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HEAT TRANSFER CHARACTERISTICS ANALYSIS OF VERTICAL BURIED HEAT EXCHANGERS

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ABSTRACT

Heat transfer characteristics of buried closed-loop heat exchange tubes directly affect the efficiency of ground source heat pump systems. To improve the heat transfer efficiency of a geothermal system, a simulation model of a shallow buried closed-loop heat exchanger in Chengdu is established. The heat transfer characteristics of U-tube heat exchangers are investigated. The influence of tube diameter, flow velocity, tube configuration and well group distribution distance on the system heat transfer was studied. The results show that the highest heat transfer efficiency of the buried tube is at the bottom of the inlet section. The optimal heat transfer fluid velocity in the inlet is around 0.6 m/s, and the continuous operation time should not exceed 10 h. The efficiency of the W-shaped structure is increased by 4.8% than U-shaped, and the uniform distribution distance arrangement is the best. The overall heat transfer performance of the borehole heat exchanger is the highest when the distribution distance is 0.5-0.75 m. Those results can provide a basis for designing buried heat exchangers and optimizing geothermal systems.

Key words: Ground source heat pump, heat exchanger, heat exchange efficiency, well group.

1. INTRODUCTION

Shallow geothermal energy is clean, environmentally friendly, and renewable. The ground coupled heat pump (GCHP) is recognised as one of the most efficient renewable energy systems. Geothermal heat exchange (GHE) is one of the most important parts of GCHP and its heat exchange performance affects the stability and economy of the entire system. Therefore, the heat exchange performance of the underground heat exchanger is important for GCHP operation.

Many researchers studied the heat transfer performance of underground heat exchangers. Yong *et al.* (2014) and Zhou *et al.* (2016) found that increasing the flow velocity can not improve the heat transfer performance of the system infinitely. Li *et al.* (2017) found that the temperature difference between the inlet and outlet temperatures is large when the inlet velocity is low, which results in serious thermal interference. Javadi *et al.* (2019) found that the triple helix buried tube has a better heat transfer performance than the single U-type. Luo *et al.* (2016) studied the heat transfer performance of double U-type, three U-type, double W-type and spiral buried tubes. The results showed that the comprehensive performance of the three U-type is the best. Mehrizi *et al.* (2016) found that the heat transfer performance of full circle W-type is better than that of single U-type and single W-type, and the series mode is better than the parallel mode. Benamar *et al.* (2015) showed that the heat exchange performance is 7% higher than traditional smooth circular tubes, and tube layout affects the ground source heat pump system. Xiao *et al.* (2015) found that the thermal resistance of multiple inputs and single outputs is reduced by 29% ~ 34% than the single U-shaped heat exchange tube, and the heat exchange resistance is reduced by 10% ~ 15% in the double U-shaped heat exchange tube. Su *et al.* (2017) found that the finned tube heat exchanger is better than that of the light tube heat exchanger when the drilling depth is shallow. Bezyan *et al.* (2015) found that the helical tube's performance is better than the W-type and U-type. Reza *et al.* (2018) designed shallow ribbed enhanced heat exchange tubes with horizontal aluminium rods (fins) and explored the effect of pitch and soil backfill soil properties on its heat exchange. Zarrella *et al.* (2013) found that the heat transfer performance of the helical tube energy reactor is better than that of the three U-shaped tubes. Zhang *et al.* (2016) found that the soil temperature response and recovery characteristics caused by the buried heat exchange tube group are affected by geological conditions. Che *et al.* (2015) established a ground source heat pump fork/sequential row simulation model and showed that the soil temperature field is greatly affected by well spacing. Based on the superposition principle of the temperature field, Li *et al.* (2015) established a heat transfer model of the tube group to couple the fluid flow in the tube, which showed that the area utilization rate of the 18-hole plum blossom arrangement is 12.5% higher than that of 16-hole square arrangement.

The difference in soil thermophysical parameters in the depth direction (Mogensen 1983) is ignored, and the whole soil layer as a homogeneous body is considered in previous research. The effect of this assumption on the results can not be ignored (Signorelli *et al.* 2007). The stratification of soil is more in line with reality (Chen *et al.* 2015), especially for different soil condi-

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tions in different regions. Geological conditions have a significant effect on heat exchange performance. The design and arrangement of heat exchangers should be based on specific geological conditions (Loveridge *et al.* 2019). Most studies focus on a single well, and the research of well groups is still insufficient. Based on the soil's physical properties in Chengdu, the heat transfer performance of a 100 m deep buried tube heat exchanger is analyzed. The vertical U-shaped tube and its influence on the surrounding soil are explored. Effects of inlet velocity, buried tube configuration (U-shaped, W-shaped, spiral) and tube diameter on the layered heat transfer performance of the buried tube are analyzed.

2. NUMERICAL SIMULATION MODEL

2.1 Geometric Model

The ground source heat pump system for a building is shown in Fig. 1. A U-shaped tube is the heat exchange part of the underground borehole heat exchanger, and the heat pump unit connects the underground heat exchange part and the building air conditioning terminal system. The earth is the heat source (winter) or radiator (summer) to provide the heat (winter) or cooling capacity (summer) for the building. A numerical simulation model is established, mainly composed of circulating working medium (water), tube line, backfill material and soil. The soil is divided into three layers (clay layer, pebble layer, and mudstone layer) according to Chengdu's geotechnical properties (Xie *et al.* 2018). The thickness and physical parameters of each layer are shown in Table 1. The drilling depth H_S is 100 m, the buried tube depth H_P is 99.5 m and the drilling diameter R_W is 0.135 m. The center spacing D_P of the tube is 0.0675 m, the outer diameter D_e is 0.032 m, the inner diameter D_i is 0.026 m and the thermal conductivity is 0.44 W/(m · K). The diameter r_s of soil area is 6 m. The heat exchange process between the U-tube heat exchanger and soil is very complex. The assumptions are given for the model:

1. The initial temperature of the whole system is 291.5 K.
2. The thermophysical parameters of soil are isotropic and remain unchanged, and the physical properties of soil and backfill material are the same (Wu *et al.* 2017).
3. There is heat conduction between the buried tube and soil.
4. Complete contact between various geological formations, geotechnical and backfill soil, backfill soil and buried tube wall, the thermal resistance between them is ignored (Yang *et al.* 2013).
6. The bottom surface is at a constant temperature, the top surface is a convective heat transfer surface with the atmosphere and the surrounding surfaces are adiabatic.

