Field Test and Numerical Simulation on Heat Transfer Performance of Coaxial Borehole Heat Exchanger

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Abstract: Ground thermal properties are the design basis of ground source heat pumps (GSHP). However, effective ground thermal properties cannot be obtained through the traditional thermal response test (TRT) method when it is used in the coaxial borehole heat exchanger (CBHE). In this paper, an improved TRT (ITRT) method for CBHE is proposed, and the field ITRT, based on the actual project, is carried out. The high accuracy of the new method is verified by laboratory experiments. Based on the results of the ITRT and laboratory experiment, the 3D numerical model for CBHE is established, in which the flow directions, sensitivity analysis of heat transfer characteristics, and optimization of circulation flow rate are studied, respectively. The results show that CBHE should adopt the annulus-in direction under the cooling condition, and the center-in direction under the heating condition. The influence of inlet temperature and flow rate on heat transfer rate is more significant than that of the backfill grout material, thermal conductivity of the inner pipe, and borehole depth. The circulating flow rate of CBHE between 0.3 m/s and 0.4 m/s can lead to better performance for the system.

Keywords: ground source heat pumps; coaxial borehole heat exchangers; improved thermal response test; sensitivity analysis

1. Introduction

Shallow geothermal energy for heating and cooling of buildings has been widely used in the world [1–4]. The technology of extracting shallow geothermal energy is called ground source heat pumps (GSHP), which have a high efficiency by circulating fluid in a closed-loop borehole heat exchanger (BHE) to exchange heat with stratum. As the core part of GSHP, the types of BHE are different, such as single U-pipe, double U-pipe, helical pipes, and coaxial borehole heat exchanger (CBHE) [5]. Some studies have shown that the application of the CBHE can potentially reduce the drilling cost and make the field installation easier [6–9], and its local thermal resistance can be ignored, compared with the U-pipe BHE [10,11]. CBHE can also provide enough heat exchange area and turbulence conditions. In the actual GSHP project, getting the accurate thermal conductivity is most important for the design of GSHP. The thermal response test (TRT) is a widely-used method to obtain the thermal conductivity of the stratum. The traditional U-pipe TRT method is still adopted for the
CBHE in the existing literature and practical engineering. However, the research shows that the accuracy of thermal conductivity obtained by the traditional TRT method cannot meet the design requirements of GSHP. Therefore, it is necessary to find a new TRT method for CBHE [9].

Numerical simulation and analytical solutions were used in the CBHE research, to some extent [12–14]. The influence of different factors on the heat transfer efficiency of CBHE has been studied: research of the CBHE with different diameter ratios and borehole depths shows that it is better to use a coaxial BHE with a lower diameter ratio and borehole depth, than a higher diameter ratio and more borehole depth, to reduce costs [14]. The optimal design of well bottom curvature was studied, and it is suggested that 500 mm well bottom curvature is preferred for higher output temperature and heat transfer rate [15]. The influence of the backfill grout materials on heat transfer indicates that the heat transfer rate increases with the backfill grout thermal conductivity and the effects are more pronounced when the grout thermal conductivity is low [16,17]. The effect of the geothermal gradient on the heat transfer efficiency was considered in both an analytical model and a numerical model, and the results confirm that increasing geothermal gradient has a positive influence towards the heat extraction [18,19]. A new analytical g-function and a transient numerical model show that the borehole heat capacity has an especially significant influence on the ground thermal response and fluid temperature at short times, and the influence weakens with time [20,21]. The flow direction of heat transfer fluid in the CBHE was studied; one research concluded that the flow direction does not affect the heat transfer efficiency [22], and the other identified that the best flow direction is the annulus as inlet [23]. Also, some researches on using abandoned oil wells as heat exchange boreholes have also been carried out, and it was found that the mean heat supply is higher than that in conventional GSHP [24].

Few researches have been carried out in the field. A field test was first conducted based on the deep borehole GSHP in Xi’an, China, and the results indicate that the average system coefficient of performance (COP) and unit COP are higher than that of conventional shallow GSHP [25]. The conventional field thermal response tests of different structures and construction conditions were carried out on the bases of the infinite line source model. Based on this, the factors affecting heat transfer efficiency were analyzed [9]. However, some scholars have shown that the mean temperature of the inlet and outlet cannot be used to replace the average temperature of the circulating fluid when using the infinite line source model to the CBHE [26]. Therefore, a distributed thermal response test has been developed, and more accurate thermophysical parameters can be obtained [7,9]; but the construction of the distributed thermal response test is difficult and costly, and, therefore, it is necessary to find a more suitable method of CBHE for engineering applications.

