Research on Influencing Factors of Heat Transfer Performance of Vertical Single U-Tube for Ground Source Heat Pump

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Abstract. The heat transfer performance of the buried heat exchanger is a key factor affecting the efficiency of the ground source heat pump. In this paper, the heat transfer model of the vertical single U-type heat exchanger is first established under the condition of variable heat flow to make it closer to the actual operating conditions, for simplicity the calculation process and the calculation time are saved. The boundary element method is used to analyze the heat resistance of the buried heat exchanger, and then the numerical simulation software is compiled to simulate the heat transfer performance of the buried heat exchanger. The results of the study show that the soil temperature changes within a range of 1.5m from the buried tube heat exchanger. The hole spacing of the buried tube heat exchanger cannot be less than 4m in practical applications; when the soil thermal conductivity increases by 25%, the heat transfer per unit depth of the buried tube heat exchanger increases by 14.8%; When the diameter of the drill hole is increased from 160mm to 300mm, the heat transfer per unit depth of the hole increases by 8.2%.

1 Introduction

The energy consumption of heating in winter in severe cold areas is relatively large. At present, coal is the main source of energy, resulting in increasingly serious environmental pollution. The temperature of the soil below 10 meters in severe cold regions is relatively stable[1], so the application of vertical buried pipe-sourced soil source heat pump system for heating in severe cold regions can achieve good energy saving and emission reduction effects[2]. Countries such as Europe and the United States have conducted research and application of the ground source heat pump system earlier[3,4]. In Asia and Japan, the research and application of the ground source heat pump system is in a leading position. Hokkaido University has successfully applied it to building heating in severe cold areas[5]. The domestic research on soil-source heat pumps is relatively short[6], and it is still in its infancy, and research on cold regions is even rarer.

The design of the buried tube heat exchanger is a key factor in determining the performance of the ground source heat pump. The coupling relationship between the buried tube and the soil has always been the focus and difficulty of the research on the soil source heat pump system[7,8]. The vertical U-shaped buried pipe form is more suitable for the soil
source heat pump system in cold areas because of its small footprint, deep soil temperature is less affected by the external environment, and stable system conditions\textsuperscript{[9,10]}. Based on the climate and geological characteristics of severe cold regions, this paper establishes a heat transfer model of U-shaped underground heat exchangers, analyzes the factors that affect the heat transfer performance of underground heat exchangers, and makes the design of underground heat exchangers more reasonable and reliable, it provides a theoretical basis for the optimal design of buried tube heat exchangers in severe cold areas.

2 Structure

The structure of the vertical single U-tube buried heat exchanger is shown in Fig. 1.

![Vertical U-pipe underground heat exchanger](image)

Figure 1. Vertical U-pipe underground heat exchanger.

The soil temperature in the northern cold regions is low. If the heating rate is too fast, it will cause the local temperature to be too low, which will affect the efficiency of the system. Therefore, it is best to use a vertical single U-shaped tube for the buried tube heat exchanger. The vertical single U-shaped buried tube heat exchanger is easy to install and is not easy to leak. It can be used in deep buried projects. The maximum buried depth of the vertical U-shaped buried tube heat exchanger currently used in China is 180m.

3 Mathematical model

In the case of variable heat flow, according to the theoretical model of the cylindrical source, the difference between the borehole wall temperature and the initial soil temperature $T_g$ at the $n$th time can be obtained from the superposition principle:

$$T_s(r_b, \tau_n) - T_g = \frac{1}{\lambda_s L} \sum_{i=1}^{n} (q(i) - q(i-1)) G \left[ F_0 \left( \tau_i - \tau_j \right) \right]$$

(1)

where, $q$ is heat transfer, W; $L$ is hole depth, m; $\lambda_s$ is thermal conductivity of soil outside the hole, W/(m·k); $F_0$ is Fourier number.

