ENHANCED HEAT TRANSFER PERFORMANCE OF A NEW HORIZONTAL BURIED TUBE HEAT EXCHANGER

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To reduce the land area of horizontal buried tube heat exchanger, a finned strengthened heat exchanger was designed, and shallow geothermal utilization system model was established. The effects of fin shape and arrangement, soil type, ambient temperature and intermittent operation on the system's heat transfer performance were investigated. The soil utilization area of the heat exchanger is increased, and the heat exchange performance of the system is enhanced by adding fins on the smooth tube,. The optimal shape of the fins is rectangular, and the optimal fin layout is horizontal. When the soil property is clay, the heat transfer is the smallest, and the heat transfer performance is improved the most compared with the smooth tube. Intermittent operation not only improves the heat exchange, but also enhances the effect of adding fins to improve the heat exchange performance of the system. Compared with the original smooth tube, the soil utilization range is increased by 20 %, and the heat exchange is increased by 42 %.

Keywords: Ground coupled heat pump. Enhanced heat transfer. Horizontal buried tube. Intermittent operation.

1. Introduction

Shallow geothermal energy has the characteristics of cleanness, environmental protection and regeneration. Ground source coupled heat pump (GCHP) is recognized as one of the most efficient renewable energy systems. One of the most important parts of GCHP system is the geothermal heat exchanger (GHE). Compared with vertical buried tube, horizontal buried tube is favored for its simpler construction and lower cost. However, the heat exchange performance of horizontal heat exchanger is low, so improving the heat exchange performance of horizontal heat exchanger is a key problem.

Many scholars have studied the enhanced heat transfer of buried tube systems. The enhanced heat transfer effect of different backfill materials has been studied by Zi et al. [1]. The results show that in summer the heat transfer performance of medium-coarse sand is higher than that of drilling slurry as backfill material. Xiao et al. [2] studied a buried tube heat exchanger with multiple inputs and a single output, and found that the thermal resistance is reduced by 29 %-34 % compared with that of a single

U-shaped heat exchange tube and a double U-shaped heat exchange tube. Su et al. [3] have studied the heat transfer performance of U-tube heat exchangers and U-fin tube heat exchangers with longitudinal fins. Bezyan et al. [4, 5] found that spiral tubes have the largest outlet temperature difference and the highest performance compared with 1-W and 1-u tubes. Reza et al. [6] found that finning can effectively enhance the heat transfer efficiency and increase the heat transfer rate to 31 %. Ma et al. [7] found that the heat exchange of rectangular straight fin buried tube heat exchanger is increased by 19.12 % compared with smooth tube. Zarrella et al. [8] showed that the heat transfer efficiency of spiral tube energy reactor is increased by about 23 % compared with three U-tubes, and is increased by 40 % compared with double U-tubes. Yue et al. [9] found that the improvement of thermal conductivity of backfill material can effectively alleviate the phenomenon of thermal short circuit of U-tube. Ma et al. [10, 11] found that groundwater seepage can enhance the heat transfer performance of buried tube heat exchangers, and the heat exchange capacity of buried tube heat exchangers would decrease with the increasing of groundwater depth. Yoon et al. [14] found that the vertical drilling thermal resistance of stainless steel threaded tube is about 25 % lower than that of U-shaped tube using traditional polybutylene tube, and the initial investment can be saved by 10 %.

The reviewed research on the enhanced heat transfer of buried tube heat exchanger is mostly aimed at the vertical tube, and the research on horizontal buried tube is still insufficient. A three-dimensional research model of a shallow geothermal utilization system is established in this paper. The optimal fin shape and layout were explored. Effects of inlet flow velocity, soil type, ambient temperature and intermittent operation on the enhancement of heat transfer was studied. The results can provide a reference for the design of the horizontal buried heat exchanger for shallow geothermal energy.

