NUMERICAL STUDY OF HEAT TRANSFER OF A SINGLE U-TUBE IN VERTICAL GROUND-COUPLED HEAT PUMP SYSTEMS

C F Ma , Z X Gu , Y T Wu
Beijing University of Technology, Beijing, China

Abstract

The heat transfer rate of a single U-tube ground heat exchanger was studied numerically. First, a 3D 60-m full scale computational model of a working single U-tube ground heat exchanger was built and numerical simulation was performed. The simulation was validated by comparing numerically calculated results with experimental results. After that, two models are built to compute the heat extraction rate of a single U-tube of a heat pump operating in both cooling and heating mode, under both continuous and cyclic operation. The effects of borehole depth, inlet temperature and velocity of the heat transfer medium on the heat transfer rate were investigated, for both cooling and heating mode, continuous and cyclic operation.

Nomenclature

\[
\begin{align*}
\alpha & \quad \text{thermal diffusion coefficient} \\
\epsilon_p & \quad \text{specific heat capacity} \\
H & \quad \text{borehole depth, m} \\
T & \quad \text{temperature} \\
\mu & \quad \text{dynamic viscosity} \\
\rho & \quad \text{density} \\
P & \quad \text{pressure} \\
q & \quad \text{heat transfer rate per unit depth.} \\
Q & \quad \text{heat flux} \\
u,v,w & \quad \text{velocity at the direction of x, y, z, respectively.} \\
X,y,z & \quad \text{rectangular coordinates}
\end{align*}
\]

1. Introduction

Ground-coupled heat pumps (GCHP) have gained worldwide recognition as a clean and efficient alternative to conventional HVAC systems for both residential and commercial buildings. The successful design and energy estimation of GCHP relies on an understanding of the heat transfer process around the ground heat exchanger of the GCHP. One of the ground heat exchangers widely used in today’s GCHP is a single U-tube heat exchanger. This type of ground heat exchanger consists of a single U-tube inserted into a vertical borehole. Heat carrier fluid circulates in the tube and exchanges heat with the ground.

The heat transfer of the U-tube to the ground has been studied extensively; both analytical and numerical methods have been proposed[1-5]. These methods are based on the equivalent diameter concept, in which the two legs of the U-tube are approximated by a single pipe and the line source or cylindrical source solution[1-3]. Neither of these methods can give reliable answers to the effect of borehole configuration on the heat transfer performance of the U-tube. Recently, some computer simulations of the U-tube borehole heat exchanger have been reported[6], but due to the complexity of the problem, some simplification such as one-dimensional flow of the medium in the U-tube has been made.

In this paper, GAMBIT, a software for constituting mathematical models, and the FLUENT, a software for numerical computing were used to achieve a numerical model in which the geometry, flow and heat transfer conditions of the U-tube are identical to real conditions. Compared with the equivalent method used by early investigators, it’s an essential progress.
This numerical investigation had two objectives: (1) to quantify the heat extraction rate of a single U-tube heat exchanger of a GCHP running in heating mode, under both continuous and cyclic operation and (2) to examine the effects of inlet velocity, inlet temperature and borehole depth on the heat transfer rate through parametric analysis.

2. Numerical Model and Governing Equations

2.1 Numerical model

A U-tube ground heat exchanger interacts thermally not only with the grouts in the borehole but also with the surrounding ground formation. For the convenience of modeling, the volume of ground that is affected by the U-tube ground heat exchanger, or the ground storage volume, can be considered a cylinder with a height equal to the depth of the borehole. The radius of the cylinder has to be carefully chosen to ensure that the soil at the edge is not affected by the U-tube in the center during the time of simulation. Taking advantage of the symmetry of the geometry and heat transfer, only half of the ground storage volume and its associated tubes, fluid, and grout are modeled, which is shown in figure 1.

This study will use commercial software (FLUENT) to construct finite volume models to simulate the heat transfer performance of a single U-tube heat exchanger. Due to the large geometric scale and complex heat transfer process involved, a 3D computational model with very fine grid and very short-term interval is necessary to carry out the simulation.

Different models have been tailor-made to suit the specific requirements of different objectives. The first objective of this paper was to quantify the heat extraction rate and three models have been built as summarized in table 1. All models have been built using the same approach; the differences lie in the geometric dimensions or boundary conditions.