Two heat transfer models are used to calculate the temperature of the hole wall. The cylindrical source theory is used for the temperature effect of the buried pipe on the hole wall; the distance between the buried pipes is large, so the temperature calculation of the other buried pipes to the hole wall uses the variable heat streamline heat source theory. Assuming that there are $n$ buried pipes, the expression expression of the $i$-th buried pipe to the temperature of the hole wall is:

$$T_i(r_b, \tau) - T_g = \sum_{j=1}^{n-1} \Delta T_{s-L}(r_{dij}, \tau) + \Delta T_{s-C}(r_b, \tau)$$

(2)
where, \( T_i(r_b, \tau) \) is the temperature of the wall of the i-th buried pipe at the moment, K; \( T_g \) is the initial temperature of the soil, K; \( \Delta T_{s,L}(r_{di}, \tau) \) is other buried Temperature response of the pipe to the wall of the hole, K; \( \Delta T_{s,L}(r_b, \tau) \) is temperature response of the i-th buried pipe itself to the wall of the hole, K.

Assuming that the circulating fluid in the buried heat exchanger meets the heat balance in a short time, within the time:

\[
c_{fj} \rho_{fj} V_f \frac{dT_s}{d\tau} = -c_{fj} \rho_{fj} V_f (T_{ici} - T_{ico}) + K_y A_b \left( T_{s \mid r_{le} > E} - T_s \right)
\]

where, \( c_{fj} \) is the specific heat capacity of the fluid, J/(kg·K); \( \rho_{fj} \) is fluid density, kg/m\(^3\); \( T_{ici} \), \( T_{ico} \) is evaporator inlet and outlet fluid temperature, K; \( V_f \) is fluid volume flow, m\(^3\); \( T_s \) is wall temperature, K; \( T_f \) is Average fluid temperature, K.

4 Simulation results and analysis

When simulating the performance of buried heat exchangers, the main physical parameters are shown in Table 1 to Table 3.

| Table 1. The parameter data of the soil and the grouting material. |
|-----------------------------------------------|
| **Initial temperature (℃)** | **Thermal Conductivity (W/(m·K))** | **Specific heat capacity (kJ/(m\(^3\)·K))** | **density (kg/m\(^3\))** |
| Soil | 10 | 2 | 2.088 | 2000 |
| Backfill material | 10 | 2.6 | 2.088 | 2000 |

| Table 2. The parameter data of the fluid. |
|------------------------------------------|
| **Fluid** | **Initial temperature (℃)** | **Flow velocity (m/s)** | **Density (kg/m\(^3\))** | **Thermal Conductivity (W/(m·K))** | **Specific heat capacity (kJ/(m\(^3\)·K))** |
| Water | 2 | 0.6 | 999.8 | 0.55 | 4.2 |

| Table 3. The parameter data of the single U-tube. |
|-----------------------------------------------|
| **Density (kg/m\(^3\))** | **Tube inner diameter (mm)** | **Branch spacing (mm)** | **Drilling depth (m)** | **Drilling diameter (mm)** | **Thermal Conductivity (W/(m·K))** |
| 1000 | 26 | 100 | 100 | 160 | 0.42 |

The relationship between soil temperature change and time around the buried heat exchanger is shown in Fig. 2. It can be seen from the figure that the change of soil temperature is larger within 1.5m from the buried heat exchanger, and the change of soil temperature is smaller outside the range of 2m, and shows a gradual downward trend. With the increase of heat exchange time, the change of soil temperature at the same radius from the buried heat exchanger showed a gradually increasing trend, but the difference in temperature change was small, and the soil temperature decreased by 13.9% after 400 hours.
of continuous operation. From the above analysis, it can be seen that in the design of buried heat exchangers, in order to reduce the influence of mutual heat exchange between buried heat exchangers, the borehole spacing should not be less than 4m.

The effect of soil thermal conductivity on the heat transfer performance of the heat exchanger is shown in Fig. 3. It can be seen from the figure that the large soil thermal conductivity is beneficial to the heat transfer of buried heat exchangers. When the soil thermal conductivity increases from 2W/(m·K) to 2.5W/(m·K), the unit hole depth of the heat exchanger The heat exchange capacity increased by 14.8%. It can be seen that in the actual engineering design, it is necessary to conduct an experimental study on the thermal conductivity of the soil around the buried heat exchanger.

