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Numerical study on the effect of U-shaped deep-buried pipe type on heat transfer performance

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Abstract: In combination with a U-shaped deep-buried drilling project for heating buildings in Xi'an, three-dimensional (3D) full-size numerical calculation models with a depth of 1000 m were established for coupling the internal and external heat transfer of U-shaped and W-shaped pipes. This is based on the measured well temperature data of a drilling project and lithology of rock and soil obtained from the tests. Furthermore, by calculating and comparing the total heat transfer quantity and heat transfer per linear meter between two types of buried pipes during the simulation, the heat transfer effect of W-shaped buried pipe versus U-shaped buried pipe was analyzed. The simulation results show that under the same flow rate and inlet water temperature of buried pipe, there is no significant difference in heat transfer per linear meter between W-shaped and U-shaped buried pipes. Considering the outlet pipe diameter of W-shaped buried pipe, the flow rate of its inlet pipe and the spacing between buried pipes can be enhanced or enlarged in practical projects. It can be concluded that W-shaped buried pipe has a better heat transfer effect than U-shaped buried pipe under certain conditions. Therefore, similar solutions can be considered to increase the heat transfer capacity of deep-buried pipes in limited space sites for practical projects, and then the building heating area can also be expanded.

1. Introduction

With the rapid development of urbanization and improvement of quality of life, energy demand is ever-increasing, and related energy problems are also increasing [1,2]. Geothermal energy, a new type of clean and environment-friendly renewable energy, has attracted much attention recently owing to its large reserve and extensive distribution. At present, the utilization of geothermal energy is mainly concentrated in shallow rock and soil areas, and the heating and cooling of buildings are achieved using buried pipes or other technologies. Because the utilization of shallow geothermal energy suffers from insufficient heating capacity and very large occupation area, utilization technologies for middle and deep geothermal energy have been proposed in recent years. Currently in Xi'an, several building heating projects extract heat using deep-buried pipes, and the depth of buried pipes is more than 2000 m.

For a geothermal energy utilization system that extracts heat using buried pipes, whether or not the pipes are shallow- or deep-buried, the heat exchanger of buried pipe is an important factor influencing



the heat transfer performance of entire system [3,4]. At present, studies on the heat transfer performance of shallow-buried pipes have been relatively mature, but for the heat transfer system of deep-buried pipes, studies on the heat transfer performance of buried pipes have just started due to their large scale from top to bottom. At present, studies on the heat transfer performance of deep-buried pipes mainly focus on the feasibility of heat transfer and the analysis and evaluation of heat transfer quantity [5,6], effect of buried pipe size, flow rate, and inlet water temperature on heat transfer [7,8], and thermal insulation property of buried pipes [9,10]. Currently, the effect of deep-buried pipe type on heat transfer performance has not been extensively studied.

For shallow-buried pipes, much attention has been paid to the effect of buried pipe's own structure on heat transfer. Zhao et al. [11] established a three-dimensional (3D) transient model to describe the heat transfer between circulating fluid and soil using finite element method with respect to three different shallow-buried pipe structures, such as U-shaped pipe, W-shaped pipe, and spiral pipe and analyzed the surface temperatures, thermal resistance variations, and heat transfer conditions of different types of buried pipes. The results indicate that under the same initial and boundary conditions, the internal thermal resistance of spiral pipe is lower than that of U-shaped and W-shaped buried pipes, and the surface temperature distribution of spiral buried pipe is more uniform. Choi et al. [12] proposed to change the structure of conventional U-shaped buried pipe into a pipe with branched pipes (such as W-shaped buried pipes) by conducting research to improve the heat transfer efficiency. Habibi [13] also reported the effect of buried pipe's structure on enhanced heat transfer. As shown in the literature, the aim of changing the overall structure of shallow-buried pipes is to increase the contact area between buried pipe and the surrounding rock and soil or cementing backfill to enhance heat transfer. Therefore, the key point in the study is to consider whether a solution similar to the enhancement on heat transfer of shallow-buried pipes can be used to enhance the heat transfer performance of deep-buried pipes.