In the above research, some achievements have been made in the study of CBHE. However, most of the existing research focuses on deep CBHE, while few focus on shallow CBHE. Deep CBHE is different from shallow CBHE in backfill material, depth, stratum condition, heat exchange pipe material, and size [9,18]. Relationships between flow direction and heat exchange efficiency published are not consistent. The traditional thermal response test method cannot meet the accuracy requirements for the calculation of the stratum thermophysical parameters when it is used in the CBHE.

Therefore, to study the above problems, an improved TRT (ITRT) was proposed and tested in the field, whose accuracy was also verified by laboratory experiments. Based on these results, a 3D thermal and hydrodynamic numerical model for CBHE was established. The influence of flow direction on heat transfer efficiency was analyzed. The thermal interference and heat transfer performance of CBHE with different influence factors were evaluated, and an optimized flow rate range is recommended.

2. Improved Thermal Response Test and Results

2.1. Theory of Thermal Response Test

The theory of linear heat source proposed by Kelvin [27] and further developed by Hellström [28] was used. It assumes that the heat transfer of the stratum is pure heat conduction, ignoring the vertical
The component of the heat flow. The heat flow from BHE to the stratum is regarded as the horizontal and radial heat flow from the borehole centerline to the stratum, and the stratum is assumed to be isotropic and homogeneous. The simplified theory can be expressed as:

$$\theta_f - \theta_0 = \frac{Q}{4\pi \lambda_s L} \left[ \ln \left( \frac{4at}{r_b^2} \right) - \gamma \right] + q \times R_b$$

where $\theta_f$ is the average fluid temperature in the BHE ($^\circ$C); $\theta_0$ is the initial temperature of the ground ($^\circ$C); $Q$ is the injected heat (W); $L$ is the borehole depth (m); $\lambda_s$ is the thermal conductivity (W/m K); $\alpha$ is the thermal diffusivity (m$^2$/s); $t$ is the time (s); $\gamma$ is the Euler constant, which has a value of 0.5772; $R_b$ is the borehole thermal resistance (m·K/W); $q$ is the heating capacity per unit borehole length (W/m); and $r_b$ is the borehole radius (m).

Equation (1) is further simplified to the following formula:

$$\theta_f = k \ln t + b$$

where

$$k = \frac{Q}{4\pi \lambda_s L}$$

$$b = \frac{q}{4\pi \lambda_s} \left[ \ln \left( \frac{4at}{r_b^2} \right) - \gamma \right] + q \times R_b + \theta_0$$

$$\theta_f = \frac{\theta_{in} + \theta_{out}}{2}$$

where $\theta_{in}$ and $\theta_{out}$ are inlet and outlet temperature, respectively ($^\circ$C).

Note that the above equations are valid only if Equation (6) is satisfied.

$$t > \frac{5r_b^2}{\alpha}$$

After obtaining slope $k$, according to Formula (3), the stratum thermal conductivity can be calculated by the following formula:

$$\lambda_s = \frac{q}{4\pi k}$$

2.2. Improved Thermal Response Test

As shown in Equation (5), the traditional TRT takes the average temperature of the inlet and outlet fluid as the average temperature of the circulating fluid, which is suitable for U-pipe BHE. However, the heat transfer process of U-pipe heat exchanger is different from that of coaxial pipe heat exchanger. When the heat exchanger is a U-pipe, the down channel and the up channel of the fluid do not contact each other, but directly transfer heat with the ground. However, when the heat exchanger is a coaxial pipe, the heat transfer process in CBHE includes two parts. The fluid exchanges heat with the ground while it goes down, nevertheless, it exchanges heat with the downward fluid instead of the ground when it goes up. There is only a thin wall between the fluid in the annular and the fluid in the inner pipe. Therefore, the heat transfer between the inner fluid and the annular fluid cannot be ignored. Thermal response refers to the thermal response between the fluid in the heat exchanger and the ground. Thus, to avoid the uncertainty caused by the thermal interference between the upstream and downstream fluids, taking the average temperature of annulus fluid as the average temperature of the fluid for the ITRT can more accurately represent the response of the stratum to the fluid than taking the average temperature of the inlet and outlet. To obtain the average temperature of the annular fluid, a temperature sensor is added, based on the traditional TRT. As shown in Figures 1b and 2a, the temperature sensor is lowered from the inner pipe of CBHE to the bottom, to measure the bottom
fluid temperature. The average temperature of the inlet and bottom can be regarded as the average temperature of the annulus fluid. Therefore, $\theta_t$ can be expressed as:

$$\theta_t = \frac{\theta_{in} + \theta_{bo}}{2}$$

(8)

