Geothermics 50 (2014) 136–147

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

Evaluation of thermal short-circuiting and influence on thermal response test for borehole heat exchanger

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ARTICLE INFO

Article history:
Received 5 January 2013
Accepted 18 September 2013
Available online 26 October 2013

Keywords:
Short-circuiting
Thermal resistance
Borehole heat exchanger
Thermal response test (TRT)

ABSTRACT

The fluid extracts or rejects heat with subsurface by downward leg of pipe (DLP) and upward leg of pipe (ULP) inside the vertical borehole heat exchanger (BHE). As the borehole diameter is only 0.11 m to 0.2 m, the temperature difference between DLP and ULP inevitably leads to thermal short-circuiting. In order to discuss how different geometrical characteristics influence on short-circuiting, the heat transfer between the two legs was investigated by a 2-D model, and then a best-fit expression of short-circuiting thermal resistance was presented in dimensionless form. A 3-D equivalent rectangular numerical model was established to evaluate the fluid temperature variations along the pipe, how the flow velocity and grout conductivity and borehole depth influence on the outlet temperature and average heat flux per unit length and short-circuiting loss rate were analyzed. By comparing the arithmetic average fluid temperature and integral average fluid temperature, it was found that the lager short-circuiting loss rate would lead to greater error for effective subsurface conductivity estimation. The experiment done in NanJing, China also validated that the smaller flow velocity and larger borehole depth would bring about the smaller measured effective subsurface conductivity during TRT.

1. Introduction

The vertical ground source heat pump (GSHP) system is causing widespread concern because of its high efficient, environmental conservation and low running cost, the borehole heat exchangers (BHEs) are most important parts of the GSHP system, a typical BHE is shown as Fig. 1, the circulating fluid extracts or rejects heat as it travels down one leg of the U-tube and returns up the other leg. Usually, the borehole diameter is about 0.11–0.2 m, and the pipe diameter is about 0.02–0.05 m, if we take the maximum borehole diameter 0.2 m and minimum pipe diameter 0.02 m as the case, the shank spacing between the two legs is only 0.02–0.18 m, the temperature difference between the two legs would inevitably lead to heat exchange with each other, this is called thermal short-circuiting, it would offset a lot of temperature difference between DLP and ULP and lead to the outlet temperature become higher in the reject heat model.

Some models have been established to describe the heat transfer inside BHE: Shonder and Beck (1999) gave a single equivalent pipe instead of the U-tube to simplify the model, the axial heat flow in the grout and pipe walls were negligible. With the assumption of identical temperature different legs of tube, Hellström (1991) derived the two-dimensional analytical solutions for the heat transfer of BHE. Xu and Spitler (2006) presented a one-dimensional numerical model which replaced the real geometry by a centered fluid with equivalent thermal mass. Based on the equivalent single core method in U-tube heat exchangers, Lamarche and Beauchamp (2007) and Bandyopadhyay et al. (2008) proposed an analytical solution for concentric cylinders as an approximation of single U-pipes. All these models neglected the thermal short-circuiting effect between DLP and ULP, they might lead to inaccurate design for BHE.

With aid of the finite element method, the factors impacting on the thermal short-circuiting consist of the subsurface and grout thermal characteristics, shank spacings and circulating fluid temperature were analyzed by Muraya et al. (1996). Zeng et al. (2003) developed a quasi three-dimensional model for BHEs based on borehole thermal resistance but using an analytical solution of the fluid temperature profiles along the borehole depth, and the thermal short-circuiting between the pipes was taken into account. Thomas Oppelt et al. (2010) studied the heat transfer of double U-pipe heat exchangers with different shank spacings by dividing grout and pipes into different temperature zones. By studying the heat transfer inside the borehole and considering the heat transfer between the branch pipes, Sharqawy et al. (2009) derived the expression of effective pipe-to-borehole thermal resistance, but the assumption of uniform borehole surface temperature might not be reasonable. Based on fully three-dimensional numerical

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http://dx.doi.org/10.1016/j.geothermics.2013.09.010

Nomenclature

t_{ground}	undisturbed subsurface temperature(K)
t_b	borehole temperature (K)
t_{fi}	inlet temperature of BHE (K)
t_{fo}	outlet temperature of BHE (K)
t_{fdwon}	fluid temperature of downward leg of pipe (K)
t_{fup}	fluid temperature of upward leg of pipe (K)
q_{12}	heat transfer between DLP and ULP (W/m^2)
ε	short-circuiting loss rate
q_L	average heat flux per unit length (W m^{-1})
d_b	borehole diameter (m)
d_{po}	branch pipe outer diameter (m)
d_{pi}	branch pipe inter diameter (m)
δ	pipe thickness (m)
d_∞	far-field diameter (m)
L_o	outer equivalent side (m)
L_i	inner equivalent side (m)
X_C	shank spacing between the center of the legs (m)
λ_p	pipe thermal conductivity (W/m K)
λ_g	grout thermal conductivity (W/m K)
λ_{TRT}	effective subsurface thermal conductivity from TRT (W/m K)
λ_s	subsurface thermal conductivity (W/m K)
$\rho_s c_s$	subsurface vol. heat capacity (J/m^3/K)
$\rho_g c_g$	grout vol. heat capacity (J/m^3/K)
t_{fmin}	lowest temperature of fluid in tube (K)
h_f	convection coefficient between the pipe and the fluid (W/m^2 K)
h_{sq}	convection coefficient between the pipe and the fluid of equivalent square (W/m^2 K)
$t_f(s)$	fluid temperature along the pipe (K)
$\overline{t_{f_{arithmetic}}}$	arithmetic average of the fluid temperature (K)
$t_{f_{integral}}$	integral average of the fluid temperature (K)
u	flow velocity (m/s)
c	specific heat of fluid (J/kg K)
H	borehole depth (m)
S	length of circulated fluid along the pipe (m)
R_{pb}	pipe-borehole thermal resistance (m^2 K/W)
Re	Reynolds number

