An analytical model for vertical-butted geothermal well with different groundwater flow directions

G S Jia¹, Z D Ma¹, L W Jin¹*, Y P Zhang¹,², Y Cao³, X Z Meng¹*

¹ Group of Building Environment and Sustainable Technology, School of Human Settlements and Civil Engineering, Xi’an Jiaotong University, Xi’an 710049, China
² Key Laboratory of Coal Resources Exploration and Comprehensive Utilization, Ministry of Land and Resources, Xi’an 710021, China.
³ China Architecture Design & Research Group, Beijing, China.

*E-mail: lwjim@xjtu.edu.cn; xzmeng@xjtu.edu.cn

Abstract. Geothermal has become a popular renewable energy in recent decades due to its properties of non-polluting, clean and large reserves. The vertical-butted geothermal well is a new structure for geothermal utilization. Two vertical boreholes with a certain distance are connected at bottoms by directional drilling to form a U-shape circulation loop. Due to the existence of the aquifers, the movement of underground water extends the heat exchange range and affects the geothermal system performance. This paper aims to develop an analytical method to solve the soil temperature field around the vertical-butted geothermal well with different flow directions. Taking the interacted effect of the two parallel pipes on the surrounding soil into consideration, the temperature distribution in the heat exchange zone is obtained. It is found that the temperature field changes significantly when the groundwater flow exists. The movement of underground water extends the downstream thermal radii from 4.8 m to 10.7 m, 10.6 m and 11.7 m when the flow directions are 0°, 45° and 90° toward the axis of the two pipes, respectively. The upstream thermal radii reduce from 5.4 m to 1.9 m for all the cases with groundwater movement. In addition, the effect of the underground water flow direction on the temperature field around the butted wells is analyzed. The results show that when the groundwater flow direction is perpendicular to the axis of the two pipes, the temperature field is the most beneficial to the performance of the vertical-butted geothermal well.

Keywords: Geothermal, Vertical-butted geothermal well, Aquifer, Soil temperature field

1. Introduction
Nowadays, under the background of the world energy shortage and environmental pollution, the application of renewable resources has become extremely important [1]. Among all the renewable resources, the geothermal energy possesses the advantages of wide distribution, large reserves and less pollution. Therefore, it has great development potential [2, 3]. The ground source heat pump system (GSHPS), which utilizes the soils and rocks as the cold or heat source, could transform the geothermal energy to high-grade energy for building heating or cooling [4]. During the utilization process, the buried heat exchanger plays a critical role, since it is in direct contact with the ground and transports the heat to the equipment on the ground. The heat absorption process of the buried heat exchanger is
complex because the heat exchange between the buried pipe and the surrounding soil is based on the coupling of heat conduction and convection when the aquifer exists [5].

Diao et al. [6] provided an analytical transient solution and regarded the heat exchanger as a line source in the infinite ground. The computed temperature response showed that the groundwater flow in the soil would significantly change the temperature field compared with conductive heat transfer. Zhang et al. [7] presented a two-dimensional mathematical model based on the Green’s function to investigate the heat transfer of energy piles with aquifer. The results indicated that with the increase of the groundwater velocity, the temperature response reduces obviously. Hu [8] proposed an analytical model based on the solution of the energy equation of the groundwater flow in the porous media. The model was validated by the experimental data for a 63 m single borehole. The results showed that when the equivalent velocity is larger than $6 \times 10^{-7}$ m/s, the deformation of the temperature field would be very conspicuous. Li et al. [9] developed a numerical model utilizing the finite element method to study the performance of the GSHPS with saturated groundwater flow and found that neglecting the groundwater would result in an error of 3% to 4% in the prediction of the field temperature. Angelotti et al. [10] presented a numerical model in MODFLOW/MT3DMS to simulate a 100 m single U-tube heat exchanger in the sandy aquifer. After validated by the existing analytical solutions, the model was adopted to study the performance of the heat exchanger under the Darcy velocities from $10^{-7}$ m/s to $10^{-5}$ m/s. The yearly operation results showed that negligible differences could be observed when the velocity is $10^{-7}$ m/s or the Peclet number is less than 0.1. However, for high velocities, up to 105% heat rate increase could be assessed compared with pure conduction condition.

