SIMULATION AND ANALYSIS OF BURIED PIPE HEAT TRANSFER PERFORMANCE UNDER LEAKAGE STATE

by

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Buried pipe leakage can lead to poor heat transfer performance and even system failure. Leakage analysis of buried tube greatly affects the operation condition diagnosis for the heat exchange in buried tube. In this study, the simulation software was applied in analyzing heat transfer process and efficiency of the buried pipes under different leakage conditions. Moreover, changes in outlet temperature, water pressure and flow rate were simulated at different positions and diverse sizes of the leakage port. According to our results, the size of leakage port greatly affected the parameter variation of the outlet port when the system started and stopped, thus affecting the cooling effect. In addition, position of the leakage port also had obvious influence on the physical state of the outlet water.

Key words: *leakage, buried pipe, heat transfer analysis, ANSYS*

Introduction

At present, heating and air-conditioning have become the universal demands, and its energy consumed in the entire society also shows an increasing trend. Heat exchanger in the buried tube represents a key part in the ground source heat pump system, whose overall efficiency is determined by ground buried pipe performance and quality. Leakage of buried pipe will lead to poor soil environment, deterioration of the heat transfer performance, and even system failure. The factors affecting the leakage of buried pipe have been analyzed. Meanwhile, the heat exchanger leakage simulation model has also been constructed [1].

Buried tube heat exchanger quality greatly affects whole system. The simulation and analysis results on the buried pipe can be employed to verify the rationality of parameter design, and guide the parameter setting and adjustment for buried pipe in practical engineering. Some researchers have adopted several buried pipe parameters, including diameter, depth, structure and thickness, to simulate the working efficiency. In addition, the flow rate, pressure, temperature and heat exchange of fluid in the tube are also analyzed.

For instance, Nam and Chae [2] established a simulation model and experimentally investigated the influences of hole depth, operation flow rate and temperature of inlet water. Han *et al*. [3] constructed the 3-D finite element model of buried pipe to simulate heat transfer under different load conditions. Zhou *et al*. [4] found that, the larger pipe diameter led to less pipe pressure loss, and an increase in flow rate resulted in the increased pressure loss in the pipeline while decreased in temperature difference. Besides, pressure difference increased

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linearly with the increasing depth under the same velocity. According to Li *et al*. [5], continuous heating worked better than intermittent heating. As suggested by Kong *et al*. [6], an increased inlet flow rate improved the heat exchanger performance, but the energy consumption coefficient should also be taken into account. Moreover, the thermal performances of smooth *U*-shaped tubes were always superior to those of petals at different speeds. Based on Liang *et al*. [7], comprehensive GSHE performance was improved by increasing the Reynolds number. When the number of Reynolds remains constant, elevating the diameter of *U*-tube improved the comprehensive performance of GSHE. Additionally, the factor of Reynolds number had larger influence on GSHE comprehensive performance than that of the factor of pipe diameter. Wang *et al*. [8] examined tube heat transfer properties at diverse impact angle conditions, and three kinds of heat exchangers with different structures were selected for investigating heat transfer and fluid-flow characteristics under different impact angles and different pipe inclinations. Habibi and Hakkaki-Fard [9] established a numerical mode according to 3-D fluid dynamics simulation using CFD. Thereafter, the as-constructed model was applied in evaluating the cost of initial installation and heating performance of the horizontal buried pipe. Sivasakthivel *et al*. [10] started from analyzing the heating performances of heat exchanges with single and double tubes, and focused on the analysis of the heating performance, ground temperature, heat recovery, heat injection rate of the heat exchangers with single and double tubes, together with their effects on the surrounding formation. The results suggested that, the heat exchanger with double *U*-shaped tubes had greater average efficiency than heat exchange with single *U*-shaped tube.

Leakage state analysis facilitates the positioning of leakage location, analysis on the cause of leakage, and estimation of the leakage severity. Some researchers have examined the medium flow and diffusion characteristics, and the relationship between pipeline parameters and medium leakage.

