Dynamic and Static Investigation of Ground Heat Exchangers Equipped with Internal and External Fins

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Abstract: Using fins on the inner and outer surfaces of pipes is one method to improve the heat transfer rate of ground heat exchangers (GHEs), thereby reducing the borehole depth and construction and operation costs. Results of 3D numerical studies of simple and finned U-tubes with outer and inner fins are evaluated for GHEs under similar physical conditions. Dynamic and static simulations show the effects of longitudinal fins on the thermal performance of borehole heat exchangers (BHEs) and heat transfer rate between circulating fluid and soil around pipes, while the dynamic tests include short timescale and frequency response tests. The results indicate that the maximum fluid temperature change is about 2.9% in the external finned pipe and 11.3% in the internal finned pipe compared to the finless pipe. The effects of the inlet velocity on temperature profiles, the patterns of the velocity and temperature contours due to the borehole curvature and the response times of the systems under various frequencies are also investigated in detail.

Keywords: ground heat exchanger; 3D simulation; finned U-tube; external fin; internal fin; dynamic simulation

1. Introduction

Ground source heat pump systems (GSHPs) offer the potential for significant energy savings, through low maintenance costs and contribute to reducing greenhouse gas emissions. GSHPs are used for heating/cooling residential and commercial buildings and for providing domestic hot water [1,2]. The use of GSHPs proved to be a technically feasible and economically viable solution as compared to other heating, ventilation, and air conditioning (HVAC) systems in cooling dominated environments such as the Arabian Peninsula where the air conditioning (A/C) systems account for 65% of the energy consumption strictly from fossil fuels [3]. The GSHPs are fully capable of meeting the cooling demands of buildings in hot climates, specifically, in the Middle East [4]. The most common type of ground heat exchangers is the vertical ground heat exchanger with the length of 100–150 m [5,6]. The empty space between pipe and borehole wall is usually filled with grout which helps to improve the heat transfer rate between circulating fluid inside pipes and ground [7]. Since the initial costs of vertical borehole heat exchangers (BHEs) are relatively high due to the limitations of drilling and manpower, efforts are being made to increase the heat transfer rate between fluid and soil around the pipes in various ways, and thus reducing the borehole depth [8].

Several methods have been proposed to calculate and reduce borehole resistance. In most thermal response test (TRT) analyses, the average of inlet and outlet temperatures of the fluid is used to...
calculate the fluid temperature along the ground heat exchanger (GHE). Some researchers have shown that the average of inlet and outlet temperatures can cause significant errors in results and suggested alternative methods for estimating the average fluid temperature [9–15].

Grout materials are used to fill spaces between pipes and the soil around the borehole which can play a key role in the heat transfer rate between the fluid and undisturbed ground. Some researchers have worked on the effects of different grout materials on the thermal performance of the GSHP systems and found the best option for grout materials [16]. Borinaga et al. [17] used four different boreholes with the same geometric and geological characteristics but different grout materials to determine the appropriate thermal conductivity. They reported a proper type of grout for the thermal response test. Erol et al. [18] evaluated the performance of various grout materials and tested the effects of adding graphite on the thermal properties of grout material.

Various numerical and analytical models have been developed based on linear source or cylindrical source theory. Using these models, the influences of different geometric and thermal properties on the static and dynamic behavior of a BHE has been investigated. Eskilson [19] proposed a G-function to describe borehole performance. G-function curves based on borehole geometry were reported by calculating the soil temperature using the finite difference method. Beier [20] developed an analytical solution for calculating the vertical temperature profile of the fluid inside the pipe and the ground temperature distribution by using Laplace transforms.

There are several studies about GSHPs based on the Computational Fluid Dynamics (CFD) method. Pu et al. [21] investigated the effects of Reynolds number, pipe diameter, and U-tube shank spacing on the thermal performance of GHEs. The results showed that by increasing the Reynolds number and the pipe diameter in laminar flow, better performance can be achieved. Esen et al. [22] performed a numerical and experimental study to evaluate the temperature distribution in GHE using three U-tube BHEs with the same diameters and different depths. Li et al. [23] compared the thermal performance of U-tube heat exchangers with four different standard diameters. Zhu et al. [24] studied the thermal performance of a double U-tube GHE and the effects of parameters such as inlet velocity, temperature, and operating distance on the temperature distribution of the soil. Lee and Lam [25] performed computer simulations of borehole heat exchanger to determine ground and borehole the temperature along depth using a finite difference model.