With regard to the existing and relatively mature heat transfer technology of U-shaped deep-buried pipes, a change in original U-shaped buried pipe into a W-shaped deep-buried pipe is proposed in this paper, and a 3D full-size model was established. Through Fluent simulation calculation, the total heat transfer quantity and heat transfer per meter of two types of buried pipes were analyzed, and the feasibility of W-shaped buried pipe in enhancing the heat transfer of deep-buried pipe is discussed.

2. Numerical calculation modeling

Combined with an actual building heating project in Xi'an using a U-shaped deep-buried pipe, a 3D full-size numerical calculation model was established for simulation analysis by using the well temperature data measured by drilling and lithology interpretation data. Considering that the model size of W-shaped buried pipe and the number of grids are very large, the depth of established model is 1000 m, and the buried pipe types are U-shaped and W-shaped.

2.1. Physical model and its geometric dimension

For the heat transfer system of a U-shaped deep-buried pipe, the structure of buried pipe is composed of three parts, namely, the outlet well (outlet pipe), inlet well (inlet pipe), and deep connecting well (connecting pipe). As shown in Fig. 1, water flows into the system from the inlet pipe, absorbs heat from the soil through the inlet pipe, outlet pipe, and connecting pipe, and finally discharges from the outlet pipe. For the heat transfer system of a W-shaped deep-buried pipe, the structure of buried pipe consists of two inlet pipes and one outlet pipe, and the deep structure of buried pipe depends on the three-way connection. The system is fed with water in two inlet pipes on both the sides; the water absorbs heat from the soil through the inlet pipe, outlet pipe, and three-way connecting pipe and then it discharges from the outlet pipe (see Fig. 1).

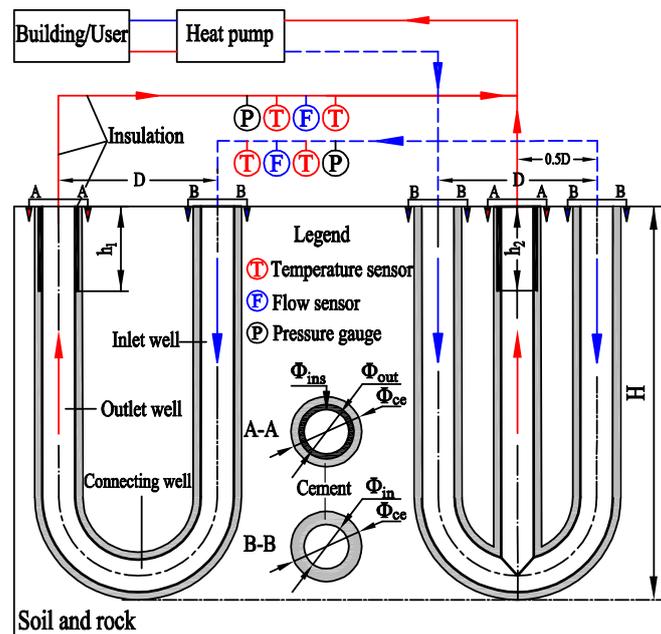


Figure 1. Schematic diagram of heat transfer system of U-shaped and W-shaped buried pipes