In view of the above brief review, this paper aims to provide a solution based on the analytical line source method to compute the ground temperature responses around the vertical-butted geothermal well, a newly proposed geothermal structure in recent years. After taking different groundwater flow rates and directions into consideration, this work also analyzes the interacted effect of the two parallel pipes on the surrounding soil and obtain the temperature distribution at different positions.

2. Simulation models and methods
The vertical-butted geothermal well (as shown in Figure 1) is a new structure for geothermal utilization. Two vertical boreholes with a certain distance are connected at bottoms by directional drilling to form a U-shape circulation loop. The cold working fluid enters the pipe and absorbs the heat from the surrounding rocks and soils. Then it delivers the heat to the equipment on the ground. Due to the existence of the aquifers with different flow directions, the movement of the underground water extends the heat exchange zone and greatly affects the geothermal system performance.

Figure 1. Diagram of vertical-butted geothermal well.

Figure 2. Top view of different groundwater flow directions around the geothermal well.
In this paper, the analytical approach is adopted to solve the problem. The solution is conducted base on the moving infinite line source theory and the method of superposition. The heat transport through the saturated porous medium contains a combination of the conduction through the solid part and the convection through the liquid phase in the pores. During this process, the governing equation can be expressed as [11],

\[
\rho_c \frac{\partial T}{\partial t} + \rho_w c_w \vec{V} \cdot \nabla T = \nabla \cdot (k \nabla T)
\]

where \( \rho_c \) and \( \rho_w c_w \) are the volumetric specific heat of the ground and the water, respectively. \( T \) is the temperature, and \( t \) denotes the time. \( \vec{V} \) is the flow rate of the groundwater and \( k \) represents the ground thermal conductivity. In order to simplify the calculation, the following assumptions are made,

1. the velocity is assumed to be along the \( x \)-coordinate as \( u_x \),
2. the saturated soil is regarded as the homogeneous medium with constant thermal properties,
3. the ground has a uniform initial temperature distribution,
4. the heat transfer rate of the buried heat exchanger per unit is a constant value,
5. the influence of the boundary is neglected, indicating that the calculation is simplified as a two-dimensional problem.

Based on the above assumptions, the temperature response of a certain point around the single pipe can be calculated using the Green’s function [11],

\[
\Delta T(x,y,t) = \frac{q}{4\pi k} \int_0^t \exp \left\{ -\frac{[x-u (t-\beta)]^2 + y^2}{4a(t-\beta)} \right\} d\beta
\]

where \( q \) represents the heat exchange rate per meter. \( x \) and \( y \) are the coordinates. \( U = u_x \rho_w c_w / \rho_c \) denotes the effective heat transport velocity. \( a \) is the ground thermal diffusivity and \( \beta \) is the integration variable.

For the vertical-buttoed geothermal well group, the two pipes are assumed to be in parallel arrangement. Therefore, the interacted effect on the surrounding soil should be taken into consideration. In this work, the vertical two pipes are placed at the origin of the coordinate separately to acquire the respective temperature responses. The superposition of the temperature responses is adopted to study the temperature distribution around the butted well. Meanwhile, different flow directions are also taken into account (as shown in Figure 2). In this study, three conditions are simulated, including the groundwater flow direction parallel to the axis, perpendicular to the axis and 45-degree toward the axis.

3. Computation and discussion

As shown in Figure 3, the two pipes in the vertical-buttoed geothermal well group are regarded as two line sources distributed in the coordinates. The detailed parameters of the ground are shown in Table 1 according to the information provided in reference [6]. The heat exchange rates per meter of pipe one and pipe two are set as -50 W/m and -40 W/m, respectively. The heat exchange rate between the fluid and the surrounding aquifer for the two pipes are different because the temperature of the working fluid in pipe 2 are higher than that in pipe 1 after absorbing heat from the ground.

