

Article

An Analytical Investigation of the Heat-Transfer Performance of a Deep U-Shaped Borehole Heat-Exchangers System in Porous Media

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Abstract

Compared with previous analytical designs for deep UBHE, the present study is new in three aspects: (1) a segmented FLS model combined with the virtual heat source method is applied to the full U-shaped path (injection, horizontal, and production wells) in a unified formulation; (2) equivalent thermal conductivity is introduced to account for groundwater seepage in porous media, avoiding the need for separate CFD or coupled numerical solvers; (3) the relationship between production well depth and the maximum effective insulation length is quantified and discussed. Deep U-shaped borehole heat-exchangers (UBHE) systems boast high heat-exchange efficiency, yet most analytical models are too simplistic, causing inaccuracies. This study proposes a segmented finite line source (FLS) model for UBHE using the virtual heat source method. Introducing equivalent thermal conductivity (k_{equ}), it treats rock-soil as a groundwater-saturated porous medium, coupling seepage's dynamic heat-transfer impact. By comparing the simulation results of the same type of research within 720 h, the average temperature difference between the models was found to be 1.31 °C, with an error rate of 5.31%, which is 40.87 percentage points lower than the existing achievements, thereby demonstrating the accuracy of this model. In addition, based on this model, the influence trends of five main factors such as seepage velocity and geothermal gradient on the system's heat exchange were drawn and analyzed. Among them, the laying length of the insulation layer was analyzed in detail. The results show that its maximum laying length should be in line with the depth node where reverse heat exchange occurs with the production well. Under the set conditions of this study, when the depth of the production well is 2500 m, the maximum laying length of the insulation layer is 1900 m.



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Keywords: deep U-shaped borehole heat exchangers; virtual heat source method; equivalent thermal conductivity; analysis of influencing factors; length of insulation layer application

1. Introduction

Rising energy consumption has caused anomalous global climate changes and led to growing energy shortages [1,2], making energy conservation a global strategic priority [3–5].

Geothermal energy, a renewable option crucial for carbon neutrality [6], is drawing increasing attention from academia and industry due to its wide availability, abundance, and eco-friendliness [7,8].

Geothermal energy is divided into shallow and deep categories [9]. With research on shallow geothermal energy in China nearing saturation [10], the focus has shifted to deep geothermal energy (500–3000 m) [11–13]. The deep borehole heat exchanger (BHE) system, a primary research target, differs from the enhanced geothermal system (EGS) as it minimizes environmental damage [14], offering a scientific method for deep geothermal resource utilization [15]. This technology involves burying pipes with backfill materials [16] and can be classified into deep coaxial borehole heat exchangers (CBHE) and deep U-shaped borehole heat exchangers (UBHE). Studies show that UBHE systems have higher heat-exchange efficiency than CBHE systems under the same conditions [17], primarily due to efficient horizontal well heat exchange. However, this also presents modeling challenges, causing slower development of the UBHE system compared to the CBHE system.

Over the past decade, research on the CBHE system has advanced significantly. Le et al. [18] pioneered the use of FEFLOW to create a 3D unsteady-state heat-transfer model for deep geothermal heat pumps. Caulk [19] modeled the reuse of abandoned oil and gas wells in California. Fang et al. [20] conducted 2D modeling to analyze stratum factor impacts on thermal performance. Song et al. [21] confirmed the high consistency between unsteady-state model simulations and actual measurements. Meanwhile, Theo et al. [22] and Cai et al. [9] also made notable contributions. In recent years, Li [23], Zhang [24], and others have achieved fruitful results in numerical research on this system.

However, compared to the CBHE system, the UBHE system has seen relatively stagnant progress, mainly due to two reasons. Firstly, there is an imbalance in modeling types, with numerical models being favored in mainstream research, while analytical models are overlooked. Although numerical models accurately reflect the UBHE system's thermal performance [25], analytical models remain essential for their convenience and efficiency. Secondly, existing analytical models for the UBHE system are overly simplified, with numerous assumptions leading to significant calculation errors and a consequent decline in industry preference.

Based on existing research of UBHE system, specific analyses reveal the following: Pan et al.'s [26] initial analytical model considered buried pipe depth's impact on borehole temperature but overlooked stratified geology and local pipe thermal distribution. Luo et al. segmented finite line [27] and cylindrical source [28] models' incorporated geothermal gradients yet failed to address rock-soil thermal property differences or deep underground analysis. Similarly, Huang et al. [29] and Ma et al. [30] models neglected borehole-area geological stratification. Only recently have models considering these factors emerged, but most remain numerical [31–33]. While a few analytical models address these issues, calculation inaccuracies persist. Recent literature on heat exchangers and thermal-hydraulic performance has further highlighted the need for accurate modeling and operational guidelines. Abdelmagied [34] analyzed the thermo-fluid characteristics and exergy of twisted tube helical coils, providing a basis for evaluating enhanced heat-transfer configurations. Gomaa et al. [35] investigated the hydraulic and thermal behavior of double concentric tubes with an inner twisted spiral tube, with implications for pipe-level thermal design. Abdelmagied [36] studied fluid and thermal flow in double-twisted helically coiled tube heat exchangers under various configurations, reinforcing the importance of geometry and flow conditions on heat exchange. Together with the body of work on deep borehole and geothermal systems cited above, these studies [34–36] underscore the value of both analytical and systematic approaches to heat-exchanger performance; the

present work contributes an analytical framework for deep UBHE systems that can support such applications.

In conclusion, enhancing the calculation accuracy of analytical models while leveraging their strengths is a key research consideration. This study introduces a segmented FLS model for simulating deep UBHE systems, utilizing the virtual heat source method. The model treats rock and soil as a saturated homogeneous porous medium, incorporating equivalent thermal conductivity (k_{equ}) to uniformly account for macroscopic sensible heat convection and microscopic thermal dispersion, thereby indirectly coupling groundwater seepage's dynamic impact on rock and soil thermal transfer. Comparisons with Bao et al.'s [37] recent findings validate the model's accuracy. A control variable analysis of five main factors—seepage velocity, inlet water temperature, geothermal gradient, flow rate, and insulation layer length—ranks their influence based on average outlet water temperature and system heat exchange. Further research explores the insulation layer's maximum laying range. In brief, the novelty of this work relative to prior designs is (i) a unified segmented FLS formulation over the entire U-shaped borehole path with the virtual heat source method; (ii) incorporation of equivalent thermal conductivity for seepage in porous media within an analytical framework; and (iii) quantitative analysis of the maximum insulation length versus production well depth and its link to the reverse heat-exchange node. Overall, this study minimizes simplifications in existing analytical models while ensuring accuracy, providing valuable references for efficient deep UBHE system operation.

2. Model Building

2.1. Physical Model

2.1.1. The System Composition and Principles

Figure 1 shows the composition and working principle of the deep UBHE system. It consists of three parts: injection wells, horizontal wells, and production wells. All are composed of fluids, pipelines, and backfill materials and are connected to the rock and soil by the borehole wall as a bridge. During operation, the fluid flows from the injection well through the horizontal well to achieve efficient heat exchange and then flows out of the system through the production well. After passing through the user end, it is returned to the injection well to achieve circulation. When flowing through the production well, due to the reverse heat-exchange phenomenon, an insulation layer needs to be added.

2.1.2. The Modeling Ideas and Assumptions

Firstly, the borehole wall is regarded as a “bridge” for heat exchange between the surrounding rock and soil outside the well and the fluid inside the pipe. The heat flow from the surrounding rock and soil outside the well passes through the borehole wall, which is the only path, to heat the fluid inside the pipe, which is shown in Figure 2.

Secondly, the concept of heat-release rate per unit time and unit length (q_l) proposed by Li et al. [38] in their study of the FLS model is applied to this model; (q_l) represents the heat flow transferred from the rock and soil to the borehole, which connects the two originally independent control equations for calculating the temperature field of the borehole wall and the fluid temperature field, achieving the transformation of the model from the physical level to the mathematical level.

