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Thermal Performance Analysis and Multi-Factor Optimization of Middle–Deep Coaxial Borehole Heat Exchanger System for Low-Carbon Building Heating

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Abstract: Ground-source heat pumps with deep borehole heat exchangers can fully utilize deep geothermal energy, effectively reducing the consumption of non-renewable energy for building air conditioning and achieving energy conservation and emissions reduction goals. However, the middle–deep coaxial borehole heat exchange (MDBHE) development is insufficient, and there is currently a lack of definitive guidelines for system optimal design and operation. This paper firstly establishes an effective and efficient system model and examines nine important parameters related to the design and operation of the MDBHE using a single-factor analysis. Thereafter, we compare and analyze the impact of different parameters through an orthogonal experimentation method. The findings reveal that the three most significant factors are borehole depth, inlet temperature, and mass flow rate, in descending order of importance. In addition, in terms of operation mode, this paper makes a comparative analysis of the operation of the MDBHE in variable flow mode and constant flow mode. The results showed that the average energy consumption of the pump in the variable flow mode decreased by 9.6%, and the surrounding ground temperature recovered at a faster rate.

Keywords: geothermal energy; ground-source heat pump; middle–deep coaxial borehole heat exchanger; optimization analysis



Citation: Liang, M.; Tu, J.; Zeng, L.; Zhang, Z.; Cheng, N.; Luo, Y. Thermal Performance Analysis and Multi-Factor Optimization of Middle–Deep Coaxial Borehole Heat Exchanger System for Low-Carbon Building Heating. *Sustainability* **2023**, *15*, 15215. <https://doi.org/10.3390/su152115215>

Academic Editors: Cancan Zhang, Bo Xu and Meibo Xing

Received: 11 September 2023

Revised: 15 October 2023

Accepted: 23 October 2023

Published: 24 October 2023



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1. Introduction

With the aggravation of the current global energy shortage, the development and utilization of renewable energy have become important tasks for all countries. As a major energy-consuming country, China is currently facing very serious energy problems. In September 2020, President Xi Jinping proposed China’s goal of “peak carbon by 2030 and carbon neutrality by 2060”. Carbon neutrality means that the anthropogenic removal of carbon dioxide offsets anthropogenic emissions over a specified period of time [1], which corresponds to the reduction in decarbonization in the production of electricity and in the heating process. The proportion of whole-life energy consumption and carbon emissions in the total energy consumption of buildings remains high [2]. It is estimated that the annual heating energy consumption in the northern region of China is about 300 million tce, which is about 30% of the national building energy consumption [3], and while consuming a large amount of coal, it also emits a large amount of pollutants. Therefore, the adoption of renewable energy is an important initiative to realize clean heating and promote the transformation of energy structure. A variety of renewable energy heating technologies can now be used for building heating, and China’s solar energy, geothermal energy, biomass energy, and other clean heating technologies are becoming increasingly mature, and many of them have entered the stage of large-scale application, among which geothermal energy heating has enormous development potential and application prospects.

The internal temperature of the earth's crust is as high as 4500 °C [4], and the earth's crust continuously dissipates heat to the surface under the effect of a temperature difference. The part of geothermal energy that can be extracted by human beings is called geothermal resources. The geothermal energy that can be utilized by ground-source heat pumps has a very low specific gravity in relation to the enormous heat energy stored within the earth's crust and is sufficient to recover within a certain period of time after a heat exchange. Moreover, the source of heat is stable, thus making geothermal energy a renewable energy source.

The research methods of middle-deep casing buried tube heat exchangers are divided into simulation calculation and experimental testing, and the simulation calculation includes an analytical method and numerical method. Since the soil depth of medium and deep buried pipe heating usually reaches 1500~3000 m, the ground temperature gradient along the depth direction cannot be ignored [5]. In this regard, Bier established a heat transfer model of a concentric tube heat exchanger considering the ground temperature gradient and obtained an analytical solution by Laplace change [6–8]. Luo et al. obtained an analytical solution considering the geothermal gradient by separating the influence of the borehole heat exchanger and the geothermal gradient [9]. Pan et al. established an analytical model of water flow heat transfer inside the borehole using the temperature distribution on the borehole wall [10]. Due to the simple calculation, the above analytical model can quickly calculate and analyze the heat transfer situation of buried pipes. In addition, the existing analytical model of the shallow borehole heat exchanger usually assumes a uniform thermal physical property of underground soil and a uniform heat flux per unit depth, which is usually quite different from the actual situation. Compared with the analytical solution, the numerical model has higher flexibility, and the simulation of the underground heat transfer process can be more practical, but the disadvantage is that the calculation workload is usually very large. The existing numerical models of the heat transfer of buried tube heat exchangers mainly use the finite element method, finite volume method, and finite difference method. The medium- and deep-buried tube heat exchanger models based on the finite element method and finite volume method have a large number of meshes and a long calculation time [11–13], which makes it difficult to simulate the whole life cycle of the medium- and deep-buried tube heat exchangers. Due to the geometric characteristics of coaxial bushing, the number of meshes in the finite difference model under cylindrical coordinates is significantly reduced compared with the finite element and finite volume models [14–16], so the workload can be greatly reduced, which is convenient for the simulation analysis and system optimization design of the whole life cycle of the medium- and deep-buried tube heat exchangers.

The heat transfer capacity of the middle-deep-buried pipe heat exchanger is closely related to drilling depth and operation mode [17–19]. The existing short-term experimental data of several practical engineering sites show that under continuous operation conditions, the heat extraction range of the heat exchanger is about 80~140 W/m [16]. When the average heating load per unit length is 100 W/m, the medium- and deep-buried tube heat exchangers can run smoothly for a long time, but if it is increased to 150 W/m, they cannot achieve continuous heating for a long time [20]. With an increase in drilling depth, the heat extraction capacity of a single well increases significantly [21,22], that is, the heat extraction per extension meter increases. By using numerical methods, Cai found that rock temperature decreased during intermittent operation for 10 years, and the proportion of rock temperature decrease increased with the increase in drilling depth [11]. Holmberg conducted a parameter performance study on the depth, flow rate, and rock and soil thermal properties of buried tube heat exchangers within the range of 200 m to 500 m, and the results show that with an increase in depth, the system performance is significantly improved and the heat load borne by the buried tube is significantly increased [14]. Li Siqi constructed a numerical model of deep well heat transfer, studied the coupling effect of well depth and other parameters on deep well heat transfer, obtained the influence law of each parameter on deep well heat transfer under different well depth conditions,

carried out parameter sensitivity analysis, and found that well depth plays a decisive role in outlet temperature. When the well depth is small, the influences of geotechnical thermal conductivity, outer pipe diameter, and flow rate are greater; when the well depth is large, the influence of inner pipe insulation is significant [12]. It can be seen that the drilling depth has a great influence on the heat transfer performance of the medium- and deep-buried tube heat exchangers.

Although the parametric analysis on the MDBHE has been investigated by many studies, this work provided an advanced work on mainly three aspects. (1) This study offers a more complete investigation of the influence of design and operational factors on the system's thermal performance, with the special newly designed parameters s_0 , s_2 , and s_4 to characterize the diameter ratio among the inner tube, annular tube, and borehole. (2) This study conducted a multiple factor optimization based on an orthogonal experiment, which included both the design parameters (borehole depth, s_0 , s_2 , s_4), operational parameters (flow rate and inlet temperature), and thermal properties of the tube/grout materials. This investigation is different from other pure design optimization or material selection methods in previous studies in the literature. (3) This study provides a quantitative verification of the benefit of variable flow rate control on system performance enhancement and energy savings. The results in this study demonstrate that by using a feasible variable flow rate mode, energy consumption can be reduced, and we can also reduce the variation range of the ground temperature.

In order to optimize the performance of ground-source heat pumps (GSHPs), the heat transfer model of the MDBHE is established by means of a semi-analytical solution (Section 2). The design and operation optimization of the MDBHE are studied from three aspects: single factor analysis (Section 3.1), multi-factor analysis (Section 3.2), and operation mode (Section 3.3).

2. Mathematical Model

2.1. Model Strategy

The research on the heat transfer model of the MDBHE is mainly divided into two categories: the numerical method and the analytical method. The numerical method discretizes the solution region and solves it with the help of the computing power of the computer. This method is relatively accurate and can be used for model verification. However, on the one hand, there is a huge difference between the depth and diameter scale of the buried tube heat exchanger; on the other hand, the actual operation life and the characteristic time measurement of the load and flow during the operation process also have a large span. Therefore, the simulation calculation takes a long time, and it also needs some simplification in practical applications. The analytical method starts from the basic heat transfer process and deduces the solution via a mathematical method, which can shorten the solving time and expand the application scope to a certain extent. However, the depth of the MDBHE is large, so that some assumptions in the simulation of a shallow-buried tube heat exchanger are not fully applicable. If the simplification range is too large, it is easy to have poor agreement with the actual operation data, so it is more complicated to seek the analytical solution of the MDBHE.

