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Numerical investigation of the backfilling material thermal conductivity impact on the heat transfer performance of the buried pipe heat exchanger

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Abstract. Based on the in-site thermal response experiment of a shallow geothermal energy plant in Guiyang, a model characterizing the heat transfer process between well-backfill material-ground material of a buried double vertical U-tube underground heat transfer system is established. Moreover, the influence of the thermal conductivity of the backfill material on the heat exchange efficiency for the summer condition is investigated. Results show that the maximum error between the outlet water temperatures calculated from model and obtained from field testing is less than 1.7%, which verifies the correctness of the model. When the thermal conductivity of the backfill is low, the heat in the buried heat exchanger is basically limited in the domain of the borehole. Furthermore, it is observed that the heat transfer efficiency increases, as the thermal conductivity increases. When the thermal conductivity of the backfill is close to that of the surrounding rock, the heat transfer efficiency increases in a faster rate. However, when the thermal conductivity of the backfill further increases, the heat transfer efficiency insignificantly increases. It is found that higher thermal conductivity of the backfill material has limited improvement on the heat exchange capacity of the buried pipe.

1. Introduction

Vertical ground-coupled heat pump system has become the dominant form of the ground source heat pump heating and cooling technology due to its energy saving, environmental protection and wide applications [1, 2]. In the ground source heat pump system, the design of the underground heat exchanger directly determines whether the performance of the whole system is acceptable or not [3]. The backfilling material of the underground heat exchanger as the filling medium between the buried heat exchanger and the soil, is an important link in the heat exchange of the ground source heat pump system. Its performance directly affects the capital expenditure of the underground heat transfer and ground source heat pump systems [4]. It is more obvious in carbonated rock areas with higher capital expenditures. The research on high-performance backfilling materials can optimize the performance of the ground source heat pump system. The backfilling material with good thermal conductivity can appropriately reduce the depth of the hole in the initial installation [5-7]. In other words, conductor materials can reduce the initial installation cost of the ground source heat pump and play an important role in the promotion of ground source heat pump technology [1].

In the construction process, the most direct backfilling material is the coarse sand backfilling or drill cuttings. This method is simple and economical. However, the heat transfer efficiency is difficult to guarantee [8]. The early backfilling materials were conventional bentonite and water mixtures. It



should be indicated that their thermal conductivity is lower than that of the geotechnical layer with higher heat transfer efficiency [8]. Remund et al. [9] performed variety of field experiments to investigate buried pipes. They showed that the backfilling material is one of the key parameters that affects the heat transfer and has significant impact in the mud formation. Moreover, Pahudhe et al [10] performed a thermal response test of double U-shaped heat exchange tubes and concluded that employing the quartz sand as the filling material can reduce the thermal resistance of the drilling by 30%. After considering the construction performance, heat transfer and mechanical strength of the backfilling material, showed that the scrap steel slag as an additive is beneficial to improve the construction performance of the backfilling material, but it leads to a decrease in the thermal conductivity [11]. Noorollahi et al. [4] summarized research results of adding other components to the backfilling material to investigate the composition impact on the system heat transfer. They showed that backfilling materials should be selected according to local conditions. Moreover, they indicated that in order to study the heat transfer efficiency of the system, the heat exchange system should also be studied, in addition to the thermal conductivity.

