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Analysis of influence of running time on heat transfer efficiency of buried tube heat exchanger under different working conditions

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Abstract: There are still some problems with the actual heat transfer in ground-source heat pump systems. In order to study the influence of different working conditions on the heat exchange efficiency of the buried tube heat exchanger, the temperature field around the buried tube heat exchanger is simulated by using fluent software. The results show that the closer the temperature field is to the tube wall, the greater the temperature change is, and it has no effect on the soil layer with larger radial distance. In summer condition, soil temperature and heat transfer increase with increasing inlet velocity of working medium. When different backfillers are used, the backfillers with relatively large thermal conductivity can improve the heat transfer and improve the heat transfer efficiency. By analyzing the influence of different working conditions on the heat transfer efficiency of the buried pipe heat exchanger, the research results can provide reference value for the practical design of buried pipe and the future heat transfer simulation optimization of the heat pump system.

1. Introduction

In recent years, due to the rapid development of China's economy, the demand for non-renewable energy such as fossil fuels has increased, which inevitably leads to the shortage of energy and the generation of greenhouse effect. Therefore, the search for alternatives to fossil fuels has become an indispensable task for our country. Because of its large reserves, stability, safety and clean characteristics, geothermal energy has become the focus of clean energy development and utilization in various countries, and the utilization of geothermal energy for heating and cooling is also a crucial approach to reaching the "double carbon" goal. In the context of dual-carbon, ground source heat pump is recognized as one of the most efficient renewable energy systems, the development of heat pump technology is a key way to achieve zero carbon energy, buried pipe is the core component of the ground source heat pump system, reasonable improvement of the buried pipe heat exchanger heat exchange efficiency is of great significance to promote the ground source heat pump system. Ground source heat pump systems have different cooling and heating loads due to the differences in climatic conditions, use scenarios and operation strategies. The design factors of the ground source heat pump system mainly include geological conditions, initial ground temperature, buried pipe spacing, buried pipe structure and arrangement mode, cooling and heat load, buried pipe depth, borehole backfill material, pipe loaded liquid and operating conditions, etc. The main influencing factors are buried pipe spacing, arrangement mode and terminal cooling and heat load[1]. After a period of operation under different working conditions, the heat transfer efficiency of the system will be affected to different degrees. Zhang Dan et al simulated the influence of different inlet temperatures of the improved thermal transfer performance of the Enhanced Geothermal System (EGS) under summer working conditions by using Fluent software. Li Wei et al. used an experimental method similar to a heat probe and Fluent software to numerically simulate the heat exchange of buried tube heat exchangers with mixed backfillers composed of different components. Based on the characteristics of soil stratification, Yu Zhongyi et al. used Fluent software to conduct a simulation study on the field of soil temperature after 20 days of operation of a 50m deep buried tube heat exchanger under summer conditions[2]. Zhang Linlin et al., based on the analytical solution of the theoretical model of moving finite long-line heat source, simulated and studied the influence of seepage flow on the single-borehole buried tube heat exchanger by using MATLAB software programming[3]. Up to now, domestic research has mainly focused on laboratory research and numerical simulation research. Domestic and foreign engineering projects that have been put into use have problems in terms of heat transfer efficiency and sustainable operation, and there are few published data.

Based on this, this paper simulates the temperature field of the ground source heat pump (GSHP) buried tube heat exchanger, studies the effect on the temperature field on the surrounding soil temperature under various operating mode and then on the heat exchange performance of the whole GSHP system, and analyzes the heat exchange performance of the system. The research results can provide reference for the optimization design of the buried tube heat exchanger of the GSHP system.

2. Model Building

2.1 Physical model

2.1.1 Hypothetical analysis of heat-exchange facility process in Underground Heat Exchangers

In this simulation, the geometric model constructed is generally a cylinder with a buried pipe well depth of 100m and a remote boundary radius of 3m, in which the diameter of the buried pipe borehole is 150mm, the nominal outer diameter of the PE pipe is 32mm, the thickness is 3mm, and the center distance of the two discrete pipes is 75mm. The actual temperature field of soil layer around vertical buried pipe is very complicated, and it is an unsteady system. Considering the deep diameter ratio of buried pipe is large, so for the sake of simplifying the calculation and facilitate the solution, the secondary factors with less influence are ignored after analysis [1, 4].

