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# Thermal Performance of Earth Air Heat Exchanger for Geothermal Energy Application in Hot Climate using CFD Simulation

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**ABSTRACT**

The Ground Air Heat Exchanger (GAHE) is a sustainable, environment friendly, and efficient device that can be used for both heating and cooling applications. Careful design of GAHE enables efficient exploit of the earth interior energy. The design of a GAHE relies on the constant temperature of the earth interior which allows consistent and reliable source of geothermal energy. By harnessing this renewable energy, a sustainable solution for heating and cooling needs is attained while minimizing the impact on environment. In this study, the performance of GAHE was examined using ANSYS Fluent 19 R1 and SOLID WORK 16.0 software. The efficiency and Coefficient of Performance (COP) of the ETHE have been investigated. The effect of air flow rate and operation conditions on the outlet air temperature have been studied. GAHE is made of Polyvinyl Chloride (PVC) pipe of 0.1 m diameter, 0.005 m thickness and 18 m horizontal length. Computer simulations were carried out for five different air velocities (1, 2, 3, 4, and 5 m/s) at various operation conditions. Results show that the 18 m pipe length is adequate to attain useful air outlet temperature giving COP values between 0.5 and 1.3. The length of the horizontal part of GAHE can be further increased for air velocities between 3 and 5 m/s. Comparison between the results obtained by the CFD model and experimental work demonstrated that the CFD model is capable of producing results with acceptable accuracy. This suggests that the CFD software can accurately model the performance of the GAHE under different operation conditions. Increasing the length of the horizontal part of the GAHE can improve its COP when higher air velocities are used.

## 1. Introduction

Energy source security is a vital purpose of energy strategy in countries across the world. Global energy security is one of the key concerns as it depends on the concentrations of the energy supplies political pressure from energy exporters [1]. The energy management system (EMS) can be used to optimize renewable energy resources as well as monitor and schedule household appliances to save energy costs [2]. Importance of studying renewable energy and employ its advantages to cope with climatic changes is significantly expanding. Resilience of a country, influenced by energy security.

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Much of the world's energy comes from fossil fuels, owned by a few countries, at prices that fluctuate and damage the environment. To overcome energy dependence and reduce environmental damage, many countries turn to renewable energy [3]. Renewable energy systems have gained popularity in recent years due to their ability to provide sustainable and efficient heating and cooling solutions [4]. The Ground Air Heat Exchanger (GAHE) is one of the promising applications to make use of earth thermal potential. The geothermal energy can be either passively or actively conveyed from the ground to the earth surface.

Analytical models provide the solution of simplified equations based on fundamental principles, while numerical models utilize computational methods to solve complex heat transfer equations [5]. Both types of models have their advantages and limitations, and researchers continue to improve and validate them through experimental data [6]. However, numerical models typically require longer calculation times due to their complex algorithms and computational requirements. Additionally, the implementation of numerical models may require specialized software and expertise, making them less accessible for some users [7,8]. On the other hand, Analytical models typically have very short calculation times and can be easily integrated into existing with programs. However, the simplifying assumption used in analytical models may decrease the accuracy of the results obtained [9,10].

The present study model aims to numerically predict the heat transfer performance of GAHE system in Iraq climate at summer season. The numerical model established by ANSYS 2019 R1 – Fluent which is identical with the experimental work established by Lattief *et al.,* [11]. The heat transfer through the GAHE is the total thermal energy loss from air due to temperature difference, Figure 1 shows the representation of thermal model of a GAHE.

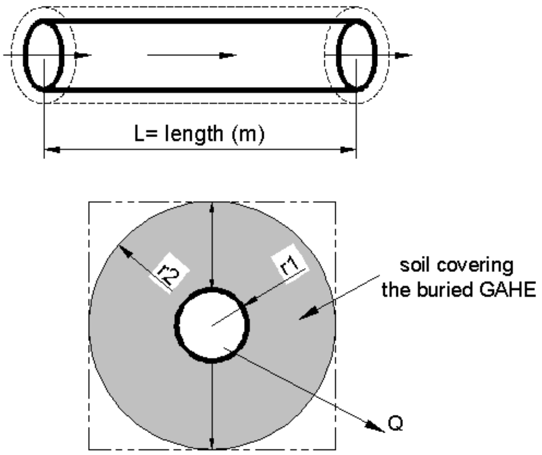


**Fig. 1.** Cross section for the configuration of three domain of the case study [4]

The heat transfer from air to the soil acress the PVC pipe the tatal heat transfer can expressed as

$$q = \dot{m} \times c_p \times \Delta T \tag{1}$$

This thermal energy is equal to the net heat transfer from air to the pipe and from pipe to the soil as consequence of temperature difference. It is represented as illustrated in Figure 2.

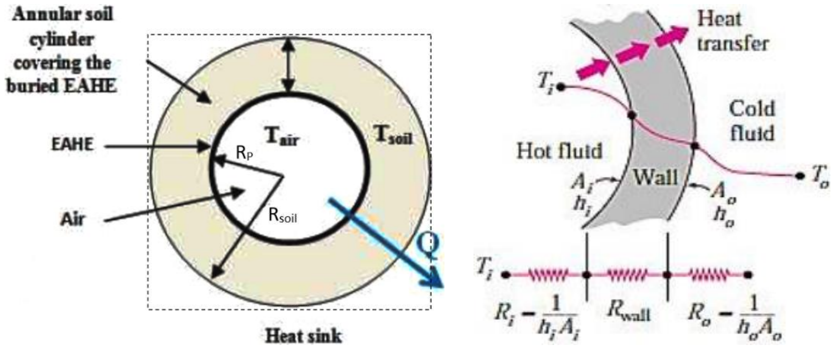


**Fig. 2.** Longitudinal schematic representation of a GAHE [4]

$$R_{air} = \frac{1}{h_i 2\pi L r_i} \tag{2}$$

$$R_{pipe} = \frac{\ln\frac{r_{o\,pipe}}{r_{i\,pipe}}}{2\pi k_{pipe} L} \tag{3}$$

$$R_{soil} = \frac{\ln\frac{r_{osoil}}{r_{i}soil}}{2\pi k_{soil} L} \tag{4}$$

$$R_{total} = R_{air} + R_{pipe} + R_{soil}$$

$$R_{total} = \frac{1}{h_i 2\pi L r_i} + \frac{\ln\frac{r_{o\,pipe}}{r_{i\,pipe}}}{2\pi k_{pipe} L} + \frac{\ln\frac{r_{osoil}}{r_{i}soil}}{2\pi k_{soil} L} \tag{5}$$

$$Q = \dot{\mathrm{m}} \times \mathrm{c_p} \times \Delta\mathrm{T} = \frac{\Delta T}{R_{\ total}} \tag{6}$$