Bailey *et al*. [11] discovered three regions at the leakage-soil interface, namely, the fluidized area out of the leakage, in which the particles moved to the terminal water head at a high speed. The moving bed area, in which the tightly bound particles slowly moved to the starting point of the jet; and the static bed area. He *et al*. [12] established a calculation model regarding leakage flow rate and leakage volume. In addition, the steady-state oil leakage model was adopted for determining the main factors that affected the leakage coefficient of orifice plate and for calculating the flow rate. He *et al*. [13] found that, more leakage led to the greater diffusion range. To be specific, the oil leakage diffusion range decreased as pipe diameter increased, and that at orifice direction increased compared with that at the remaining directions. Moreover, a deeper buried depth of pipeline resulted in a closer contour of pressure field to a concentric circle, along with a wider diffusion range. The diffusion edges no longer maintained a smooth shape after the leak was stopped. Zhu *et al*. [14] investigated steady-state flow rate by considering different pipe pressures, opening positions and sizes, and soil stratification. The opening size greatly affected the wetted area around the pipe. Wu *et al*. [15] examined fluid-flow and heat transfer of both tube and shell heat exchangers under leakage state. Deng *et al*. [16] put forward an approach for simulating natural gas release from the ruptured high pressure piping, and released gas diffusion was also investigated under diverse terrains. Further, influences of the diameter and pressure of the pipe, hydrogen sulfide content and wind speed on diffusion were also investigated within the actual terrain. Chen *et al*. [17] put forward one numerical approach for calculating the pressure wave propagation velocity within the liquid piping. This improved method enhanced the accuracy in predicting the leakage location of the assembled pressure liquid piping. Ostapkowicz [18] proposed the solution algorithms of negative pressure wave method and gradient method for the efficient detection of leakage. These methods were evaluated with the minimal measuring equipment. Li *et al*. [19] put forward one approach in line with CFD for depicting underwater gas release as well as the diffusion behavior of pipeline leakage. The relationship between rise time, release rate, leakage state and surface area was analyzed.

The effect of buried pipe on soil temperature must be considered in designing buried pipe system. Excessive soil temperature changes will reduce heat transfer performance in the meantime of destroying the ecological environment. Some researchers have analyzed changes in soil temperature around the buried pipe.

Kayaci and Demir [20] analyzed relationship between heat exchanger parameters of buried pipe and the soil temperature. Oosterkamp *et al*. [21] examined soil surface boundary condition effects on calculation of heat transfer around the underground pipelines. The soil temperature, radiation balance on soil surface, together with the weather factors, were measured. Their findings were then compared to those measured in experimental apparatus.

The effects of leakage hole position and size on buried pipe fluid heat transfer are rarely investigated. In this paper, ANSYS was employed for simulating and analyzing the pressure and temperature of outlet, as well as flow rate of the buried pipe. Besides, we simulated fluid flow process and performance of the system under different leakage conditions.

Model establishment

The design of this study was as follows. Firstly, GAMBIT was used to establish the normal operation model based on the actual engineering buried pipe parameters. Meanwhile, ANSYS was also utilized to simulate the outlet temperature and verify that it varied within the appropriate range. Then, the surrounding soil temperature was simulated, and attention should be paid to verify that it was not of high warming every year, and did not damage the soil ecological environment.

Specifically, GAMBIT was adopted to establish the initial leakage model, and the leakage ports were set-up at three positions of 30 m, 60 m, and 90 m, respectively, away from the inlet. In this study, a total of five leakage states were analyzed. The widths and locations of the leak orifices were shown below 10 mm and 30 m depth, 5 mm and 60 m depth, 10 mm and 60 m depth, 15 mm and 60 m depth, and 10 mm and 90 m depth. Afterwards, five ANSYS files were designed, and different positions were set as the leakage ports. Moreover, the working state of buried pipe in summer was simulated and calculated for 30 days.

Finally, for each leakage state, ANSYS was utilized to calculate the outlet state change, including temperature, flow rate and outlet pressure. The changes in these physical quantities affected heat transfer process in heat pump unit.

Buried pipe used in this design was a vertical buried pipe, which was drilled in the soil and filled with filling materials after the *U*-shaped pipe was set inside. Notably, the filling materials played a dual role, which not only enhanced the heat transfer effect of heat pump unit, but also played a role of sealing, thus effectively preventing the groundwater pollution infiltration and preventing the effect of heat exchanger.

Compared with the series connection of heat exchanger, the smaller outer diameter of parallel connection u-tube should be selected, which reduces the consumption of numerous tubes and reduces the heat transfer fluid quantity. The *U*-tube aperture also affects the borehole scope, which is relatively small, and a smaller borehole reduces the difficulty and cost of drilling in practice.

