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# Modeling and Analysis of Spiral Type Ground Heat Exchanger for Geothermal Heat Pumps

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**ABSTRACT**

The use of geothermal heat pump systems in residential and commercial buildings around the world is increasing. The cost of ground heat exchanger due to its high share in the total system cost is a key parameter in deciding whether or not to use the heat pumps. The ground heat exchanger cost reduction is therefore, very important in the economic viability of the geothermal heat pump projects. In this paper, the evaluation of a ground heat exchanger in the form of a spiral tube is done using a 3D numerical model of the heat transfer. Furthermore, the thermal efficiency, analysis is conducted for shallow, wide boreholes. Moreover, the effect of aluminum fins inside the ground (inside the well) is evaluated in order to increase the soil and heat exchanger contact area and rise the system performance. In addition, using fins with a high heat transfer coefficient can increase the overall system efficiency by engaging more soil under the ground. The simulated borehole has 1m diameter and 10m depth. In order to reach and outperform the conventional U-tube ground heat exchangers, the impact of parameters such as fluid velocity, thermal conductivity, pitch and specific heat capacity in backfill material and sounding ground on the performance of the system is investigated. The proposed settings and configurations in this paper leads to an increase of about 30% in the heat transfer rate of the system. This improvement is due to the high thermal conductivity of aluminum fin in the soil. Additionally, the heat transfer rate from the tube to the soil is augmented especially at the end-points of the fins.

## 1. INTRODUCTION

The worldwide energy demand has substantially increased in last decade. This demand is mostly supplied by fossil fuels. The intensive use of fossil fules in energy supply causes a significant distraction in living environment and energy cost increase. These economic and environmental concerns calls for alternative methods of supplying energy, and finding ways for transition from fossil-based energy resources to renewable energy resources[1], [2].

Utilization of geothermal energy is expanding around the world dramatically. Geothermal energy not only is a clean energy source, but also it is renewable and sustainable as it can be produced continually for the long term. Geothermal energy may originate from shallow hot water or very deep high temperatures of magma[3]. Geothermal energy development for generating heat and power is a thriving international market and ever-increasing because of reliable costs and higher availability (high capacity factor)[4].

The shallow geothermal resources exist in lower depths and are available in most of the countries around the world. The ground heat for heating and cooling purposes can be accumulated and extracted from the earth using heat pump technology. The ground source heat pumps (GSHP) are commonly used because of their high coefficient of performance (COP) and their lower operation and maintenance (O&M) costs. The GSHP is known as a capable renewable energy heating and cooling system with high efficiency. Among all heating and cooling systems, the GSHP has the lowest $CO_2$ emissions, therefore, the lowest environmental cost [5], [6], [7]. However, one of its disadvantages is relatively high initial capital cost, especially in developing countries such as Iran. One of the main effective cost parameter is the cost of drilling, especially in case of deep wells and installation of ground heat exchangers in them [6], [8]. In this study, based on heat pump projects cost structure, a novel low depth and high diameter boreholes for installation of spiral type coil is proposed and numerically modeled. The method contributes in reducing the installation cost of the ground heat exchanger. The spiral type of geothermal heat exchangers include a closed loops using polyethylene tubes [9].

Recently, many studies have been done to reduce the cost of ground heat exchanger by proposing different ground coil design. Dehghan et al. assessed a new u-type model [9]. The presented model reduces drilling and eliminate up to 20% of GSHP costs. Similarly, Farabi-Asl et al. [10] conducted a study on reducing GSHP heat exchanger costs, which resulted to 22–36% savings in overall costs by improving water pumping and injection design. Bezyan et al. [11] studied three different tube types of 1-w-shape, 1-u-shape, and spiral type with inlet temperature 35 °C in cooling mode. Results of the study revealed that reductions in the outlet temperature difference of spiral, u-shape, and w-shape coils are 7.7, 4.3, and 4.9 °C, respectively. The concluded that due to the highest outlet temperature difference in spiral shape coil, it is the best choice among others.

## 2. THE 1D -3D MODEL OF THE SPIRAL COIL

A 1D-3D modeling approach is a method for simulating geothermal heat pumps heat exchanger in Comsol software. Using this method, a complex 3D domain can be transformed into a simplified domain. This method is much faster than 3D solving. In addition, the number of meshes in this method is much less than the 3D method, especially for a spiral coil that has many curves and needs more mesh. Figure 1 shows the proposed domain for this numerical modeling for the spiral coil in 1D and 3D model.

