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# Vertical temperature profiles and borehole resistance in a U-tube borehole heat exchanger

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ABSTRACT

The design of ground source heat pump systems requires values for the ground thermal conductivity and the borehole thermal resistance. In situ thermal response tests (TRT) are often performed on vertical boreholes to determine these parameters. Most TRT analysis methods apply the mean of the inlet and outlet temperatures of the circulating fluid along the entire borehole length. This assumption is convenient but not rigorous. To provide a more general approach, this paper develops an analytical model of the vertical temperature profile in the borehole during the late-time period of the in situ test. The model also includes the vertical temperature profile of the undisturbed ground. The model is verified with distributed temperature measurements along a vertical borehole using fiber optic cables inside a U-tube for the circulating fluid. The borehole thermal resistance is calculated without the need for the mean temperature approximation. In the studied borehole, the mean temperature approximation overestimates the borehole resistance by more than 20%.



## 1. Introduction

Ground-source heat pump (GSHP) systems have been developed to increase energy efficiency for the heating and cooling of buildings. GSHP systems often use vertical boreholes as ground heat exchangers, which couple heat pumps to the ground. A common design uses a circulating fluid in a closed loop to carry heat between the heat pump and the ground heat exchanger with a U-tube (Fig. 1a). In the United States the space around the U-tube in the borehole is often filled with grout to prevent water and contaminants from migrating along the vertical borehole. In Sweden the common practice is to allow groundwater to fill the borehole around the U-tube (Gustafsson et al., 2010).

The design of the ground heat exchanger requires values for the ground thermal conductivity and the borehole thermal resistance, which is the thermal resistance between the borehole wall and the circulating fluid. An in situ thermal response test (TRT) on a borehole is a method to estimate both parameters as proposed and demonstrated by Mogensen (1983). Early analysis methods for determining the ground thermal conductivity are based on methods by Carslaw and Jaeger (1959) and Ingersoll and Plass (1948). Eklöf and Gehlin (1996) and Austin et al. (2000) built early portable units for field tests. Gehlin and Spitler (2003) and Sanner et al. (2005) review the history of in situ TRTs. Hellström (1991) presented analytical solutions for determining the thermal resistance of the borehole if the placement of the U-tube is known.

During a typical in situ thermal response test a pump circulates a fluid through a controlled heat source and the U-tube in a closed loop. The equipment on the ground surface includes the pump, electric heater as the heat source, flow meter, temperature sensors, and data acquisition system. In an ideal test, the electric heater supplies heat to the fluid at a constant rate. The temperatures of the fluid are measured at the inlet and outlet locations of the U-tube. Sometimes, as an alternative to the electric heater, a reversible heat pump is used to heat or cool the fluid (Witte et al., 2002).

In another variation of a TRT, Raymond et al. (2010) place heating cables inside the pipes as the heat source. Thermistors are placed along the cables to measure temperatures at specified depths. Monitoring the temperatures continue after the heat injection is stopped. The ground thermal conductivity and borehole thermal resistance are determined by using data during both the heat injection and recovery periods (Raymond et al., 2011a,b).

Most analysis methods for the in situ test use the mean of the inlet and outlet fluid temperatures, ($T_{in}$ and $T_{out}$, respectively) at each time increment to represent the average temperature along the length of the ground heat exchanger. This mean temperature is an approximation to the true average temperature of the circulating fluid. The difference between this average loop temperature and the undisturbed ground temperature, $T_s$, represents the temperature difference driving the heat transfer between the circulating fluid

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**Nomenclature**

| | |
|---|---|
| $a$ | constants |
| $A$ | constants |
| $B$ | constant |
| $c$ | volumetric heat capacity, J/(K m) |
| $C$ | constants |
| $\cosh^{-1}(x)$ | inverse hyperbolic function with argument $x$ |
| $d$ | diameter, m |
| $h$ | convective film coefficient, W/(K m$^2$) |
| $k$ | thermal conductivity, W/(K m) |
| $L$ | length of borehole, m |
| $N$ | dimensionless thermal conductance |
| $p$ | power in $p$-linear average |
| $Q$ | heat input rate, W |
| $r$ | radius, m |
| $R$ | thermal resistance, (K m)/W |
| $T$ | temperature, °C |
| $w$ | volumetric fluid flow rate, m$^3$/s |
| $x_s$ | distance between center of pipe and center of borehole, m |
| $z$ | vertical depth coordinate, m |

*Greek symbols*

| | |
|---|---|
| $\alpha_{ij}$ | constants |
| $\alpha_s$ | thermal diffusivity, m$^2$/s |
| $\beta$ | constant |
| $\delta_i$ | constants |
| $\Delta T_p$ | $p$-linear average temperature, K |
| $\Delta T_s$ | temperature difference from undisturbed ground temperature, K |
| $\Delta T_1$ | temperature change along segment in pipe 1, K |
| $\Delta T_2$ | temperature change along segment in pipe 2, K |
| $\rho$ | density, kg/m$^3$ |
| $\zeta$ | position along fluid path in U-tube, m |

