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Natural convection in groundwater-filled boreholes used as ground heat exchangers

Jeffrey D. Spitler[a,*], Saqib Javed[a], Randi Kalskin Ramstad[b]

[a] *Building Services Engineering, Chalmers University of Technology, 412 96 Gothenburg, Sweden*
[b] *Department of Geology and Mineral Resources Engineering, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway*

HIGHLIGHTS

- Thermal resistance in groundwater-filled boreholes depends on natural convection.
- We performed experiments over a wide range of thermal conditions.
- We correlated convection in annulus to modified Rayleigh number.

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ABSTRACT

In most of the world, borehole heat exchangers used with closed-loop ground source heat pump systems are backfilled with a low permeability grout to prevent water contamination. However, in Scandinavian countries, a different approach is taken – the borehole is sealed at the top and cased down to solid bedrock. The borehole then naturally fills with groundwater in the annular space between the U-tube and the borehole wall. Compared to grouted boreholes, the groundwater filling is advantageous in that it generally results in low borehole thermal resistance due to buoyancy-driven natural convection enhancing the heat transfer. Although this phenomena has been reported in several papers since the late 1980s, no calculation models have been available for use in either design tools or simulation programs. This paper presents experimental measurements from a single well-instrumented borehole under a range of heat transfer rates and annulus temperatures. Nusselt numbers for natural convection in the annulus are correlated against modified Rayleigh number. The results are verified by comparing to borehole thermal resistances predicted with the correlations to actual measurements from a range of boreholes in Sweden and Norway.

1. Introduction

Ground source heat pump systems used for heating and cooling are perhaps the most widely used renewable energy system in the world, with millions of systems installed worldwide. Ground source heat pump systems may be either "open-loop" (with the working fluid of the heat source/sink being groundwater) or "closed-loop" (with the working fluid in the ground heat exchanger isolated from the groundwater). For closed-loop systems the working fluid in the ground heat exchanger is often a water/antifreeze mixture. Both types of systems have advantages and disadvantages, but closed-loop systems using a single U-tube made of high-density polyethylene (HDPE) are far and away the most common variant.

In many parts of the world, the annulus[1] region of a borehole heat exchanger is generally backfilled with grout to prevent ground water contamination; this is legally mandated in some locales. The grout often consists of bentonite clay, sometimes with additives to enhance heat transfer. In Scandinavian countries, however, a different design is common – instead of grouting the borehole, the borehole is sealed at the top and cased down to solid bedrock, which typically lies within a few meters from the surface. The boreholes are naturally filled with groundwater through small cracks and fractures in the bedrock. In a grouted borehole, heat transfer within the annulus is conductive. In contrast, within the annular region of a groundwater-filled borehole, heat transport is largely driven by

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* Corresponding author at: School of Mechanical and Aerospace Engineering, Oklahoma State University, Stillwater, OK 74074, USA. Tel.: +1 405 744 5900.
E-mail address: spitler@okstate.edu (J.D. Spitler).

[1] We refer to the region between the tubes and the wall of the borehole as the "annulus" even though, strictly speaking, it is not a cylindrical annulus.

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Nomenclature

The reader should note that most of the definitions can be applied locally at a specific depth in the borehole or as a mean value over the whole borehole.