The ambient temperature T_s is 293.15 K, the inlet fluid temperature T_i is 308 K and the inlet flow velocity u_f is 0.6 m/s.

Table 1 Geotechnical parameters in Chengdu (Xie *et al.* 2018)

Geology	Thickness (m)	Density (kg/m^3)	Thermal conductivity (W/(m · K))	Specific heat (J/(kg · K))	Initial temperature (K)
Clay layer	5	1600	1.2	1420	291.5
Pebble layer	20	1840	1.62	1180	291.5
Mudstone layer	75	2530	2.01	940	291.5

2.2 Model Verification

Using the soil's thermophysical parameters within 100 m of Nanjing (Ma *et al.* 2020), the soil is divided into 10 layers. The U-tube material is HDPE, and the diameter is 25 mm. The inlet temperature is 308 K, and flow velocity are 0.6 m/s, 0.8 m/s, 1.0 m/s, and 1.2 m/s respectively. The system runs continuously for 48 hours. Actual (Li *et al.* 2020) and simulated outlet water temperatures under different velocities are shown in Fig. 2. There is a maximum difference of 0.25 K between the actual and simulated outlet temperatures at 0.6 m/s. The relative error of the outlet temperature is 0.083%. There, the heat transfer model is reasonable.

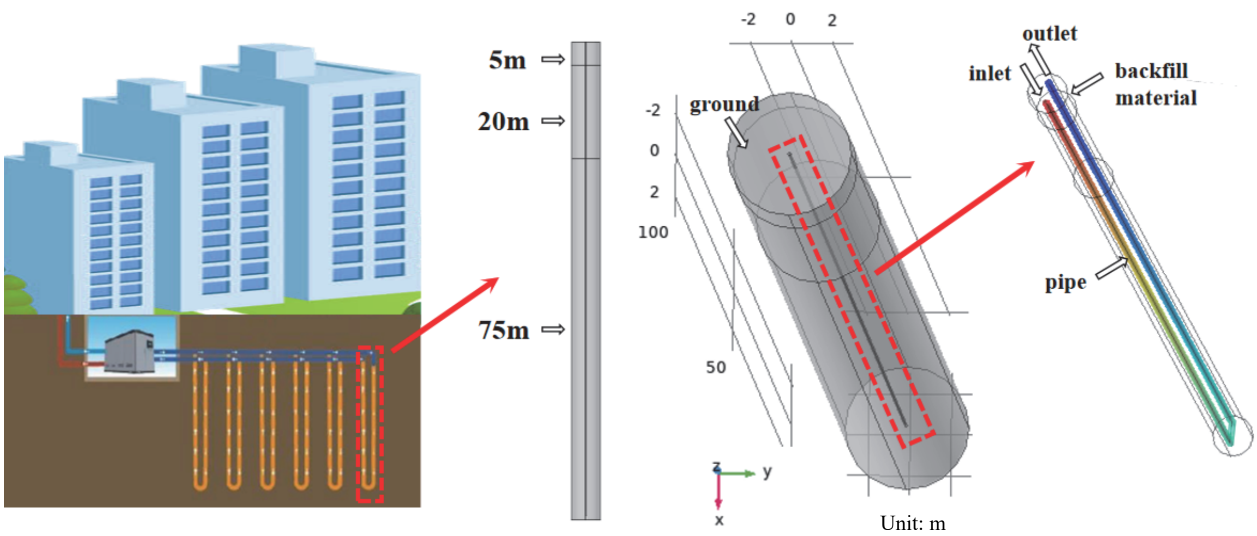


Fig. 1 Heat exchange model of U-tube

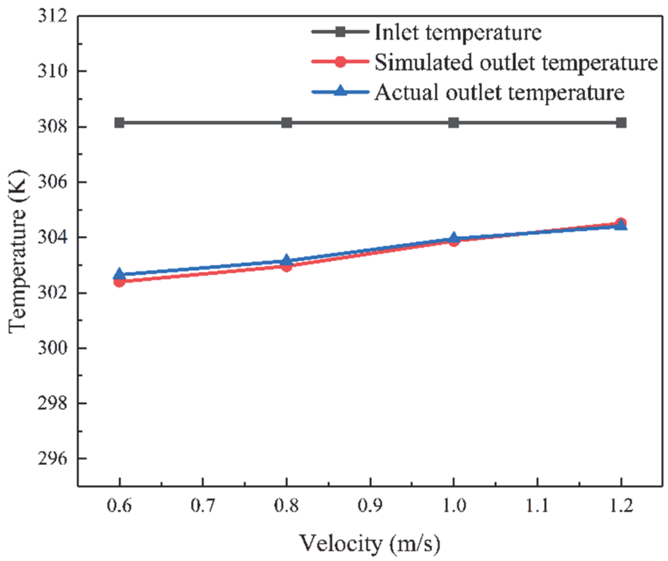


Fig. 2 Actual and simulated outlet water temperatures under different velocities

3. HEAT TRANSFER PERFORMANCE OF SINGLE WELL

3.1 Heat Transfer Performance of U-Tube

Figure 3 shows the water temperature at different depths at 18 h and 24 h when the tube's inner diameter is 26 mm and flow velocity is 0.6 m/s. The water temperature in the tube shows a downward trend along the flow direction, but the change rate gradually decreases. This is because the working medium in the tube continuously exchanges heat with the surrounding soil while flowing. Its temperature gradually decreases. So, the heat transfer efficiency and temperature drop rate decrease. Water temperatures in the flow direction are the same at different times, but overall heat transfer efficiency decreases with time.

