 m in both cases, but the outlet air temperature at this length is 27.25℃ and 31.5℃ when Ts equal 25.5℃ and 30℃, respectively. Therefore, to improve the performance of the heat exchanger, Ts should be as low as possible.

6. 1. Outlet Air Temperature Equation Previously, the effect of different parameters on the performance of the heat exchanger was discussed; all these parameters can effectively improve the system's performance. In this part of the research, we will try to find an equation that links all these variables shown in Table 4 as a function of the outlet air temperature. The parameters mentioned in the table are considered independent variables of the EAHE system. More than 100 simulated cases were conducted, and 1100 outlet air

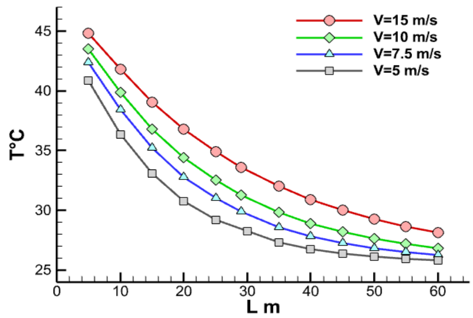

Figure 10. Outlet air temperature under the different air velocities with 100 mm pipe diameter, 50°C inlet air temperatures, and soil thermal conductivity is 1.5 (W/m K)

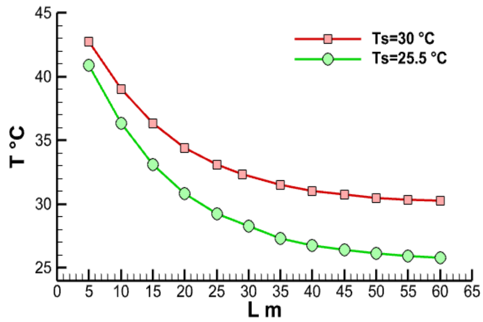

Figure 11. Outlet air temperature under the two soil temperatures (Ts) 25.5and 30 ºC with 100 mm pipe diameter and 50ºC inlet air temperatures

temperature values were recorded. Designed experiments type screening was used to find an equation that relates all the variables as a function of the outlet temperature using the Minitab 19 program. Screening designs are the most widely used designs for industrial experimentation. Screening designs typically require fewer trial runs than other designs. It contains three levels per continuous factor to estimate square and linear terms. The temperature equation was obtained as a function of the six variables as follows:

$$T_{out} = 0.93 + 45.2D + .6679T_{in} + 0.3375V - 0.3067L - 1.211K_s + 0.002925L^2 + 0.2862DL - 0.008792T_{in}L - 0.02687LK_s + 0.01217LT_s \quad (13)$$

It should be noted that depending on the influence of the variables, certain parts of the equation have positive and some others have negative impacts; for example, as the length of the pipe increases, the temperature decreases, making its value appear as negative, and so on for the other variables. Also, it can be found that only the parameter L's behavior in the equation is nonlinear. Figure 12 compares the current model with the EAHE outlet air temperature experimental result of Misra et al. [18] (Figure 12(a)) for an air velocity of 5 m/s, 45 ºC inlet air temperature, and soil temperature of 27 ºC., and also that of Agrawal et al. [11] (Figure 12(b)) for an air velocity of 3.5 m/s, 38.1 ºC inlet air temperature and soil temperature of 22 ºC, and present experimental result (Figure 12(c)). The results confirm that this equation is valid and can be used to estimate the air temperature outlet of the EAHE system for different cases of similar models.

It is essential in designing the earth-to-air heat exchanger to obtain the lowest temperature and maximum airflow leading to the highest cooling capacity of the outlet ail. The length of the pipe should be as small as possible from the economic and occupying space point of view. So, EES (Engineering Equation Solver) software was used to find where the outlet temperature reaches a specific value. Figure 13(a) shows the length of the pipe to get a suitable outlet air temperature (T_{out}) at different airflow velocities (V). The relationship between L and V for four outlet temperature values 26, 27, 28, and 29ºC are displayed, while the K_s, T_{out}, T_s, and D are 1.5 (W/m K), 50ºC, 25.5ºC, and 0.075m, respectively. As expected, it can be seen that when the T_{out} decreases, the length of the pipe increases. Curves are approximately linear, and similar behavior is expected to be observed at different velocities. Figure 13(b) represents the relationship between V and L under the same conditions as the previous case but at D=0.2 m. Compared to Figure 13(a), it is noticed that the length needed to reach the desired T_{out} value increases significantly by increasing D. An asymptotic behavior is seen at higher velocities and lengths. For example, at a velocity of 12.5 m/s, a 60m length of pipe is required to achieve the T_{out} of 28ºC. For T_{out}=27 and 26ºC, the equation could not find a length of