In this study, the buried pipe parameters of an actual operating system were used. Its structure is shown in fig. 1. The pipe center spacing was 0.07 m, the backfill diameter was

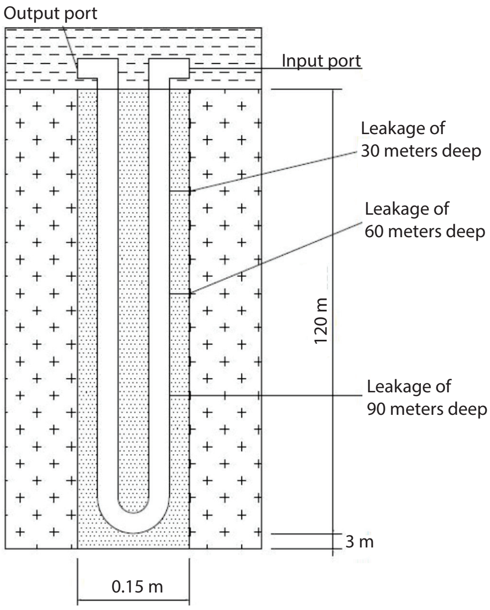

Figure 1. Structure diagram of the heat the exchanger of the buried tube

0.15 m, the average drilling spacing was 4.5 m, the effective depth of hole was 120 m, and the initial underground soil temperature was 17.9 °C. The heat exchanges between the soil and the buried pipe were 53 W/m and 44 W/m in summer and winter, respectively.

The single hole with double *U*-shaped pipe, namely, the HDPE100 pipe, was utilized within the heat exchanger of the buried pipe, with the pipe pressure of 1.6 MPa. For the heat exchanger of buried pipe, pipeline leakage may lead to ground water and environmental pollution, and the maintenance cost is also quite high. Therefore, plastic pipe and pipe fittings with good chemical stability, corrosion resistance, thermal conductivity, and small flow resistance should be selected for the design of buried pipe. When selecting the material in this design, the commonly used HDPE100 tube is selected according to the requirement of wall strength.

To analyze the leakage state, the leakage ports were set at 30 m, 60 m, and 90 m, respectively, away from the inlet.

Soil surrounding the heat exchanger of the buried pipe should be close to infinity, for the sake of simulation analysis on soil temperature within *U*-shaped buried pipe are. However, the radius of affected soil was taken as 2.25 m and the surface soil thickness was 0.5 m to detect changes in temperature. With these parameters, the heat exchanger in the buried tube was plotted with the aforementioned factors.

Heat transfer medium temperature in the buried pipe of single hole double *U*-tube heat exchanger alters with the changes in soil depth and inlet temperature of the heat transfer medium. Meanwhile, there is mutual heat transfer between the two *U*-shaped tubes, which also affects the efficiency of heat transfer in heat exchanger.

The flow within the pipeline satisfies the conservation of energy, moment, and mass. With ANSYS, conservation of energy and mass remains constant, as calculated:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial z}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \tag{2}$$

$$\frac{\partial \varepsilon}{\partial t}+U_j\frac{\partial \varepsilon}{\partial x_j}=\frac{\partial}{\partial t}\left[\left(v+\frac{v_t}{\partial x_i}\right)\frac{\partial \varepsilon}{\partial x_i}\right]+C_1 S+C_{1\varepsilon}C_{3\varepsilon}\frac{\varepsilon}{k}v_t\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)\frac{\partial U_i}{\partial x_j}-C_2\frac{\varepsilon^2}{k+\sqrt{v\varepsilon}} \tag{3}$$

$$C_1=\max\left[0.43\frac{\eta}{\eta+5}\right] \tag{4}$$

$$\eta = S\frac{k}{\varepsilon} \tag{5}$$

where T [°C] is the temperature, v [m^{2}s^{-1}] – viscosity of fluid, v_t – the stands for the coefficient of eddy viscosity, U_i and U_j [ms^{-1}] are the mean speeds at x_i- and x_j-directions, respectively, k [J] – the indicates kinetic energy, S – the stands for modulus of strain tensor mean rate, and ε [%] – the suggests turbulent fluctuation dissipation rate.

There are three steps in ANSYS thermal analysis. The first step is pretreatment, which is conducted to establish the model for the entity to be analyzed. Then, the grid is divided after the model is constructed. The second step is to solve, which is to apply the load and the conditions to the model constructed in the first step and then calculate. The third step is post-processing, which is to analyze and process results calculated in the second step. The output of ANSYS thermal analysis mainly includes temperature, flow and pressure. Besides, the results can be viewed in different ways, like a cloud diagram, a loss diagram and a list.

