Effects of aquifer on heat exchange process in geothermal applications

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Abstract. Geothermal energy has been widely used in the field of the building heating through the ground heat exchanger (GHE). The groundwater flow in the aquifer is one of the significant factors affecting the heat exchange process between the GHE and ground by promoting the pure conduction to the conjugated convection and conduction heat transfer. In this paper, the variations of the ground temperature field and the thermal influence radii subject to the existence of aquifers were investigated numerically. The geometrical models consisting of a coaxial heat exchanger, multiple aquifer and aquifuge layers were established to study the effect of groundwater velocities and the number of aquifer layers on the GHE system. The results reveal that the heat exchange capacity of the GHE is enhanced when the groundwater velocity increases. The increased number of aquifer layers can also enhance the heat exchange capacity with the tested groundwater velocity at 315 m/a or 31.5 m/a, but would weaken it with the velocity of 3.15 m/a. In addition, it is found that the aquifer temperature field is affected by the aquifer layer, and the thermal influence radius of GHE is dominated by the groundwater velocity of aquifers when the velocity is larger than the critical velocity. Conversely, the thermal influence radius is governed by the thermal diffusivities of aquifuges for the groundwater velocity smaller than the critical velocity.

Keywords: ground heat exchanger, aquifer, ground temperature, thermal influence radius

1. Introduction

Geothermal energy has been extensively used in the building heating by the Ground Source Heat Pump (GSHP) system. Recently the medium-deep geothermal energy becomes an important application form due to the higher ground temperature compared with the shallow geothermal energy. The ground heat exchanger (GHE) is one of the most critical components of GSHP systems to extract heat from the rocks and soils. The factors that affect the heat exchange between GHEs and ground can be classified into two kinds. One is the material and structure of the GHE and borehole [1,2] which can be adjusted manually. The other is the ground properties which cannot be controlled, such as the geothermal gradient and rock-soil (both aquifer and aquifuges layers) thermophysical properties [3]. Particularly, the groundwater in aquifers can change the heat exchange between GHE and ground from the pure conduction to the conjugated conduction and convection heat transfer.

Sutton et al. [4] presented the Moving Infinite Line Source method to investigate the effects of groundwater on the heat transfer in the horizontal direction. It was found that when the Peclet number
is larger than 0.01, the ground thermal resistance involving the convection in the aquifer is different from that only considering the pure conduction. Scorpo et al. [5] defined the influence length which is important for one GHE to be as unaffected as possible by the others. A very low groundwater velocity can reduce the influence length in the direction perpendicularly to the flow direction. Thus, GHEs should be set in the perpendicular direction to the groundwater flow. Guan et al. [6] simulated a model with the aquifer for the U-tube GHE. The results also illustrated that the heat transfer of the GHE is greatly affected by the groundwater flow. The above mentioned literature dealt the heat exchange only with the effects of aquifer. However, the rocks and soils are alternatively layered in nature, including aquifers with different groundwater velocities and aquifuges with static water. Li et al. [7] established a model with the layered soils of sand and clay. The results demonstrated that the temperature stratification becomes more obvious with the increase of the heat extraction. Song et al. [8] draw conclusions that the outlet temperature of the GHE increases as the groundwater velocity and aquifer thickness increase. Chen et al. [9] built the models including one or six aquifer layers. The GHE outlet temperature hardly increases compared with the model without aquifer. Although the above researches considered both the aquifers and aquifuges, however, there is less study on the temperature field in the depth direction of the ground consisting of multiple aquifer and aquifuge layers.

In order to investigate the effects of multiple aquifer and aquifuge layers on the GHE heat exchange capacity, ground temperature field along the depth as well as the thermal influence radius, this paper focuses the heat extraction process with groundwater velocities of 315 m/a (meter per annual year), 31.5 m/a, 3.15 m/a, and 0 m/a. The two models of single aquifer layer and multiple aquifer layers are established, and the GHE outlet temperature and temperature field under different conditions are numerically obtained. Furthermore, the heat exchange capacity of GHE and the variation for thermal influence radius are discussed in detail to provide instructions for the design of GHE system.

2. Numerical Scheme

2.1. Statement of the problem

In this study, a part of the medium-deep GHE is chosen to establish the two models with different conditions. The two models with a depth of 100 m consist of aquifers, aquifuges, and the coaxial heat exchanger. Model 1 includes two aquifuge layers and one aquifer layer, and Model 2 includes three aquifer layers and four aquifuge layers, as shown in Figure 1. The thickness of aquifer layers in the two models is 10 m. The detailed rock-soil thermophysical properties of aquifers and aquifuges are given in Table 1.

