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Calculation Tool for Effective Borehole Thermal Resistance

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Abstract
This paper presents a tool for computing thermal resistance of single U-tube ground heat exchangers placed in vertical boreholes. The tool is complete in the sense that it can compute both local and effective thermal resistances for either grouted or groundwater-filled boreholes. For grouted boreholes, it utilizes the highly accurate multipole method. For groundwater-filled boreholes, it utilizes recently-published convection correlations. Thermal property routines for water and water-antifreeze mixtures allow calculation of the interior convective thermal resistance for a wide range of cases.

Keywords – ground source heat pumps, ground heat exchangers, borehole thermal resistance

1. Introduction

Ground source heat pump systems are energy-efficient and environmentally-friendly means of providing building heating and cooling. Design of the ground heat exchangers for these systems can be challenging for several reasons including estimation of the borehole thermal resistance. The borehole thermal resistance is the thermal resistance between the fluid in the U-tube and the borehole wall. Lower borehole thermal resistance leads to more favorable entering heat pump fluid temperatures and better heat pump performance. Mogensen [1] first identified the borehole thermal resistance as a parameter of interest in ground heat exchanger design. Since that time, there have been numerous methods proposed for calculating borehole thermal resistance in the case of grouted boreholes. Either a single or double U-tube heat exchanger involves multiple eccentrically placed cylinders within another cylinder and therefore leads to difficulties in analyzing the conduction heat transfer problem. Therefore, a number of simplified methods, which are usually accurate only over a narrow range of geometries, have been developed. The multipole method developed by Claesson and Bennet [2] is accurate over a wide range of geometries, but is mathematically challenging to implement.

In Scandinavia, it is common practice to construct borehole heat exchangers by lowering a U-tube in a groundwater-filled borehole. Where the bedrock and

groundwater levels are close to the surface, this can be a very effective design with relatively low borehole thermal resistance on the order of 0.05-0.06 K/(W/m) [3] for typical conditions. Several authors have shown that the borehole thermal resistance can vary with both heat transfer rate and annulus temperature due to variations in the buoyancy-driven flow and heat transfer. Convection correlations [4] have recently been published that take into account the temperature and heat transfer effects on the buoyancy-driven flow in the borehole annulus.

When a thermal response test is used to measure borehole thermal resistance it inherently includes the effects of internal heat transfer between tubes ("short-circuiting") in the ground heat exchanger, and is referred to as the effective borehole thermal resistance. Hellström [5] developed analytical relationships between the local borehole thermal resistance (R_b) and the effective borehole thermal resistance (R_b^*). For many boreholes, particularly those of depths less than 100 m, there is little effect of short-circuiting and it may be neglected. However, the short-circuiting effect increases as either the depth or conductance between the legs increases and/or as the mass flow rate in the heat exchanger decreases. As there are some trends towards increasing borehole depth, it is important to be able to account for short-circuiting in the calculation of effective borehole thermal resistance.

This paper reports on an Excel/VBA spreadsheet that calculates borehole thermal resistance for both grouted and groundwater-filled boreholes with single U-tubes.

2. Methodology

An Excel/VBA spreadsheet was developed that calculates both borehole thermal resistance and effective thermal resistance for grouted or ground-water-filled boreholes with single U-tubes. The inputs are summarized in Table 1; some inputs apply to grouted or groundwater-filled boreholes only and are marked parenthetically to that effect. Each aspect of the calculation is described briefly below.

a. Interior convective resistance and pipe resistance

Properties (dynamic viscosity, density, specific heat, thermal conductivity) for pure water and mixtures of water with propylene glycol, ethylene glycol, ethyl alcohol and methyl alcohol are provided by routines described by Khan [6]. For Reynolds number of 2300 or above, the Gnielinski [7] correlation is used; below 2300 the Nusselt number is set to 4. The conductive resistance is readily determined from the pipe dimensions and conductivity.

b. Multipole algorithm – grouted boreholes

The multipole method is a mathematically-complex algorithm which can be used to calculate conductive thermal resistance for any number of arbitrarily placed pipes in a borehole. The multipole method solves the conduction heat transfer problem using line sources and multipoles. Derivation of the multipole method is described in [8]. The multipole method has been compared with several numerical methods with remarkable accuracy [9-11] and is often used as a reference method. There has been some confusion in the literature between 0th and 1st order closed form expressions that can be

derived from the multipole method and the full implementation of the method which can use additional multipoles to better account for the composite geometry. Our implementation can calculate any order, though little accuracy is gained for most cases in going beyond the 3rd or 4th order calculation. The multipole method is implemented in about 1000 lines of VBA code, adapted from the original [12] Fortran code.

