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Borehole resistance and vertical temperature profiles in coaxial borehole heat exchangers

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HIGHLIGHTS

- ▶ Proposed model calculates vertical temperature profile in borehole heat exchanger.
- ▶ Borehole fluid circulates through coaxial pipes.
- ▶ Distributed temperature sensing (DTS) system verifies model in a test borehole.
- ▶ Proposed model estimates the borehole thermal resistance using temperature profile.
- ▶ Proposed model estimates borehole resistance better than conventional methods.

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ABSTRACT

Ground source heat pump systems are often coupled to the ground by circulating a fluid through vertical Borehole Heat Exchangers (BHEs). The design of a system requires estimates of the ground thermal conductivity and the borehole thermal resistance, which are usually determined by an in situ thermal response test on a completed borehole. The usual test interpretation methods average the inlet and outlet fluid temperatures and use this mean temperature as the average temperature along the borehole length. This assumption is convenient but does not strictly apply. For a coaxial heat exchanger this paper develops an analytical model for the vertical temperature profiles, which can be used instead of the mean temperature approximation to estimate borehole resistance. The model is verified with measured temperatures on a BHE, where an optical technique allows continuous measurements along a coaxial borehole during a distributed thermal response test. A sensitivity study shows that the proposed method corrects errors in the mean temperature approximation, which overestimates the borehole resistance in a coaxial borehole.

1. Introduction

Ground source heat pump (GSHP) systems are used to heat and cool commercial and residential buildings with reduced energy and maintenance costs. The heat pump is often coupled to the ground by circulating a fluid through Borehole Heat Exchangers (BHEs). Different geometries are used for the borehole heat exchanger. One or two U-pipes may be placed in an essentially vertical borehole. Other designs [1,2] have coaxial geometries such as pipe-in-pipe coaxial configuration or arrangements with multiple pipes around an inner pipe. Another possible configuration is a multi-chamber pipe package with several external chambers attached to an inner tube. The present study focuses on the coaxial design with emphasis on the pipe-in-pipe geometry. An analytical model is developed for calculating the vertical temperature profiles within the circulating fluid. The calculated profiles are verified with measured temperature data during a thermal response test.

In a pipe-in-pipe coaxial borehole heat exchanger design (Fig. 1), an inner pipe is placed inside a larger outer pipe, forming an annular cross-section between them. Grout or groundwater fills the space between the outer pipe and the borehole wall. The circulating fluid may enter the heat exchanger through the inner pipe or the annulus and flows downward. The fluid travels upward through the other pathway. Some coaxial designs do not use grout. For example, Zanchini et al. [3] study a design where the outer pipe, made of stainless steel, is directly driven into the ground. In this case the grout (or groundwater) ring would be omitted in Fig. 1. Acuña and Palm [1] describe another design without grout where a flexible tube is placed in the borehole and filled with

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Nomenclature

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

Greek

α	thermal diffusivity, m^2/s
γ	constant
δ_i	constants
ΔT	temperature difference from undisturbed ground temperature, K
μ	dynamic viscosity, kg/(m s)
ρ	density, kg/m^3

Subscripts

an	annulus
b	borehole
D	dimensionless
eo	outside of external pipe
ei	inside of external pipe
fi	circulating fluid inside of inner pipe
fo	circulating fluid outside of inner pipe
g	grout
in	borehole entrance
m	mean temperature approximation
out	borehole exit
p	*p*-linear temperature approximation
po	outside of inner pipe
pi	inside of inner pipe
pw	pipe wall
rs	reference value for ground or soil
s	ground or soil
v	actual vertical temperature profile solution
w	water
1	flow path number 1
2	flow path number 2

water to push the tube against the borehole wall. This flexible tube serves as the outer pipe in which an inner tube is inserted.

Although most studies of borehole heat exchangers, as reviewed by Yang et al. [4], have considered the U-tube geometry, the coaxial design has been around for decades. Studies on coaxial heat exchangers include the work by Braud et al. [5], Mei and Fischer [6], and Morita et al. [7]. Yavuzturk and Chiasson [8] and Hellström [2,9] studied both U-tube and coaxial geometries, and their results suggest that the coaxial geometry may have some advantages in reducing the borehole thermal resistance, which represents the resistance between the circulating fluid and the borehole wall. Decreasing this resistance increases the heat transfer between the fluid and the ground.

In order to design a set of boreholes, an engineer needs information about the ground thermal conductivity and the borehole thermal resistance. An in situ Thermal Response Test (TRT) provides estimates of both parameters [10,11]. The test equipment often includes an electric heater, which serves as a controlled heat source. The fluid is pumped through a closed loop that includes the heater and borehole heat exchanger. As the heated fluid circulates through the BHE, heat is transferred into the ground. Although an electrical heater is usually used, tests have been performed with other equipment. For example, Witte et al. [12] and Gustafsson [13] describe a reversible heat pump to heat or cool the circulating fluid.

During a test, the transient temperatures are recorded at the inlet and outlet connections to the borehole heat exchanger. If a simple line-source model [12,14,15] is applied, the mean of these two temperatures is usually calculated at each time step as a representative average for the fluid temperature along the borehole length. Then, the TRT data are analyzed based on the temperature rise of the mean temperature, which is plotted versus the logarithm of time (Fig. 2). During the early times, the thermal storage properties of the circulating fluid, the pipes and the grout affect the shape of the temperature curves. As the influence of these initial borehole effects diminishes, the ground properties dominate the changes in the

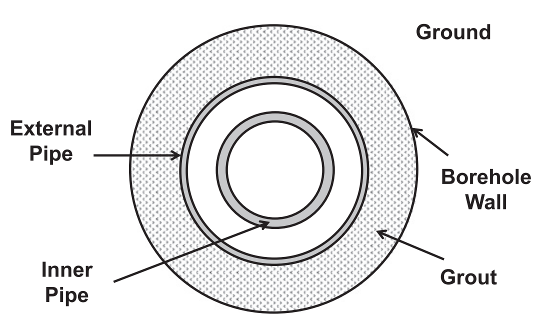

Fig. 1. Cross section of a pipe-in-pipe coaxial borehole heat exchanger.

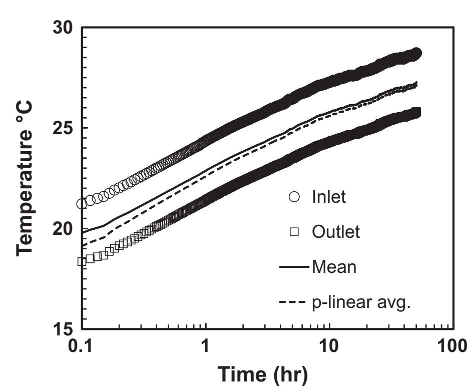

Fig. 2. Temperatures from a thermal response test.