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Reliability Design of Vertical Heat Exchanger for Ground Source Heat Pump Based on Monte Carlo Method

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ABSTRACT

The working environment of the ground source heat pump buried pipe significantly influences the complexity of its heat transfer process, with many uncertain influencing factors involved. This paper utilizes the Montacaro stochastic simulation method to simulate the heat transfer process of the heat exchanger under random conditions, taking into account these influencing factors. Furthermore, a reliability analysis of the simulation results is conducted, and a proposed reliability calculation method for determining the borehole length of the buried tube heat exchanger is presented.

1. Introduction

In previous research on buried pipes, the heat transfer characteristics of various factors affecting the heat transfer process have been analyzed (Du Tiantian, 2020). These factors include soil thermal properties, boundary conditions, and initial conditions. However, it is important to note that these factors have significant uncertainties. Previous analyses were based on deterministic values, which may not accurately represent real-world conditions. Ignoring the essential characteristics of uncertainty in influencing factors can lead to problems such as excessive investment in soil source heat pump systems or insufficient heat exchange function. This can hinder the promotion and application of ground source heat pumps (Meng Qingfeng, 2012). Given this information, it is clear that there is a dire need for more thorough research to explore the influence of uncertainties and variations in key influencing factors on the heat transfer processes of buried tube heat exchangers. This would allow for a better understanding of the potential limitations and challenges that may arise when developing and implementing ground source heat pump systems.

2. Random factor analysis

The heat transfer process of buried pipes is closely related to complex geometric and physical conditions. There are great uncertainties in soil thermal properties, initial conditions, boundary conditions, geometry and spatial layout of buried pipes. Therefore, these uncertainties must be taken into account when establishing the heat transfer model of the buried tube heat exchanger. Ignoring these uncertainties will lead to the inaccuracy of the prediction of the buried pipe heat transfer model, which may vary greatly. Such inaccurate models of buried pipe heat transfer can lead to bad decisions when designing buried pipe systems, resulting in significant economic and environmental costs. In addition, ignoring these uncertainties may hinder the development of scientific and rational heat transfer models for buried tube heat exchangers, which is essential for the safe and efficient operation of buried tube heat exchangers. (Liu Zhuodong and Guan Changsheng, 2010). In order to accurately study the temperature field of buried pipes and account for the randomness of these parameters, it is essential to conduct random analysis of the buried pipe heat transfer (Zhou Yingying, 2015).

The thermal physical properties of soil have an important impact on the performance of the ground source heat pump system, such as the size and change of soil thermal conductivity, specific heat capacity and other parameters, which have a great role in determining the heat exchange efficiency and long-term stability of the ground source heat pump system. (Yue Liyan and Han Zhisheng, 2012; Li Chao et al., 2022). In practical engineering, soil thermal physical

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properties are typically determined using field testing methods combined with parameter estimation techniques. However, uncertain factors such as changes in soil temperature, limitations in measurement technology and methods, external accidental disturbances, and sensor deviations can lead to uncertainty in measurement data. Therefore, there is significant uncertainty associated with determining soil thermal property parameters through field measurements.

Secondly, although the initial temperature of the fluid inside the buried pipe may be different from the initial temperature of the soil outside the pipe, the temperature of the pipe and the surrounding soil will tend to be the same after a period of time due to the phenomenon of heat transfer. The temperature difference between the two is the driving force for heat transfer. For example, in winter, the fluid in the pipe with an initial temperature of 4 ℃ may be affected by the surrounding air temperature, resulting in a gradual increase in the surface temperature of the pipe and a certain heat accumulation inside the pipe. Therefore, the initial temperature of the soil directly impacts both the depth of the buried pipe and the determination of the optimal distance between buried pipes(Liang Fang, 2019). Since soil temperature varies across different regions, it is essential to conduct field tests to measure soil temperature when designing a buried pipe system. However, it is important to note that field tests may be influenced by test methods and conditions, leading to potential deviations in measured soil temperatures. As a result, there may be some randomness in determining the initial temperature parameter for designing a buried pipe.