2.1.2 Selection of simulation parameters

In this simulation, high-density non-metallic polyethylene material is selected as the buried pipe; Special grout materials and sand and stone for backfilling materials; The fluid heat transfer working medium in the pipe uses local tap water, and lets it be in a turbulent state, and assumes that the incoming flow speed is 0.5m/s unchanged; Taking a certain place in China as an example, the thermal physical property parameters of the materials are shown in Table 1.

The calculation and analysis of the temperature distribution of the soil layer in the buried pipe showed that the temperature of the soil from 0 to 20 meters below the surface remained basically unchanged, but the temperature of the soil in this section changed with the change of the surface temperature. For the convenience of calculation, it was considered that the temperature of the soil in this section was basically the same as that of the soil below 20 meters. The average annual temperature of the soil below 20 meters in this area is basically 14℃, so the initial calculated temperature of the soil in the system is 14℃.

Table 1: Material thermophysical parameters

	Density/ (kg/m^3)	Specific Heat Capacity/ (J/(kg·K))	Thermal conductivity/ (W/(m·K))
Soil(0 to 20m)	1500	3600	1.1
Soil(20 to 100m)	2000	2400	2.1
PE tube	960	0.33	2.26
Backfill material(sand and gravel)	1600	920	1.28
Backfill material(grout)	1900	1245	2.05
Working medium (winter)	999.8	4204	0.56
Working medium(summer)	994.7	4174	0.62

2.1.3 Creation of geometric model and mesh division

Mesh partition is a key step, and the mesh quality has a direct impact on the accuracy and efficiency of Ansys Fluent. Since the buried pipe in the model is a slender structure with a relatively large depth-to-diameter ratio, and the volume of backfill and soil in the model accounts for a large proportion, in order to ensure easy control of mesh quantity and better mesh quality, Gambit2.4.6 was used to select structured mesh to divide the grid.

2.1.4 Definition of boundary conditions

The boundary conditions include the values of flow variables and heat variables at the boundary. In this simulation, the κ-ε model of the standard turbulent flow model is adopted. The control Equation "k-epsilon", the time characteristic "Unsteady" and the Energy Equation "are selected. Then define boundary conditions: Set type of buried pipe inlet to "VELOCITYINLET" and outlet to "OUTFLOW"; Then set the inlet flow rate and incoming water temperature, as well as the temperature of the buried pipe, backfill and soil area and other related physical property parameters.

2.2 Mathematical model

The fluid flow in the U-shaped tube of the buried tube heat exchanger is generally turbulent and incompressible. It follows the mass conservation equation, momentum conservation equation and energy conservation equation, and adopts the standard κ-ε model to coupling the whole heat transfer process of the buried tube heat exchanger[5].

Mass conservation equation

The mass conservation law in the tube can be expressed as the sum of the mass flow rate per unit time and volume of the buried pipe output and the mass change rate in the buried pipe is equal to the mass flow rate of the buried pipe input. The law of conservation of mass is also commonly referred to as the continuity equation. As shown in the following equation:

$$\iint_{cs} \rho\left(\vec{v}\bullet\vec{n}\right)dA + \frac{d}{dt}\iiint_{cv} \rho dV = 0 \tag{1}$$

In the formula, $\rho\left(\vec{v}\bullet\vec{n}\right)$ —— the mass flow rate per unit area, also known as mass flux.

ρdV ——the mass of any microelement volume in the control body.

Momentum conservation equation

For X-Y-Z rectangular coordinate system, if the components of force vector $\vec{F}$ and velocity vector $\vec{v}$ in X, Y and Z directions are represented by F_x , F_y, F_z and v_x, v_y, v_z respectively, then the component formula of momentum conservation equation in each coordinate direction is:

$$\sum F_x = \iint_{cs} v_x \rho\left(\vec{v}\bullet\vec{n}\right)dA + \frac{d}{dt}\iiint_{cv} v_x \rho dV \tag{2}$$

$$\sum F_y = \iint_{cs} v_y \rho\left(\vec{v}\bullet\vec{n}\right)dA + \frac{d}{dt}\iiint_{cv} v_y \rho dV \tag{3}$$

$$\sum F_z = \iint_{cs} v_z \rho\left(\vec{v}\bullet\vec{n}\right)dA + \frac{d}{dt}\iiint_{cv} v_z \rho dV \tag{4}$$

$\sum F_i$ ——the sum of the component forces acting on the control body in the direction i;

$v_i \rho\left(\vec{v}\bullet\vec{n}\right)dA\left(=v_i dq_m\right)$ ——The i-direction momentum of the fluid input or output as the flow dq_m passes through the microplane dA ;

$v_i \rho dV$ ——The momentum in the i direction of the fluid element dV at any point in the control body.