Finally, MATLAB R2023b is used to program the above process. Each output of q_l can be used to calculate the temperature distribution in the next cycle, and ultimately, the outlet water temperature and system heat exchange can be output, completing a full modeling process.

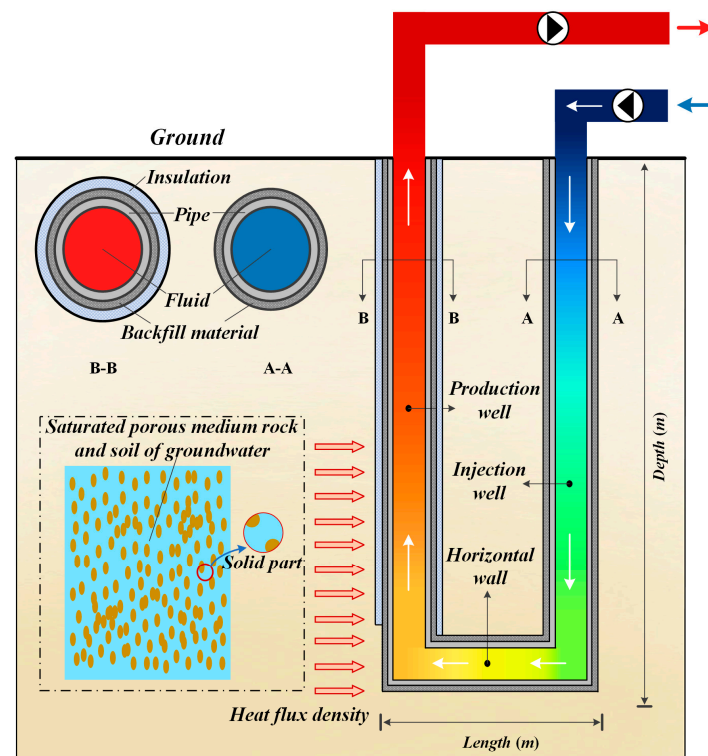


Figure 1. Composition and working principles of the UBHE system.

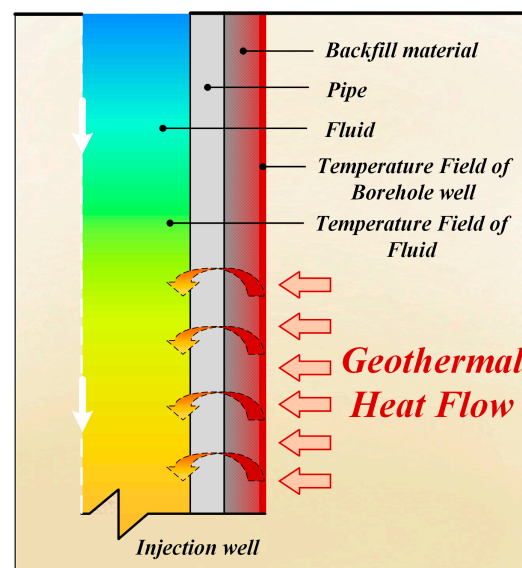


Figure 2. Core ideas of modeling.

In addition, the following assumptions are made about the model:

- (1) The rock-soil is regarded as a homogeneous porous medium saturated with groundwater. Heat conduction within the rock-soil is limited to the axial and radial directions, and the temperature variation over time is considered. Thus, it is treated as a two-dimensional unsteady-state heat conduction problem;
- (2) The working fluid is water and is incompressible. Both fluid flow and heat transfer are treated as one-dimensional problems, with the temperature and velocity averaged across the cross-section;
- (3) The thermal physical parameters of the rock-soil mass and pipe materials are isotropic constants.

Justification and influence of assumptions: (1) Homogeneous porous medium and 2D conduction simplify the analytical solution while retaining the dominant physics; neglecting 3D effects may slightly underestimate thermal interaction near bends. (2) One-dimensional fluid treatment is standard for long borehole segments and reduces the model to coupled ODEs; cross-sectional averaging may underestimate peak temperatures in low-flow regions. (3) Constant thermophysical parameters keep the Green's function formulation tractable; temperature-dependent properties would require an iterative or numerical solution and typically introduce a 10% variation for the operating range considered.

2.2. Mathematical Model

All equations in this section have been retypeset with a math typesetting program and appropriate spacing between equations for readability. All non-original equations are cited to their sources [38–40].

2.2.1. Derivation of the Segmented FLS Model

(1) The derivation of the segmented FLS model:

First, begin with the point source: the temperature field function $G(x, t; x', t')$ formed by a unit-intensity instantaneous point source at time t' and point coordinates (x', y', z') is expressed as [39]

$$G(X, t; X', t') = \frac{[\rho c / (t - t')]^{3/2}}{8\pi^{3/2} \sqrt{k_x k_y k_z}} \exp\left\{-\frac{\rho c}{4(t - t')} \left[\frac{(x - x')^2}{k_x} + \frac{(y - y')^2}{k_y} + \frac{(z - z')^2}{k_z} \right]\right\} \quad (1)$$

Here, X represents the point coordinates (x, y, z) , X' represents (x', y', z') , and k_x, k_y, k_z , respectively, represents thermal conductivity in the x, y , and z directions, $(W/(m \cdot K))$.

If this point source continuously releases heat from $t' = 0$ to $t' = t$, the integral time term yields the temperature response function $\theta_p(X, t)$:

$$\theta_p(X, t) = \frac{(\rho c / \pi)^{3/2}}{8\sqrt{k_x k_y k_z}} \int_0^t \frac{1}{(t - t')^{3/2}} \exp\left\{-\frac{\rho c}{4(t - t')} \left[\frac{(x - x')^2}{k_x} + \frac{(y - y')^2}{k_y} + \frac{(z - z')^2}{k_z} \right]\right\} dt' \quad (2)$$

Set the following parameters and substitute them into the equation to simplify and obtain Equation (3):

$$\kappa_{zx} = k_z/k_x, \quad \kappa_{zy} = k_z/k_y, \quad \tau^{-2} = t - t', \quad d = \sqrt{\kappa_{zx}(x - x')^2 + \kappa_{zy}(y - y')^2 + (z - z')^2}$$

$$\theta_p(X, t) = \frac{(\rho c / \pi)^{3/2}}{4\sqrt{k_x k_y k_z}} \int_{1/\sqrt{t}}^{\infty} \exp\left(-\frac{d^2 \tau^2}{4\alpha_z}\right) d\tau = \frac{1}{4\pi d \sqrt{\alpha_x \alpha_y}} \operatorname{erfc}\left(\frac{d}{2\sqrt{\alpha_z t}}\right) \quad (3)$$

Among them, $\alpha_x, \alpha_y, \alpha_z$ represents the thermal diffusivity in the x, y , and z directions, (m^2/s) . The complementary error function was adopted for the final calculation step.

The FLS model can be derived from the point source model [38]: a vertical line source of length L placed in a semi-infinite uniform anisotropic medium, with one end at the medium surface $z = 0$ and a unit time length heat generation rate of q_l , is obtained by moving the point source through the point (x', y', z') .

Then, starting from Equation (3), integrating the spatial term along the z -axis yields the temperature field function:

$$\theta(z, t) = \frac{q_l}{4\pi \sqrt{k_x k_y}} \int_0^L \frac{1}{d} \operatorname{erfc}\left(\frac{d}{2\sqrt{\alpha_z t}}\right) dz' \quad (4)$$

Here, the concept of the virtual heat source method is introduced. Rationale for using the virtual heat source method: It is adopted to satisfy the constant surface temperature (Dirichlet) boundary condition at the ground surface in a semi-infinite domain without solving the full 3D problem; the mirror image line source cancels the normal heat flux at the surface so that the superposition yields the correct temperature field below the surface and keeps the derivation analytically tractable [39]. It is assumed that there is a mirror image line source on the symmetrical side of the semi-infinite medium, similar to the original line source. The combined effect of the two keeps the surface temperature of the medium constant (Figure 3). Main limitations of this method: (1) It assumes a homogeneous semi-infinite medium and constant surface temperature; (2) it does not directly represent time-varying surface conditions or lateral heterogeneity; (3) extension to the full U-shaped path relies on segmentation and superposition, which may underestimate thermal interference between segments in strongly transient regimes.