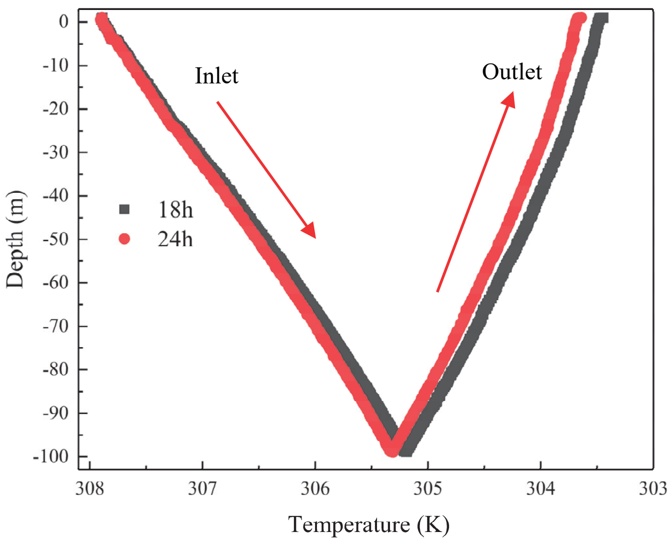


Fig. 3 Water temperature at different depths

Figure 4 shows the soil excess temperature curve with time. The excess temperature increases with the system operation, and it rises by about 6K after 24 hours. The excess temperature increases rapidly in the early stage, but the growth rate decreases along operating time. Because the excess temperature is low in the early stage, the system's heat transfer performance is better, and the rapid accumulation of heat leads to a rapid increase in the excess temperature. That also leads to a decrease in heat transfer performance and heat accumulation rate, and the growth rate of excess temperature decreases. The soil temperature tends to be stable value finally.

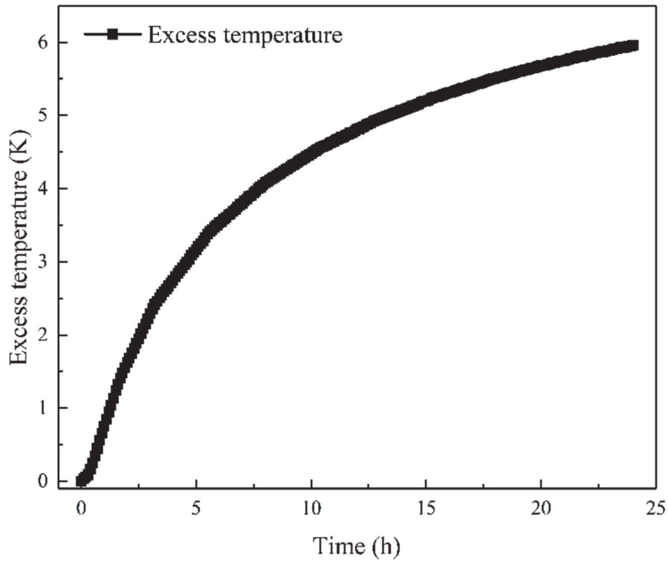
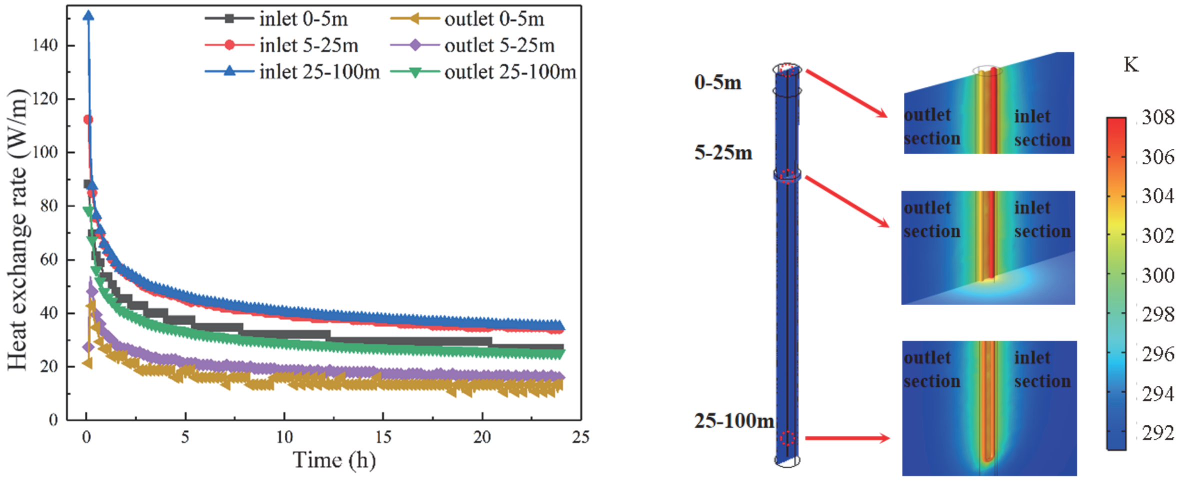


Fig. 4 Soil excess temperature curve with time

Soil's physical properties have a great effect on the system. According to different soil layer depths, the buried tube is divided into 6 sections: inlet 0-5 m, 5-25 m, 25-100 m, and outlet 0-5 m, 5-25 m, 25-100 m. The heat exchange rate per unit length of tube and temperature of U-type heat exchangers at different sections are shown in Fig. 5. The heat transfer changes of each section show drastic changes in the initial stage and then tend steadily. In the outlet section, there is an increasing process in the early stage due to the influence of the initial temperature in the tube. For the heat exchange of different soil layers, the maximum heat exchange per unit length is in the inlet 25 m-100 m section for a higher soil thermal conductivity. For the same soil layer, the heat exchange per unit pipe length in the inlet section is larger than that in the outlet section.