The geometric dimensions of U-shaped and W-shaped buried pipes are shown in Fig. 1. To make the heat transfer conditions of two types of buried pipes comparable, the dimensions of inlet and outlet pipes of two buried pipes are both $\Phi 139.7 \times 7.72$ (Φ_{in} , Φ_{out}), and the cementing external diameters are both 215.9 mm (Φ_{cem}). The spacing D between the inlet and outlet pipes of U-shaped buried pipe and that between the two inlet pipes of W-shaped buried pipe are both 140 m, while the spacing between the inlet and outlet pipes of W-shaped pipe is 0.5 D . The buried depths of two buried pipes are both 1000 m. Although a part of outlet pipe near the ground will cause heat loss due to the high outlet water temperature, considering the design conditions in the study (the inlet water temperature was set to 5 °C later in this study, it can be confirmed from calculation that the real-time outlet water temperatures of buried pipes are less than shallow rock and soil temperature, i.e., heat loss does not occur), and the heat insulation heights of outlet section of two types of buried pipes are set to 0 m. Combined with the thermostatic rock and soil layer near the ground, the temperature of drilling well, lithology of rock and soil, and other measured data, multilayer models were established for U-shaped and W-shaped buried pipes to perform parameter setting (see section 2.3 below). The topmost unit was divided into two parts with a thickness of 20 m and 40 m, and the units were further divided into eight units with a thickness of 100 m, one unit with a thickness of 90 m, and one unit with a thickness of 50 m. In this manner, each model has 12 units along the depth direction of buried pipes, and the calculation area around the buried pipe has a radius of 20 m outward along the axis of buried pipe.

2.2. Governing equation

The continuity, momentum, and energy equations describing the heat transfer by flowing water in the tube and the thermal differential equations describing the heat transfer between the tube walls, rock and soil, and cement can be expressed as follows.

$$\partial(\rho\phi) / \partial t + \text{div}(\rho U \phi) = \text{div}(\Gamma_{\phi} \text{grad} \phi) + S_{\phi} \quad (1)$$

where ρ is the density of flowing medium in the U-bend tube, kg/m^3 ; t is the time, s; ϕ is a general physical quantity; U is the velocity of flow medium in the U-bend tube, m/s; Γ_{ϕ} is the diffusion flux, and S_{ϕ} is the source term.

FLUENT software was used for simulation in this study, and the standard k-epsilon turbulence model was selected. The continuity, turbulent kinetics, dissipation, and momentum and energy equations in

three directions were used to solve the model. The second-order upwind discretization schemes were used, and the SIMPLE pressure correction method was used.

2.3. Model settings

In terms of model settings, for the temperature boundary of rock and soil, the outer edge of each rock-soil layer with a radial distance of 20 m was defined as the constant-temperature boundary. The temperature is the same as the initial temperature, and the soil's upper surface is the adiabatic boundary. The upper and lower distributions of the initial rock and soil temperature were obtained from actual measurements [14]. For the thermophysical parameters of rock and soil, parameters such as density and specific heat of rock and soil were obtained by special experimental measurements on the rock core [14]. The lithological characteristics of each thickness unit were obtained according to the weight-averaged value of interpretation data based on the volume proportion of different components within the thickness unit.

Gambit was used to establish a 3D full-size calculation model of U-shaped and W-shaped buried pipes and conduct grid partitioning. Grid density can affect the reliability of calculation. Generally speaking, the denser the grid, the more reliable the result. However, this consumes more calculation time and requires a computer with higher performance accordingly. Therefore, under the premise that the reliability of calculation results is guaranteed, the grid number should be less as far as possible. Under the principle that the relative errors of real-time outlet temperatures of pipes corresponding to three more dense grid densities are less than 1%, the grid density of pipe body is 634 cells per meter, the grid density of well's cementing body is 320 cells per meter [14], and the grid density of rock and soil is 1600 cells per meter. In addition, considering the stability issue under different time steps, 3600 s was used as the time step in calculation [14].

3. Calculation results and analysis

In this section, combined with the model established above, the heat transfer conditions of U-shaped and W-shaped buried pipes were analyzed. To visually compare the heat transfer conditions of these two buried pipes, an open-type system was used in the simulation analysis. The inlet water temperature of buried pipe and the circulating flow rate were controlled to be constant in all the simulated conditions with respect to the two buried pipe types. By comparing the outlet water temperature of buried pipe and the corresponding heat transfer quantity, the effect of buried pipe type on the heat transfer of deep-buried pipe was evaluated.