![Figure 1 Schematic diagram of the computational model](image)

| Table 1 Geometric dimension of the computational models |
|---------------------------------|----------------|---------------|---------------|
| Model                          | A (validation) | B (continuous) | C (cyclic)    |
| Borehole Depth                 | 60m            | 70m           | 50m           |
| Borehole Diameter              | 300mm          | 300mm         | 300mm         |
| Inner Tube Diameter            | 25mm           | 25mm          | 25mm          |
| Outer Tube Diameter            | 31mm           | 31mm          | 31mm          |
| Distance between Axes          | 180mm          | 180mm         | 180mm         |
| Far Field Radius               | 3m             | 6m            | 3m            |

Model A was a full-scale numerical replica of an existing single U-tube heat exchanger. Model B was used to simulate the heat transfer of a U-tube of a GCHP running in heating mode under continuous operation, the simulation period was up to 92 days. Because of the long period of simulation, the far-field radius was specifically set to 6m to avoid possible thermal interruption on the far-field boundary during the simulation time. Model C was used to simulate the cyclic operation of a GCHP.
The second objective involves parametric analysis. Four models have been built to carry the parametric analysis. The borehole depths of the four models are 60, 70, 85, and 100m, respectively. The far-field radius of the four models was set to 3m. The other geometric parameters of the models were the same in the table 1.

2.2 Governing equations

The actual heat transfer processes occurring in a single U-tube ground heat exchanger include: (1) the convective heat transfer between the heat transfer medium in the U-tube and the tube wall; (2) the conduction of heat in the tube wall; and (3) the conduction of heat in the grout and the ground soil.

A number of assumptions are used to develop the model and a brief discussion of these assumptions is provided as follows:

1. The grout and the ground formation are homogeneous, respectively.
2. There is no thermal contact resistance at any interface.
3. The initial temperature is uniform through the whole domain.
4. The far field boundary temperature is taken as a constant equal to the initial value.
5. The heat transfer mechanism in the grout and the ground formation is confined to conduction only and the presence of water flow is not considered.

With the foregoing assumptions, the governing equations of the problem can be written as follows.

Fluid flow and convective heat transfer for the heat transfer medium in a single U-tube

\[
\rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) = \mu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) \]

\[
\rho \left( \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right) = \mu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) \]

Conduction heat transfer in the tube wall, the grout and the ground formation

\[
\frac{\partial T}{\partial t} = a \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \]

2.3 Turbulence models

Turbulent pipe flow is modeled using a low Reynolds boundary layer \( \kappa - \varepsilon \) turbulence model.

2.4 Initial and boundary conditions

A good estimate of the initial ground temperature or undisturbed ground temperature is necessary
for the simulation. The undisturbed ground temperature is not uniform along the borehole due to the geothermal gradient, but Eskilson showed in 1987 that it is not necessary to consider the temperature variation along the borehole. The undisturbed ground temperature is assumed to be homogenous and the mean temperature along the borehole is taken as a good approximation of it.

The mean temperature along the borehole was determined by circulating heat transfer medium through the U-tube and during the process both the inlet and outlet temperatures were collected, the average of inlet and outlet temperatures was taken as the mean temperature along the borehole. The heat transfer medium in the U-tube, the tube wall, the grout and the ground soil were set to the same initial temperature.

The boundary types were set as follows:
(1) Inflow was set as a velocity inlet
(2) Outflow was set as outflow
(3) Top wall was set as a wall
(4) Side and bottom walls were set as wall with constant temperature
(5) The symmetry wall was set as symmetry.

The boundary conditions were illustrated in Figure 2. The ground formation temperature at the bottom and the side wall is fixed at the initial temperature, which equals the undisturbed ground temperature. In order to reduce the geometrical complexity of the model, the top soil layer and the horizontal pipes were not included in the model. The top wall of the model exchanges heat with the top soil layer through conduction. The top soil layer then exchanges heat with air by means of convective heat transfer. The typical depth of the top soil layer is 2m. Thus, the existence of the top soil layer can be approximated using the thin-wall thermal resistance model in FLUENT. The thin-wall resistance model treats the top soil layer as a wall having a thickness of 2m and solves a 1D conduction equation to calculate the thermal resistance offered by the top soil layer. The typical air temperature is 20°C in summer and -10°C in winter and the heat transfer coefficient of natural convection can be computed using correlation

\[ Nu = C (GrPr)^n \] (7)

where \( C = 0.54 \) for winter, \( C = 0.58 \) for summer. The symmetry wall was set to symmetry type in FLUENT.