Considering the complexity of heat transfer in the *U*-tube buried pipe, the following conditions should be assumed in model construction of this study:
- pressure loss within piping was ignored, and the heat transfer process within pipe was always at the constant disguised heat transfer temperature,
- heat transfer coefficient in the pipe was ignored due to the influence of gravity, and
- soil was the single soil, which had consistent physical data, including, density, specific heat and thermal conductivity.

Some parameters of materials to be analyzed were adjusted. Table 1 shows the parameters to be adjusted.

Table. 1 Material physical properties

Materials	Density [kgm^{-3}]	Volume specific heat capacity [kJm^{-3}K^{-1}]	Thermal conductivity [Wm^{-1}K^{-1}]
Water	998.2	4182	0.6
U-shaped pipe	1200	1710	0.42
Backfill	2000	1500	2.3
Soil	1780	1180	1.44

The thermophysical property of soil in this paper is a constant, but in practice, the thermophysical properties of soil are different at different depths and under different geological conditions. Therefore, reasonable determination of soil thermophysical properties is of great significance to the accuracy of numerical calculation.

The purpose of grid division is to change the model into a finite element, in other words, grid division is to divide the complex model into several small and simple individuals, but these individuals are correlated with and constrain each other to form a whole. As for the liquid and solid types, the former includes water and air, whereas the latter include tube, mortar, sand (ordinary soil), and sand-up (surface soil). In this study, the surfaces of water-in (inlet), water-out (outlet), sand-down (soil infinity), sand-far (soil periphery), sand-up-far (surface soil periphery), air-far (air periphery) and air-top (top of air) were set.

According to the simulation results, the soil temperatures at different depths and radii were observed. As seen from the results, the soil simulation output temperature within the range of 2.25 m conformed to the design requirements, and the temperature increase within one year was less than 0.2 °C.

According to the simulation results, the temperatures at the critical time point were determined, which were the soil temperatures with diverse radii (0.1 m, 0.5 m, 1 m, and 2.25 m) at the depth of 50 m and 100 m. As observed from the results, the temperatures increased by 0.12448 and 0.12442 relative to the initial temperature during the 800 hours operation in summer at the radius of 2.25 m and the depths of 50 m and 100 m. Moreover, the temperatures increased by 0.13552 and 0.13543 °C relative to the initial temperature during the 860 hours operation in summer. Reducing the operation time of buried tube heat exchanger in summer further balance the heat exchange.

The ANSYS was used to output the outlet temperature data. The initial temperature was 17.9 °C, which represented the initial soil temperature. After the unit started to work and the underground heat exchanger worked for some time, the simulated temperature was consistent with the design temperature of the underground heat exchanger within heat pump unit. In addition, soil temperature changed a little at the end of summer, which had little influence on buried pipe heat transfer efficiency. If heat was persistently released into the soil, the soil temperature continued to rise, although it maintained efficient operation in certain time period, causing damage to the ecological environment.

Leakage state analysis

The working conditions of the buried pipe were analyzed under leakage condition. Specifically, the leakage port was set at 10 mm, and the temperature, water pressure and flow rate of the outlet port were calculated when it was 30 m, 60 m, and 90 m away from the inlet, respectively. Then, the temperature, outlet water pressure and fluid flow rate were calculated for the leakage ports with the widths of 5 mm, 10 mm, and 15 mm and were 60 m away from the inlet.

The model is constructed in the present work, and then ANSYS is used for calculating heat transfer under the *U*-shaped pipe leakage condition. We first determine the types, materials and specifications of buried tube heat exchangers. Then, the ground heat exchanger geometric model is constructed using the GAMBIT modeling software, and the model is later simulated and analyzed by ANSYS. Afterwards, the ground-source heat exchanger's efficiency is simulated at different conditions.

At 18:00 o'clock on the fourth day (295200 seconds), the water distribution is shown in fig. 2. As observed from the water layout, water flowed out of the leakage port and into the soil gap. If the soil clearance was horizontal, the leakage liquid flowed horizontally, and the water diffused up and down gradually.