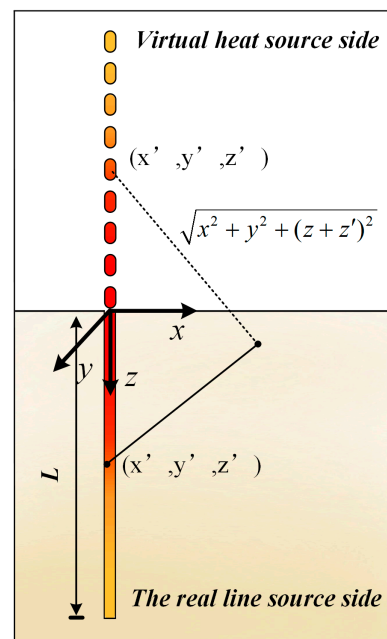


Figure 3. Schematic diagram of the virtual heat source method.

The virtual heat source part is shown in Equation (5):

$$\theta'(z, t) = -\frac{q_l}{4\pi\sqrt{k_x k_y}} \int_0^L \frac{1}{d'} \operatorname{erfc}\left(\frac{d'}{2\sqrt{\alpha_z t}}\right) dz' \quad (5)$$

Among them, $d' = \sqrt{\kappa_{zx}(x - x')^2 + \kappa_{zy}(y - y')^2 + (z + z')^2}$.

By superimposing the functions on both sides, the final temperature field function of the FLS model is obtained as shown in Equation (6):

$$\theta_{fls}(z, t) = \theta + \theta' = \frac{q_l}{4\pi\sqrt{k_x k_y}} \int_0^L \left[\frac{\operatorname{erfc}(d/2\sqrt{\alpha_z t})}{d} - \frac{\operatorname{erfc}(d'/2\sqrt{\alpha_z t})}{d'} \right] dz' \quad (6)$$

Finally, Equation (6) is expanded: each of the three well sections is modeled following the above steps, and the point heat source coordinates and temperature field functions for each section are respectively obtained. As shown in Figure 4, $i = 1, 2, 3$ respectively represents each well section in the flow sequence.

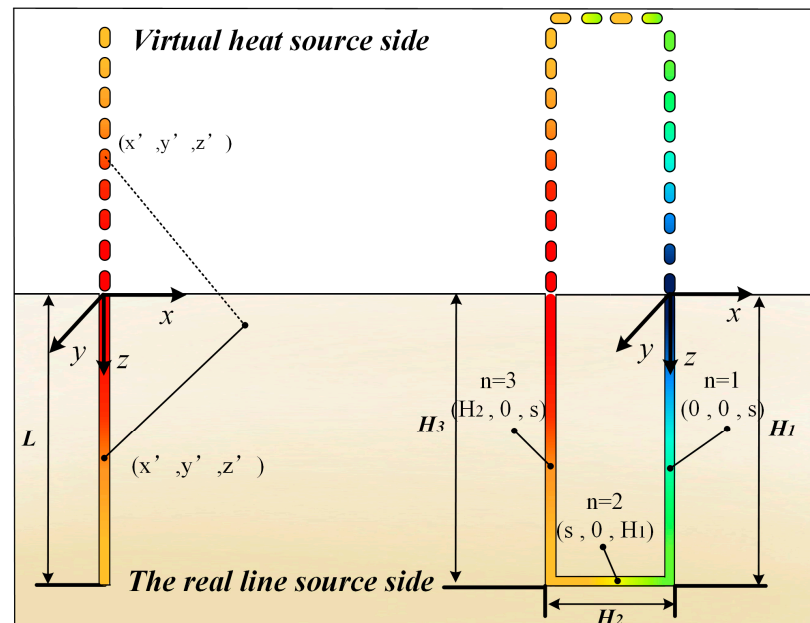


Figure 4. Schematic diagram of the extended virtual heat source method.

Coordinates and ranges of each section:

$$n = 1, x' = 0, y' = 0, z' = s, X' = (0, 0, s), 0 < s \leq H_1$$

$$n = 2, x' = s, y' = 0, z' = H_1, X' = (s, 0, H_1), H_1 < s \leq H_2$$

$$n = 3, x' = H_2, y' = 0, z' = s, X' = (H_2, 0, s), H_2 < s \leq H_3$$

The corresponding d is expressed as follows:

$$n = 1, d_1 = \sqrt{x^2 + y^2 + (z - s)^2}, d_1' = \sqrt{x^2 + y^2 + (z + s)^2}$$

$$n = 2, d_2 = \sqrt{y^2 + (z - H_1)^2 + (x - s)^2}, d_2' = \sqrt{y^2 + (z - H_1)^2 + (x + s)^2}$$

$$n = 3, d_3 = \sqrt{(x - H_2)^2 + y^2 + (z - s)^2}, d_3' = \sqrt{(x - H_2)^2 + y^2 + (z + s)^2}$$

Here, the moving coordinate is set as s , and H_i represents the buried pipe length of each well section.

Substitute them in sequence into Equation (6), and finally establish the temperature field function (7) of the segment FLS model for calculating the borehole temperature field of the deep UBHE system:

$$T_b(s, t) = \frac{q_l}{4\pi k_{eff}} \sum_{n=0}^3 \int_{H_{n-1}}^{H_n} \left[\frac{\text{erfc}(d_n/2\sqrt{\alpha_{eff}t})}{d_n} - \frac{\text{erfc}(d_n'/2\sqrt{\alpha_{eff}t})}{d_n'} \right] ds \quad (7)$$

Among them: $n = 0, T_b(s, t) = 0$; $n = 1, H_{n-1} = 0$.

Equation (8) is the expression for the heat flux density of the borehole:

$$q_l = \frac{T_b(s, t) - T_f(s, t)}{R \cdot l} \quad (8)$$

Among them, R is the total thermal resistance of the system, ($\text{m} \cdot \text{K}/\text{W}$), T_f denotes the temperature distribution of the fluid, ($^{\circ}\text{C}$), and l represents the unit length, (m).

(2) The incorporation of equivalent thermal conductivity:

Based on this and referring to existing research [40], the thermal conductivity and volumetric specific heat capacity in the segmented FLS model are modified as follows:

$$k_{\text{equ}} = k_s + \rho_f c_f v_f L_c \quad (9)$$

$$\rho_{\text{equ}} c_{\text{equ}} = \varphi \rho_f c_f + (1 - \varphi) \rho_s c_s \quad (10)$$

where $\rho_{\text{equ}} c_{\text{equ}}$ represents the volumetric specific heat of the porous medium; k_s is the thermal conductivity of the solid part, (W/(m·K)); v_f represents the seepage velocity, (m/s); L_c represents the characteristic length, (m); and φ denotes the porosity of the porous medium.

