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Thermal performance analysis of the coaxial borehole heat exchanger

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Abstract
In order to improve the efficiency of the ground source heat pump systems, the effect on the performance of various borehole heat exchangers (BHEs) should be investigated carefully. This paper aims to study the thermal performance of coaxial borehole heat exchangers (CBHEs). A three dimensional model was established based on the commercial computational fluid dynamics software FLUENT to simulate the performance of CBHE. The heat exchange rates were analyzed and compared with that of a single U tube BHE. The soil temperature distribution around the CBHE and single U BHE is presented. The Effects of pipe material, flow direction and flow rate on the thermal performance of CBHE are discussed. The simulation results show that these factors have different degree of influence on the system performance.

Keywords - ground source heat pump; coaxial borehole heat exchanger; thermal performance

1. Introduction

As an energy saving environmental friendly technology, ground source heat pump (GSHP) has been widely used in commercial and residential buildings. In a GSHP system, there are two different kinds of heat exchangers: horizontal heat exchangers and vertical heat exchangers or Borehole Heat Exchangers (BHEs). BHEs for ground coupled heat pumps may be divided into three different main geometries: a single U-bent polyethylene tube, two U-bent polyethylene tubes, two coaxial circular tubes, typically an internal polyethylene tube and an external stainless steel tube, either inserted in a borehole which is then grouted or directly driven into the soil, without drilling.

U-bent polyethylene tube is the main form of the bore heat exchangers used [1, 2] for the convenience in installing. Some researchers studied the performance of U-tube and coaxial borehole heat exchangers [3, 4] and indicated that the coaxial borehole heat exchangers have some superiorities with lower borehole resistance.

Jalaluddin and Akio [5] investigated the performance of U-tube, double-U tube and multi-U tube GHE in different operation modes. Taoufik et al [6] used a combination between the finite volume method (FVM) and the boundary element method (BEM) to study the transient heat transfer process of a buried coaxial exchanger. The outcomes of the developed model are compared to that obtained from the CFD package Fluent and both results are in conformity. In his study, the interior tube made of Polyvinyl Chloride (PVC) is considered thermally insulator and the thermal resistance of the exterior tube is supposed to be negligible.

By the numerical study, Zanchini et al [7] investigated the effects of flow direction and thermal short-circuiting on the performance of small-size coaxial ground heat exchangers and showed that the performance of the Coaxial Borehole Heat Exchangers (CBHEs) could be improved by increasing the diameter of the inner tube while leaving the outer tube unchanged. Zanchini et al [8] also studied the effect of some factors of CBHEs by the software package COMSOL. Li et al [9] constructed a three-dimensional model with software FLUENT based on the inner heat source theory. They also presented a new multi-function ground source heat pump (MFGSHP) system which supplied hot water with heating/cooling to mitigate the heat imbalance of soil.

Beier et al [10] developed a transient model which can calculate the temperature of the circulating fluid during a thermal response test (TRT) for the coaxial heat exchanger. Acuña et al [11] carried out Distributed Thermal Response Test (DTRT) on two coaxial pipe-in-pipe BHEs at different flow rates with three heat injection rates. Acuña and Palm [12] quantified the global and local ground thermal conductivities and borehole thermal resistances, and made a discussion on how to evaluate borehole resistance in CBHEs.

Beier et al [13] developed an analytical model to calculate the vertical temperature profile and estimate the borehole resistance for coaxial borehole heat exchanger.

There are some researches about the CBHEs, but the three dimension numerical studies about it are limited. This paper aims to study the thermal performance of CBHE. In this paper, a three dimensional model was established to simulate the performance of single tube BHE and CBHE respectively by using the commercial computational fluid dynamics software FLUENT. The heat exchanger rate was analyzed and compared with that of single U tube GHE. And soil temperature distribution is presented. Effects of pipe material, flow direction and flow rate on the thermal performance of coaxial heat exchanger are discussed.

2. The Coaxial Borehole Heat Exchanger

A typical coaxial exchanger is shown in Fig. 1, which consists of two concentric tubes inserted in the soil.

The tool of GAMBIT was used to establish the model and divide the mesh. And the gridding (see Fig. 2) was leaded by FLUENT to simulate the performance of single U tube BHE and CBHE.

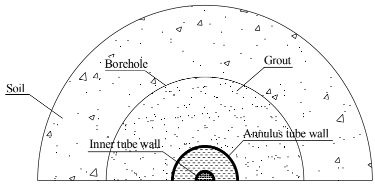

Fig.1 Cross section of the coaxial heat exchanger.

