Long-term Performance Analysis of Deep Geothermal Energy Heating Systems Using TRNSYS

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Abstract: In recent years, deep geothermal energy has gained significant prominence and has witnessed widespread application and development in the realm of building heating. Nevertheless, much of the research has predominantly concentrated on the structural and operational performance of deep borehole heat exchangers, often neglecting the exploration of the operational dynamics associated with above-ground components in the context of deep geothermal energy heating systems.

This study places its primary focus on the field of deep geothermal energy heating systems. It utilizes the TRNSYS software to enable real-time dynamic interactions among system components and explores the long-term thermal response characteristics of the system as it adjusts to dynamic variations across various operational scenarios. This research holds substantial importance in achieving the efficient utilization of deep geothermal energy for building heating systems and makes a substantial contribution to the broader adoption of geothermal energy resource development and utilization technology.

The findings of this investigation unveil that extended periods of system operation show a noteworthy impact: a mere 0.1 m/s increase in the borehole exchanger's inlet flow rate results in a corresponding 2.03°C increase in the average inlet temperature of the borehole exchanger and a 0.76°C rise in the average outlet temperature. After 20 years of uninterrupted system operation, the inlet water temperature of the borehole exchanger stabilizes at approximately 16-18°C, while the outlet temperature stabilizes at 25°C. This confirmation underscores the alignment of both the inlet and outlet temperature of the borehole exchanger with the system's operational requirements.

Moreover, with each consecutive 5-year operational period, several noteworthy temperature changes are observed: the temperature at the bottom of the borehole exchanger decreases by approximately 0.8°C, the average temperature along the outer pipe diminishes by about 0.7°C, the average temperature along the inner pipe experiences a decrease of roughly 0.8°C, and the average temperature of the outer pipe wall within the geotechnical layer declines by approximately 0.7°C, and the heat loss along the inner pipe decreases by approximately 0.5 kW.

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Keywords: Deep borehole heat exchanger heating system; Numerical simulation; Heat extraction performance; Subsurface temperature attenuation.

1 Introduction

In the 21st century, global urbanization has surged from 39% to 58%, accompanied by an annual increase in energy consumption of approximately 2% [1]. These trends have given rise to urgent global challenges, including a sharp rise in energy demand and the increasingly severe issue of ecological pollution. In recent years, China has placed a growing emphasis on the development of new energy sectors, with a long-term commitment to clean and low-carbon technologies. A critical aspect of China's sustainable development lies in how the traditional building heating industry can navigate this evolving energy landscape to identify the most optimal energy solutions [2]. One approach that has garnered significant attention in recent years is the use of Deep Borehole Heat Exchangers (DBHE) for harnessing subterranean heat. The heat exchanger is drilled into the high-temperature rock body of 2,000 to 3,000 m underground by means of a perforator, and the DBHE is installed in the drilled holes, so as to extract the geothermal energy of the rock body, and then supply the heat to the building by means of the high-temperature heat pump technology. Presently, both domestic and international research efforts related to DBHE predominantly focus on assessing heat extraction performance and ensuring the stability of system operations.

Within the realm of heat extraction performance analysis, researchers, such as the team led by Kong Yanlong and Shao Haibing, employed diverse methodologies to evaluate heat extraction from deep borehole heat exchangers[3]. Their findings offered valuable practical insights for engineering applications. Furthermore, teams under the leadership of Fang Zhaohong and Bu Xianbiao conducted in-depth analyses on the factors influencing the performance of these heat exchangers[4,5]. Their research showed that key parameters, such as water temperature, heat extraction power, and the rock temperature field, exhibit time-dependent trends. Moreover, an increase in the geothermal temperature gradient leads to a substantial rise in heat extraction power. Regarding system operation stability, studies by Cai and Deng indicated that the outlet temperature of Deep Borehole Heat Exchangers (DBHE) remains relatively stable under continuous operation, and real-world projects demonstrated high Coefficients of Performance (COP) for heat pump units[6,7]. Researchers worldwide have conducted numerous studies on depth geothermal energy heating technology. These studies have accurately assessed the heat exchange capacity of deep borehole heat exchangers, developed various numerical models, and optimized them based on design and structural parameters.