Yang and Lee [26] performed a dynamic thermal analysis on a 4-ton residential GSHP and observed a design trade-off between cooling and heating modes. They obtained the optimal value of the evaporator area fraction in both cooling and heating modes.

Kharseh et al. [3] studied the energy savings by using GSHP systems in the residential buildings sector in cooling-dominated environments. It was found out that the energy savings by using GSHPs when compared to the conventional air source heat pump system are much higher. Similary, Beckers et al. [27] performed a techno-economic analysis on a hybrid ground-source heat pump systems for cooling-dominated applications. The results of their simulation showed that a ground-source heat pump-based system helped the owner to save up to 30% of lifetime electricity consumption as compared to an air-source heat pump-based system. In contrast, the air-source heat pump-based system can have up to 10% lower total cost of ownership due to the lower upfront capital cost. A study by Salem and Hashim [4] discussed that the commercial buildings in Dubai have fairly high occupancy, fluctuating demands, and extensively diverse cooling requirements within individual zones, which are difficult to meet effectively and efficiently with conventional HVAC systems. They concluded that there is potential for the efficient use of ground couple heat pumps (GCHPs) in Dubai commercial buildings leading to significant savings in energy usage and operating costs and substantial reduction in CO₂ and NOx emissions over a 20 year life cycle as opposed to other HVAC options.

The performance of fins for enhancing heat transfer of heat exchangers generally has been considered previously [28] and Bouhucina et al. [29] investigated the influence of internal fins on the dynamic and thermal performance of U-tube GHEs. Using fins increased heat transfer rate up to 7%. Saeidi et al. [30] performed a numerical simulation of GSHPs with a spiral pipe and investigated the
effects of a fin on the outer surface of the spiral pipes. The results showed that fins can improve thermal conductivity due to increased surface area.

Previous studies have been conducted to find a method to increase the thermal efficiency of GSHP systems. These methods were based on borehole configuration, thermal properties of the ground and grout materials, and generally finding suitable solutions to reduce the borehole depth. To the best of the authors' knowledge, the impacts of internal and external fins on the thermal performance of U-tube GHEs have not been compared yet which is the aim of the current study. Moreover, both dynamic and static behavior of simple and finned U-tube GHEs will be evaluated to obtain the best efficiency. For the dynamic tests, various conditions such as short timescale response and sinusoidal response tests will be investigated for the BHE equipped with fins. The velocity of the inlet flow with the resultant flow filed patterns and the frequency of the input temperature with its effects on the response time and amplitudes are other important parameters that are added to this investigation.

2. Case Study

The geometry of the simple U-tube ground heat exchanger consists of a U-tube, grout materials, and soil around the borehole, Figure 1. The grout materials and the surrounding soil are considered as two cylinders with different radii, the radius of the ground is approximately 16 times the radius of the borehole.

The cross-sections of simple and finned U-tubes are illustrated in Figure 2. The details of the geometry of U-tube GHE are provided in Table 1. The borehole has a diameter of 128 mm and a depth of 25 m, which includes a vertical U-tube with a thickness of 2 mm. The ground around the borehole is a cylinder of 2 m in diameter with the same depth as the borehole. In finned pipes, six longitudinal fins with dimensions of $2 \times 6 \text{ mm}^2$ (2 mm thickness and 6 mm length) are used in each leg of the U-tube. The fins are placed in a symmetrical arrangement relative to the horizontal axis.