*Subscripts*

| | |
|---|---|
| $b$ | borehole |
| $D$ | dimensionless |
| $f$ | circulating fluid |
| $in$ | borehole entrance |
| $m$ | mean temperature approximation |
| $out$ | borehole exit |
| $po$ | outside of pipe |
| $pi$ | inside of pipe |
| $pw$ | pipe wall |
| $rs$ | reference value for ground or soil |
| $s$ | ground or soil |
| $w$ | water |
| 1,2 | pipe number |

and the undisturbed ground. The mean temperature approximation simplifies the calculations, but the method implicitly assumes the heat transfer rate is uniform along the length of the borehole, which does not strictly occur.

The mean temperature during an in situ test is often graphed with the logarithm of time as shown in Fig. 2 for a data set from the borehole described in Section 3. The late-time data follow a linear trend, which is consistent with a model representing the borehole as a line-source (Carslaw and Jaeger, 1959; Ingersoll and Plass, 1948). The ground thermal conductivity is inversely proportional to the late-time slope. A change in the input heat rate causes the jump in the temperature at 2.1 h. Even without this jump the early-time data would not follow the late-time trend due to the effects of the thermal storage of the circulating fluid, finite borehole diameter, location of the U-tube, and the grout (or water) outside the U-tube.

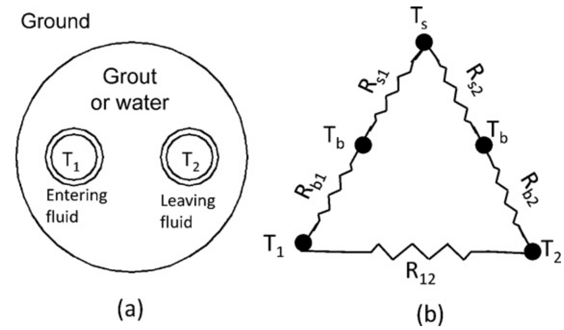


**Fig. 1.** (a) Borehole geometry and (b) thermal resistance model.

Marcotte and Pasquier (2008) argue that the use of the mean temperature under some conditions may lead to an overestimation of the borehole resistance. They introduce a $p$-linear approximation where the circulating fluid temperature varies linearly along the flow path between $|T_{in} - T_s|^p$ and $|T_{out} - T_s|^p$. Marcotte and Pasquier suggest a value of $p$ approaching −1 be used. They base their argument on calculations with a finite element model to generate the entire vertical temperature profiles of the circulating fluid. Du and Chen (2011) and Lamarche et al. (2010) modify the $p$-linear approximation by using the borehole wall temperature, $T_b$, as a reference temperature instead of the undisturbed ground temperature, $T_s$. Thus, the specific value of $p$ used by Marcotte and Pasquier does not apply to the different equations used by Du and Chen, and Lamarche et al. The version by Marcotte and Pasquier is easier to apply to a TRT test data set, because $T_b$ is not usually measured. Du and Chen and Lamarche et al. use borehole models to estimate $T_b$ in their applications of the $p$-linear approximation. Until recently vertical temperature profiles have not been measured in the circulating fluid along the borehole to check such models with field data.

Acuña et al. (2009) and Acuña (2010) have measured the entire vertical temperature profile of the circulating fluid during a TRT. In addition, they measure the vertical temperature profile in the undisturbed rock. The temperature measurements are made with fiber optic cables placed inside the U-tube. Laser light is guided down the cables, and an optical method based on Raman scattering gives the temperatures along the cables. Fujii et al. (2009) have also applied this measurement technique to ground heat exchangers.

To help interpret this new vertical temperature data set, the present paper develops an analytical model of the borehole to calculate the vertical temperature profiles of the circulating fluid and heat transfer rates to the ground. The vertical temperature profile

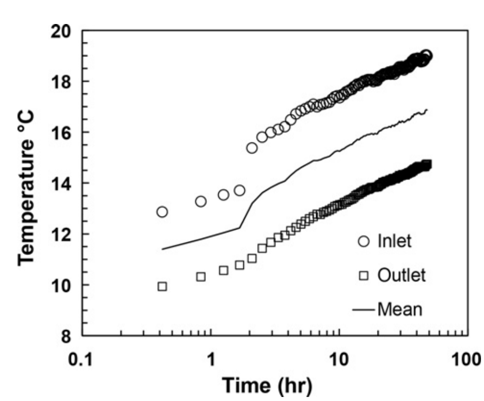


**Fig. 2.** Circulating fluid temperatures during an in situ thermal response test.