Energy conservation equation

The energy conservation equation is a basic law in the flow heat exchange, which is actually the first law of thermodynamics, and is defined as: the increase rate of thermodynamic energy in the particle = the net heat flow into the particle - the work done by the volume force and the surface force on the particle.

$$\dot{Q} - \dot{W} = \iint_{cs} e\rho\left(\vec{v}\bullet\vec{n}\right)dA + \frac{dE_{cv}}{dt} \tag{5}$$

$$\frac{dE_{cv}}{dt} = \frac{d}{dt}\iiint_{cv} e\rho dV \tag{6}$$

$\dot{Q}$ ——The amount of heat exchanged between the fluid system and the outside world per unit time;

$\dot{W}$ ——The amount of work exchanged between the fluid system and the outside world per unit time;

$e\rho\left(\vec{v}\bullet\vec{n}\right)dA$ ——Energy input or output per unit time fluid passing through dA , or energy flow;

E_{cv} ——The instantaneous total energy in the control body;

$e\rho dV$ ——The storage energy of any microfluid of volume dV .

The formula is a general energy conservation equation for the control body. In the formula, the left term is the migration energy, the right term is the storage energy, and the unit of each term is J/s or W.

Studying the heat transfer process between the ground heat exchanger and the soil is the key content of the soil source heat pump system. Amount of heat is transferred between the heat exchanger as well as the soil directly affects the heat transfer performance of the heat pump system. Therefore, the analysis of the heat transfer mechanism of the buried tube heat exchanger in the soil is the basic work of the soil source heat pump system[6].

Fluid heat transfer equation in ground tube heat exchanger

$$\frac{\partial T_l}{\partial t} = -u\frac{\partial T_l}{\partial z} - \frac{2\alpha}{\rho_l c_l r_i}\left(T_l - T_g\right)\Big|_{r=r_i} \quad (7)$$

T_l ——the fluid temperature in the heat exchanger, K;

u ——the fluid velocity in the heat exchanger, m/s;

T_g ——the heat exchanger tube wall temperature, K;

α —— the coefficient of convective heat transfer between the tube wall and the fluid in the heat exchanger, $W/(m\bullet K)$;

ρ_l ——the fluid density, kg/m^3.

shaped wall conducts heat

$$\rho_g c_g \frac{\partial T_g}{\partial t} = \frac{\lambda_g}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_g}{\partial r}\right) + \frac{\partial}{\partial z}\left(\lambda_g \frac{\partial T_g}{\partial z}\right) \quad (8)$$

T_g —— the tube wall temperature, K;

ρ_g —— the tube wall density, kg/m^3;

c_h —— the specific heat capacity of the tube wall, $J/(kg\bullet K)$;

λ_h —— the thermal conductivity of the tube wall, $W/(m\bullet K)$.

Soil layer conducts heat

$$\rho_t c_t \frac{\partial T_t}{\partial t} = \frac{\lambda_t}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_t}{\partial r}\right) + \frac{\partial}{\partial z}\left(\lambda_t \frac{\partial T_t}{\partial z}\right) \quad (9)$$

T_t —— the soil temperature, K;

ρ_t —— soil density, kg/m^3;

c_t —— the specific heat capacity of soil, $J/(kg\bullet K)$;

λ_t —— the thermal conductivity of the soil, $W/(m\bullet K)$.

Initial condition

$$t=0,\quad T_l = T_g = T_h = T_t = T_0 = T_\infty \quad (10)$$

t —— the simulation duration, s;

T_0 ——the initial soil temperature, K;

T_∞ —— the initial soil temperature at infinity, K.

Boundary condition

Working medium entry condition at the mouth of buried pipe

$$T_l(z=0)=T_{lin} \tag{11}$$

Remote boundary condition

$$T_\infty = T_t = T_0 \tag{12}$$

$$\lambda_t \frac{\partial T_t}{\partial r}\Big|_{r=r_\infty} = 0 \tag{13}$$

Boundary conditions of soil and backfill

$$\lambda_h \frac{\partial T_h}{\partial r}\Big|_{r=r_h} = \lambda_t \frac{\partial T_t}{\partial r}\Big|_{r=r_h} \tag{14}$$

$$T_h = T_t\Big|_{r=r_h} \tag{15}$$

Boundary conditions of buried pipe wall and backfill

$$\lambda_g \frac{\partial T_g}{\partial r}\Big|_{r=r_0} = \lambda_h \frac{\partial T_h}{\partial r}\Big|_{r=r_0} \tag{16}$$

$$T_g = T_h\Big|_{r=r_0} \tag{17}$$

3. Analysis of calculation results

First, taking the summer working conditions as an example, three soil cylinders were selected in the r direction, namely, plane A (r=0.1m), plane B (r=0.5m) and plane C (r=1m).