Nonetheless, the majority of these studies have predominantly concentrated on the design and operational aspects of subterranean heat exchangers, while affording limited attention to the operational dynamics of the above-ground components within deep geothermal energy heating systems. In practical engineering, deep borehole heat exchangers are dynamically linked with building heating loads and heat pump units [8]. The COP of the heat pump unit undergoes dynamic variations during operation, resulting in continuous fluctuations in borehole heat extraction. These fluctuations have a direct impact on the overall system's power consumption and heating load, thereby influencing the operational characteristics of the system. This paper introduces a system model centered around the heat pump unit, which dynamically adjusts the energy distribution between the borehole side and the load side. This adjustment takes into account variations in the heat pump unit's COP, offering a more precise depiction of the borehole heat exchanger's performance throughout system operation. Moreover, it models the influence of changes in flow rates on both the borehole side and the load side of the heat pump unit concerning borehole heat extraction. This research delves into the operational characteristics of medium-depth borehole geothermal heating systems under dynamic responses to multiple factors, which are crucial for optimizing borehole heat extraction and enhancing system efficiency.

2 Modelling And Validation

2.1 Heat transfer process analysis

In the realm of DBHE, two predominant configurations exist: the U-tube heat exchanger and the casing heat exchanger. This investigation primarily centres on the casing heat exchanger, a prevalent choice for our study [9]. The Deep Borehole Heat Exchanger (DBHE) is composed of four primary components: an inner tube, an outer tube, cement insulation, and the surrounding geotechnical layer. The complex heat transfer interactions between the circulating fluid and the geotechnical temperature field within this medium-depth buried tube heat exchanger necessitate several simplifying assumptions within our model [10]:

- It is assumed that the initial subsurface temperature field follows a linear function based on a constant geothermal gradient, with no consideration of the impact of groundwater seepage on the subsurface temperature field.
- Using finite line source theory, the interior of the borehole is approximated as a one-dimensional temperature field.
  Left: 2 cm;
- The heat extraction properties of the subsurface material in the radial direction are considered to remain constant.
- Performance parameters of the circulating fluid, borehole material, and cement grouting are assumed to be unaffected by temperature variations.

Model Solution.

The model is developed on the foundation of a set of assumptions grounded in the finite line source theory. Under this framework, the heat transfer dynamics of the circulating fluid within the tube are idealized as a one-dimensional heat transfer phenomenon. Simultaneously, the temperature distribution in the geotechnical medium surrounding the tube is simplified as a two-dimensional heat transfer process.

The energy exchange process between the fluids inside the inner and outer pipes is quantitatively defined by the following energy equations:

$$\frac{\partial T_{f_r}}{\partial t}+\frac{\partial (V_{f_r}\cdot T_{f_r})}{\partial z}=\frac{k_{ff}(T_{f_{an}}-T_{f_r})}{\rho_f A_r c_{pf}} \tag{1}$$

Where T_{f_r} is the temperature of the circulating water inside the inner pip /°C; V_{f_r} is the flow rate of the circulating water inside the inner pipe /m·s^{-1}; k_{ff} is the heat transfer coefficient between the circulating fluid inside the inner and outer tube / W·m^{-1}·k^{-1}; $T_{f_{an}}$ is the temperature of the circulating fluid inside the outer tube/°C; A_r is the cross-sectional area of the inner tube /m^2.