The research object of this paper is the MDBHE, which is mainly used for heating buildings, so the fluid operation mode is that the fluid flows in from the outer tube and flows out from the inner tube. In this paper, the heat transfer of the buried tube heat exchanger is divided into two parts: the convection heat transfer of the fluid inside the tube and the heat conduction outside the tube. At the interface of the two parts, the corresponding temperature and heat flux are equal. Combined with the actual situation, the model adopts some assumptions to simplify the problem, as follows:

- (a) The thermal physical parameters of the soil and tube materials are constant and do not change with temperature.
- (b) The ground surface temperature is a constant.
- (c) Groundwater seepage is not considered.

- (d) The energy and mass flow balance are considered in the water flow heat transfer inside the coaxial tube, and the conservation of momentum is not included in the modeling.
- (e) A linear geothermal gradient is assumed for the ground.

2.2. Model Detail

The convective heat transfer of fluid in tubes is mainly calculated by the finite difference method and energy equation. Equations (1) and (2) can be obtained by using the energy equation [23], where C_1 and C_2 are, respectively, the heat capacity per unit length of the outer tube and the inner tube, and the calculation method is shown in Equations (3) and (4). R_1 and R_2 are the thermal resistance between the outer tube fluid and borehole wall and the thermal resistance between the inner and outer tube fluid, respectively. The calculation method is shown in Equations (5) and (6).

$$C_1 \frac{\partial t_{f1}}{\partial \tau} = \frac{t_{f2} - t_{f1}}{R_2} + \frac{t_b - t_{f1}}{R_1} - Mc_f \frac{\partial t_{f1}}{\partial z} \quad (1)$$

$$C_2 \frac{\partial t_{f2}}{\partial \tau} = \frac{t_{f1} - t_{f2}}{R_2} + Mc_f \frac{\partial t_{f2}}{\partial z} \quad (2)$$

$$C_1 = \frac{\pi}{4} (d_{1i}^2 - d_{2o}^2) \rho_f c_f + \frac{\pi}{4} (d_{1o}^2 - d_{1i}^2) \rho_1 c_1 + \frac{\pi}{4} (d_b^2 - d_{1o}^2) \rho_g c_g \quad (3)$$

$$C_2 = \frac{\pi}{4} d_{2i}^2 \rho_f c_f + \frac{\pi}{4} (d_{2o}^2 - d_{2i}^2) \rho_2 c_2 \quad (4)$$

$$R_1 = \frac{1}{\pi d_{1i} h_1} + \frac{1}{2\pi k_{p1}} \ln \frac{d_{1o}}{d_{1i}} + \frac{1}{2\pi k_g} \ln \frac{d_b}{d_{1o}} \quad (5)$$

$$R_2 = \frac{1}{\pi d_{2i} h_2} + \frac{1}{2\pi k_{p2}} \ln \frac{d_{2o}}{d_{2i}} + \frac{1}{\pi d_{2o} h_1} \quad (6)$$

Here, t_b , t_{f1} , and t_{f2} are the temperatures of the borehole wall, outer tube fluid, and inner tube fluid, respectively; M is the mass flow rate of the fluid in the tube; c_f , c_1 , c_2 , and c_g are the specific heat capacities of the fluid, outer tube, inner tube, and grout, respectively. ρ_f , ρ_1 , ρ_2 , and ρ_g are the densities of the fluid, outer tube, inner tube, and grout, respectively. k_{p1} , k_{p2} , and k_g are the thermal conductivity of the outer tube, inner tube, and grouting, respectively. h_1 and h_2 are the convection heat transfer coefficients in the annular channel and inner tube, respectively. The calculation process for the heat transfer coefficient is simplified according to the actual project and can be obtained according to Equations (7)~(9), respectively [14]. d_b , d_{1o} , d_{1i} , d_{2o} , and d_{2i} are the borehole diameter, the outer and inner diameter of the outer tube, and the outer and inner diameter of the inner tube, respectively.

$$h = Nu \frac{k}{D} \quad (7)$$

$$Nu = \frac{(f/8)(Re - 1000)Pr}{1 + 12.7 \left(\frac{f}{8}\right)^{0.5} (Pr^{\frac{2}{3}} - 1)} \quad (8)$$

$$f = (0.79 \ln Re - 1.64)^{-2} \quad (9)$$

Then, Equations (1) and (2) are discretized, respectively, and Equations (10) and (11) are obtained. Here, the superscript j refers to the current time node, and the superscript $j + 1$ refers to the next time node. In addition, there are two boundary conditions: a constant inlet temperature ($T_{f1,1} = T_{in}$) and an equal fluid temperature at the lowest point of the inner and outer tubes ($T_{f1,x} = T_{f2,x}$). From this, the fluid temperature after different times can be solved.

$$T_{f1,i}^{j+1} \left[\frac{C_1}{\Delta\tau} + \frac{1}{R_2} + \frac{1}{R_1} - \frac{MC_f}{\Delta z} \right] + T_{f1,i+1}^{j+1} \left[\frac{MC_f}{\Delta z} \right] + T_{f2,i}^{j+1} \left[-\frac{1}{R_2} \right] = T_{f1,i}^j \left[\frac{C_1}{\Delta\tau} \right] + T_{b,i}^j \left[\frac{1}{R_1} \right] \quad (10)$$

$$T_{f1,i}^{j+1} \left[-\frac{1}{R_2} \right] + T_{f2,i}^{j+1} \left[\frac{C_2}{\Delta\tau} + \frac{1}{R_2} + \frac{MC_f}{\Delta z} \right] + T_{f2,i+1}^{j+1} \left[-\frac{MC_f}{\Delta z} \right] = T_{f2,i}^j \left[\frac{C_2}{\Delta\tau} \right] \quad (11)$$

For the heat conduction outside the tube, the segmented finite line heat source model is used. The temperature at each point can be seen as a superposition of the initial temperature and the excess temperature caused by the heat source. Through the segmented treatment of the heat source, the excess temperature of each position point can be obtained, as shown in Equation (12). In the subsequent calculation, in order to avoid too much repeated calculation, the terms except heat flow in Equation (12) are rewritten into the corresponding coefficient matrix form, as shown in Equation (13). The value in the coefficient matrix has nothing to do with the value of heat flow, and the required coefficient matrix can be prepared in advance for repeated calculation.

$$\theta(r, z, \tau) = \sum_{j=1}^N \sum_{i=1}^n q \frac{\left(i, \frac{\tau}{\Delta\tau} - j \right) - q \left(i, \frac{\tau}{\Delta\tau} - j - 1 \right)}{4\pi k} \int_{(i-1) \times z_0}^{i \times z_0} \left(\frac{\operatorname{erfc} \left(\frac{\sqrt{r^2 + (z-h)^2}}{2\sqrt{a\Delta\tau j}} \right)}{\sqrt{r^2 + (z-h)^2}} - \frac{\operatorname{erfc} \left(\frac{\sqrt{r^2 + (z+h)^2}}{2\sqrt{a\Delta\tau j}} \right)}{\sqrt{r^2 + (z+h)^2}} \right) dh \quad (12)$$

$$\left\{ \begin{array}{l} \begin{bmatrix} a_{11} & \cdots & a_{1j} \\ \vdots & \ddots & \vdots \\ a_{i1} & \cdots & a_{ij} \end{bmatrix} \\ a_{ij} = \sum_{j=1}^N \sum_{i=1}^n \frac{1}{4\pi k} \int_{(i-1) \times z_0}^{i \times z_0} \left(\frac{\operatorname{erfc} \left(\frac{\sqrt{r^2 + (z-h)^2}}{2\sqrt{a\Delta\tau j}} \right)}{\sqrt{r^2 + (z-h)^2}} - \frac{\operatorname{erfc} \left(\frac{\sqrt{r^2 + (z+h)^2}}{2\sqrt{a\Delta\tau j}} \right)}{\sqrt{r^2 + (z+h)^2}} \right) dh \end{array} \right. \quad (13)$$

Here, $\theta(r, z, \tau)$ is the excess temperature after a time of τ s at a radius of r m and a depth of z m; q is the heat flow; $\Delta\tau$ is the time step; k is the thermal conductivity; and a is the thermal diffusivity.

In addition, in the system simulation, if the given input is the heating load, it can be converted to the corresponding inlet temperature by Equation (14).

$$Q = c_f M \Delta T \quad (14)$$

Here, Q is the heating load; ΔT is the temperature difference.

2.3. Model Validation

In models involving discrete and unsteady heat transfer simulations, both the time step and the number of nodes affect the computational speed and accuracy of the simulation. In order to ensure the accuracy of the simulation results, the time step and radial step are

independently verified. As shown in Figure 1, the time step $\Delta t = 3600$ s and the radial step $\Delta z = 20$ m selected in this paper meet the calculation accuracy requirements.