Researches showed that increasing the proportion of the bentonite can improve the thermal conductivity of backfilling materials, mainly composed of sand and bentonite mixture [12]. However, when the bentonite component is in contact with the saline-alkaline soil, the thermal conductivity of the backfilling material changes. Therefore, the efficiency of the heat exchange system decreases [13]. Wan et al. [14] investigated the thermal conductivity of loess and tailing materials with various moisture content and mixing ratios, which provided ideas for improving the low thermal conductivity of the loess backfilling material in the northwest of China. Moreover, Li et al. [3] studied the heat transfer system of the vertical U-shaped buried pipe in the cold region. By installing the pipe isolator, the higher thermal conductivity of the backfilling material leads to enhance the heat exchange and increase the thermal interference between buried pipes. In the stratum with high permeability and low thermal conductivity, high permeability increases the vertical infiltration. On the other hand, lower thermal conductivity means higher thermal resistance of the drilling. Thus, economic sand should be used as the backfilling material and fill clay layer of certain thickness to block vertical seepage [15]. Considering the heat-osmotic coupling condition of the well group heat-exchange, the heat transfer of the well group may generate the heat accumulation [16]. Based on the heat exchange site of a single U-type buried pipe in the US, Han Chanjuan et al. [17] found that the thermal conductivity of the backfilling material have a great influence on the heat transfer of the system during continuous operation, while the thermal conductivity and specific heat control the heat transfer efficiency under the intermittent operation mode. This conclusion was obtained by performing a numerical simulation. In this study, based on the on-site thermal response test of the ground-coupled heat pump system in China's carbonate rock area, it is intended to investigate the influence of the backfilling material thermal conductivity on the heat transfer efficiency of the system. The present study can provide a reference for the development of the low temperature energy from the shallow layer in the carbonate area.

2. Numerical method and model construction

2.1 Physical model

The research in this study is carried out, based on a shallow geothermal energy project in Guiyang. The surrounding stratum of the heat exchanger is the dolomite of Cambrian Middle-Upper Loushanguan Group. Moreover, the thermal conductivity of the measured rock mass, thermal diffusivity and specific heat capacity are $5.066\text{W}/(\text{m}\cdot\text{K})$, $2.714\text{mm}^2/\text{s}$ and $1.907\text{MJ}/(\text{m}^3\cdot\text{K})$, respectively. Furthermore, the drilling depth and bore diameter of the on-site thermal response test are 100m and 150mm, respectively. The double "U" heat exchanger, made from Polyethylene (PE) is positioned under the hole. The thermal conductivity, outer diameter and the wall thickness of the PE pipe are $0.45\text{W}/(\text{m}\cdot\text{K})$, 32mm and 3mm, respectively. Moreover, the pipe spacing is 30mm.

Based on the geothermal engineering conditions, this simulation considered the underground area

of the U-pipe geothermal system. Figure 1 indicates that the system consists of three parts: the U-pipe, the well filling material and the underground rock mass. The drilling depth of the system is 100m and the diameter of the wellhead is 150mm. The well condition is consistent with engineering conditions. The well contains two sets of U-pipe heat exchangers, arranged in a crossed configuration. Figure 1 illustrates the arrangement. The U-pipe is made of PE material with an inner diameter of 29mm and the thickness of 3mm. The inner pipe is considered as an open flow path. The area except the U-pipe in the well is filled with solid materials. Moreover, the area outside the well is considered as dense rock with no groundwater flow. The heat exchange system of the buried pipe in the model has a vertical depth of 100m and extends 15m with the double "U" pipe heat exchanger as the center. Thus the radial width of the heat exchange system reaches to 30mm. Figure 2 shows that an unstructured grid is applied to the model. Furthermore, the pipe wall is properly dense and gradually sparse outward.

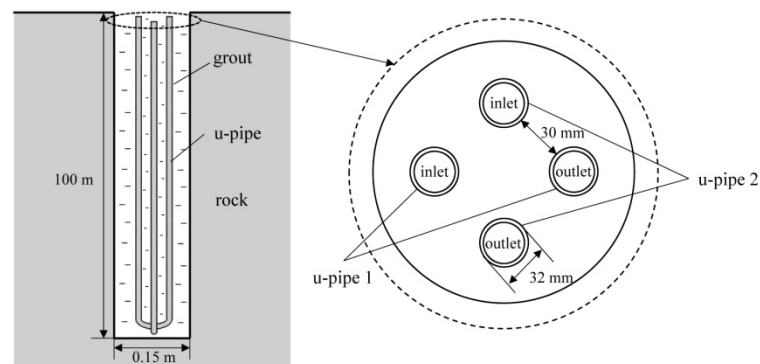


Fig.1 Physical model and geometrical dimensions of the double “U” heat exchanger for a shallow cryogenic energy engineering project

