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Accuracy of borehole thermal resistance calculation methods for grouted single U-tube ground heat exchangers

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HIGHLIGHTS

- First systematic comparative study of methods for calculating borehole resistance.
- Of 10 methods, only 1st order multipole method gives high accuracy for all cases.
- Similarly for internal resistance, only one method gives acceptable accuracy.
- Grout resistance is shown to vary with pipe resistance and ground conductivity.

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ABSTRACT

The borehole thermal resistance – that is, the thermal resistance between the fluid in the U-tube and the borehole wall – is both a key performance characteristic of a closed-loop borehole ground heat exchanger and an important design parameter. Lower borehole thermal resistance leads to better system performance and/or lower total borehole length and possibly lower installation costs. Borehole thermal resistance may be determined using in situ thermal response testing, but for design purposes, it is important to be able to predict the borehole thermal resistance prior to installation. Due to the complexity of calculating it, numerous simplified methods have been proposed. This paper reviews published methods for calculating borehole thermal resistance for grouted boreholes with single U-tubes and compares their results against a rigorous analytical method.

Another quantity that is particularly important for deep boreholes is the internal thermal resistance – that is, the thermal resistance between the upward-flowing and downward-flowing fluid paths in the borehole. Short-circuiting between the two legs has the effect of reducing the total heat transfer and can be quantified as an adjustment to the borehole thermal resistance, resulting in an effective borehole thermal resistance. A few simplified methods for calculating internal thermal resistance are compared against a rigorous analytical method.

The simplified methods for calculating both borehole thermal resistance and internal thermal resistance are compared in parametric studies spanning the range of borehole diameters, pipe spacing, ground thermal conductivities and grout thermal conductivities found in practice. Many of the simplified methods work well with some combinations of parameters and poorly with others. The first-order multipole expressions are closed-form algebraic expressions that give results within 2% (for borehole thermal resistance) and 6% (for internal thermal resistance) over the entire range of parameters. This represents significantly better accuracy than any of the other simplified methods and, therefore, the first-order multipole algorithm is recommended for single U-tube applications when the tubes are symmetrically placed.

1. Introduction

Ground source heat pump (GSHP) systems are among the fastest-growing technologies used for space heating, cooling and hot water provision. The worldwide installed capacities of GSHP systems have increased from under 2000 MWt in 1995 to over 15,000 MWt in 2005 and to over 50,000 MWt in 2015. In the same period, the thermal energy utilized by GSHP systems is estimated to have increased from just over 500 GWh in 1995 to over 24,000 GWh in 2005 and to approximately 91,000 GWh in 2015 [1]. Although, GSHP systems use electric power to operate compressors, circulation pumps, and other auxiliary systems, the

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Nomenclature

h_{pi}	convection coefficient at the inside pipe wall, W/m^2-K
N	number of pipes in the borehole; $N = 2$ for single U-tube
q_b	heat rejection rate per unit length of borehole, W/m
q_1	heat rejection rate per unit length of pipe 1, W/m
q_2	heat rejection rate per unit length of pipe 2, W/m
r_b	radius of the borehole, m
r_{eq}	equivalent radius of the U-tube legs, m
r_{pi}	inner radius of the pipe making up the U-tube, m
r_{po}	outer radius of the pipe making up the U-tube, m
R_a	total internal borehole thermal resistance; see Eq. (8), m-K/W
R_b	local or average borehole thermal resistance between fluid in U-tube(s) to borehole wall, m-K/W
R_b^*	effective borehole thermal resistance, m-K/W
R_g	grout thermal resistance; resistance between outer pipe wall of U-tube to borehole wall, m-K/W
R_p	total fluid-to-pipe resistance for a single pipe – one leg of the U-tube, m-K/W
R_{pc}	conductive thermal resistance for a single pipe – one leg of the U-tube; see Eq. (10), m-K/W
R_{pic}	inner convective thermal resistance for a single pipe – one leg of the U-tube; see Eq. (11), m-K/W
R_{1-2}	thermal resistance between U-tube legs 1 and 2, m-K/W
R_{1-b}	thermal resistance between U-tube leg 1 and borehole wall, m-K/W
R_{2-b}	thermal resistance between U-tube leg 2 and borehole wall, m-K/W
s	shank spacing i.e. center-to-center distance between two legs of the U-tube; see Fig. 2, m
S_b	borehole shape factor; see Eq. (19), dimensionless
T_b	mean temperature at the borehole wall, K
T_f	mean fluid temperature inside the U-tube, K
T_{f1}	fluid temperature in U-tube leg 1, K
T_{f2}	fluid temperature in U-tube leg 2, K
β	dimensionless thermal resistance of one U-tube leg; see Eq. (14)
θ_1	dimensionless parameter; see Eq. (14)
θ_2	dimensionless parameter; see Eq. (14)
θ_3	dimensionless parameter; see Eq. (14)
λ	thermal conductivity of the ground, W/m-K
λ_g	thermal conductivity of the grout, W/m-K
λ_p	thermal conductivity of the pipe, W/m-K
σ	thermal conductivity ratio; see Eq. (14), dimensionless