**Figure 1.** (a) Stratum profile. (b) CBHE installation. (c) Limestone powder. (d) Medium-coarse sand.

**Figure 2.** Diagram of thermal response test (TRT) equipment. (a) Schematic diagram of TRT. (b) Physical diagram of TRT.
2.3. In Situ ITRT

The GSHP project, located in Wuhan, China, is used to heat and cool an office building. The ground heat exchanger adopts CBHE. The geological survey showed that the site strata are as follows: 0–7.0 m is the quaternary overburden, and below 7.0 m is limestone. Two boreholes, B1 and B2, which were drilled by an air DTH hammer, are 50 m apart, and there is no groundwater. The effective depth of B1 is 160 m, which is backfilled with limestone powder, while that of B2 is 108 m, which is backfilled with medium–coarse sand. The inner and outer pipes of CBHE are made of HDPE with thermal conductivity of 0.40 W/m·K. Table 1 shows the relevant parameters of the two boreholes. Figure 1a–d show the stratum profile, CBHE installation, limestone powder, and medium–coarse sand, respectively.

Table 1. Structure parameters of B1 and B2.

| Borehole | B1        | B2        |
|----------|-----------|-----------|
| Diameter (mm) | 150       | 150       |
| Depth (mm)    | 160       | 108       |
| Pipe material | HDPE      | HDPE      |
| Thermal conductivity of pipe (W·m⁻¹·K⁻¹) | 0.4       | 0.4       |
| Density of pipe (10³ kg/m³)    | 950       | 950       |
| Specific heat (J/kg·K)         | 2300      | 2300      |
| Outer pipe diameter/wall thickness (mm) | 90/8.3    | 90/8.3    |
| Inner pipe diameter/wall thickness (mm) | 40/3      | 40/3      |
| Thermal conductivity of water (W·m⁻¹·K⁻¹) | 0.618     | 0.618     |
| Density of water (10³ kg/m³)    | 998       | 998       |
| Specific heat (J/kg·K)         | 4182      | 4182      |
| Backfill material              | Limestone | Medium–coarse sand |

After the construction and installation of the CBHE, the water was injected into it, and it was left for a week to keep the temperature of water and stratum the same. Then, the initial ground temperature was measured by the temperature sensor Pt100 with an accuracy of ±0.5%. The temperature was recorded every meter in the range of 0–10 m, and every 10 m in the range of 10 m to the bottom. After that, the ITRT of two CBHE was run for 48 h. One set of ITRT data, including temperature, flow rate, heat power, and pressure loss, were automatically collected every 2 min. The flow direction of water is from the annulus into and out of the inner pipe. The ITRT diagram is shown in Figure 2a,b.

2.4. Results of the In Situ ITRT

The initial temperature profile of the stratum is shown in Figure 3. It can be seen from Figure 3 that, within 10 m, the ground temperature is greatly affected by the surface air temperature, and the stratum temperature rises gradually below 10 m. Therefore, in this paper, the average temperature below 10 m is taken as the initial average temperature of the stratum. The initial average temperatures of B1 and B2 are 19.56 °C and 19.34 °C, respectively, and their geothermal gradients are 0.0169 °C/m, and 0.0158 °C/m, respectively.
Pressure loss of B1 and B2 are 22.05 kPa and 22.53 kPa, respectively. According to Equation (6), the CBHE can reach a steady state after 6 h, as shown in Figure 5a–d, which are the average temperature of inlet and bottom versus logarithmic time. Based on Equation (3), the thermal conductivity of B1 and B2 from ITRT are 2.192 W/m·K and 2.204 W/m·K, respectively. The average heat power of B1 and B2 are 8.204 kW and 7.337 kW, respectively, and the heat power during the ITRT.

**Figure 3.** Distribution of initial temperature profile of stratum.

Figure 4a,b show the inlet, bottom, and outlet temperature, the flow rate, pressure loss, and the heat power during the ITRT. The average flow rates of B1 and B2 are 1.553 m³/h and 1.986 m³/h, respectively. The average heat power of B1 and B2 are 8.204 kW and 7.337 kW, respectively, and the pressure loss of B1 and B2 are 22.05 kPa and 22.53 kPa, respectively. According to Equation (6), the CBHE can reach a steady state after 6 h, as shown in Figure 5a–d, which are the average temperature of inlet and bottom versus logarithmic time. Based on Equation (3), the thermal conductivity of B1 and B2 from ITRT are 2.282 W/m·K and 2.269 W/m·K, respectively, and the thermal conductivity of B1 and B2 from TRT are 2.192 W/m·K and 2.204 W/m·K, respectively.