The fluid energy equation for the outer pipe circulation is as follows:

$$\frac{\partial T_{f_{an}}}{\partial t}+\frac{\partial (V_{f_{an}}\cdot T_{f_{an}})}{\partial z}=\frac{k_{fg}(T_g-T_{f_{an}})}{\rho_f A_{an} c_{pf}}-\frac{k_{ff}(T_{f_{an}}-T_{f_r})}{\rho_f A_{an} c_{pf}} \tag{2}$$

Where $V_{f_{an}}$ represents the flow rate of the circulating fluid within the outer pipe/m·s^{-1}; k_{fg} signifies the heat transfer coefficient denoting the heat exchange between the circulating fluid and the cementing material inside the outer pipe, expressed in Watts per meter per Kelvin/ W·m^{-1}·k^{-1}; T_g stands for the temperature of the cementing material; A_{an} denotes the cross-sectional area of the outer pipe/ m^2.

Simulation system construction.

TRNSYS, a transient system simulation software, is predominantly employed for modeling renewable energy applications, system design, optimization, and dynamic simulations of multi-source energy systems. In the context of a TRNSYS-based deep borehole heat exchanger heating system, it comprises interconnected components, including the borehole heat exchanger, heat pump unit, and plate heat exchanger. The accurate selection of simulation modules for these components is critical for an accurate portrayal of system performance.

1) Model parameters of DBHE

The parameter settings of the correlation model are shown in Table 1.

Table 1. Values of the model parameters

Parameters	Notation	Value
Borehole depth	H	2000(m)
Borehole of diameter	Rb	0.7(m)
Inner pipe diameter	R1	0.1778(m)
Outer pipe diameter	R2	0.11(m)
Thermal conductivity of outer pipe	λR	40 W·m^{-1}·K^{-1}

Parameters	Notation	Value
Thermal conductivity of inner pipe	λr	0.45 $W\cdot m^{-1}\cdot K^{-1}$
\`Thermal conductivity of soil	λs	2.1 $W\cdot m^{-1}\cdot K^{-1}$
Geothermal gradient	G	30 $°C\cdot km^{-1}$
Fluid flow rate in outer pipe	V	$0.7 m\cdot s^{-1}$

2) Simulation of the coupled computational logic of the system

This paper presents the design of a medium-depth borehole geothermal heating system, employing a variable speed control mode to enable seamless transitions between the heating season and the non-heating season. In accordance with the specifications of the ground source heat pump unit, which is capable of withstanding a maximum inlet water temperature of 37°C, we have set this temperature as a threshold in our model. When the outlet water temperature of the borehole heat exchanger exceeds this threshold, the system redirects the heat supply to the building end through a plate heat exchanger. Conversely, when the temperature falls below this threshold, the system switches to supply heat to the building end through the heat pump. Figure 1 illustrates the computational logic of the model developed in this paper. By establishing interconnections between various sub-modules, this model achieves real-time dynamic responses between the components of the medium-depth borehole geothermal heating system.

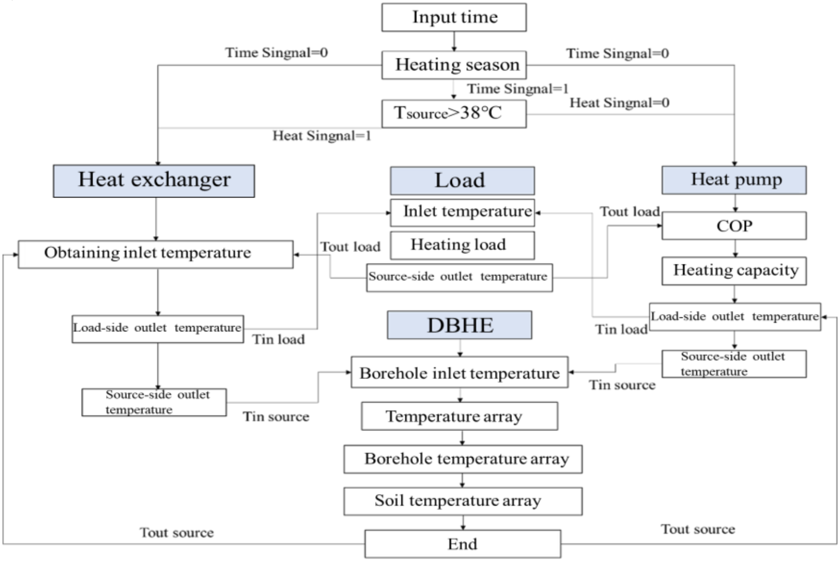

Fig. 1. System Calculation Logic Diagram

Based on the module selection and parameter configuration established in the preceding study, the medium-depth borehole geothermal heating system has been meticulously assembled in accordance with a comprehensive system coupling computation logic. As illustrated in Figure 2, the prominent red line within the schematic delineates the circulation system located on the load side of the medium-depth borehole geothermal heating system.

