Long-term Effects of Ground Source Heat Pumps on Underground Temperature

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Abstract: Ground Source Heat Pumps (GSHPs) have received significant attention in recent years because of their energy efficiency. Most studies are interested in the performance of GSHPs. However, little research has been done on the underground temperature distribution and change affected by GSHPs. This study set up a numerical model in Comsol Multiphysics and simulated the underground temperature over 100 years. The long-term underground temperature around an energy pile was investigated without considering groundwater movement. Parameters and boundary conditions were examined before the simulation. The temperature changes at different depths and distances were presented. Temperature decreases were found in half-compensation and no-compensation conditions, and the decrease processes were found happened mainly within the first decade.

Keywords: long-term effects, GSHP, underground temperature, Comsol Multiphysics simulation.

1. Introduction

Geothermal energy can be used to generate electricity or to heat or cool buildings by using Enhanced Geothermal Systems (EGS) or Ground Source Heat Pumps (GSHPs). There is approximately 140×10^6 EJ heat available in the upper 5 km of the Earth's surface due to the molten metal core of the Earth, the decay of radioactive materials, and the large amount of solar energy. The current rate of the world's energy consumption is about 500 EJ/year, which means only 1% of the Earth's surface heat energy can meet 2800 years of the world's energy demand[1]. The GSHP system, which can pump heat from the ground in winter and inject heat from the outside to the ground, has received much attention. The system buries pipes in which fluid is applied to extract or dissipate heat in the ground from 2m to 200m in depth. The efficiency of the heat pump is evaluated by the coefficient of performance (COP), which is the ratio of output heat over the input electrical power. The heat exchange between the GSHP system and the ground is affected by the temperature difference, as well as by the absorber pipe and fluid properties. For GSHP systems, the current COP is about 3.5-5.5. Compared with AC (air conditioning) systems, which have a COP of 1.5-2.5, GSHP systems are more energy efficient. Closed loop systems, which are always installed in vertical boreholes with U-tubes or coaxial tubes or in horizontal trenches with line tubes or coil tubes, have much more potential for widespread applications.

Many studies are interested in the heat transfer between the heat exchanger and the ground, and most focus on the performance of the heat exchanger. Their purpose is to evaluate the COP of GSHPs. Based on the studies on COP, it is believed that a U-tube is better than a coaxial tube in both performance and heat output except for the cost of drilling [2]. For the application of GSHP, a guide of the system design [3] was published, and studies of designing GSHP system with high COP [4] have been conducted. For the part of modeling, a detailed review [5] introduced the methods of modeling the heat transfer of GSHPs and summarized the heat transfers outside and inside the borehole. The long-term performance of borehole heat exchanger (BHE) fields was simulated with and without considering the groundwater movement [6][7], and it was concluded that the groundwater movement has a significant impact on the long-term performance of GSHPs. In the modeling of a borehole, the cross section model with infinite borehole length was found less accurate than the vertical section model with finite borehole length [8]. A model of the vertical borehole U-tube heat exchanger with an imposed heat flux of 2500W on the U-tube was set up, and then simulated the performance of a pavement heating system as a supplemental heat rejecter [9]. Other heat exchanger models and applications such as the horizontal heat exchanger model[10], the foundation heat exchanger model[11], and the energy pile heat exchanger model[12][13][14] were also investigated. A case study [15] and in-situ tests [16][14] were conducted as well. The heat exchangers that were casted in concrete piles of building foundations [17] were also studied. In the research, the diameters of the concrete piles were from 1500 to 4000mm, and the depths were 20m; the average heat extraction rate from the ground per pile was about 48W/m with the maximum value of 124W/m, and the average heat injection rate was 110W/m with the maximum value of 164W/m. The one-year underground temperature at the depths of -1m, -10m, and -19m and the distances of 0.5m and 2m from the boundary of the pile was measured, but the long-term temperature was not monitored.

On the other hand, little research on the effects on ground temperature and underground temperature distribution from GSHPs has been developed. As a result, a simulation of the long-term performance of GSHPs would not be accurate if it uses fixed underground temperature. In addition, the underground temperature would decrease as the GSHP system extracts heat from the soil and do so even more rapidly in the superposition area between two heat exchangers [14]. Furthermore, the GSHP system would collapse if the underground temperature drops too much. The current study is to simulate the long-term effects of the GSHP system on the underground temperature distribution with the lower boundary condition of a constant heat flux and the upper boundary condition of ground surface temperature. The results of this study can be used for the design of GSHP systems and analysis of the long-term effects of GSHPs on the environment. The first part of this paper will test the boundary conditions and set up a model in Comsol Multiphysics. The second part will discuss the results and develop further research.