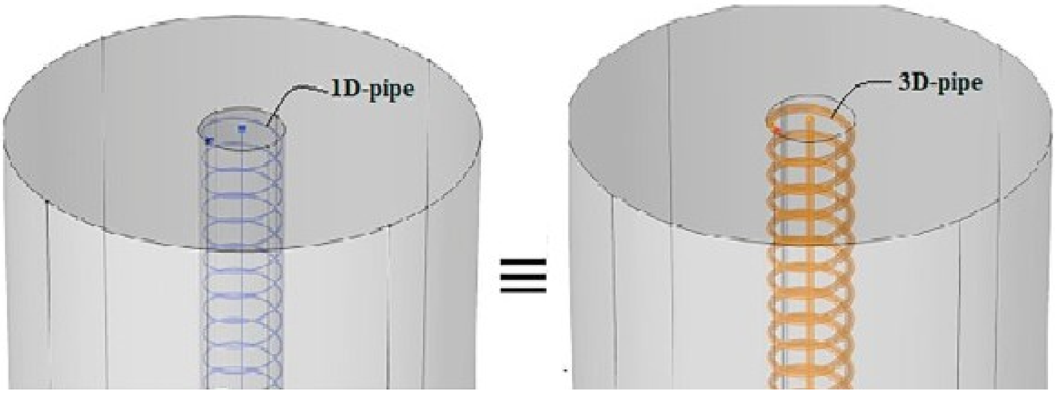


**Figure 1 the proposed domain for spiral coil numerical modeling in 1D and 3D**

### 2.1 Physical properties

The pitches used for the tube are 0.33 m, and the well depth is 10m with 1m diameter. The pipe has an internal radius of 16mm and a thickness of 3mm. In this model, the soil radius is 2.5m, and the soil depth is considered 12m for a borehole with 10m depth. For the return pipe, a spiral type heat exchanger is chosen. The outlet pipe passes through the center of the spiral pipe. The fins are linked to the pipe horizontally. Starting with the upper fin, the next one is mounted with 90° shift at 0.08 m lower height. In total, 120 fins are inserted into borehole wall.

### 2.2 Properties and material type

After designing the models in comsole, materials are added to each region of the model. Table 1 shows materials and their characteristics used in the model. However, the characteristics of the backfill material and soil in the model is almost same.

**Table 1. The physical properties of materials**

| Title | Unit | Soil | Backfill material | Fluid (water) | aluminum fins |
|---|---|---|---|---|---|
| Density | (kg/$m^3$) | 1950 | 2500 | 998 | 2707 |
| Thermal conductivity | (W/ K) | 1.5 | 1.8 | 0.60 | 204.2 |
| Specific heat | (J/kg K) | 800 | 880 | 4181.5 | 896 |

### 2.3 Governing equations

In this section, the basic equations for the simulation of the model with Comsol is presented..

The continuity equation is given equation 1.

$$\frac{\partial(A_{pipe}\rho)}{\partial t} + \frac{\partial(A_{pipe}\rho u_f)}{\partial z} = 0 \quad (1)$$

In equation 1, $u_f$ represents the fluid velocity, $\rho$ is the density, and the heat conversion area is shown by $A_{pipe}$.

The momentum equation is given in equation 2.

$$\frac{\partial(\rho u_f)}{\partial t} = -\frac{\partial p}{\partial z} - f_D \frac{\rho_f}{2D_h} u_f|u_f| + F \quad (2)$$

where, p (N/m$^2$) is the pressure, and F (N/m$^3$) is a force like gravity.

Using equation 1 and equation 2, the energy equation is obtained as follows:

$$\frac{\partial(\rho_f A_{pipe} c_f T)}{\partial t} + \frac{\partial(\rho_f A_{pipe} c_f u_f T)}{\partial z} = \frac{\partial}{\partial z}\left(A_{pipe} k_f \frac{\partial T}{\partial z}\right) + f_D \frac{\rho}{2D_h} |u_f|^3 + Q_{wall} \quad (3)$$

where, $\rho_f$ (kg/m$^3$) shows the fluid density, $c_f$ (J/(kg·K)) represents the specific heat at constant pressure, T (K) is the temperature. Also, $k_f$ (W/(m·K)) is the thermal conductivity, $D_h$ is the hydraulic diameter in the tube. The source is determined by $Q_{wall}$ (SI unit: W/m)) that shows the heat transfer at surrounding walls of the tube and is given in equation 4:

$$Q_{wall} = hZ(Text - T_0) \tag{4}$$

The overall heat transfer coefficient consists of internal, wall, and external resistances.