The heat exchange rate per unit length of outlet 0-5 m section is the smallest. On the one hand, 0-5 m section has the lowest soil thermal conductivity and the lowest working medium temperature, which resulting in the minimum heat exchange capacity. On the other hand, the temperature of inlet 0-5 m section is the highest as shown in Fig. 5(b). The soil temperature between the two tubes is more than 306 K. The thermal interference between the inlet and outlet sections is serious, which resulting in a thermal short circuit effect and affecting the heat exchange of the 0-5 m section.



(a) Heat exchange rate at different sections (b) Temperature distribution

Fig. 5 Heat exchange rate per unit length and temperature of U-type heat exchangers at different sections

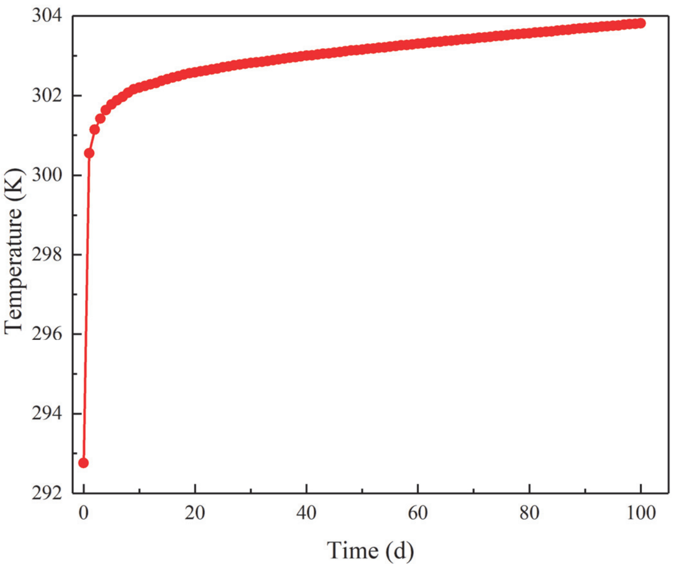
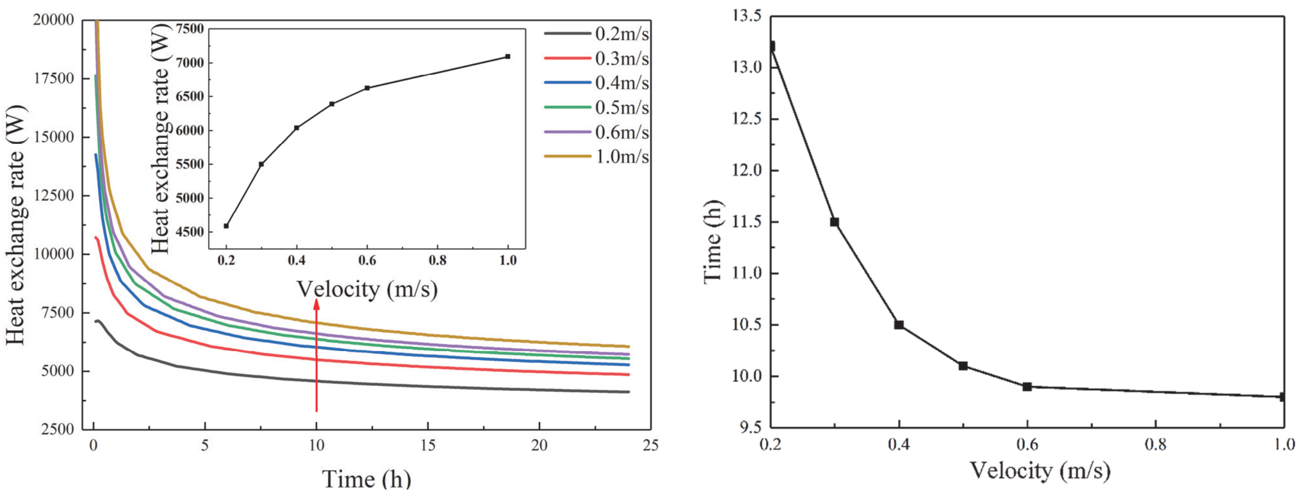


Fig. 6 Outlet water temperature after 100 days of continuous operation

Figure 6 shows the outlet water temperature after 100 days of continuous operation. The outlet temperature increases about 10°C in the first ten days. Then the change rate decreases with time, and the change value is about 1.8°C in the next 90 days because the working fluid exchanges heat with the surrounding soil during the operation. In the initial stage, the soil temperature around the tube is low and the system's heat exchange performance is the best. As the soil temperature around the tube grows, the heat exchange efficiency decreases, which results in a smaller temperature change.

3.2 Effects of Inlet Velocity

As shown in Fig. 7(a), the heat exchange rates are the same under different velocities. The heat exchange rate decreases rapidly in the first 2 h, and then the rate gradually tends to be stable. Moreover, the heat transfer efficiency change rate decreases gradually with velocity increases. From 0.2 m/s to 0.6 m/s, the heat transfer is increased by 34.6%. While it is only 16% when the velocity is from 0.6 m/s to 1.0 m/s. Therefore, increasing flow velocity can improve the system heat exchange efficiency, but the improvement effect decreases.