c. Natural convection - groundwater-filled boreholes

In order to calculate borehole thermal resistance for a groundwater-filled borehole, it is necessary to find the convective resistances in the annulus between the pipe outer wall and the annulus water temperature (R_{poc}) in Figure 1 and between the annulus and the borehole wall (R_{BHWc}). The convection correlations developed by Spitler, et al. [4] are based on experimental measurements of a single borehole in Gothenburg and were validated by comparisons to measurements of effective borehole thermal resistance for 30 other boreholes in Norway and Sweden. They were tested under both heat extraction and heat injection conditions and a range of heat transfer rates and annulus temperatures. Higher heat transfer rates lead to higher temperature differences and hence higher differences in density. In turn, the higher differences in density lead to increased velocity of the recirculating flow within the annulus and decreased thermal resistances. Annulus temperature also has an influence on the natural convection. As water temperature approaches the maximum density point near 4°C, the derivative of density with respect to temperature approaches zero, resulting in reduced effect of buoyancy and increased thermal resistances. These effects have been demonstrated in both field [13, 14] and laboratory [15] experiments. The correlations used in the calculation tool account for these effects and use hydraulic diameter as a scaling parameter.

Table 1. Summary of user inputs

| Input	Units
Weight concentration of antifreeze	%
Antifreeze type	-
Volume flow rate	m^3/hr
Heat transfer rate (Groundwater-filled BH)	W/m
Outside diameter of U-pipe	m
Inside diameter of U-pipe	m
Thermal conductivity of U-pipe	W/m·K
Roughness ratio of U-pipe	-
Height of borehole	m
Shank spacing (Grouted BH)	m
Borehole diameter	m
Backfill: grout or groundwater	-
Grout thermal conductivity (Grouted BH)	W/m·K
Ground thermal conductivity (Grouted BH)	W/m·K
Calculation option for R_b^*: uniform T or q	-
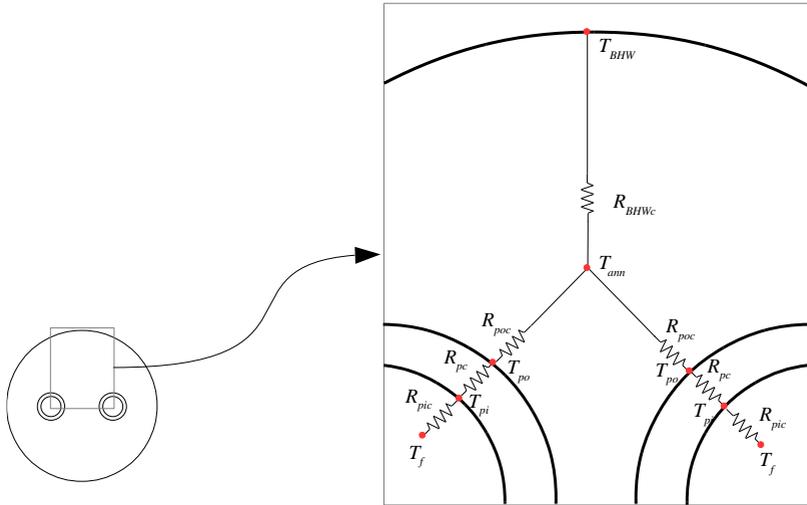
Fig. 1 Thermal resistance network for groundwater-filled borehole

d.   Short-circuiting

Several methods [16, 17] for treating short-circuiting in ground heat exchangers, based on an improved calculation of mean fluid temperature, have been proposed. We use the method described by Hellström [5] that gives the effective borehole thermal resistance that can be used with the simple mean fluid temperature. This method is consistent with estimates of borehole thermal resistance made with thermal response tests. Hellström gave two expressions based on idealized temperature profiles – one for uniform borehole wall temperature and one for uniform heat flux; for the few cases in [4] where the short-circuiting is significant, the uniform temperature approximation gave better accuracy in predicting the effective borehole thermal resistance. Both methods are implemented in the spreadsheet and the user may pick either one. Both methods also require knowledge of the internal thermal resistance. For grouted boreholes, it is determined with the multipole method; for groundwater-filled boreholes it may be determined with the thermal resistance network shown in Figure 1.