3.1. Initial temperature and velocity field

Combined with the existing well logging data of a deep-buried pipe, the rock structure of model was set up. The initial temperature and velocity field within the calculation domain of U-shaped and W-shaped buried pipe are shown in Fig. 2.

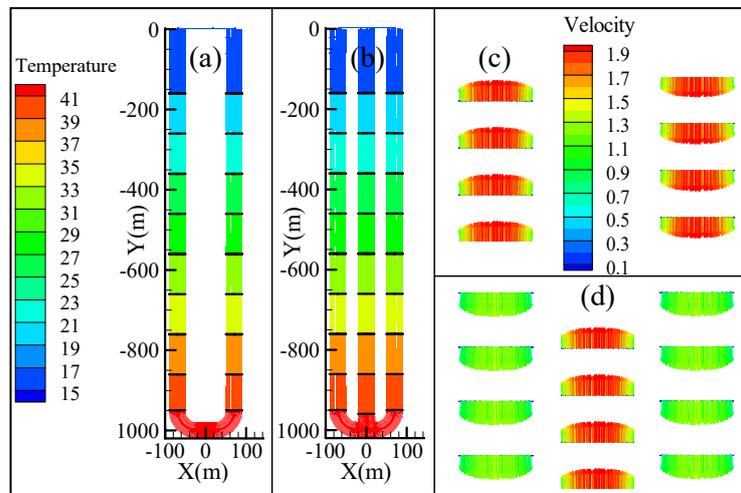


Figure 2. Initial temperatures and velocity fields of U-shaped and W-shaped buried pipes. (a) Initial temperature of U-shaped buried pipe, (b) initial temperature of W-shaped buried pipe, (c) velocity vector of U-shaped buried pipe, (d) velocity vector of W-shaped buried pipe

Fig. 2 shows that with the increase in buried pipe depth, the initial field temperature of two buried pipe types gradually increases. With regard to the circulating flow rate in buried pipe, the flow rate should be constant to control the variable in the comparison and analysis of two buried pipe types on heat transfer intensity. Therefore, in the simulation settings, the flow rate in U-shaped buried pipe is 19.69 kg/s (inlet velocity: 1.63 m/s and outlet velocity: 1.63 m/s), and that in W-shaped buried pipe is 19.69 kg/s as well (inlet velocity of each pipe on two sides: 0.81 m/s, outlet velocity: 1.63 m/s). Because the flow rate of the two buried pipe types should be consistent, the flow rate (or flow velocity) of each inlet pipe of W-shaped buried pipe is only half of that (or flow velocity) of U-shaped buried pipe. Fig. 2 (d) shows that the velocity vector corresponding to the inlet pipe is obviously smaller as well.

3.2. Heat transfer comparison of two buried pipe types

3.2.1. *Water temperature variation of buried pipes.* For the simulation of two buried pipe types, the inlet water temperature of buried pipe was set to be constantly 5 °C with a constant flow rate of 19.69 kg/s, and the real-time outlet water temperature of buried pipe was monitored. Fig. 3 shows the changes in the inlet and outlet temperatures of U-shaped and W-shaped buried pipes during the 240-h simulation operation.

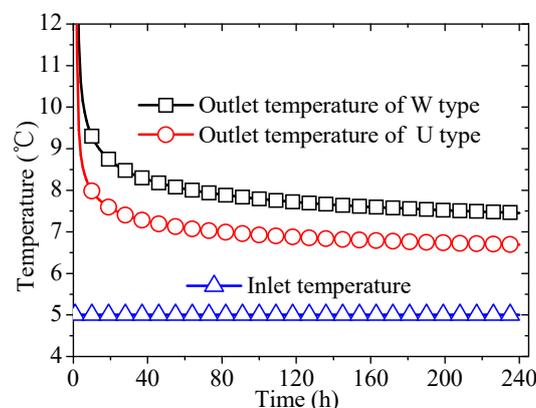


Figure 3. Inlet and outlet temperature variations of two buried pipe types with time

Fig. 3 and simulation data show that when the inlet water temperature of buried pipe is kept constant under the open-type system, the outlet water temperature of buried pipe gradually decreases with the increase in running time, and the decreasing rate slows down with time. By comparing the outlet water temperatures of two buried pipe types, the average outlet water temperatures of W-shaped and U-shaped buried pipes are 7.98 °C and 7.06 °C during the 240-h simulation operation, respectively. With the increase in the heat transfer area of buried pipe, the outlet water temperature of U-shaped buried pipe increases.