The effect of circulating medium flow rate on the heat exchange performance of buried heat exchangers is shown in Fig. 4. It can be seen from the figure that the flow rate of the circulating medium of the buried heat exchanger increases, and the heat transfer per unit depth of the hole gradually increases. When the flow rate of the circulating medium is 0.4m/s, 0.6m/s and 0.9m/s The average heat transfer per unit depth of the buried heat exchanger is 23.1W/m, 24.5W/m and 25.6W/m, respectively. From the above analysis, it can be seen that increasing the flow rate of the circulating medium can increase the heat exchange per unit depth of the buried heat exchanger, but the increase is less than the increase in the flow rate. Therefore, when determining the circulating medium flow rate of the buried heat exchanger, the power consumption of the circulating pump should be comprehensively considered.

**Figure 2.** Soil temperature around the underground heat exchanger over time.

**Figure 3.** Influence of heat conductivity on the heat exchange performance of exchanger.
Figure 4. Influence of flow speed on the performance of heat exchanger.

The influence of the buried pipe diameter on the heat exchange performance of the buried heat exchanger is shown in Fig. 5. It can be seen from the figure that the other conditions remain unchanged. When the inner diameter of the tube is increased from 20mm to 26mm, the average heat transfer per unit depth increases by 28.2%. From this, it can be seen that proper increase in the inner diameter of the tube can increase the heat transfer per unit depth of the hole.

The effect of the borehole diameter on the heat exchange performance of the buried heat exchanger is shown in Fig. 6. It can be seen from the figure that with the increase of the borehole diameter, the heat exchange per unit depth increases. When the borehole diameter increases from 160mm to 300mm, the average heat exchange per unit depth increases by 8.2%. The reason for analysis is that the thermal conductivity of the backfill material in the hole is greater than the thermal conductivity of the soil. As the diameter of the borehole increases, the heat transfer coefficient between the fluid in the pipe and the wall surface of the borehole increases, resulting in a greater amount of heat per unit depth increase.

Figure 6. Influence of hole diameter on the performance of heat exchanger.

Figure 7. Influence of the backfill material’s thermal conductivity on the performance of heat exchanger.
The effect of the thermal conductivity of the backfill material on the heat transfer performance of the heat exchanger is shown in Fig. 7. It can be seen from the figure that as the thermal conductivity of the backfill material in the hole increases, the heat transfer per unit depth of the hole gradually increases. When the thermal conductivity of the backfill material increases from 2W/(m·K) to 3.2W/(m·K), the average heat transfer per unit depth increased by 4.5%. The main reason is that when the thermal conductivity of the backfill material increases, the heat transfer coefficient between the fluid in the tube and the wall surface of the borehole increases, which results in an increase in the amount of heat transfer per unit depth of hole.

5 Conclusion

Through simulation research, the following conclusions can be obtained:

(1) The change in soil temperature is greater within 1.5m from the buried heat exchanger, and the change in soil temperature outside the 2m range is smaller, so when designing the buried heat exchanger, in order to reduce buried heat exchange, due to the mutual heat exchange between the devices, the distance between the holes must not be less than 4m.

(2) The thermal conductivity of the soil, the thermal conductivity of the backfill material in the hole, and the flow velocity of the circulating medium all affect the heat transfer per unit depth of the buried tube heat exchanger. Among them, the thermal conductivity of the soil has the greatest influence on the heat transfer of the buried tube heat exchanger. When the thermal conductivity of the soil increases by 25%, the heat transfer per unit depth of the heat exchanger increases by 14.8%.

(3) Increasing the inner diameter of the buried pipe and the diameter of the borehole can increase the heat transfer per hole depth of the buried pipe. Among them, the effect of increasing the diameter of the drill hole is the most obvious. When the diameter of the drill hole is increased from 160mm to 300mm, the heat transfer per unit depth increases by 8.2%.

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