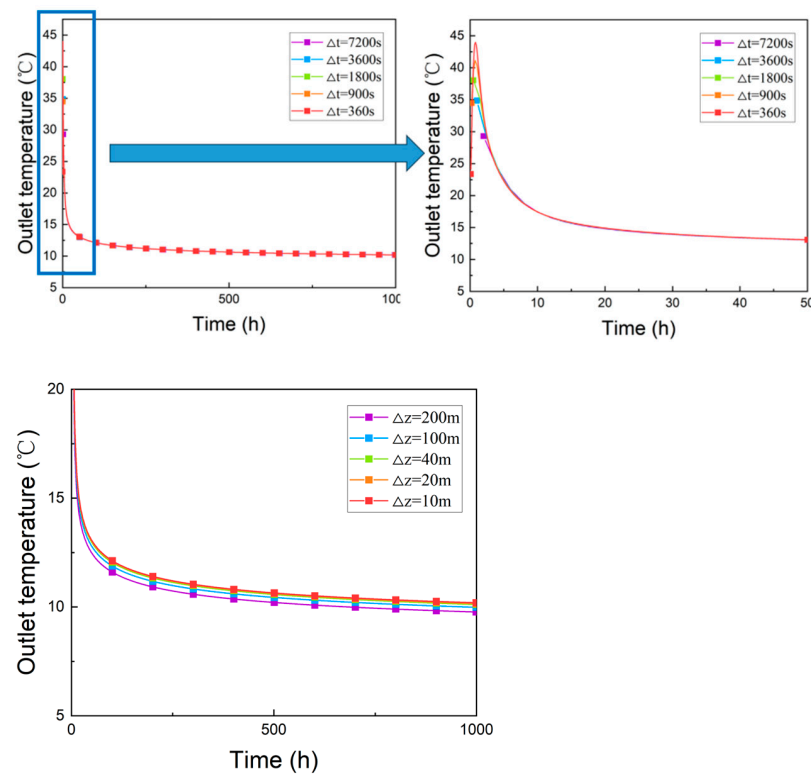


Figure 1. Time step and radial step independence test for the model validity.

After the heat transfer model of the buried tube heat exchanger is established, it needs to be compared and verified with the actual operation data to determine the reliability. Therefore, the running data of a residential project in Chang'an District of Xi'an City is selected and compared with the above model [24]. The simulation results are shown in Figure 2, and the average outlet temperature error is 4.4%, and the mean absolute deviation between simulation and experimental data is 0.92 °C, which is within the acceptable range.

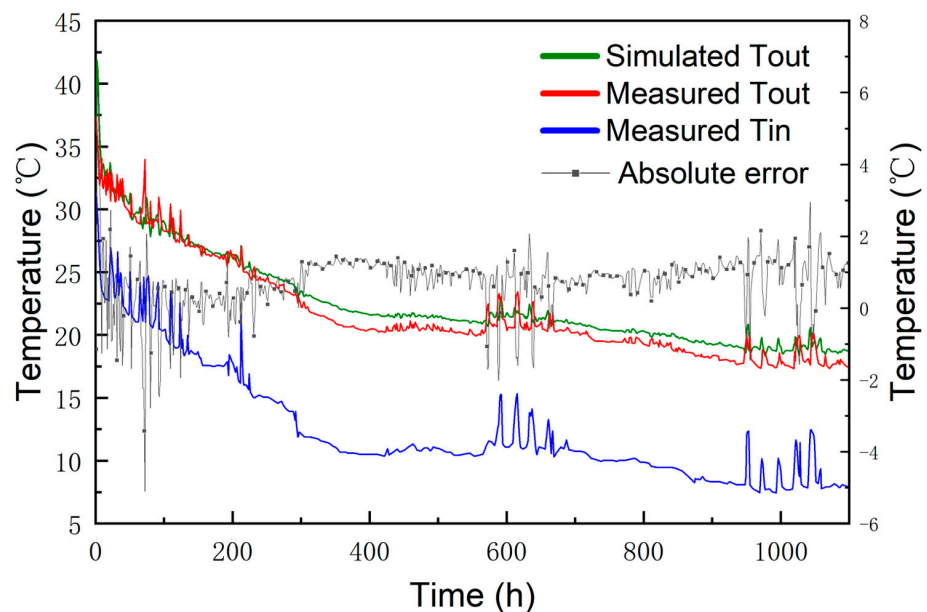


Figure 2. Simulated and measured values of outlet temperature.

3. Results and Analysis

3.1. Single-Factor Analysis of MDBHE

The performance of the MDBHE system is affected by many factors, such as the buried tube depth, operation strategy, and so on. The key parameters should be studied and discussed in the optimization design. Ground related parameters also have an impact on the heat exchange capacity of the buried tube heat exchanger. The higher the temperature of the ground in contact, the better the heat extraction of the buried tube heat exchanger. However, in practical engineering, the selection space of ground-related thermal property parameters is generally limited. Therefore, in this paper, the borehole depth, mass flow rate, inlet temperature, buried tube radial structure parameters, and thermal conductivity of the selected material are selected as the influencing factors for the analysis and research. The default parameters are shown in Table 1, and the evaluation indexes are the heat extraction per unit meter (W/m) and outlet temperature (°C).

Table 1. Calculation parameters.

Parameter	Value	Parameter	Value
Borehole depth, H	2000 m	Thermal conductivity of outer tube, k_{p1}	40 W/(m·K)
Borehole diameter, d_b	0.25 m	Volumetric specific heat capacity of outer tube, $(\rho c)_{p1}$	3800 kJ/m ³ ·K
Outer diameter of outer tube, d_{1o}	0.19 m	Thermal conductivity of inner tube, k_{p2}	0.4 W/(m·K)
Inner diameter of outer tube, d_{1i}	0.17 m	Volumetric specific heat capacity of inner tube, $(\rho c)_{p2}$	2200 kJ/m ³ ·K
Outer diameter of inner tube, d_{2o}	0.12 m	Mass flow rate, M	9 kg/s
Inner diameter of inner tube, d_{2i}	0.10 m	Ground surface temperature	10 °C
Thermal conductivity of subsurface, k_s	2 W/(m·K)	Geothermal temperature gradient	3 °C/100 m
Thermal diffusivity of subsurface, a_s	0.73×10^{-6} m ² /s	Heating period	120 d
Thermal conductivity of grout, k_g	1.5 W/(m·K)	Inlet temperature	15 °C
Volumetric specific heat capacity of grout, $(\rho c)_g$	2500 kJ/m ³ ·K		

3.1.1. Borehole Depth

The MDBHE is developed on the basis of a shallow-buried tube heat exchanger, so the buried tube depth is an important design parameter for it. Since 120 days is usually the length of a heating season, all the results obtained in the following sections are based on this simulation length. It should be noted that the whole study is mainly focused on thermal performance, with few concerns about other factors. As shown in Figure 3, with an increase in the depth of the buried tube, the heat extraction per unit meter and the outlet temperature gradually increase, and the increase is basically linear. Because the deeper the geological layer, the higher the temperature the fluid can reach, the more heat can be extracted. The heat extraction per unit meter of the MDBHE with a buried tube depth of 2800 m is 111.8 W/m, which is 2.54 times that of the buried tube depth of 1200 m (44.1 W/m). In addition, the evaluation index selected in this paper is the heat extraction per unit meter. If the whole borehole is considered as a unit, the total heat extraction of the MDBHE with a buried tube depth of 2800 m will reach 5.91 times that of the buried tube depth of 1200 m. It can be seen that the borehole depth has a considerable influence on heat extraction. Increasing the borehole depth can improve heat extraction, outlet temperature, land area, etc. However, on the other hand, increasing the borehole depth will also lead to a sharp rise in borehole costs.

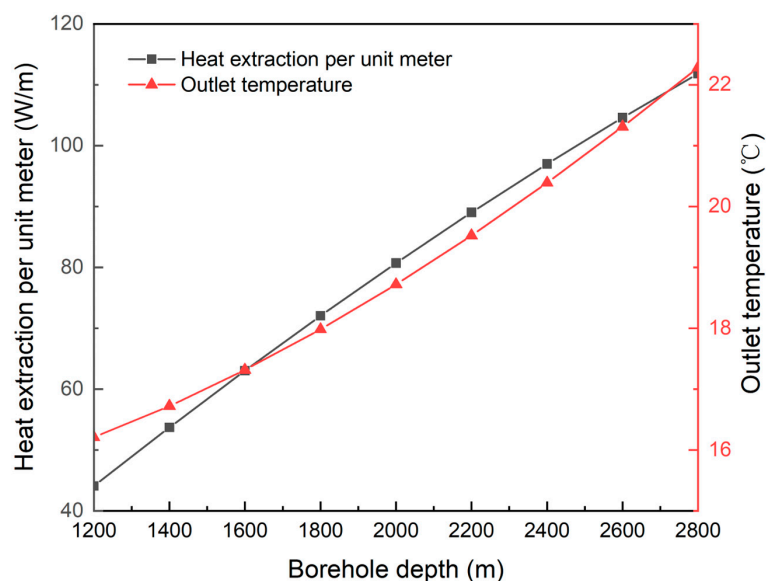


Figure 3. Change in heat extraction per unit meter and outlet temperature with borehole depth.

3.1.2. Mass Flow Rate

The mass flow rate is also a key factor affecting the performance of the MDBHE. As shown in Figure 4, the heat extraction per unit extension meter increases with the increase in the mass flow rate, while the outlet temperature decreases with the increase in mass flow rate. On the one hand, the larger the flow rate, the less the residence time of the fluid in the borehole and the less heat the fluid absorbs in the outer tube. However, at the same time, the heat dissipation in the inner tube is also reduced, and the increased fluid volume supplements the heat extraction. On the other hand, a higher flow rate will cause turbulence in the tube line, increasing heat extraction. Therefore, the heat extraction increases with the increase in the mass flow rate, which is an approximately logarithmic fitting, and the outlet temperature gradually decreases with the increase in the mass flow rate. When the fluid flow rate increased from 5 kg/s to 9 kg/s, the corresponding heat extraction per unit meter increased from 70.0 W/m to 80.7 W/m, with an increase rate of 15.3%. When the fluid flow rate increased from 9 kg/s to 13 kg/s, the corresponding heat extraction per unit meter increased from 80.7 W/m to 84.2 W/m, and the growth rate decreased to 4.3%.