Thirdly, the design scheme of buried pipeline needs to consider various factors in various aspects and make the optimal choice in combination with the actual situation, including but not limited to: The diameter and material of the buried pipeline, the backfill material used, the spacing between the buried pipeline and the fluid flow in each pipeline, etc., these factors are not only related to the safety and stability of the buried pipeline, but also affect the reliability of the pipeline, buried depth and a series of problems. Therefore, these factors must be fully considered in the design process, and optimized and adjusted in combination with the actual situation to ensure that the design scheme of the buried pipeline can meet the actual needs and achieve the best use effect. (Li P C, 2019). In the process of designing the buried tube heat exchanger system, due to the complexity of the actual operating environment, it is usually unable to provide specific parameter values, but to give a rough range of values. In the actual calculation process, the designer must take into account the randomness of the parameters themselves, and make appropriate adjustment and optimization according to the actual situation to ensure the rationality and reliability of the design

Finally, groundwater seepage also has a promoting effect on the heat transfer efficiency of the buried pipe (Bao Lingling et al., 2023). In the design process of the buried tube heat exchanger, the viscous resistance coefficient, inertial resistance coefficient and physical property parameters of the backfill material are the key factors that must be considered, and these parameters have a direct impact on the heat transfer effect and stability of the buried tube heat exchanger. However, in practical applications, the measurement and calculation of these parameters are difficult due to the complexity of backfill materials. In most cases, designers can only use some empirical formula to calculate, and these formulas are usually based on approximations, not actual data. Therefore, these parameters themselves have great uncertainty, which may have a great impact on the performance of the buried tube heat exchanger.

3. Monte Carlo random simulation method

3.1 Theoretical basis of Monte Carlo method

In the field of stochastic analysis of buried pipes, some scholars have carried out relevant research. For example, Zhou Jize conducted a preliminary stochastic analysis on the random load of buried pipes by multiplying the cold and hot loads by a coefficient of variation respectively, and then estimating the length of buried pipes under different probability loads using the probability distribution function. In addition, scholars such as Pian-Changsheng and Zeng Shaojie used the principle of self-help method to explain the randomness of thermal properties of rock and soil, and proposed a reliability design method for buried pipes based on semi-empirical formulas. However, there are many random parameters involved in the design calculation of the buried tube heat exchanger of the ground source heat pump, and the calculation process is also quite complex, so complex mathematical processing is often needed in the calculation process, and sometimes the parameters in the model need to be simplified. For such problems, Monte Carlo method can be used as an effective solution.

As a solution, the Monte Carlo method is widely used in scientific research and engineering technology. This method, also known as statistical test method, is a computer simulation technology and calculation method based on random numbers. In practical application, Monte Carlo method can obtain the required statistical data and results by simulating a large number of random events, which can provide a better basis for decision-making and solve problems (Hyuk Chun Noha and Taehyo Park,2006). The basic idea of this method is to realize the effective description and research of random phenomena by using a mathematical model which can completely and accurately describe the target variable as a random simulation model. In order to better discover and understand the nature of random phenomena, it is necessary to incorporate the main random parameters affecting the target variables into the model as much as possible to ensure the accuracy and reliability of the model.

In the process of stochastic simulation, the sampling process is a crucial part, because it directly determines the probability distribution of the target variable. If the sampling process is not properly designed, it is easy to lead to excessive deviation of the generated data, which will affect the accuracy and reliability of the model. Therefore, in the process of random simulation, it is necessary to adopt a reasonable sampling method to ensure that the probability distribution of the target variable is as close as possible to the real situation.

MATLAB software is a powerful mathematical calculation software, it has its own random number generation function, can be directly sampled according to the distribution characteristics of the required samples. The random numbers generated by MATLAB software have good distribution characteristics, which can effectively improve the accuracy and reliability of random simulation. In addition, MATLAB software also provides a wealth of statistical analysis functions, which can be statistical analysis and visual display of the generated data, so as to better understand and analyze the results of random simulation. (Ma Feng and Feng Sheng, 2005).