2.2.2. The Temperature Field of Borehole Walls

(1) Control equations for fluid flow in a pipe:

Based on the model assumptions, the fluid temperature field function within the deep UBHE system is as follows:

$$\rho c V \frac{\partial T_f(s, t)}{\partial t} + \rho c V \frac{\partial T_f(s, t)}{\partial s} = \frac{T_b(s, t) - T_f(s, t)}{R} \quad (11)$$

As shown in Figure 5, the system thermal resistance consists of four parts, where ①–④ represent R_e , R_m , R_i , and R_l , respectively:

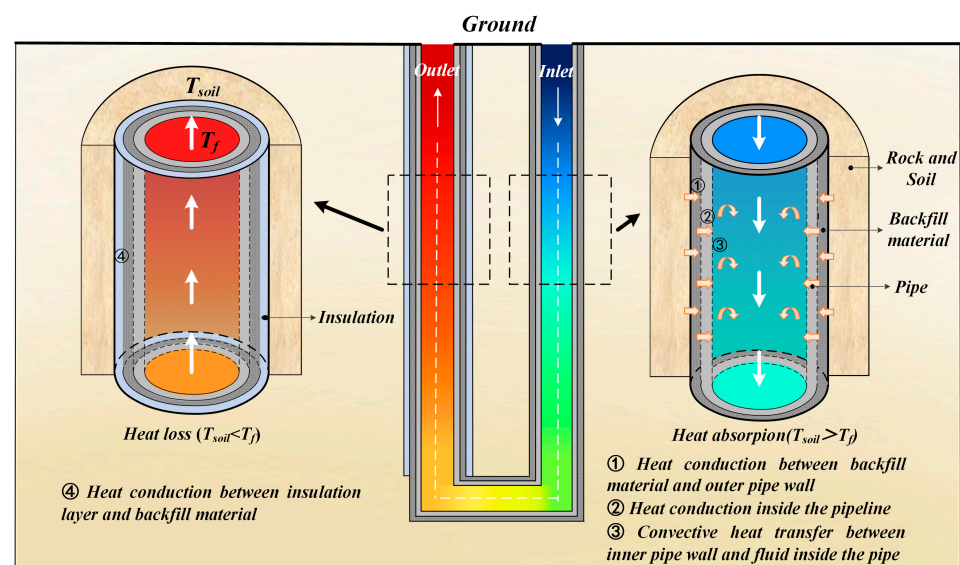


Figure 5. Schematic illustration of the heat-exchange principle.

The thermal resistances of the system and its components are as shown in Formula (12):

$$R = R_i + R_m + R_e + R_l \quad (12)$$

$$R_e = \frac{1}{2\pi k_b} \ln \frac{r_b}{r_{p,o}} \quad (13)$$

$$R_m = \frac{1}{2\pi k_p} \ln \frac{r_{p,o}}{r_{p,i}} \quad (14)$$

$$R_i = \frac{1}{2\pi r_{p,i} h_f} \quad (15)$$

$$R_I = \frac{1}{2\pi k_I} \ln \frac{r_I}{r_b} \quad (16)$$

where r is the borehole radius, (m); $r_{p,i}$ and $r_{p,o}$ represents the internal and external radius of the pipe, respectively, (m); h_f is the convective heat-transfer coefficient, ($\text{W}/\text{m}^2\cdot\text{K}$); k_p , k_b , and k_I are the thermal conductivity of the backfill material, the pipe, and the insulation layer, respectively, ($\text{W}/\text{m}\cdot\text{K}$); r_I is the insulation layer radius, (m).

(2) Initial and boundary conditions:

$$T_f(s, 0) = T_{in} = T_{out} \quad (17)$$

$$T_b(s, 0) = T_0 + k_{geo} \cdot s \quad (18)$$

Among them, for the fluid, T_{in} and T_{out} are constants representing the inlet temperature and outlet temperature of the given system at the initial moment, at which time the fluid temperature inside the pipe is uniform everywhere, ($^{\circ}\text{C}$). T_0 is the temperature of surface, ($^{\circ}\text{C}$), and k_{geo} is the geothermal gradient, ($^{\circ}\text{C}/\text{m}$).

The inlet and outlet temperatures at the connection points of each well section are continuous and equal.

2.2.3. Iterative Calculation Route

As shown in Figure 6, the main process flow of the model after programming is as follows.

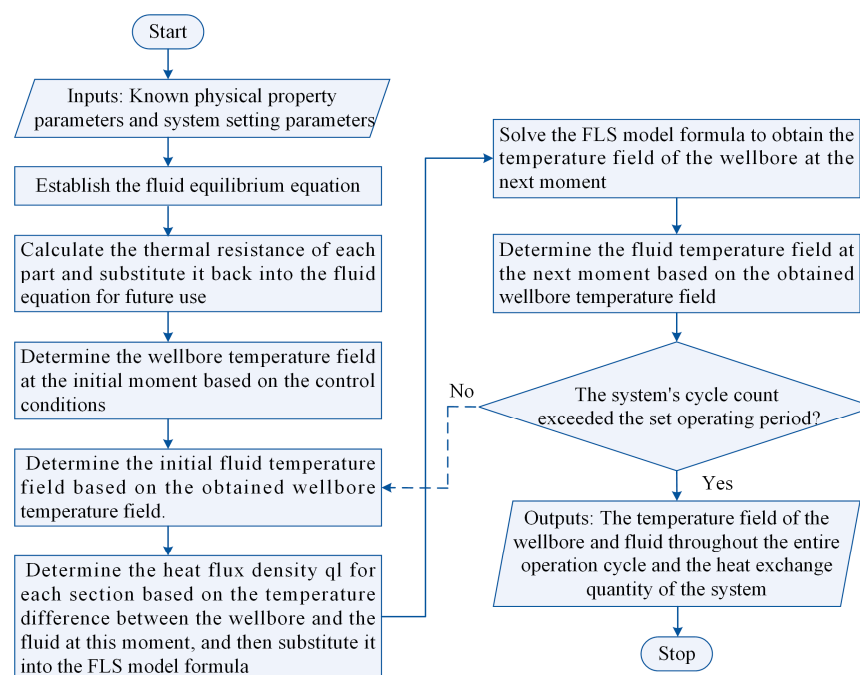


Figure 6. Iterative calculation route.

3. Result

3.1. Parameter Conditions

This study is conducted by verifying the existing research [37]. Experimental/validation setup: The present work is an analytical and simulation study; no new laboratory experiment was conducted. Validation is performed by comparing the current model outputs (outlet temperature and heat exchange) with the reference numerical/analytical results of Bao et al. [37] under identical geometry, flow rate, geothermal gradient, and porous media parameters. The same time horizon (720 h) and the same

initial and boundary conditions are used so that the comparison is strictly like-for-like. All parameter settings in the model are kept consistent with the comparison model. Therefore, all the parameter settings in the model here are kept consistent with the comparison model.

Table 1 shows the basic parameters of the system. Hydraulic diameter: For each well section (injection, horizontal, and production), the hydraulic diameter D_h is defined as $4A/P$, where A is the cross-sectional flow area, and P is the wetted perimeter. For the circular pipe flow in this study, D_h equals the inner diameter of the pipe: injection well $D_h = 2 \times 224 \text{ mm} = 448 \text{ mm}$; horizontal well $D_h = 2 \times 147 \text{ mm} = 294 \text{ mm}$; production well $D_h = 2 \times 224 \text{ mm} = 448 \text{ mm}$ (see Table 1 for inner radius).

Table 1. Parameter values used for model validation in this study.

Influencing Factors	Initial Value	Unit
Borehole depth	2500	m
Horizontal tube length	650	m
Outer radius of the injection well	311.7	mm
Outer radius of the horizontal well	168.3	mm
Outer radius of the production well	244.5	mm
Inner radius of the injection well	224	mm
Inner radius of the horizontal well	147	mm
Inner radius of the production well	224	mm
Thermal capacity of the pipe	3.8×10^6	J/(m ³ ·K)
Thermal conductivity of the pipe	41	W/(m·K)
Volumetric specific thermal capacity of the backfill material	2.5×10^6	J/(m ³ ·K)
Thermal conductivity of the backfill material	1.5	W/(m·K)
Thickness of the insulation layer	0.018	mm
Length of the insulation layer	200	m
Thermal conductivity of the insulation layer	0.0312	W/(m·K)
Geothermal gradient	0.03	°C/m
Volume flow rate of water	69.81	m ³ /h
Thermal capacity of water	4.174×10^3	J/(m ³ ·K)
Average atmospheric temperature	15.7	°C

Since the length of the insulation layer is not mentioned, a commonly used value is selected here.

