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Vertical temperature profile in ground heat exchanger during in-situ test

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ABSTRACT

Ground source heat pump systems often use closed-loop heat exchangers, which depend on the soil thermal conductivity and borehole thermal resistance as parameters. An in-situ thermal response test provides a method to estimate these two parameters. In analyzing the in-situ test, one commonly uses the mean of the measured inlet and outlet temperatures of the circulating fluid as a representative fluid temperature along the entire ground loop. This assumption is convenient but not rigorous. In this paper an analytical model of the actual vertical temperature profile in the ground loop has been developed for the late-time period of the in-situ test. With this model one can estimate the soil thermal conductivity and borehole thermal resistance without the mean temperature approximation. In addition, the model identifies dimensionless groups that guide a sensitivity study of the errors introduced by the mean temperature approximation. The error in the total thermal resistance is less than 5% if the volume flow rate is maintained above a threshold, which increases linearly with the total length of the borehole. The analysis also indicates a *p*-linear averaging method gives smaller errors than the mean temperature approximation.

1. Introduction

Ground source heat pump (GSHP) systems are used to heat and cool buildings for high energy efficiency and low maintenance cost. GSHP systems are often coupled to the ground by circulating a fluid through a buried U-tube loop. In many installations the U-tube is placed in a vertical borehole where a grout mixture is added to fill the space between the U-tube and the borehole wall (Fig. 1a). Many local governments require grout to be placed in the borehole to prevent water and contaminants from traveling along the vertical borehole.

The soil thermal conductivity and borehole thermal resistance are important parameters needed to predict the heat transfer rates for the design of GSHP systems. In-situ thermal response tests [1,2] are conducted in order to estimate the average soil thermal conductivity along the depth of the borehole. The tests also provide an estimate of the borehole thermal resistance.

The equipment for an in-situ test is illustrated in Fig. 2, where an electric heater at the surface serves as a controlled heat source. Water is pumped through the U-tube and exchanges heat with the ground. Although an electrical heater is usually used as the heat source, in-situ tests have been performed with other equipment. Witte et al. [3] describe a reversible heat pump to heat or cool the circulating fluid through the ground loop. In the ideal test the heat input rate is constant during the test and can be determined from the power input into the electrical heater.

Transient temperatures of the circulating fluid are recorded at the supply and return connections of the ground loop. At each time increment the mean of these two temperatures is usually taken to be representative of the average temperature along the borehole length. The arithmetic average or mean is simply

$$T_m = \frac{T_{in} + T_{out}}{2} \quad (1)$$

The difference between this average loop temperature and the distant undisturbed soil (or rock) temperature represents the temperature difference driving the heat transfer between the circulating fluid and the 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 of the two temperatures is often plotted versus the logarithm of time, as shown in Fig. 3, for a data set from an in-situ test. The early-time data are affected by the thermal storage of the circulating fluid, location of the U-tube, and grout thermal properties. As the influence of these borehole effects diminish, the soil properties have the dominate influence. The late-time data fall on a linear trend, which is predicted by a simple line-source model

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Nomenclature

a_1, a_2	constants
c	volumetric heat capacity, J/(m K)
C_1, C_2	constants
C_3, C_4	constants
d	diameter, m
h	convective film coefficient, W/(m^2 K)
k	thermal conductivity, W/(m K)
L	length of borehole, m
m	slope, °C
N	dimensionless thermal conductance
Nu	Nusselt number
Q	heat input rate, W
r	radius, m
R	thermal resistance, (m K)/W
Re	Reynolds number
t	time, s
T	temperature, °C
V	velocity of circulating fluid, m/s
w	volumetric flow rate, m^3/s
x_s	distance between center of pipe and center of borehole, m
z	vertical depth coordinate, m

Greek

α	thermal diffusivity, m^2/s
γ	constant
ΔT	temperature difference from undisturbed soil temperature, °C
μ	viscosity of circulating fluid, kg/(m s)
ρ	density of circulating fluid, kg/m^3

