Effects of aquifers on soil temperature distribution around deep buried heat exchanger

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Abstract. Deep buried heat exchanger has been increasingly applied into the building heat source through the utilization of geothermal energy. During the geothermal system design process, the aquifer is an important factor that affects the overall performance prediction. The flow of underground water at different positions changes the temperature distribution of the soils around the buried pipe and then influences the heat exchange at different depths. Consequently, the variation of the temperature field causes the thermal radius of the heat exchanger no longer regularly distributed, which affects the determination of the well spacing. With the aims of improving the accuracy of performance estimation, the aquifer effect is carried out by this study. The solution to the moving line source theory is used to acquire the temperature response at different positions. The overall effect of the underground water with different velocities on the performance is evaluated. The soil temperature distribution in the heat exchange zone with aquifers at different depths is studied in detail. The predicted thermal influence radius at different depths with various groundwater velocities and soil thermal properties showed that the temperature distribution around the buried heat exchanger is largely influenced by the groundwater movement. Under the simulation condition, the thermal radius increases from less than 10 m for pure conduction condition to a maximum value of 25.3 m with groundwater flow. The aquifer enhances the heat absorption of the heat exchanger, but the high flow rate also leads to a large thermal radius. The obtained thermal influence radius under different conditions can provide guidance for the design of the geothermal system.

Keywords: Geothermal energy, Deep buried heat exchanger, Aquifer, Soil temperature distribution, Thermal influence radius

1. Introduction
The geothermal energy has become one of the major choices for building energy supply in recent decades. During the utilization process, the ground coupled heat exchanger (GCHE) is well known as an essential part of the geothermal system [1-3]. Among different types of heat exchangers, the vertical deep-buried heat exchanger is usually used for building heating and its depth is generally greater than 2000 m [4]. Compared with horizontal heat exchangers or shallow buried heat exchangers, it possesses the advantages of high efficiency, less ground area occupation and stable heat distribution.
source temperature [5]. Therefore, it has been widely used in different engineering projects and a great deal of relevant research has been carried out.

The factors that affect the performance of the buried pipe mainly include the ground properties, the pipe structure, the working fluid, the grout backfill material and the aquifer around the pipe [4, 6, 7], etc. Among these factors, the existence of aquifer has a big impact on the buried heat exchanger. Compared with pure conduction conditions, the groundwater flow would bring the advective heat transport between the buried pipe and the surrounding soils [7]. The heat is transported by the moving water and the temperature distribution changes accordingly. Then the temperature field and the design of the geothermal system can be different from the pure conduction condition.

Wang et al. [8] conducted an experiment of buried heat exchanger under groundwater flow in Baoding, China. The depth of the borehole is 78 m and the inlet water temperatures were set as 6 °C, 8 °C, 25 °C and 30 °C, respectively. After more than 20 hours’ operation, the results showed that the presence of aquifer enhanced the heat exchange performance of the buried pipe. On average, the heat extraction rate in summer and the heat injection rate in winter were increased by 9.8% and 12.9%, respectively. Sutton et al. [9] presented a ground resistance for the calculation of vertical borehole heat exchangers with groundwater movement based on the moving line heat source solution. The quantitative analysis showed that when Peclet number is larger than 0.1, the ground resistance would differ markedly from the pure conduction condition. Choi et al. [10] established a computational model to study the thermal behavior of a borehole heat exchanger array under different flow directions and rates. The depth of the borehole was 200 m and each array consisted of nine boreholes. After validated by the moving infinite line source and finite line source models, a 15-year operating was carried out. The results showed that when Peclet number was larger than 0.05, the groundwater movement could induce the heat accumulations and improve the performance of the heat exchanger array.

In order to evaluate the influence of aquifers on the deep buried heat exchanger with the depth of several thousand meters, this paper adopts the solution to the moving infinite line source model to study the temperature response of the ground. The key parameters are taken into consideration, including the groundwater velocity, the ground thermal conductivity, the soil density and the soil specific heat. The objective is to obtain the soil temperature distribution and the thermal radius caused by heat absorption from the deep buried heat exchanger at different depths. The results of the soil temperature field can serve as a reference for the calculation of heat exchanger performance. The thermal radii at different depths can be used as guidance for the well spacing design between neighboring heat exchangers to reduce the interacted effect and improve the performance of the geothermal system.