2. Computational model

2.1. Physical model

The enhanced heat transfer model is shown in Fig. 1. A single straight tube heat exchange tube is used as the underground heat exchange part. To explore the heat transfer characteristics of the finned form of the layout, three layouts are designed.

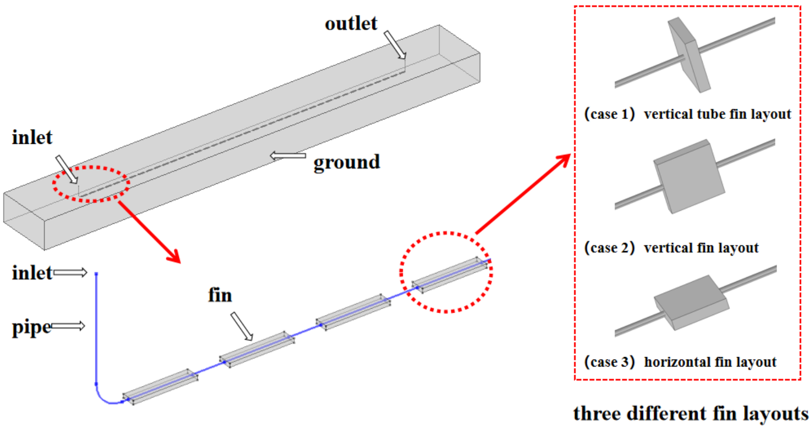


Fig. 1 Enhanced heat transfer model

The system is mainly composed of circulating working medium (water), horizontal tube, backfill materials, fins and soil. The soil is divided into three layers (clay layer, pebble layer, and mudstone layer) in Chengdu [13]. The depth of the shallow underground heat exchanger discussed is in the range of 0-5 m (clay layer: density is 1600 kg/m^3, thermal conductivity is 1.2 W/(m·K), specific heat capacity is 1420 J/(kg·K)). The depth of horizontal buried tube is 2 m. To keep the soil temperature in the infinite distance unchanged, the soil with a width of 5 m is taken from the left and right sides of the horizontal buried tube. The length of the heat exchange tube is 60 m, and the length of soil layer is 80 m, so the three-dimensional geometric control body is 80 m×10 m×5 m (L×W×H). Outer diameter of the buried tube is 0.032 m, the inner diameter is 0.026 m, and the thermal conductivity of the tube wall is 0.4 W/(m·K). The fin plate is made of aluminum plate with a density of 2707 kg/m^3, thermal conductivity of 204.2 W/(m·K) , and a specific heat capacity of 896 J/(kg·K). In order to solve the numerical model conveniently, there are some assumptions:

(1) Initial temperature of the whole system is 291.5K [13].

(2) The thermophysical parameters in each layer of rock and soil are isotropic and remain unchanged, and the physical properties of soil and backfill material are the same [14].

(3) Negligible seepage, it is assumed that 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 [15].

(5) Solar radiation heat transfer is negligible.

The soil's bottom surface temperature is 291.5 K. The ambient temperature is 303.15 K during the day and 296.15 K at night, with an average temperature of 301.15 K. The inlet fluid temperature is 303 K and the inlet velocity is 0.2 m/s. The transient study is adopted in this study, and the time step is set for 1 h. The soil temperature measuring point is set at the entrance section of the system tube line at 10 m and the soil depth is 2 m.

2.2. Governing equations

The numerical model has been implemented in the commercial software Comsol Multiphysics, where the flow and heat transfer of the fluid in the tube are described by the following equation [16]:

$$\frac{\partial A_p \rho_f}{\partial t} + \nabla \cdot (A_p \rho_f \vec{u}) = 0 \tag{1}$$

$$\rho_f \frac{\partial \vec{u}}{\partial t} = -\nabla p - f_D \frac{\rho_f}{2d_p} \vec{u} \left|\vec{u}\right| \tag{2}$$

$$\rho_f A_p c_{pf} \frac{\partial T_f}{\partial t} + \rho_f A_p c_{pf} \vec{u} \nabla T_f = \nabla \cdot A_p \lambda_f \nabla T_f + f_D \frac{\rho_f A_p}{2d_p} \left|\vec{u}\right|^3 + q_p \tag{3}$$