For a spiral pipe, hZ is calculated taking equation 5:

$$(hZ)_{eff} = \frac{2\pi}{\frac{1}{r_o h_{int}} + \frac{1}{r_N h_{ext}} + \sum_{n=1}^{N}\left(\frac{\ln\left(\frac{r_n}{r_{n-1}}\right)}{k_n}\right)} \tag{5}$$

where Z (m) is the tube environment that is wet, h (W/($m^2$ K)) is the overall heat transfer coefficient, Text (K) is the external diameter of the tube, $\mathbf{h_{int}}$ (W/($m^2$ K)) represents the internal heat transfer coefficient, and $\mathbf{r_{po}}$ ,$\mathbf{r_{pi}}$ (m) are the internal and external radius, respectively. Thegoverning equation for the heat transfers of soil, backfill material, and fin, which are solid, is shown in equation 6:

$$\rho_s c_p \frac{\partial T}{\partial t} = \nabla(k_s \nabla T) \tag{6}$$

where, $\rho_s$ is the density and $k_s$ is considered for the soil, backfill material, and fin.

The heat transfer rate is calculated using equation 7:

$$\dot{Q} = \dot{m} c_p (T_{in} - T_{out}) \tag{7}$$

The heat transfer rate per pipe unit is shown in equation 8:

$$Q_L = \frac{\dot{Q}_{comp}}{L} \tag{8}$$

In this equation, the heat transfer rate is considered per well unit and L is the well depth.

### 2.4 Boundary conditions and initial states

The initial temperature of soil and backfill material is assumed to be 18.2 °C, which is equal to the soil temperature in Tehran, Iran.

The initial temperature of the ground surface is set to 30 °C, which is the simulation temperature of the soil in summer. Also, the initial temperature of the inlet fluid is assumed to be 35 °C with the inlet and outlet fluid velocity of 0.2 m/s. The initial step is 0.0015 s and the maximum step is considered to be 600s.

The mesh is extra fine in the pipeline with the minimum element size of 4.5 mm. Moreover, at sensitive points like inlet and outlet areas, extremely fine meshes are used. For other areas, the free tetrahedral mesh with fine mesh is used. The minimum sizes of the elements are considered to be 7mm, 2.5cm, and 2.2cm for fin, soil, and borehole, respectively.

### 2.5 Model validation

For the validation of simulation, the outcomes of the study by Dehghan & Kuker [12] is used. In their model, the tube has a radius of 0.014m with 0.003m thickness, 4m depth and borehole diameter of 0.45m using 0.1m pitch. The test is examined at 150hr without any stop, the volume flow rate is 15 lit/min. The simulation model has a good match with the experimental data and particularly, they fit perfectly (Figure 2).

In this paper, the impact of a set of parameters on the velocity was assessed. These parameters include changes in pitch, thermal conductivity, and specific heat of pipe. Also, the impact of the aluminum fins inside the soil is elaborated. The fins are mainly for increasing the heat transfer between the tube and the soil as well as for enhancing the system efficiency.

