Numerical Simulation of the Effect of Borehole Depth on Heat Transfer Efficiency

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ABSTRACT
Borehole depth affects the heat transfer efficiency of buried pipe for ground source heat pump. In this paper, COMSOL is used to simulate the heat transfer process in the buried pipe with the depth of 80m-150m according to the data of thermal response test of a project in Tongren, China. The temperature of the circulating fluid is obtained, and the heat transfer efficiency of different borehole depth is analyzed. It is concluded that the heat transfer increases with the increase of the borehole depth, but the heat transfer per meter showing a downward trend.

1. Introduction
Drilling cost accounts for a large proportion of the initial investment in ground source heat pumps (GSHP), especially in areas with typical Karst topography. The deeper the borehole is, the greater the cost becomes. However, the heat transfer efficiency does not improve with the depth of the borehole linearly. Yu et al. (2008) experimented the heat transfer performance of the buried heat exchangers and analyzed the rules of the change of heat flux in the depth of the underground pipe are analyzed under different drilling depth conditions. It is concluded that the water flow and the depth of drilling in the buried pipe have little effect on the heat transfer per meter well and will cause the change of the water temperature of the outlet pipe. It is necessary to consider the economy, select a reasonable drilling depth. Xia (2014) based on the measurement data of a project in Chongqing and the numerical simulation, concluded that the single well heat transfer increases with the increase of drilling depth, but the increase is smaller and smaller. Drilling depth increased to a certain value, the increase in the amount of heat transfer to the buried pipe is very small. Liu (2013) used Origin 8.0 to fit the ground drift of the
Lei, et al.

GSHP with different borehole depth, the total energy consumption of the system and the initial investment of the underground heat exchangers, and finally determined the optimum borehole depth.

This paper simulated the circulating temperature and analyzed the heat transfer efficiency with different borehole depths, incorporating the effects of the ground water runoff and the physical properties of different strata.


The classical cylindrical heat source model assumes that the heat exchange between the borehole and the soil is carried out under constant heat flow boundary conditions, soil isotropic. When there is groundwater seepage, the vertical U-shaped ground heat exchangers and the surrounding soil heat transfer is a three-dimensional unsteady process (Fang, 2004).

2.1 Fluid Transfer in U-shaped Buried Pipe

In the U-shaped buried pipe fluid will generally maintain a turbulent state. The heat transfer equation of the pipe flow in U-shaped buried pipe is:

\[
\rho A C_p u \cdot \nabla T = \nabla \cdot (A k \nabla T) + f_D \frac{\rho}{2d_h} |u|^3 + Q_{wall}
\]  

Where \( \rho \) is fluid density, \( \text{kg/m}^3 \); \( A \) is pipe cross-sectional area, \( \text{m}^2 \); \( u \) is pipe velocity tangential fluid velocity, \( \text{m/s} \); \( C_p \) is heat capacity, \( \text{J/kg} \cdot \text{°C} \); \( T \) is temperature, \( \text{°C} \); \( k \) is thermal conductivity, \( \text{w/m} \cdot \text{°C} \); \( Q_{wall} \) is the source/sink produced by the heat exchange between the tube wall and the surrounding area , \( \text{w/m} \); \( f_D \) is a function of the Reynolds number and the surface roughness divided by the pipe diameter.

2.2 Fluid Flow Equation in U-shaped Buried Pipe

The fluid flow in the U-shaped buried pipe is generally turbulent, and the flow in the piping system can be described by the steady-state momentum equation and the continuous equation.

\[
0 = -\nabla P - f_D \frac{\rho}{2d_h} u |u| + F
\]  

\[
\nabla \cdot (A \rho u) = 0
\]  

Where \( P \) is pressure, \( \text{N/m}^2 \); \( F \) is volume force, \( \text{N/m}^3 \).

2.3 Backfill Material and Heat Transfer in the Soil

The heat transfer in the backfill material and the soil is mainly heat conduction. Assuming that the initial temperature of the strata is constant, the temperature of the formation in the model is a piecewise function about the depth of the formation. Can be used to describe the law of heat conduction, such as:

\[
\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = Q
\]
Where $Q$ is heat flux density, W. The negative sign indicates that the heat transfer direction is opposite to the direction in which the temperature rises.

3. Examples of Engineering

The project is located in Tongren, northeast of Guizhou Province, China, which is the characteristics of typical Karst landform development. The rock types in the area are mainly composed of carbonate rock and clastic rock. Upper clay weathering crust is generally thick 4-8m, a small part of the thickness of up to 15m (Song and Duan, 2015). The cold and heat load of building reach to 16326kW and 12600kW, respectively.

Drilling strata are mainly dense limestone and dolomite, the upper casing is shallow, bedrock exposed. The higher drilling cost is mainly due to hard rock formation. As a result, in the karst area to promote the use of ground source heat pump, to meet the load requirements, optimization of borehole depth can improve the ground heat pump heat transfer efficiency.

The simulation conditions refer to the geological survey report. The first layer is artificial backfill, and more gravel; the second layer is the Quaternary cover layer, the clay layer; the third layer is the weathering dolomite; the fourth layer is weaker and weathered dolomite. The thermal properties of the formation are shown in Table 1. The stratigraphic data is derived from a geological survey report of a project in Tongren, China.