Among them, Eq. (1) is the mass equation, Eq. (2) is the momentum equation, and Eq. (3) is the energy equation. A_p is the cross-sectional area of the tube. ρ_f is the fluid density. u is the flow velocity. p is the pressure. d_p is the inner diameter of the tube. f_D is the friction coefficient. c_{pf} is the volumetric specific heat capacity of the fluid. T_f is the fluid temperature. λ_f is the fluid thermal conductivity. q_p is the source term of heat transfer between the fluid and external environment of the tube.

$$q_p = h_e Z_p \left(T_{ext} - T_f \right) \tag{4}$$

where h_e is the effective heat transfer coefficient between the fluid and the tube. T_{ext} is the temperature outside of the tube. The fourth term in Eq. (3) represents the heat dissipation caused by viscous shear, which can be calculated using the model [17]:

$$f_D = 8\left[\left(\frac{8}{R_e} \right)^{12} + \left(A + B \right)^{-1.5} \right]^{\frac{1}{12}} \tag{5}$$

$$A = \left[-2.457 \ln \left(\left(\frac{7}{R_e} \right)^{0.9} + 0.27\left(e / d_p \right) \right) \right]^{16} \tag{6}$$

$$B = \left(\frac{37350}{R_e} \right)^{16} \tag{7}$$

where Re is the Laylow number. The thermal conductivity of soil is described by the following equation [18].

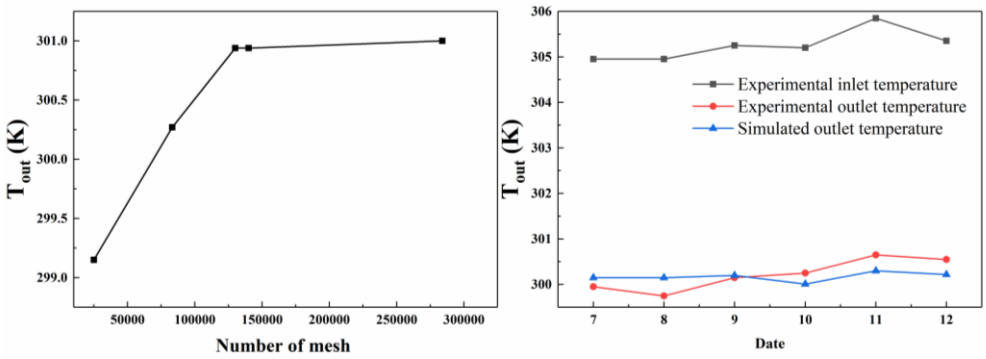
$$\rho_s c_{ps} \frac{\partial T}{\partial t} = \lambda_s \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + Q_s \tag{8}$$

where ρ_s is the density of the soil. c_{ps} is the volumetric specific heat capacity of the soil. T is the soil temperature. λ_s is the thermal conductivity of the soil. Q_s is the heat source contained in the soil.

2.3. Model verification

The experimental conditions of the horizontal buried tube ground source heat pump in Chongqing University are chosen as working conditions [19] for verification. The buried depth is 1.2 m, the outdoor average temperature in summer is 300.95 K, and the inlet velocity is 0.72 m/s.

As shown in Fig. 2, when the grid rises from 15000, the outlet temperature does not change much. Therefore, the grid is divided into 15000. To verify the correctness of the numerical model, under the summer operating condition, the given operating condition (taking the inlet temperature from July 7 to July 12) is simulated six times in succession for one day each time. The average value of the outlet temperature for each simulation is compared with the measured temperature. It can be seen that the temperature difference between the two is very small, the maximum temperature deviation is 0.4 K, the maximum outlet temperature error is 0.13 %, and the maximum outlet temperature difference error is 7.6 %, which fully proves the reliability of the model.