It can be seen from FIG. 1 that the temperature change of plane A is greater than that of plane B and plane C, indicating that the closer the place is to the tube wall, the greater the temperature change. In addition, surface C kept the temperature of 287K unchanged for A period of time in the early stage, but the temperatures of surface A and surface B changed almost instantaneously, indicating that when the heat exchange between the buried tube heat exchanger and the soil, the farther the soil layer is from the tube wall, the more time is needed for heat exchange and the less the impact is.

Taking summer conditions as an example, inlet flow rates of 0.5m/s and 0.7m/s were selected respectively. It can be seen from Figure 2 that different inlet flow rates also have a great impact on the heat exchange of the buried tube heat exchanger.

When the inlet flow rate is different, the greater the flow rate is, the greater the heat transfer, but the greater the heat exchange, the lower the refrigeration efficiency of the buried tube heat exchanger, and the lower the operating performance of the buried tube heat exchanger under summer conditions. On the contrary, the greater the heat exchange, the more conducive to improving the heating efficiency, but also improve the operating performance of the buried tube heat exchanger in winter conditions.

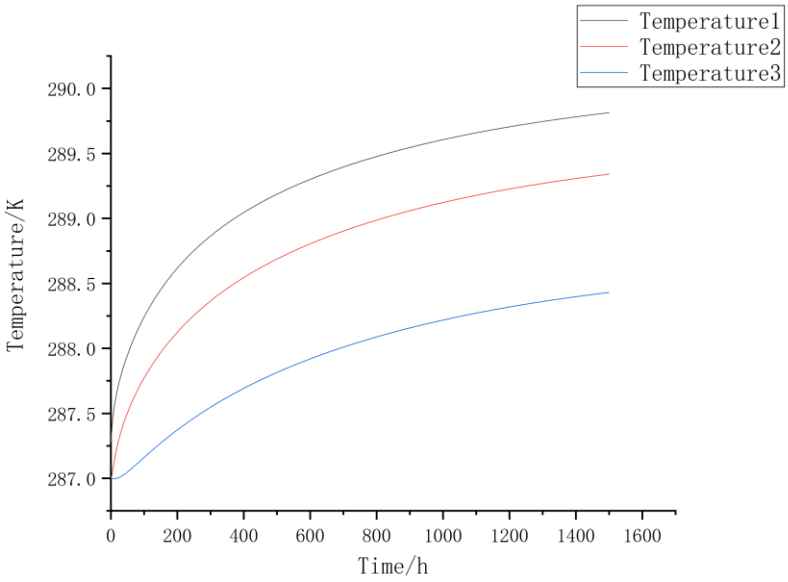

Figure 1: Temperature change of soil layer at different distance with running time

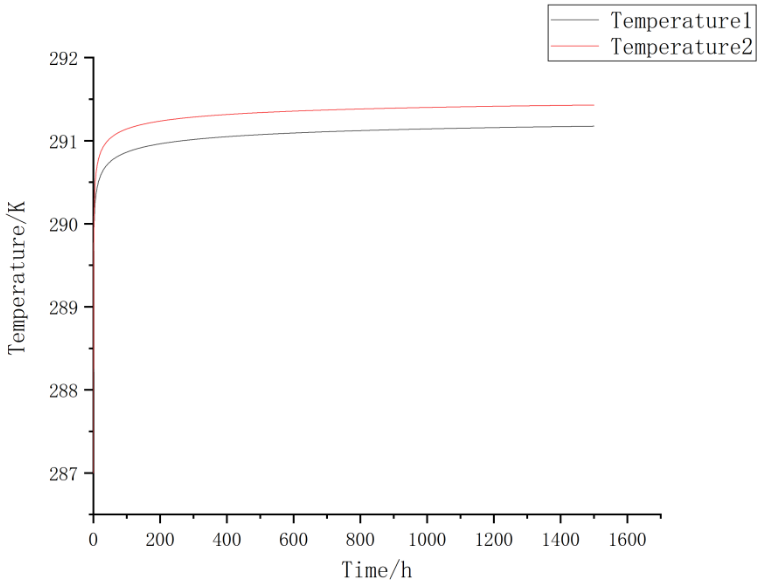

Figure 2: Variation of outlet fluid temperature of buried pipe with operating time under different inlet flow rates