A_{po}	outer pipe wall area per meter of borehole, m
c_f	specific heat of the circulating fluid in the U-tube, J/kg K
D_h	hydraulic diameter of the borehole; see Eq. (19), m
g	gravitational acceleration, 9.81 m/s^2
h_{pi}	convection coefficient at the inside pipe wall, W/m^2 K
h_{po}	convection coefficient at the outside pipe wall, W/m^2 K
h_{BHW}	convection coefficient at the borehole wall, W/m^2 K
H	depth of the borehole, m
k_g	thermal conductivity of the ground, W/m K
k_p	Thermal conductivity of the pipe, W/m K
k_w	thermal conductivity of the water in the annulus, W/m K
N_p	number of pipes in the annulus; for single U-tube, $N_p = 2$
Nu_{ann}	Nusselt number for the annulus
Nu_{BHW}	Nusselt number for the borehole wall
Nu_{po}	Nusselt number for the outer pipe wall
q	heat rejection rate per unit length of borehole, W/m
q''_{po}	heat transfer rate at the pipe outer wall, W/m^2
q''_{BHW}	heat transfer rate at the pipe outer wall, W/m^2
r_b	radius of the borehole, m or mm
r_{pi}	inner radius of the pipe making up the U-tube, m or mm
r_{po}	outer radius of the pipe making up the U-tube, m or mm
R_b	local or average borehole thermal resistance, K/(W/m)
R_b^*	effective borehole thermal resistance, K/(W/m)
R_{ann}	convective thermal resistance of the annulus, K/(W/m)
R_{pc}	conductive thermal resistance for a single pipe – one leg of the U-tube, K/(W/m)
R_{pic}	inner convective thermal resistance for a single pipe – one leg of the U-tube, K/(W/m)
R_{poc}	outer convective thermal resistance for single pipe – one leg of the U-tube, K/(W/m)
R_{BHWc}	convective thermal resistance at the borehole wall, K/(W/m)
R_{12}	thermal resistance between the two legs of the U-tube, K/(W/m)
Ra_{ann}^*	modified Rayleigh number for the annulus
Ra_{po}^*	modified Rayleigh number at the pipe outer wall
Ra_{BHW}^*	modified Rayleigh number at the borehole wall
T_{ann}	temperature in the annulus, °C
T_{BHW}	temperature at the borehole wall, °C
T_f	mean fluid temperature inside the U-tube, °C
T_{pi}	temperature at the inner pipe wall, °C
T_{po}	temperature at the outer pipe wall, °C
T_0	initial or undisturbed temperature of the ground, °C
U_{ann}	conductance of the annulus region, W/m K
V_f	volume flow rate of the circulating fluid in the U-tube, m^3/s
α_g	thermal diffusivity of the surrounding ground, m^2/s
α_w	thermal diffusivity of the water in the annulus, m^2/s
β	volumetric thermal expansion coefficient for water, 1/K
ν_w	kinematic viscosity of the water in the annulus, m^2/s
ρ_f	density of the circulating fluid in the U-tube, kg/m^3

buoyancy-induced natural convection, sometimes assisted by advective flow through large fractures.

The performance of the ground source heat pump system depends on a properly sized ground heat exchanger – that is, the number of boreholes, depth, and spacing that, when combined with the borehole heat exchanger design, will provide adequate entering fluid temperatures to the heat pump over the life of the system. For a single U-tube configuration, the design includes the diameter and wall thickness of the U-tube, the type of grout or backfill used, and whether or not the U-tube position is controlled in some manner. The design, taken as a whole, is often characterized by the borehole thermal resistance, the thermal resistance between the fluid in the U-tube and the borehole wall. In general, the lower the borehole thermal resistance, the smaller the required ground heat exchanger size. Of course, the capacity of the ground heat exchanger is also limited by the thermal properties of the ground, so there are limits as to how much the ground heat exchanger size can be reduced.

Mogensen [1] first proposed measuring borehole thermal resistance with a thermal response test (TRT) where a constant heat rejection or extraction pulse is imposed on the borehole. Using the infinite line source solution, he derived an expression for the thermal resistance based on extrapolating the long-term temperature response back to time zero. The temperature difference at that time divided by the heat input or extraction rate per unit length of the borehole gives the borehole thermal resistance. Eklöf and Gehlin [2] also used the infinite line source solution, but derived a form that gives the instantaneous borehole thermal resistance, from which they take a mean value as the best estimate. Beier and Smith [3] give a derivation for an approach that is essentially the same as Mogensen. Gehlin and Hellström [4] compared four methods for estimating thermal conductivity and borehole resistance from three sets of thermal response test results. The methods were based on two variants of the infinite line source solution, an analytical cylinder source solution and parameter estimation coupled with a numerical method. The line source methods and numerical methods gave results that were within a few percent of each other, the cylinder source method was somewhat higher, though as the test time exceeded two days, the differences decreased. Witte [5] reported a detailed error analysis of thermal response tests and estimated an uncertainty of ±11.5% in the borehole thermal resistance for a typical example.

These techniques, which may be applied to either groundwater-filled boreholes or grouted boreholes, are quite useful, but don't address the need for estimation of borehole thermal resistance as part of the design process, before any boreholes have been drilled. For grouted boreholes, methods for estimating the borehole thermal resistance [6–9] are reasonably well established and have been reviewed by Lamarche et al. [10]. Claesson and Hellström [11] provide an updated treatment of the multipole method recommended by Lamarche et al.

The situation in groundwater-filled boreholes is somewhat more complex because the natural convection in the annulus region varies with heat transfer rate and fluid temperature. Several studies have investigated the effect of buoyancy driven natural convection on borehole thermal resistance; some have also examined effects on effective ground thermal conductivity. In one of the first studies addressing this topic, Claesson and Hellström [12] used in-situ and laboratory measurements to study the role of convective heat transfer in water-filled boreholes. The in-situ measurements taken on a 25-borehole field had borehole thermal resistance values which were 25% lower than the simulated cases with no convection considered. (That is, compared to simulated cases where the water was quiescent and hence the heat transfer was by conduction.) The laboratory measurements were taken using a 3-m high cylinder which simulated the