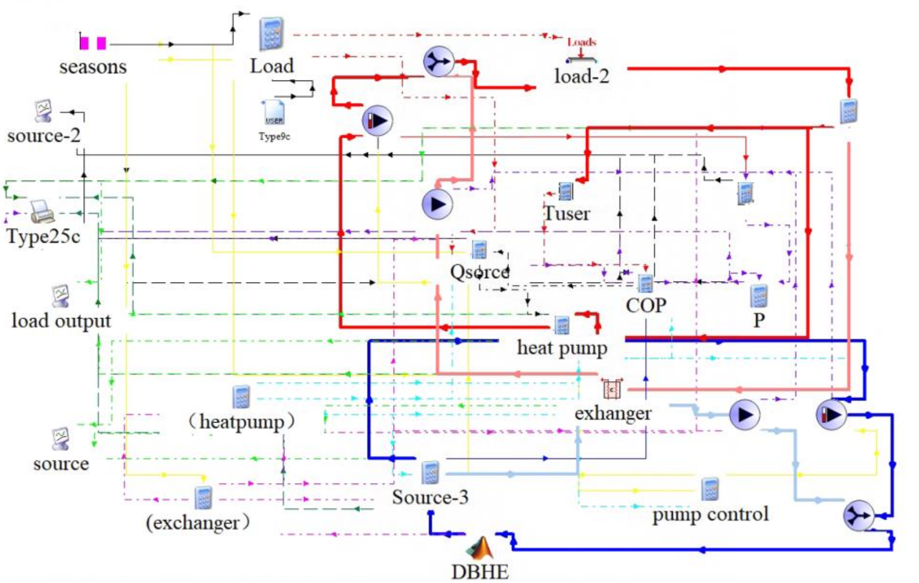

Fig. 2. Simulation model of deep borehole heat exchanger heating systems

2.2 Model validation

This section serves to validate the precision of the deep borehole heat exchanger model, assess the disparities between this model and the simulation outcomes obtained from the OpenGeoSys model, as well as the Beier analytical model, thus substantiating the robustness of the model developed within this study.

The data results of the model in this paper are compared with the Beier analytical solution model. As shown in the figure 3 the larger error occurs in the later stage of the heat exchange process, the maximum relative error is 5.2% and 3.15%, respectively, and the overall computational error is less than 10%, which indicates that the model in this paper can accurately simulate the medium-depth borehole heat exchanger.

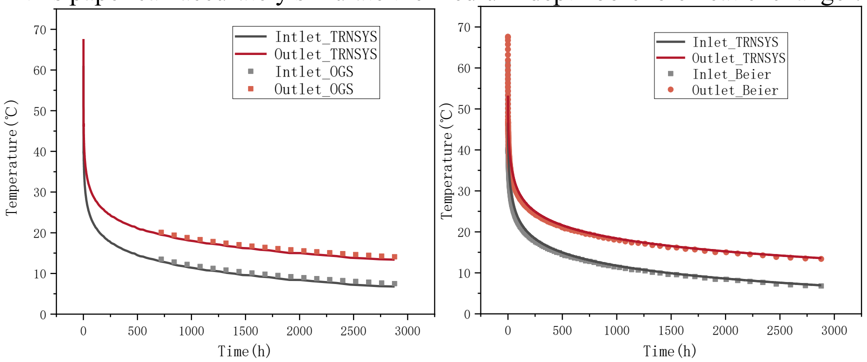

Fig. 3. The results of model validation. (a) Results of this model compared to the OGS model(b) Results of this model compared to the OGS model

