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Validation of borehole heat exchanger models against multi-flow rate thermal response tests

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ABSTRACT

A recently developed vertical borehole ground heat exchanger model that accounts for transit time effects and time-varying short-circuiting heat transfer has been validated against two multi-flow-rate thermal response tests (MFR-TRT). The MFR-TRT, when performed with a wide range of flow rates, results in significant changes in the borehole thermal resistance, the borehole internal thermal resistance, and the short-circuiting heat transfer between the two legs of a single U-tube. The model accounts for short-circuiting by an analytically computed weighting factor that is used to determine the mean fluid temperature. The weighting factor portion of the model can be readily utilized in other ground heat exchanger models that currently rely on a simple mean fluid temperature. Use of the weighting factor is shown to give significantly better estimations of entering and exiting fluid temperature than using the simple mean fluid temperature. The new model is also compared to an alternative approach − using an effective borehole thermal resistance. While both the effective borehole thermal resistance model and the weighting factor give quite good results a few hours after a step change in flow rate, the weighting factor model gives much better results in the first few hours after a step change in flow rate.

1. Introduction

Ground source heat pumps (GSHP) are used to efficiently cool buildings during the summer and heat buildings during the winter (Self et al., 2013). In GSHP systems the heat pump is often coupled to the ground through vertical boreholes (Yang et al., 2010). Water or a water/anti-freeze mixture circulates through a closed loop that links the heat pump with buried pipes in boreholes. In a recent survey Lund and Boyd (2016) report that there are approximately 4.19 million equivalent units installed worldwide based on a 12 kW baseline (typical size for USA and Western European homes).

A single U-tube of high density polyethylene (HDPE) is the most common choice in the United States for the pipe configuration within the borehole (Fig. 1a). Grout is placed outside of the pipes to fill the space between the outer pipe surfaces and the borehole wall. In some locations such as Sweden, the space between the pipes and borehole wall is filled with groundwater (Acuña et al., 2009; Javed, 2012). Other pipe configurations include double U-tube and coaxial pipe-within-pipe arrangements.

Analysis, modeling and design of borehole heat exchangers has been an ongoing field of research for many years. It is complicated by the large ranges of length and time scales that are inherent in trying to transfer heat between the ground and GSHPs using borehole heat exchangers. Heat transfer models for borehole heat exchangers have been reviewed by Javed et al. (2009), Yang et al. (2010), Li and Lai (2015) and Spitler and Bernier (2016). An early approach modeled the borehole as a line source of heat (Carslaw and Jaeger, 1959). Then, the heat from the line source conducts radially outward through the ground. With a constant heat input rate the temperature of the circulating fluid increases with time; time-varying heat transfer rates are handled with superposition. The line-source model is used to estimate the time-varying borehole wall temperature; the mean fluid temperature can then be estimated based on a borehole thermal resistance.

This brings us to the questions of how to determine the mean fluid temperature and how to determine the borehole thermal resistance. In many borehole heat transfer models, a local borehole thermal resistance, R_b, is used with the mean temperature. The local borehole resistance is the thermal resistance between the circulating fluid and the borehole wall. The local borehole resistance has components associated with the grout thermal conductivity, the pipe wall thermal conductivity and the convection film inside the pipes. The resistance can be calculated from a 2D model of steady-state heat conduction

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Nomenclature

a_1, a_2	Coefficients
c	Volumetric heat capacity, J/(K m^3)
C_1,C_2, C_3	Coefficients
C_4,C_5, C_6	Coefficients
C_D	Dimensionless fluid storage coefficient
f	Weighting factor
h	Convective heat transfer coefficient (W/(K m^2)
k	Thermal conductivity, W/(K m)
L	Depth of borehole, m
N	Dimensionless thermal conductance
Q	Heat input rate, W
r	Radial coordinate or radius, m
R	Thermal resistance, (K m)/W
Re	Reynolds number
s	Pipe spacing (center-to-center), m
t	Time, s
T	Temperature, °C
V	Volume, m^3
w	Volumetric fluid flow rate, m^3/s
z	Vertical depth coordinate, m