Table 2 shows the parameters of porous media after introducing k_{equ} .

Table 2. Thermal physical parameters of the porous media.

Influencing Factors	Initial Value	Unit
Equivalent volume specific heat capacity	1.091×10^6	J/(m ³ ·K)
Equivalent thermal conductivity	4.3139	W/(m·K)
Porosity	0.379	%
Seepage velocity	7.062×10^{-7}	m/s

3.2. Comparison of Simulation Results

The results are shown in Figure 7: Figure 7a indicates that the outlet water temperature drops significantly at the beginning of the operation and then stabilizes. After 200 h, the error rate is less than 10% and drops significantly, reaching the lowest at the end of the simulation. Figure 7b,c show that the maximum and minimum temperature differences during the simulation process are 2.69 °C and 0.66 °C, respectively, with an average absolute temperature difference of 1.31 °C. The maximum and minimum error rates are

9.49% and 2.89%, respectively, with an average of 5.31%, all within the acceptable range, which demonstrates the accuracy of this model. Error and uncertainty: The reported temperature difference and error rate are relative to the reference [37]. Uncertainty in the comparison arises from (i) possible differences in numerical implementation (time step and convergence) and (ii) parameter uncertainty (e.g., k_{equ} , geothermal gradient); a conservative estimate of the relative uncertainty in the mean outlet temperature is in the order of a few percent. Sensitivity of the outlet temperature to key parameters is discussed in Section 4.

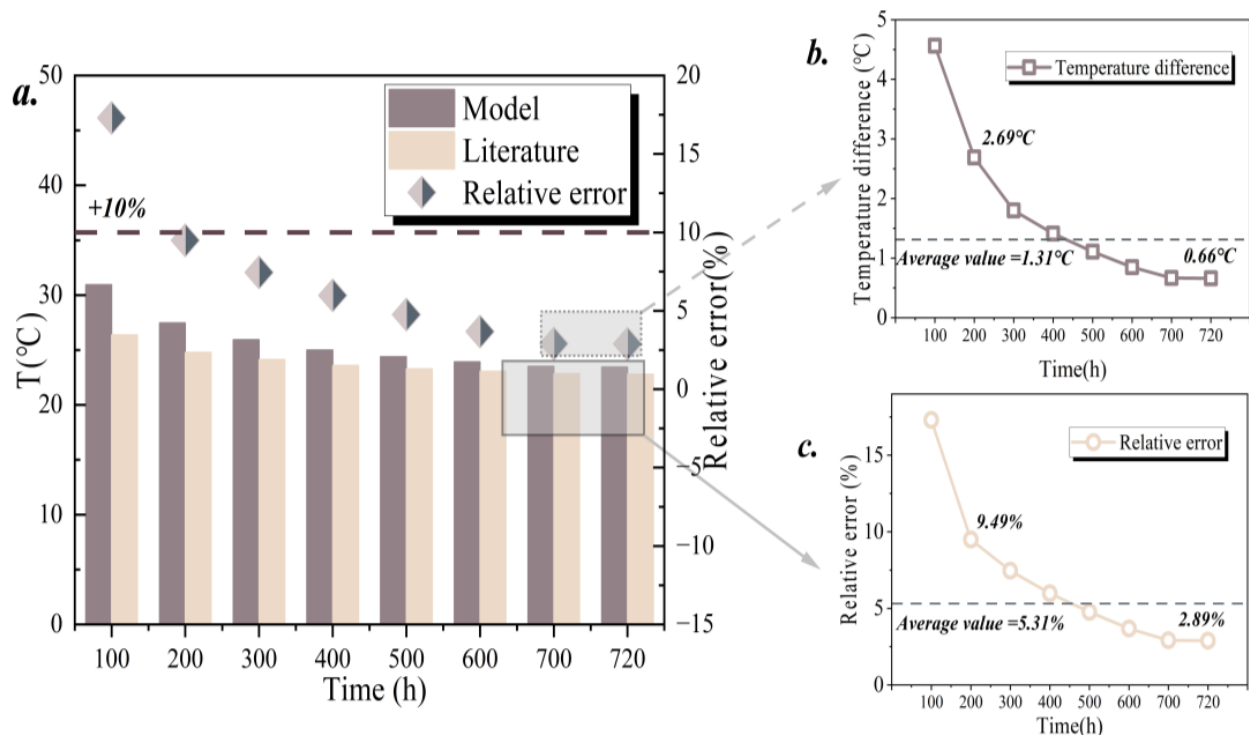


Figure 7. (a) Comparison of outlet temperatures. (b) Temperature difference. (c) Error rate. High-resolution versions of (b,c) are provided in the revised submission.

3.3. Analysis of the Fluid Temperature Field

After verification, the temperature field of the fluid inside the pipe was analyzed. The initial water inlet temperature was set at 10 $^{\circ}\text{C}$, with each vertical well section being 2500 m long (100 m per section) and each horizontal well section being 650 m long (50 m per section), totaling 63 sections; the insulation length was 200 m.

As shown in Figure 8, initially, the fluid temperature inside the pipe was approximately twice that of the later stage, and it significantly decreased and gradually stabilized after operation. The analysis revealed that from the inlet to the horizontal well section, the fluid absorbed heat, and the temperature dropped at about 1900 m from the production well. From this point on, the fluid and the rock-soil had a reverse heat exchange, resulting in heat loss. Therefore, the influence of the insulation length will be further simulated and analyzed in Section 4.5. Additionally, due to the insulation layer's effect, the fluid temperature decreased very slowly at 200 m from the outlet. Interpretation of fluid temperature fields at different times: At early times, the fluid is still cold relative to the formation, so heat is absorbed along the injection and horizontal sections and the temperature rises; the peak appears near the bottom of the production well. As time increases, the formation around the borehole is cooled (or warmed), and the temperature field evolves: the axial gradient weakens, and the spatial profile becomes flatter. The drop at 1900 m in the production well corresponds to the depth where the fluid begins to lose heat to the formation (reverse heat exchange). The insulation layer near the outlet limits this loss, so the temperature decline

is slow in the top 200 m. The later-time curves thus reflect the approach to a quasi-steady distribution dominated by geothermal gradient, flow rate, and insulation length.

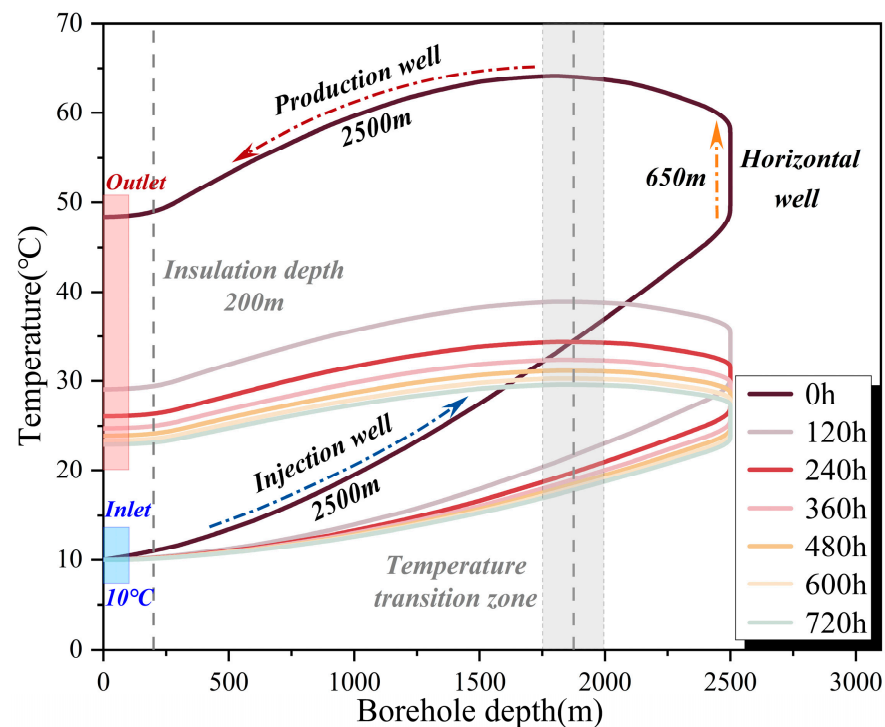


Figure 8. Fluid temperature fields at different times.