In the third step, need to choose the appropriate mathematical model to more accurately simulate the relationship between variables in the real world, and then write a program based on the selected mathematical model and, depending on the requirements of the program, use the appropriate algorithm to generate search optimization results. In this process, it is necessary to input the obtained random samples into the written program, and then carry out a series of operations to obtain a new set of random samples. In the calculation process, the parameters of the model need to be constantly changed to obtain a new set of random samples, and these samples are analyzed and compared to determine the optimal model parameters. Finally, this process is repeated N times to obtain N groups with certain distribution characteristics of the target variable values, and these results are analyzed and compared to determine the optimal model parameters.

3.2 Monte Carlo reliability analysis method

According to the law of large numbers, using Monte Carlo digital simulation method does not guarantee probability (Guan Changsheng and Chen Xuyi, 2010):

$$P_f = N_f / N \tag{1}$$

Where, N is the sample size of the target value obtained by random simulation, and N_f target is determined in advance to be worthy of the maximum design value. N_f is the quantity of the target sample value greater than the maximum design value, that is, the sample value falling into the uncertain region; $N-N_f$ is the quantity of the sample value less than the maximum design value, that is, the sample value falling into the effective region. The unguaranteed probability is approximated by the unguaranteed frequency (N_f / N).

4. Case study for vertical heat exchanger

In 2010, a villa built in Jimo City, Qingdao, the total construction area is 430m^2, and the air conditioning area accounts for 370m^2 This villa consists of three floors, one underground and two above grounds, with a height of about 3m. The maximum cooling load in summer is 22.5 kW and the maximum heating load in winter is 19.4 kW. During the construction process, through the use of advanced air conditioning technology, not only the temperature and humidity of each floor can be accurately controlled, but also the indoor air quality of the entire villa can be guaranteed.

The implementation object of this project is a complex building. In order to create a comfortable office environment, a soil source heat pump air conditioning system is adopted. By burying two parallel double U-type pipes in the ground, the soil is used as a heat exchange medium to absorb the heat in the underground soil, and then the heat is transferred to the room to achieve indoor temperature regulation. In the process of buried pipeline construction, the backfill material selected for the project is the original mud backfill, which can ensure the stable operation of the soil source heat pump system and the service life of the soil source heat pump system. In addition, the properties of surrounding rock and soil are analyzed. The surrounding rock and soil layer are sandstone. This geological condition is conducive to the operation of the soil-source heat pump system. The project adopts a more mature drilling method to ensure the construction quality of the project and ensure the stable operation of the soil source heat pump system.

4.1 Determine the design of the buried tube heat exchanger under the conditions

In the design of the buried tube heat exchanger, for some parameters given in the form of intervals in the specification, or the parameter values measured by experimental methods, a more conservative value is usually selected as the design basis to ensure the reliability and stability of the equipment. This practice can not only effectively reduce the risk of failure during the operation of the equipment, but also improve the service life and safety performance of the equipment, so that it can reach the best state. In addition, this conservative design can also avoid equipment failures and safety accidents caused by improper parameter selection, so as to ensure the normal operation of equipment and personnel safety. Therefore, when designing a buried tube heat exchanger, it is very necessary to choose a more conservative value as the design basis.

In practical engineering, such as heating and cooling systems, the semi-empirical formula method is generally used to design and calculate the buried pipe, which is often used to estimate the heat transfer performance of the buried pipe. These formulas can calculate and determine the total length of buried pipe drilling to meet the engineering design requirements in order to achieve a cost-effective and efficient operating mechanism to achieve the best possible results. Especially in the implementation of different temperature and pressure conditions, such calculation methods are particularly important, and can provide key reference information for engineers to optimize the buried pipe design and verify its feasibility.