Based on the two models, the outlet temperature and ground temperature field under different groundwater velocities can be obtained. Furthermore, the effect of the aquifer can be studied by calculating the heat exchange between GHE and ground, and the thermal influence radius variation caused by the aquifer.

| Table 1. Thermophysical properties of materials |
|---|

![Figure 1. The schematic diagram of the two models.](image-url)
Material | Thermal conductivity (W/(m·℃)) | Density (kg/m³) | Specific heat capacity (J/(kg·℃)) | Porosity
--- | --- | --- | --- | ---
Water | 0.600 | 998.2 | 4182 | /
PE pipe | 0.420 | 940.0 | 2300 | /
Steel pipe | 40.000 | 7850.0 | 498 | /
Backfilled soil | 1.992 | 1650.0 | 1048 | /
Aquifer | 2.596 | 2606.7 | 878 | 0.35
Aquifuge | 2.721 | 2691.7 | 794 | 0.06

2.2. Numerical method
This paper considers the problem of extracting heat from the medium-deep ground. The initial temperature of ground was set at 50℃, which was the temperature at 1000 m underground according to the literature [8]. The heat exchange between the annular flow and inner flow should be reduced as much as possible to improve the GHE heat exchange capacity. Thus, the inner pipe is considered as the insulation layer and the inner flow is ignored. The inlet temperature of annular flow was chosen as 19℃. The pressure-outlet was chosen as the boundary of the aquifer and annular flow outlets in the models. The aquifer and annular flow inlets were the velocity-inlet and mass-flow-rate inlet, respectively.

The following assumptions were adopted in the simulation process:
(1) The rocks and soils in the aquifers and aquifuges are regarded as the isotropic porous media;
(2) To focus on the effect of the aquifer, the initial temperature of the ground is assumed to be constant along the z-direction;
(3) There is no mass transfer between aquifers and aquifuges;
(4) The flow direction of the groundwater is along with the x-direction.

The SIMPLE method was used in the simulation by FLUENT. The aquifers were the laminar model and the annular flow was the k-ε turbulent model. The power-law discrete scheme was adopted in the momentum, turbulent kinetic energy and turbulent dissipation rate equations. The second-order upwind discrete scheme was used in the energy equation. The transient term was set as the implicit scheme.

2.3. Validation
The numerical simulation accuracy and calculation time were affected by the number of mesh elements. When the number of mesh elements is larger than $1.82 \times 10^6$, the variation of the outlet temperature is extremely small as shown in Figure 2. Considering the calculation time and results, the number of mesh elements of $1.82 \times 10^6$ was selected.

In order to verify the numerical simulation method, the model with an aquifer of 50 m was calculated. The inlet and outlet temperatures obtained from the current simulation and from the literature [6] are compared in Figure 3. The results agree well with those reported in the literature. This indicates that the current numerical scheme is verified to carry out the study of the aquifer effects on heat exchange capacity of GHEs.

![Figure 2. The outlet temperature variation with the number of mesh elements.](image1)

![Figure 3. The inlet and outlet temperatures of the validation model.](image2)
3. Results and discussion

3.1. Heat exchange capacity of GHE

The heat exchange amount of GHE can be calculated by the difference between the inlet and outlet temperatures. It is observed from Figure 4 that the larger groundwater velocity \( u_x \) could result in the higher outlet temperature for the two models. The results illustrate that the groundwater flow can improve the heat exchange capacity of GHE. Comparing Model 1 with Model 2, the outlet temperature of Model 1 is lower than that of Model 2 under \( u_x = 315 \) m/a or 31.5 m/a. Comparatively, when the velocity is 3.15 m/a or 0 m/a, the outlet temperature of Model 1 is larger than that of Model 2.

![Figure 4](image)

**Table 2.** Specific heat rate under different velocities on the 120th day.

| Groundwater velocity (m/a) | 315   | 31.5  | 3.15  | 0     |
|----------------------------|-------|-------|-------|-------|
| Specific heat rate of Model 1 (W/m) | 144.7 | 124.5 | 119.5 | 119.4 |
| Specific heat rate of Model 2 (W/m) | 190.6 | 130.2 | 115.3 | 114.9 |

3.2. Ground temperature field

The aquifer can also have a huge influence on the vertical temperature field of the ground. Figures 5 (a)-(d) and (e)-(h) show the ground temperature field on the \( xz \) plane for Model 1 and Model 2, respectively. Compared with the temperature field under \( u_x = 0 \) m/a (Figures 5 (a) and (e)), the aquifer temperature becomes lower on the downstream while it becomes higher on the upstream (Figures 5 (b)-(d) and (f)-(h)). The temperature of the aquifuge layer near the aquifer layer has the same trend. It is concluded that the aquifuge temperature is affected by aquifer due to the heat transfer in the \( z \) - direction. After that, the heat transfer between aquifers and GHEs would be affected. Moreover, due to the small temperature difference between the inlet and outlet, the temperature variation along the \( z \) - direction is slight.