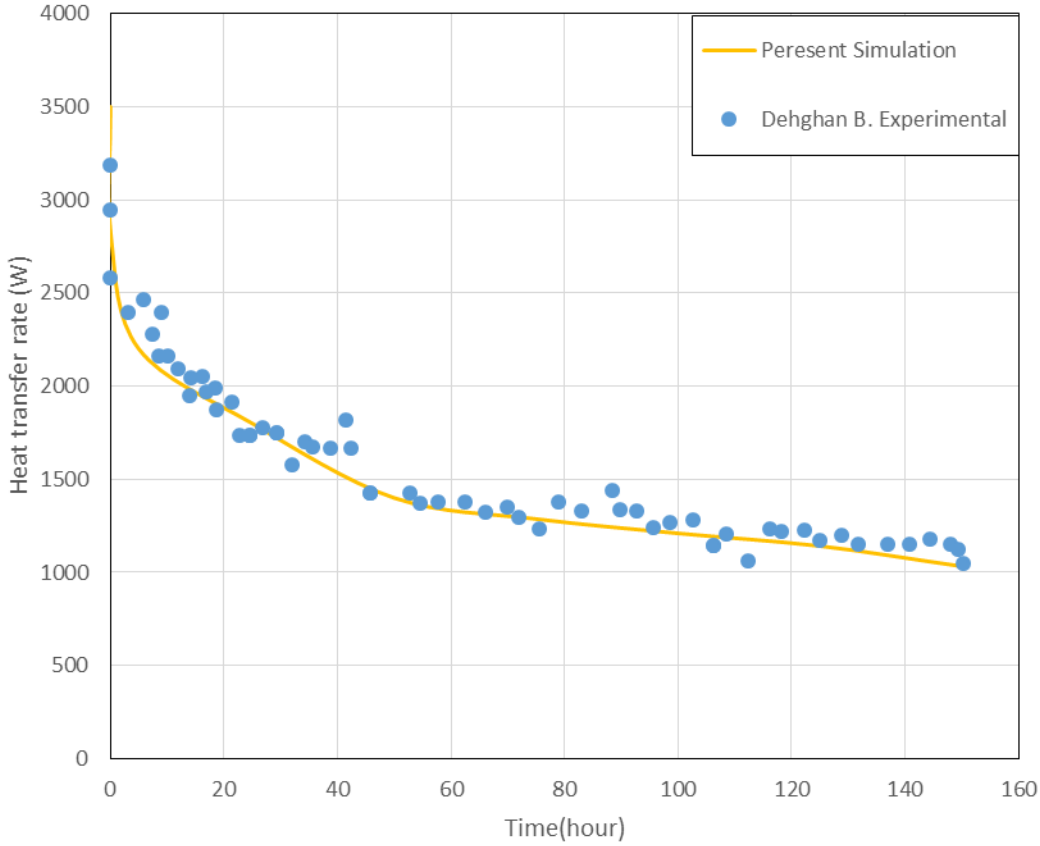


Figure 2 Validation of the CFD model heat transfer rate for numerical and experimental data Simulation and result

## 3. RESULT AND DISCUSSION

### 3.1 Soil depth

To determine the best well depth, two depth cases of 12 and 15 m were considered for a 10m borehole. After 48 hours of simulation, the fluid output temperature was compared in 12m case and 15m case. The difference between two cases is minimal. However, considering the temperature-time diagram (Figure 3), at the end of the soil and at the depth of 12 m, there is no thermal effect on the soil before 50 hours. Even after 50 hours, there is still a minimal effect on the soil. The temperature changes are only 0.3 from 50 to 240 hours, indicating that the appropriate height for the soil in this study is 12 meters.