(a) Mesh independence verification (b) Temperature comparison

Fig. 2 Mesh independence verification and outlet temperature comparison

3. Results and discussions

3.1. Fin structure and layout optimization

Four cross-sectional shapes (square, circle, rectangle, ellipse) and three layouts are set up. The total volume of the fin is equal, the number of fins is 40, the thickness is 0.1 m, and the area is 0.785 m^2. The specific fin layout is shown in Fig. 1. Fig. 3 shows the temperature difference in different fin layouts. The temperature difference between the inlet and outlet of the working medium in the vertical and horizontal fin layout is much higher than that in vertical tube fin layout, and the temperature difference is increased by more than 49.6 %. The vertical fin layout is slightly improved compared to the horizontal. Because the vertical fin layout is closer to the ground, the shallow horizontal buried tube will be affected by the external temperature.

To maintain a relatively stable heat exchange, the horizontal layout is chosen for simulation. Fig. 4 shows the temperature difference between inlet and outlet overtime under the horizontal fin layout with four different cross-section fins. The rectangular fin has the largest heat exchange temperature difference, and the efficiency is increased by more than 7 % compared with the square and circular.

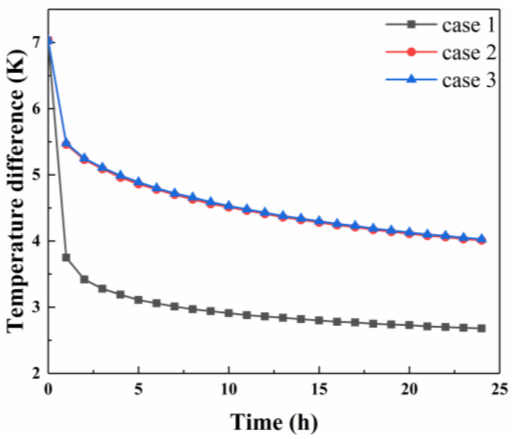


Fig. 3 Temperature difference in different fin layouts

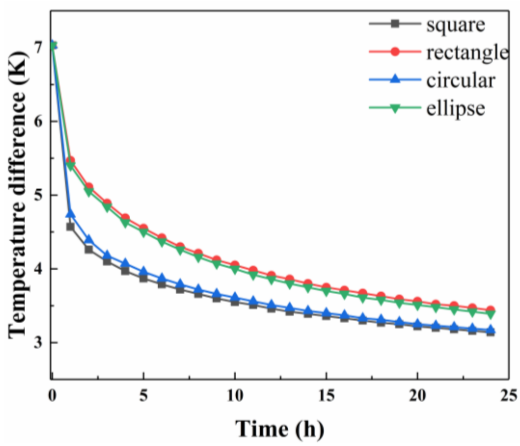


Fig. 4 Temperature difference in different cross-section shapes

The temperature differences in different fin lengths, widths and thicknesses are shown in Fig. 5 As the fin length increases, the temperature difference is increased by about 0.26 K for each 0.1 m. This indicates that the enhanced heat exchange performance of the fins is greatly affected by the length of the fins. Because the larger the fins are, the larger the area of the heat exchange tubes covered by them can be exchanged, and the enhanced heat exchange performance is stronger. However, as the arrangement length is longer, the distance between the two fins is closer, and the thermal interference between those is more serious. The increasing rate of the temperature difference is reduced with the increasing of the fin length.

The temperature difference between the entrance and exit increases with the increasing of the width, but the growth rate decreases. The plate width is from 0.11 m to 0.22 m, the temperature difference growth is about 3.8 K/m. While the plate width is from 0.44 m to 0.89 m, the growth value is about 0.87 K/m, and the cahnge rate is reduced by 37 %. This is due to the heat exchange efficiency of the fin decreases with the increasing of the fin height.