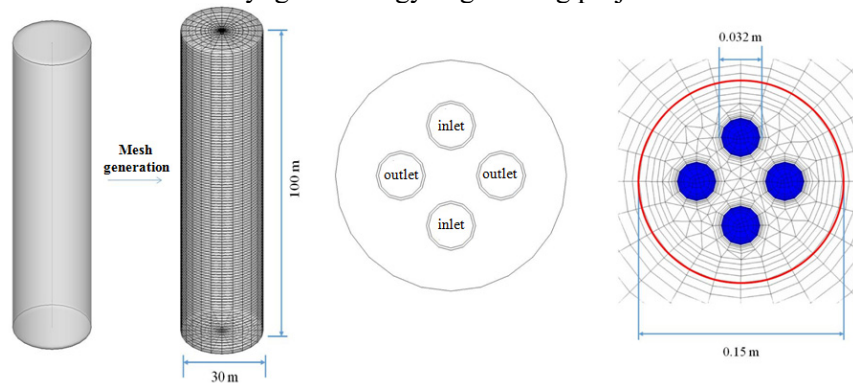


Fig. 2 Schematic diagram of the double “U” heat exchanger model and grid splitting

2.2 Control equation

In the model established in this study, the geothermal system is composed of the U-pipe, filling materials and underground soils. In order to simplify the model and reduce the amount of calculations, we assume all parts as homogeneous materials.

The N-S equation is used to simulate the working fluid flow in the U-pipe and the k-ε double equation model is used to simulate the turbulence in the pipe. The Reynolds averaged Navier Stokes (RANS) equations are expressed as the following:

Continuity equation:

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (1)$$

Momentum equation:

$$\frac{\partial(\rho u_j)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_i} = -\frac{\partial P}{\partial x_j} + \frac{\partial}{\partial x_i} \left[\mu \frac{\partial u_j}{\partial x_i} - \rho \overline{u'_i u'_j} \right] \quad (2)$$

Where $\overline{u'_i u'_j}$ is the averaged product of velocity component fluctuations. In order to close the RANS equation, the $k - \varepsilon$ equation needs to be further calculated:

k equation is expressed as:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = + \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G - \rho \varepsilon \quad (3)$$

ε equation is expressed as:

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho \varepsilon u_i)}{\partial x_i} = + \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \frac{\varepsilon}{k} (C_{\varepsilon 1} G - C_{\varepsilon 2} \rho \varepsilon) \quad (4)$$

μ_t is turbulent viscosity and it is defined as:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (5)$$

G is the generation term of the turbulent kinetic energy (k) and it is defined as:

$$G = \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j} \quad (6)$$

In equations (3) to (5), σ_k , σ_ε , $C_{\varepsilon 1}$, $C_{\varepsilon 2}$ and C_μ are real constants and their values are 1.0, 1.3, 1.44, 1.92 and 0.09, respectively.

For the energy conservation of working fluids inside the U-pipe and other solid areas, the energy equation without internal heat source is used to solve:

$$\frac{\partial(\rho C_p T)}{\partial t} + \frac{\partial(\rho C_p T u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left(\lambda \frac{\partial T}{\partial x_j} \right) \quad (7)$$

Where, u , ρ , P , μ , C_p and T denote the speed, density, pressure, viscosity, specific heat under setting pressure and temperature, respectively.

2.3 Initial conditions, boundary conditions and other parameters

Initially, the temperature in the underground area is set to 16.2°C. The top of the calculation area is the surface and considered to be a constant temperature boundary with a temperature of 16.2°C. The rock boundary is set to an adiabatic boundary. There are rock layers with the thickness of 20m around the wellbore and at the wellbore bottom. The setting of the boundary conditions during the calculation time does not affect the heating process in the well. The entry of U-pipe is a setting flow boundary with an injection flow of 1200L/h with the temperature of 32°C. The working fluid is water.