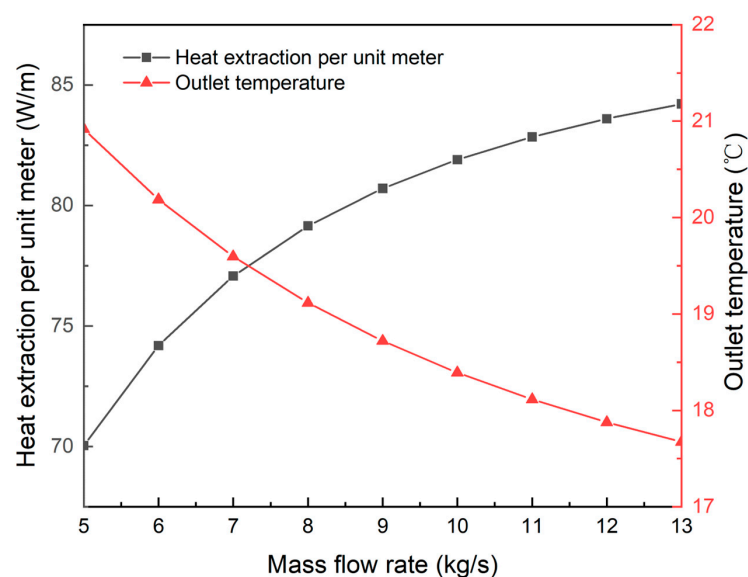


Figure 4. Change in heat extraction per unit meter and outlet temperature with mass flow rate.

3.1.3. Inlet Temperature

The performance of the MDBHE is also affected by the inlet temperature. As shown in Figure 5, the heat extraction per unit extension meter decreases with the increase in the inlet temperature, while the outlet temperature increases with the increase in the inlet temperature. As the inlet temperature increases, the temperature difference between the fluid and the outside world decreases, so less heat can be extracted from the ground. In addition, if the inlet temperature is higher, the upper fluid temperature of the MDBHE will be higher than the surrounding ground, so that heat is lost to the ground. Therefore, the generally lower inlet temperature can make the MDBHE obtain higher heat extraction. However, there are risks, such as freezing, if the inlet temperature is too low, and a much lower outlet temperature will induce degradation of the heat pump COP. The fluid at the inlet temperature warms up to the outlet temperature after heat exchange with the ground, so the outlet temperature increases with the inlet temperature.

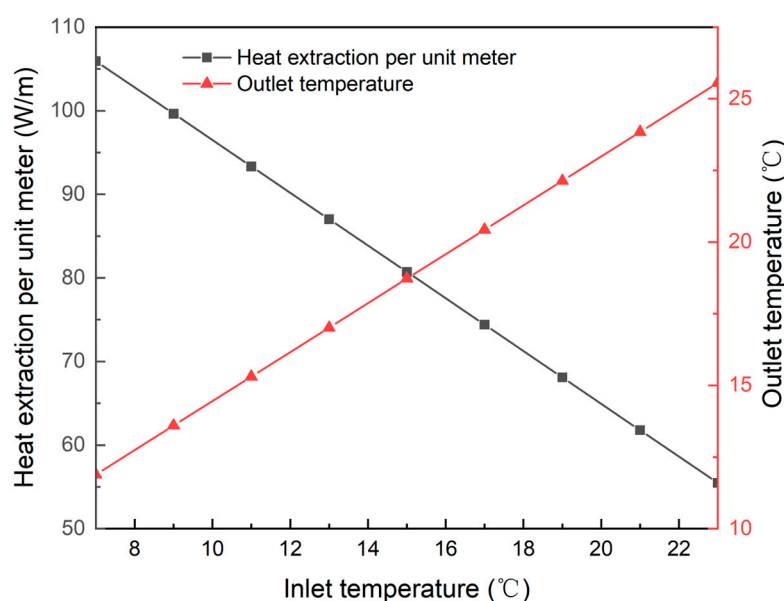


Figure 5. Change in heat extraction per unit meter and outlet temperature with inlet temperature.

3.1.4. Buried Tube Radial Structure Parameters

For the MDBHE, geometric parameters such as the borehole and tube diameter are also key factors to be considered in the design. In this paper, the buried tube radial structure parameters are divided into five parts: s_0 , s_1 , s_2 , s_3 , and s_4 , as shown in Figure 6. Among them, s_1 and s_3 are the tube thickness, which is not considered due to the small proportion and is set to a fixed value (10 mm); s_0 , s_2 and s_4 represent the inner tube size, outer tube ring size, and backfill ring size, respectively. It should be noted that the thickness of the inner tube is very important because it will influence the thermal short-circuit between the annular and center flows. However, the thickness of the center pipe usually follows some manufacturing codes, and in engineering practice, it is somehow a constant value.

(a) Buried tube radial structure parameters, s_0

The sizing of the tube will change the characteristic length in calculating the Reynolds number, which will directly determine the value of the Nusselt number and thus influence the convective heat transfer coefficients h_1 and h_2 . As shown in Figure 7, with the increase in the radial structure parameter s_0 of buried tube, the heat extraction per unit meter and the outlet temperature both increase gradually. The larger the diameter of the inner tube, the longer the fluid stays in the inner tube, and the more heat will be lost to the outer tube. However, while s_0 increases, the outer tube diameter and borehole diameter will still increase even if s_2 and s_4 remain unchanged. The increase in the borehole of the outer

tube will increase the heat exchange area between the fluid and the ground. This increase in heat extraction is greater than the decrease in heat extraction due to the direct increase in the diameter of the inner tube. Therefore, the heat extraction per unit meter and outlet temperature are still increasing overall.

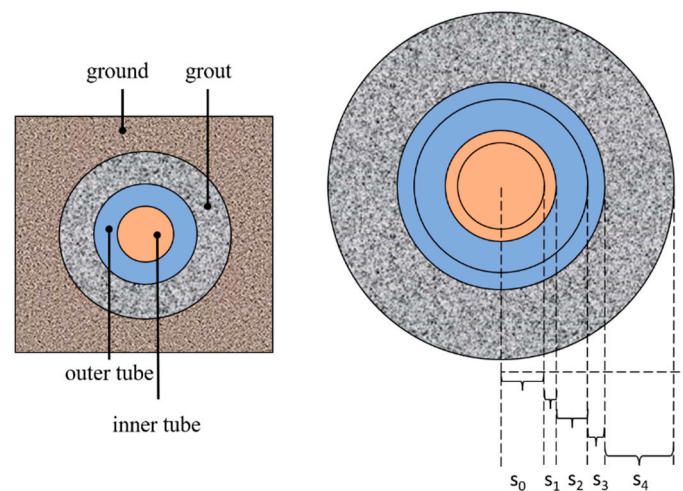


Figure 6. Schematic diagram of buried tube radial structure parameters.

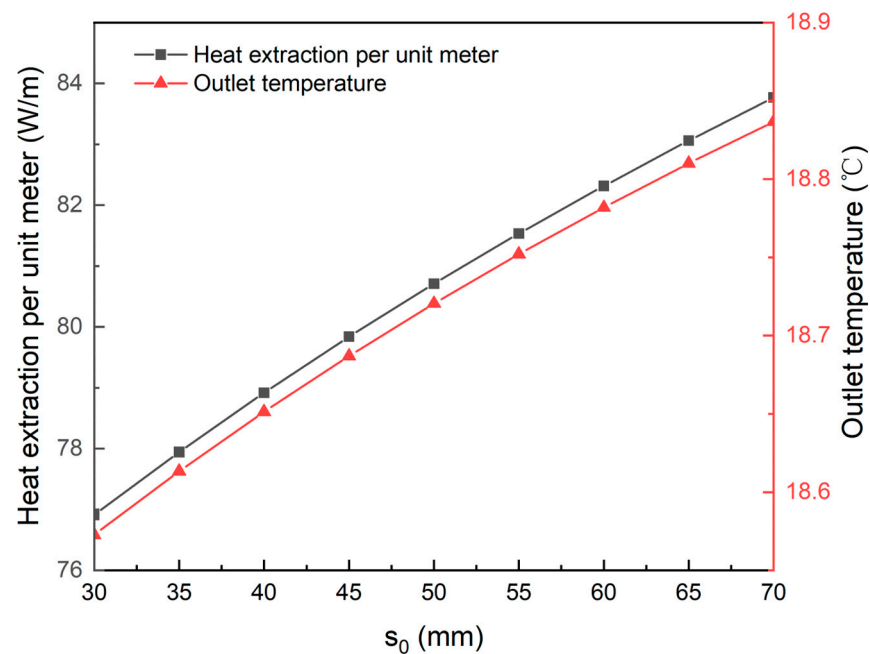


Figure 7. Change in heat extraction per unit meter and outlet temperature with s_0 .