With the increasing of fin thickness, the temperature difference between inlet and outlet increases, and the growth value is about 4.2 K/m, while the overall temperature difference growth rate decreases slightly. This is because the thickness is relatively small, and the overall heat transfer is obvious when the thickness increases, but the heat transfer efficiency of fins will also decrease when the thickness is larger.

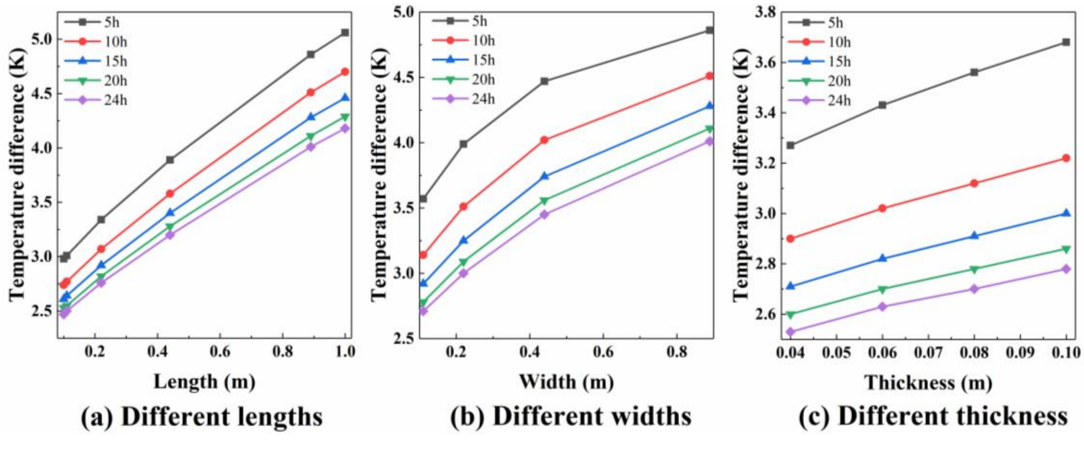
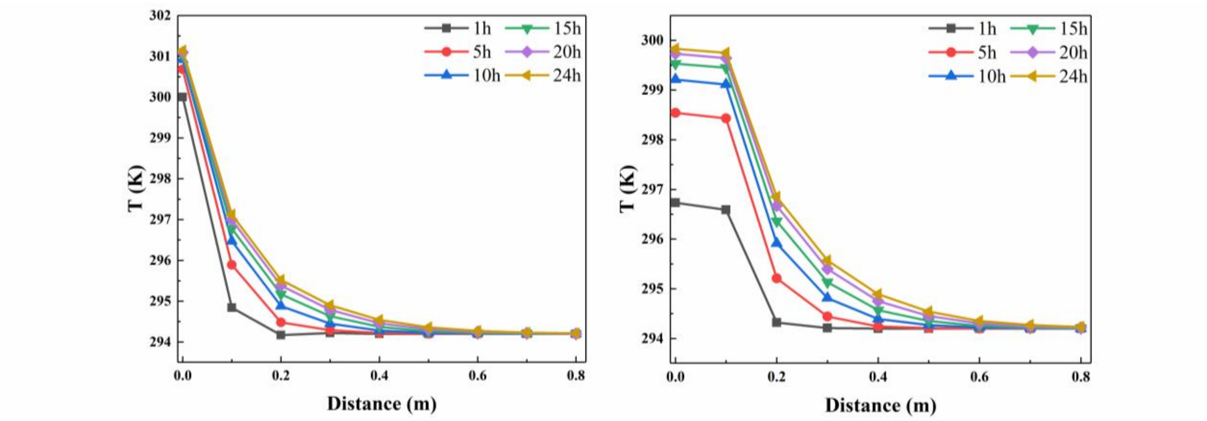


Fig. 5 Temperature difference in structural parameters

3.2. Enhanced heat transfer performance with fins

Fig. 6 shows the soil temperature of two modes (without fins and with fins) at different times. There is a large temperature gradient within the horizontal distance of 0.2 m for the tube without fins, and the radius of the soil temperature influence range is about 0.6 m. The tube with fin presents a small temperature gradient within a horizontal distance of 0.1 m, and the temperature gradient increases after 0.1 m. This is because it is in the fin area within 0.1 m, and that is the soil area outside 0.1 m. The thermal conductivity of the aluminum plate is high and the soil thermal conductivity is low.