(a) Heat exchange rate (b) Time diagram of 90% decrease in heat exchange

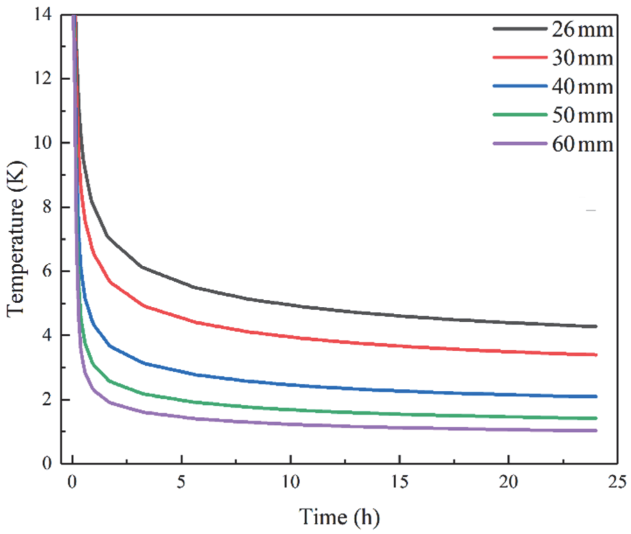
Fig. 7 Heat transfer performance under different velocities

When the decrease rate of heat exchange efficiency reaches 90%, the system reaches stability. A timing diagram of 90% decrease in heat exchange under different velocities is shown in Fig. 7(b). The higher the flow velocity is, the shorter the system's efficient operation time is. After the flow velocity exceeds 0.6 m/s, the efficient operation time is about 10 h, which indicates that the flow velocity has little effect on the efficient operation time. To ensure efficient operation of the system, the continuous operation time should not exceed 10h in a working cycle of one day.

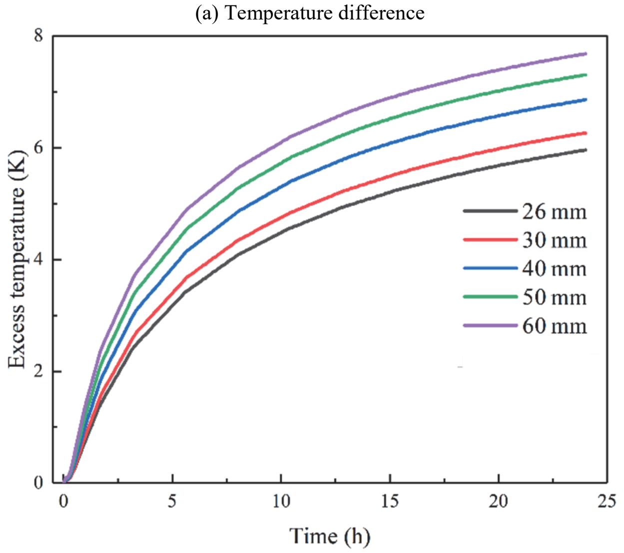
3.3 Effects of Tube Diameter

As shown in Fig. 8(a), the smaller the tube diameter, the larger the curvature radius of the temperature difference curve. Then, the longer the working medium's temperature change is, the longer the transition period is. That is because the heat exchange capacity of the soil is limited. For the working medium of large flows, the larger the heat exchange area between the soil and the tube, the higher the heat exchange efficiency is. That result in the soil reaches thermal saturation rapidly, and the soil temperature rises rapidly. The transition period of the temperature change is shorter. As shown in Fig. 8(b), the excess temperature of the soil under different tube diameters shows an upward trend with time, but the rate gradually decreases. That is because the increase in the soil temperature leads to a decrease in the heat transfer performance. Therefore, the temperature rise rate decrease.

Figure 9 shows the heat exchange rate with different tube diameters. The heat exchange rate changes significantly in the initial 5 h and then tends to be stable. The temperature difference decreases with the increase of the tube diameter. That is because the heat exchange area between soil and tube increases with increasing tube diameter. Under the same inlet temperature and inlet flow velocity, the heat exchange increases and the soil temperature rises, which results in the decrease of heat exchange temperature difference. The larger the tube diameter is, the greater the heat exchange is. However, the increase rate decreases as the tube diameter increases, which indicates the heat exchange rate does not increase infinitely with the increase of the tube diameter. The shorter the continuous operation time is, the greater the heat exchange is. The larger the tube diameter is, the greater the decrease of the heat exchange per unit time.



(a) Temperature difference



(b) Excess temperature

Fig. 8 Temperature difference and excess temperature under different tube diameters

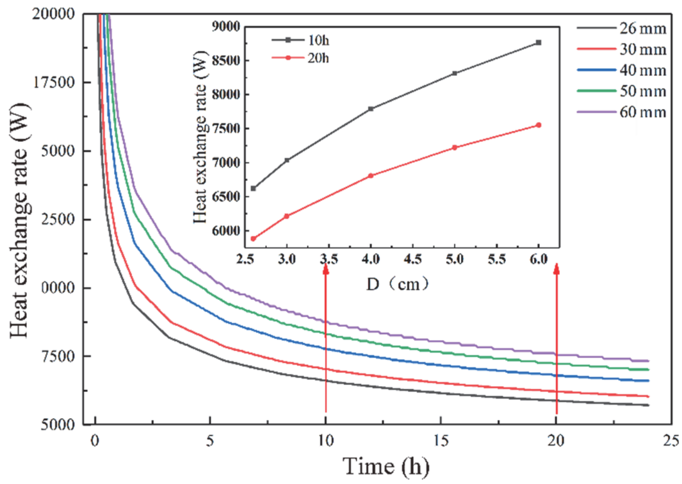


Fig. 9 Heat exchange rate with different tube diameters

3.4 Comparison of Different Tube Configuration

W-shaped and spiral-shaped underground heat transfer tubes are studied to explore the influence of different tube configurations on heat transfer performance. As shown in Fig. 10, the W tube spacing is 33.75 mm, the spiral tube pitch is 0.3 m, and the spiral outer diameter of the spiral tube is 90 mm.

