Evaluation of heat exchange rate of GHE in geothermal heat pump systems

Liu Jun, Zhang Xu*, Gao Jun, Yang Jie

Institute of HVAC&Gas Engineering, College of Mechanical Engineering, Tongji University, Shanghai 200092, China

A R T I C L E   I N F O

Article history:
Received 29 October 2008
Accepted 19 April 2009
Available online 31 May 2009

Keywords:
Geothermal heat pump
Ground heat exchanger
Linear source theory
Cylindrical source theory
Thermal resistance
Heat exchange rate

A B S T R A C T

Total thermal resistance of ground heat exchanger (GHE) is comprised of that of the soil and inside the borehole. The thermal resistance of soil can be calculated using the linear source theory and cylindrical source theory, while that inside the borehole is more complicated due to the integrated resistance of fluid convection, and the conduction through pipe and grout. Present study evaluates heat exchange rate per depth of GHE by calculating the total thermal resistance, and compares different methods to analyze their similarities and differences for engineering applications. The effects of seven separate factors, running time, shank spacing, depth of borehole, velocity in the pipe, thermal conductivity of grout, inlet temperature and soil type, on the thermal resistance and heat exchange rate are analyzed. Experimental data from several real geothermal heat pump (GHP) applications in Shanghai are used to validate the present calculations. The observations from this study are to provide some guidelines for the design of GHE in GHP systems.

© 2009 Elsevier Ltd. All rights reserved.

1. Introduction

Geothermal heat pump, also called ground source heat pump, has been widely used in Europe and the United States as one of the basic renewable technologies. As it is significantly beneficial to the energy saving and CO₂ emission reduction in the area of built environment, the geothermal heat pump technology has aroused great attention in China and some other developing countries since 1990s. Nevertheless, geothermal heat pump is not as popular as the air source heat pump. The reason is that, in addition to the geological condition and high initial cost, one key limiting factor lies in the lack of reliable and widely accepted calculation model and design method for the ground heat exchangers. Therefore, it is of practical importance to evaluate the methods for the heat transfer of GHE and to propose some systematic rules for real applications. Such work is required to finally find out the real optimum size of GHE under different conditions.

At the beginning of GHP system design, researchers may often resort to thermal response test to find out the thermal conductivity of soil, λs [1–8] or heat exchange rate per depth of GHE, q [9,10], while some often do not know how to translate the information of λs into q. According to linear source theory (LST) and cylindrical source theory (CST), λs is used to calculate thermal resistance of soil, which along with that inside the borehole constitutes the total thermal resistance of GHE, then the heat exchange rate per depth of GHE is calculated by the total resistance. In this work, several factors influencing the thermal resistance and heat exchange rate of GHE are analyzed based on the LST and CST with their calculation of thermal resistance. Comparisons of the two methods are extensively made to determine their similarities and differences for engineering applications. Experimental data from some in-situ tests in Shanghai are used to validate the theories and methods. Finally, guidelines are proposed for the design of ground heat exchangers.

2. Thermal resistance of GHE

The heat transfer process between GHE and surrounding soil is very complex, it has close relations to (a) local conditions: the local climatic conditions and hydrogeological conditions, the thermal properties of soil, the soil temperature distribution, (b) GHE parameters: the type of GHE, the depth, diameter and spacing of borehole, the shank spacing, materials and diameter of the pipe, the fluid type, temperature, velocity inside the pipe, the thermal conductivity of backfill, (c) operation conditions: the cooling and heating load, heat pump system control strategy and operating characteristics, the thermal buildup of soil. Although, the heat transfer process can be divided into steady heat transfer inside the borehole (When the running time is greater than the critical time, that is F₀ > 5, the impact of heat capacity of objects inside the borehole can be neglected, the heat transfer process inside the borehole is steady,) and transient heat transfer outside it. Thermal
2.1. Thermal resistance inside the borehole

Thermal resistance of fluid convection is defined as

\[ R_{\text{conv}} = 0.5 \frac{1}{\pi d_i h_i} \]  

(1)

The convection coefficient, \( h_i \), is determined by Dittus–Boelter correlation

\[ h_i = \frac{0.023Re^{0.8Pr^{0.4}}}{d_i} \]  

(2)

Thermal resistance of conduction in the pipe is defined as

\[ R_{\text{cond}} = 0.5 \frac{\ln(d_o/d_i)}{2\pi \lambda_p} \]  

(3)

Thermal resistance of grout can be computed by shape factor method and equivalent diameter method. Shape factor method is used to describe the heat conduction characteristics of a complicated geometry.

\[ R_{\text{grout}} = \frac{1}{\lambda_p \beta_0 (d_b/d_o)^{\beta_1}} \]  

(4)

where \( \beta_0 \) and \( \beta_1 \) are the shape factors of \( R_{\text{grout}} \), whose values depend on the relative location of U-tube pipes in the borehole. Remund [11] studied three configurations as shown in Fig. 1, the corresponding values are provided in Table 1. To be mentioned, configuration B would be an appropriate design assumption in most situations, as it represents an average spacing along the entire borehole length. While configuration A is a conservative design assumption, configuration C is a risky design assumption.