4. Discussion

4.1. Effects of Groundwater Seepage Velocity

According to the equivalent thermal conductivity calculation formula, it can be known that the change of seepage velocity will have a significant impact on the heat exchange of the system. To explore its influence, the outflow temperature and heat exchange of the UBHE system under different seepage velocities (1×10^{-9} m/s, 1×10^{-8} m/s, 1×10^{-7} m/s, and 1×10^{-6} m/s, respectively) were simulated.

As illustrated in Figure 9, increasing seepage velocity at a constant operation time directly enhances equivalent thermal conductivity (k_{equ}), thereby boosting system heat-exchange efficiency. This results in higher outflow temperatures and increased heat exchange, with the effect becoming more pronounced at higher seepage velocities. For instance, at 120 h, temperature and heat exchange growth rates rose from 1.40% to 30.68% and from 2.28% to 46.76%, respectively. Conversely, at a constant seepage velocity, extending operation time decreases outflow temperature and system heat exchange, though both stabilize as the system approaches steady-state conditions. For example, at a seepage velocity of 1×10^{-7} m/s, temperature change rates dropped from 10.39% to 1.89% and heat-exchange change rates from 15.83% to 3.31%.

By incorporating equivalent thermal conductivity and modeling rock and soil as a uniform, groundwater-saturated porous medium, the FLS model effectively accounts for seepage influence through thermal conductivity increments. Correlation and comparison with the literature: The dependence of outlet temperature and heat exchange on seepage velocity is consistent with the trend reported in [37] and with numerical studies that include groundwater flow (e.g., Huang et al. [31]); the quantitative comparison with [37] is given in Section 3.2 (mean temperature difference 1.31 °C; mean error rate 5.31%). This approach provides a valuable reference for analyzing complex heat-exchange processes in deep strata.

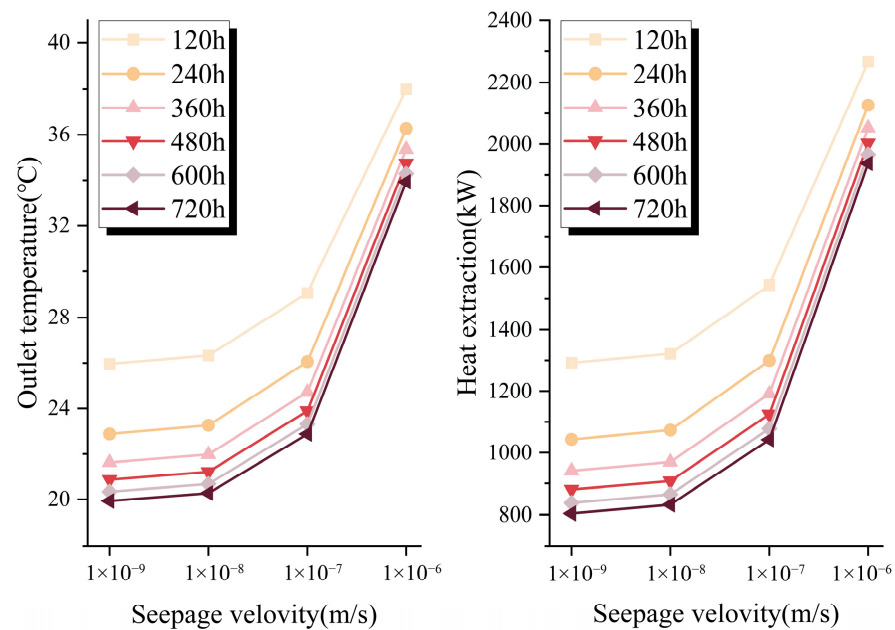


Figure 9. Effects of seepage velocity on the outlet temperature and heat exchange.

4.2. Effects of Inlet Temperature

Inlet temperature variations significantly impact outlet temperature in the UBHE system. With the inlet water temperature set between 5–15 °C, Figure 10 illustrates the corresponding changes in outlet water temperature and system heat exchange. As the inlet temperature increases from 5 °C to 15 °C, the average outlet temperature rises from 22.08 °C to 27.89 °C. Conversely, the average system heat exchange decreases from 1383.46 kW to 1044.08 kW.

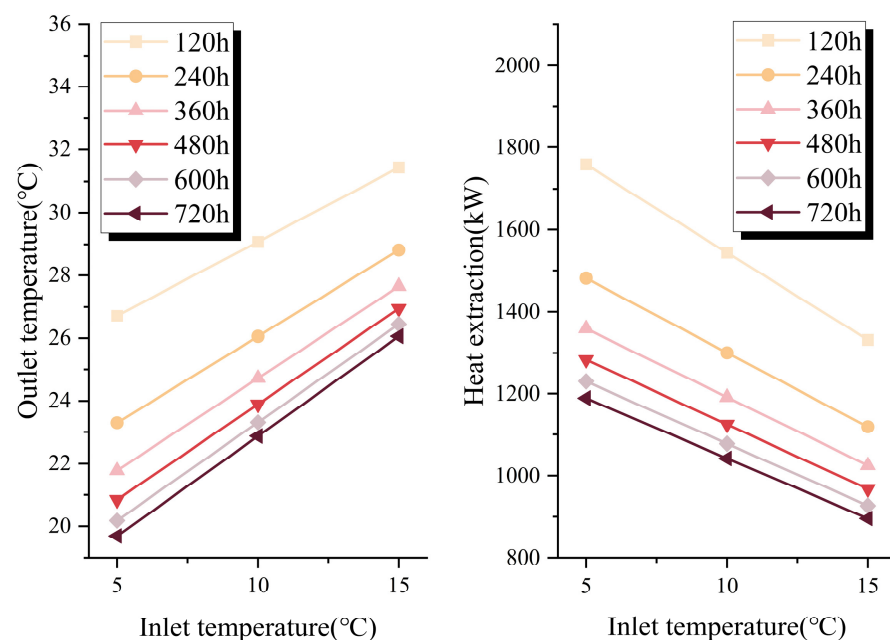


Figure 10. Effects of the inlet temperature on the outlet temperature and heat exchange.

Although a higher inlet water temperature results in a higher outlet water temperature, the overall heat-exchange capacity of the system declines because of the diminished temperature differential. Consequently, increasing the inlet water temperature does not effectively improve the system's heat-exchange performance.

4.3. Effects of Geothermal Gradient

High geothermal gradient zones (≥ 0.03 °C/m) are ideal for geothermal resource development. Thus, simulations are conducted using average geothermal gradients from several typical Chinese regions, including the Songliao Basin [41], the North China Basin, southeast coastal areas, and basins in South China [42,43].

As depicted in Figure 11, an increase in the geothermal gradient generally raises the average outlet water temperature (from 26.39 °C to 31.06 °C) and heat-exchange rate (from 1326.75 kW to 1705.50 kW). At a constant operation time (e.g., 120 h), a 0.005 °C/m rise in geothermal gradient leads to an approximate 2.33 °C temperature increase and 189 kW boost in heat-exchange capacity, indicating a nearly proportional improvement. With a fixed geothermal gradient (e.g., 0.035 °C/m), outlet temperature and heat-exchange capacity gradually decline over time, but the rate of decline weakens (from 11.17% to 2.07%), showing a strong tendency to stabilize. Given regional geological differences and varying groundwater hydrogeological conditions, a thorough geological assessment is essential before activating a geothermal well to ensure efficient resource utilization.