Many studies studying GAHE systems under various climates and regions have been published [12]. Agrawal *et al.,* [13] suggested that the earth tube heat exchanger ETHE must be kept at a depth of 3–4 m because temperature of the soil in depth more than 4m does not significantly change. Instead, it only raises the cost. Bansal *et al.,* [14] investigated the effect of material of buried pipe and air velocity on the heat performance of GAHE system in cold region. Two horizontal pipes one made of PVC and the other of mild steel with 0.15 m inner diameter and length of 23.42 m were buried under depth of 2.7 m in a flat dry soil land. The observed temperature rise in the range of (4.1-4.8) °C for the flow velocities 2–5 m/s and the mild steel pipe is more suitable than the PVC pipe for these applications. Greco and Masselli [15] analyzed the geometrical characteristics such as the pipe length, diameter, and depth in the soil to determine the efficient design of GAHE system under different operation condition such as air temperature and velocity to control the thermal performance systems. Wu *et al.,* [16] numerically investigated the thermal performance and cooling capability of GAHE systems. The numerical model based on computational fluid dynamics (CFD) by using superposition technology for evaluating the effects of the operating parameters (i.e., the pipe length, radius, depth, and air flow rate) on the thermal performance and cooling capacity of the GAHE. A daily cooling capacity up to 74.6 kWh can be obtained from an earth–air–pipe system installed in Southern China. Xamán *et al.,* [17] performed a numerical study to evaluate the effect of thermal insulation thickness on the thermal performance of GAHE work under a humid-hot climate. The insulation fixed on the outlet section of the GAHE. The higher insulation thickness did not significantly improve the cooling or heating capacity of the GAHE, while the insulation with thickness of 0.05 m improves the heating air temperature at the outlet by 2.6°C and cooling air temperature by 1.3°C compared to the case without insulation. Bisoniya [18] established a one-dimensional model of the GAHE systems utilizing a set of equations for simplified design for calculating the earth's undisturbed temperature (EUT). To ensure greater accuracy, more recently developed correlations for friction factor and Nusselt number are used in the calculations. The main conclusion is that a longer pipe of smaller diameter buried at a greater depth and having lower airflow velocity results in an increase in performance of the EAHE system. Ali *et al.,* [19] developed a MATLAB model to investigate the effect of designs of the GAHE system for heating and cooling application. The airflow velocity considers the impact parameter for analyzing and evaluating the GAHE. It observed that air flow velocity reduced from 77.05 m/s to 0.1926 m/s when the diameter increased from 0.1 m to 2 m. Zhou *et al.,* [20] created 3-D numerical model by using ANSYS- FLUENT to simulate the proposed cylindrical phase change material-assisted GAHE (CPCM-GAHE). The results show that PCM improves the heat transfer through the GAHE most of the time, in addition delaying its transition from heating to cooling mode while accelerating its transition from cooling to heating mode. Gan [21] developed a computer program for modeling and simulation heat and moisture transfer in soil in addition for evaluation the thermal performance of GAHE. The developed model has been considering the dynamic variations in climatic, load, and soil conditions. It founding that, the important of dynamic interactions between the three parameters (heat exchanger, soil, and atmospheric conditions) in the evaluation of GAHE. Niu *et al.,* [22] Developed a one-dimensional steady-state model to simulate and predict the cooling capacity and the thermal performance of the GAHE considering the heat and mass transfer between air and pipe. The model was calibrated by comparing it to experimental data from a previous renewable energy testing facility. A polynomial regression models for predicting the cooling capacities including total, sensible and latent cooling capacity with high accuracy were obtained. Astina and Nugraha [23] developed a numerical model for simulation of the GAHE in Indonesia. The simulation equipped a 12 $m^3$ of soil used as a heat exchange medium which exchanging heat with pipes surface area of 24.4 $m^2$. The cooling capacity obtained was 1,002–1,282 watts, depending on soil condition. Increasing the airflow velocity as well as pipe diameter led to a reduction of average temperature difference by 47.2% per m/s. In the case of increasing the thickness of pipe and soil depth, the average temperature difference increased by 6.06% per meter.

Despite extensive research work in geothermal areas, the majority of the published papers considered low seasonal variation in temperature. In this paper, a 3-D numerical model will be developed using ANSYS-FLUENT 2019R1 to predict the GAHE thermal performance and temperature distribution along PVC pipe buried at a depth of 4 m in humidified soil. The GAHE will be studied under the continuous high-temperature weather in Baghdad City, Iraq during summer to evaluate its cooling performance. The parametrical study such as temperature and velocity distribution along the GAHE will be validated with experiment results recorded in reference 8. The numerical model in the present study investigated other parameters have reasonable influence on the thermal performance of GAHE, these parameters can be summarized as follow

i. The effect of the soil temperature variation in vertical direction along the inlet and outlet pipes which represented the depth of buried pipe of GAHE.
ii. The thickness of soil surrounding the pipe of GAHE is taken as 500 mm, thus the simulation will be more accurate and reality.
iii. The pipe thickness is considered although it is very small comparing with other geometry.

## 2. Computational Methodology

The governing equations in any flow/heat transfer problem involve continuity, Navier-Stokes equations, and energy equations. Time-averaged Navier-Stokes equations of fluid flow called Reynolds-averaged Navier-Stokes (RANS) equation. For incompressible flow, the continuity and RANS equations can be written as [24,25].

### *2.1 Governing Equation*

The following governing equations have been solved in the present study.

(i) Continuity equation

$$\rho\left[\frac{\partial}{\partial \mathrm{x}}(\mathrm{u})+\frac{\partial}{\partial \mathrm{y}}(\mathrm{v})+\frac{\partial}{\partial \mathrm{z}}(\mathrm{w})\right]=0 \quad (7)$$

(ii) Momentum equation

The numerical solution has been recognized with 3-D, thus the momentum equation is characterized in three directions of x, y, and z as follows

<u>x-momentum equation</u>

$$\rho\left[\frac{\partial}{\partial x}(uu)+\frac{\partial}{\partial y}(vu)+\frac{\partial}{\partial z}(wu)\right]=-\frac{\partial p}{\partial x}+(\mu+\mu_t)[\frac{\partial u^2}{\partial x^2}+\frac{\partial u^2}{\partial y^2}+\frac{\partial u^2}{\partial z^2}] \quad (8)$$

<u>y-momentum equation</u>

$$\rho\left[\frac{\partial}{\partial x}(uv)+\frac{\partial}{\partial y}(vv)+\frac{\partial}{\partial z}(wv)\right]=-\frac{\partial p}{\partial y}+(\mu+\mu_t)[\frac{\partial v^2}{\partial x^2}+\frac{\partial v^2}{\partial y^2}+\frac{\partial v^2}{\partial z^2}] \quad (9)$$