During the calculation process, the rock, filling, wall material and working fluid are in given physical properties and values of their physical properties are shown in Table 1:

Table 1. Physical parameter settings

Material	density (kg/m ³)	thermal conductivity (W/m/°C)	specific heat (J/kg/°C)	Viscosity (Pa·s)
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rock	2400	5.066	930	\
filling material	2100	0.5~5.0	900	\
PE pipe wall	910	0.45	2300	\
working fluid	998	0.6	4182	0.001

2.4 model calculation

After completing the mathematical model of the underground heat transfer process of the U-shaped pipe, a mathematical model is applied to the Fluent (a fluid dynamics simulation software) through the user-defined function (UDF). The underground heat transfer process of the U-shaped pipe is simulated, based on the calculation advantages of fluid dynamics for complex fluid motion.

3. Simulation results and discussion

3.1 Model verification

The on-site thermal response test is the main method for testing the thermophysical properties of the rock mass [18, 19]. The original temperature, thermal conductivity and thermal resistance of the rock along the buried pipe is calculated through the response curve of the inlet and outlet fluid temperatures from the buried pipe heat exchanger [20,21]. In order to verify the correctness of the numerical analysis of the model, we calculate working conditions of the on-site thermal response test, in the shallow geothermal energy project. The simulation setting is consistent with the parameter value of the on-site thermal response test. The simulation is performed for the summer operation. The measured thermal conductivity in the laboratory is $2.3277\text{W}/(\text{m}\cdot\text{K})$, which is between the backfilling material of the borehole wall and the “U” heat exchanger. Moreover, the initial ground temperature of the fluid, backfilling material and surrounding rock in the buried heat exchanger is 16.2°C , while the injection temperature is 32°C . The heat exchange medium in the heat exchanger is water with the flow of 1181L/h and the flow rate of 0.309 m/s .

In the case of continuous operation of the buried pipe heat exchanger for 48 hours, the outlet water temperature of the double “U” pipe is obtained by the on-site thermal response test and numerical simulation. Figure 3 shows the distribution of the outlet water temperature against time. From the comparison between the test and the simulation curve, the model calculation basically reproduced the whole process of the on-site thermal response test. It is observed that the maximum error between the test and simulation calculation of outlet water temperature of the buried pipe heat exchanger is 1.7%. Therefore, the results are basically the same. It indicates that the established model and its numerical calculation method are acceptable.

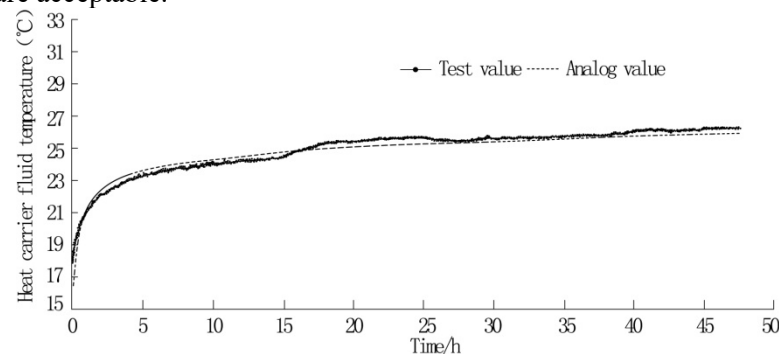


Fig.3 Comparison between the experiment and the numerical simulation for the outlet water temperature from the buried pipe heat exchanger

3.2 Influence of different backfilling materials on the heat transfer performance

The backfilling material is a heat transfer medium connecting the buried pipe heat exchanger and the rock mass. Increasing the thermal conductivity of the backfilling material can reduce the thermal resistance of the buried pipe heat exchanger, which can improve the heat exchange efficiency of the buried pipe [9, 18]. In order to study the effect of thermal conductivity of different backfilling materials on the heat transfer performance of buried pipe heat exchangers, $0.5\text{W}/(\text{m}\cdot\text{K})$ is used as the base and the heat flux is increased to $5.0\text{W}/(\text{m}\cdot\text{K})$ at intervals of $0.25\text{W}/(\text{m}\cdot\text{K})$.