As shown in Fig. 11, the temperature difference between the three tubes exhibits the same trend, and the W-shaped tube is significantly higher than the other two tubes. The heat transfer increase of W-shaped and spiral tubes compared with U-shaped tubes is shown in Fig. 12. The heat exchange rates of W-shaped tubes and spiral tubes change greatly at the beginning and show fluctuation, and then the two curves gradually approach stability. Compared with the U-shaped tube, the heat exchange rate of the borehole heat exchanger with the W tube is increased by about 10% in the first 2 h, and it tends to a stable increase of 4.8%. At the same time, the spiral tube has no improvement compared to the U-shaped tube.

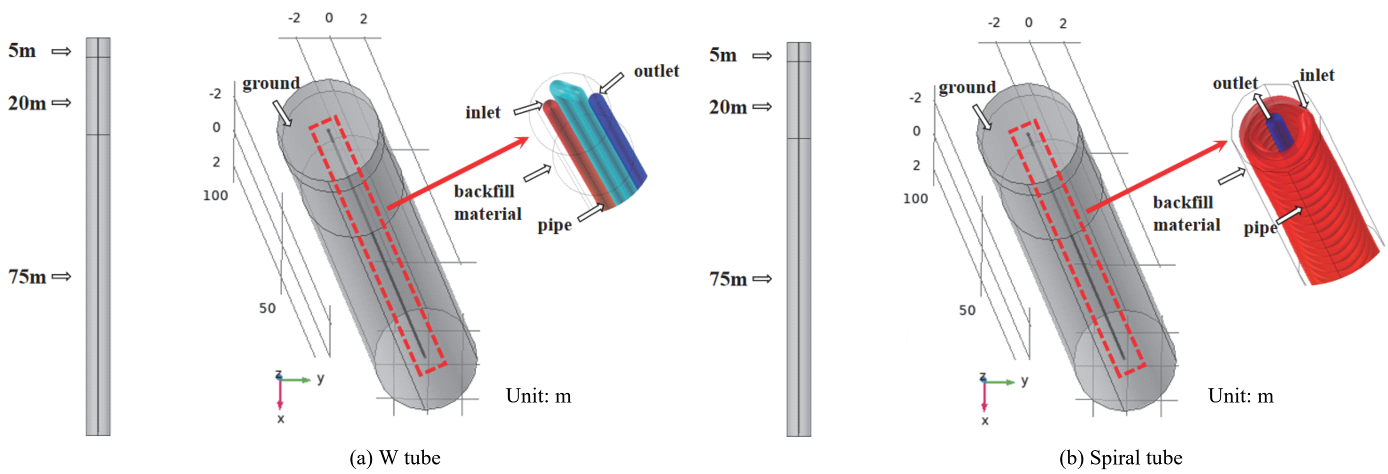


Fig. 10 Model of W-shaped and spiral tubes

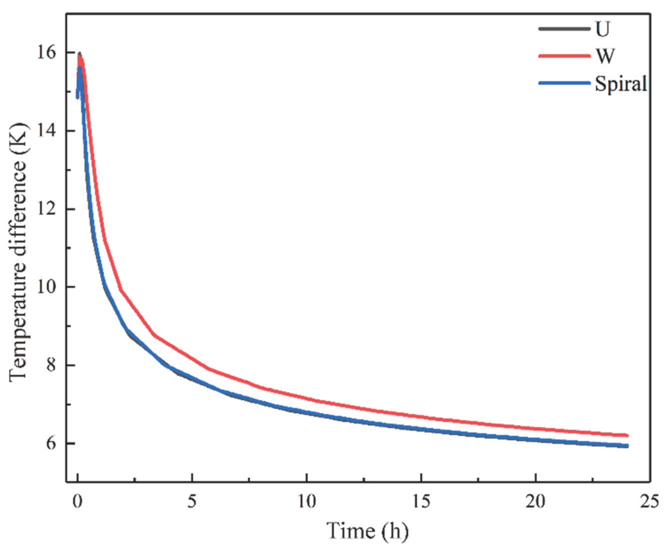


Fig. 11 Temperature difference of U-shaped tube, W-shaped tube and spiral tube

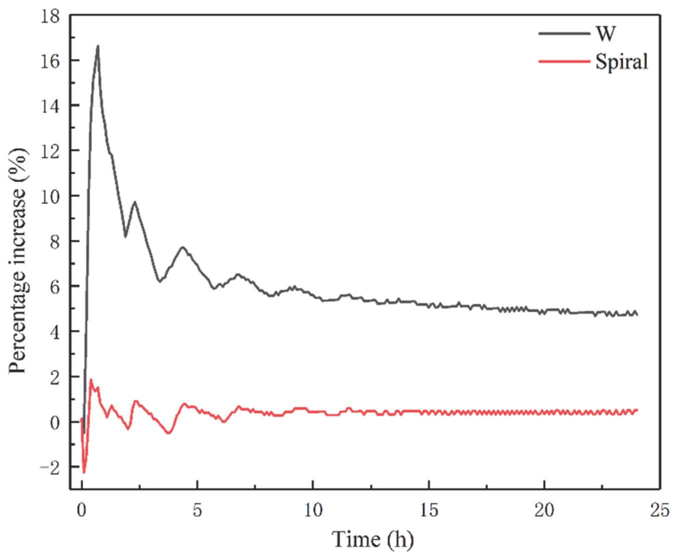


Fig. 12 Heat exchange increase of W-shaped and spiral tube compared with U-shaped tube

4. WELL GROUP HEAT TRANSFER PERFORMANCE

During the operation of the ground source heat pump, the heat exchange between the single well heat exchanger and soil has an effect on the surrounding soil temperature, and the effect radius is within a certain range. When well groups operate simultaneously, different well distribution distances have different effects on heat transfer. To study the influence of the distribution distance on the heat transfer of the well group, a heat exchange model of the well group is established, as shown in Fig. 13. The same three wells are arranged based on the U-tube single well. The four wells are arranged at four points in a square, and the distances between the two wells are equal. Take a square soil area, and each well is the same distance from the nearest soil boundary. The boundary conditions are consistent with the single well. The temperature measurement point of the well group is arranged in the middle of the four single wells.