**Figure 4.** Improved thermal response test (ITRT) result of B1 and B2. (a) ITRT conditions and results of B1. (b) ITRT conditions and results of B2.
3. Validation via Laboratory Experiment

3.1. Laboratory Experiment

To verify the accuracy of the thermal conductivity obtained by the ITRT, thermophysical parameters of the rocks collected in the ITRT areas were measured in the laboratory. The complete ground samples could not be taken, because the boreholes were drilled using an air DTH hammer. Therefore, the rock samples collected in this study were from the geological survey of the building served by the GSHP, with a sampling depth of 10 m, 20 m, and 30 m, respectively. Considering that the stratum in this area is limestone with single lithology, and the existing literature shows that the thermal conductivity of rock mass is little affected by the depth when the burial depth is shallow [29]. Thus, the rock samples in this study are representative. In addition, the thermophysical parameters of the saturated limestone powder and saturated medium–coarse sand were measured to obtain the thermal properties of the grout. The ISOMET2114 was adopted in laboratory experiments, which has accuracy of ±5%. The ISOMET 2114 is a portable hand-held measuring instrument for direct measurement of heat transfer properties of a wide range of isotropic materials, including cellular insulating materials, plastics, glasses, and minerals. It is equipped with two optional types of measurement probes: needle probes for soft materials, and surface probes for hard materials [30]. Figure 6 shows the limestone rock samples.
3.2. Results of Laboratory Experiment

Tables 2 and 3 show the properties of three rock samples, that were collected on site, and backfill grout materials. During the backfilling, water was added continuously, and the grouting was in the saturated state. Therefore, the thermal conductivity and specific heat capacity of limestone and medium–coarse sand are under the saturated state. Table 4 shows the comparison of thermal conductivity measured by ITRT, TRT, and laboratory experiments. It can be seen that, among the three test methods, the relative error between ITRT and laboratory experiments are 5.89% and 6.43%, respectively, and the relative error between TRT and laboratory experiments are 9.61% and 9.11%, respectively. This shows that the ITRT for CBHE proposed in this paper can obtain high-precision thermal conductivity, which can provide a design basis for practical engineering.

Table 2. Ground properties from the laboratory test.

| Thermal Properties                          | Samples   | S1       | S2       | S3       | Average Value |
|-------------------------------------------|-----------|----------|----------|----------|---------------|
| Thermal conductivity (W·m⁻¹·K⁻¹)          |           | 2.357    | 2.522    | 2.396    | 2.425         |
| Density (10³ kg/m³)                       |           | 2.32     | 2.35     | 2.3      | 2.32          |
| Specific heat (J/kg·K)                    |           | 1040     | 1044     | 1050     | 1045          |

Table 3. Properties of backfill grout materials.

| Grout Material                          | Limestone | Medium–Coarse Sand |
|-----------------------------------------|-----------|--------------------|
| Thermal conductivity (W·m⁻¹·K⁻¹)        | 1.47      | 2.61               |
| Specific heat (J/kg·K)                  | 1132      | 1145               |
| Density (10³ kg/m³)                     | 2065      | 1938               |

Table 4. Comparison of thermal conductivity.

| Borehole | B1     | B2     |
|----------|--------|--------|
| Thermal conductivity from ITRT (W·m⁻¹·K⁻¹) | 2.282   | 2.269  |
| Thermal conductivity from TRT (W·m⁻¹·K⁻¹)   | 2.192   | 2.204  |
| Thermal conductivity from laboratory experiment (W·m⁻¹·K⁻¹) | 2.425   |        |
| Relative error between ITRT and laboratory experiments | 5.89%   | 6.43%  |
| Relative error between TRT and laboratory experiments | 9.61%   | 9.11%  |
4. Numerical Simulation

4.1. Model Description

Two 3D models, which are equal to the actual size of B1 and B2, including the CBHE, the fluid in the heat exchanger, the backfill grout material in the borehole, and the surrounding stratum, were established, respectively. Figure 7 shows the schematic diagram of the numerical model. In the numerical calculations, only two heat transfer modes are considered: one is the heat conduction among the stratum, backfill grout material, and outer pipe, and the other is the heat convection between the fluid and the heat exchange pipes. It was assumed that: (1) the heat transfer mechanism between the stratum and backfill grout material is heat conduction; (2) the contact between the stratum and the backfill grout material, the backfill material, and the heat exchanger is sufficient, and the influence of the contact thermal resistance was ignored; (3) the thermophysical parameters of the stratum and fluid remain constant; and (4) the stratum is homogeneous and isotropic. The thermophysical parameters of the stratum and fluid were obtained through the ITRT and laboratory experiments, as shown in Tables 1–3.