3.2.2. Heat transfer comparison of buried pipes. The inlet and outlet water temperatures and flow rates of buried pipe were monitored in real time during the simulation calculation. The corresponding heat transfer intensity of two buried pipe types can be calculated using Equation (2). By further calculating the total buried length of two buried pipe types, the heat transfer per linear meter of buried pipe can be obtained, and the heat transfer per linear meter can be calculated using Equation (3).

$$Q = c \cdot G \cdot \Delta T \quad (2)$$

$$q_l = Q / L \quad (3)$$

In Equations (2) and (3), Q is the heat transfer intensity, W; c is the specific heat capacity of water, J/(kg·K); G is the flow rate, kg/s; ΔT is the difference between inlet and outlet water temperatures of buried pipe, K; q_l is the heat transfer per linear meter of buried pipe, W/m; L is the total length of buried pipe, m.

According to the simulation data, the heat transfer intensity and heat transfer per linear meter of two buried pipe types are plotted. As shown in Fig. 4, (a) represents the real-time heat transfer quantity of two buried pipe types during the 240-h simulation operation and also represents the heat transfer increment of W-shaped buried pipe compared with that of U-shaped buried pipe, and (b) represents the heat transfer per linear meter of two buried pipe types within 240-h simulation operation and the increase in heat transfer per linear meter of W-shaped buried pipe compared with U-shaped buried pipe.

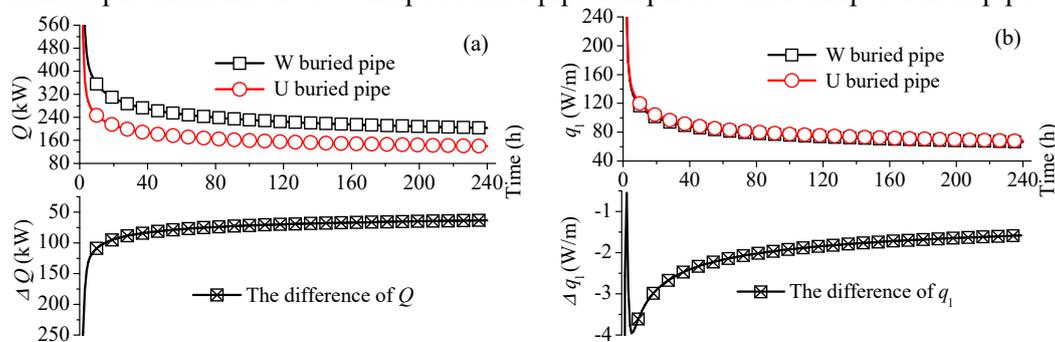


Figure 4. Heat transfer conditions of W-shaped and U-shaped buried pipes. (a) Real-time heat transfer and comparison of two buried pipe types during the simulation, (b) real-time heat transfer per linear meter and comparison of two buried pipe types during the simulation

Fig. 4 shows that under the open-type system, the heat transfer quantities of two buried pipe types decrease constantly and slow down over time. The total heat transfer quantity of W-shaped buried pipe is significantly higher than that of U-shaped buried pipe. This is because W-shaped buried pipe has one more inlet pipe than U-shaped buried pipe (Fig. 1). By comparing the average heat transfer of buried pipes during the 240-h simulation operation, the value of W-shaped buried pipe was found to be 246.04 kW, and the increased percent is 44.58% compared with the 170.17 kW of U-shaped buried pipe.