Figure 4 shows the temperature distribution of the buried pipe heat exchanger at a depth of 50m after 10 days, 30 days and 90 days, when the thermal conductivity of the backfilling material are $0.5\text{W}/(\text{m}\cdot\text{K})$, $2.75\text{W}/(\text{m}\cdot\text{K})$ and $5.0\text{W}/(\text{m}\cdot\text{K})$, respectively. Figure 4 indicates that, when the thermal conductivity of the backfilling material is the minimum (i.e. $0.5\text{W}/(\text{m}\cdot\text{K})$), the temperature of the heat exchange medium in the buried pipe heat exchanger is high and the temperature variation range is basically limited to the drilling. As time goes on, its diffusion range is still small. The temperature of the heat exchange medium in the heat exchanger reduces as the thermal conductivity of the backfilling material increases. Moreover, the range of temperature conduction to the outside grows.

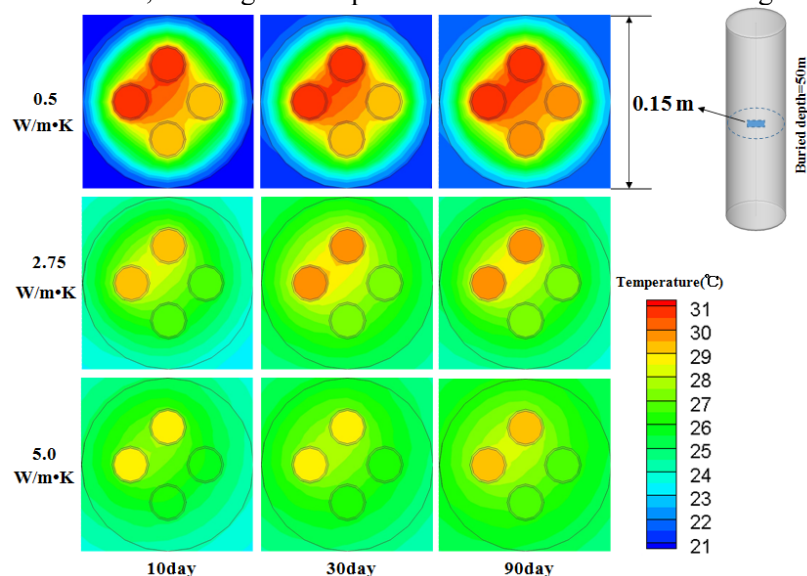


Figure.4 Temperature distribution at a depth of 50m for different thermal conductivities (0.5 , 2.75 and $5.0\text{ W}/(\text{m}\cdot\text{K})$) of typical backfilling materials

Figure 5 shows the variation of the outlet temperature of the buried pipe heat exchanger with time, for different thermal conductivities of the backfilling material. Three thermal conductivities, equal to $0.5\text{W}/(\text{m}\cdot\text{K})$, $2.75\text{W}/(\text{m}\cdot\text{K})$ and $5.0\text{W}/(\text{m}\cdot\text{K})$ are considered in this study. Figure 5 illustrates that all outlet temperatures reach a relatively stable state after about 15 days of simulation operation. However, there is longer stabilization time for backfilling materials with low thermal conductivities and shorter stabilization time for backfilling materials with high thermal conductivities. When the thermal conductivity of the backfilling material is $0.5\text{W}/(\text{m}\cdot\text{K})$, the outlet temperature becomes stable after about 6 days with a temperature of 29°C . The relative injection water temperature drops 3°C . On the other hand, when the thermal conductivity of the backfilling material is $5.0\text{W}/(\text{m}\cdot\text{K})$, the outlet temperature reaches to the stability after about 15 days with a temperature of 27°C . In other words, the temperature of the injection water drops 5°C . With the increase of the thermal conductivity of the backfilling material, the outlet temperature of the buried pipe heat exchanger gradually drops and the heat exchange efficiency is improved. However, the outlet temperature of the buried pipe heat exchanger does not reduce at the same rate. According to simulation results, when the thermal conductivity of the backfilling material increases from a low value to the thermal conductivity of the surrounding rock, the heat transfer efficiency rises faster. On the contrary, the heat transfer efficiency