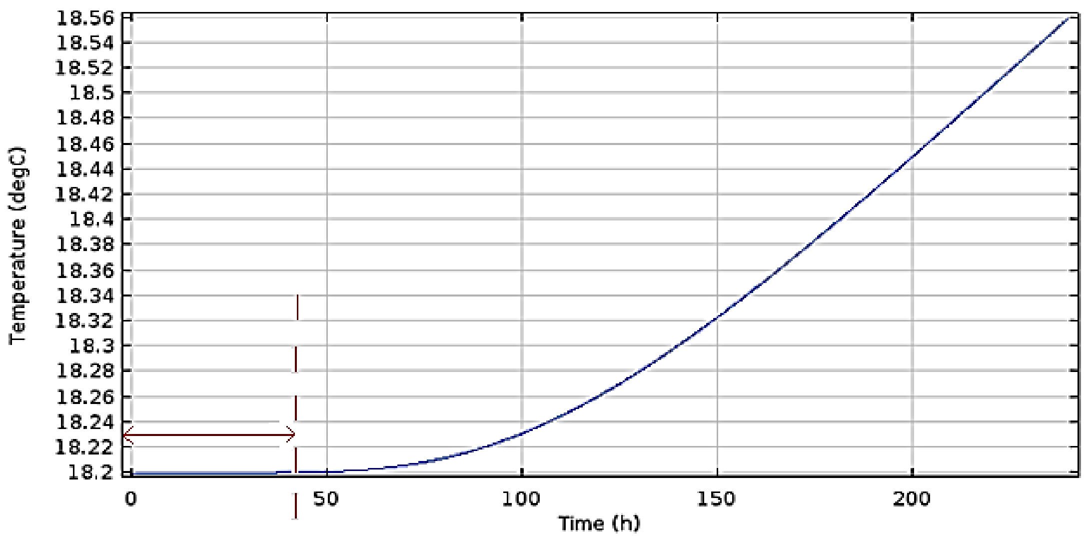


**Figure 3. Variation of outlet temperature in the 12m depth, the bottom of the soil temperature**

### 3.2 The effect of the fin on soil and its heat transfer

As previously mentioned, the borehole diameter is 1 meter and is relatively larger than the boreholes used in the conventional u-tube geothermal systems. Hence, it is possible to insert the tube and fins manually inside the ground. This has two advantages: first, it the tube can be fixed tightly in the ground as a foundation; second, if the fins are made of aluminum or copper or metal with a high thermal conductivity, the heat transferred to the soil or taken from the soil can be increased by engaging a larger volume of the soil.

According to **Error! Reference source not found.**, each ring is connected with 4 fins, each fin is 90 degrees away from the other one, and a total of 120 fins are inside the ground. In this paper, 5 types of fins with different lengths and diameters are investigated. The fins are made of aluminum. The fins' characteristics and their effect on the exit temperature are shown in **Error! Reference source not found.**. The calculated temperature at the best mode reaches to 0.84 °C, which caused a 30% improvement in the heat transfer.

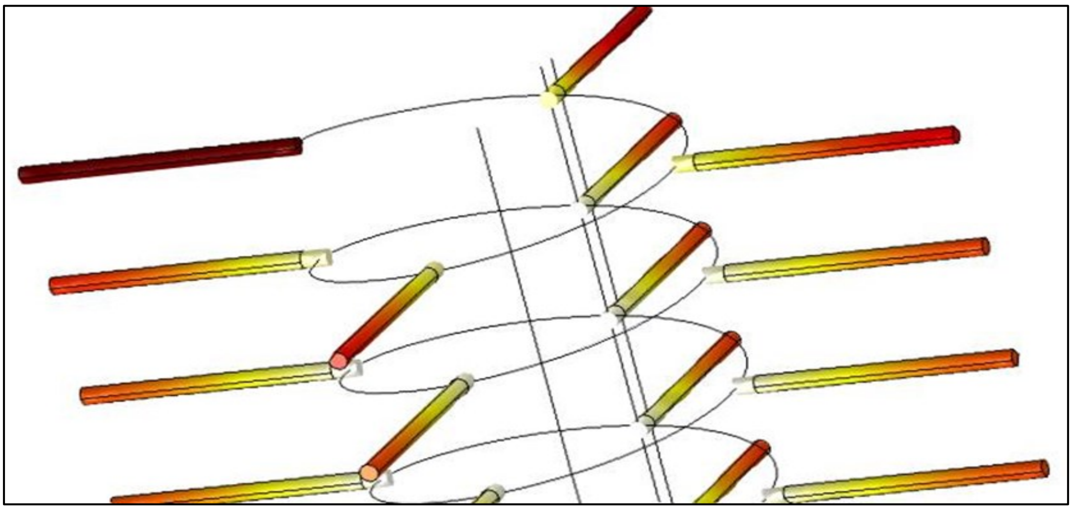

**Figure 4 Close view of the spiral pipe ground coil with aluminum fins**

**Table 2. The aluminum fins shape and their effect on the outlet temperature after 48 h**

| Case | Length | Diameter | $T_{out-r}$(°C) | Increase performance system with fin |
|---|---|---|---|---|
| 1 | 0.5m | 0.03m | 31.78 | 18.1 |
| 2 | 1m | 0.03m | 31.742 | 19 |
| 3 | 0.5m | 0.05m | 31.70 | 21 |
| 4 | 0.75m | 0.05m | 31.488 | 28 |
| 5 | 0.5m | 0.07m | 31.429 | 31 |

As shown in Figure 4, the rate of the heat transfer to the soil increased significantly along the fins. To compare the heat transfer in the with-fin configuration with no-fin configuration, a point at the depth of 5m and the distance of 1m from the borehole center is considered. While the soil temperature at this point in with-fin configuration reaches to 23°C after 18.8h, in no-fin configuration it reaches to the max temperature of 21°C after 48 hours. The results revealed that not only the heat transfer area increases in with-fin configuration, but also, the heat transfer rate rises up to 2.5 times more compared to the no-fin configuration.

In the next step, two tubes with different spacing were simulated for 720 hours (one month). In the first case, a center-to-center distance of 7 meters between tubes were considered. Figure 6 shows the variation of the outlet temperature for the with and without fin configurations as a function of time.