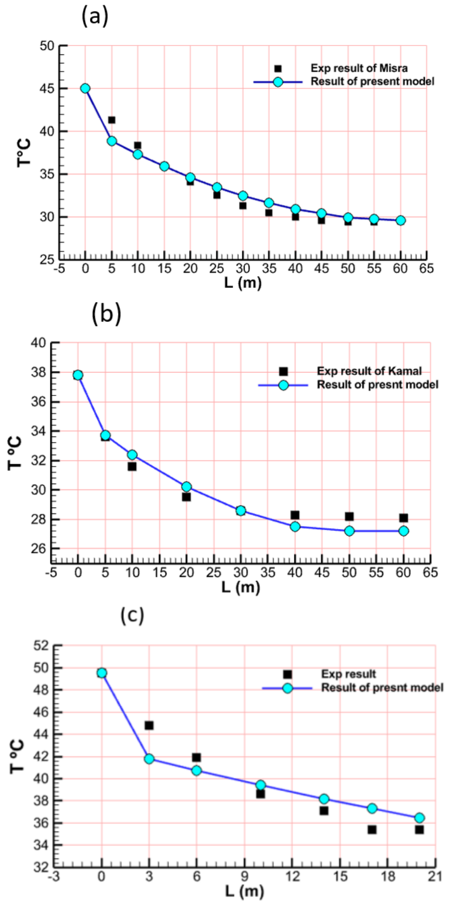

Figure 12. Compares the current model with the experimental result of (a) (Misra et al.) [18]. (b) (Kamal et al.)[11]. (C) The present experimental result

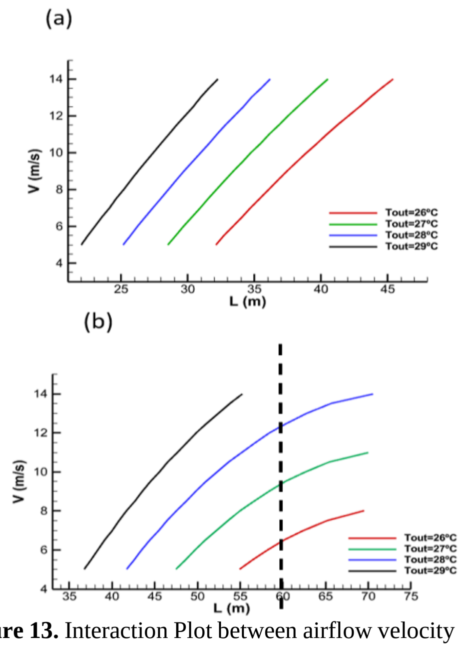

Figure 13. Interaction Plot between airflow velocity V and pipe length L when Tout=26,27,28 and 29 ºC for (a) pipe diameter 0.075 m and (b) pipe diameter 0.2 m

the pipe in the desired limit at a velocity higher than 9.5 and 6.5m/s, respectively. For these cases, a pipe longer than 60m is needed to obtain the desired T_{out}.

The minimum length required for all the considered T_{out} values in the figure is 23.5 m for D=0.075m and 36m for D=0.2m. The length needed to reach 26 ºC, 27 ºC, 28 ºC, and 29 ºC at a velocity of 6m/s is 38.2m, 43.3m, 49.9m, and 58.2m, respectively. It means that to decrease the outlet temperature 1ºC, 16.6%, 14.7%, and 13.8% increase in the length is required for T_{out} values of 27 ºC, 28 ºC, and 29 ºC. While these values change to 39.9m, 45.2m, 52m, and 62.1m for the velocity of 7m/s, requiring 19.4%, 15%, and 13.2% increase in the length to achieve 1ºC reduction in outlet temperature.

All the T_{out} values (26 ºC, 27 ºC, 28 ºC, and 29 ºC) can be achieved for D=0.075 in lengths lower than 60m, while for D=0.2, only T_{out}=29 ºC can be achieved in a length shorter than 60m, and other T_{out} values may not be achieved in some higher velocities.