Subscripts

b	borehole
D	dimensionless
f	circulating fluid
g	grout
in	borehole entrance
m	mean temperature approximation
out	borehole exit
p	*p*-linear temperature approximation
po	outside of pipe
pi	inside of pipe
pw	pipe wall
s	soil
v	vertical temperature model
1	pipe number 1
2	pipe number 2
1 hr	one hour

[3–5] for the borehole. An explanation of this model is given in Appendix A. As the model shows, the soil thermal conductivity, k, is inversely proportional to this late-time slope,

$$k = \frac{Q}{4\pi\ m\ L\ \log(e)} \tag{2}$$

where Q is the heat input rate, L is the length of borehole, and m is the late-time slope. If natural logarithm of time instead of the common logarithm is used on the horizontal axis (Fig. 3) the factor $\log(e)$ is removed from Eq. (2). Note the late-time slopes of the inlet fluid temperature, the outlet fluid temperature and the mean temperature are all the same. Thus, the value of the soil thermal conductivity could theoretically be determined from any of these curves. The estimate for soil thermal conductivity is not sensitive to the choice of using the mean temperature approximation.

The borehole resistance [3,5] can be estimated from the line-source equations in Appendix A as

$$R_b = \frac{1}{4\pi k_s \log(e)}\left[\frac{T_{m,1hr} - T_s}{m} - \log\left(\frac{4\alpha_s t_{1hr}}{\gamma r_b^2}\right)\right] \tag{3}$$

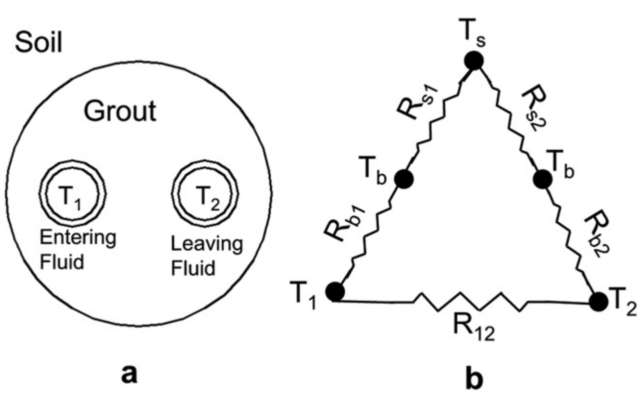

Fig. 1. (a) Borehole geometry and (b) thermal resistance model.

The temperature $T_{m,1hr}$ is the extrapolated mean temperature of the late-time trend evaluated at 1 h. The choice $T_{m,1hr}$ and the corresponding time are selected for convenience. Using a different time and the corresponding temperature on the late-time trend line gives identical results. If a second borehole in the same soil has a larger borehole resistance, a thermal response test would yield the same late-time slope. However, the late-time data would fall on a parallel trend above the current late-time trend [5].

More sophisticated models have been applied to analyzed borehole tests. For example Shonder and Beck [6,7] and Austin et al. [8] have applied numerical models and parameter estimation techniques to estimate soil thermal conductivity and borehole resistance. Yet these models still use the mean temperature approximation. Their work and other recent work are described in review articles by Sanner et al. [1] and Yang et al. [2].

Marcotte and Pasquier [9] use a finite element model to demonstrate that the use of T_m may lead to an over estimation of

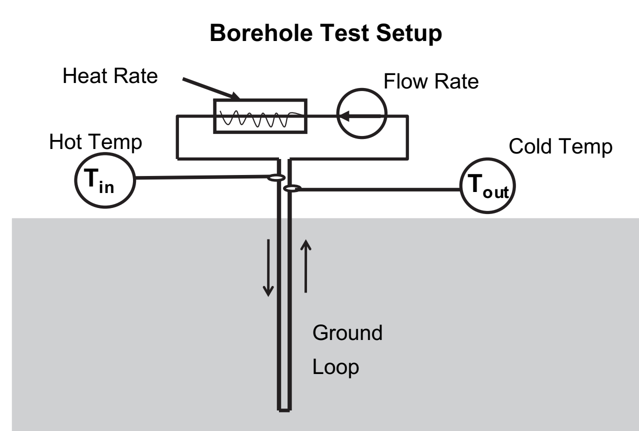

Fig. 2. Typical setup for in-situ thermal response test.