It seems that the distances like 6 or 7 meters is appropriate for 1 month. But it looks like the soil recovery is of significance. Whether the nonstop operating (after 3 months) is good or stopping after each month for the soil recovery. Moreover, it can be conducted for the simple and fin equipped model by taking more spiral pipe and different distances into account.

Figure 6 and Figure 7 show the temperature distribution in the center of the system (z=-5) after 720 hours for 5 different distances of two pipes (inlet and outlet). It is obvious that in the center (x=0), by decreasing the pipes distance, the temperature is increased. This augmentation does not affect the output temperature of the fluid after 720 hours. Hence, this result should be assessed under simulation time of longer than one month.

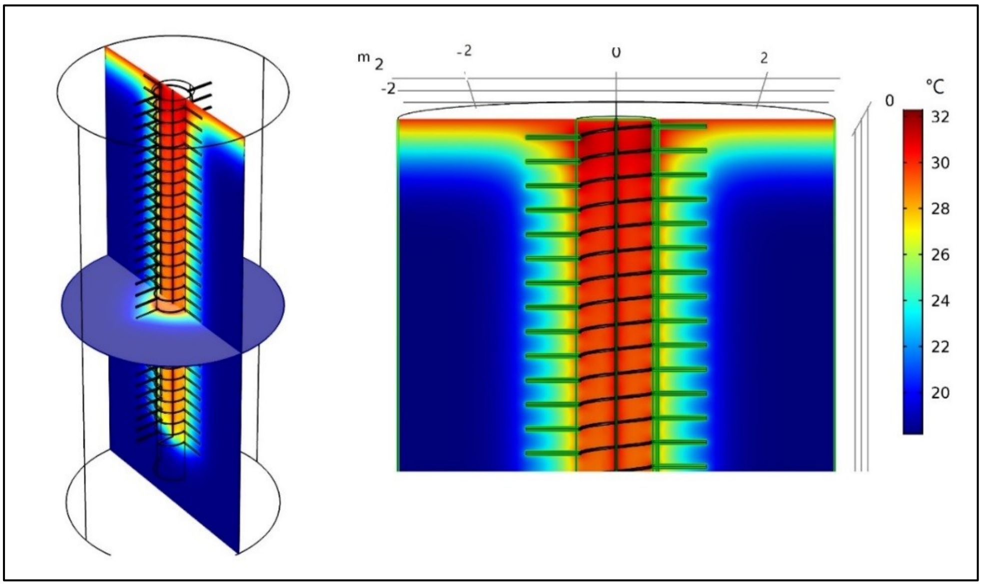


**Figure 4 Cross-section of the model with fins after 48h**

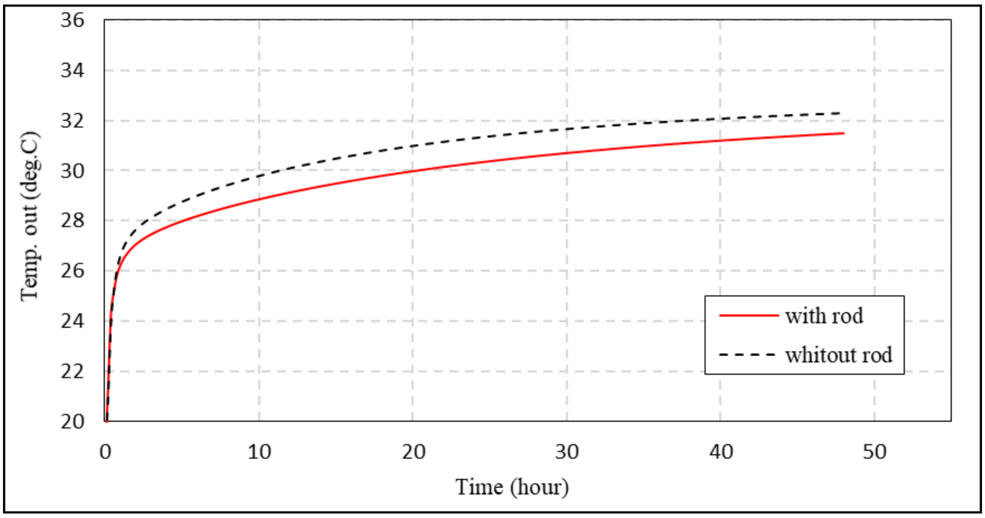