3 Results

3.1 Long-Term Performance Analysis of the Fixed Operating Condition System

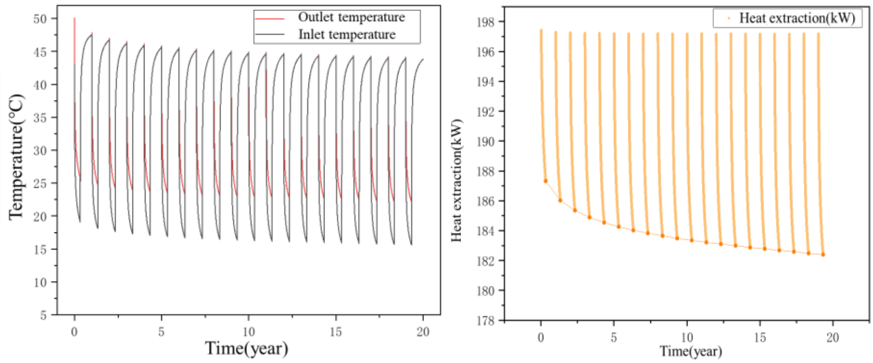

Fig. 4. Changes in heat extraction performance of deep geothermal energy heating systems in long-term operation. (a)Trends in temperatures of DBHE (b) Trends in heat extraction of DBHE

In Figure 4 (a), we observe the variations in inlet and outlet water temperatures of the ground source heat exchanger over time. As the system operates, both inlet and outlet temperatures gradually decrease. In the first heating season, the plate heat exchanger runs for 170 hours before transitioning to heat pump operation. During this period, the DBHE's inlet temperature drops from 32.68°C to 13.2°C, and the outlet temperature decreases from 44.13°C to 22.5°C. The average inlet temperature of the DBHE is 16.25°C, 3.94°C lower than in the first heating season, and the average outlet water temperature is 25.76°C, 4.1°C lower than in the first heating season. This data indicates that with an inlet flow velocity of 0.5 m/s in the outer pipe, the average water temperature of the ground source heat exchanger decreases by 16%.

Figure 4 (b) presents the dynamic changes in heat extraction from the ground source heat exchanger as it operates over time. The heat extraction gradually diminishes, amounting to a reduction of 4.75 kW compared to the first heating season, equating to an average decrease of approximately 5%. During the initial year of operation, specifically in the non-heating season, the inlet and outlet water temperatures of the ground source heat exchanger experience an increase to 47.23°C. This increase is attributed to the heat recovery effect of the soil temperature field, resulting in an average water temperature of 45.01°C during the non-heating season. In contrast, in the twentieth year of operation, during the non-heating season, the inlet and outlet water temperatures of the ground source heat exchanger increase by 3.6°C due to the heat recovery effect of the soil temperature field, and the average water temperature during the non-heating season is 36.78°C. This signifies an 8.23°C decrease in the average water temperature during the non-heating season, representing a substantial reduction of approximately 18.3% compared to the first year of operation.

The average Coefficient of Performance (COP) initially reaches approximately 0.59 and undergoes significant changes primarily in the early operational stages. Over time, the average COP stabilizes, reflecting system convergence. In Figure 5(b), we observe a progressive increase in heat extraction from the ground source heat exchanger as the system operates. During the first heating season, the system's energy consumption rises from 50.8 kW to 60.69 kW, resulting in an average energy consumption of 57.37 kW for the heating season. In contrast, during the final heating season, the system's energy consumption increases from 50.81 kW to 65.62 kW, with an average energy consumption of 61.87 kW for the heating season. This marks a 4.5 kW increase in average energy consumption, roughly equivalent to a 7.8% rise compared to the first heating season. Similar to heat extraction and COP trends, system energy consumption exhibits significant early-stage changes and subsequently stabilizes with increasing operation time.