Subsequently, the influence of leakage hole on the outlet water temperature was analyzed. The overall change curve is exhibited in fig. 3. The leakage port was 10 mm. The outlet temperature was higher when the leakage port was 30 m from inlet, while that was lower when the leakage port was 60 m away from the ground.

When the leakage ports were 5 mm and 60 m away from the inlet, the temperature of the outlet slightly fluctuated, while that fluctuated significantly when the leakage port was 15 mm, which had significantly adverse effect on cooling.

The temperature change curve on day 30 is displayed in fig. 4. As observed from the figure, when the leakage port was 15 mm, the outlet temperature was lower in the working period and higher in the stopping period.

Moreover, the influence of leakage port on flow rate, unit kg/s, was analyzed. According to the overall flow, the leakage port was set at 10 mm, the flow rates at 30 m, 60 m, and 90 m were 17.9885 kg/s, 17.9883 kg/s, and 17.9881 kg/s respectively. The total flow was larger

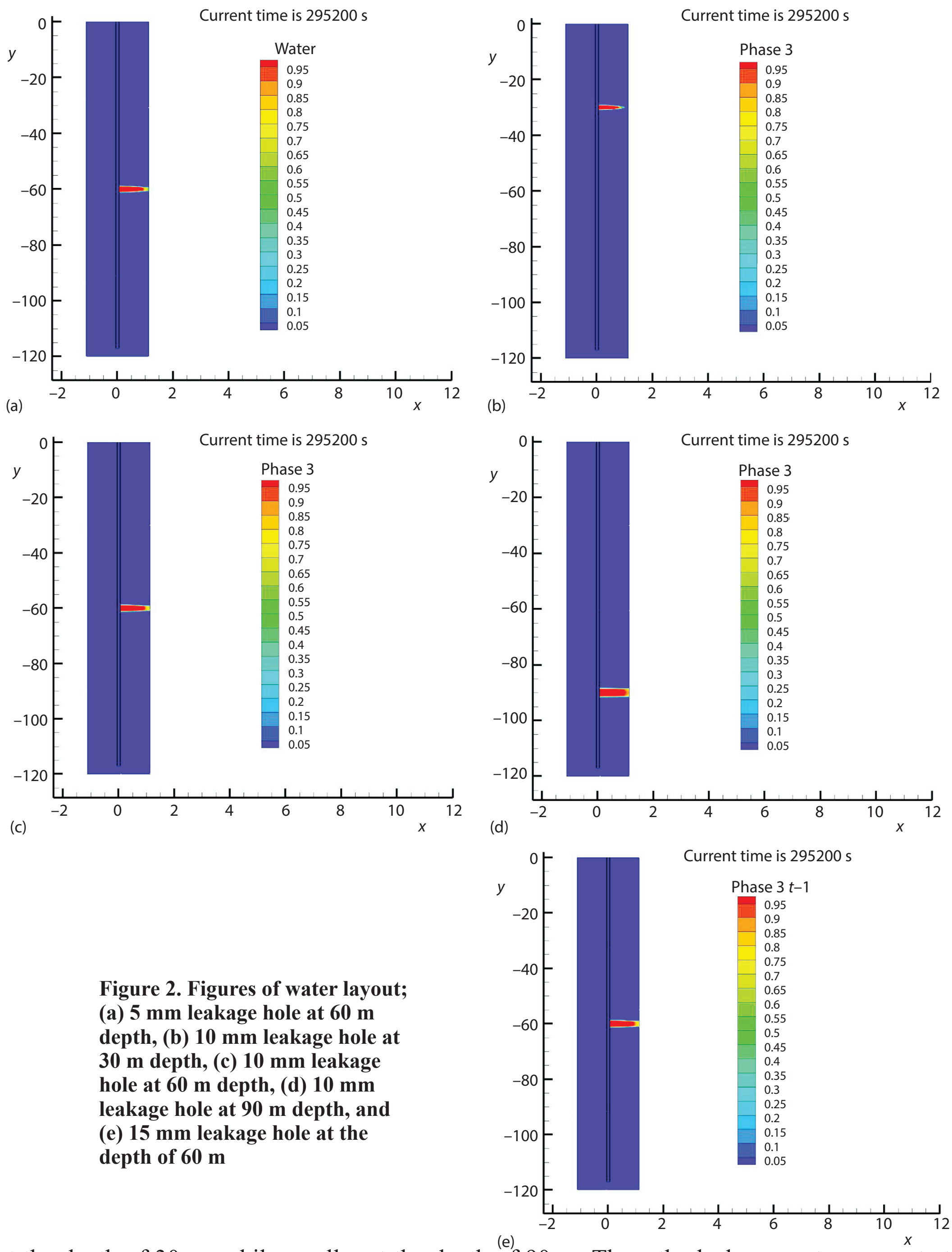

Figure 2. Figures of water layout; (a) 5 mm leakage hole at 60 m depth, (b) 10 mm leakage hole at 30 m depth, (c) 10 mm leakage hole at 60 m depth, (d) 10 mm leakage hole at 90 m depth, and (e) 15 mm leakage hole at the depth of 60 m