(b) Buried tube radial structure parameters, s_2

As shown in Figure 8, with the increase in the radial structure parameter s_2 of the buried tube, the heat extraction per unit meter and the outlet temperature both increase gradually. Increasing the diameter of the outer tube can improve the heat recovery capacity because the heat exchange area between the fluid and the outside world is increased and the fluid residence time in the outer tube is longer. The annular region represented by the radial structure parameter s_2 of the buried tube is directly related to the diameter of the outer tube. The outlet temperature also has gradually increased because of the improvement in the heat exchange capacity of the heat exchanger.

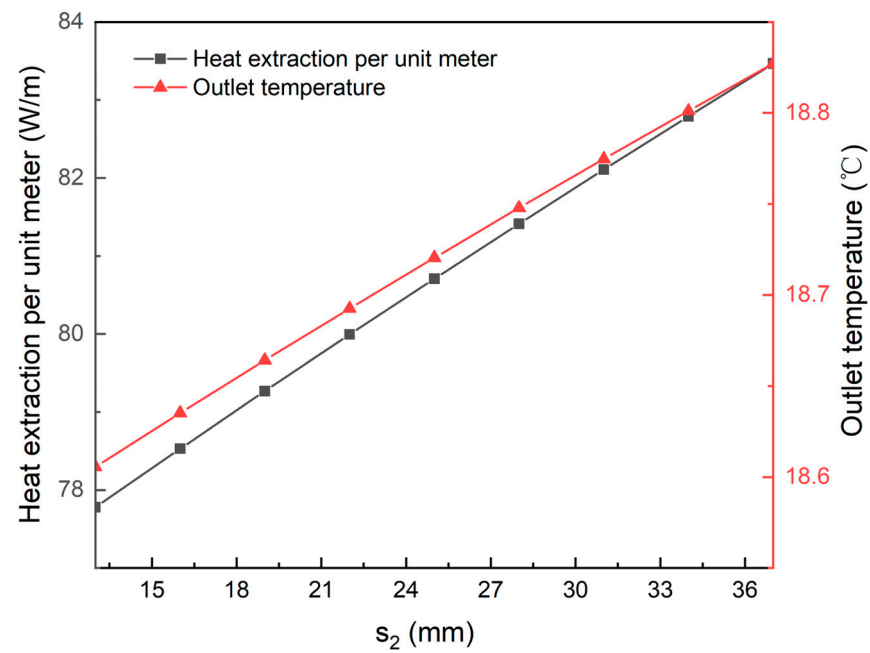


Figure 8. Change in heat extraction per unit meter and outlet temperature with s_2 .

(c) Buried tube radial structure parameters, s_4

As shown in Figure 9, with the increase in the radial structure parameter s_4 of buried tube, the heat extraction per unit meter and the outlet temperature both decrease gradually. The backfill material is located between the outer tube and the ground, so the thicker the backfill part, the greater the thermal resistance between the fluid and the ground. This results in a decrease in heat exchange between the fluid and the ground. The radial structure parameter s_4 of the buried tube represents the radial distance of the ring region of the backfill part. Therefore, the heat extraction per unit meter and the outlet temperature will decrease with an increase in s_4 .

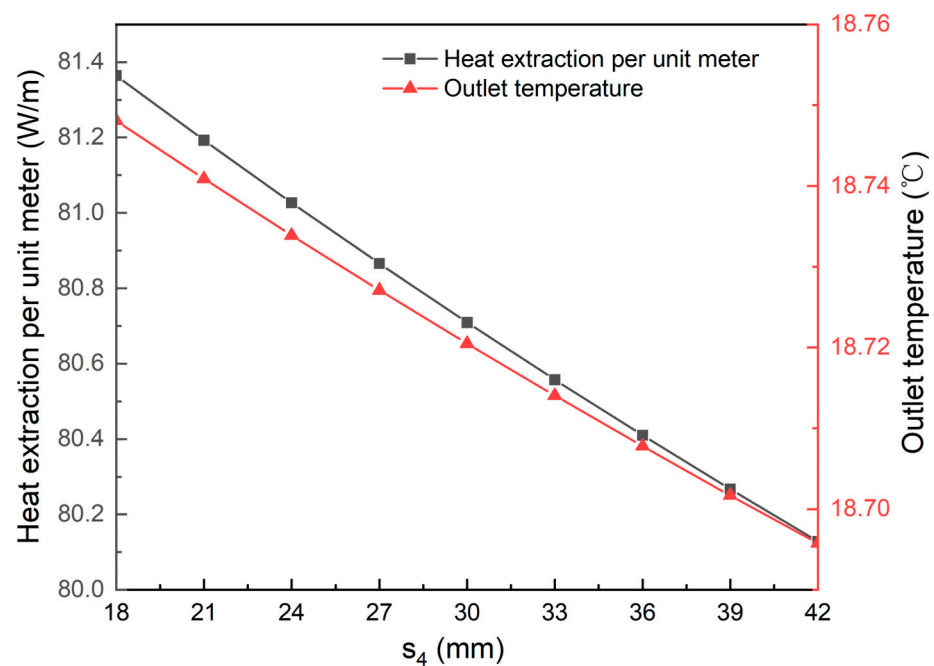


Figure 9. Change in heat extraction per unit meter and outlet temperature with s_4 .

3.1.5. Thermal Conductivity of the Selected Material

For the MDBHE, it is also necessary to consider the thermal conductivity of the tube and backfill material. The thermal conductivity of the inner tube, outer tube, and grout will be analyzed and discussed below.

(a) Thermal conductivity of inner tube

As shown in Figure 10, with the increase in the thermal conductivity of the inner tube, both the heat extraction per unit meter and the outlet temperature gradually decrease. The fluid enters from the outer tube, extracts heat from the ground, heats up, reaches the bottom, goes up from the inner tube, and finally flows out of the buried tube. In the upward flow, some of the heat originally extracted by the fluid will be lost to the outer tube due to the temperature difference. The greater the thermal conductivity of the inner tube, the more heat is lost, so the heat extraction per unit meter and the outlet temperature will gradually decrease. If the thermal conductivity of the inner tube is large, there will be a thermal short-circuit phenomenon, which greatly reduces the system's performance.

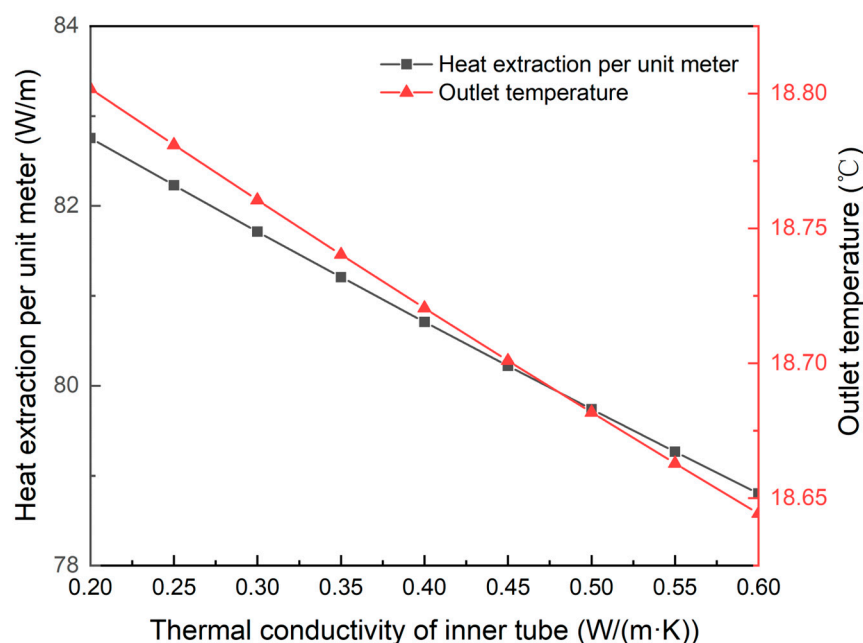


Figure 10. Change in heat extraction per unit meter and outlet temperature with thermal conductivity of inner tube.

(b) Thermal conductivity of outer tube

As shown in Figure 11, with the increase in the thermal conductivity of the outer tube, the heat extraction per unit meter and the outlet temperature both increase gradually. As the thermal conductivity of the outer tube increases, the thermal resistance between the fluid and the ground decreases, and more heat can be transferred at the same temperature difference. Therefore, the heat extracted from the ground by the fluid increases with the increase in the thermal conductivity of the outer tube, and the outlet temperature also increases.

(c) Thermal conductivity of grout

As shown in Figure 12, with the increase in the thermal conductivity of the grout, the heat extraction per unit meter and the outlet temperature both increase gradually. Similar to the thermal conductivity of the outer tube, the increase in the thermal conductivity of the grout will reduce the thermal resistance between the fluid and the ground, improve the heat extraction, and make the outlet temperature of the fluid higher.