<u>z-momentum equation</u>

$$\rho\left[\frac{\partial}{\partial x}(uw)+\frac{\partial}{\partial y}(vw)+\frac{\partial}{\partial z}(ww)\right]=-\frac{\partial p}{\partial z}+(\mu+\mu_t)[\frac{\partial w^2}{\partial x^2}+\frac{\partial w^2}{\partial y^2}+\frac{\partial w^2}{\partial z^2}] \quad (10)$$

(iii) Energy equation

$$\rho\left[\frac{\partial}{\partial_x}(uc_PT)+\frac{\partial}{\partial_y}(vc_PT)+\frac{\partial}{\partial_z}(wc_PT)\right]=\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)-\frac{\partial}{\partial x_i}(\frac{\partial T}{\partial x_i}\frac{c_p\mu_t}{\sigma_t}) \quad (11)$$

The pressure, velocity, temperature, and turbulence parameters were represented in terms of local turbulence kinetic energy (k) and diffusion rate (ε) for each node in the computational domain. The turbulent viscosity is equal to $\mu_t=\rho c_\mu\frac{k^2}{\varepsilon}$ , k is $k=\frac{1}{2}u'^2$ and ε is dissipation rate, thus the effective viscosity is given as

$$\mu_{eff}=\mu+\ \mu_t \quad (12)$$

The turbulence model adopted in this investigation was the k-epsilon technique ·The realizable k-epsilon turbulent model was employed to solve the turbulence energy and diffusion rate terms. The realizable model is more popular and accurate for flow separation, re-attachment, and intricate secondary flows than the standard k-epsilon technique [24]. The following extra equations are resolved in the realizable k-epsilon technique to calculate the kinetic energy and dissipation rate, respectively

$$\rho\frac{\partial}{\partial x_j}\left(ku_j\right)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon-Y_M+S_K \qquad (13)$$

$$\rho\frac{\partial}{\partial x_j}\left(\varepsilon u_j\right)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+\rho C_1 S_\varepsilon-\rho C_2\frac{\varepsilon^2}{k+\sqrt{\nu\varepsilon}}+C_{1_\varepsilon}\frac{\varepsilon}{k}C_{3_\varepsilon}G_b+S_\varepsilon \qquad (14)$$

The details of each term of these equations and the constants were given in the study by Zhang *et al.,* [7] contains the details of the terms and constants used in the equations.

### *2.2 Numerical Methodology*

The case study was modeled and solved depend on the Finite Volume Method (FVM) approach. The three-dimensional geometry was established by utilized the solid work 2016 software. The numerical model solved by utilizing the ANSYS 19 R1 -FLUENT.

The available solution approach of the 3-D model to simulate the fluid motion, and heat transfer, and the computational grid must adapt to the solver method employed [4].

#### *2.2.1 Description of physical model*

The physical model of case study includes three parts can be described as follow

i. The Soil: represent a constant temperature domain which surrounding (perfect contact) the pipe of GAHE.
ii. Ground air heat exchanger GAHE: this is the main part that is represented by PVC pipe with inner diameter of 0.05 m and thickness of 0.005 m and the total effective length of pipe is equal to 28 m.
iii. The air: is the high temperature media pass through the GAHE pipe with different velocities. The heat transfer between the air and soil through the pipe wall as consequence of temperature difference.

The properties of the material are listed in the Table 1.

**Table 1**
Properties of material used in the physical model [26]

| Domain | Density ($\rho$) Kg/m$^3$ | Specific heat ($cp$)j/kg-k | Thermal conductivity ($K$) W/m-k | Viscosity ($\mu$) m$^2$/s |
|---|---|---|---|---|
| soil | 1549.81 | 1474.6 | 1.528 | - |
| Pipe (PVC) | 1330 | 950 | 0.16 | - |
| Air | 1.225 | 1006.4 | 0.0242 | $1.789\times10^{-5}$ |

The arrangement of three parts is illustrated in Figure 3.

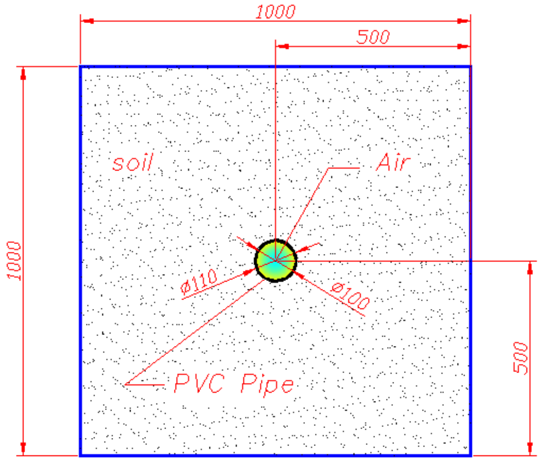
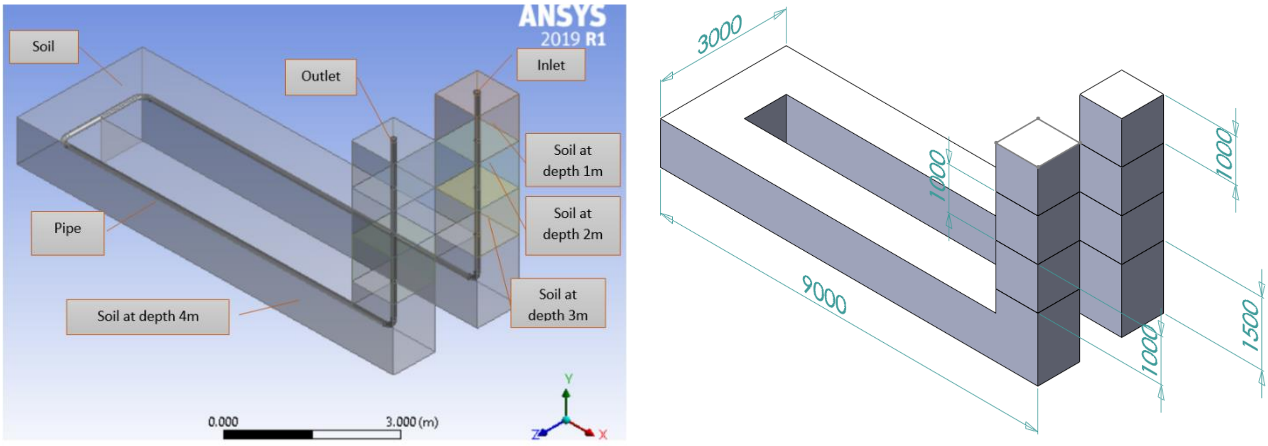


**Fig. 3.** Cross section for the configuration of three domain of the case study

### *2.3 Geometrical Setup and Boundary Conditions*

### *2.3.1 The geometry*

The 3-D geometry of the GAHE were created by using Solid Work 2016 software, the geometry of GAHE consist of three parts assembled to together for representing the computational model for GAHE case study as shown in Figure 4(a). The GAHE pipe dimensions are 0.10 m in inner diameter with a thickness of 0.005 m, the total length of the pipe is 24 m. while the soil is represented as a square with a dimension of 1×1 m surrounding the pipe as illustrated in Figure 4(b). As the temperature of soil varied with respect to the depth, the depth is divided into 4 segments (Figure 4(b)) to allow the use of 4 different boundary conditions to improve the results from the numerical model [8].