| Table 1. Geometric properties of U-tube ground heat exchanger (GHE). |
|---|---|
| **Parameters** | **Value** |
| Borehole diameter (mm) | 128 |
| Inner diameter of pipe (mm) | 30 |
| Outer diameter of pipe (mm) | 34 |
| Distance between centers of U-tube pipes (mm) | 55 |
| Borehole length (m) | 25 |
| Ground diameter (m) | 2 |
The mesh generation is performed based on both structured and unstructured grids. After defining the boundaries and edges of different parts of the geometry as lines or curves, a two-dimensional grid is created in Cartesian coordinates and then this 2D grid is extended in the direction of depth. The cells are equally or exponentially distributed in different parts of the geometry. For this purpose, a high number of cells are considered for places with steep temperature slope, for example, near the borehole and pipe walls. For the areas where the temperature slope is low, the size of the cells is increased. Figure 3 shows the computational mesh of the simple U-tube GHE. The upper and lower surfaces around the borehole are made up of 600 cells, which have bigger sizes in the middle part. The borehole is divided vertically into 70 layers with different distances. The curved area of the U-tube at the bottom of the pipe requires finer and different mesh from the other domains of the geometry due to the complexity of the geometry. Around the curved edges, using unstructured meshes is more practical.

Although the accuracy of the calculations increases with the number of cells, the higher computation time should also be considered. As a result, by examining the grid independency test, it is possible to obtain a suitable and optimal mesh with the necessary accuracy to achieve the final results and to avoid increasing computation time. Grid independency of simple and finned U-tube GHE has been investigated by varying the number of cells from coarse mesh to finer mesh. Table 2 shows the outlet fluid temperature in the simple U-tube GHE under the steady-state condition for different mesh cells. A total cell number of $330 \times 10^3$ is used for smooth U-tube GHE since no temperature change is observed after increasing the number of cells. Grid independency for finned U-tube GHEs is presented in Table 3. Due to the small dimensions of the fins used on the inner and outer surfaces of the pipes, the numerical models require a finer grid size than a simple pipe. The number of cells specified in GHEs with external and internal fins is $500 \times 10^3$ and $420 \times 10^3$, respectively.

**Table 2. Grid-independency test of smooth U-tube GHE.**

|                  | Mesh 1 | Mesh 2 | Mesh 3 |
|------------------|--------|--------|--------|
| Elements number ($\times 10^3$) | 174    | 330    | 500    |
| Fluid outlet temperature (°C)    | 24.86  | 24.85  | 24.85  |
Table 3. Grid-independency test of finned U-tube GHEs.

| Mesh | U-tube with external fins | Fluid outlet temperature (°C) |  | Mesh | U-tube with internal fins | Fluid outlet temperature (°C) |
|------|--------------------------|-------------------------------|---|------|---------------------------|-------------------------------|
| 1    | Element number (×10^3)   | 300                          | 24.64 | 2    | Element number (×10^3)   | 300                          |
| 2    | Fluid outlet temperature (°C) | 500                          | 24.71 | 3    | Fluid outlet temperature (°C) | 600                          |
| 3    |                          | 600                          | 24.72 |      |                          | 600                          |

Figure 3. Three-dimensional mesh: (a) computational mesh around borehole; (b) half of computational domain.

3.2. Solver

The physical properties of circulating fluid, U-tube, backfill material, soil, and aluminum fins are demonstrated in Table 4. For pipes, high-density polyethylene (HDPE) material is considered. The selected grout material is a combination of silica sand and bentonite. Water is used as the fluid inside the pipes.

Table 4. Physical properties of materials.

| Material      | Density (kg/m^3) | Specific Heat Capacity (J/kg·K) | Thermal Conductivity (W/m·K) |
|---------------|------------------|---------------------------------|------------------------------|
| Fluid         | 997              | 4148                            | 0.6                          |
| U-tube        | 950              | 1500                            | 0.44                         |
| Grout         | 1800             | 840                             | 0.73                         |
| Soil          | 2200             | 2000                            | 2.5                          |
| Aluminum fin  | 2700             | 904                             | 237                          |
The undisturbed ground temperature is defined as the initial temperature of the entire simulation domain, including fluid, U-tube, grout, and soil. This study is performed for the cooling mode of the system; therefore, the fluid is warmer than the surrounding soil. The constant temperature boundary condition is applied to the outer boundary of the simulation domain where there is no heat flux along this boundary and its temperature should not change until the end of the simulation.