![Figure 7. Numerical model diagram of coaxial borehole heat exchanger (CBHE).](image)

4.2. Governing Equation and Mesh Discretization

In this work, only conduction heat transfer among the outer pipe, backfill grout material, and stratum, and the convective heat transfer of fluid flow were considered. FLUENT was adopted as the simulation solver. The energy conservation equation of a solid is as follows [14]:

\[ \lambda_s \nabla^2 T = 0 \]  

(9)

where \( \lambda_s \) is the thermal conductivity and \( T \) is the temperature.

At the same time, convective heat transfer of fluid flow is also considered; the continuity, momentum, and energy equations are:

\[ \nabla (\rho_f u) = 0 \]  

(10)

\[ \nabla (\rho_f u u) = \nabla p + \rho_f g \]  

(11)

\[ \nabla (\rho_f c_p u T) = \nabla (\lambda_f \nabla T) \]  

(12)

where \( \rho_f \) is the fluid density, \( u \) is the fluid flow rate, \( g \) is the gravity acceleration, \( c_p \) is the fluid specific heat, \( \lambda_f \) is the thermal conductivity of fluid, \( T \) is the temperature, and \( p \) is the fluid stress tensor.

The model is discretized into hexahedral meshes, because hexahedral meshes are conducive to the calculation accuracy, and reduce the total number of meshes at the same time. The mesh for the model is shown in Figure 8. Fine structure mesh was applied in CBHE and fluid parts where the severe
heat transfer occurs, while gradually coarser mesh was implemented in the surrounding stratum to minimize the computational cost. The number of nodes and elements of the model are 6,037,499 and 6,016,076, respectively.

![Mesh discretization](image)

**Figure 8.** Mesh discretization. (a) Radial to borehole axis view. (b) Vertical to borehole axis view. (c) Local borehole view.

### 4.3. Initial and Boundary Conditions

According to the ITRT results, the geothermal gradients of the two boreholes B1 and B2 are 1.69 °C/100 m and 1.57 °C/100 m, respectively. The initial temperature distribution of the stratum can be expressed by the following formula:

\[ T_z = T_s - \frac{T_g}{100}z \]  

(13)

where \( T_z \) is the initial stratum temperature at depth \( z \) (m); \( T_s \) is the initial temperature of the ground surface (°C); and \( T_g \) is the geothermal gradient (°C/100 m).

According to the measured initial average temperature and geothermal gradient, the ground surface temperatures of B1 and B2 are 18.21 °C and 18.49 °C, respectively.

We neglected the influence of the ground surface temperature change on CBHE, because the study shows that when the depth of borehole exceeds 25 m, there is almost no effect [31]. The contact wall between the fluid and pipe is the coupling wall. The radial boundary in this work is 2.5 m, and the radial boundary wall was assumed to be adiabatic. The inlet temperature measured by TRT is fitted as the inlet boundary conditions of the two numerical models, and the fitting equations are as follows:

\[ T_1 = 17.56t^{0.063}, \quad R^2 = 0.96 \]
\[ T_2 = 16.06t^{0.075}, \quad R^2 = 0.98 \]

(14)

(15)

### 4.4. Heat Transfer Evaluation of CBHE

The heat transfer process of CBHE includes two parts; one is the heat transfer between the annulus fluid and stratum, and the other is the heat transfer between the fluid in the annulus and the inner pipe. The heat transfer rate between the annulus fluid and the stratum can be expressed as follows:

\[ Q_{bot} = cm(T_{in} - T_{bot}) \]  

(16)

However, the actual heat transfer rate we finally get is the heat transfer rate between the inlet and the outlet, which is expressed as follows:

\[ Q_{out} = cm(T_{in} - T_{out}) \]  