Taking winter conditions as an example, it can be seen from Figure 3 that different soil types have significant changes in soil temperature. 0-20m of the soil has a low thermal conductivity, 20-100m of the soil has a high thermal conductivity, in winter conditions, the first 20m of the working medium and the soil heat exchange, 0-20m of the soil and the working medium temperature difference is large, so the temperature change is large, resulting in the temperature of the working medium rise, soil temperature decrease, with the running time, the working medium temperature and the soil temperature close. When entering 20-100m, the heat transfer slows down and the final temperature becomes stable[7-9].

Soil in most areas will be stratified, and different layers of soil generally have different heat transfer properties. The stratification model is closer to the actual soil thermal property parameters, which has different effects on the heat transfer effect of the buried tube heat exchanger. Increasing the thickness of the soil layer with high thermal conductivity can enhance the overall heat transfer energy efficiency of the buried tube heat exchanger. The greater the thickness of the high thermal conductivity soil layer, the higher the heat transfer efficiency than that of a single soil layer and the better the heat transfer effect along with the operation time of the ground source heat pump.

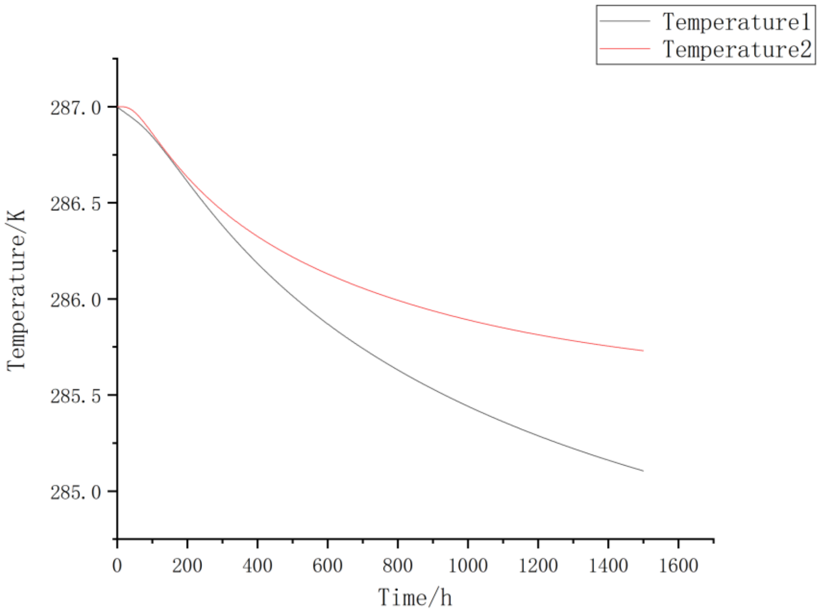

Figure 3: Variation of outlet fluid temperature of buried pipe with operating time under different soil types

Taking winter and summer conditions as an example, it can be seen from FIG. 4 and 5 that different backfillers also have significant changes in soil temperature. When the thermal conductivity of backfill is high and the thermal conductivity of backfill is low, the buried pipe return water temperature is higher in winter condition and lower in summer condition, so the actual efficiency of the heat pump will be closer to the efficiency under rated condition. The backfill of the buried heat exchanger is an important link in the construction of the ground source heat pump system. If the backfill is not selected or constructed properly, the performance of the heat pump will be reduced with the progress of the running time.

Therefore, it is necessary to seriously study and optimize the backfill, develop a new type of backfill materials, improve the backfill construction process, we must combine theoretical analysis with practical engineering for in-depth research, and finally find efficient and economical backfill materials.