The lengths of heat transfer pipes of two buried pipe types were calculated. W-shaped buried pipe is 3057.08 m long; U-shaped buried pipe is 2057.08 m long. Then, the heat transfer per linear meter of two buried pipe types was obtained. As shown in Fig. 4 (b), it shows a slight difference in the heat transfer per linear meter of W-shaped and U-shaped buried pipes, and the value of W-shaped buried pipe is slightly smaller than that of U-shaped buried pipe. By comparing the average heat transfer per linear

meter of buried pipes during the 240-h simulation operation, the value of W-shaped buried pipe is 80.48 W/m, while that of U-shaped buried pipe is 82.72 W/m, with a difference of -2.24 W/m and only -2.71% .

Combined with the content in section 2.1, to make the heat transfer conditions of two buried pipe types comparable, the same dimension was used for three wells (two inlet pipes and one outlet pipe) of W-shaped buried pipe and two wells of U-shaped buried pipe when the model was established. In addition, in section 3.2, the flow rate in W-shaped buried pipe is also consistent with that in U-shaped buried pipe during the simulation, i.e., the two inlet pipes of W-shaped buried pipe actually operate at a lower flow rate (half of the outlet pipe). Under the aforementioned model's dimension and simulation conditions, the average heat transfer per linear meter of W-shaped buried pipe is only -2.71% different from that of U-shaped buried pipe, i.e., there is no significant difference in the heat transfer per linear meter of buried pipes. In practical engineering, if the outlet pipe of W-shaped buried pipe has a larger pipe diameter and the flow rates of two inlet pipes are increased simultaneously, the heat transfer per linear meter of W-shaped buried pipe is certainly better than that of U-shaped pipe. On the other hand, combined with Equation (3), it is observed that the heat transfer per linear meter of W-shaped and U-shaped buried pipes is affected by the length of deep connecting pipes (the maximum spacing of two buried pipe types, represented by D in Fig. 1). For W-shaped buried pipe, the two inlet pipes always have a relatively low temperature in running, thus fully transferring heat with the surrounding rock and soil. However, for U-shaped buried pipe, with the increase in connecting pipe length, the heat transfer of unidirectional fluid with rock and soil along the flow direction slows down due to the continuous rise of its temperature. Therefore, the longer the connecting pipe length, the more obvious the heat transfer enhancement effect of W-shaped buried pipe.

4. Conclusions

In combination with a U-shaped deep-buried drilling project for heating buildings in Xi'an, 3D full-size numerical calculation models with a depth of 1000 m for coupling the internal and external heat transfer of U-shaped and W-shaped pipes were established based on the temperature data of well drilling and lithology of rock and soil obtained from the tests. By comparing the total heat transfer quantity and heat transfer per linear meter between the two types of buried pipes during the simulation operation, the heat transfer effect of W-shaped buried pipe versus U-shaped buried pipe was analyzed. The following conclusions are drawn:

(1) For the open-type system, the heat transfer quantity of W-shaped and U-shaped buried pipes decreases with time, and the decrease slows down over time. In the simulation operation for 240 h, the average heat transfer quantity of W-shaped buried pipe is 246.04 kW, and the increased percent is 44.58% compared with the 170.17 kW of U-shaped buried pipe.

(2) By comparing the heat transfer per linear meter of buried pipe within 240 h, the average heat transfer per linear meter of W-shaped buried pipe is 80.48 W/m, and that of U-shaped buried pipe is 82.72 W/m. The difference between the two values is -2.24 W/m, only -2.71% .

(3) In practical engineering, if the outlet pipe of W-shaped buried pipe has a larger pipe diameter and the flow rates in two inlet pipes are increased simultaneously, the heat transfer per linear meter of W-shaped buried pipe will be better than that of U-shaped pipe. On the other hand, the larger the spacing between the buried pipes, i.e., the longer the connecting pipe length, the more obvious the heat transfer enhancement effect of W-shaped buried pipe.

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