(17)
Therefore, there will exist heat transfer loss between the bottom and the outlet. The heat transfer loss ratio is:

\[ \alpha = \frac{Q_{\text{bot}} - Q_{\text{out}}}{Q_{\text{out}}} = \frac{T_{\text{out}} - T_{\text{bot}}}{(T_{\text{in}} - T_{\text{bot}})} \]  

(18)

where \( Q_{\text{bot}} \) is the heat transfer rate at bottom (W); \( Q_{\text{out}} \) the is heat transfer rate at outlet (W); \( c \) is the heat capacity of fluid (J/kg·°C); \( m \) is the mass flow rate (kg/s); \( \alpha \) is the heat loss ratio, %; and \( T_{\text{in}}, T_{\text{bot}}, \) and \( T_{\text{out}} \) are the inlet, bottom, and outlet temperature, respectively.

4.5. Model Validation

Based on the results of the ITRT and laboratory experiments, two numerical models of B1 and B2 were simulated. The outlet and bottom temperature of TRT and the simulation results were compared. It can be seen from Figure 9a,b that the evolution trend of the TRT and numerical simulation results show a good synchronization when the inlet temperature remains the same. The maximum relative errors of \( \theta_{\text{out}} \) and \( \theta_{\text{bot}} \) of B1 and B2 between TRT and simulation results are no more than 5%, respectively. The relative errors of pressure loss between TRT and simulation results are 5.31% and 6.57%, respectively. The main reasons for the error are as follows: (1) in the actual construction, the compactness of the backfill material is not enough, and the contact with the CBHE and stratum is not sufficient; and (2) during the ITRT, the temperature sensor placed in the inner pipe of CBHE influences the flow state of the fluid, which is ignored in the numerical model. Therefore, the models established in this work are reasonable.

![Figure 9](image1.png)

**Figure 9.** Comparison between TRT and simulation of B1 and B2. (a) Comparison between simulation and test results of B1. (b) Comparison between simulation and test results of B2.

4.6. Influence of Flow Direction on Heat Transfer

For the CBHE, the two flow directions of heat transfer fluid are flowing from the annulus to the inner pipe (annulus-in) and flowing from the inner pipe to the annulus (center-in), respectively. As shown in Figure 10, outlet temperature under the two flow directions changes with different depths. It can be seen that, within the depth of the borehole, the outlet temperature is constant at the same depth and different flow directions, indicating that the flow direction does not affect the heat transfer, if only the outlet temperature is considered.

For further study, the fluid temperature profile in CBHE with a depth of 160 m is shown in Figure 11. It is obvious that the outlet temperature of different flow directions is the same, but the fluid temperature distribution in CBHE is different. For the annulus-in direction, the temperature of the fluid decreases from the inlet to the bottom, but increases from the bottom to the outlet, which indicates that there is a serious thermal short circuit between the fluid in the annulus and the inner
pipe. For the center-in direction, the fluid temperature decreases from the inlet to the bottom and then to the outlet; the thermal short circuit cannot be reflected from the temperature profile.

![Outlet temperature with different depths.](image)

**Figure 10.** Outlet temperature with different depths.

![Fluid temperature profile.](image)

**Figure 11.** Fluid temperature profile.

Different fluid temperatures of the two directions have different effects on the stratum temperature field. Figure 12a,b show the stratum temperature profile, where 0.1 m away from CBHE, axis changes with depth under different working conditions and different flow directions. It can be seen from Figure 12a that under the cooling condition in summer, the annulus-in direction has a great influence on the stratum temperature distribution, and the temperature in the shallower position is higher than that in the deeper position. However, the center-in direction has little influence on the stratum temperature distribution, and the geothermal gradient of 1.51 °C/100 m has little change, compared with the initial geothermal gradient of 1.69 °C/100 m. On the contrary, the annulus-in direction has less influence on the stratum temperature distribution than the center-in direction under heating conditions in winter.

In order to reduce the disturbance to the stratum temperature field, based on the above results, it was suggested to adopt the center-in direction under the cooling condition, and the annulus-in under the heating condition.
4.7. Sensitivity Analysis

In the above study, the thermal short circuit can be reflected obviously by the fluid temperature in the direction of annulus-in. In order to study the influence of various factors on the heat transfer characteristics in the annulus-in direction, the sensitivity of the heat transfer characteristics at 48 h of the B1 model under the cooling condition was studied. In the following sensitivity study, model parameters refer to Tables 1–3, and each sensitive factor changes independently while other parameters remain unchanged.