Subscripts

g	grout
s	subsurface
i	inlet
o	outlet
f	fluid
p	pipe
b	borehole
∞	far-field
DLP	downward leg of pipe in borehole
ULP	upward leg of pipe in borehole

simulations, Lamarche et al. (2010) compared the different approaches and proposed good practice to evaluate the borehole thermal resistances between the fluid and the borehole, the interference resistance between the DLP and ULP was also analyzed, but he did not give an expression of short-circuiting thermal resistance for engineering applications.

Base on line-source model, Gehlin and Hellström (2003) found the way to estimate the subsurface thermal conductivity by measuring the inlet and outlet fluid temperature of BHE, but this model neglected the thermal short-circuiting effect which would make the fluid temperature change nonlinearly along the pipe. Fujii et al. (2006, 2009) demonstrated that the thermal properties were shown as a function of borehole depth because of the temperature varying with the depth during thermal response test (TRT).

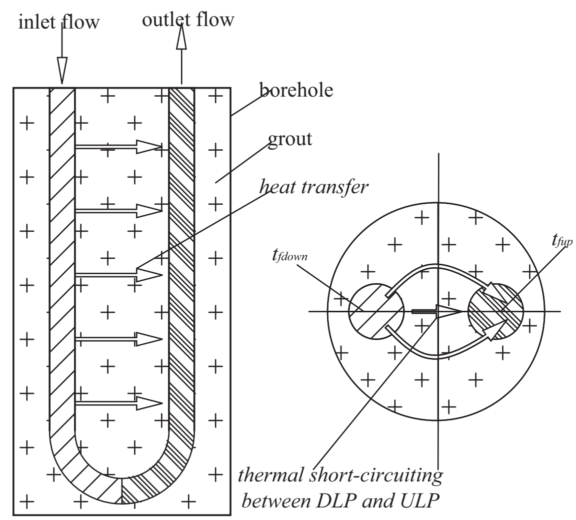

Fig. 1. Schematic diagram of typical vertical borehole exchanger.

The primary objective of this work is to study the relation between the geometrical characteristics of BHE with thermal short-circuiting and to obtain the expression of the short-circuiting thermal resistance for BHE design. In addition, the circulating fluid temperature variations along the pipe was analyzed, the rules of outlet temperature and short-circuiting loss rate and average heat flux per unit length variations with the flow velocity and grout thermal conductivity and borehole depth were particularly probed and expected to obtain relatively good measures to improve overall heat transfer of BHE and reduce short-circuiting loss rate. How the different flow velocity and borehole depth influence on the fluid temperature variations and the effective subsurface conductivity estimation would be also discussed. The methodology consists of numerical simulation, analysis and experiments.

2. Analysis of short-circuiting thermal resistance

2.1. Problem statement and mathematical model

It is well known that the borehole thermal resistance or thermal interference resistance do not depend on the initial temperature, the fluid temperature and is only a function of the thermal conductivity and the geometry of the BHE Raymonda et al. (2007). In order to probe how the geometrical characteristics influence on thermal short-circuiting, a two-dimensional steady-state model was established to study the heat transfer inside a single U-tube, it was assumed that heat transfer of BHE was predominantly radial at a given depth and the groundwater flow was not taken into account. The physical model and the coordinate system were shown as Fig. 2.

Under Cartesian x–y coordinate system, the governing energy equation in the grout area and subsurface area could be written as Eqs. (1) and (2), respectively.

$$\lambda_g\left(\frac{\partial^2 T_g}{\partial r^2}+\frac{1}{r}\frac{\partial T_g}{\partial r}\right)=0 \quad r=\sqrt{x^2+y^2}\le\frac{d_b}{2} \tag{1}$$

$$\lambda_s\left(\frac{\partial^2 T_s}{\partial x^2}+\frac{\partial^2 T_s}{\partial y^2}\right)=0,\quad \sqrt{x^2+y^2}\ge\frac{d_b}{2} \tag{2}$$

The undisturbed temperature (t_{ground}) was 290.55 K, the temperatures of DLP (t_{fdwon}) and ULP (t_{fup}) were set 305.15 K and 301.15 K, respectively, the borehole wall was set continuum boundary but