![Temperature](image)
3.3. Thermal influence radius

The ground temperature variation range on the downstream is positively correlated with the groundwater velocity in Figure 5. Thus, there is a position where the soil temperature no longer changes, meaning that its temperature approaches to the initial soil temperature (< 0.5°C, [5]). The thermal influence radius is defined as the distance of this position to the centreline of GHE to reflect the influence range of GHEs.

Comparing the thermal influence radii at \( z = -50 \) m in the two models from Table 3, it reflects that the increase of the increased number of aquifer layers has no effect on the thermal influence radius of the intermediate aquifer. The thermal influence radius differences between the intermediate aquifer and the other adjacent two aquifers are less than 0.01 m. The thermal influence radius of aquifers is affected by the increased number of aquifer layers. The differences of thermal influence radius between the two models at \( z = -37.5 \) m and -62.5 m are 0.02 m for \( u_x = 3.15 \) m/a, and 0.13 m for \( u_x = 31.5 \) m/a.

The results demonstrate that the thermal influence radii of aquifers are larger than that of aquiferous for \( u_x = 31.5 \) m/a and 315 m/a, and less for \( u_x = 3.15 \) m/a in Figure 6. Therefore, the radii of aquifers and aquiferous are equal under a critical velocity. The thermal influence radius of GHE is determined by the groundwater velocity in aquifers when the velocity is larger than the critical velocity. Conversely, the radius is depended on the thermal diffusivity of aquiferous as the velocity is less than the critical velocity.

**Table 3.** The thermal influence radius on the 120th day.

| Position | Thermal influence radius of model 1 (m) | Thermal influence radius of model 2 (m) |
|----------|----------------------------------------|----------------------------------------|
|          | \( u_x = 31.5 \) m/a                  | \( u_x = 3.15 \) m/a                  |
| \( z = -25.0 \) m | 8.52                                  | 8.52                                  |
| \( z = -37.5 \) m | 8.66                                  | 8.49                                  |
| \( z = -50.0 \) m | 18.62                                 | 7.72                                  |
| \( z = -62.5 \) m | 8.65                                  | 8.48                                  |
| \( z = -75.0 \) m | 8.50                                  | 8.50                                  |

**Figure 5.** The ground temperature field under different velocities in the two models on the 120th day.

**Figure 6.** The thermal influence radii under different velocities in the two models on the 120th day.
Based on the above analysis, the thermal influence radii of GHE in Model 1 are 144.00 m and 18.62 m for $u_r = 315$ m/a and 31.5 m/a at $z = -50$ m. It is 8.52 m for $u_r = 3.15$ m/a and 0 m/a at $z = -17$ m. For Model 2, the thermal influence radii of GHE are 144.07 m and 18.63 m for $u_r = 315$ m/a and 31.5 m/a at $z = -25$ m, and 8.50 m and 8.49 m for $u_r = 3.15$ m/a and 0 m/a at $z = -12$ m, respectively. After the thermal influence radius of GHE is obtained, it can be used to determine the GHE spacing.

4. Conclusion
In this paper, two models with one aquifer layer and multiple aquifer layers were established and numerically simulated to investigate the heat extraction process under different groundwater velocities. The outlet temperature and ground temperature field of different conditions were obtained. The heat exchange capacity of GHE and thermal influence radii were discussed. The conclusions are as follows.

(1) The heat exchange capacity of GHE could be improved when the groundwater velocity increases. It also can be enhanced by the increased number of aquifer layer when the groundwater velocity is 315 m/a or 31.5 m/a, but the heat exchange capacity is weakened as the velocity is 3.15 m/a.

(2) The temperature field of aquifers is affected by the aquifer due to the heat transfer in the $z$-direction.

(3) The increased number of aquifer layers has little effect on the thermal influence radius of the aquifers, while it has an impact on the aquifuges. The thermal influence radius of GHE is dominated by the groundwater velocity of aquifers as the velocity is larger than the critical velocity. Conversely, the thermal influence radius is governed by the thermal diffusivities of aquifuges for the groundwater velocity smaller than the critical velocity. The analysis on the thermal influence radius can provide instructions for configuring GHEs.

Acknowledgments
The authors are grateful for the support by the Key Laboratory of Coal Resources Exploration and Comprehensive Utilization, Ministry of Land and Resources, China (KF2019-14), the Fundamental Research Funds for the Central Universities (xzy202019019) and the Key Scientific Research Innovation Team Project of Shaanxi Province (2016KCT-16).

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