4.7.1. Backfill Grout Materials

As shown in Figure 13a,b, limestone, medium–coarse sand, and original mud were adopted as the backfill grout materials in this work. The medium–coarse sand has better heat transfer characteristics than the original mud and limestone. With the increase of thermal conductivity of grout, the heat transfer rate is also higher. Compared with limestone powder, the outlet temperature of the medium–coarse sand decreases by 0.93%, the heat transfer rate of outlet and bottom increases by 7.70% and 7.08%, and the heat loss ratio decreases by 0.57% (Figure 13b). Both the outlet and bottom heat transfer rate increase, but the heat loss ratio decreases, because when the thermal conductivity of the grout increases, the heat transfer between the fluid and the stratum is strengthened, while the heat transfer between the annulus fluid and the inner pipe fluid is unchanged.
4.7.2. Inlet Temperature

Figure 14a,b describe the influence of inlet temperature on the outlet temperature and heat transfer rate. When the inlet temperature increases from 33 °C to 36 °C, the outlet temperature increases from 29.77 °C to 32.05 °C, and the heat loss ratio increases from 20.94% to 36.7%, increasing by 7.66% and 75.26%, respectively. The outlet heat transfer rate reduces from 9.39 KW to 5.3 KW, and the bottom heat transfer rate reduces from 11.88 KW to 8.37 KW, reducing by 43.56% and 29.55%, respectively. It is obvious that the outlet heat transfer rate reduction is larger than the bottom heat transfer rate reduction; therefore, the heat loss ratio improves as the inlet temperature increases. This indicates that the heat transfer increment between the annulus and inner pipe fluid is larger than that between annulus fluid and stratum, which causes more serious heat loss.

![Figure 14. Sensitivity of heat transfer rate and heat loss ratio to inlet temperature.](image)

Figure 14. Sensitivity of outlet temperature and heat transfer rate to inlet temperature. (a) Sensitivity of outlet temperature to inlet temperature. (b) Sensitivity of heat transfer rate and heat loss ratio to inlet temperature.

4.7.3. Flow Rate

To evaluate the effect of the flow rate on the outlet temperature and the heat transfer rate, different flow rates were studied. It can be seen from Figure 15a,b that the bottom heat transfer rate shows a small dependence, while the outlet temperature and heat transfer rate first increase rapidly, and then slow down. This shows that when the flow rate increases, the heat transfer time becomes shorter, and there is not enough time for heat to transfer from the fluid to the stratum; therefore, the outlet temperature increases. However, with the increase of flow rate, the turbulence intensity and convective heat transfer coefficient are enhanced, and the Reynolds number and the Nusselt number increase, which promotes heat transfer in the turbulent flow. Therefore, the total heat transfer rate is increased [9]. When the flow rate continues to increase, the influence on the outlet temperature and heat transfer rate is gradually weakened. At the same time, with the increase of flow rate, the change range of the heat transfer rate at the outlet is larger than that at the bottom, which indicates that the heat transfer intensity between the annulus fluid and the inner pipe fluid decreases greatly with the increase of flow rate; therefore, the heat loss decreases greatly. When the flow rate increases from 0.1 m/s to 0.7 m/s, the outlet temperature and heat transfer rate increase by 12.52% and 37.56%, respectively, and the heat loss rate decreases by 73.40%.
Figure 15. Sensitivity of outlet temperature and heat transfer rate to flow rate. (a) Sensitivity of outlet temperature to flow rate. (b) Sensitivity of heat transfer rate and heat loss ratio to flow rate.

4.7.4. Thermal Conductivity of Inner Pipe

Figure 16a,b show the influence of thermal conductivity of the inner pipe on the outlet temperature and heat transfer rate. It can be seen from Figure 16a that the outlet temperature is little affected by the thermal conductivity of the inner pipe. When the thermal conductivity of the inner pipe increases, the heat transfer rate at the outlet decreases slightly, while the heat transfer rate at the bottom increases greatly. Therefore, the heat loss ratio increases rapidly, which is also obvious from Figure 16b. The reason is that when the thermal conductivity of the inner pipe increases, the heat transfer between the fluid in the annulus and inner pipe is strengthened, and the thermal short circuit is more serious. However, the change of inner pipe thermal conductivity mainly affects the heat transfer inside the fluid itself, but has little effect on the heat transfer between the fluid and the stratum. This shows that, although the thermal conductivity of the inner pipe has a great influence on the heat transfer loss, it has little influence on the final heat transfer rate. Therefore, the change of the heat transfer rate at the outlet is not significant.