According to the previous studies [29], since the fluid velocity is an important parameter in the heat transfer and the temperature change of the fluid along the borehole length, the same mass flow rate in pipes as a boundary condition is not a proper condition and the same inlet velocity is applied for the inlet condition of the pipes. The focus is on investigating the effects of the inner and outer fins on ground heat exchangers with the same physical dimensions and same inlet velocity; so, finding the more effective fin cannot be based on the same flow rate or the same hydraulic diameter. Comparing the simple and finned pipes with the same mass flow rate at the inlet of pipes showed that the axial velocity in the finned U-tube (inner surface) will be higher than the simple U-tube because of the hydraulic diameter reduction which changes the heat transfer rate significantly.

The incompressible Newtonian fluid is used inside the pipes. The soil is considered homogeneous and the physical properties of the fluid, pipe, grout material, and soil are assumed to be constant. The temperature of the ground’s surface boundaries is constant and uniform, and any changes in the temperature of the ground over depth and time are ignored. The flow rate is constant along the pipe. A laminar flow is considered for all the simulations. The continuity and momentum equations are solved with the energy equation which is considered as [21,31]:

$$\frac{\partial}{\partial t}(\rho T) + \frac{\partial}{\partial x_j}(\rho U_j) = \frac{\partial}{\partial x_j}\left(\frac{\mu}{Pr} \frac{\partial u_i}{\partial x_j}\right)$$

(1)

where $u$ is velocity vector, $\rho$ is fluid density, $\mu$ is dynamic viscosity, $T$ is temperature vector and $Pr$ represents the molecular Prandtl number. The heat conduction in grout and ground is illustrated in Equation (2),

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T$$

(2)

where $\alpha$ is the thermal diffusivity of grout and ground.

4. Validation

The experimental results of Beier et al. [32] have been used for validation. TRT analysis was performed to evaluate the thermal performance of an 18.3 m borehole including a U-shaped pipe. An aluminum cylindrical pipe with an inner diameter of 126 mm was considered as the borehole wall. The borehole was located in a large sandbox. The square cross-section box with sides of 1.8 m used as the ground around the well was filled with wet sand. The geometric and physical configurations of the borehole are listed in Table 5.

| Table 5. Geometric and thermal properties for the experimental test of Beier et al. [32]. |
|---------------------------------------------------------------|
| **Parameters**                     | **Value**                     |
| Borehole diameter (mm)         | 126                           |
| Inner diameter of pipe (mm)     | 27.33                         |
| Outer diameter of pipe (mm)     | 33.40                         |
| Distance between centers of U-tube pipes (mm) | 53                  |
| Borehole length (m)             | 18.3                          |
| Pipe thermal conductivity (W/m-K) | 0.39                        |
| Grout thermal conductivity (W/m-K) | 0.73                        |
| Ground thermal conductivity (W/m-K) | 2.82                        |
| Average volumetric flow rate (L/s) | 0.197                     |
| Initial temperature of ground and grout (°C) | 22                     |
Figure 4 shows the comparison between the inlet/outlet flow temperatures from the current numerical simulation and the experimental data of Beier et al. [32]. The inlet temperature of both 2D and 3D models are the same as that of experimental results. The 3D outlet temperature is closer to the experimental results. The maximum temperature difference between the present 3D model and the experimental results is 1.2%, providing acceptable agreement.

5. Results and Discussions

5.1. Long Timescale Response

Initially, the static behavior for the smooth and the finned U-shaped GHEs is investigated. All the results presented in this section are obtained from steady-state simulations [33]. The fluid inlet temperature has a value of 30 °C and far-field temperature is considered to be 15 °C. In addition, the initial temperature of the whole simulation domains is assumed to be equal to the soil temperature around the borehole. Different fluid velocities are considered as 0.02, 0.04, 0.06 m/s. The results are shown in Table 6. The selected velocities keep the laminar flow condition inside the pipes.