risers slower and outlet temperature of the heat exchanger tends to reach the stability. This is consistent with the results of P. Remund et al. [9], because the thermal resistance of the backfilling material decreases as the thermal conductivity increases. However but when it reaches a certain value, the degree of the thermal resistance reduction becomes smaller.

Therefore, as the intermediate heat transfer medium between the buried pipe heat exchanger and the surrounding rock, the thermal conductivity of the backfilling material is not as large as possible. When the thermal conductivity of the backfilling material is slightly higher than that of the surrounding rock, the thermal resistance of the backfilling material can be reduced at certain extent and the heat transfer efficiency is improved. However, after the thermal conductivity of the backfilling material increases to a certain extent, it is difficult to improve the heat transfer capacity of the buried pipe [8].

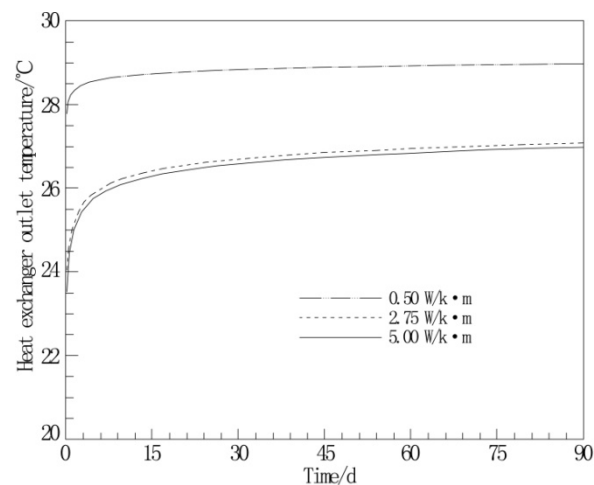


Fig.5 Dynamics effect of the thermal conductivity of the backfilling material on the outlet temperature of the heat exchanger

4. Conclusions

(1) Comparing results obtained from the numerical simulation with the ones from the on-site thermal response test indicates that the maximum error is 1.7%. It is concluded that the numerical simulation is verified. Moreover, it is found that the Fluent software is a powerful method to numerically investigate the buried pipe problem and can be applied to the engineering simulation of the ground-coupled heat pump.

(2) When the thermal conductivity of the backfilling material is low, the temperature of the heat exchange medium in the buried pipe heat exchanger is high and the temperature variation range is basically limited to the drilling. As the thermal conductivity of the backfilling material increases, the temperature of the heat exchange medium in the heat exchanger also reduces. Moreover, the range of the temperature conduction to the outside also increases and the heat exchange efficiency is improved. It is concluded that, when the thermal conductivity of the backfilling material is close to that of the surrounding rock, the heat transfer efficiency increases fast. On the other hand, when it is greater than the thermal conductivity of the surrounding rock, the heat transfer efficiency is not obviously increased.

(3) The thermal conductivity of the backfilling material is not as large as possible. When the thermal conductivity of the backfilling material is slightly higher than that of the surrounding rock, the thermal resistance of the backfilling material slightly reduces and the heat transfer efficiency improves. It is found that when the thermal conductivity of the backfilling material increases to a certain extent, it is difficult to improve the heat transfer capacity of the buried pipe [8].

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