| Initial ground temperature/°C | Advection velocity/m·s⁻¹ | Ground thermal conductivity/W·m⁻¹K⁻¹ | Thermal diffusivity/m²·s⁻¹ | Distance between the two pipes/m |
|-----------------------------|-----------------|---------------------------------|-----------------|-----------------------------|
| 50                          | 1×10⁻⁶          | 4.5                             | 2.66×10⁻⁷       | 10                          |
The computation is carried out through FORTRAN computer programming. The temperature distribution along the y-direction under different groundwater flow directions (Case 1, Case 2 and Case 3) after 100 days operating are shown in Figure 4. It can be seen that when the flow rate equals zero (i.e., pure conduction, as shown in Figure 4 (d)), the temperature is symmetric about $y = 20$ m (the position of the pipes). Besides, at $x = 20$ m and $x = 30$ m, the temperature shows the greatest variation because of the two line sources. Similar variations can also be observed when the groundwater flow direction is parallel to the x-direction (as shown in Figure 4(a)). However, the temperature field varies greatly due to the existence of the water migration. For example, when $x = 25$ m (between the two line sources), the lowest ground temperature is 49.2°C for Case 4. But for Case 1, the ground temperature at the same position is 48.8°C. When $x = 35$ m (downstream of the aquifer), the temperatures for Case 4 and Case 1 are 49.6°C and 48.9°C, respectively. The above comparison indicates that the movement of water promotes the heat transfer along the x-direction and makes the thermal radius of the vertical-buttoed heat exchanger larger downstream. Without groundwater migration, the downstream thermal radius (the largest downstream influence distance) is 4.8 m. The groundwater flow extends the downstream thermal radii to 10.7 m, 10.6 m and 11.7 m for Case 1, Case 2 and Case 3, respectively. Correspondingly, the upstream thermal radius (the largest upstream influence distance) is 5.4 m for the pure conduction condition and decreases to 1.9 m with the groundwater movement. The above calculation of thermal radius can serve as a reference in the spacing determination of adjacent wells. The distance between the neighboring well groups should be larger than the thermal radius so that the interacted effect between two groups caused by the groundwater flow can be avoided.

On the other hand, the flow direction of the groundwater influences the temperature field around the geothermal wells. Figure 5 shows the temperature distributions around the vertical-buttoed well for different groundwater flow directions. It can be clearly seen that compared with pure conduction condition, the groundwater movement deforms the isotherm shape around the two pipes. As mentioned above, when the flow direction is parallel to the x-axis, the temperature distributed symmetrically. However, when the aquifer crosses the axis of the two pipes with an angle (for Case 2 and Case 3), the low-temperature area moves to the downstream of the aquifer, leading to an irregular temperature distribution. The isotherm shape changes from concentric circles to ellipses and the upstream temperature gradient increases, which would contribute to the heat exchange between the buried pipe and the aquifer. Besides, after the comparison among Case 1, Case 2 and Case 3, it is noted that when the groundwater flow direction is perpendicular to the axis (Case 3), the isotherms around the two pipes intersect downstream and the average temperature gradient of the aquifer around the two pipes is larger than Case 1 and Case 2. During the heat exchanger design process, the arrangement of the neighboring two well groups should refer to the flow direction of the groundwater. For each vertical-buttoed geothermal well group, the axis of the two pipes can be arranged...
perpendicular to the groundwater flow direction so that the heat exchange between two buried pipes can be enhanced due to large temperature gradient of the aquifer. Particularly, the neighboring pipes should not be arranged along the flow direction considering the interacted effect.

**Figure 4.** Temperature distribution along the \( y \)-direction.
4. Conclusions
This paper presented an analytical method based on the moving line source method to obtain the temperature response caused by the vertical-butted geothermal well with aquifer of different flow directions. Using the method of superposition, the temperature distribution around the well was conducted and analyzed in detail. The following are the main conclusions.
(1) The existence of the groundwater flow significantly changes the temperature distribution around the vertical-butted well. Compared with pure conduction condition, the groundwater flow extends the downstream thermal radii to 10.7 m, 10.6 m and 11.7 m for Case 1, Case 2 and Case 3, respectively. During the spacing determination process, the distance between the neighboring well groups should be larger than the calculated thermal radius to avoid the interacted effect between two groups.
(2) The flow direction of the groundwater affects the temperature field around the geothermal well. The low temperature area moves to the downstream while the angle between the flow direction and the axis of the two pipes increases. The upstream thermal radii reduce from 5.4 m to 1.9 m for all the three cases with groundwater movement.
(3) When the groundwater flow direction is perpendicular to the axis of the two pipes, the average temperature gradient of the aquifer around the two pipes is the largest. This arrangement method would conduce to the heat exchange between the pipes and the surrounding aquifer.

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