Using internal fins to the mentioned dimensions have reduced the cross-section area by about 1.11 times compared to the smooth pipe. Therefore, the mass flow rate in the pipe with internal fins has decreased compared to the other two models by the same ratio. A comparison of the outlet fluid temperatures between three pipes shows that the fluid temperature change of the pipe with the inner fins is greater than that of the pipe with the outer fins. According to the values listed in Table 6, the temperature change of the fluid in the pipe with external fins at velocities of 0.06, 0.04, and 0.02 m/s has increased up to 2.9%, 2.2%, and 0.5% compared to that of the simple pipe. These values are increased to 11.3%, 9% and 5% for the pipe with internal fins.

Table 6. Numerical results of simple and finned U-tube GHEs.

| Velocity (m/s) | 0.06 | 0.04 | 0.02 |
|---------------|------|------|------|
| Simple U-tube | Flow rate (kg/s) | 0.042 | 0.028 | 0.014 |
|               | Reynolds number  | 2049  | 1366  | 683  |
|               | Outlet fluid temperature (°C) | 25.20  | 23.73  | 20.88  |
|               | Borehole wall temperature (°C) | 20.46  | 19.93  | 18.72  |
Transient simulation results of simple and finned U-tube GHE are shown in Figure 5. The inlet velocity 

5.2. Short Timescale Response

Transient simulations of BHE show the dynamic behavior of the system in a short timescale [33]. To evaluate and compare the thermal responses of three numerical models, the inlet fluid temperature is applied. Applying a periodic condition of the fluid inlet temperature instead of constant value is a useful way to describe the thermal response of the borehole heat exchangers in short timescales [33]. The outlet fluid temperature has reached 24.86 °C and the far field temperature (the soil temperature) is considered 15 °C, which has been used as the initial temperature of whole simulation domains (including the pipe, the fluid, grout materials and the soil). The outlet temperature of all three pipes reached a steady state after 330 min and no change was observed in the graphs after this time. The simulation is for the cooling mode of the system, and the inlet temperature of the fluid is higher than the temperature of the initial temperature and that of the soil around the borehole. The fluid temperature decreases as it passes through the pipe.

Table 6. Cont.

| Velocity (m/s) | 0.06 | 0.04 | 0.02 |
|---------------|------|------|------|
| Flow rate (kg/s) | 0.042 | 0.028 | 0.014 |
| Reynolds number | 2049 | 1366 | 683 |
| Outlet fluid temperature (°C) | 25.06 | 23.59 | 20.83 |
| Borehole wall temperature (°C) | 20.67 | 20.08 | 18.78 |

| U-tube with inner fins | Flow rate (kg/s) | 0.038 | 0.025 | 0.013 |
|------------------------|------------------|-------|-------|-------|
| Reynolds number | 1945 | 1297 | 648 |
| Outlet fluid temperature (°C) | 24.66 | 23.13 | 20.42 |
| Borehole wall temperature (°C) | 20.50 | 19.89 | 18.55 |

![Figure 5. Outlet temperature of fluid in simple and finned U-tube GHE.](image)

The outlet fluid temperature has reached 24.86 °C in a simple pipe, 24.71 °C in a pipe with external fins and 24.28 °C in a pipe with internal fins. The difference between the inlet and outlet temperatures of the fluid in the simple U-tube is 5.14 °C and in the finned U-tube on the outer and inner surfaces is 5.29 °C and 5.72 °C, respectively. The temperature reduction in the fluid in the outer and inner finned U-tube has increased, respectively, 2.9% and 11% compared to the simple pipe.

Frequency Response Test

BHEs are affected by temperature fluctuations at different ranges of time scales. Therefore, applying a periodic condition of the fluid inlet temperature instead of constant value is a useful way to
describe the thermal response of the borehole heat exchangers in short timescales [33]. To evaluate and compare the thermal responses of three numerical models, the inlet fluid temperature is applied as a sinusoidal function with the same amplitude and different frequencies. The inlet velocity for all three pipes is 0.053 m/s. The mass flow rates for the simple and external finned U-tube are 0.038 kg/s and for the U-tube with internal fins is 0.034 kg/s. The inlet fluid temperature is applied as follows [33]:

\[
T_{in} = T_1 + a_{in} \sin(2\pi ft) = T_1 + a_{in} \sin\left(\frac{2\pi}{B} t\right)
\]  

(3)

where \(a_{in}\) is the inlet wave amplitude, \(T_1\) is the mean of the wave, \(f\) is the frequency and \(B\) is the period.

