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Performance of earth-water heat exchanger for cooling applications

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Abstract. In this paper, the thermal performance of a horizontal earth tube heat exchanger is investigated. A two-dimensional model has been created using ANSYS Fluent to study the performance of a horizontal earth water heat exchanger (EWHE). The effect of inlet water temperature, water velocity, soil thermal conductivity and ground surface temperature on the rate of heat transfer has been analyzed. The results have indicated a direct relation between soil thermal conductivity and the rate of heat transfer. On the other hand, an inverse relation has been observed between ground surface temperature and the rate of heat exchanged.

1 Introduction

The increasing energy demand worldwide magnifies the need for efficient energy systems. In the GCC region and during summer peak time, cooling load presents about 70% of the overall energy consumption. The need for efficient cooling system pushes engineers to look for innovative cooling solutions. While geothermal cooling has long been identified as an effective method for reducing the cooling load, very few studies tackled its utilization in the Middle East, particularly in the GCC region. Hence, geothermal has not been implemented in this region except in rare cases.

In consistence with the sustainable development goals to reduce consumption and utilize renewables, earth water heat exchanger (EWHE) has drawn the interest of different research groups. The Earth's massive thermal capacitance provides a passive mean of heating and cooling [1]. Geothermal cooling has been investigated in various regions as a method of decreasing the cooling load [2]. While there are different configurations for ground heat exchangers, a commonly used setup is the closed loop horizontal heat exchanger due to its low cost and ease of installation [3]. It consists of an array of pipes connected in series or parallel and buried at 1 to 2 meters depth with a heat carrier medium flowing through, typically air or water. T'Joen and his team [4] performed a parametric study on earth-air heat exchanger (EAHE) and an EWHE system using a one-dimensional analytical model. They concluded that the resistance due to the depth of burial under the ground is more dominant in the case of EWHE in comparison to EAHE. Also, they reported that the EWHE is easier to install since it requires a much smaller tube diameter [4]. On the other hand, EAHE is prone to water condensate which could impact the performance of EAHE.

Several researches in prior studies developed numerical models to optimize the performance of a ground heat exchanger as a function of several parameters mainly tube length, ground temperature and inlet water temperature. Florides and Kalogirou compared different systems and applications of ground heat exchangers. Furthermore, they evaluated the reliability of various one, two and three-dimensional models developed to aid in studying the performance of ground heat exchangers. Based on their study [5], they reported that an increase in tube length increases the effectiveness of the heat exchanger. The opposite trend has been observed when increasing the tube diameter [5]. Congedo and his team assessed the performance of horizontal ground heat exchangers with different configurations. Using CFD analysis to obtain results, they observed that ground thermal conductivity had the greatest impact on the rate of heat transfer and the effect of the fluid velocity was found significant as well but to a lesser extent. In contrast, the depth, at which the horizontal ground heat exchanger was buried, was found to be of low importance [6]. Overall, they concluded that a helical configuration would provide the maximum rate of heat transfer [6]. A research team [7] has demonstrated the potential of utilizing geothermal heat exchangers to achieve the goal of zero-energy buildings through analyzing EAHE and EWHE in both passive and active modes. Gao et al. have prepared a comprehensive review of papers studying the performance of ground heat exchangers (GHE) integrated with various heating and cooling technologies [7]. Bezyan et al. compared the performance of a vertical spiral heat exchanger to 1-U-shaped and 1-W-shaped configurations. Considering both serial and parallel connections, they identified the spiral-shaped in serial connection to be the best performing configuration [8].

Although ground heat exchangers have been deployed since the 1970s, they are still being studied for optimized performance. In this paper, the performance of a horizontal pipe at a depth of 1 meter is analyzed using ANSYS Fluent release 19.1. The water outlet temperature is studied as a function of critical parameters including inlet water temperature, flow velocity, soil thermal conductivity and

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ground surface temperature. The effect of each parameter and its level of significance on the rate of heat exchange is obtained.