at the depth of 30 m, while smaller at the depth of 90 m. Then, the leakage ports were set at different sizes. When the leakage port was 5 mm, there was less leakage along with larger total outflow. By contrast, the leakage was large and the total outflow was small when the leakage port was 15 mm.

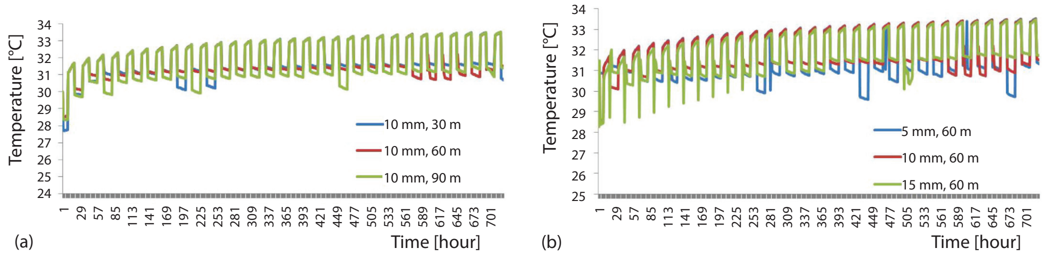

Figure 3. Water outlet temperatures under different leakage conditions; (a) temperatures of the 10 mm leakage port at different depths from the ground and (b) temperatures with different leakage sizes at the depth of 60 m

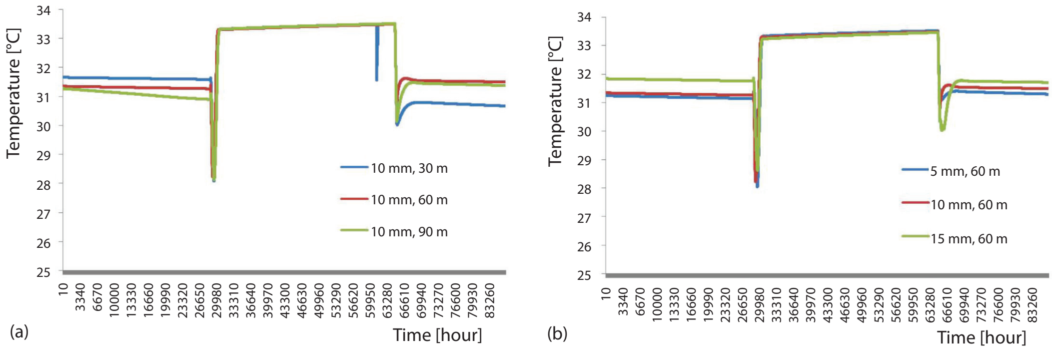

Figure 4. Water outlet temperatures under different leakage conditions on day 30; (a) temperatures of the 10 mm leakage port at different depths from the ground on day 30 and (b) temperatures at the depth of 60 m with different leakage sizes on day 30

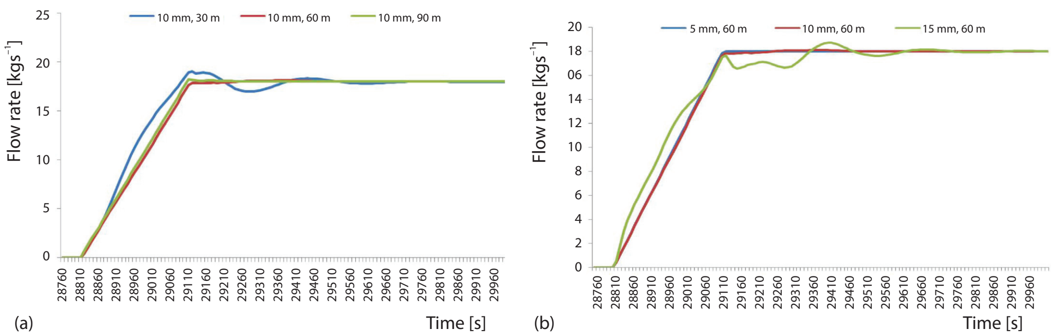

Figure 5. Flow rates under different leakage conditions when the switch is on at day 30; (a) flow rates when the leakage port is 10 mm away from the inlet at different depths and (b) flow rates with different sizes of leakage orifices at a distance of 60 m from the inlet