The outlet fluid temperature by variation of amplitude (\(a_{out}\)) and mean number (\(T_2\)) is defined as:

\[
T_{out} = T_2 + a_{out} \sin(2\pi ft + \phi) = T_2 + a_{out} \sin\left(\frac{2\pi}{B} t + \frac{2\pi}{\Delta B}\right)
\]

(4)

where \(\phi\) is the phase shift and \(\Delta B\) is the time shift of outlet wave that shows delay in the system responses. The outlet temperature of the fluid obtained from the 3D simulation in response to the inlet temperature as a sine wave with 80 and 40 min periods (frequency of 1/4800 Hz and 1/2400 Hz) and the amplitude of 8 °C for three simple and finned U-tubes are shown by Figures 6 and 7. By increasing the wave frequency (1/2400 Hz), the output wave amplitude decreases due to the reduction in the system response time compared to the first mode (1/4800 Hz).

**Figure 6.** Fluid inlet and outlet temperatures with a frequency of 1/4800 Hz: (a) simple U-tube; (b) U-tube with outer fins; (c) U-tube with inner fins; (d) comparison of fluid outlet temperatures in three simple and finned U-tubes.
Figure 7. Fluid inlet and outlet temperatures with a frequency of 1/2400 Hz: (a) simple U-tube; (b) U-tube with outer fins; (c) U-tube with inner fins; (d) comparison of fluid outlet temperatures in three simple and finned U-tubes.

According to Table 7, the difference between the average value of the input and output waves, with a frequency of 1/4800 Hz, in the simple pipe is 4.46 °C, in the pipe with external fins is 4.59 °C and in the internally finned pipe is 4.97 °C. The use of external fins increases temperature reduction in the fluid by 2.9% compared to a simple U-tube and the internal fins increase temperature reduction in the fluid by 11%. By doubling the frequency, the average value of the output wave has not changed compared to the first frequency, but the wave amplitude has decreased by 35% in the simple pipe, 39% in the pipe with the outer fins and 49% in the inner finned pipe.

Table 7. Input and output wave characteristics with different frequencies.

| Inlet Temperature                      | Amplitude of Wave | Mean of Wave |
|----------------------------------------|-------------------|--------------|
| Outlet temperature (°C) with a frequency of 1/4800 | Simple U-tube     | 2.62         | 23.54        |
|                                        | U-tube with outer fins | 2.40         | 23.41        |
|                                        | U-tube with inner fins | 2.06         | 23.03        |
| Outlet temperature (°C) with a frequency of 1/2400 | Simple U-tube     | 1.69         | 23.54        |
|                                        | U-tube with outer fins | 1.46         | 23.41        |
|                                        | U-tube with inner fins | 1.04         | 23.03        |
It was expected that finned GHEs have faster thermal responses than the smooth one. A comparison of the phase shift between the inlet and outlet temperature of the fluid in the three U-tubes shows that the thermal response of the three numerical models is almost simultaneous. The time shift of the outlet temperature of the simple and the externally finned pipes is 1200 s and in the internally finned pipe is 1320 s in a frequency of 1/4800 Hz. The time shift values at the second frequency of 1/2400 Hz for simple and externally finned pipes is 900 s and in pipes with internal fins is 1020 s.

5.3. Fluid Velocity Effects with Sinusoidal Inlet Temperature

A comparison of the fluid outlet temperature at different velocities with the Reynolds of 1200, 1800, 2300 for simple and finned U-tubes is illustrated in Figure 8 and the outlet values are listed in Table 8. For all cases, the laminar flow condition is considered. The inlet temperature is considered the same as the previous section with a period of 80 min.