2 Numerical analysis

The effects of the parameters, soil thermal conductivity, water inlet temperature, fluid velocity and ground surface temperature are investigated in this study. The simulations are performed using ANSYS FLUENT Release 19.1, which uses finite volume method. Water is flowing in at a higher temperature than that of the ground temperature, thus the heat exchanger is in the cooling mode. The flow is turbulent and incompressible given that the Reynolds number at a velocity of 2.5 m/s is found to be greater than 10,000. Therefore, realizable k-ε model with enhanced wall function option has been adopted along with the energy equation. The CFD main setup parameters are outlined in **table 1**.

Table 1. Simulation parameters

Element	Description
Solver	Semi-Implicit Method for Pressure Linked Equations (SIMPLE)
Energy	Second Order Upwind discretization
Momentum	Second Order Upwind discretization
Turbulence model	First Order Upwind discretization

The governing equations to the steady state 2-D flow are conservation of mass, momentum and of energy and are shown below:

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

$$\frac{\partial(\rho u_j u_i)}{\partial x_j} = \frac{\partial P}{\partial x_j} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \rho\overline{\acute{u}_i \acute{u}_j}\right] \quad (2)$$

$$\frac{\partial(\rho u_j T)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\frac{\mu}{Pr}\left(\frac{\partial T}{\partial x_j}\right) - \rho\overline{\acute{T}_i \acute{u}_j}\right] \quad (3)$$

2.1. Geometry and properties

A 2D-Geometry consisting of a single pipe 16 mm in diameter, 200 meters in length which has been created using Design Modeler. The material properties of sand domain and water domain has been set as shown in table 2. In this study, the properties including specific heat capacity, soil thermal conductivity and density are considered constant and temperature independent.

Table 2. Material properties

Property	Water	Sand
$C_p\ (J/kg \cdot K)$	4185	856
$\rho\ \ (kg/m^3)$	997	2600
$\lambda\ (W/m \cdot K)$	0.6	1

Schematic in **figure 1** resembles the model of a horizontal EWHE. The upper rectangle represents the sand domain with a depth of one meter. The lower rectangle represents the water domain with water inlet on left-side and water outlet on the right-side. The upper surface temperature is set to be constant and the pipe radius is 8 mm with symmetry along the bottom axis.

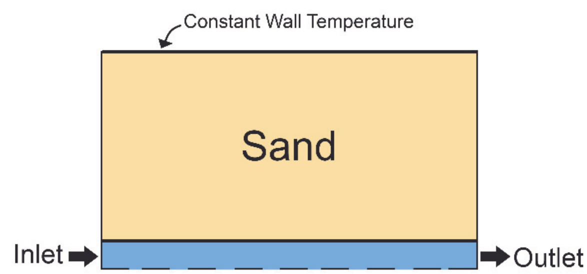

Fig. 1. Schematic of geometrical model (not to scale).

2.2 Mesh independence study

Figure 2 shows the variation of temperature versus pipe length for three different mesh sizes. The mesh independence test is carried out starting with mesh #1 which consists of 24,012 nodes followed by a finer mesh with edge sizing of the water domain and the sand domain with a total of 34,848 nodes. The temperature versus length of the pipe plot shows that results are overlapping for mesh #2 and #3 which consist of 34,848 and 48,606 nodes, respectively. Therefore, mesh #2 has been selected to analyze the performance of the EWHE.

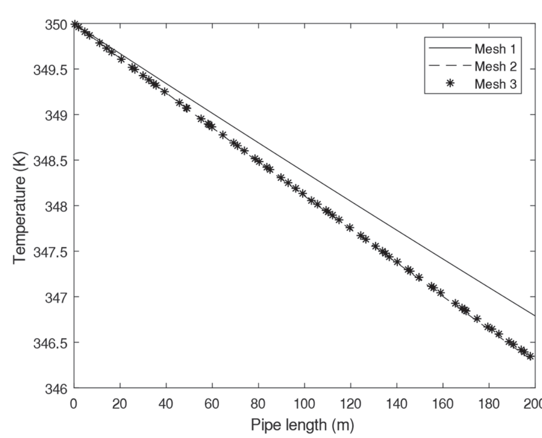

Fig. 2. Mesh independence test.