3.   Results and Discussion

Sample results and validation against experimental measurements from several boreholes are presented. The effect of thermal short-circuiting is proportional to the ratio of the tube-to-tube conductance to the thermal capacitance of the working fluid and is more important as borehole depth significantly exceeds 100 m.

a. Grouted borehole – sensitivity to depth

For grouted boreholes, the thermal resistance is not directly affected by the depth, but the short-circuiting increases with depth and, hence, the effective borehole thermal resistance is affected by depth. Figure 2 shows the borehole thermal resistance and effective thermal resistance for a grouted borehole as a function of borehole depth and two grout thermal conductivities corresponding to bentonite grout and a moderately enhanced grout. The other parameters are given in Table 2.

Table 2. Grouted borehole parameters for Figure 2

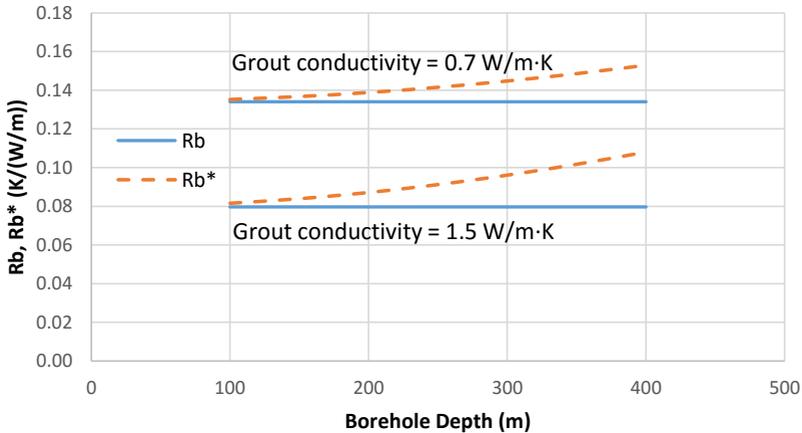| Parameter	Value
Weight concentration of antifreeze	23%
Antifreeze type	Ethyl alcohol
Volume flow rate	3.1 m^3/hr
Outside diameter of U-pipe	0.04 m
Inside diameter of U-pipe	0.0352 m
Thermal conductivity of U-pipe	0.48 W/m·K
Shank spacing	0.01 m
Borehole diameter	0.11 m
Ground thermal conductivity	3.0 W/m·K

Fig. 2 Borehole thermal resistance and effective borehole thermal resistance for grouted borehole

As shown in Figure 2, the borehole thermal resistance does not depend on depth, but increasing the grout conductivity significantly reduces the borehole thermal resistance. The effective borehole thermal resistance, shown as a dashed line, is approximately the same as the borehole thermal resistance at depths of 100 m or less. But increasing the depth leads to more short-circuiting and higher effective borehole

thermal resistance. This effect is more pronounced for the cases with higher grout conductivity as the internal resistance between the tubes is lower.

b. Groundwater-filled borehole – sensitivity to depth

For the grouted borehole, the resistances are not affected by power input. But for the groundwater-filled borehole, the buoyancy-driven convection depends on the power input. For this section, it has been fixed at 15 kW of heat extraction. Therefore, the heat extraction rate per unit length of borehole varies between 150 W/m for a 100 m borehole and 37.5 W/m for a 400 m borehole. The mean fluid temperature inside the U-tube is held constant at 15°C. Other parameters are as shown in Table 2. Figure 3 shows that the borehole thermal resistance increases with depth – this is due to the decreasing heat extraction rate per unit length which leads to lower buoyancy-driven convection rates. The effective borehole thermal resistance increases even more rapidly with depth due to the increased short circuiting.
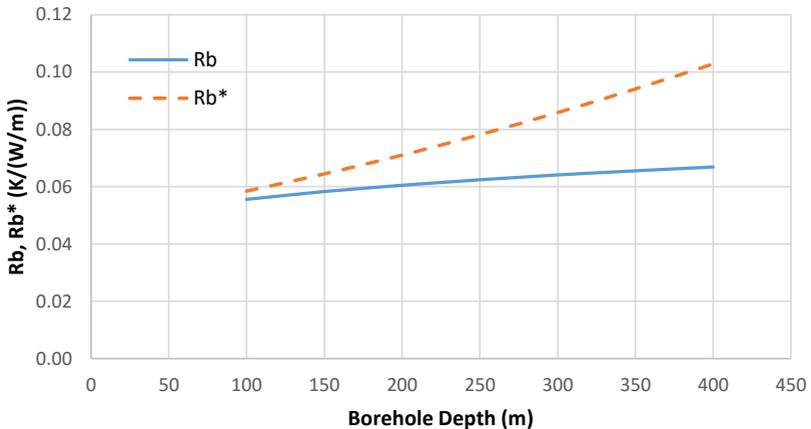