Figure 16. Sensitivity of outlet temperature and heat transfer rate to inner pipe thermal conductivity. (a) Sensitivity of outlet temperature to thermal conductivity of inner pipe. (b) Sensitivity of heat transfer rate and heat loss ratio to thermal conductivity of inner pipe.
4.7.5. Borehole Depth

Outlet temperature and heat transfer rate have dependence on borehole depth, as shown in Figure 17a,b. It can be seen that, with the increase of borehole depth, the outlet temperature gradually decreases, and the outlet heat transfer rate, the bottom heat transfer rate, and the heat loss ratio gradually increase. This is because the deeper the borehole, the larger the heat exchange area between the fluid and the stratum and between the inner pipe fluid and the annulus fluid. At the same time, it can be seen that with the increase of borehole depth, the growth rate of heat loss rate gradually decreases. This is because with the increase of drilling depth, the increase of heat exchange area between fluid and stratum is larger than that between annulus fluid and inner pipe fluid. When the depth increases from 120 m to 200 m, the outlet temperature decreases by 4.21%, the heat transfer rate at the outlet and the bottom and heat loss ratio increase by 45.32%, 65.22%, and 35.75%, respectively. However, through further calculation, it is found that the change of heat transfer rate per meter of the borehole is not significant.

![Figure 17. Sensitivity of outlet temperature and heat transfer rate to borehole depth. (a) Sensitivity of outlet temperature to borehole depth. (b) Sensitivity of heat transfer rate and heat loss ratio to borehole depth.](image)

Through the above sensitivity analysis, the flow rate and inlet temperature have great influence on the heat transfer performance of CBHE. Increasing the flow rate and reducing the inlet temperature can greatly improve the heat transfer rate of CBHE. The heat transfer rate of CBHE is better with the increase of borehole depth. However, the contribution of increasing borehole depth to heat transfer rate mainly comes from the increase of heat transfer area, but the heat transfer rate per meter of the borehole has no obvious improvement. The thermal short circuit is the most sensitive to the thermal conductivity of the inner pipe, but the change of the thermal conductivity of the inner pipe will not improve the actual heat transfer rate. The influence of inlet temperature and flow rate on the thermal short circuit is significant, which can be reduced by decreasing inlet temperature and increasing flow rate. Thermal short circuit shows a weak dependence on backfill material and borehole depth.

4.8. Optimum Flow Rate Range

Figure 18a shows the effect of the flow rate on the heat transfer rate of CBHE under different inlet temperature. It is obvious that at different inlet temperatures, the heat transfer rate rises with the increase of flow rate. A fast increase in the heat transfer rate is resulted when the flow rate is less than 0.4 m/s; however, the increase rate decreases when the flow rate is above 0.4 m/s. Therefore, increasing the flow rate within 0.4 m/s has a significant effect on improving the heat transfer rate of CBHE.
Pressure loss is affected by flow rate. It can be seen, from Figure 18b, that the pressure loss increases slightly when the flow rate is less than 0.4 m/s. However, the pressure loss rises sharply when the flow rate is greater than 0.4 m/s. Excessive pressure loss will cause pump power consumption, which greatly increases the load of GSHP. Therefore, reasonable flow rate is very important for the initial investment of GSHP.

Based on the above analysis, although increasing the flow rate will increase the heat exchange rate, the pump consumption will also be greatly increased. Therefore, combining these two factors, it is suggested that the flow rate ranging from 0.3 m/s to 0.4 m/s is a better operation range for all CBHE whose size is the same as in this paper.

5. Conclusions

In this paper, based on the proposed ITRT method, the field test was carried out and verified by indoor experiments, and then numerical simulation was conducted. The main conclusions are as follows:

1. The method proposed in this study, of using the average temperature of bottom and inlet fluid as the average temperature of circulating fluid to solve the stratum thermal conductivity, has a high accuracy.
2. Considering that the disturbance of the stratum temperature field will have a great impact on the underground organisms, it is suggested to adopt the anulus-in direction under the cooling condition, and the center-in direction under the heating condition.
3. Through sensitivity analysis, the backfill grout material, the thermal conductivity of inner pipe, and the borehole depth have little effect on the heat transfer performance of CBHE, while the flow rate and inlet temperature have significant effect. Heat loss and heat transfer rate can be controlled by flow rate and inlet temperature.
4. An inlet flow rate between 0.3 m/s and 0.4 m/s, corresponding to volume flow rate range from 3.24 m³/h to 4.31 m³/h, will lead to a better heat transfer performance.

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