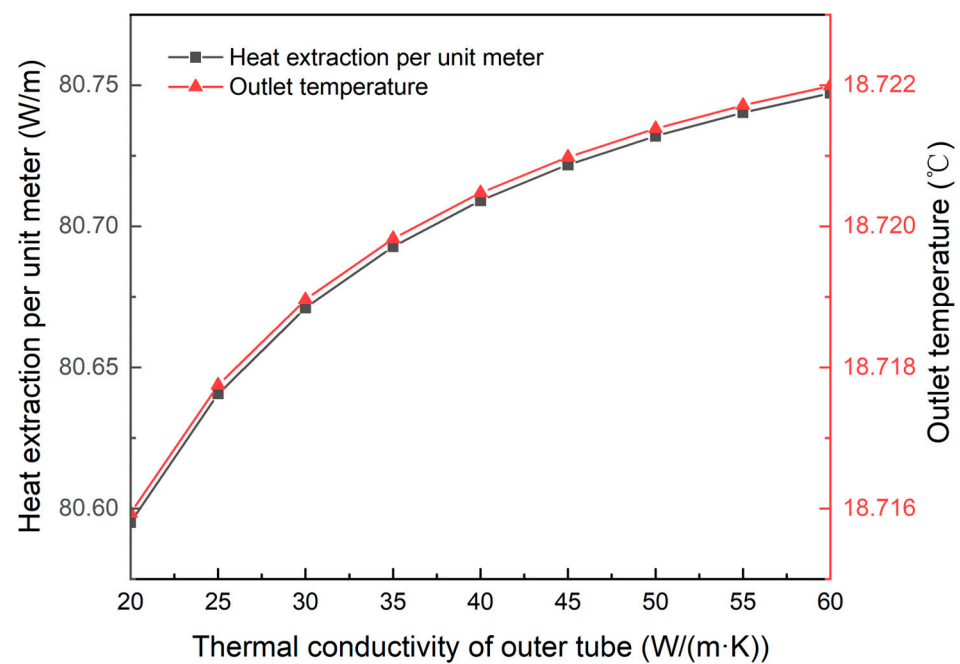


Figure 11. Change in heat extraction per unit meter and outlet temperature with thermal conductivity of outer tube.

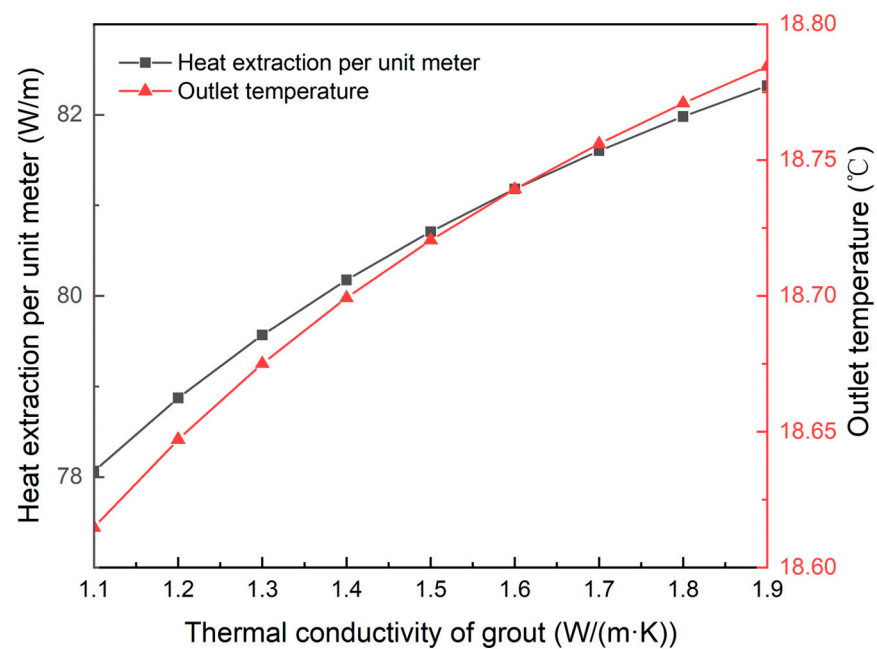


Figure 12. Change in heat extraction per unit meter and outlet temperature with thermal conductivity of grout.

3.2. Multi-Factor Analysis of MDBHE

An orthogonal experimental design is a kind of design method used to study multi-factors and multi-levels. Some representative points are selected from the comprehensive experiment according to orthogonality. These representative points have the characteristics of uniform dispersion, neatness and comparability. In this paper, the orthogonal experiment method is used to analyze and discuss the multi-factor influence of the MDBHE.

3.2.1. Design of Orthogonal Experiment Table

In this paper, the heat extraction per unit meter was taken as the index, and nine influencing factors were selected, including the borehole depth, mass flow rate, inlet temperature, buried tube radial structure parameter, and thermal conductivity of material selection, with three levels for each factor, as shown in Table 2. The heat extraction per unit meter can simply and effectively reflect the heat transfer capacity of the MDBHE. The nine influencing factors selected are those discussed in the single-factor influence analysis above.

Table 2. Orthogonal experiment table.

L ₂₇	Influencing Factor								
	Borehole Depth	Mass Flow Rate	Inlet Temperature	s ₀	s ₂	s ₄	Thermal Conductivity of Inner Tube	Thermal Conductivity of Outer Tube	Thermal Conductivity of Grout
	m	kg/s	°C	mm	mm	mm	W/(m·K)	W/(m·K)	W/(m·K)
1	1500	5	10	30	15	20	0.2	10	1
2	1500	5	10	50	25	30	0.6	50	2
3	1500	5	10	70	35	40	0.4	30	1.5
4	1500	10	20	30	25	40	0.2	30	2
5	1500	10	20	50	35	20	0.6	10	1.5
6	1500	10	20	70	15	30	0.4	50	1
7	1500	15	15	30	35	30	0.2	50	1.5
8	1500	15	15	50	15	40	0.6	30	1
9	1500	15	15	70	25	20	0.4	10	2
10	2000	5	20	30	35	30	0.6	30	1
11	2000	5	20	50	15	40	0.4	10	2
12	2000	5	20	70	25	20	0.2	50	1.5
13	2000	10	15	30	15	20	0.6	50	2
14	2000	10	15	50	25	30	0.4	30	1.5
15	2000	10	15	70	35	40	0.2	10	1
16	2000	15	10	30	25	40	0.6	10	1.5
17	2000	15	10	50	35	20	0.4	50	1
18	2000	15	10	70	15	30	0.2	30	2
19	2500	5	15	30	25	40	0.4	50	1
20	2500	5	15	50	35	20	0.2	30	2
21	2500	5	15	70	15	30	0.6	10	1.5
22	2500	10	10	30	35	30	0.4	10	2
23	2500	10	10	50	15	40	0.2	50	1.5
24	2500	10	10	70	25	20	0.6	30	1
25	2500	15	20	30	15	20	0.4	30	1.5
26	2500	15	20	50	25	30	0.2	10	1
27	2500	15	20	70	35	40	0.6	50	2

3.2.2. Results and Analysis of Orthogonal Experiment

The experiments in each orthogonal table were simulated by establishing the heat transfer model of the MDBHE, and the simulation results were recorded, as shown in Table 3. It can be seen that the nine influencing factors, in order from largest to smallest, are borehole depth, inlet temperature, mass flow rate, buried tube radial structure parameter s₂, thermal conductivity of the inner tube, buried tube radial structure parameter s₀, thermal conductivity of grout, thermal conductivity of the outer tube, and buried tube radial structure parameter s₄. The trend of a single-factor-level change is consistent with the analysis in Section 3.1.

Table 3. Orthogonal experiment visual analysis table.

L ₂₇	Influencing Factor									Heat Extraction per Unit Meter
	Borehole Depth	Mass Flow Rate	Inlet Temperature	s ₀	s ₂	s ₄	Thermal Conductivity of Inner Tube	Thermal Conductivity of Outer Tube	Thermal Conductivity of Grout	
	m	kg/s	°C	mm	mm	mm	W/(m·K)	W/(m·K)	W/(m·K)	
1	1500	5	10	30	15	20	0.2	10	1	62.7
2	1500	5	10	50	25	30	0.6	50	2	67.1
3	1500	5	10	70	35	40	0.4	30	1.5	71.0
4	1500	10	20	30	25	40	0.2	30	2	41.5
5	1500	10	20	50	35	20	0.6	10	1.5	43.3
6	1500	10	20	70	15	30	0.4	50	1	41.5
7	1500	15	15	30	35	30	0.2	50	1.5	58.9
8	1500	15	15	50	15	40	0.6	30	1	54.1
9	1500	15	15	70	25	20	0.4	10	2	65.0
10	2000	5	20	30	35	30	0.6	30	1	52.9
11	2000	5	20	50	15	40	0.4	10	2	55.9
12	2000	5	20	70	25	20	0.2	50	1.5	62.5
13	2000	10	15	30	15	20	0.6	50	2	76.2
14	2000	10	15	50	25	30	0.4	30	1.5	81.9
15	2000	10	15	70	35	40	0.2	10	1	84.9
16	2000	15	10	30	25	40	0.6	10	1.5	94.1
17	2000	15	10	50	35	20	0.4	50	1	102.4
18	2000	15	10	70	15	30	0.2	30	2	108.2
19	2500	5	15	30	25	40	0.4	50	1	79.2
20	2500	5	15	50	35	20	0.2	30	2	95.8
21	2500	5	15	70	15	30	0.6	10	1.5	70.4
22	2500	10	10	30	35	30	0.4	10	2	119.7
23	2500	10	10	50	15	40	0.2	50	1.5	117.7
24	2500	10	10	70	25	20	0.6	30	1	115.2
25	2500	15	20	30	15	20	0.4	30	1.5	84.6
26	2500	15	20	50	25	30	0.2	10	1	89.0
27	2500	15	20	70	35	40	0.6	50	2	99.2
k1	56.1	68.6	95.3	74.4	74.6	78.6	80.1	76.1	75.8	
k2	79.9	80.2	74.0	78.6	77.3	76.6	77.9	78.3	76.0	
k3	96.7	83.9	63.4	79.8	80.9	77.5	74.7	78.3	80.9	
R	40.6	15.3	32.0	5.4	6.3	2.0	5.4	2.2	5.2	