The soil temperature influence range of the tube with fin reaches 0.7 m. This show that the fin can significantly increase the influence range of the heat exchange tube, and more soil can be used. The soil use range can be increased by 20 %, and the soil temperature around the buried tube is lower.



(a) without fins **(b) with fins**

Fig. 6 Soil temperature at different times in two modes

Fig. 7 shows the outlet temperature with and without fins. The temperature difference between the inlet and outlet of the non-finned heat exchange tube drops sharply at the beginning of the system operation, and the change with fins is relatively gentle. This is because the available soil range of the system increases after adding fins, the overall soil temperature rises more slowly than non-fins structre, and the deterioration of heat exchange is alleviated. It can be seen that fin structure can increase the heat transfer temperature difference by 0.9 K.

Fig. 8 shows the exchange per unit tube length and heat exchange increase ratio with and without fins. The average heat transfer efficiencies of non-finned and finned structres are 13.31 W/m and 21.56 W/m, and the heat transfer efficiency of the plates is about 42 % higher than that of the non-finned structre.

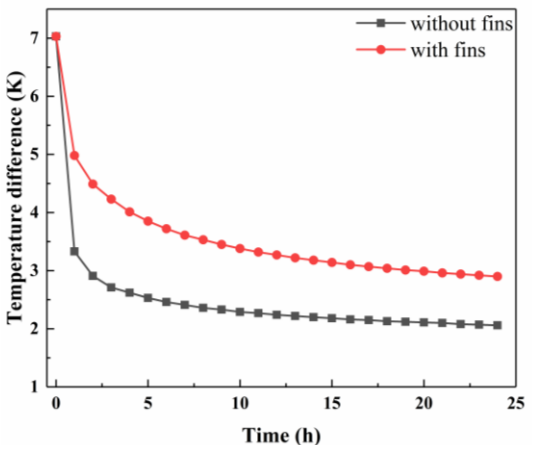


Fig. 7 Temperature difference in two structres

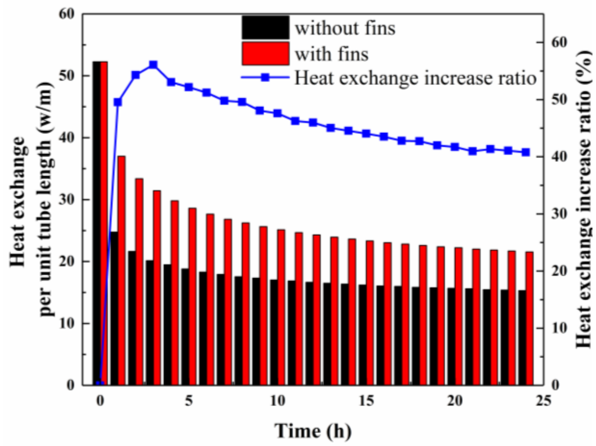


Fig. 8 Heat exchange per unit tube length and increase ratio in two modes

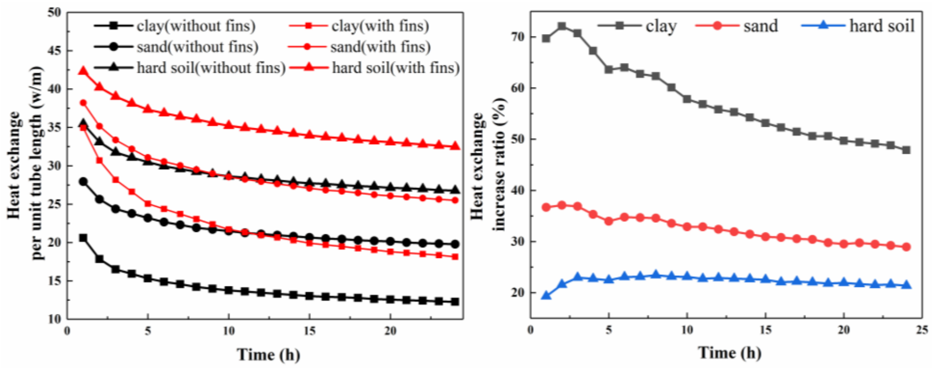
3.3. Effect of soil types and ambient temperature

With clay, sandy soil, and hard soil as representatives, the enhanced heat transfer process was simulated. The physical parameters of the three soil types are shown in Table 1 [20]. Fig. 9 shows the heat exchange and its increase ratio in different soils. After adding fins, the heat exchange of the three soil types has been greatly improved. The heat exchange of hard soil is the highest, and that of clay is the lowest. This is because the heat exchange per unit tube length is closely related to the thermal conductivity of the soil. Compared with no fins, the heat exchange increase of clay is the largest with fins, which is about 50 %, while the exchange of hard soil is the smallest 23 %. This is because adding fins can increases the thermal conductivity of soil in the influence range. The smaller the original thermal conductivity of soil is, the effect is more obvious. The finned structures have a better heat transfer enhancement effect in soil with low thermal conductivity.