Fig. 3 Borehole thermal resistance and effective borehole thermal resistance for ground-water filled borehole

c. Grouted borehole – sensitivity to flow rate

The thermal resistance of grouted boreholes is not greatly affected by the flow rate as long as the flow is in the turbulent regime. Figure 4 shows the thermal resistances of a grouted borehole with three different flow rates as solid lines. The resistances are determined with a grout conductivity of 1.5 W/m·K, mean fluid temperature of 20 °C and other parameters of Table 2. The minor differences in borehole thermal resistances are due to small variations in convective flow resistances inside the U-tube due to different flowrates. On the other hand, the effective borehole thermal resistance, shown as dashed lines, increase significantly with decreasing flowrates. The effective borehole thermal resistances are significantly higher for deeper boreholes. For example, the

difference in effective thermal resistances values of a 100 m borehole with flowrates of 1 m³/hr and 3.1 m³/hr is over 20 %, whereas for a 400 m deep borehole the difference is over 150 % with the same flowrates. The three flowrates of Figure 4 all represent turbulent flow in the U-tube, with Reynolds numbers of approximately 4100, 8300, and 13000 for the three flowrates of 1 m³/hr, 2 m³/hr, and 3.1 m³/hr, respectively.
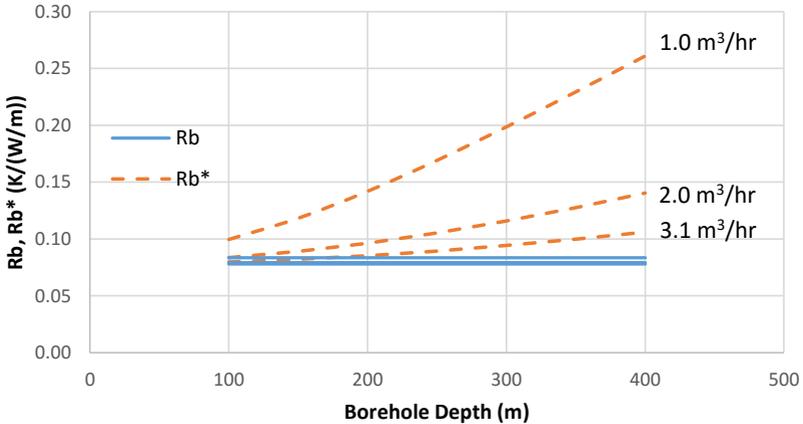

Fig. 4 Borehole thermal resistance and effective borehole thermal resistance for grouted borehole with changing flow rates