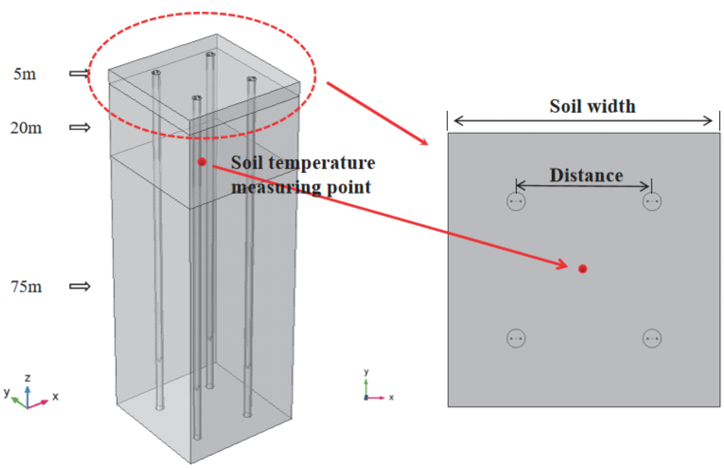
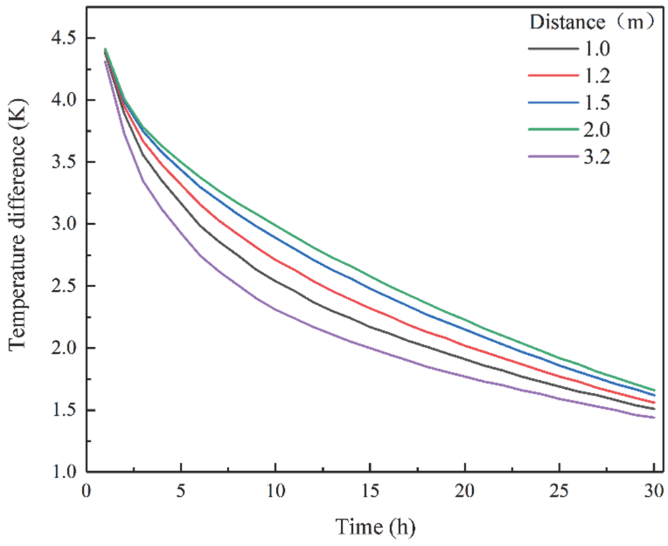


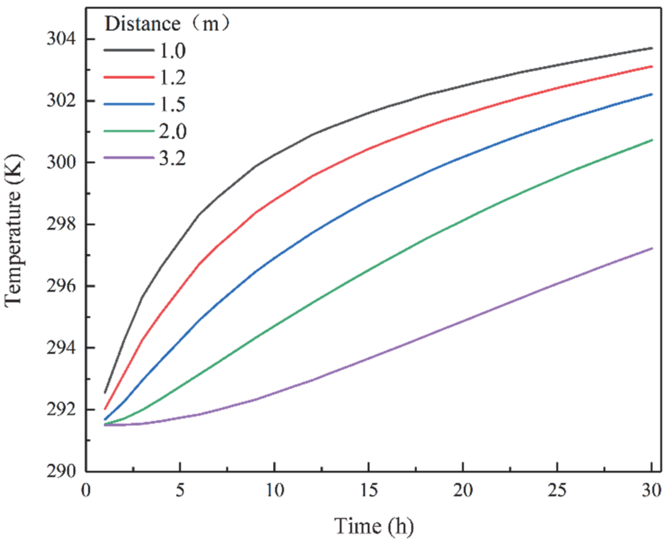
Fig. 13 Heat exchange model of well group

4.1 Layout Uniformity Influence

When the soil width is 4 m, the temperature difference, outlet and soil temperatures in well group are shown in Fig. 14. The temperature difference between the inlet and outlet gradually decreases. The greater the difference between the distribution distance of the well group and 2 m, the smaller the temperature difference is, and the greater the temperature difference drop is. The temperature difference between the inlet and outlet is the largest when the distribution distance is 2 m. It can be seen from Fig. 14(b) that the smaller the distribution distance is, the higher the soil temperature and the worse the heat transfer performance. The greater the distribution distance, the greater the temperature difference and the worse the heat transfer performance. When the soil width is two times the distribution distance, the temperature difference is the largest, and the efficiency is the highest. At this time, the distribution distances of the three nearest wells to each well are equal, which indicates that the heat exchange efficiency is the highest when the wells evenly space.



(a) Temperature difference



(b) Soil temperature

Fig. 14 Temperature difference and soil temperature in well group

4.2 Heat Transfer Performance of Buried Tubes in Different Layouts

When the soil width is twice the distribution distance, the soil temperature at different distribution distances shows in Fig. 15. The smaller the distribution distance, the higher the soil temperature, the smaller the excess temperature is, and the worse the heat transfer is.

Figure 16 shows the outlet temperature and temperature differences at different distribution distances. The outlet water temperature shows an upward trend with the operation and changes sharply in the initial stage. The smaller the distribution distance is, the smaller the high-temperature difference appears at the outlet temperature. The larger the distribution distance is, the lower the temperature and the larger the temperature difference becomes. That is because the heat storage capacity of the soil is limited, and the smaller the distribution distance, the smaller the soil volume used by a single well, and the soil temperature rises. High soil temperature leads to the deterioration of the heat transfer performance, resulting in the temperature difference between the inlet and the outlet decreasing.