(a) (b)

**Fig. 4.** Geometry of case study

### *2.3.2 The mesh of geometry*

ANSYS Meshing tool produces the mesh using Mesh Controls and Mesh Methods. Two types of mesh were produced to discretize the computational domain: (i) the air zone is tetrahedron, and (ii) the soil and the pipe is hexahedron. Figure 5 presents the mesh of the computational domain of the system.

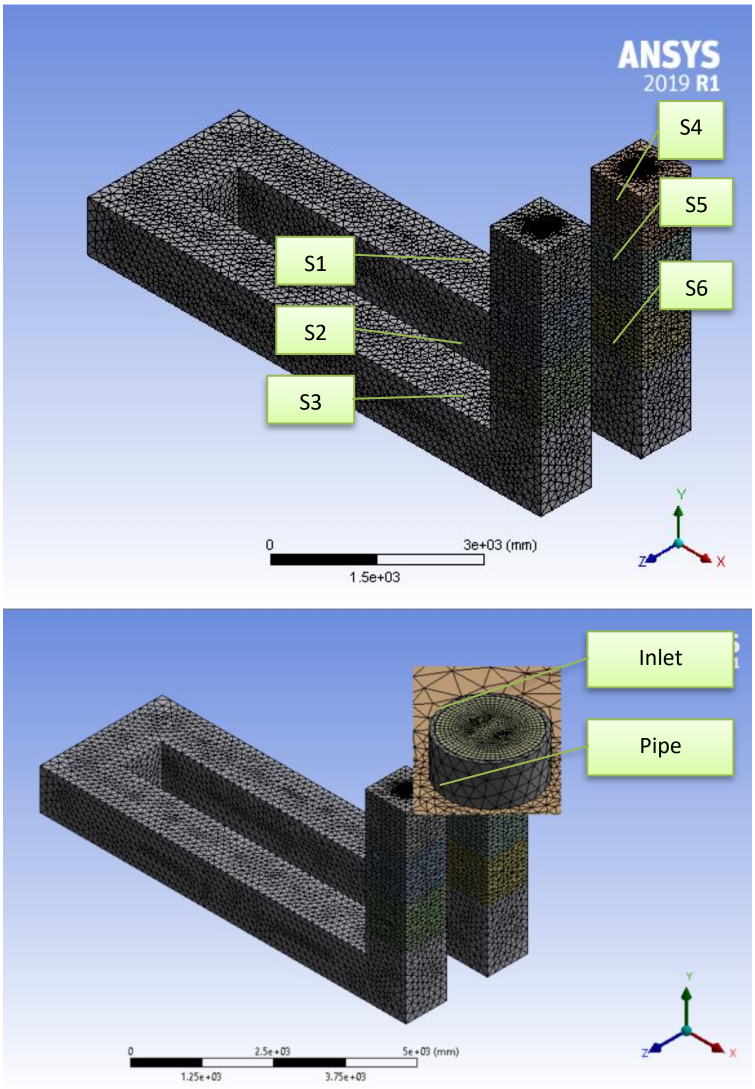


**Fig. 5.** Mesh of the computational domain

The number of elements in the discretized domain was 5837219 elements. The element size varies according to the computational domain, generally. The element size of the air and pipe domain is 2mm, and the soil is 30 mm. For better accuracy, the edge size of the interface between the pipe and soil was divided into 60 divisions, and all contact surfaces between pipe and soil were refined to achieve more accurate conditions to calculate the interface of heat transfer between the pipe wall and the soil domain. Both meshes generated for the case study were orthogonal quality to improve the solution accuracy.

### *2.3.3 Assumption of case study solution*

The following assumptions and methodologies are used to reach the numerical solution.

i. Steady, three-dimensional, and fully turbulent flow.
ii. Uniform and constant velocity at the Inlet of the pipe
iii. The physical properties and temperature of the soil are constant.
iv. The soil is rigid and completely contact with GAHE pipe.
v. The fluid is incompressible with constant properties.
vi. No slip boundary condition at the wall.

The governing equations were solved using the coupled scheme technique, and the realizable k-epsilon turbulent model was used. For the other transport equations, a second-order upwind separation strategy was adopted.

### *2.3.4 Boundary conditions*

With the prescription of the behavior of the flow variables at the boundaries of computational domains, the impact of the external surroundings on the flow and dispersion is taken into consideration. To complete the solution, a variety of boundary conditions must be adopted. Boundary conditions must be specified to be suitable for the physics of a specific case under solution. The boundary conditions are chosen to be compatible with the flow conditions used in the tests. Inlet, outlet, and thermal boundary conditions.

The air inlet is the inlet of air flowing through the pipe. The suitable boundary condition for this surface, which represents the specific physics of the case study, is velocity inlet. The air velocities used in the present study were 1, 2, 3, 4, and 5 m/s with thermal conditions as temperature equal to 320.2 K for summer.

The outlet surface at the air computational domain represented the air outlet flow. The appropriate boundary condition is the outflow boundary due to it giving a wide range of freedom it offers to air flow out from the EAHE with computing velocity and temperature.

On the earth tube heat exchanger wall, velocity is taken to be zero (no slip), i.e. U=0, V=0, and W = 0 in the X, Y, and Z direction. The thermal condition of wall is temperature which is equal to soil in depth directions and for horizontal zone of EAHE.

The boundary conditions used in this study are given in Table 2. The values of each boundary condition for cases investigated in the present study are listed in Table 3.

**Table 2**
The boundary condition of computational model

| Boundary condition | Variable | Notes |
|---|---|---|
| Inlet | Velocity inlet | (1, 2, 3, 4, and 5) m/s<br>Temperature = as desired in each case study |
| outlet | outflow | |
| Variable fluxes | $h\,(T_c - T\,) = -k\dfrac{\partial T}{\partial n}$ | |
| Walls (soil) | $u = v = w = 0$ | |
| Nonslip boundary condition | T = as desired in each case study | |

**Table 3**
Boundary condition used in numerical analysis

| Case | Inlet velocity (m/s) | Temperature (K) | | | | |
|---|---|---|---|---|---|---|
| | | Air inlet | S1 & S4 | S2 & S5 | S3 & S6 | S7 |
| 1 | 1 | 319.9 | 317.3 | 305.8 | 301.7 | 298.7 |
| 2 | 2 | 320.6 | 31.7.3 | 305.8 | 301.7 | 298.8 |
| 3 | 3 | 320.3 | 31.7.3 | 305.8 | 301.7 | 298.8 |
| 4 | 4 | 320.6 | 31.7.3 | 305.8 | 301.7 | 298.6 |
| 5 | 5 | 321.6 | 31.7.3 | 305.8 | 301.7 | 298.9 |

## 3. Performance Characterization

The effectiveness and coefficient of operation are the variables considered in the present work.