In order to make the optimization results more intuitive, four cases were selected for a comparative analysis, as shown in Table 4. Here, Case 0 is the basis, and each parameter is the intermediate level value in the orthogonal experiment. Each parameter in Case 1 is the optimal value selected by combining a single-influencing-factor analysis and an orthogonal experiment. In Case 2, only the borehole depth is the same as in Case 0, and the rest are the same as in Case 1. In Case 3, the borehole depth, mass flow rate and inlet temperature are the same as in Case 0, and the rest are the same as in Case 1. It can be seen that the increase rate of the heat extraction per unit meter is as high as 71.2% when Case 1 with the best parameter values is selected compared with Case 0. Because the depth of the buried tube has a great influence on its heat transfer capacity and the selection range in the actual project may be limited, Case 2 after the borehole depth is excluded is set. The results show that the heat extraction per unit meter of Case 2 is 39.1% higher than that of Case 0. Case 4 further excluded the two operating parameters of mass flow rate and inlet temperature, and the optimization of the six design parameters still increased the heat extraction per unit meter by 12.3%. Therefore, for the MDBHE, the optimization of various parameters can greatly improve its heat transfer capacity.

Table 4. Increase rate of heat extraction per unit meter under different parameters.

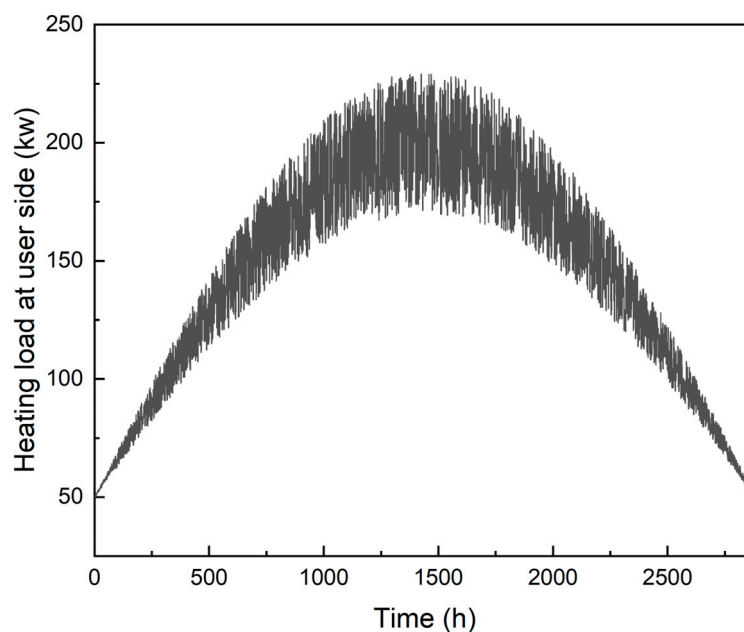
Case	Borehole Depth	Mass Flow Rate	Inlet Temperature	s_0	s_2	s_4	Thermal Conductivity of Inner Tube	Thermal Conductivity of Outer Tube	Thermal Conductivity of Grout	Heat Extraction per Unit Meter	Increase Rate
	m	kg/s	°C	mm	mm	mm	W/(m·K)	W/(m·K)	W/(m·K)	W/m	%
0	2000	10	15	50	25	30	0.4	30	1.5	81.9	0
1	2500	15	10	70	35	20	0.2	50	2	140.2	71.2
2	2000	15	10	70	35	20	0.2	50	2	113.9	39.1
3	2000	10	15	70	35	20	0.2	50	2	91.9	12.3

3.3. Variable Flow Operation Simulation Analysis

In actual engineering projects, the heating load on the user side will change with an increase in time. For the MDBHE with fixed flow, if the flow setting is too small, it is difficult to meet the heat demand, and if the flow setting is too large, it will waste resources. A single flow rate cannot match the changing heat load. In this paper, the operation of the MDBHE in variable flow mode and constant flow mode is simulated and compared.

3.3.1. Variable Flow Operating System Model

The time-by-time heat load curve of the user side is generated by combining the sine function and random number, and the time-by-time changes are shown in Figure 13. In the variable flow mode, the flow rate is adjusted every 24 h according to the difference between the current heat load on the user side and the temperature of the inlet and outlet fluids, so that it is more consistent with the current heat load on the user side. If the heating load on the user side increases, the fluid flow increases. If the heating load on the user side decreases, the fluid flow is reduced.

**Figure 13.** Hourly variation diagram of heating load at user side.

3.3.2. Simulation and Analysis of Different Operating Modes

Based on the heat transfer model of the MDBHE, the operation of the buried tube under different operating modes is simulated. The mass flow rate changes of the two modes are shown in Figure 14. In the variable flow mode, the fluid flow is smaller than that in the constant flow mode when the heating load on the user side is relatively small and larger than that in the constant flow mode when the heating load on the user side is large. The inlet temperature and outlet temperature changes of the fluid under different operating

modes are shown in Figure 15, and the differences are small. That is, the MDBHE can also be used as a heat source equivalent to that under constant flow mode in variable flow mode.

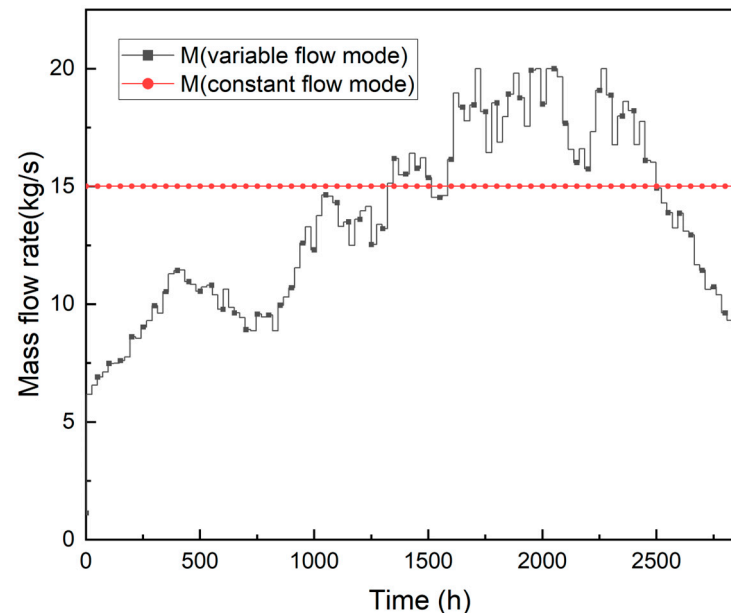


Figure 14. Mass flow rate changes in different operating modes.

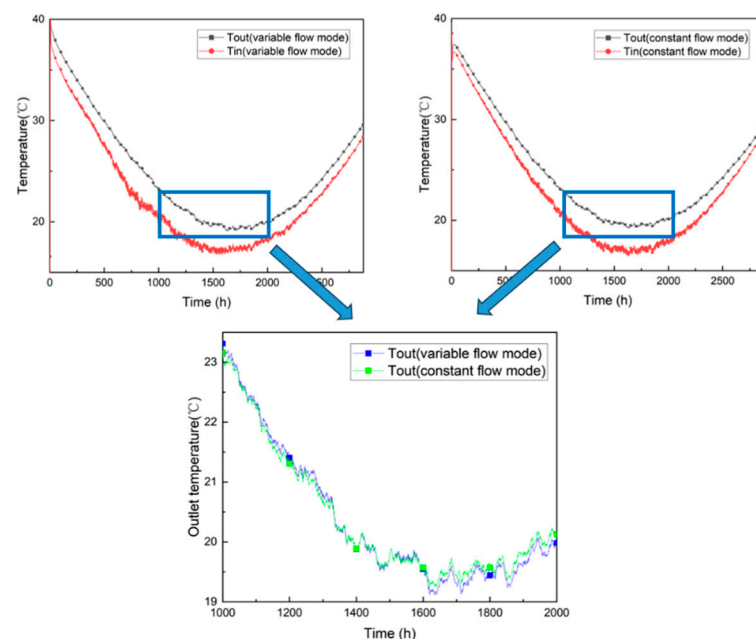


Figure 15. Simulation results of inlet temperature and outlet temperature under different operating modes.

In addition, the variable flow operation mode has some advantages compared with the constant flow operation mode, as shown in Table 5. The average energy consumption of the pump in the variable flow mode is reduced by 9.6% compared with that in the constant flow mode when the difference in heat extraction per unit meter and the average COP [25] are small. After the end of a heating period, the decrease in ground temperature in the variable flow mode is also slightly smaller than that in the constant flow mode, indicating that the ground temperature recovers faster, which is conducive to the long-term operation of the MDBHE.

Table 5. Simulation results under different operating modes.