2.3 Boundary conditions

The base case is simulated with a water inlet velocity, upper surface temperature and inlet temperature as shown in **table 3**. The pipe outlet condition is set as constant pressure outlet and the boundary conditions for the wall separating the water domain and the sand domain are set as coupled wall. This will solve the Navier-Stokes equations in the fluid zone and the heat conduction equations in the solid zone (known as conjugate heat transfer).

Table 3. Boundary conditions

Parameter	Value
Upper surface temperature (K)	300
Inlet water temperature (K)	350
Inlet water velocity (m/s)	2.5
Outlet water pressure (kPa)	0

3 Results and discussion

3.1. Effect of soil thermal conductivity

Several studies in literature reported soil thermal conductivity values ranging between 1 W/m.K with values up to 3 W/m.K [9]. It is influenced by the water content, saturation degree, temperature and mineral composition [10]. To evaluate the effect of varying soil thermal conductivity, all other parameters including fluid velocity, inlet temperature and ground surface temperature are kept constant.

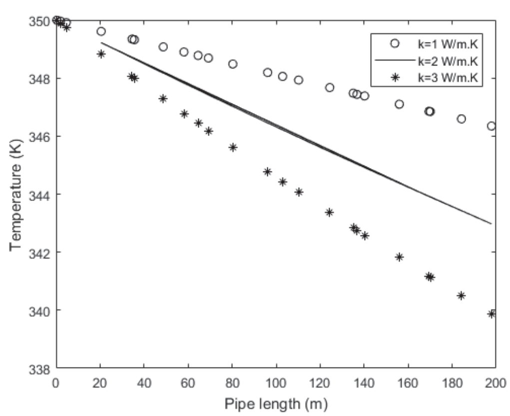

Fig. 3. Effect of soil thermal conductivity on water outlet temperature.

In **figure 3**, the effect of soil thermal conductivity on water outlet temperature is presented. It was observed that as soil thermal conductivity increases, the amount of heat transfer from the pipe to the soil increases, hence water outlet temperature decreases. The increase in rate of heat exchange is proportional to the increase in soil thermal conductivity. This is deduced from the decreasing outlet temperature at higher soil thermal conductivities. Thus, it is critical to test the soil thermal conductivity prior to the installation of a ground heat exchanger since this will dramatically dictate the size and length of an EWHE. A soil thermal conductivity of 3 W/mK resulted in a temperature drop greater than 10 degrees. In general, sizing the EWHE will depend on the application requirements.

3.2 Effect of fluid velocity

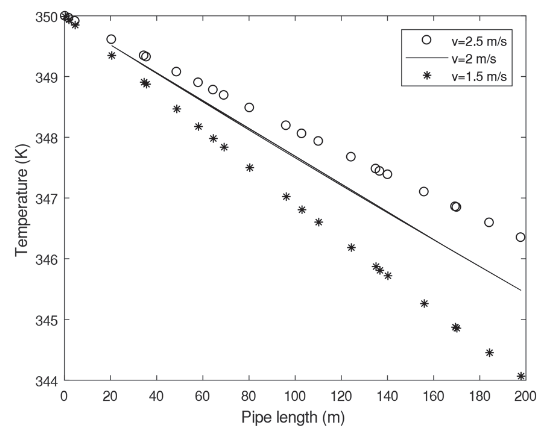

Fig. 4. Effect of fluid velocity on water outlet temperature.

In **figure 4**, the effect of fluid velocity on water temperature is shown. Water outlet temperature increases with an increase in fluid velocity. A higher velocity results in a greater mass flow rate. The rate of heat transfer can be determined as follow

$$\dot{Q} = \dot{m}\, C_p\, \Delta T \tag{4}$$

Where $\dot{Q}$ is defined as the rate of heat transfer, $\dot{m}$ is the mass flow rate of the fluid and C_p is the specific heat capacity. An inverse relation was observed between the mass flow rate and ΔT for a constant rate of heat transfer. It is expected that as the velocity increases the Reynolds number increases, but the time of contact between the fluid and the ground is reduced. For cooling applications, a higher ΔT is desired. Thus, a compromise is to be made between flow rate and residence time to optimize heat transfer.