The numerical calculation was conducted through the whole computational domain using the commercial CFD software FLUENT 6. The thermophysical properties used in the simulation is shown in Table 2.
3. Model Verification

The effectiveness of the modeling approach was verified by comparing the computed outlet temperature of the heat transfer medium with the outlet temperature measured from a test single U-tube of a GCHP operating in cooling mode. The simulation was conducted on model A, which has identical geometry with the test single U-tube. The inlet temperature and inlet velocity used in the simulation were set based on measurements taken from the test single U-tube. The side and bottom walls of the model were set at a constant temperature equal to the undisturbed temperature measured in situ. The air temperature was 20°C and the heat transfer coefficient was computed using equation 1. Figure 3 shows a comparison of computed and measured outlet temperature. The simulation was conducted for 24 hours and the deviation reduced with the elapse of simulation time. The relative error at the 24th hour is 2.8%, which assured us the correctness of the modeling approach and this approach was used to build all the models used in this paper.

![Table 2 Thermophysical properties used for numerical simulation](image)

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m³)</th>
<th>Specific heat [J/(kgK)]</th>
<th>Thermal conductivity [W/(mK)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground formation</td>
<td>1600</td>
<td>1645</td>
<td>1.8</td>
</tr>
<tr>
<td>Grout</td>
<td>1860</td>
<td>840</td>
<td>2</td>
</tr>
<tr>
<td>HDPE Pipe</td>
<td>950</td>
<td>2300</td>
<td>0.44</td>
</tr>
<tr>
<td>Water(4°C)</td>
<td>997</td>
<td>4178</td>
<td>0.608</td>
</tr>
</tbody>
</table>

4. Results and Discussion

Model B was used to simulate the heat transfer performance of a single U-tube of a GCHP operating in heating mode, under continuous operation. Time variations of heat extraction rate per unit borehole length were numerically calculated. The inlet velocity was set at 0.6m/s and the inlet temperature was set at 4°C. The far field boundary temperature was set at 17°C. The air temperature was -10°C and the calculated heat transfer coefficient was 1.56W/m².

The heat extraction rate during the start-up period was computed, with time steps as small as 1 second. The relationship between the heat extraction rate and the elapsed time for the first 6 hours is illustrated in Figure 4. From this figure it is clear that the heat extraction rate increases sharply, and gradually decreases with time after peaking at an early stage. The early rise of the heat extraction rate can be explained as follows. Before the startup of the GCHP, the fluid in the U-tube, the U-tube wall, the grout and the ground were at equilibrium state and had the same initial temperature. After that with the inflow of the low temperature water, the fluid temperature was lowering, and so did the U-tube wall temperature. However, the thermal diffusivity of the U-tube wall was so small that the rate at which the U-tube wall temperature dropped is slower than that of the fluid. The temperature difference between the fluid and the U-tube wall was increasing with the elapse of time, which resulted in the rise of the heat extraction rate.

Figure 5 and 6 show the relationship between the heat extraction rate of a single U-tube and elapsed time for the first 24 hours and 92 days, respectively. Except for the startup stage in Figure 4 the heat extraction rate decreases with the elapse of time. The effect of cyclic operation on the heat extraction rate was also investigated. The simulation was conducted on model C, which was a 50-m single U-tube of a GCHP operating in heating mode. The far field radius was set to 3m. The inlet velocity was set to 0.6m/s and the inlet temperature was set to 3°C. The other boundary conditions were the same as model B. The cyclic operation period extended for three days. During each day, the heat...
pump ran for 16 hours and experienced a shut-up period of 8 hours. The relationship between the heat extraction rate and elapsed time under cyclic operation is shown in Figure 7. Figure 7 shows that the heat extraction rate decreases with the elapse of time during the 16 hours of continuous operation. After a shut-up period of 8 hours the heat extraction rate was greater than that at the end of the continuous operation but less than that at the start of the continuous operation.

Some parametric analysis was carried to investigate the effects of various parameters on the heat extraction rate. The parameters considered are (1) the inlet velocity (2) the inlet temperature and (3) the borehole depth. Since the emphasis is on the effects of various parameters on the heat extraction rate during the steady state period, a steady state model is assumed. In the steady state model the far field radius was set to 3m. Parametric studies were performed under both cooling and heating mode.