2. Boundary Conditions

The ground surface temperature is affected mostly by the atmosphere and solar energy till 5 meters. The temperatures of the ground surface and air at their boundary are normally about equal, and the temperature difference in the ground decreases exponentially with the depth increases. The maximum and minimum temperature values, however, occur later than the corresponding values at the surface. Normally, when the depth is below 5 to 10m, the ground temperature keeps constant throughout the year, and the average annual temperature keeps constant with the depth, and increases with a gradient because geothermal heat flows from the center of the Earth to the surface[18][19][20]. The average continental heat flux from the interior of the Earth is 0.060W/m^2 with the range from 0.036 to 0.092W/m^2 [21]. The lower boundary condition of the constant heat flux 0.075W/m^2 was used for simulating the heat transfer near an underground nuclear waste repository [19]. The authors also suggest that the upper boundary condition is better as a fixed temperature at the depth of 10m, and lateral boundary conditions are no-flux with the distance of 10 times the depth, which ensures any error from the boundary conditions less than 1%. With these boundary conditions, the long-term underground temperature should keep constant when the soil temperature is undisturbed.

In many models, the lower boundary conditions were set to be a constant temperature, and the upper boundary conditions were set to be an adiabatic condition. The settings are acceptable for short-term single borehole simulations but are debatable for long-term simulation. The reasonable settings are a constant heat flux for the lower boundary and air temperature for the upper boundary.

3. Use of COMSOL Multiphysics

In this study, a single pile (borehole) was investigated, and models were built in the finite element software, Comsol Multiphysics.

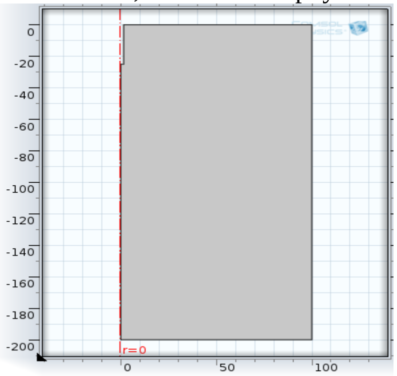

Figure1. Computational domain for 2D models of the ground temperature

The ground was assumed to be an isotropic and homogeneous solid with the heat capacity of

Cp=1480[J/(kg*K)] and the thermal conductivity of k=2.35[W/(m*K)] and without considering the groundwater movement. A 2D-axial symmetry model in the polar coordinates was set up first to verify the boundary conditions, and then thermal load conditions were added to the proper boundaries of the model to simulate the long-term effects on the underground temperature from the GSHP heat exchanger. The lower boundary condition was set to be a fixed heat flux q0=0.075[W/m^2]. The lateral boundary was assumed to be adiabatic. The ground surface temperature Ts followed equation (1) with the amplitude of A=20[K] and the average temperature of Ta=284.15[K] (i.e. 11℃).

$$Ts=A*\sin(2\pi t/\tau)+Ta \qquad (1)$$

where τ equals 31536000[s] (i.e. one year). Figure1 shows the dimensions of the axial symmetric model, where H and R represent the depth and the radius of the pile, respectively. In this study H=25m and R=0.75m were used. The dimensions of the ground were much bigger than the heat exchanger borehole dimensions in order to minimize the error introduced by the boundary conditions. The geothermal gradient was set to be 0.029[K/m] for the initial value; therefore, the initial ground temperature Tg follows equation (2).

$$Tg=284.15[K]-0.029[K/m]*z \qquad (2)$$

where z is the depth.

A total of 200 years of underground temperature was investigated before thermal loads were added on the pile boundaries, and then a total of 100 years of temperature in the ground was simulated after adding the thermal loads. Three sets of thermal loads, with full heat compensation, half heat compensation, and without heat compensation, were studied. The temperature changes below the depth of 10m under these thermal load conditions were calculated. The thermal loads are presented in equations (3), (4), and (5), respectively, which are illustrated in Figure 2. The positive values represent the heat injected into the ground, and the negative values represent the heat extracted from the ground. The time dependent process was performed for the heat transfer, and the governing equation is as equation (6).