2. Methodology

The heat transfer in the porous media with groundwater movement is governed by the following partial differential equation [11],

\[
\rho c \frac{\partial T}{\partial t} + u_s \rho_w c_w \frac{\partial T}{\partial x} - \lambda \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) = 0
\]  

(1)

where \( \rho \) and \( \rho_w \) are the densities of the soil and the groundwater, respectively. \( c \) and \( c_w \) are the specific heat of the soil and the groundwater, respectively. \( T \) represents the temperature of the soil. \( t \) is the time and \( u_s \) is the velocity of groundwater oriented in the x-direction. \( x, y, z \) are the space coordinates and \( \lambda \) denotes the bulk thermal conductivity of the porous medium. Assuming the ground is homogeneous porous medium with constant properties and the initial soil temperature is uniform around the line source, the two-dimensional solution to the governing equation in the polar coordinate can be obtained as [10],

\[
\Delta T(r, \phi, t) = \frac{q}{4\pi\lambda} \exp \left( \frac{Ur}{2a} \cos \phi \right) \int_0^{4\pi/a^2} \frac{1}{\eta} \exp \left( -\frac{1}{\eta} \frac{U^2 r^2 \eta}{16a^2} \right) d\eta
\]  

(2)
where $\Delta T$ is the temperature change. $r$ and $\phi$ are the polar coordinates, $r = \sqrt{x^2 + y^2}$. $q$ is the heat exchange rate of the borehole per meter, and $U = u_\phi \rho \varepsilon_c / \rho c$ denotes the effective heat transport velocity. $a$ represents the thermal diffusivity and $\eta$ is the integration variable. In the present study, the above-mentioned equation was solved through coding FORTRAN computer program.

3. Simulation results and discussion

In order to study the soil temperature distribution around the deep buried heat exchanger with groundwater flow, the aquifer is assumed to be at different depths with different thermal properties according to the references [13-15] (as shown in Table 1). The heat exchange rate per meter of the heat exchanger is -50 W/m because the deep buried heat exchanger absorbs heat from the ground in winter. The thickness of the aquifer is 50 m and the velocities are set as $0$ m/s (pure conduction), $5\times10^{-8}$ m/s, $10^{-7}$ m/s, $5\times10^{-7}$ m/s, and $10^{-6}$ m/s for simulation. The average temperature gradient is assumed to be $3^\circ C$/hm and the ground surface temperature is 10$^\circ$C. The schematic of the 3D model used in the present study is shown in Figure 1.

![Figure 1. Diagram of the deep buried heat exchanger with groundwater.](image)

| Position of the aquifer | Ground thermal conductivity/W·m$^{-1}$·K$^{-1}$ | Initial ground temperature/$^\circ$C | Soil density/kg·m$^{-3}$ | Soil specific heat/J·kg$^{-1}$·K$^{-1}$ | Thermal diffusivity/m$^2$·s$^{-1}$ |
|------------------------|-----------------------------------------------|-----------------------------------|------------------------|---------------------------------------|----------------------------------|
| $d = 500$ m            | 1.59                                          | 25                                | 1760                   | 1433                                  | 6.3$\times10^{-7}$                |
| $d = 1000$ m           | 1.76                                          | 40                                | 2070                   | 878                                   | 9.68$\times10^{-7}$               |
| $d = 1500$ m           | 1.88                                          | 55                                | 2270                   | 848                                   | 9.76$\times10^{-7}$               |
| $d = 2000$ m           | 2.69                                          | 70                                | 2650                   | 752                                   | 1.35$\times10^{-6}$               |

Table 1. Parameters assigned to aquifers at different depths.

Figure 2 shows the temperature distribution along the $x$-direction under different groundwater velocities after 100 days. It can be seen that for all the cases, as $x$ becomes larger (away from the heat exchanger), the temperature rapidly increases first and then slowly get closer to the initial ground temperature. When the velocity is $10^{-7}$ m/s or $5\times10^{-8}$ m/s, the curve is extremely closer to the pure condition curve (i.e., $v = 0$ m/s), indicating that the movement of aquifer has little impact on the temperature distribution when the flow rate is small. When the aquifer velocity increases, the soil temperature next to the heat exchanger becomes larger, demonstrating that the large velocity contributes to the heat transport along the flow direction. The temperature difference between the heat exchanger and the nearby soil becomes larger, enabling the pipe to absorb more heat from the soil. Besides, when the velocity is higher, the cold part of the aquifer is capable of moving to further...
position. Then, the radius of the thermal influence due to the existence of the buried heat exchanger becomes larger. In order to quantitatively analyze the influence, the thermal radius of the heat exchanger under different aquifer velocities and positions are shown in Figure 3.