Figure 14(a) shows the relationship between Tin and pipe length for two pipe diameters of 0.1m and 0.15m, hen T_{out}, T_{in}, T_s, V, and Ks are 28ºC, 50 ºC, 25.5 ºC, 7.5 m/s, and 1.5 (W/m K), respectively. It is noted that when the T_{in} increases, the length required to obtain a specific Tout value will be increased; for example, to get T_out= 28 ºC at T_in= 50ºC, the length of the pipe is expected to be 31m at a D= 0.1 m, while for the D=0.15 m it will

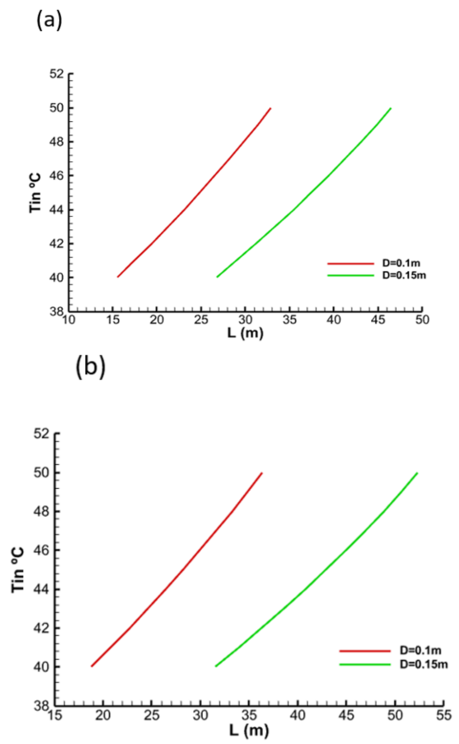

Figure 14. Interaction Plot between inlet temperature Tin and pipe length L when Tout=28 ºC and pipe diameter D=0.1and 0.15 m at (a) airflow velocity V=7.5 m/s and (b) airflow velocity V=10 m/s

be 46 m. For the same conditions and at a velocity of 10 m/s, as shown in Figure 14(b), the length required to obtain a T_{out} of 28 ºC increases compared to the previous case, the pipe length of 37 m and 53 m for T_{in} of 50 °C and a pipe diameter of 0.1 m and 0.15 m is required, respectively. The rate of increase is higher for the diameter of 0.1 m (19%) rather than 0.15m (15%).

7. CONCLUSION

Experimental and numerical studies have been conducted to investigate the effect of design parameters (pipe diameter, pipe length, inlet air temperature, soil temperature, airflow velocity, and soil thermal conductivity) on EAHE system performance in hot and dry climates. Since the temperature distribution varies based on the type of soil and the season, it was measured in an open area clear of vegetation in the city of Karbala (Central Iraq) as the first experimental activity. It has been observed that the temperature decreases with increasing depth, the temperature of the soil remaining constant after a depth of about 4 m. An EAHE system was installed in the Karbala, and the effect of different parameters was experimentally investigated. To reduce the cost of study and extend the number of parameters to be considered and their range, a 3D model is created based on the experimental results performed to study the effect of different parameters. The simulation results were compared to experimental results, which were in good agreement. The following conclusions have been drawn based on the numerical and experimental results.

With increasing the length of the pipe, the outlet air temperature of the EAHE system decreases, and the heat transfer grows to a certain length beyond which the change is very slight (asymptotic behavior). For example, for a pipe diameter of 100 mm at a depth of 3 m and thermal conductivity of 1.5 (W/m K), the pipe length of 35 m was sufficient when using an air velocity of less than 10 m/s.

The heat transfer rate rises, and the outlet air temperature grows with the increase in air velocity. An airflow velocity of less than 7m/s can be used to cool enclosed and small spaces when a small mass flow rate of air at a relatively low temperature is required and vice versa. Using an air velocity higher than 15m/s is not recommended because the outlet air temperature does not drop much, especially when using a relatively large pipe diameter. For example, at a pipe diameter of 0.2m, airflow velocity of 15m/s, and inlet air temperature of 50 ºC, the outlet air temperature at a length of 60m was as high as 38 ºC.

The outlet air temperature decreases with decreased pipe diameter. According to the results of this study, it is preferable to use a pipe diameter of 0.1 m to cool closed areas in the city of Karbala since it was able to prepare air with a temperature of less than 29 ºC at a velocity of

10m/s, a pipe length of 40 m, and an ambient temperature of 50 ºC.