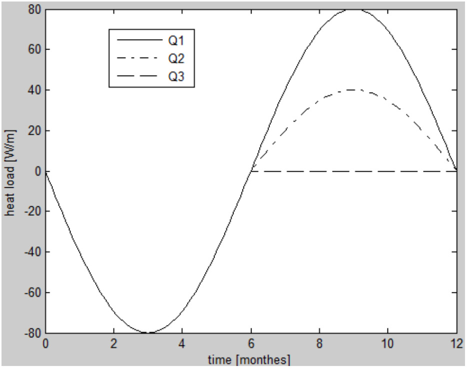

Figure2. Thermal load curves for full compensation (Q1), half compensation (Q2), and no compensation (Q3). The injective heat loads are different, but the extractive heat loads are the same.

$$Q_1=-80*\sin(2\pi t/\tau) \qquad (3)$$

$$Q_2=-60*\sin(2\pi t/\tau)-20*|\sin(2\pi t/\tau)| \qquad (4)$$

$$Q_3=-40*\sin(2\pi t/\tau)-40*|\sin(2\pi t/\tau)| \qquad (5)$$

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u}\cdot\nabla T = \nabla\cdot(k\nabla T) + Q \qquad (6)$$

4. Results and Discussion

The temperature values for 200 years at the depth of -10m, -15m, -25m, -40m and -60m are revealed in Figure 3. The temperature of the ground is considered to be constant before heat loads were added, and the parameters and boundary conditions are considered suitable for this simulation.

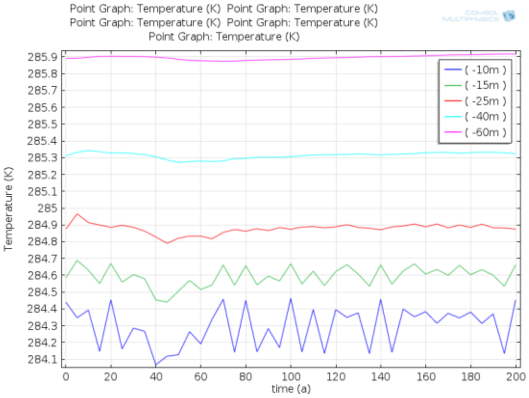

Figure3. Temperature at the depth of -10m, -15m, -25m, -40m ,and -60m in the 200-year span.

Figure 4 shows the difference in the isothermal lines at the end of the 100th year between the full heat compensation condition and no heat compensation condition. The heat gradient in Figure 4 (a) shows that the heat transfer is from the pile to the ground, which is because it is just at the end point of the heat injection, and the pile temperature is higher than the ground temperature. However, the heat transfer is always from the ground to the pile in (b). Compared to the isothermal lines in Figure 4 (b), the temperature disturbed area in (a) is smaller than that in (b). This indicates that the GSHP without heat injection will impact a larger area in underground temperature. The distance from the center of the pile to the point with maximum curvature at -15m is about 20m, and this distance will increase with the increase of the heat extraction load.

The data in Table 1 show the temperature changes, compared to the initial values, in different distances to the center of the pile and depths under three different heat compensation conditions. The temperature changes at the end of 5th, 10th, 50th, 100th year are presented. With the full compensation, the temperature around the pile even increased slightly rather than decreased. When there was no heat injection, however, the temperature at the depth of -15m decreased about 4.17[K] after 100 years. An interesting finding is that the decrease process happened mainly within the first decade. The temperature changes remained nearly constant after that. With the half heat compensation, the temperature around the pile also decreased, and the values fluctuated.

In the three heat conditions, the influence distances were about 10m but not more than 20m.The influence depths were less than 60m. In the conditions of half-compensation and no-compensation, the area that the temperature decreased mostly was at the depth of -15m and within 0.5m from the pile boundary.

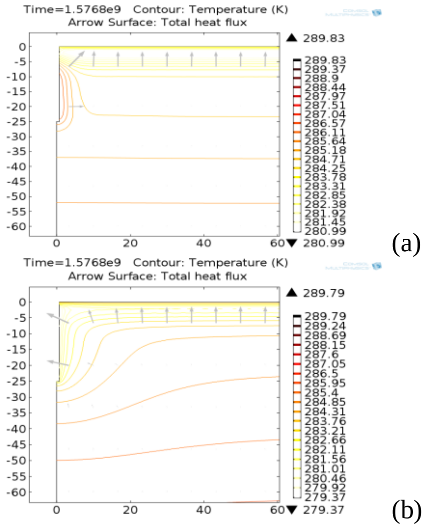

Figure4. Isothermal lines of ground at the end of the 100th year with full heat compensation (a) and without heat compensation (b). The arrows indicate thermal gradient directions.