Changes in outlet pressure under different leakage states when switching on at the 30th day is presented in fig. 5. The leakage port was set at 10 mm. From the curve of flow change in a short time, the jump fluctuated greatly when it was 30 m from inlet. The jump became smaller when it was 90 m from inlet.

Then, the leakage port was set at 60 m away from the inlet. When the leakage port was 5 mm, the jump fluctuation was small, while the flow rate had a large delay when the leakage port was 15 mm.

In addition, the pressure changes under different states were also analyzed. The pressure was approximately 513.3671 kPa. There was little difference in pressure between states.

On the 30th day, the changes in outlet pressure under different leakage states are shown in fig. 6 under switching on status. The influence of leakage location on the outlet pressure was analyzed. The leakage port was set to 10 mm at first. When the leakage locations were 30 m and 90 m away from inlet, the pressure fluctuated greatly in the opening and closing moments. The pressure slightly fluctuated when the leakage port was 60 m from inlet.

Further, the influence of the leakage port size on the outlet pressure was also analyzed. The leakage port was set at 60 m away from the inlet. It was observed from the figure that, the fluctuation was small when the leakage port was 5 mm, while that was large when the leakage port was 15 mm.

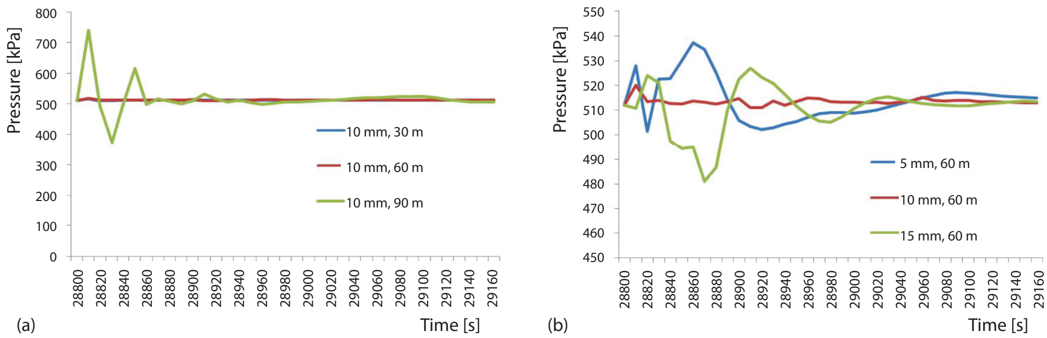

Figure 6. Outlet pressures under different leakage conditions when the switch is on at day 30; (a) pressures of the 10 mm leakage port at different depths from the inlet and (b) the leakage pressures at a distance of 60 m from the inlet for different leakage port sizes

Conclusions

Several kinds of leakages have little impact on the outlet pressure value. However, when the size is large, the pressure fluctuates greatly when the system is started and stopped. The location of leakage port affects the temperature value, and the size of leakage port has great influence on the temperature during the system start-up and shutdown, thus interfering with the cooling effect. The location of leakage port also affects the flow transients. The flow close to the inlet fluctuates greatly. Besides, the size of leakage port also has great impact on the instantaneous response capacity of the flow. The flow rate fluctuates greatly in the presence of a large leakage port size.

In this study, we assume the pure thermal conductivity of a single soil, while neglect the soil water effect on it. To reduce these errors, more studies should be carried out to examine the effects of groundwater leakage and soil stratification.

Nomenclature

k – kinetic energy, [J]
S – modulus of strain tensor mean rate
T – temperature, [°C]
U_i – speed at xi directions, [ms^{-1}]
U_j – speed at xj directions, [ms^{-1}]
v – viscosity of fluid, [m^{2}s^{-1}]
v_t – coefficient of eddy viscosity

Greek symbols

α – coefficient of thermal diffusivity
ε – turbulent fluctuation dissipation rate, [%]

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