![Soil temperature distribution along the x-axis at different depths.](image)

Figure 2. Soil temperature distribution along the x-axis at different depths.

It can be seen from Figure 3 that for the same depth, the thermal radius shows an obvious increasing trend as the groundwater velocity becomes larger. For the pure conduction condition (without groundwater flow), the thermal radii at different depths are from 6.9 m to 9.1 m. Corresponding to the temperature distribution, as mentioned previously, the thermal radius under the low velocity ($10^{-7}$ m/s or $5 \times 10^{-8}$ m/s) is close to the pure conduction situation. For all the depths, the thermal radii are approximately or less than 10 m. However, a significant increase can be observed when the velocity is larger than $10^{-7}$ m/s. When the groundwater velocity is $5 \times 10^{-7}$ m/s, the thermal radii are approximately 16 m for $d = 1000$ m, 1500 m and 2000 m. For the largest velocity, the influence radius can be up to 25.3 m. This is attributed to the accompanied heat transfer enhancement along the groundwater movement direction. The faster water migration promotes the expansion of the low temperature region and the influence radius caused by the heat absorption from the buried heat exchanger grows larger. For different depths, the increasing trends of the thermal radii are similar. But when the depth equals 500 m, the overall thermal radius is much lower than the other three conditions because of the relatively lower effective heat transport velocity (as shown in Figure 4). Particularly, when $u_x = 10^{-6}$ m/s and $d = 2000$ m, although the thermal diffusivity of the soil is the largest, the
calculated effective heat transport velocity is smaller than those at \( d = 500 \) m and \( d = 1000 \) m, leading to a smaller thermal radius than the other two conditions.

The results show that larger groundwater velocity can promote the heat transfer between the heat exchanger and the surrounding soils and rocks. However, the effective heat transport velocity is more applicable to reflect the overall heat transfer rate through the aquifer. With the increase of the groundwater velocity, the effective heat transport velocity increases from \( 10^{-7} \) m/s to \( 2 \times 10^{-6} \) m/s. Besides, the thermal radius becomes larger and therefore may affect the nearby heat exchangers. Therefore, the well spacing should be taken into consideration in the engineering project according to the groundwater velocities. During the design process, the temperature field of the aquifer around the deep buried heat exchanger should be calculated in advance according to the soil thermal properties and the groundwater flow rate. Then the thermal radius can be obtained so that the neighbouring geothermal well groups could be placed outside the influence area to avoid either interacted effect or too large area occupation.

![Figure 3. Thermal radius at different depths with different aquifer velocities.](image)

![Figure 4. Effective heat transport velocities at different depths with different aquifer velocities.](image)
4. Conclusions
This paper adopted a two-dimensional moving infinite line source method to predict the temperature distribution and the thermal radius around a 2000 m deep buried heat exchanger at different depths. The analytical method, together with the predicting results, can serve as a tool to obtain the temperature field of the aquifer around the deep buried heat exchanger and guide the design of the geothermal well, especially the spacing between the neighbouring well groups. The following are the major conclusions.
(1) The temperature field around the deep buried heat exchanger is largely affected by the aquifer at different depths. The flow of aquifer promotes the heat transport through the rock stratum. The thermal radius increases from less than 10 m for pure conduction condition to a maximum value of 25.3 m with groundwater movement.
(2) Compared with the flow rate of the groundwater, the effective heat transport velocity is more applicable to reflect the heat transfer rate through the aquifer. As the groundwater velocity becomes larger, the effective heat transport velocity increases from $10^{-1} \text{ m/s}$ to $2\times10^{-6} \text{ m/s}$, which accelerates the heat transfer in the aquifer.
(3) At a certain depth, the higher effective heat transport velocity leads to higher temperatures around the heat exchanger. The temperature difference between the heat exchanger and the nearby soil becomes larger, which can be conducive to the heat absorption of the buried heat exchanger.
(4) Despite the above point, the high effective heat transport velocity extends the influence radius caused by the geothermal well and the performance of the nearby heat exchangers may be affected. When arranging the buried pipes of the geothermal system, the well spacing should be larger than the calculated influence distance to avoid the interacted effect caused by the neighbouring well groups.

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