The heat transfer is enhanced, and the outlet air temperature decreases when the soil is fully saturated since its thermal conductivity increases with water content. The soil temperature dramatically affects the performance of the heat exchanger, which depends mainly on the depth of pipe burial. The heat transfer increases when the soil temperature decreases.

Based on the experimental and numerical results, an approximate equation was constructed to evaluate the EAHE system outlet air temperature as a function of the pipe diameter, pipe length, inlet air temperature, soil temperature, airflow velocity, and soil thermal conductivity ($T_{out} = f(T_{in}, D, L, K_s, T_s)$). Also, a code is written in EES (Engineering Equation Solver) to find the location at which the air temperature reaches a certain value.

Using the obtained equation, it was found that although all considered T_{out} values can be achieved for lower diameters of the pipe (such as 0.075 m) in the desired lengths (lower than 60m), for higher diameters (such as 0.2 m), some lower T_{out} values (26 ºC and 27 ºC) may not be achieved in velocities more than 10 m/s. The heat EAHE can be used in places with a high temperature of 50 ºC for cooling purposes and to obtain air at a temperature of 27 ºC. It is proposed as future work to investigate the possibility of using the EAHE to ventilate and cool open areas.

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Persian Abstract

چکیده

انرژی زمین گرمایی کم عمق، توسط مبدل حرارتی زمین به هوا (EAHE)، برای خنک کردن ساختمان ها با حداقل مصرف انرژی استفاده می شود. پارامترهای مهمی که بر عملکرد مبدل حرارتی تأثیر می‌گذارند باید بررسی شوند تا طراحی مناسبی به دست آید. انرژی زمین گرمایی کم عمق، توسط مبدل حرارتی زمین به هوا (EAHE)، برای خنک کردن ساختمان ها با حداقل مصرف انرژی استفاده می شود. پارامترهای مهمی که بر عملکرد مبدل حرارتی تأثیر می‌گذارند باید بررسی شوند تا طراحی مناسبی به دست آید. این مقاله به صورت عددی و تجربی تأثیر قطر لوله، طول لوله، دمای هوای ورودی، دمای خاک، سرعت جریان هوا و هدایت حرارتی خاک را بر عملکرد مبدل حرارتی در شرایط آب و هوایی گرم و خشک بررسی می‌کند. توزیع دمای خاک از سطح زمین تا عمق ۷ متری در شهر کربلا (مرکز عراق) در فصل تابستان اندازه گیری شد. آزمایش تجربی برای EAHE در خاک اشباع شده از آب و دمای هوای محیط ٤١ درجه سانتیگراد، ٤٥ درجه سانتیگراد و ٤٩.٥ درجه سانتیگراد با چهار سرعت مختلف انجام شد. درصد کاهش در دمای هوای خروجی EAHE در ۹ متر بر ثانیه به ترتیب ۲۸.۳٪، ۲۵.۵٪ و ۱۹.۵٪ بود. همچنین مدل سه بعدی ایجاد شد و نتایج شبیه سازی با نتایج تجربی که تطابق خوبی داشتند مقایسه شد. معادله ای برای دمای هوای خروجی به عنوان تابعی از قطر و طول لوله، دمای هوای محیط، دمای خاک اطراف لوله و هدایت حرارتی خاک پیدا شد. معادله به‌دست‌آمده با نتایج تجربی فعلی و نتایج تجربی متون داده‌های گزارش‌شده مقایسه شد. در نتیجه توافق بسیار خوبی مشاهده شد. نتایج نشان داد که پارامتر Lطول لوله قوی ترین رفتار غیرخطی را در معادله ایجاد می کند. برای موارد در نظر گرفته شده، در قطرهای ۷۵ و ۱۰۰ میلی متر، یک رفتار خطی تقریبی برای طول مورد نیاز برای دستیابی به دمای خروجی خاص مشاهده شد. از نتایج به دست آمده می توان نتیجه گرفت که تغییر نوع خاک از خشک (k=0.5 W/m K)به خاک اشباع مورد شهر کربلا، (k=1.5 W/m K)باعث کاهش حدود ۲۵ درصدی طول خاک شد. لوله. همچنین، نتایج نشان داد که در سرعت هوای ۷ متر بر ثانیه، طول مورد نیاز برای به دست آوردن ۲٦ درجه سانتی گراد در خروجی EAHE 1/62 متر است که ٥٥ درصد بیشتر از حالت ۲۹ درجه سانتی گراد (۳۹/۹ متر) است.