In Table 8, as the inlet velocity increases, the mean and amplitude values of the fluid outlet temperature increase for the cooling purpose; increasing the velocity reduces the difference between the inlet and outlet temperatures of the fluid ($dT$). By increasing the velocity, the heat transfer rate between the pipe and the surrounding soil increases, but the fluid temperature change decreases. At low velocities, the fluid remains longer in the pipe, which increases the temperature change of the fluid [34].

![Figure 8. Cont.](image-url)
Figure 8. Cont.
Figure 8. Fluid temperature trends under different velocities: (a) simple U-tube; (b) U-tube with outer fins; (c) U-tube with inner fins; (d) comparison of simple and finned pipes.

Table 8. Output wave parameters with a frequency of 1/4800 Hz at different velocities.

| Velocity (m/s) | Amplitude of Wave (°C) | Mean of Wave (°C) | dT |
|---------------|------------------------|------------------|----|
| Simple U-tube |                        |                  |    |
| 0.035         | 1.59                   | 22.10            | 26.7% |
| 0.053         | 2.62                   | 23.54            | 19%  |
| 0.070         | 3.24                   | 24.26            | 15.4% |
| U-tube with outer fins |                  |                  |    |
| 0.035         | 1.40                   | 21.98            | 27.4% |
| 0.053         | 2.40                   | 23.41            | 19.6% |
| 0.070         | 3.00                   | 24.14            | 16%  |
| U-tube with inner fins |                  |                  |    |
| 0.035         | 1.12                   | 21.57            | 29.8% |
| 0.053         | 2.06                   | 23.03            | 21.5% |
| 0.070         | 2.68                   | 23.81            | 17.6% |

According to Figure 8, as the velocity of flow decreases, the phase shift of the fluid outlet temperature increases which means a delay in the thermal response of the BHE. Output temperature time shift for the simple U-tube for the first velocity ($v = 0.07$ m/s) is 960 s, for the second velocity ($v = 0.053$ m/s) is 1200 s and for the third velocity ($v = 0.035$ m/s) is 1680 s. These values for the externally finned pipe are 1020 s, 1200 s and 1680 s and for the internally finned pipe are 1080 s, 1320 s and 1740 s, respectively.

Figure 9 shows a comparison of borehole wall temperature for the simple and finned pipes at different velocities. According to the results obtained in the previous section, as the velocity of the fluid decreases, the difference between the inlet and outlet temperatures of the fluid increases and the average temperature of the fluid decreases in the cooling mode. As a result, by reducing the temperature difference between the fluid and the soil around the GHE, the heat transfer rate will be reduced.
Table 9 shows borehole temperature trends under different velocities. The fourth column shows the borehole wall temperature changes in three modes of pipes ($dT_{bore}$). The problem that should be considered in the comparison between simple and internally finned pipes, with the same fluid velocities, is the reduction in mass flow rate in the finned pipe due to the reduction in the cross-section. By comparing three numerical models, the increase in borehole wall temperature for the pipe with outer fins is more than two other pipes in applied velocities. This temperature change for the simple U-tube for the velocity of 0.035 m/s is more than that of the internally finned U-tube, but by increasing the fluid velocity, the bore wall temperature change for the finned pipe is more than the smooth one with the velocity of 0.07 m/s.

Figure 9. Cont.
Figure 9. Borehole wall temperature trends under different velocities: (a) simple U-tube; (b) U-tube with outer fins; (c) U-tube with inner fins.