d. Groundwater-filled borehole – sensitivity to annulus temperature

For the cases shown in Figure 3, the annulus groundwater temperature and the heat extraction rate per unit length both varied over the depth. With the new convection correlations implemented in the tool, it is possible to isolate the effects of heat transfer rate and annulus temperature. For Figure 5, the heat rejection rate was kept constant at 35 W/m for a 200 m deep borehole. However, the mean fluid temperature was varied so that the annulus temperature varies between 2°C and 21°C. The shape of the curves in Figure 5 is notably non-linear. The "hump" near 4°C is caused by the maximum density point of water – in this range, the partial derivative of density with respect to temperature is very low, resulting in a low buoyant driving force and higher thermal resistances.
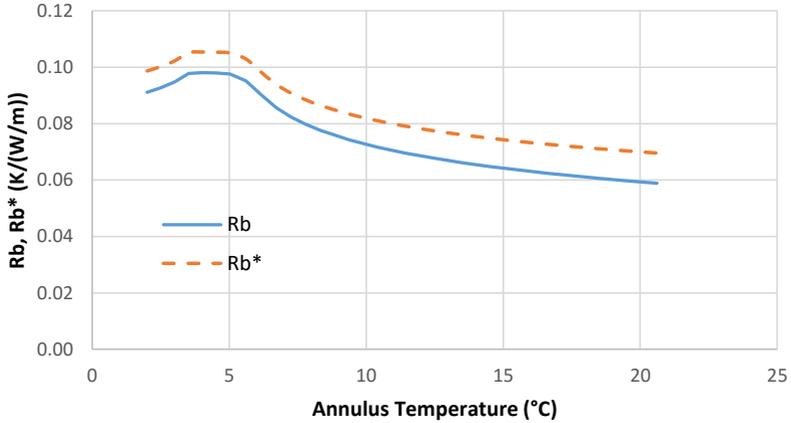
Fig. 5 Borehole thermal resistance and effective borehole thermal resistance for ground-water filled borehole with fixed heat rejection rate, but changing mean fluid temperature

e. Groundwater-filled borehole – sensitivity to heat transfer rate

In this section, we have varied the heat transfer rate, but contrived to keep the annulus groundwater temperature constant at 8.9°C. As shown in Figure 6, the borehole thermal resistance increases with decreasing heat transfer rate. Again, as the heat transfer rate decreases, the buoyant forces driving flow and convection heat transfer are lower, resulting in lower heat transfer coefficients and higher borehole thermal resistance.
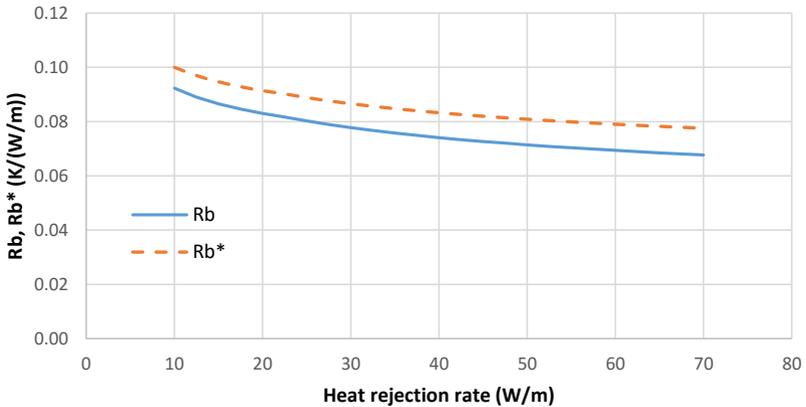

Fig. 6 Borehole thermal resistance and effective borehole thermal resistance for ground-water filled borehole with fixed annulus groundwater temperture

4. Conclusions

A tool for computing borehole thermal resistance and effective borehole thermal resistance for vertical single U-tube ground heat exchangers has been presented. One unique feature is calculation of resistance values for the annular region of groundwater-filled boreholes using recently developed correlations. For grouted boreholes, the multipole algorithm has been utilized and any order multipole solution may be found – the tool does not rely on 0th or 1st order multipole expressions.

Besides the obvious usefulness of the tool for computing borehole thermal resistance and effective borehole thermal resistance as part of design procedures, the tool can also show the sensitivity of the thermal resistances to various parameters, such as how the depth of the ground heat exchanger or the flow rate affects the amount of short-circuiting.

Use of the convection correlations for groundwater-filled boreholes also allows us to investigate the sensitivity of the borehole thermal resistance to both the heat transfer rate and the annular temperature independently. This is impossible to do experimentally with a single thermal response test as the annular temperature and heat transfer rate tend to be closely correlated.

The tool at present can be used for single U-tube ground heat exchangers. Future work includes extension to double U-tube and co-axial heat exchangers. For grouted boreholes, there are no significant barriers to this extension – for double U-tube heat exchangers, the multipole algorithm can be used and for co-axial heat exchangers, simple analytical expressions suffice for conductive resistance. However, for groundwater-filled boreholes with double U-tube and co-axial heat exchangers, additional experimental work leading to heat transfer correlations is still needed.

Acknowledgments

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