Table 1 Three typical soil physical properties parameters

Type	Density kg/m^3	Thermal conductivity W(m•K)	Specific heat J(Kg•K)	Thermal diffusivity 10^{-6}•m^2/s
Clay	1500	0.9	1100	0.545
Sand	2000	2	700	1.430
Hard-soil	2500	3.2	1400	0.914

Fig. 10 shows the outlet temperature under different ambient temperatures. In the initial stage, the outlet temperature of the working medium is not affected by ambient temperature and it gradually changes after 48 h. The difference becomes more obvious with the increase of operation time. After 10 days of operation, the difference in the ambient temperature is 5 K, and the difference of the outlet temperature in the working medium at different ambient temperatures can reach 0.1 K. The heat exchange is increased by 4 % when the temperature decreases by 5 K.



(a) Heat exchange (in two modes)

(b) Heat exchange increase ratio (Compared with without fins)

Fig. 9 Influence of soil type in two modes (with fins and without fins)

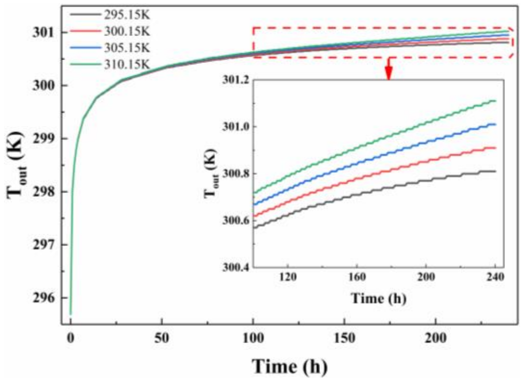


Fig. 10 Outlet temperature for different ambient temperatures

3.4. Effect of intermittent operation

The intermittent operation mode of 12h ON and 12h OFF is adopted. Fig. 11 shows the temperature difference with and without fins for different operating modes. The intermittent operation curve is a continuous temperature difference curve under working conditions. Intermittent operation can significantly improve the heat exchange temperature difference of the system. The heat exchange temperature difference of the finned tube is much higher than that of the non-finned tube. The daily average temperature difference is about 0.89 K, and the heat exchange is increased by about 42 %. It can be seen from Fig. 12 that the soil excess temperature around the buried tube in the case of the finned tube is significantly lower than that without fins, and the excess temperature is lower and has a better heat transfer performance.