From this study, the long-term underground temperature near an energy pile was obtained. However, the temperature distribution and influence distance due to temperature decrease, which are under different thermal loads remain unclear. If the influence distance is broad enough and another GSHP lies within the distance, there will be an impact on the performance of the neighboring GSHPs. If the underground temperature greatly decreases within the first

Table1. Underground temperature changes at the selected points at the end of 5th, 10th, 50th, and 100th year under different heat compensations

Distance to pile center (m)		1				11				21			
Temperature Change (℃)		At the end of years											
Depth (m)		5 a	10 a	50 a	100 a	5 a	10 a	50 a	100 a	5 a	10 a	50 a	100 a
No compensation	-10	-1.84	-4.06	-4.12	-4.14	-0.67	-0.85	-0.98	-1.54	-0.25	-0.40	-0.44	-0.46
	-15	-1.71	-4.03	-4.13	-4.17	-0.47	-0.77	-0.79	-1.11	0.01	-0.24	-0.31	-0.36
	-25	-1.03	-2.47	-2.63	-2.70	-0.30	-0.54	-0.61	-0.77	0.03	-0.16	-0.28	-0.35
	-40	-0.10	-0.18	-0.36	-0.42	-0.05	-0.12	-0.27	-0.36	0.00	-0.04	-0.18	-0.24
	-60	0.00	-0.01	-0.16	-0.16	0.00	-0.01	-0.10	-0.14	0.00	0.00	-0.09	-0.13
Half compensation	-10	-0.58	-0.22	-1.47	-0.85	-0.34	-0.25	-0.70	-0.33	-0.13	0.00	-0.48	-0.20
	-15	-0.42	-0.12	-1.42	-0.86	-0.15	-0.10	-0.62	-0.35	0.09	0.20	-0.37	-0.12
	-25	-0.27	-0.18	-0.90	-0.66	-0.09	-0.13	-0.41	-0.34	0.08	0.08	-0.23	-0.15
	-40	-0.04	-0.07	-0.14	-0.18	-0.02	-0.03	-0.11	-0.13	0.01	0.02	-0.06	-0.08
	-60	0.00	0.00	-0.02	-0.04	0.00	0.00	-0.01	-0.04	0.00	0.00	0.00	-0.03
Full compensation	-10	1.46	1.60	1.33	1.62	0.02	-0.22	-0.20	-0.25	0.02	-0.25	-0.22	-0.28
	-15	1.64	1.84	1.47	1.87	0.21	0.04	-0.05	0.01	0.22	0.01	-0.07	-0.02
	-25	0.93	1.11	0.81	1.11	0.12	0.09	-0.05	0.06	0.14	0.08	-0.06	0.04
	-40	0.01	0.05	-0.04	0.06	0.02	0.05	-0.04	0.06	0.03	0.05	-0.04	0.06
	-60	0.00	0.01	-0.01	0.04	0.00	0.01	-0.01	0.04	0.00	0.01	-0.01	0.04

decade, the GSHP system will collapse before its influence distance affects the neighboring GSHPs. Therefore, further study is suggested to change the thermal loads to investigate the relationship between the underground temperature decrease and the influence distance. In addition, it will be better to modify the model in further studies. A porous medium with groundwater movement is suggested to simulate the ground because the groundwater has a great impact on the performance of GSHPs and underground temperature distribution. Then, double piles or multi-piles can be simulated.

5. Conclusions

A numerical model was set up in Comsol Multiphysics to simulate the underground temperature for 100 years. Before simulation, the parameters and boundary conditions were verified as suitable. The simulated undisturbed underground temperature increased with depth at a gradient, and the average annual ground temperature at a certain depth kept constant throughout the year. Three types of thermal loads, with full heat compensation, half heat compensation, and no heat compensation, were studied. According to the simulation results, the underground temperature did not decrease under the thermal load with full heat compensation; the temperature decreased under the other two thermal loads, and the decrease processes happened mainly within the first decade. The area where the temperature decreased the most was at 0.5m from the pile boundary. The influence distance due to the temperature drop at the given thermal load under no heat compensation condition was about 20m in horizontal and less than 60m in vertical, and it will increase with the increase of the extraction thermal load.

Further study is suggested to use the porous medium as the ground model and add the effects of groundwater movement. The relationship between the influence distance and the temperature decrease is also suggested for further study.

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