3.3 Effect of fluid inlet temperature

It is established that a high temperature difference between the inlet fluid and the outlet fluid indicates an enhanced performance of the EWHE [11]. The effect of inlet temperature is shown in **figure 5** where inlet temperature was varied between 330 K and 350 K. The slope at an inlet temperature of 350 K is steeper compared to the other cases which indicates a greater heat exchange rate. Thus, inlet temperature is a significant parameter that has a major impact on the outcome of the heat exchanger [12]. The inlet temperature to the system will depend on the cooling load, a greater load results in a higher temperature.

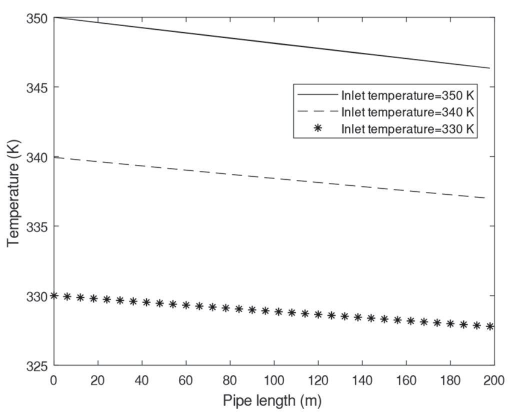

Fig. 5. Effect of fluid inlet temperature on water outlet temperature.

3.4 Effect of ground surface temperature

The soil surface temperature has a major impact on the EWHE thermal behavior [13]. Water temperature along the length of the pipe at different ground surface temperatures is plotted in **figure 6**. An inverse relation exists between surface temperature and rate of heat transfer. The soil surface temperature depends on geographical location, solid properties, ground depth and seasonal weather. To minimize the effect of weather, it is recommended to install the EWHE at least 2 meters below the ground surface.

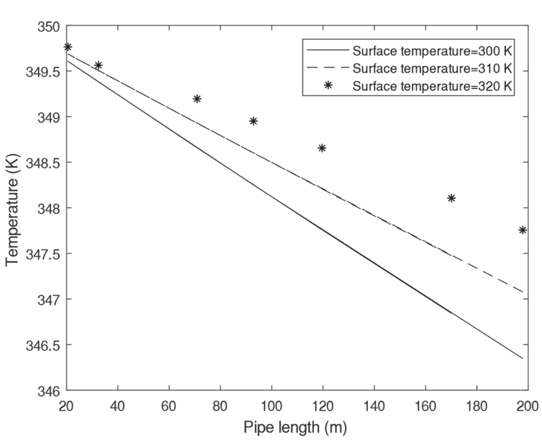

Fig. 6. Effect of surface temperature on water outlet temperature.

According to the results above, placing the ground heat exchanger in a shaded area would enhance the performance and increase the rate of extracted heat. It is clear that these results call for field experiment since EWHE performance depends on soil temperature, soil properties, season effect and soil thermal radiation condition (shaded and unshaded area) [14].

4 Conclusion

This work studies the performance of a horizontal ground heat exchanger. The impact of soil thermal conductivity, water velocity, water inlet temperature and surface temperature have been evaluated. In conclusion, the effect of soil thermal conductivity is significant and has a greater influence in comparison to other parameters. The depth at which the pipe is buried is critical since the temperature gradient will not only affect the rate of heat exchange but the soil thermal conductivity as well (based on soil particle size, compaction and humidity). EWHE presents an effective method for reducing peak cooling loads since it acts as a heat sink with a temperature significantly lower than that of the ambient air. Air can be cooled indirectly through connecting the heat exchanger to the existing air conditioning system.

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