Fig. 13 shows the heat exchange increment of intermittent operation compared with continuous operation for 7 days. In the case of with (without) fins, the heat exchange per unit tube length difference between intermittent operation and continuous operation is the heat exchange increment with (without) fins. The heat exchange per unit tube length of intermittent operation is increased by at least 75 kW, and the heat exchange increases more obviously with time. Compared with the non-finned tube, the intermittent operation of the finned tube has a greater increasing of heat exchange than the continuous operation. The difference between the improved heat exchange under the two modes increases with the increasing of operating time, and the improvement of the fin tube on the seventh day is 1.71 times than that of the no-fin tube, which indicates that adding fins can effectively enhance the thermal recovery effect.

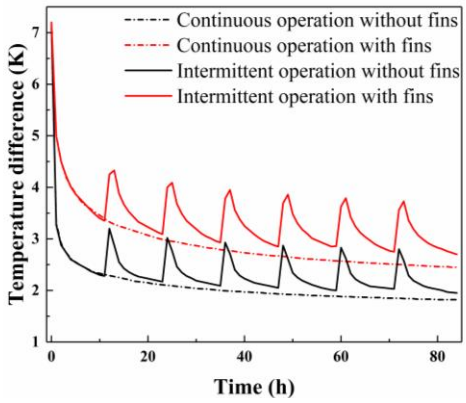


Fig. 11 Temperature difference for different operating modes

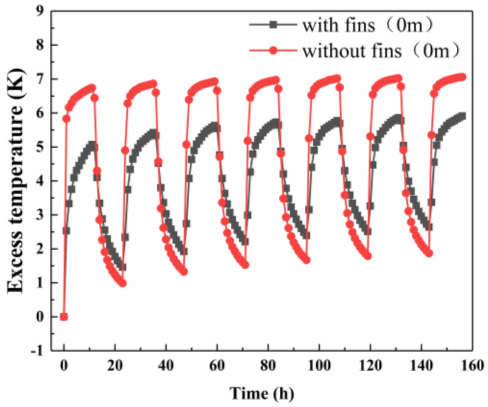


Fig. 12 Soil excess temperature in intermittent operation

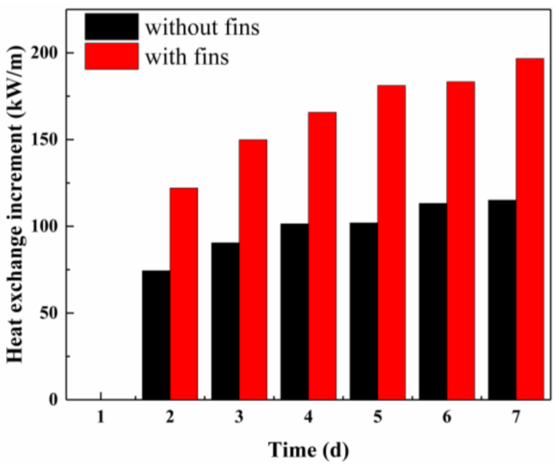


Fig. 13 Heat exchange increment for intermittent operation compared to continuous operation in two modes

4. Conclusions

(1) A new horizontal buried tube heat exchanger is designed, which greatly enhances the heat exchange performance of the system by adding fins compared with the original smooth tube. The soil utilization range is increased by 20 %, and the heat exchange is increased by 42 %.

(2) The optimal shape of the fins is rectangular, and the optimal fin layout is horizontal. When the thickness and width of fins are small, the heat exchange is greatly affected. When the thickness and width of fins exceed 0.22 m, the length of fins is the key factor that affecting the overall heat exchange. The finned tube has more effect on heat transfer enhancement of soil with low thermal conductivity. In summer, the ambient temperature decreases by 5 °C, and the heat exchange of the system increases by 4 %.

(3) Adding fins can effectively enhance the thermal recovery effect of the system. Under intermittent operation, the finned tube has a better heat transfer performance than the non-finned tube.

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