<table>
<thead>
<tr>
<th>Depth(m)</th>
<th>Thermal Conductivity (W/m·℃)</th>
<th>Density (kg/m³)</th>
<th>Specific heat capacity J/(kg·℃)</th>
<th>Thermal diffusion coefficient $(10^{-6}m^2·s^{-1})$</th>
<th>Seepage velocity $(10^{-6}m·s^{-1})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-8</td>
<td>1.4</td>
<td>1530</td>
<td>960</td>
<td>0.128</td>
<td>0</td>
</tr>
<tr>
<td>8-14</td>
<td>2.0</td>
<td>1600</td>
<td>1645</td>
<td>0.073</td>
<td>1</td>
</tr>
<tr>
<td>14-17</td>
<td>2.4</td>
<td>1860</td>
<td>840</td>
<td>0.091</td>
<td>1</td>
</tr>
<tr>
<td>17-150</td>
<td>3.06</td>
<td>3197</td>
<td>837</td>
<td>0.121</td>
<td>0</td>
</tr>
</tbody>
</table>

4. COMSOL Simulation Condition Setting and Result

COMSOL is used to simulate the heat transfer process between the buried pipe and strata under the influence of groundwater seepage and strata temperature. Selection of non-isothermal pipeline flow and porous media heat transfer module modeling. The model is set at a thickness of 152m and a width of 6m. The ground boundary temperature is set to 20 °C. The formation temperature is shown in Figure 1 below.
The simulation parameters are set to refer to the actual parameters of the field thermal response of a project in Tongren City and the data in the literature (Wang et al., 2011). The model parameter settings are shown in Table 2.

**Table 2: Model parameter settings**

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>The outer diameter of the buried pipe (mm)</td>
<td>32</td>
</tr>
<tr>
<td>The wall thickness of the buried pipe (mm)</td>
<td>3</td>
</tr>
<tr>
<td>Thermal conductivity of buried pipe wall (W/m·℃)</td>
<td>0.36</td>
</tr>
<tr>
<td>Surface roughness of buried pipe wall (Pull pipe)(mm)</td>
<td>0.0015</td>
</tr>
<tr>
<td>U-type buried pipe pin spacing (mm)</td>
<td>90</td>
</tr>
<tr>
<td>Borehole diameter (mm)</td>
<td>150</td>
</tr>
<tr>
<td>Circulating fluid flow rate (m/s)</td>
<td>0.6</td>
</tr>
<tr>
<td>Inlet temperature (℃)</td>
<td>30</td>
</tr>
<tr>
<td>The width of the model (m)</td>
<td>6</td>
</tr>
<tr>
<td>The depth of the model (m)</td>
<td>152</td>
</tr>
</tbody>
</table>

### 4.1 Simulation Results

Borehole depth of 150m, U-tube water temperature of 30 ℃, after 90h circulation, the strata temperature changes as shown in Figure 2 (a). Figure 2 (b) is a schematic diagram of the partial magnification of Figure 2 (a).
4.2 Analysis of Temperature Variation in Buried Tubes

In the model of different depth of the pipe, after 90h circulation, the inlet water interval temperature and the outlet pipe temperature are shown in Figure 3 and 4, respectively.
As the depth increases, the temperature drop in the outlet pipe becomes less. The heat transfer process occurs mainly in the inlet pipe. When the well depth is 80m, the minimum temperature of the inlet pipe is at 70m-80m at the bottom of the inlet pipe, and the temperature of the circulating liquid drops to 0.061 °C. The temperature drop in the outlet pipe temperature at the outlet pipe depth of 10m-20m where the temperature dropped to 0.029 °C. When the depth is 150m, the temperature of the inlet pipe is reduced the minimum at the depth of 140m-150m in the depth of the inlet pipe, and the temperature of the circulating liquid drops to 0.049 °C. The temperature drop in the outlet pipe at least in the deep depth of 10-20m at the temperature dropped to 0.008 °C. When the geological conditions are constant, increasing the depth of the buried pipe has little effect on heat transfer.

4.3 Heat Transfer Per Unit Length

When the depth is increased from 80m to 150m, the total heat of single well is increasing, but the heat transfer per meter is decreasing. When the well depth is 80m, the total heat transfer is 9.4kW, heat transfer per meter is 0.11kW/m. When the well depth is 150m, the total heat transfer is 14.63kW, heat transfer per meter is 0.09kW/m. The heat transfer of two 80m deep wells is 4.17kW higher than that of a 150m deep well. That is, the depth increased by 87.5%, the total heat increased by 55.6%, heat transfer per meter decreased by 18.1%. With the increase in depth, the heat transfer per meter decreased significantly. When the construction site is suitable, it is recommended to compare the heat transfer per meter to select the shallow borehole depth.

![Figure 4: Total heat transfer for different depths and per meter heat transfer](image)

5. Conclusions

Drilling costs account for a large proportion of the initial investment of the GSHP. Increasing the heat transfer efficiency of the GSHP can save drilling costs. When using ground source heat pumps in complex geological conditions, it is necessary to consider the heat transfer per meter in
the case of different borehole depths to improve the heat transfer efficiency of the GSHP. The optimal borehole depth can be determined by using combination numerical simulation and field thermal response testing. It is advisable to compare the heat transfer per meter when the site is suitable, especially in areas where the bedrock is shallow and has typical Karst topography.

Acknowledgement

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