### 3.1 Effectiveness of Earth Tube Heat Exchanger

The effectiveness of EAHE expressed as the following equation [2]

$$\varepsilon = \frac{T_{air\ in} - T_{air\ out}}{T_{air\ in} - T_{soil}} \tag{15}$$

In addition, the coefficient of performance COP is investigated by calculating the heat capacity (q) as follow [2]

$$q = \dot{\mathrm{m}} \times \mathrm{c_p} \times \Delta\mathrm{T} \tag{16}$$

where
$\dot{\mathrm{m}} = \text{the mass flow rate of air in} \frac{\mathrm{kg}}{\mathrm{s}}$
$\mathrm{c_p} = \text{spesific heat of the air in kJlkg.K}$
ΔT = air temperature difference between inlet and outlet.

The effectiveness can be written as [2].

$$\mathrm{COP} = \mathrm{q/W} \tag{17}$$

where
W = the power of electrical blower (watt).

## 4. Monitoring Point

According to the experimental work by Lattieff *et al.,* [11], there were seven monitoring points for measuring and recording the air temperature at different locations of GAHE pipe. Two of these points are located at the inlet and outlet of GAHE (Tin) and (Tout) respectively, while the others are distributed along horizontal part of GAHE as (T1) and (T2), (T3), (T4) and (T5). other five monitoring point for recording the soil temperature with respect to the depth were distributed as (T6), (T7), (T8), (T9) and (Tsoil), at surface of soil, 1, 2, 3 and 4 m depth respectively, and the (Tamb) is used for recording the ambient temperature. as show in Figure 6.

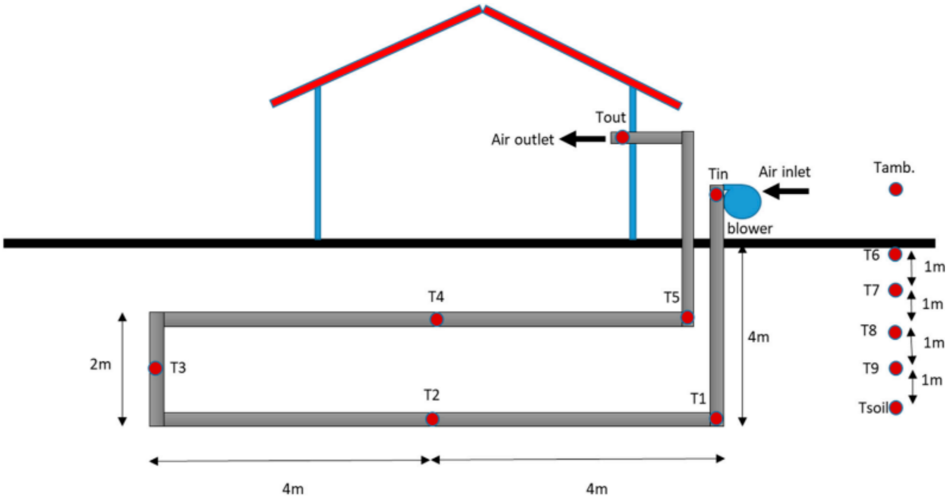


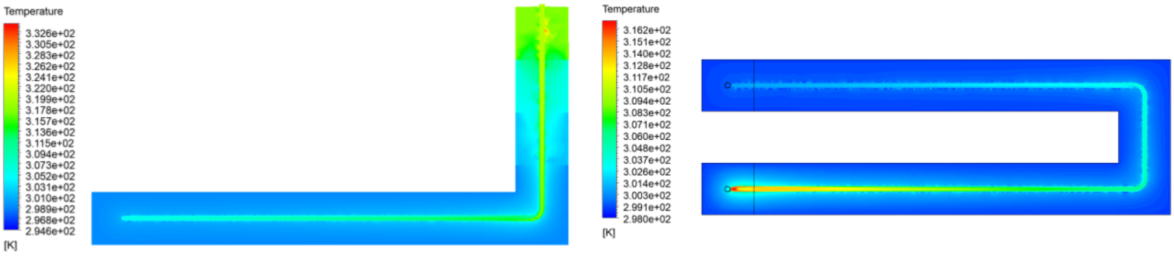
**Fig. 6.** Monitoring point in the experimental work by Lattieff *et al.,* [11]

## 5. Results and Discussions

### *5.1 Temperature Distribution*

The temperature of airflow into the vertical part of GAHE is decreases with depth until reaches the horizontal part due to the reduction of soil temperature with depth. Figure 7(a) illustrated the temperature variation along the vertical plane through the inlet. The surface soil temperature is 44.1°C at the surface which decreases to 41.4, 32.6, 28.5, and 27.5 °C at depths of 1, 2, 3, and 4 m, respectively. As the temperature of air flow into the GAHE is 46.7 °C, therefore, there is no significant heat transfer throughout the first meter, but its gradually rises with depth increasing until reaches to the horizontal part of GAHE. Figure 7(b) shows the temperature variation along the horizontal plan through the horizontal part of GAHE, it can be observed that there is a high-temperature difference in the horizontal part of the EAHE, especially at the first 11 meters. This temperature gradient is significant for the heat transfer between the air and the soil, as it allows for maximum heat exchange. The temperature difference steeply decreases with the rest of horizontal pipe thus, the rate of heat transfer is dropped until reaches to the end of horizontal part.

Figure 7(c) demonstrated the temperature distribution of air flow at the vertical section toward the outlet opening. It is obvious that, there is no significant temperature difference between air and the soil because of the transferring most of heat from the air to the soil at first vertical and the horizontal parts of GAHE. In other words, the GAHE pipe length is sufficient for cooling air with velocity of 1m/s and temperature of 46.7 °C. It noticed that at the vertical section of outlet, the soil temperature is increases with decreases of soil depth. In this situation there is a reversable heat transfer process (heat transfer from soil to the air) beginning approximately at depth of 3.5 m and growths with reduction of depth until the air out from the pipe of GAHE, this procedure has a negative influence of the performance of GAHE.