Equivalent diameter method means the two legs in the U-tube in the U-tube are replaced by a single concentric cylindrical heat source (or sink), the equivalent diameter given by Claesson and Dunand [12] is as follows:

\[ d_e = \sqrt{2d_o} \]  

(5)

The equivalent diameter given by Gu and O’Neal [13,14] is as follows:

\[ d_e = \sqrt{2d_0 L_s} \quad (d_o < L_s < d_b) \]  

(6)

When equivalent diameter method is used for computing the thermal resistance inside the borehole, thermal resistance of fluid and pipe should remain constant, the mass flow rate and heat capacity of the fluid should also be constant. Application of this method is especially advantageous when an analytical solution developed for a single cylindrical source is available.

\[ R_{\text{grout}} = \frac{1}{2\pi \lambda_p} \ln \left( \frac{d_b}{d_e} \right) \]  

(7)

\( R_{\text{grout}} \) can be calculated by combining equation (5) or (6) with equation (7), the corresponding values are 0.0943 W/(m K) and 0.0739 W/(m K), taking case A0 in Table 3 for example. The result of equation (4) is 0.0807 W/(m K). After validation, the result of equation (4) is close to equation (7), so equation (4) is adopted in the following analysis.

2.2. Thermal resistance outside the borehole

For both linear source theory and cylindrical source theory, the heat transfer process outside the borehole to make the following assumptions: (1) Thermal properties of the soil are isotropic and uniform. (2) Ignoring the effect of ground surface. (3) Ignoring thermal contact resistance between the pipe and the grout, between the grout and the soil.

For a pipe transferring heat at a constant rate of \( q \), the temperature difference \( \Delta T \) between the initial soil temperature and the fluid temperature is as follows:

\[ \Delta T = t_i - t_w = \frac{q}{2\pi \lambda_s} \int \frac{e^{-\beta^2}}{\beta} d\beta = \frac{q}{2\pi \lambda_s} I(x) \]  

(8)

When \( r = r_h \), thermal resistance of soil is as follows:

\[ R_s = \frac{t_h - t_w}{q} = \frac{1}{2\pi \lambda_s} \left( \frac{r_h}{2\sqrt{\alpha t}} \right) = \frac{1}{2\pi \lambda_s} I \left( \frac{1}{2\sqrt{\lambda_s t}} \right) \]  

(9)

When \( 0 < x < 1 \), the \( I \)-function is calculated by

\[ I(x) = 0.5(\ln x^2 - 0.57721566 + 0.99999193x^2) \]
\[ -0.24991055x^3 + 0.05519968x^4 - 0.00976004x^5 \]
\[ + 0.00107857x^{10} \]  

(10)

And when \( x \geq 1 \),

\[ I(x) = \frac{1}{2x^2 \exp(x^2/2)} \]  

(11)

where

\[ A = x^8 + 8.5733287x^6 + 18.059017x^4 + 8.637609x^2 + 0.2677737 \]

\[ B = x^8 + 9.5733223x^6 + 25.6329561x^4 + 21.0996531x^2 + 3.9684969 \]

Table 1  
Shape factor related to different configurations of U-tube pipes in borehole.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>( \beta_0 )</th>
<th>( \beta_1 )</th>
<th>Correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>20.10</td>
<td>-0.9447</td>
<td>0.9926</td>
</tr>
<tr>
<td>B</td>
<td>17.44</td>
<td>-0.6052</td>
<td>0.9997</td>
</tr>
<tr>
<td>C</td>
<td>21.91</td>
<td>-0.3796</td>
<td>0.9697</td>
</tr>
</tbody>
</table>

![Fig. 1. Configurations of U-tube pipes in borehole.](image-url)
دریافت فوری
متن کامل مقاله

امکان دانلود نسخه تمام متن مقالات انگلیسی
امکان دانلود نسخه ترجمه شده مقالات
پذیرش سفارش ترجمه تخصصی
امکان جستجو در آرشیو جامعی از صدها موضوع و هزاران مقاله
امکان دانلود رایگان ۲ صفحه اول هر مقاله
امکان پرداخت اینترنتی با کلیه کارت های عضو شتاب
دانلود فوری مقاله پس از پرداخت آنلاین
پشتیبانی کامل خرید با بهره مندی از سیستم هوشمند رهگیری سفارشات