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

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ABSTRACT

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.

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 CO_2 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, λ_s [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 λ_s into q. According to linear source theory (LST) and cylindrical source theory (CST), λ_s 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 $F_o > 5$, 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

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resistance inside the borehole includes thermal resistance of fluid convection, and that of solid conduction in the pipe and grout. Thermal resistance outside the borehole is that of conduction in the soil. This paper works for the widely used vertical single U-shaped pipe to analyze the thermal resistance of GHE, which is a composite resistance of overall heat transfer process in the GHE.

2.1. Thermal resistance inside the borehole

Thermal resistance of fluid convection is defined as

$$R_{\mathrm{conv}} = 0.5\frac{1}{\pi d_i h_i} \tag{1}$$

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

$$h_i = \frac{0.023 Re^{0.8} Pr^n \lambda_f}{d_i} \tag{2}$$

Thermal resistance of conduction in the pipe is defined as

$$R_{\mathrm{cond}} = 0.5\frac{\ln(d_o/d_i)}{2\pi\lambda_p} \tag{3}$$

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.

$$R_{\mathrm{grout}} = \frac{1}{\lambda_g \beta_0 (d_b/d_o)^{\beta_1}} \tag{4}$$

where β_0 and β_1 are the shape factors of R_{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 are replaced by a single concentric cylindrical heat source (or sink), the equivalent diameter given by Claesson and Dunand [12] is as follows:

$$d_e = \sqrt{2} d_o \tag{5}$$

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

$$d_e = \sqrt{2 d_o L_s} \; (d_o < L_s < d_b) \tag{6}$$

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.

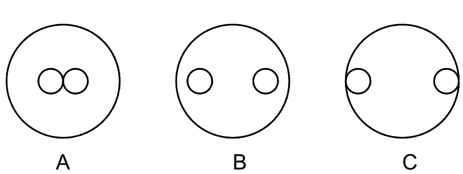

Fig. 1. Configurations of U-tube pipes in borehole.

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

Configuration	β_0	β_1	Correlation coefficient
A	20.10	−0.9447	0.9926
B	17.44	−0.6052	0.9997
C	21.91	−0.3796	0.9697

$$R_{\mathrm{grout}} = \frac{1}{2\pi\lambda_g}\ln\left(\frac{d_b}{d_e}\right) \tag{7}$$

R_{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 moisture migration. (4) Ignoring the impact of groundwater advection. (5) 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 ΔT between the initial soil temperature and the point under consideration at or near the pipe can be estimated using Kelvin line source theory [15] as defined below:

$$\Delta T = t_r - t_\infty = \frac{q}{2\pi\lambda_s}\int_{\frac{r}{2\sqrt{a\tau}}}^{\infty}\frac{e^{-\beta^2}}{\beta}\,d\beta = \frac{q}{2\pi\lambda_s} I(x) \tag{8}$$

When $r = r_b$, thermal resistance of soil is as follows:

$$R_s = \frac{t_b - t_\infty}{q} = \frac{1}{2\pi\lambda_s} I\left(\frac{r_b}{2\sqrt{a\tau}}\right) = \frac{1}{2\pi\lambda_s} I\left(\frac{1}{2\sqrt{Fo}}\right) \tag{9}$$

When $0 < x \le 1$, the I-function is calculated by

$$I(x) = 0.5(-\ln x^2 - 0.57721566 + 0.99999193x^2 - 0.24991055x^4 + 0.05519968x^6 - 0.00976004x^8 + 0.00107857x^{10}) \tag{10}$$

And when $x \ge 1$,

$$I(x) = \frac{1}{2x^2 \exp(x^2)}\frac{A}{B} \tag{11}$$

where

$$A = x^8 + 8.5733287x^6 + 18.059017x^4 + 8.637609x^2 + 0.2677737$$

$$B = x^8 + 9.5733223x^6 + 25.6329561x^4 + 21.0996531x^2 + 3.9684969$$