(a) temperature distribution along inlet pipe (b) temperature distribution contour at depth 4m

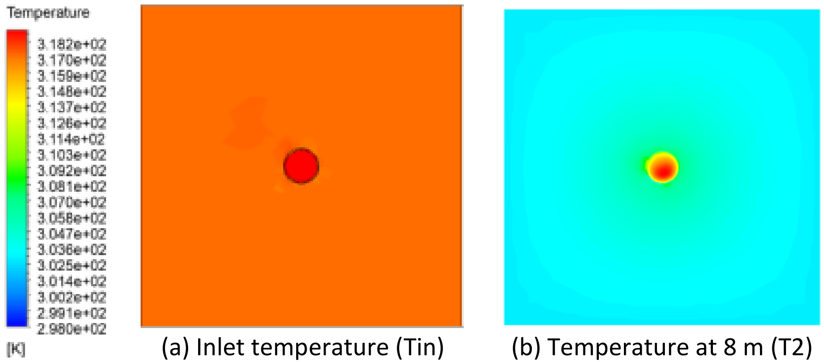
(c) temperature distribution along outlet pipe

**Fig. 7.** Temperature contours in different location of GAHE with air velocity of 1 m/s

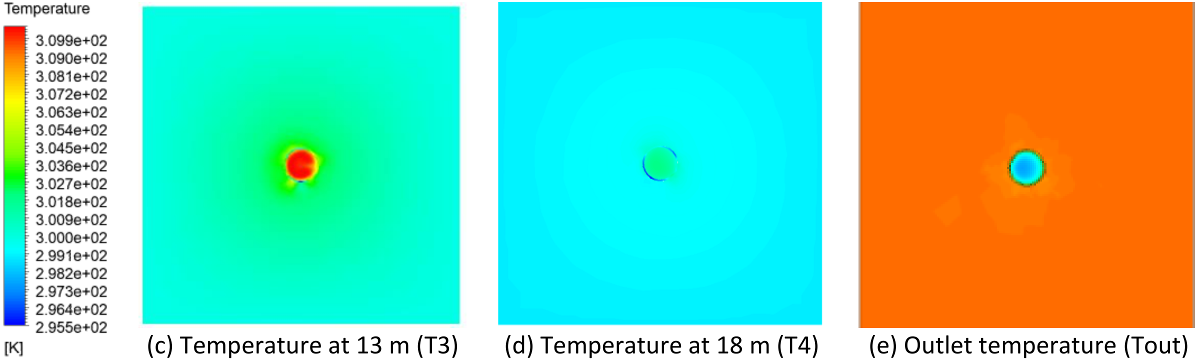
### *5.2 Temperature Distribution with Monitoring Point*

Figure 8 shown the temperature distribution contours at the monitoring points. Figure 8(a) illustrated the temperature contour at the inlet of GAHE pipe, it's obvious, there is a small temperature difference between the air and the soil at the inlet zone, the soil layer temperature at the surface is (317.3 k) and ambient air temperature (319.9.5 k), thus the air temperature slightly droops to (317.14 k) at the end of vertical section due to heat transfer between air and soil.

As the air flowed through the horizontal part of the GAHE pipe, the rate of heat exchanging between air and soil will increasing as a consequence of increasing the temperature difference. The air temperature sharply decreases from 317.4 k (T1) to 309.9 k (T2) at the first four meters of horizontal pipe length as show in Figure 8(b). This behavior continues along the horizontal part of GAHE, the air temperature decreases to 304.1 k (T3) and 301.9 k (T4) as shown in Figure 8(c) and Figure 8(d) respectively. At the end of horizontal part, the air temperature reaches to 299.9 k (T5). Thus, there are significant drop in the air temperature at the horizontal part of GAHE as illustrated in Figure 8(e). The air subjected to a reverse heat transfer process in the last vertical part of the GAHE toward the outlet. In this part heat transfer from the soil to the air a consequence of the high soil temperature, especially in the layers near to the surface. The soil temperature is 301.7 k, 305.8 k, and 317.4 k at point (T9), (T8) and (T7) respectively and the air temperature reaches to 303.41 k at the outlet (Tout).



(a) Inlet temperature (Tin) (b) Temperature at 8 m (T2)



(c) Temperature at 13 m (T3) (d) Temperature at 18 m (T4) (e) Outlet temperature (Tout)

**Fig. 8.** Temperature distribution contours at monitoring point along the GAHE with air flow velocity of 1 m/s

### *5.3 Effect of Velocity*

The amount of heat transported between the GAHE and the soil as well as the temperature distribution are both significantly influenced by the air velocity entering the EAHE pipe. With an airflow velocity of 2 m/s, Figure 9 depicts the temperature distribution in the horizontal portion of GAHE. It was shown that the temperature gradient at a velocity of 2 m/s is lower than that at a velocity of 1 m/s by comparison with Figure 8(a). This is due to the fact that more air is drawn into the PVC pipe as air velocity increases. In other words, as air velocity rises, so does the magnitude of the heat associate with the air mass. Consequently, either the GAHE pipe needs to be longer or the air needs more time to transfer heat more effectively. Therefore, at higher velocities, the 18-meter length of pipe is ineffective.

Figure 9(b), Figure 9(c), and Figure 9(d) illustrate the temperature distribution in the GAHE with respect to air velocity of 2, 3, 4, and 5 m/s. it is obvious that as the air velocity increases, the temperature gradient decreases. The temperature distribution for air velocities of 1, 2, 3, 4, and 5 m/s are demonstrated in Figure 10.