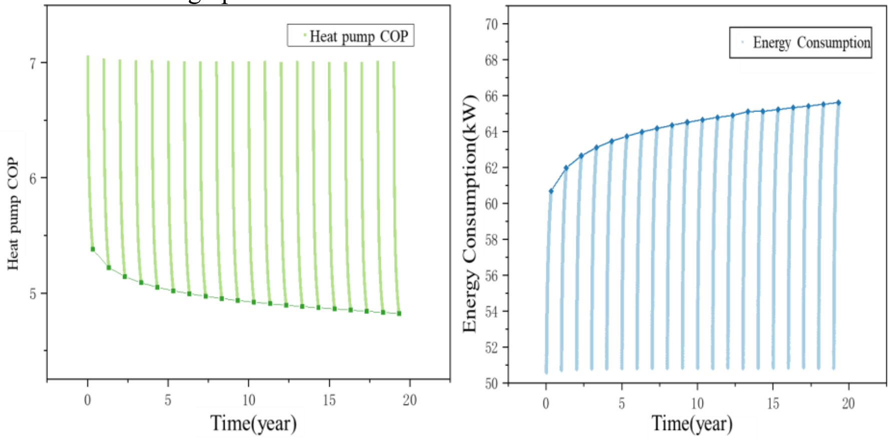

Fig. 5. Changes in heat extraction performance of deep geothermal energy heating systems in long-term operation. (a)Trends in temperatures of DBHE (b) Trends in heat extraction of DBHE

The average Coefficient of Performance (COP) initially reaches approximately 0.59 and undergoes significant changes primarily in the early operational stages. Over time, the average COP stabilizes, reflecting system convergence. In Figure 5(b), we observe a progressive increase in heat extraction from the ground source heat exchanger as the system operates. During the first heating season, the system's energy consumption rises from 50.8 kW to 60.69 kW, resulting in an average energy consumption of 57.37 kW for the heating season. In contrast, during the final heating season, the system's energy consumption increases from 50.81 kW to 65.62 kW, with an average energy consumption of 61.87 kW for the heating season. This marks a 4.5 kW increase in average energy consumption, roughly equivalent to a 7.8% rise compared to the first heating season. Similar to heat extraction and COP trends, system energy consumption exhibits significant early-stage changes and subsequently stabilizes with increasing operation time.

3.2 Long-Term Heat Decay Patterns in the Soil Thermal Exchange within the System

In order to investigate the heat exchange mechanism and the decay characteristics within the soil, a comparative analysis was conducted, focusing on the temperature variations in the ground source heat exchanger at the conclusion of the 5th, 10th, and 20th heating seasons.

In Figure 6(a), we present the soil temperature profiles following a five-year operation of the model, concluding at the end of a heating season with an inlet flow velocity of 0.5 m/s. The soil temperatures along the pipe wall exhibit an increase, rising from 15.84°C to 31.82°C, with an average wall temperature of 23.14°C. As the ground source heat exchanger consistently draws heat from the surrounding soil, these temperatures gradually decrease, marking a maximum thermal influence radius of 13.99 meters at this juncture.

Figure 6(b) illustrates the water flow distribution within the pipe after running the model for five years. Along the depth, the water temperature along the outer pipe increases from 14.82°C to 25.78°C, while the water temperature along the inner pipe increases from 24.08°C to 25.78°C, resulting in an inner pipe heat loss of 37.3 kW.