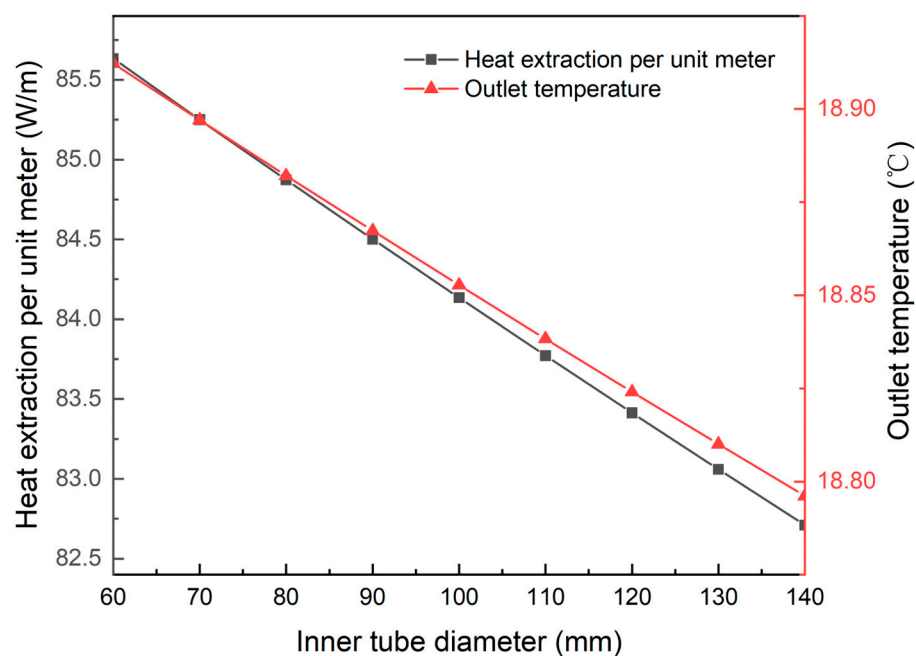
Operation Mode	Heat Extraction per Unit Meter	Average COP	The Average Energy Consumption of the Pump	Average Value of Borehole Ground Temperature Change	Absolute Maximum of Borehole Ground Temperature Change
	W/m		kW	°C	°C
Variable flow mode	59.54	5.72	265.84	−10.81	−35.99
Constant flow mode	59.59	5.71	294.00	−10.84	−36.76

4. Discussion

4.1. Limitations of the Analysis of Influencing Factors

In Section 3.1.4, the influencing factors selected in this paper are different from other literature studies. Theoretically, the increase in the inner tube diameter will reduce the heat extraction of the MDBHE, but s_0 is not a simple inner tube diameter parameter.

Next, the effect of the inner tube diameter on the performance of the MDBHE is studied in this paper. In the supplementary experiment, the sum of s_0 and s_2 is set to a constant value, and when s_0 increases/decreases, s_2 decreases/increases, so the increase or decrease in s_0 will not affect the outer tube diameter and borehole diameter. The simulation results are shown in Figure 16. With the increase in the inner tube diameter, both the heat extraction per unit meter and the outlet temperature gradually decrease, thus confirming the above. The larger the inner tube diameter, the greater the increase in the residence time of the fluid in the inner tube. In this way, more heat is lost to the outer tube, resulting in less heat extraction.

**Figure 16.** Change in heat extraction per unit meter and outlet temperature with inner tube diameter.

Furthermore, this study mainly focuses on the system's thermal performance, while the hydraulic performance related to the functions of the water pump and the pressure drop in the tube is not well considered. It is planned to comprehensively include the operation and power consumption of water pumps related to different designs of heat exchangers and operation modes.

4.2. Limitations of Operational Optimization

In the practical engineering application of the MDBHE, it is imperative to consider the economy of the system. The selection and calculation methods of economic evaluation indicators are more diversified. On the one hand, it is necessary to consider realistic factors to ensure that it is in line with the actual situation. On the other hand, it should also be easy to analyze and facilitate research and replication. At the same time, the economic evaluation indicators are also highly contemporary. They are also related to the level of science and technology at that time, local policies, and so on. A specific economic evaluation was not included in the evaluation index in this paper, which will be improved in subsequent research.

4.3. Limitations of Simulation Model

A computationally efficient and accurate model is the pursuit of almost every engineering study. The proposed model of a single deep borehole heat exchanger is solved by using the finite difference model for the water flow inside the tube and the modified finite line source method for the heat transfer in the ground. Those two parts are coupled by the borehole wall temperature condition, and this condition should be updated at each time step in the dynamical simulation program. The computational efficiency is not very high, which is caused by the intrinsic simulation mechanism, and updates of the ground soil temperature in the finite line source method must use all the heat flux values at the borehole wall surface all the time, which makes the simulation slower in long-term calculations. A new design of the algorithm should be put forward to overcome this defect. Moreover, the proposed model is also limited to a single borehole, and multiple-borehole scenarios should be considered in future studies, with special attention being paid to the geometric layout of the borehole array and its long-term thermal performance.

5. Conclusions

In order to improve the heat extraction of the MDBHE, the influence trend and magnitude of different parameters on the heat extraction of the MDBHE were studied. Furthermore, the operation of the MDBHE in variable flow mode and constant flow mode was compared and analyzed. The main conclusions are as follows:

- (1) The influences of different parameters on the heat extraction of the MDBHE are different. The nine parameters selected in this paper, in descending order of their effects, are borehole depth, inlet temperature, mass flow rate, buried tube radial structure parameter s_2 , thermal conductivity of the inner tube, buried tube radial structure parameter s_0 , thermal conductivity of the grout, thermal conductivity of the outer tube, and buried tube radial structure parameter s_4 .
- (2) The parameter optimization of the MDBHE can notably improve the heat extraction. In this paper, the heat extraction of the optimal parameter group is increased by 71.2%. If only six parameters related to design and material selection are considered, the heat extraction is also increased by 12.3%.
- (3) The variable flow operation mode has some advantages compared with the constant flow operation mode. Compared with the constant flow mode, the variable flow mode has little difference in heat extraction, and the average pump energy consumption is reduced by 9.6%. Moreover, the ground temperature around the MDBHE recovers faster in the variable flow mode, which is conducive to the long-term operation of the ground-source heat pump system.

Considering the limitations of this study, some future work is to be carried out. Firstly, a faster simulation program for the long-term analysis of the MDBHE system should be studied to accelerate both single- and multiple-borehole systems, and the hydraulic analysis model should be included and coupled with thermal models. Secondly, the proposed orthogonal experiment for parameter optimization is only a rough way of selecting a better combination of system parameters, so a rigorous optimization algorithm should be implemented for searching for a global solution. Thirdly, the MDBHE system should join

with other renewable systems for the study of zero-energy buildings and community with better solution of integrated energy system.

Author Contributions: Conceptualization, M.L. and Y.L.; data curation, L.Z.; formal analysis, M.L., J.T. and L.Z.; funding acquisition, Y.L.; investigation, M.L.; methodology, J.T., L.Z. and Z.Z.; software, N.C.; validation, N.C.; writing—original draft, M.L., J.T. and Z.Z.; writing—review and editing, Y.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partially funded by the National Natural Science Foundation of China (No. 52008182) and the Open Project Program of Building Energy-Saving Engineering Technology Center in Anhui Province under Grant No. AHJZNX-2021-01.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors wish to acknowledge the technical support of the Hubei Electric Power Planning and Design Institute Co., Ltd.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

Variables

a	Thermal diffusivity of material (m^2/s)
C_1	Heat capacity per unit length of the outer tube ($\text{J}/(\text{m}\cdot\text{K})$)
C_2	Heat capacity per unit length of the inner tube ($\text{J}/(\text{m}\cdot\text{K})$)
C_f	Heat capacity of fluid ($\text{J}/(\text{kg}\cdot\text{K})$)
d_{1i}	Inner diameter of annular tube (m)
d_{1o}	Outer diameter of annular tube (m)
d_{2i}	Inner diameter of inner tube (m)
d_{2o}	Outer diameter of inner tube (m)
h	Borehole depth (m)
h_1	Convection heat transfer coefficients in annular channel ($\text{W}/(\text{m}^2\cdot\text{K})$)
h_2	Convection heat transfer coefficients in inner channel ($\text{W}/(\text{m}^2\cdot\text{K})$)
k	Thermal conductivity of material ($\text{W}/(\text{m}\cdot\text{K})$)
M	Mass flow rate (kg/s)
n	Number of borehole segmentation
N	Superposition number in time series
q	Heat flow intensity per length (W/m)
Q	Heating load (kW)
r	Radius distance (m)
R_1	Thermal resistance between the outer tube fluid and borehole wall ($(\text{m}\cdot\text{K})/\text{W}$)
R_2	Thermal resistance between the inner and outer tube fluid ($(\text{m}\cdot\text{K})/\text{W}$)
T_{f1}	Downward fluid flow temperature ($^{\circ}\text{C}$)
T_{f2}	Upward fluid flow temperature ($^{\circ}\text{C}$)
z	Axis distance (m)

Greeks

ρ	Density of material (kg/m^3)
θ	Excess temperature ($^{\circ}\text{C}$)
$\Delta\tau$	Time step (s)
ΔT	Temperature difference ($^{\circ}\text{C}$)

Lower script

1	Downward tube
2	Upward tube
i	Inner
o	Outer
s	Soil

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