**Figure 5 Variation of outlet temperature with and without fin**

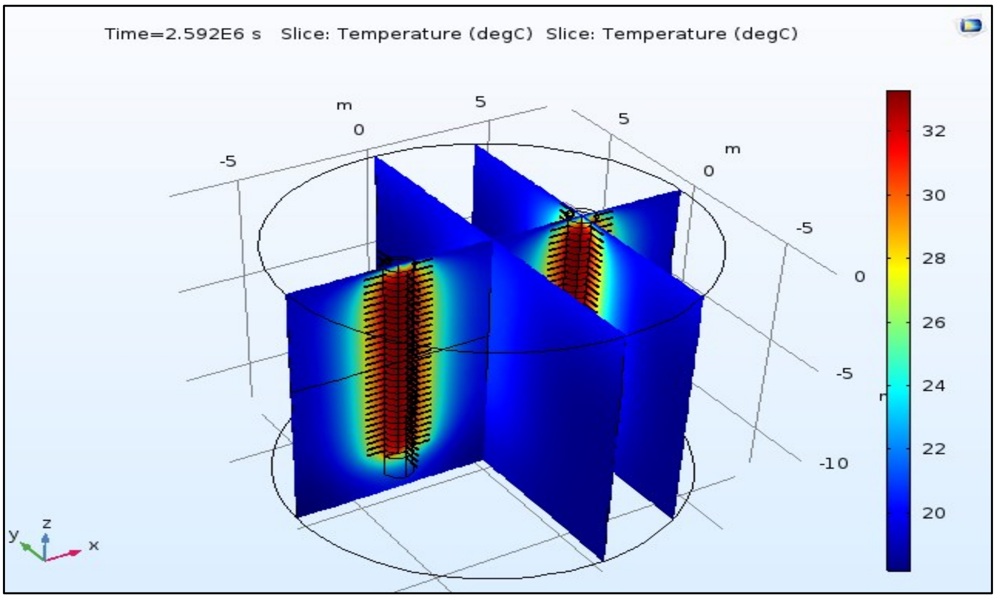


**Figure 6 the temperature distribution in the center of the system (z=-5) after 720 hours for 5 different distances of two pipes**

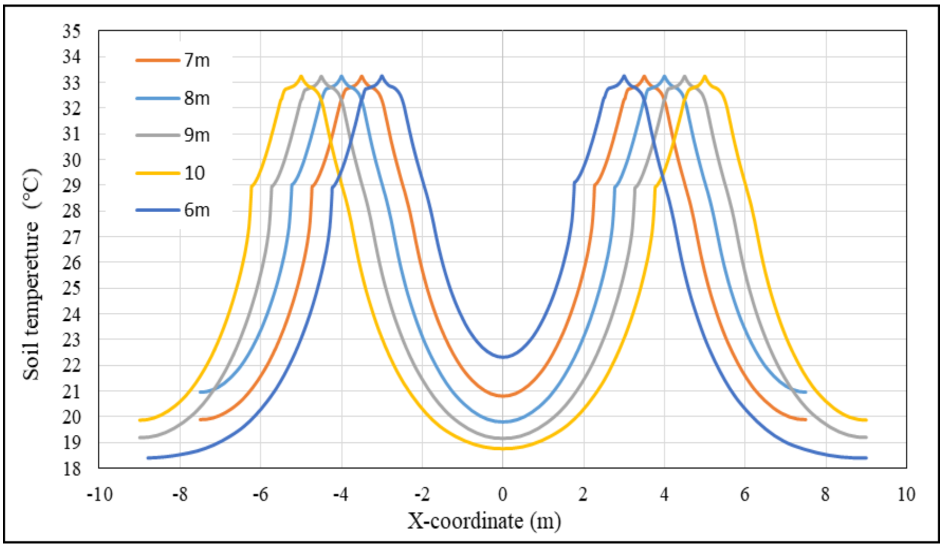


**Figure 7 the temperature distribution in the center of the system (z=-5) after 720 hours**

### 3.3 The effect of the borehole backfill and soil material on the system performance

In this section, the effect of the parameters such as soil material and backfill material on the system performance and the out fluid temperature is presented. The model results show that changes in outlet temperature are dependent on the alternation of thermal conductivity. For a different soil and backfill material and keeps constant the other properties of the model results are evaluated. Table 2 shows the material type and properties used in the simulation.