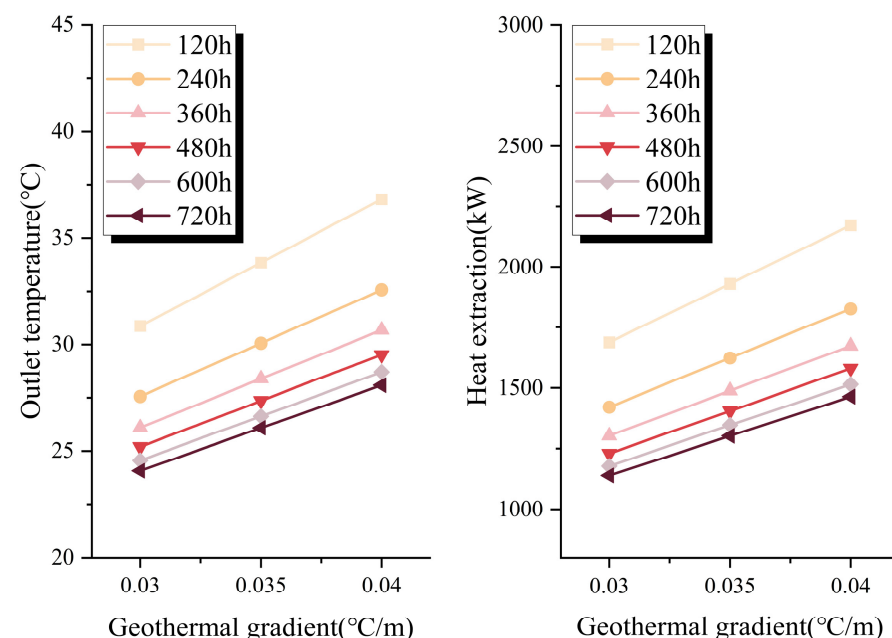


Figure 11. Effects of geothermal gradient on the outlet temperature and heat exchange.

4.4. Effects of Flow Rate

Variations at the flow rate exert a direct influence on the heat-transfer behavior of the system. As illustrated in Figure 12, when the flow rate increases from 60 m³/h to 69.84 m³/h and further to 80 m³/h, the average outlet water temperature declines from 25.21 °C to 24.99 °C and then to 24.64 °C, whereas the corresponding average heat exchange increases from 1058.27 kW to 1213.32 kW and finally to 1357.76 kW.

The results reveal an inverse relationship between fluid flow rate and outlet temperature, while system heat exchange increases with flow rate. Both parameters initially change rapidly but gradually stabilize, approaching equilibrium. Early flow rate increases significantly affect thermal performance but further increases yield, diminishing returns due to reduced fluid residence time and limiting thermal interaction with the subsurface. Therefore, optimizing operations requires selecting a flow rate that balances efficient heat extraction with outlet temperature needs.

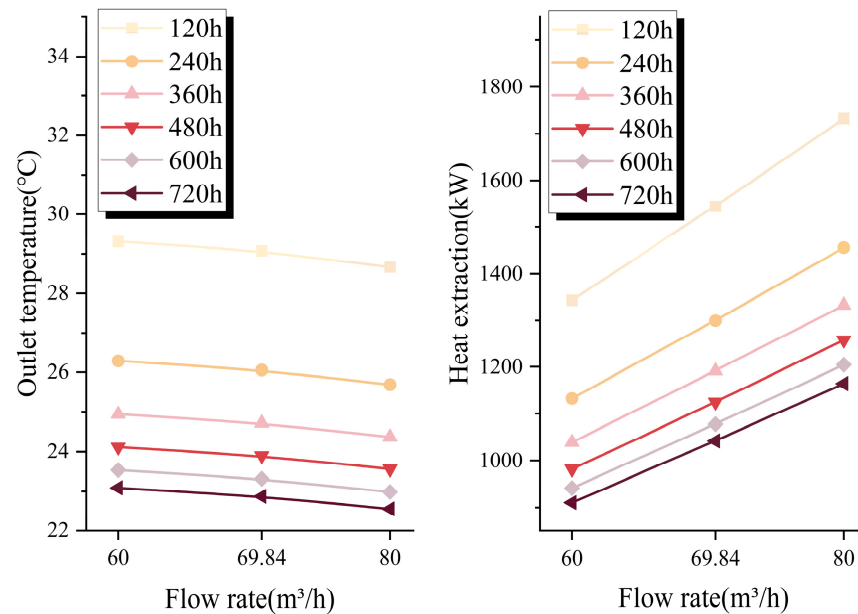


Figure 12. Effects of flow rate on the outlet temperature and heat exchange.

4.5. Effects of Insulation Layer

4.5.1. Influencing Trends

The production well section in deep UBHE systems features a distinct heat-exchange mechanism, with potential reverse heat exchange and heat loss in the outlet section, while the inlet section still allows for heat extraction. To assess the rationality of insulation layer application, this section simulates the impact of insulation layer lengths (100–300 m, a relatively short range) on system heat-exchange efficiency, as shown in Figure 13.

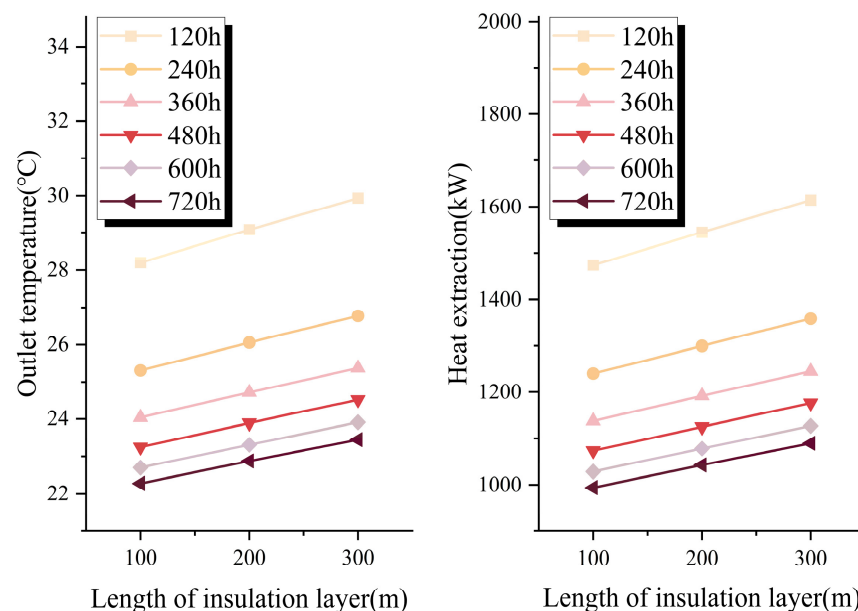


Figure 13. Effects of the insulation layer on the outlet temperature and heat exchange.

It is concluded that for every 100 m increase in insulation layer length, the system's average outlet water temperature rises by 0.68 °C ($\approx 2.7\%$) and average heat-exchange efficiency increases by 55.28 kW ($\approx 4.6\%$), with nearly proportional improvements. This suggests that even relatively small increases in insulation length significantly enhance system heat-exchange efficiency.

4.5.2. Maximum Laying Range

Given the clear influence trend and well section length constraints, the next step is to determine the maximum insulation layer length. Sensitivity and uncertainty: The main conclusions are robust to parameter uncertainty: Outlet temperature and heat exchange are most sensitive to seepage velocity and geothermal gradient; a $\pm 10\%$ change in k_{equ} or geothermal gradient typically leads to a few percent change in mean outlet temperature. The optimal insulation length (1900 m for 2500 m well depth) is insensitive to small changes in flow rate or inlet temperature within the ranges tested. A simulation is first conducted for a production well depth of 2500 m, as shown in Figure 14.