$$L_C = \frac{CAP_C(R_P + R_S F_C)}{T_{\max} - T_\infty} . (\frac{CPO_C + 1}{COP_C}) \tag{2}$$

$$L_H = \frac{CAP_H(R_P + R_S F_C)}{T_\infty - T_{\min}} . (\frac{CPO_H - 1}{COP_H}) \tag{3}$$

$$R_S(\mathrm{X}) = \frac{I(\mathrm{X}_{rb})}{2\pi k_s} \tag{4}$$

$$I_{rb} = \frac{r_b}{2\sqrt{a\tau}} \tag{5}$$

$$R_P = \frac{1}{2\pi r_i h} + \frac{1}{2\pi k_p} \ln \frac{\sqrt{nr_0}}{\sqrt{nr_0} - (r_0 - r_i)} + \frac{1}{2\pi k_b} \ln \frac{r_b}{\sqrt{nr_0}} \tag{6}$$

Where, R_S *and* R_P are classified as pipe wall thermal resistance and rock and soil thermal resistance. L_C is the length of the borehole in the summer refrigeration condition. L_H is the length of the borehole under the winter heating condition. CAP is the heat pump cooling capacity (or heat production). $T_{\max}$ is the maximum inlet water temperature of the heat pump unit. $T_{\min}$ is the lowest inlet water temperature of the unit. F is the operating share of heating and cooling of the heat pump system. r_b is the radius of the hole. a is the average diffusion rate of rock and soil. K_s is the average thermal conductivity of rock and soil. r_0 is the inner diameter of the buried pipe. h is the heat transfer coefficient of the convective heat exchange surface. r_i is the radius of the buried tube. k_p is the thermal conductivity of the buried pipe material. k_b indicates the thermal conductivity of the backfill material.

By transforming equation (2) and (3), the design outlet water temperature formula of the buried pipe is obtained:

$$T_{\min} = T_\infty - \frac{CAP_H(R_P + R_S F_C)}{L_H} \bullet \frac{CPO_H - 1}{COP_H} \tag{7}$$

$$T_{\max} = T_{\infty} + \frac{CAP_C(R_P + R_S F_C)}{L_C} \bullet \frac{CPO_C + 1}{COP_C} \qquad (8)$$

The design calculation of buried pipes in engineering involves the calculation of all parameters according to predetermined numerical values. Due to the random nature of many parameters in the formula for calculating the total length of drilling holes, in the reliability design of buried pipe heat exchangers, these random parameters are considered to follow a normal distribution or uniform distribution, and random sampling is conducted. The Monte Carlo simulation method is used to randomly simulate equation (7) and（8）, allowing for the determination of the water temperature at the outlet of buried pipes according to a certain probability distribution. An engineering example is used to illustrate the differences between reliability design methods and traditional design methods.

Monte Carlo stochastic simulation method is used to simulate the heat transfer process of the buried tube heat exchanger. The steps are as follows:

(1) Through the analysis of the above formula, the temperature of the outlet of the buried pipeline can be taken as the output result, while the input variables include random parameters, such as the length of the pipeline, the change rate of water temperature, and the thermal conductivity of the pipeline material. Therefore, we can use MATLAB programming language to write related programs, through the use scientific computing libraries to calculate function values. The program is written according to the calculation formula (2) ~ (8) of the design calculation formula of the buried tube heat exchanger. It is necessary to pay attention to the use of random number generators to ensure that the value of random variables is within a reasonable range to ensure the accuracy of calculation results.

(2) To determine the distribution type of random influencing factors, it is first necessary to collect data and observe the distribution of data and characteristic parameters to determine its type. Once the distribution type of the random influencing factors is determined, then the random parameters can be sampled using the corresponding distribution function. At the same time, repeated sampling techniques need to be used to ensure that the generated random variables are sufficiently diverse and representative. Finally, a programming language can be used to generate 1000 sets of random variables to meet the needs of practical applications

(3) It is necessary to build a simulation program, which can process the sample data, and then simulate the corresponding output variables based on the sample data, and view the distribution of the output variables for later analysis and optimization. Then, according to the simulation results, the output variables are analyzed to ensure the reliability of the output variables. In the process of analysis, it is necessary to consider the distribution of output variables, mean value, variance and other factors to ensure the accuracy and reliability of the simulation results. Finally, according to the analysis results, the simulation program is optimized to improve the accuracy and reliability of the simulation. In the process of optimization, it is necessary to consider the algorithm and parameters of the simulation program to improve the efficiency and accuracy of the simulation.