At first, 4cp modes (500 to 3500 (J/kg K)) are considered with 4 different thermal conductivity modes of 0.5 to 2 W/mK, which the lines are in constant-k conditions. By increasing the thermal conductivity, constant-k lines get closer, which is more prominent for the backfill material than the soil.

The changes in the thermal conductivity with constant-cp are shown for two areas of backfill materials and soil with a range of thermal conductivity from 0.5 to 5 (J/kg K) (Figure 8). As shown in the figure, by increasing the thermal conductivity, the effect of soil thermal properties is greater than that of the backfill material on heat exchange, in both modes with fin and without fin.

The thermal conductivity of the soil and backfill materials is enhanced and it is observed that the effect of increasing this parameter is greater for soil rather than the backfill material. This is because of the connection between soil and exchanger in spiral mode. Also, the spiral pipe is closer to the walls than the center of the borehole.

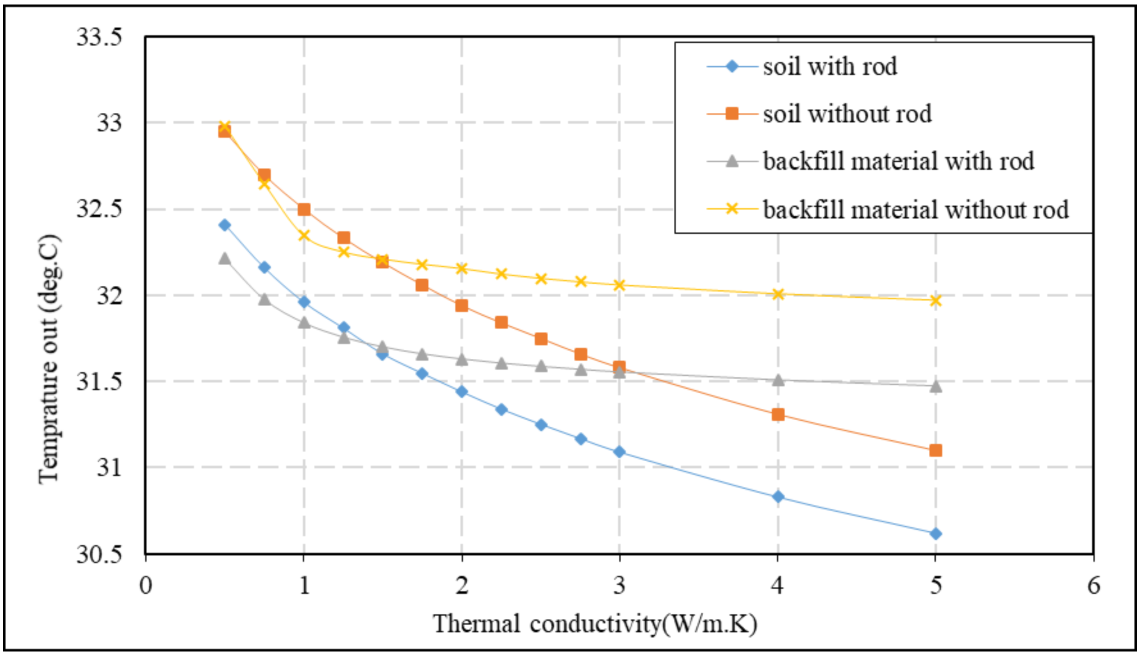


**Figure 8 Influence of backfill material and soil thermal conductivity in two-mode (with fin and without rod)**

## 4. CONCLUSION

In this paper, a 1D-3D model was used for simulating the geothermal heat exchanger employing Comsol software. We considered a tube in a spiral form with a shallow depth of 10m and large diameter of 1m. The geothermal heat pump efficiency was enhanced by changing parameters like thermal conductivity in the soil, backfill material and by adding fins in the soil. The results are listed below:

- The best-suggested model for simulating the geothermal pipes is a 3D model. This model is appropriate due to its high accuracy and the ability to make the calculation time slower.
- The heat transfer was improved utilizing 120 horizontal aluminum fins in the soil linked to the exchanger. By analyzing 5 different rods with different lengths and diameters, the temperature difference was increased by 0.84℃, which can improve the heat transfer up to 30%.
- By increasing the thermal conductivity of the soil and backfill material, it was observed that this change has more effect on the ground soil rather than the backfill materials.

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