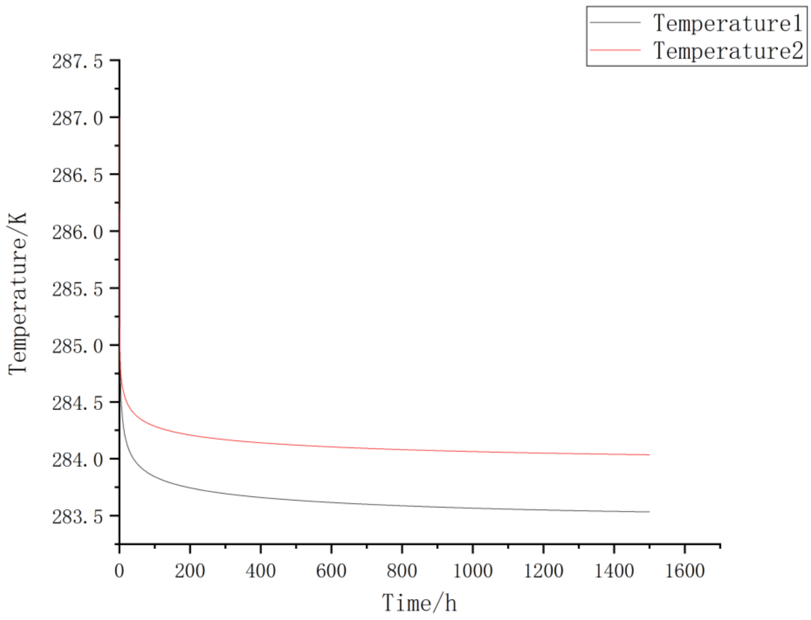

Figure 4: Variation of outlet fluid temperature of buried pipe with operating time under different backpacking (Summer)

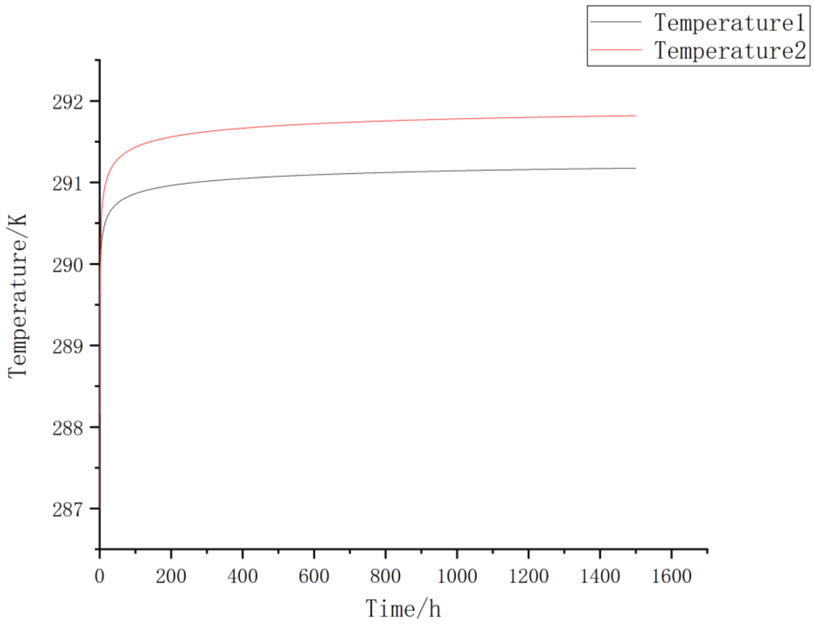

Figure 5: Variation of outlet fluid temperature of buried pipe with operating time under different backpacking (Winter)

4. Conclusions

Through the simulation analysis of Fluent, this paper concluded that the change of inlet flow rate, soil type and backfill would affect the distribution of surrounding soil temperature field and the heat transfer efficiency of ground source heat pump. Therefore, it has occasion to select the site selection of the project, the determination of inlet current velocity and the selection of backfill. In this way, under the premise of ensuring the heat transfer intensity and the soil area can be fully utilized, it also ensures that the winter heat exchanger can absorb enough heat required for heating, and the summer can extract enough cold from the soil.

Although the influence of running time on the heat transfer efficiency of the buried tube heat exchanger under different working conditions is roughly analyzed by numerical simulation, further research can be carried out from the following aspects in the future.

This paper only considers the average inlet temperature and average inlet velocity under winter and summer conditions in a short period of time, ignoring the changes in atmospheric and soil temperature, buried pipe spacing, seepage action and thermal interference, etc., and can consider the effects of all these factors on the ground source heat pump system under long-term operation. In order to simplify the simulation, only the stratification of two layers of soil was considered in this paper. Since soil is a complex multi-phase mixture, the soil types are different in different underground regions, so the heat transfer characteristics of soil layers at different depths should also be considered, and only two backfillers with different thermal and physical properties were studied in this paper. The influence of the thermal properties of other borehole backfill materials on the temperature distribution of the buried pipe system and the surrounding soil can also be considered, and the soil layer with different properties of backfill materials can be further studied.

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