thermal energy provided by the GSHP systems is typically 2–5 times higher than the consumed electric energy, hence making them quite energy efficient. The energy efficiency of GSHP systems can be further enhanced by optimizing the design and operation of these systems [2,3].

A GSHP system typically consists of a heat pump, a vertical ground heat exchanger and a distribution system [4]. The key challenge when designing a GSHP system is to size the ground heat exchanger appropriately. With an under-sized ground heat exchanger, the heat pump entering fluid temperatures will be less favourable – hotter in cooling mode and/or colder in heating mode – leading to a lower coefficient of performance (COP) and additional electricity consumption. With an over-sized ground heat exchanger, the required pumping energy as well as the energy embodied in materials, e.g. heat exchanger pipes, are both considerably higher due to additional pressure losses, higher pressure rating requirements, additional energy consumed by the drilling and additional materials used for larger/deeper ground heat exchangers. From a life-cycle perspective, a poorly sized ground heat exchanger results in an inefficient GSHP system with higher financial costs and/or lower environmental performance.

Two design parameters, i.e. ground thermal conductivity, λ, and borehole thermal resistance, R_b, are required for sizing of ground heat exchangers. While ground thermal conductivity is a physical property of the ground surrounding the boreholes, the borehole thermal resistance depends on both the thermal properties of the borehole components including U-tube and grouting, and also on the physical arrangement of the U-tube in the borehole. A poor estimate of the borehole thermal resistance can lead to under-sized or over-sized ground heat exchangers, in turn leading to excess electrical energy consumption. Significant adverse effects of inaccurate borehole thermal resistance estimations on the sizing of the ground heat exchanger and on the performance of the GSHP system have been reported by several researchers including Cho and Choi [5], and Javed [6], among others. The focus of this paper is on accurate calculation of the borehole thermal resistance.

The borehole thermal resistance is both a key performance characteristic of the ground heat exchanger and an important design parameter – the lower the thermal resistance, the better the performance and/or the lower the total required borehole length. Lower total required borehole length might or might not lead to lower total installation cost. Many innovations have been proposed to reduce borehole thermal resistance – e.g. thermally-enhanced grout, thermally-enhanced HDPE pipe, and numerous configurations besides the single U-tube. To date, only improvements that take little additional time to install, such as thermally-enhanced grout, have received widespread acceptance. Though more sophisticated configurations can reduce the borehole thermal resistance and the required total borehole length, if they take too long to install or have a higher investment cost, it is often more economically feasible to simply drill deeper or drill more boreholes.

Even though heat transfer between a borehole heat exchanger and the ground is necessarily transient, the steady-state borehole thermal resistance is a useful quantity for either characterizing the performance of a borehole heat exchanger or for analysis of borehole heat exchangers [7]. The heat transfer between the heat carrier fluid in the pipes of the U-tube and the borehole wall often approaches a quasi-steady condition. For this heat transfer, a local borehole thermal resistance can be defined:

$$R_b = \frac{T_{f,l} - T_b}{q_b} \tag{1}$$

where $T_{f,l}$ is the local mean fluid temperature (K),
T_b is the borehole mean wall temperature (K),
q_b is the heat transfer rate (from the borehole to the ground) per unit length (W/m).

Although many methods for computing borehole thermal resistance implicitly assume that the borehole wall temperature and pipe wall temperatures are uniform, this is not the case. Non-uniform temperature distributions lead to resistance that depend on the temperature distribution. This dependence is further discussed and illustrated in Section 7 of the paper.

In any discussion of borehole thermal resistance, it is important to clearly distinguish the terms “borehole thermal resistance” (R_b) and “effective borehole thermal resistance” (R_b^*). Mogensen [8] introduced the concept of borehole thermal resistance by giving