In order to ensure that the heat exchange capacity of the buried pipe can meet the needs of the cold load of the building, when designing the buried pipe heat exchanger, it is necessary to accurately calculate some parameters given in the form of intervals in the specification, or scientifically determine them through experiments, and under certain conditions, more conservative values are generally adopted for these parameters. To ensure that the heat transfer capacity of the buried tube heat exchanger can meet the needs of the building cooling load. Tab.1 shows the values of the parameters in the design process of the buried pipe, which directly affect the heat exchange capacity and service life of the buried pipe heat exchanger, so the values must be strictly in accordance with the specifications and standards in the design process

Tab. 1. Values of each parameter in the design of a villa buried pipe in Jimo

Parameters	Values	Parameters	Values
Drilling radius r_b (m)	0.068	U-tube outside diameter r_0 (m)	0.0165
Inside diameter of U-tube r_i (m)	0.0125	U-tube thermal conductivity k_p (W/(m • k))	0.42
Maximum inlet temperature of heat pump T_{max} (℃)	30	Rock and soil thermal conductivity k_s (W/(m • k))	2.1
Thermal diffusivity of rock and soil a (m²/s)	1.27×10^{-6}	Average soil temperature T_∞ (℃)	15
Performance coefficient COP of heat pump in summer	5.5	Cooling run share F	1
Heat pump rated cooling capacity CAPC (kW)	22.5	Running time τ	5875

Tab.1 shows the values of each parameter in the buried pipe design. According to the above data, the total length of the drill hole of the buried pipe heat exchanger is calculated by using the method of semi-empirical formula in engineering design.

$$L_C = \frac{CAP(R_P + R_S F_C)}{T_{\max} - T_\infty} \bullet \frac{COP_C + 1}{CPO_C} = 734m \qquad (9)$$

4.2 Reliability design of buried tube heat exchanger

Under the random condition considering the influence factors of the buried tube heat exchanger, the Monte Carlo random simulation method is used to simulate the drilling length randomly. This is because the semi-empirical formula (7) and (8) has enough accuracy and is widely used in practical engineering calculation, and can meet the requirements of engineering calculation. At the same time, the values of many random parameters involved in this formula, such as drilling depth, bottom hole pressure, rock characteristics, and the statistical types of these parameters, such as normal distribution or lognormal distribution, will directly affect the accuracy of the final calculation results. Therefore, these random parameters must be analyzed and studied in detail to determine the degree of their influence on the calculation results, and on this basis, the appropriate model is selected for simulation calculation to ensure the accuracy and reliability of the calculation results. The values and statistical types of random parameters involved in the formula are shown in Tab. 2.

In order to ensure the reliability and effectiveness of the buried pipeline, reliability design calculation is needed. In this process, many factors need to be taken into account, such as the total length of the hole, the depth of the hole and the ambient temperature. The total borehole lengths of 734m, 700m, 650m and 600m provided are respectively included in formula (9) for random simulation. Through detailed analysis and comprehensive calculation, the probability density curve and probability density accumulation curve of the temperature at the outlet of the buried pipeline are finally obtained, as shown in Fig. 1 and Fig. 2. These curves provide a better understanding of the temperature distribution at the outlet of the buried pipeline, thus providing a more accurate reliability design.