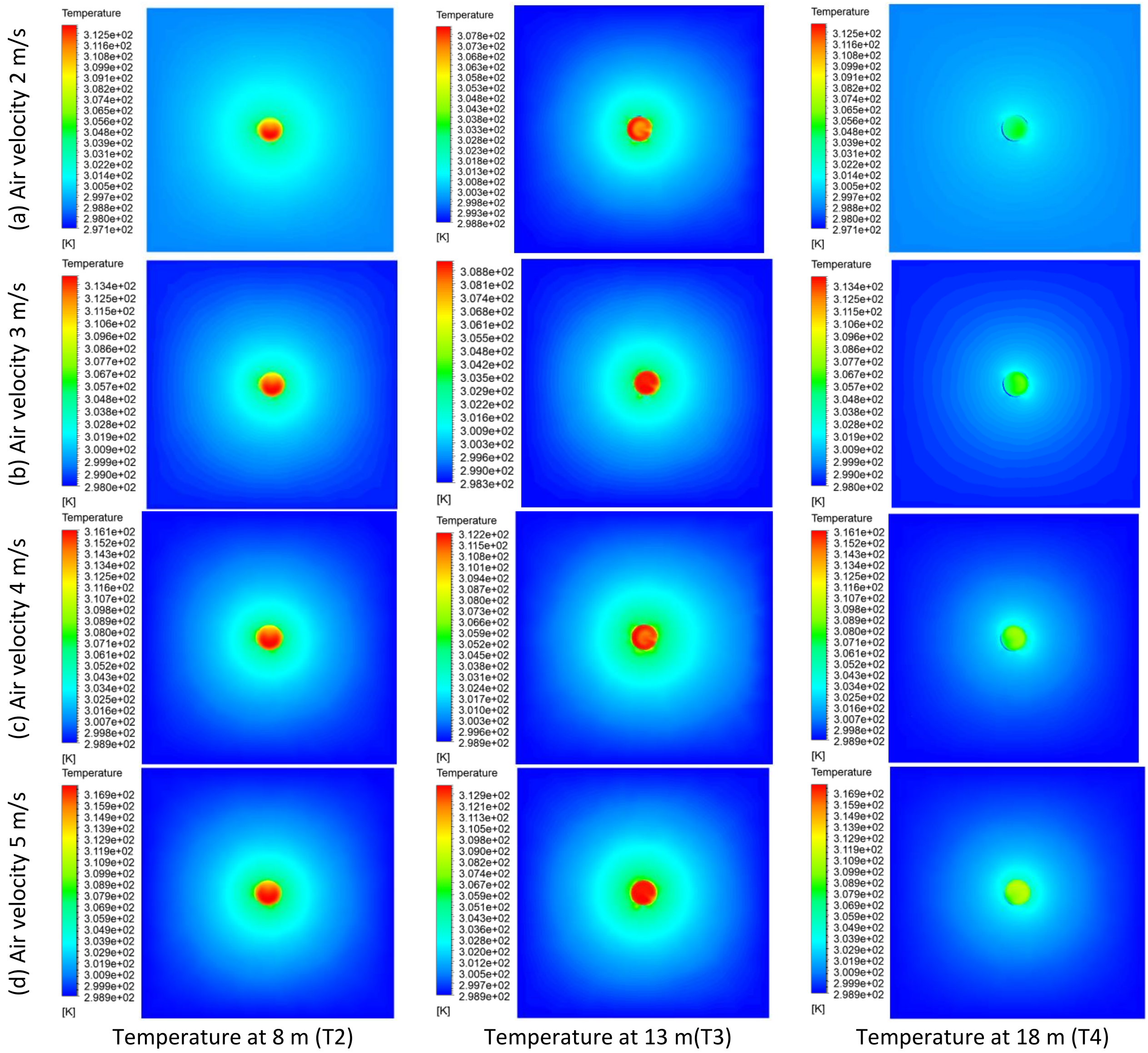


**Fig. 9.** Temperature Contours at monitoring point for different air velocity

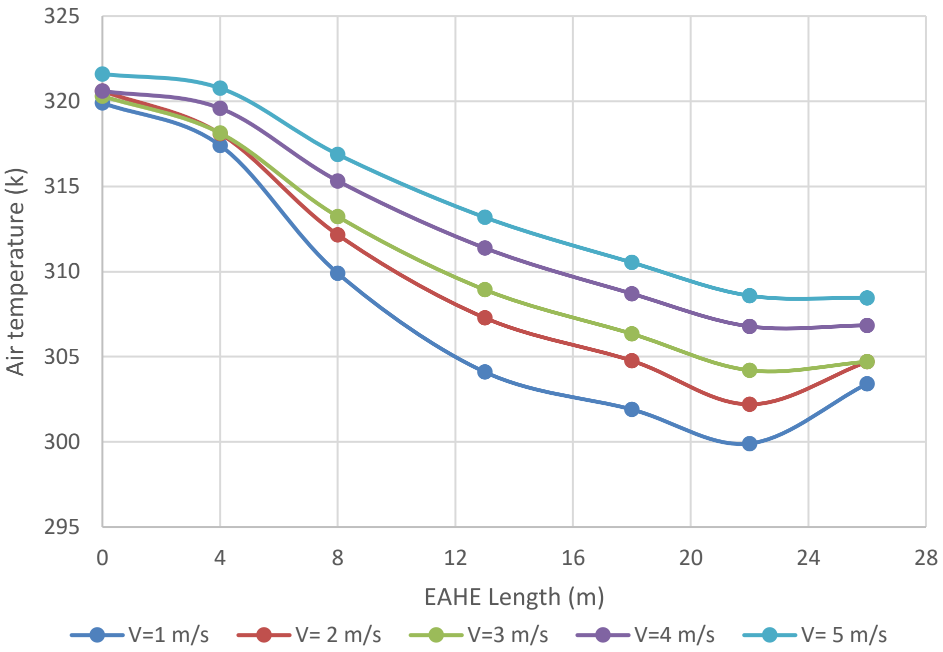


**Fig. 10.** Air temperature distribution at monitoring point along the GAHE with different air velocities

### *5.4 Comparison with the Experimental Work*

In order to validate the model, the geometry has been generated with the same geometry dimensions used in experimental measurements. In addition, the mesh has been modified because the geometry is large, and the number of nodes and elements is high. Therefore, comparing the numerical solution results with the experimental results will give an indication of the accuracy of the GAHE model. The experimental work conducted by Lattieff *et al.,* [11] also includes the measurement of other important parameters, such as the overall thermal performance. These additional parameters provide a comprehensive understanding of the EAHE system's efficiency and effectiveness. By comparing these experimental results with the numerical solution, a more robust validation of the GAHE model can be achieved. Figure 11 shows the experimental and numerical results of the air temperature difference at the inlet and outlet. The inlet temperature is one of the operation conditions in the experimental work and is adopted as a boundary condition in the numerical analysis. While air outlet temperature is a result of both the experimental and numerical works. Figure 10 shows the results of the temperature difference, it is obvious the high agreement between the numerical and experimental data, which indicates the high accuracy and suitability of the numerical model. The high agreement between the numerical and experimental data suggests that the numerical model can effectively predict the air outlet temperature based on the given inlet temperature. This finding highlights the reliability and applicability of the numerical analysis in studying the thermal behavior of the system.