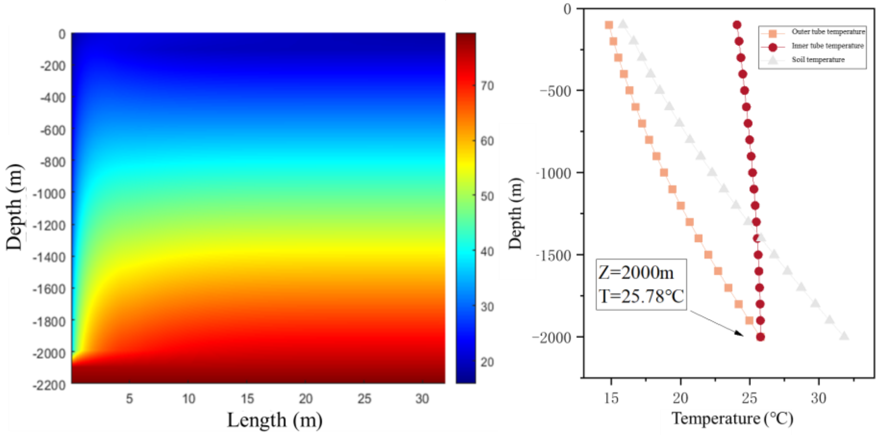

Fig. 6. The temperature characteristics of the soil after the completion of the 5th heating season. (a) The soil temperature distribution chart (b)Temperature distribution curve along the length of the ground source heat exchanger

The findings reveal that with every 5 years of continuous operation, the temperature at the base of the ground source heat exchanger pipe experiences a decrease of approximately 0.8°C. Moreover, the average water temperature along the inner and outer pipes registers a reduction of roughly 0.71°C and 0.8°C, respectively. Meanwhile, the average temperature of the soil surrounding the outer pipe wall diminishes by approximately 0.73°C. In addition, there is a decrease of about 0.6 kW in heat loss along the inner pipe.

4 Conclusions

(1) Over extended periods of operation, each 0.1 m/s increase in the boreholes' inlet flow rate results in an approximate 2.03°C rise in the average inlet water temperature, while the average outlet water temperature of the boreholes increases by approximately 0.76°C. Following two decades of uninterrupted system operation, the inlet water temperature of the buried heat exchanger reaches a stable range of 16-18°C, and the outlet temperature consistently stabilizes at 25°C. This confirmation underscores the sustained alignment of both the inlet and outlet temperatures of the buried heat exchanger with the operational criteria of the system. For each 0.1 m/s increase in the inlet flow rate of the boreholes, the Coefficient of Performance (COP) of the heat pump unit decreases by roughly 2%, and the system's energy consumption rises by approximately 1.085 kW. Additionally, with every additional 5 years of operation, the temperature at the base of the buried heat exchanger experiences a decrease of around 0.8°C. The average temperature along the outer pipe decreases by approximately 0.71°C, and the average temperature along the inner pipe registers a decrease of roughly 0.8°C. The average temperature of the outer pipe wall within the geotechnical layer experiences a decline of approximately 0.73°C, accompanied by a reduction of about 0.6 kW in heat loss along the inner pipe.

(2) Concerning system operational parameters, during the initial heating season, when the inlet flow rate of the boreholes increases from 0.5 m/s to 0.7 m/s, the COP of the heat pump unit declines from 5.86 to 5.74, indicating a reduction of approximately 2%. During the twentieth heating season, when the inlet flow rate of the boreholes increases from 0.5 m/s to 0.7 m/s, the Coefficient of Performance (COP) of the heat pump unit decreases from 5.27 to 5.17, marking a decrease of approximately 1.9%. This underscores the conclusion that after two decades of uninterrupted borehole operation, each 0.1 m/s rise in the inlet flow rate results in a decline of approximately 2% in the COP of the heat pump unit. Additionally, the system's energy consumption increases from 55.06 kW to 56.26 kW, constituting an increase of approximately 2.2% due to the same inlet flow rate increment in the initial heating season. In the twentieth heating season, when the inlet flow rate of the boreholes increases from 0.5 m/s to 0.7 m/s, the system's energy consumption rises from 60.94 kW to 61.91 kW, showing an increase of approximately 1.6%.

(3) For each additional 5 years of system operation, the buried heat exchanger experiences several alterations: the temperature at the base of the heat exchanger decreases by approximately 0.8°C, the average water temperature along the outer pipe declines by about 0.7°C, the average water temperature along the inner pipe decreases by approximately 0.82°C, and the average temperature of the outer pipe wall within the geotechnical layer registers a decline of roughly 0.7°C. Additionally, there is a reduction of about 0.5 kW in heat loss along the inner pipe.

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