Figure 8 to Figure 11 are results of a single U-tube of a GCHP operating in the heating mode. Figure 8 indicates the relationship between the heat extraction rate of a single U-tube heat exchanger and inlet velocity under various inlet temperatures. The inlet velocities were set at 0.12, 0.15, 0.2, 0.25, 0.3, 0.4, 0.6, 0.8, 1.0 and 1.2m/s, respectively, and the corresponding flow regimes changed from transitional flow to turbulent flow. From Figure 8 it can be seen that for any given inlet temperature, the heat extraction rate increases with increasing inlet velocity.

Figure 9 shows the relationship between the heat extraction rate and the inlet temperature under different inlet velocities. The inlet temperatures were set at 2, 4, 6, and 8 \(^\circ\)C, respectively and the heat extraction rate of the U-tube for different inlet velocities were calculated. It can be seen from Figure 9 that the heat extraction rate decreases linearly with increasing inlet temperature for different inlet velocities.
Figure 10 shows the effect of borehole depth on the heat extraction rate, the inlet velocity was set at 0.6m/s. It can be seen from the figure that the heat extraction rate remains roughly constant with increasing borehole depth for different inlet temperatures.

Figure 11 shows the relationship between the heat extraction rate and the borehole depth. The inlet temperature was set at 2. It can be seen that the lower the inlet velocity the greater the influence of the borehole depth on the heat extraction rate. For velocities greater than 0.4m/s, the borehole depth has little effect on the heat extraction rate. For lower velocities the heat extraction rate decreases with increasing borehole depth. This can be explained as follows; the deeper the borehole the longer the time the heat transfer medium stayed in the borehole and the bigger the temperature rise of the heat transfer medium, hence the heat extraction rate decreases because of the lesser temperature difference between the water and the ground formation. Increasing the inlet velocity will reduce the time water stays in the borehole and consequently the temperature rise of the water and the effect on heat extraction rate is negligible.

Figure 12 to Figure 15 are results of a single U-tube of a GCHP operating in cooling mode. Figure 12 shows the relationship between the heat rejection rate of a single U-tube heat exchanger and inlet velocity for various inlet temperatures. The inlet velocities were set at 0.12, 0.15, 0.2, 0.25, 0.3, 0.4,
0.6, 0.8, 1.0 and 1.2 m/s, respectively, and the corresponding flow regimes changed from transitional flow to turbulent flow. From Figure 12 it can be seen that for any given inlet temperature, the heat rejection rate increases with increasing inlet velocity.

Figure 11 Relationship between heat extraction rate and borehole depth for different inlet velocities

Figure 12 Relationship between heat rejection rate and inlet velocity for different inlet temperatures

Figure 13 Relationship between heat rejection rate and inlet temperature for different inlet velocities

Figure 14 Relationship between heat rejection rate and borehole depth for different inlet temperatures

Figure 13 shows the effect of increasing inlet temperature on the heat rejection rate for different inlet velocities. The inlet temperatures were set at 20, 25, 30 and 35. In the cooling mode of a GCHP, a U-tube ground heat exchanger rejects heat to the ground formation, the higher the inlet temperature, the bigger the temperature difference between the heat transfer medium and the ground formation, hence the bigger the heat rejection rate. From Figure 13, it can clearly be seen that the heat rejection rate increases linearly with increasing inlet temperature for different inlet velocities.
Figure 14 shows the relationship between the heat rejection rate and the borehole depth. The inlet velocity was set at 0.4m/s and the inlet temperatures were set at 20, 25, 30 and 35°. It can be seen that the effect of borehole depth on the heat rejection rate is very small when inlet velocity is 0.4m/s.

Figure 15 is the relationship between the total heat rejection rate and borehole depth for different inlet temperatures. The inlet velocity was set at 0.4m/s. It shows clearly that the total heat rejection rate increases linearly with increasing borehole depth.

5. Conclusions

A 3D full scale modeling approach was used to numerically compute the time variation of the heat extraction rate of a single U-tube ground heat exchanger of a GCHP operating in heating mode. The effectiveness of this approach was verified by comparing the numerical results with field experiment results. The heat extraction rate decreases with time during continuous operation. During cyclic operation, thermal recovery of soil in the shut-up period increases the heat extraction rate.

Parametric analysis results show that for all inlet temperatures, increasing inlet velocity will enhance the heat exchange rate, for both heating mode and cooling mode. Heat extraction rate decreases linearly with increasing inlet temperature for all inlet velocities in the heating mode and increases linearly in the cooling mode. Borehole depth has little effect on the heat extraction/rejection rate when the inlet velocity is larger than 0.4m/s.

References