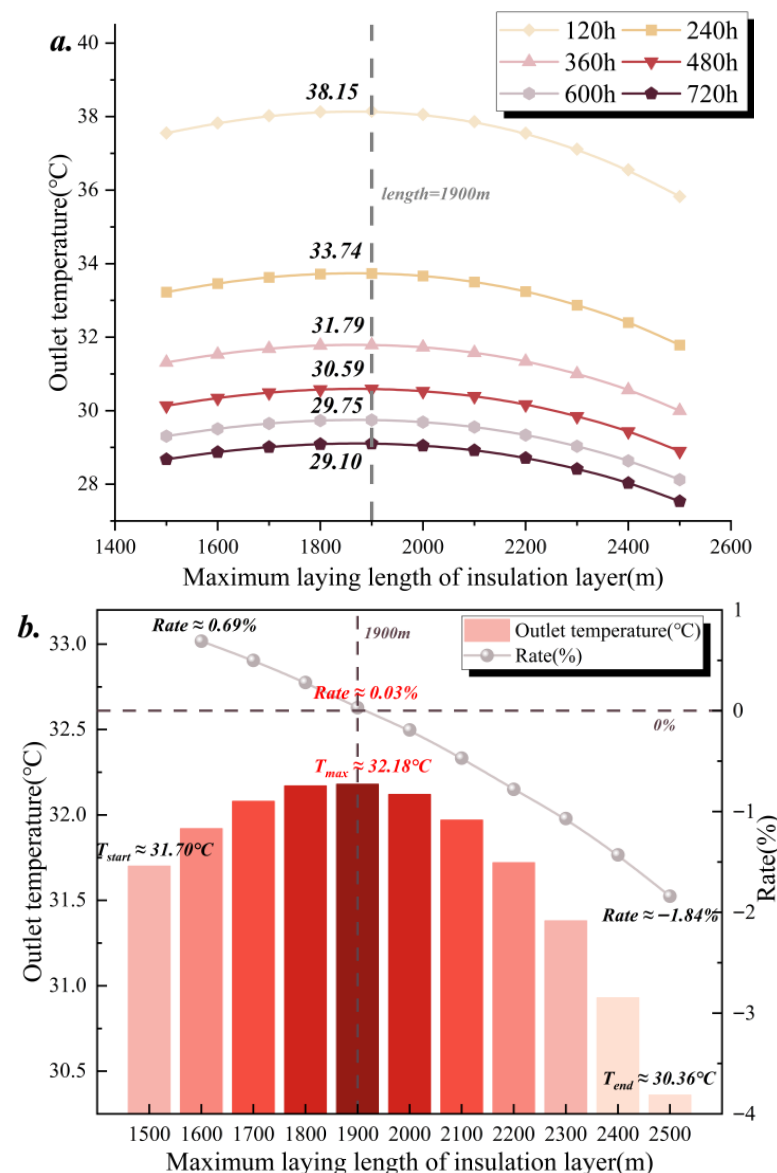


Figure 14. (a) Different running times. (b) Average temperature at each length.

As shown in Figure 14a, outlet water temperature trends remain consistent across operation cycles but no longer change proportionally. The maximum outlet temperature (29.10°C at 720 h) occurs when the insulation layer reaches 1900 m.

Figure 14b reveals that between 1500–1900 m, average temperature rises slightly (31.7°C to 32.18°C), but the growth rate declines sharply (0.69% to 0.03%), indicating limited efficiency gains without heat loss. Beyond 1900 m, temperatures drop (32.12°C

to 30.36 °C, a 1.84% decrease), showing that heat extraction persists but becomes less effective. Therefore, for the production wells in this study, the optimal insulation length is approximately 1900 m, which also corresponds to the node where the fluid begins to undergo reverse heat exchange. This is consistent with the fluid temperature distribution analysis results in Section 3.3. Relationship between production well depth and insulation layer length: For a given geometry and flow condition, the depth at which reverse heat exchange starts is determined by the energy balance along the production well; this depth is close to the optimal maximum insulation length. Under the conditions of this study (production well depth 2500 m), the maximum effective insulation length is 1900 m. In general, a deeper production well allows a longer insulation layer before heat extraction is impaired; the relationship is not linear because it depends on geothermal gradient, flow rate, and inlet temperature. A correlation between production well depth and maximum insulation length under the same other parameters is given in the revised discussion (see Table/Figure in Section 4.5.2). Validation in this study is limited to comparison with the reference [37]; future work will include validation against experimental or field data when available.

5. Conclusions

This study established a segmented FLS model considering porous media based on the virtual heat source method. The model's advantages were verified by comparing it with existing research, and simulation analyses were conducted on the key factors influencing the thermal performance of deep UBHE systems.

The conclusions are as follows:

- (1) Under the premise that the temperature change trends of the two models are consistent, the average outlet water temperature of this model increases by 1.31 °C, and the average error rate between the models is 5.31%, which is 40.87 percentage points lower than the existing research results, verifying the high accuracy of this model;
- (2) Treating rock and soil as porous media and introducing equivalent thermal conductivity can significantly enhance the simulation accuracy of deep UBHE systems. To make the system operate more efficiently, it is essential to conduct in-depth research on the hydrogeological conditions of the selected site in advance in practical engineering;
- (3) Analysis shows that different factors have varying degrees of influence on the thermal performance of the system: The outlet temperature is most affected by the equivalent seepage velocity, followed by the geothermal gradient, the laying length, and the flow rate; in terms of heat exchange, the equivalent seepage velocity has the greatest impact, followed by the flow rate, with the geothermal gradient and laying length having relatively smaller influences. During operation, parameter adjustments should be made in combination with actual conditions—focusing on higher temperatures, greater heat exchange, or a balance between the two;
- (4) When the insulation layer is placed near the outlet, every 100 m increase raises the average outlet water temperature by 0.68 °C ($\approx 2.7\%$) and boosts heat exchange by 55.28 kW ($\approx 4.6\%$), showing a proportional and significant effect. Near the pipe bottom, the maximum effective insulation length is 1900 m, beyond which heat extraction is impaired. This aligns with the depth at which reverse heat exchange occurs in the production wells. Across the optimal insulation length threshold, fluid temperature changes are asymmetric, with a sharper decline beyond the threshold than the rise below it. In addition, economic and other factors must be balanced to optimize system performance.

6. Patents

- (1) Patent Title: Dynamic assessment method for deep geothermal energy
- (2) Patent Number: ZL 2024 1 0694896.1

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Conflicts of Interest: The authors have no conflicts to disclose.

Abbreviations

Re	Reynolds number
Nu	Nusselt number
Pr	Prandtl number
BHE	borehole heat exchangers
UBHE	U-shaped borehole heat exchangers
CBHE	coaxial borehole heat exchangers
Variables	
ρ	density, kg/m ³
c	specific heat capacity, J/(kg·°C)
V	flow rate, m ³ /s
R	system thermal resistance, °C/W
T	simulated temperature, °C
l	length of segments, m
H	length of the pipe, m
α	thermal diffusivity, m ² /s
μ	molecular viscosity, pa·s
r	radius, m
x	horizontal axis, m
z	vertical axis, m
k	thermal conductivity, W/(m·°C)
t	running time, h
h	convective coefficient, W/(m ² ·°C)
Q	heat-exchange capacity, kW
q_l	heat flux density, W/m
k_{geo}	geothermal gradient, °C/m
v	flow velocity, m/s
s	coordinates of mobile point source, m
Subscripts	
1	injection well
2	horizontal well
3	production well
in	inlet

out	outlet
b	borehole wall
p	pipe
i	inner wall
o	outer wall
I	insulation layer
equ	equivalent parameters
f	fluid
s	solid

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