Tab. 2. Statistical characteristics of parameter of buried pipe

Parameters	Variable symbol (unit)	Type of statistic	Parameter distribution
Initial soil temperature	t_0 (℃)	Normal distribution	[14,0.3]
Soil thermal conductivity	k_s (W/m・k)	Even distribution	[2.1,3.5]
Thermal diffusivity of soil	a (m^2/s)	Even distribution	[0.75e-6, 1.27e-6]
Borehole radius	r_b (m)	Normal distribution	[0.075,0.005]
Outer diameter of buried pipe	r_0 (m)	Normal distribution	[0.016,0.0001]
Average rock and soil temperature	T_∞(℃)	Normal distribution	[14,0.3]
Maximum outlet water temperature of buried pipe in summer	T_{max}(℃)	Approximate normal distribution	[26.38, 1.48]

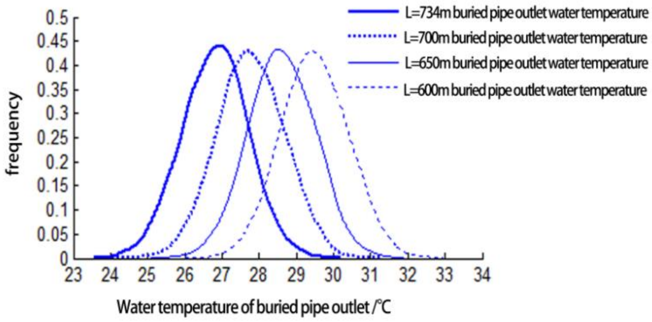

Fig. 1. Probability density curve of buried pipe outlet water temperature under different drilling length

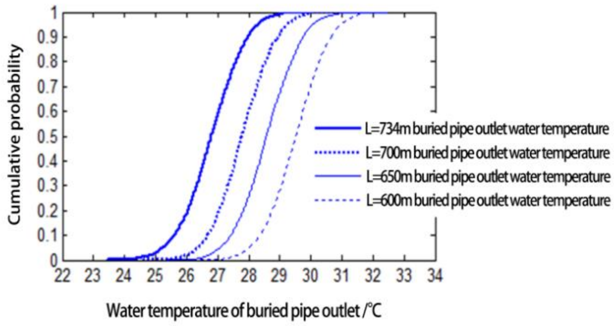

Fig. 2. Probability accumulation curve of buried pipe outlet water temperature under different drilling lengths

According to the random simulation results in Fig.1 and Fig.2, under the influence of various random factors, the water temperature at the outlet of the buried pipe approximately follows a normal distribution under different drilling lengths. If the design outlet temperature of the buried pipe is taken as a certain value, the probability value of the temperature at the outlet of the buried pipe under different total drilling lengths can be obtained. Fig. 3 shows the probability distribution curve of unguaranteed water temperature at the outlet of the buried pipe under different drilling lengths when the design outlet temperature of the buried pipe is 30℃ and 31℃ respectively. Tab. 3 summarizes the probability of unguaranteed water temperature at the outlet of the buried pipe under different drilling lengths.

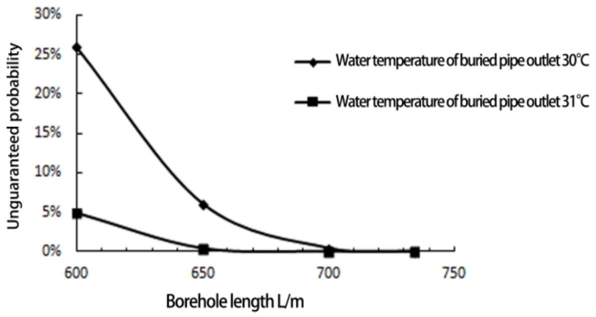

Fig. 3. The probability distribution curve of water temperature at the outlet of buried pipe under different drilling length is not guaranteed

Tab.3. The water temperature at the outlet of the buried pipe under different drilling lengths is not guaranteed

Total length of hole L/m	Unguaranteed probability	
	The outlet temperature of the buried pipe is 30°C	The outlet temperature of the buried pipe is 31°C
734	0	0
700	0.44%	0
650	6.10%	0.38%
600	26%	4.90%

According to the random simulation results, when the design outlet water temperature of the buried pipe is 30℃, it is considered that the cooling capacity of the heat pump unit can be guaranteed if the water temperature of the buried pipe outlet is lower than 30℃. When the total length of the drilling hole is 734m, the cumulative probability of the water temperature of the buried pipe outlet is 100%, then the probability of the corresponding buried pipe outlet water temperature is 0 under this working condition. When the total length of the drilling hole is 700m, the probability of the water temperature at the outlet of the buried pipe is 0.44%. When the total length of the borehole is 650m, the probability of the water temperature corresponding to the buried pipe outlet is not guaranteed to be 6.1%. When the total length of the drilling hole is 600m, the probability of the water temperature corresponding to the buried pipe outlet is 26%.