Table 9. Borehole wall temperature with a frequency of $1/4800$ Hz at different velocities.

| Velocity (m/s) | Amplitude of Wave (°C) | Mean of Wave (°C) | $dT_{bore}$ |
|---------------|------------------------|-------------------|-------------|
| Simple U-tube |                        |                   |             |
| 0.035         | 0.59                   | 19.09             | 27%         |
| 0.053         | 0.85                   | 19.61             | 30.7%       |
| 0.070         | 0.99                   | 19.87             | 32%         |
| U-tube with outer fins |                |                   |             |
| 0.035         | 0.62                   | 19.21             | 28%         |
| 0.053         | 0.89                   | 19.80             | 32%         |
| 0.070         | 1.04                   | 20.07             | 34%         |
| U-tube with inner fins |                |                   |             |
| 0.035         | 0.56                   | 19.04             | 26%         |
| 0.053         | 0.82                   | 19.64             | 30.9%       |
| 0.070         | 0.97                   | 19.93             | 33%         |

5.4. Axial Velocity and Temperature Contours

The effects of longitudinal internal fins on the incompressible fluid flow inside U-tube GHE are investigated. The results are presented for different fluid velocities under steady-state conditions. Figure 10 shows axial velocity contours for two cases of a smooth U-tube and internally finned U-tube at different velocities. The two selected cross-sections of the pipe, in which the velocity contours are drawn, are located in the curvature of the inlet and outlet legs of the U-tube at a depth of 24.94 m under the ground surface.
Initially, the fluid velocity is uniform at the inlet of the pipe. Then the fluid velocity is increased at the center of the pipe cross-section, while the velocity of the fluid attached to the wall of the pipe approaches zero because of the viscous effects [21]. The flow contours are symmetric until the flow passes the end of the straight pipe. Figure 10 shows that the symmetric patterns of the velocity contours both in simple and finned pipes are changed according to the curvature of the pipes similar to the previous studies of heat exchangers [28,35]. The velocity contours of the inlet pipe are less affected by the curvature of the pipe than those of the outlet pipe. As the fluid velocity increases, the flow field pattern becomes more complex and the high-velocity flow is pushed to one side of the pipe. The presence of internal fins attenuates the effects of secondary flow and makes the flow patterns close to the straight pipes.

Figure 11 shows the temperature contours at three different velocities with the same method and selected cross-sections of the pipe mentioned in velocity contours (Figure 10). $\theta^*$ is a dimensionless temperature parameter which is illustrated in Equation (5):

$$
\theta^* = \frac{T - T_{min}}{T_{max} - T_{min}}
$$

Similar to the velocity contours, with the increase in fluid velocity, because of strong secondary flow effects in curved pipes [28,35] the temperature field patterns become more complex.

![Figure 10. Axial velocity contours for smooth (left) and finned U-tube (right) at different velocities; (a) inlet pipe; (b) outlet pipe.](image-url)
6. Conclusions

The influence of using fins in inner and outer surfaces of U-tube GHEs was investigated under the cooling mode. Internal fins increase the heat transfer rate more effectively. A GHE equipped with internal fins experiences enhanced fluid temperature changes along the borehole. For more details, under steady conditions (long timescale responses), when the fluid outlet temperature difference between a simple U-tube and a U-tube with external fins was 0.14 °C, the temperature difference between a simple U-tube and a U-tube with internal fins reached 0.6 °C, showing more than four times increase. Increasing the inlet fluid velocity can make the differences more noticeable; by changing the inlet fluid velocity in the range of 0.02–0.06 m/s, the fluid temperature change in the internally finned U-tube is increased by 5–11.3%, compared to the simple U-tube, while the fluid temperature change is just increased by 0.5–2.9% when the external fins are used. For the dynamic behavior, the priority of the inner fins is obvious too; for the short timescale response, with the inlet velocity of 0.053 m/s, the temperature change of the fluid in the outer and inner finned U-tube was increased up to 2.9% and 11% compared to the simple pipe. Short timescale responses by applying sinusoidal function boundary condition to the inlet fluid temperature show that the thermal responses of the smooth and finned GHEs are almost simultaneous by a considerable time shift. Simple and external finned pipes react up to two minutes faster than the pipe with internal fins. The fast, thermal response of the BHE helps to better fluid and ground temperature recovery which affects the performance of the ground source heat pump system.

Using fins has a positive effect on the fluid temperature changes inside the pipe and heat transfer rate between fluid and borehole wall. By using fins, in particular, internal fins, it is possible to increase the GSHP system’s efficiency, decrease the length of the tubes and reduce the initial costs of the system.

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