Greek

α	Thermal diffusivity, m^2/s
β	Dimensionless resistance of pipe wall
γ	Constant
θ_1,θ_2,θ_3	Coefficients

Subscripts

a	Total internal
avg	Average
b	Borehole
D	Dimensionless
eq	Equivalent
f	Circulating fluid
g	Grout
i	Index
in	Borehole entrance
m	Mean temperature approximation
o	Outer
out	Borehole exit
old	Old value
p	Pipe
pc	Pipe conductive
pic	Pipe inner convective
s	Ground (or soil)
sf	Steady flux
tr	Transit time
wa	Weighted average
1	Pipe number 1
2	Pipe number 2

Superscripts

*	Effective

within and around the borehole cross-sectional area. Expressions to estimate the local borehole resistance have been developed based on analytical methods (Hellström, 1991; Claesson and Hellström, 2011;Javed and Claesson, 2009), detailed numerical models (Sharqawy et al., 2009; Liao et al., 2012) and physical experiments (Paul, 1996; Remund, 1999).

The mean fluid temperature can be computed as the simple mean of the inlet and outlet temperatures,

$$T_m = \frac{T_{in} + T_{out}}{2} \tag{1}$$

As the length of the borehole increases and/or the fluid flow rate decreases the heat transfer between the two pipes (Fig. 1) becomes more important and changes the shapes of the vertical temperature profiles of the circulating fluid. Two approaches (Javed and Spitler, 2016) to addressing this deviation are found in the literature. In the first approach Hellström (1991) defined an effective borehole thermal resistance, R_b*, that accounts for the deviation and which can be applied using the simple mean fluid temperature. From his work analytical expressions for the ratio of effective to local resistances are available for two cases with different simplifying assumptions (Claesson and

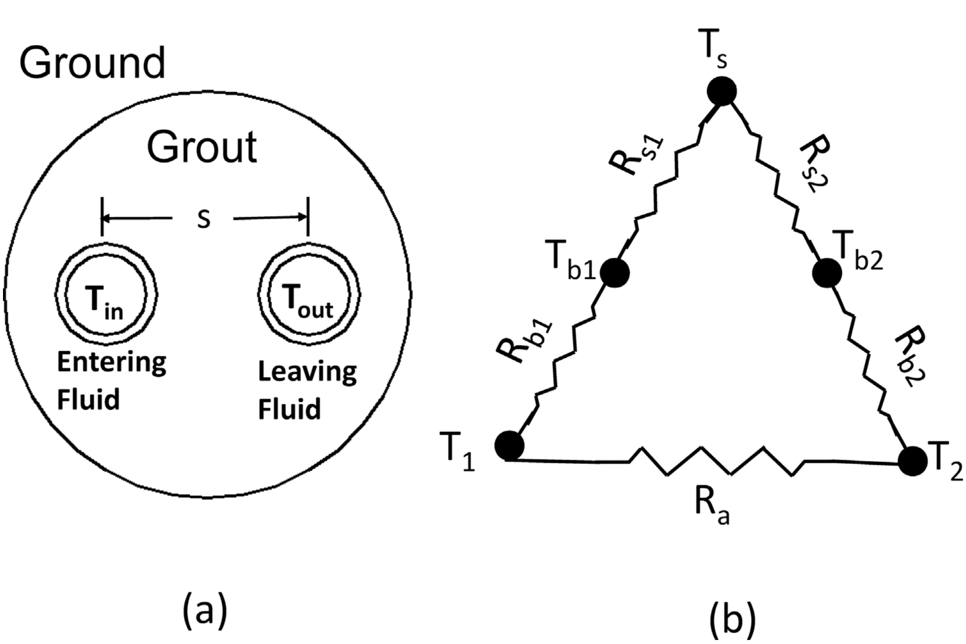

Fig. 1. (a) Borehole cross section and (b) thermal resistance network for single U-tube BHE.