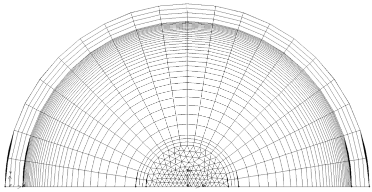

Fig.2 Gridding in the horizontal direction in the coaxial heat exchanger.

The assumptions in the model development are as follows: The thermal properties (thermal conductivity, density and heat capacity) of soil and grout are the same in the region. The heat transfer between the surface and the underground soil is neglected. The thermal characteristics of ground and water are constant and independent of the temperature.

Boundary conditions are assumed as follows: The ground temperature was constant at the top surface and bottom of the model, and bottom of the simulated area and the undisturbed soil are adiabatic. The parameters of the CBHE are listed in Table 1.

Table 1. The parameters of the coaxial heat exchanger

Borehole diameter （m）	Borehole depth （m）	Outer diameter of the outer tube （m）	Inner diameter of the outer tube （m）	Outer diameter of the inner tube （m）	Inner diameter of the inner tube （m）
0.25	60	0.885	0.80	0.025	0.020

Three models with different spatial grid discretizations were set up to determine the optimum computational mesh.

The grid was divided after the 3-D model was developed. Three grid numbers were compared to seek the suitable grid sparsity. The grid numbers were 91500 (N1), 180040(N2) and 368760 (N3) respectively. Meshing N2 was used in the simulation here after the sensitivity analysis.

3. Results and Discussion

3.1 The heat exchange rate

The heat exchange rates of single U BHE and CBHE were compared by simulation. The depth and the diameter of the borehole is 60 m and 250 mm, respectively. The thermal conductivities of the soil and the grout are 2.5 W/(m.K). The initial soil temperature is 18 ℃. The inlet water temperature is assumed to be 37 ℃ for cooling mode. The flow rate is 1.9 m3/h. The heat exchange rates of heat exchangers were simulated and the results are shown in Fig. 3.

As shown in Fig.3, after the operation of 48 h, the heat exchange rate of coaxial exchanger and single U tube are 73.1 W/m and 57.2 W/m. respectively.

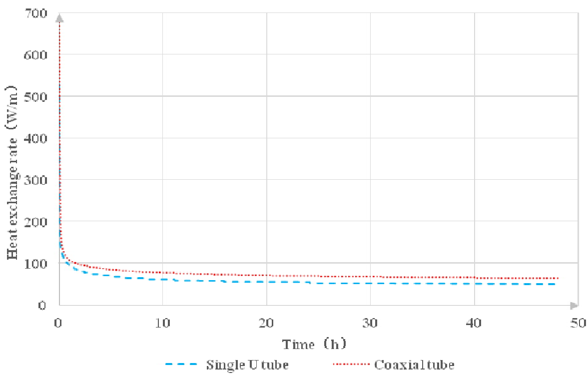

Fig. 3 The heat exchange rate of the two heat exchangers.

3.2 The effect of material of pipe

The pipe material of the coaxial borehole heat exchanger has influence on the heat exchange. Six combination of material of inner pipe and outer pipe of coaxial exchanger were analyzed. The material of outer pipe is PPR, PE and galvanized steel respectively, and the inner pipe is PPR, PE respectively. The simulating results of outlet water temperature and heat exchange rate in different situation are shown in Table 2.

Table 2. The heat exchanger rate of the coaxial heat exchanger with inner and annulus pipe of different material at 48 h.

Inner tube material	Heat exchanger rate with different annulus tube material (W/m)		
	PPR	PE	galvanized steel
PPR	78.2	90.6	106.3
PE	78.3	90.5	106.3

PPR:k=0.2W/(m·K）;PE:k=0.45 W/(m·K）;galvanized steel(k=45 W/(m·K）)

As shown in Table 2, the materials of inner and outer pipe have different effect for the heat exchange rate of the exchanger. Outer pipe plays more important role in the system. The thermal conductivity of inner tube material has little effect on the heat exchange.

3.3 The effect of flow direction

There are two flow ways in the coaxial heat exchanger. In case one, the fluid flow from the annulus to the inner tube. And in case two the fluid flows from the inner tube to the annulus.

The outlet water temperature and heat exchange rate were simulated in order to compare the effect of different inlet and outlet manner. The parameters were set as follows: the inlet water temperature is 37 ℃, the water velocity is 0.5 m/s, the thermal conductivity of soil and grout are both 2.5 W/(m•K）. The soil initial temperature is 18 ℃. The annulus tube material is PPR, and the inner tube material is PE. The heat exchange rate after 48 h operation with the annulus- in and centre-in flow direction are 64.9 W/m and 49.9 W/m respectively. We found that the heat exchange rate in annulus-in method is about 20-30 % higher than that of centre-in flow direction.