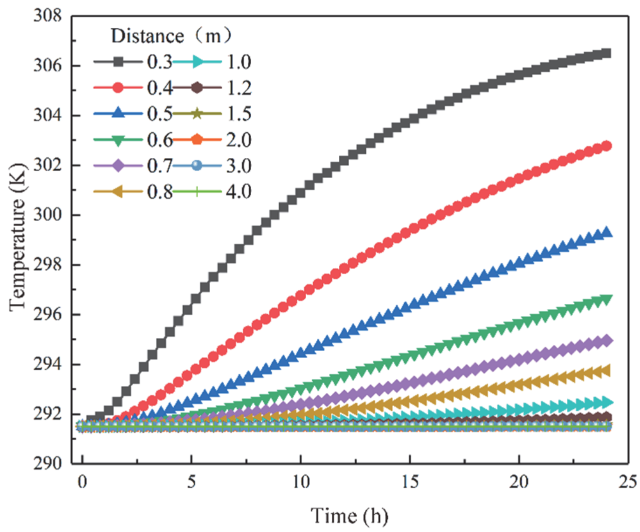


Fig. 15 Soil temperature at different distribution distances

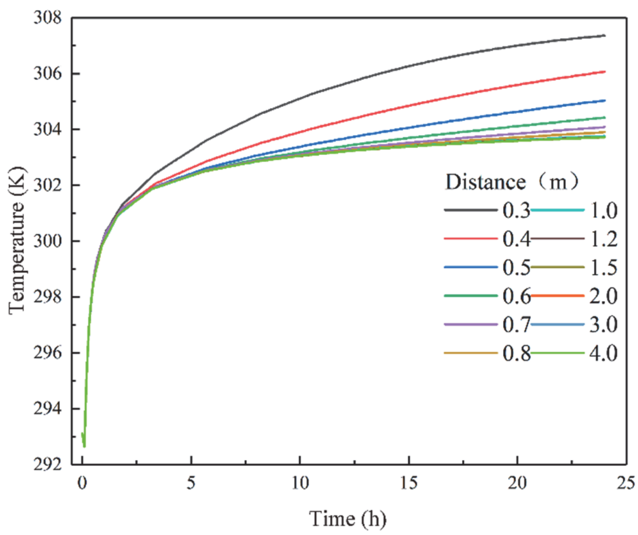


Fig. 16 Outlet temperature under different distribution distances

Figure 17 shows temperature difference and heat exchange rate per unit area with distribution distances. The temperature difference changes sharply when the distribution distance is small. There is thermal interference between wells when the distribution distance is small. The larger the distribution distance is, the smaller the thermal interference is. When the distribution distance is greater than 1 m, the thermal interference between wells is small. The heat transfer per unit area shows a downward trend with the increase in distribution distance, and the decrease tends to be gentle when it is greater than 2 m. The reason is that, although the temperature difference increases with the increase of distribution distance, the area increase leads to the decrease of heat exchange per unit area. When the distribution distance exceeds 2 m, the heat exchange rate per unit area is less than 800. The intersection line of temperature difference and heat exchange efficiency is about 0.5 m, and the temperature difference and heat exchange per unit area is relatively large in that case. Under this distribution distance, the quality of the system's working fluid and heat exchange performance are high. After the distribution distance is greater than 0.75 m, the temperature difference changes very little and the heat exchange per unit area decreases rapidly. More soil cannot be used efficiently, and the soil utilization rate is low. Therefore, the optimal distance for the distribution distance of the group is between 0.5-0.75 m.

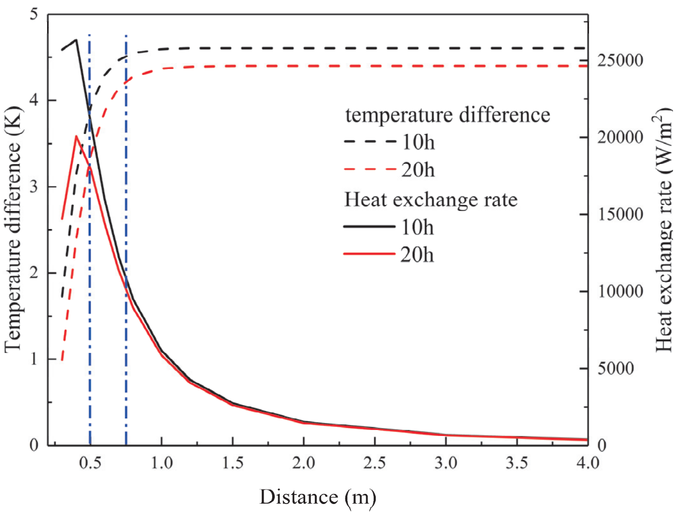


Fig. 17 Temperature difference and heat exchange change rate per unit area with distribution distance

5. CONCLUSIONS

1. The temperature difference between inlet and outlet fluid and the heat transfer of the borehole heat exchanger decrease rapidly in the initial stage and finally becomes stable. The section with the highest heat transfer of the borehole heat exchanger is in the inlet 25-100 m. As the flow velocity increases, the heat transfer of the borehole heat exchanger increases. However, the working fluid quality decreases, and the growth rate of heat transfer efficiency decreases with the flow velocity. When the flow velocity exceeds 0.6 m/s, the heat exchange is stable after the system operates 10 hours. As the tube diameter increases, the thermal efficiency increases, but the working fluid quality decrease, and the growth rate of heat transfer decreases.
2. The trend of the outlet temperature of the three configurations is similar. Compared with the U-shaped tube, the W tube has a greater temperature difference, and the heat exchange rate of the borehole heat exchanger is improved. In the first two hours, the relative heat exchange rate increased by about 10% and finally tended stabilize at 4.8%.
3. The heat transfer per unit area of the heat exchanger decreases with the increase of the well distribution distance. The temperature difference hardly changes after the distribution distance exceeds 0.75 m, and the working fluid quality is no longer improved. The optimal distance for the distribution distance of the well group is between 0.5-0.75 m.

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DATA AVAILABILITY

The data and/or computer codes used/generated in this study are available from the corresponding author on reasonable request.

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

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