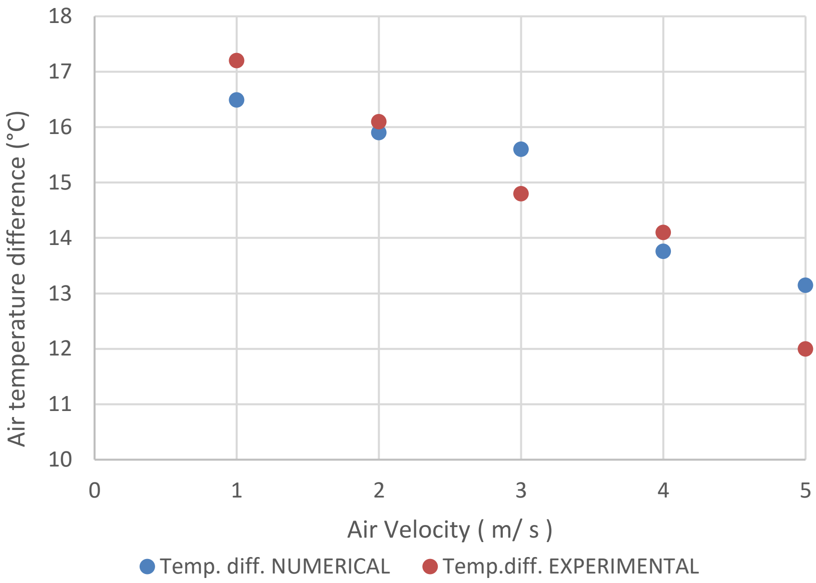


**Fig. 11.** Comparison of experimental and numerical air temperature difference

Figure 12 shows the effectiveness of GAHE from experimental and numerical results, as the effectiveness significantly depends upon the temperature of the air at the inlet and outlet and the soil temperature; in other words, it is directly dependent on the air temperature difference. Thus, according to Figure 12, the experimental and numerical effectiveness are in agreement with each other. This indicates that the numerical simulations accurately capture the behavior of the experimental system.

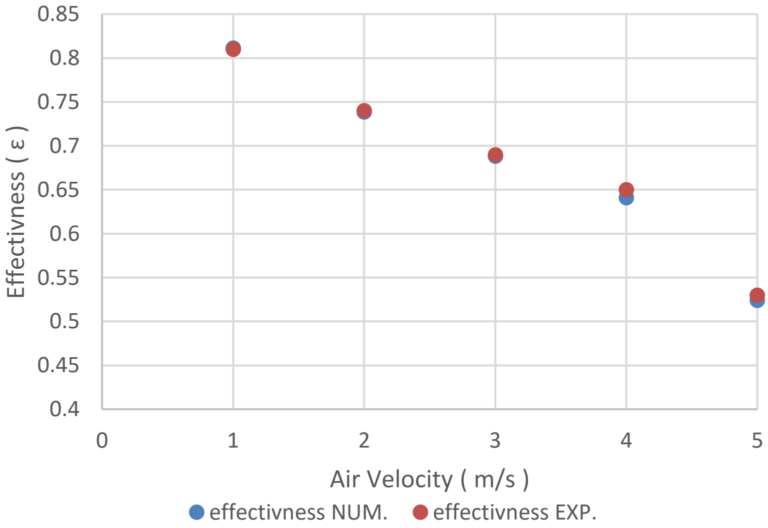


**Fig. 12.** Comparison of experimental and numerical EAHE effectiveness

In addition to experimental work, numerical analysis was used to investigate the COP of the GAHE. The COP values from experimental and numerical studies are shown in Figure 13. The COP of the GAHE from CFD results and experimental measurement are in good agreement. This suggests that both experimental and numerical approaches provide consistent results regarding the COP of the GAHE. Furthermore, the agreement in air temperature difference and effectiveness supports the reliability of these findings.

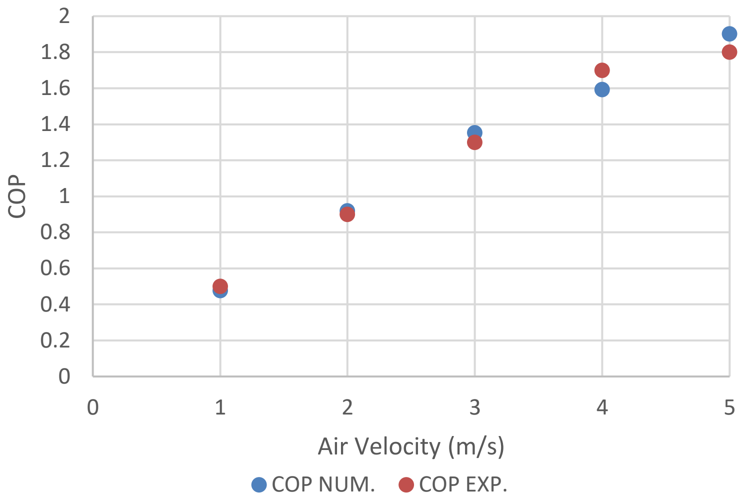


**Fig. 13.** Comparison of experimental and numerical COP of EAHE

## 6. Conclusions

As the design and investigation of GAHE are difficult and expensive, computational fluid dynamic CFD offers a quick and low-cost solution to evaluate the thermal characteristics of GAHE. CFD simulations allow researchers to analyze the fluid flow and heat transfer within a GAHE system, providing valuable insights into its performance. By accurately predicting the thermal characteristics, CFD can help optimize the design and operation of GAHE systems, ultimately reducing costs and improving efficiency. From the numerical analysis, some conclusions can be summarized as follows

i. The CFD model is valid and can be used for simulation and evaluation of the thermal performance of GAHE. It takes into account various factors such as fluid flow, heat transfer, and boundary conditions to provide a comprehensive analysis. This model has been validated against experimental data and has shown reliable results, making it a useful tool for assessing the thermal behavior of GAHE systems.

ii. Low efficient heat transfer was observed at the vertical pipe because the high temperature of soil with depths up to 1 m prevents effective heat exchange. The lack of sufficient temperature difference between the soil layers and the pipe reduces the transfer. Additionally, the vertical orientation of the pipe limits convection currents that could aid in heat transfer, further reducing its efficiency.

iii. For air velocity up to 3 m/s, effective heat exchange occurs at the first 10 meters of the GAHE pipe; thus, the 18 m length of the GAHE is adequate for effective thermal operation. The GAHE needs to be longer than 18 m because this length is insufficient for active heat transfer between air and soil at higher velocities up to 5 m/s. At higher velocities, up to 5 m/s, the air requires a longer contact time with the soil to achieve efficient heat transfer. Therefore, extending the length of the GAHE beyond 18 meters would ensure effective thermal operation at these higher velocities.

iv. Reversible heat transfer in the outlet vertical pipe as heat transfer from the air to the soil occurs near the outlet of the vertical pipe due to temperature rise as layers get closer to the soil surface. The outlet vertical pipe needs to be insulated to minimize heat transfer and maintain the air at a consistent temperature gradient within the system. This insulation prevents the air from gaining heat from the soil as it travels through the pipe. According to this, the GAHE is successfully removing heat from the air and transferring it to the soil. The importance of the horizontal part of the GAHE being properly designed and sized to ensure maximum heat transfer efficiency is highlighted by the temperature gradient. A well-designed and sized horizontal part of the EAHE is crucial to optimize heat transfer efficiency. This temperature gradient indicates that a properly functioning GAHE system can effectively extract heat from the air and efficiently transfer it to the soil, making it an essential factor in achieving optimal performance.

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