3.4 The effect of flow rate

The conditions in the simulation are as follows: the depth of the borehole is 60 m. The inlet water temperature are 37 ℃ and 6 ℃ in cooling and heating mode respectively. For the single U tube, the thermal conductivity of soil and grout are both 2.5 W/ (m•K). The PE tube is used and the diameter is 32 mm for single U tube heat exchanger. For the coaxial heat exchanger, the PE tube are used both in inner and annulus tube. The simulation results are shown in Fig.4. When the flow rate increased from 0.5 to 2.5 m3/h, the heat exchange rate increased from 50 to 58 W/m and 54 to 77 W/m respectively for single U tube and coaxial tube in cooling mode, and 31 to 38 W/m and 33 to 50 W/m respectively for single U tube and coaxial tube in heating mode. The effect of flow rate on the heat exchange of coaxial tube is greater than that of single U tube. The difference of the heat exchange rate of two heat exchangers is relatively larger and the advantage of using coaxial tube is more obvious when the flow rate is higher.

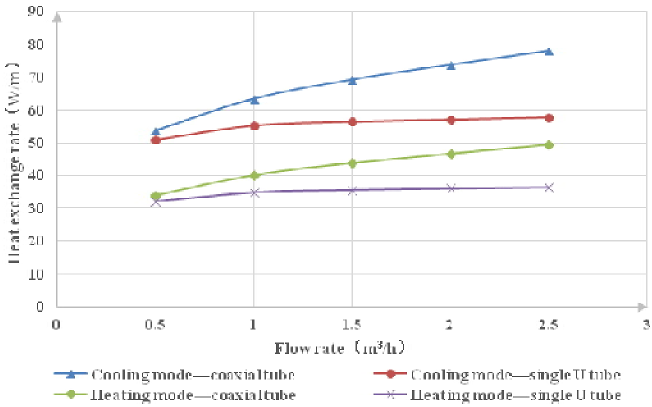

Fig. 4 The heat exchange rate of the two heat exchangers in different flow rate.

3.5 The soil temperature distribution

In order to compare the soil temperature distribution of the tubes, the simulation was made for the operation of 480 h based on the models of single tube and coaxial exchanger. The parameters are the same as the above section. The annulus-in flow direction and PE material with inner tube were adopted. The simulation results of the soil temperature are shown in Fig. 5.

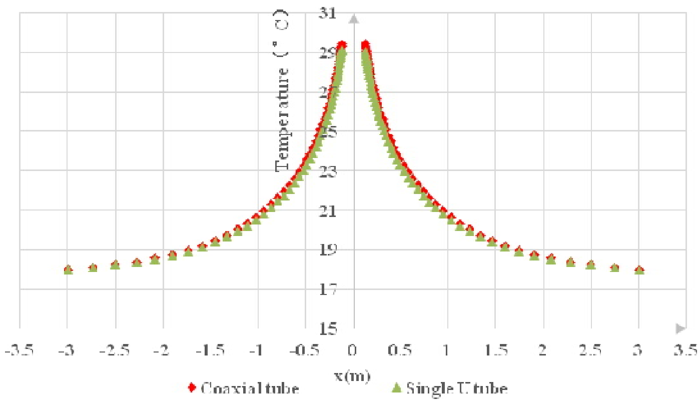

Fig. 5 The soil temperature after 480 h operation at the depth of 30 m (X is the horizontal distance from the borehole centre).

As shown in Fig. 5, the soil temperature at X=1 and -1 m is 20.7 ℃ and 20.5 ℃ respectively for coaxial and single U tube exchanger. It means the thermal influence radius of coaxial borehole heat exchanger is a little larger than that of single U tube. This may be due to the larger heat exchange rate for CBHE.

4. Conclusions

The Fluent Gambit software tool is used to generate the computational mesh. The heat exchange rate and thermal influencing radius of single U tube and CBHE, effect of flow direction of water, flow rate and the pipe material on the heat exchange of CBHE were investigated by commercial software Fluent. The following conclusions were obtained:

After the operation of 48 h, the heat exchange rates of coaxial (73.1 W/m) is 27.8% higher than that of single U tube BHE (57.2 W/m).

The thermal influence radius of coaxial borehole heat exchanger is a little larger than that of single U tube after the operation of 480 h.

The heat exchange rate in annulus-in method is 20-30 % higher than that of center-in flow direction.

Increasing the flow rate will increase the heat exchange of single U and coaxial borehole heat exchanger. The effect of flow rate on the heat exchange of coaxial tube is greater than that of single U tube.

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