If the design outlet temperature of the buried pipe is 31℃, the probability that the water temperature of the buried pipe outlet is not guaranteed is 0 when the drilling length is 734m and 700m. When the total length of the borehole is 650m, the probability of the water temperature at the buried pipe outlet is not guaranteed to be 0.38%. When the total length of the borehole is 600m, the probability of the water temperature corresponding to the buried pipe outlet is 4.9%.

4.3 Comparative analysis of the results

In order to meet the needs of the maximum cooling load in summer, the design of the buried pipeline will adopt a more conservative parameter value under specific conditions, in order to avoid a series of risks and losses caused by overload operation, such as rupture, leakage, corrosion and other problems, so as to ensure the safe and stable operation of the pipeline. In the early stage of design, it is necessary to fully consider the differences in geological conditions, the influence of buried depth and other factors, especially the different effects of geological conditions on the physical and chemical properties of buried pipelines, such as soil pH, water content, temperature, etc., these factors will have an impact on the selection of pipeline materials, anti-corrosion treatment, insulation measures, etc. At the same time, the influence of different burial depths on cold air transport, such as heat dissipation effect and resistance loss of pipelines, should be deeply analyzed, so as to select the best burial depth. Finally, by optimizing the parameters of the buried pipeline, the reasonable drilling length is calculated to be 734 m, which can not only ensure the cooling capacity of the pipeline, but also avoid the excessive investment in the initial project, but also give full play to the cooling capacity of the pipeline and avoid the waste of resources.

Considering the randomness of the factors affecting the heat transfer process of the buried tube heat exchanger, especially the complexity of environmental factors and geological conditions, it is necessary to introduce some uncertainty and randomness in the design and construction process, allowing the random parameters to change within a certain range. Therefore, using Monte Carlo stochastic simulation method to simulate the drilling length and analyze the reliability of the simulation results can predict and evaluate the performance and reliability of the buried tube heat exchanger more accurately.

If the design outlet temperature of the buried pipe is 31℃, the probability that the water temperature of the buried pipe outlet is not guaranteed is 0.38%, it is equivalent to drilling 650 m, 84 m less than under certain conditions, which means that in practical applications, it is necessary to comprehensively consider the specific geological conditions and environmental factors to determine the optimal drilling length and buried pipe depth to ensure the performance and reliability of the buried pipe heat exchanger.

In the actual construction process, the unit drilling depth is usually about ¥100 yuan. For example, for the villa project in Jimo, it is calculated that if the drilling depth is 84 meters different, it will lead to a cost difference of about ¥8000 yuan. This is because, in this project, the depth of each drilling is determined according to the specific needs and design of the project, and the change of drilling depth will directly affect the cost of the project. In addition, if the length of the buried pipeline can be reduced by reducing the length of the drill hole, then this will also help reduce the initial project investment. These findings are of great significance for reducing the initial investment cost of such projects, and can better help control the cost of projects, thus improving the economic benefits of projects.

5. Summary

In this paper, we propose the use of the Monte Carlo stochastic simulation method to account for the randomness of influencing factors in buried tube heat exchangers. We apply this method to stochastically simulate the heat transfer process of a buried tube heat exchanger. Using a soil source heat pump system in a villa in Jimo as an engineering example, we randomly simulate the heat transfer process of the buried tube heat exchanger. Our results show that when the non-guarantee rate of the maximum cooling capacity of the buried tube in summer is 6.1%, the corresponding drilling length is 650m. This is compared with a drilling length of 734m calculated under certainty conditions, resulting in a reduction by 84m. These findings demonstrate that our reliability design method is significant for shortening drilling hole lengths and reducing initial project investments.

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