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Joint use of quasi-3D response model and spectral method to simulate borehole heat exchanger

Philippe Pasquier*, Denis Marcotte

Department of Civil, Geological and Mining Engineering, Polytechnique Montréal, P.O. Box 6079, Centre-Ville, Montréal, Québec, Canada H3C 3A7

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ABSTRACT

A quasi-3D model is used as a response model to generate normalized transfer functions of a borehole heat exchanger model. A solution is achieved by convolving in the spectral domain the transfer function of a given node with an input function describing the temperature change of the fluid over time. To demonstrate the accuracy and validity of the method, three comparison scenarios are studied. These scenarios compare the temperatures of a reference numerical model, the temperatures measured in the scope of a laboratory experiment, and during a field thermal response test. It is shown that the combined use of a spectral method and response model provides, in a few seconds, a temperature solution whose error is below or comparable to the measurement's uncertainty.

1. Introduction

Simulation of ground coupled heat pump systems or interpretation of thermal response tests (TRT) rely on a borehole heat exchanger (BHE) model to describe the relationship between the temperature of a heat carrier fluid and the heating or cooling power applied to this fluid. A wide variety of analytical solutions exists (Ingersoll et al., 1954; Carslaw and Jaeger, 1986; Lamarche and Beauchamp, 2007a; Zeng et al., 2002) to describe this relationship. However, these analytical models do not account for the fluid advection in the pipes and the thermal capacity of the BHE components (with the notable exception of Young (2004) and Lamarche and Beauchamp (2007b) models).

To better reproduce the short-term behaviour of a BHE, several finite element models integrating the thermal conductivity and capacity of each component and the fluid advection have been used (Marcotte and Pasquier, 2008; Bauer et al., 2011; Wagner et al., 2012). For TRT interpretation, this helps minimizing the *calibration error* (discrepancy between noisy field measurements and model prediction) and what Witte (2013) defines as the *error of the evaluation model* (inability of a model to reproduce, even with true parameter values, a noiseless measured signal). However, as emphasized by Bauer et al. (2011), using a complete finite element model to assess the uncertainty of a TRT is not practical due to their long computation time.

Nonlinear optimization methods are now more commonly used to interpret TRTs (Wagner and Clauser, 2005; Wagner et al., 2012; Marcotte and Pasquier, 2008; Li and Lai, 2012), which requires several solutions of the direct problem. It is therefore desirable to maintain a reasonable solution time for the direct problem, while reducing the error associated with the model itself. With this in mind, several researches suggested to describe the BHE and its surrounding ground as a network of interconnected resistances and capacities (De Carli et al., 2010; Zarrella et al., 2011; Bauer et al., 2011; Wetter and Huber, 1997) or to use spectral element method (Al-Khoury, 2010). These contributions differ by the BHE geometry, how the BHE components are discretized, and by the way the heat carrier fluid is accounted for. But yet, all these models are solved sequentially, namely time step by time step, which can be numerically challenging and time consuming for model integrating fluid advection (Bauer et al., 2011) or subject to a significant heating power variation.

To rapidly solve a problem involving time-varying heat flux, Marcotte and Pasquier (2008a) expressed an analytical model as a convolution product and suggested to solve it through a spectral approach. They showed that the joint use of analytical-based model, cubic spline interpolator, and fast Fourier transforms could lead to a reduction of computation time of several thousand times. The technique was later used to construct the *g-function* (Eskilson and Claesson, 1988) of a field made of several BHEs (Pasquier et al., 2013; Cimmino et al., 2012) and to find the heat flux

* Corresponding author. Tel.: +1 514 340 4711x4558.
E-mail addresses: philippe.pasquier@polymtl.ca (P. Pasquier), denis.marcotte@polymtl.ca (D. Marcotte).

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Nomenclature

Symbols

α	constant input over the response model's domain [K]
c	specific heat [J kg^{-1} K^{-1}]
C	heat capacity [J K^{-1}]
D	distance between a pipe and the borehole centre [m]
k	thermal conductivity [W/(m K)]
Nu	Nusselt number
n	number of resistances used to represent a main resistance, or normal vector
Q	heating power of a TRT [W]
R	thermal resistance [K/W]
R_{12}	thermal resistance between the fluid present in the pipes [mK W^{-1}]
R_a	equivalent thermal resistance [mK W^{-1}]
R_b	equivalent borehole thermal resistance [mK W^{-1}]
r	radius [m]
ρ	density [kg/m^3]
t	time [s]
T	temperature [K]
T_1	temperature of the fluid in the downward pipe [K]
T_2	temperature of the fluid in the upward pipe [K]
$\bar{T}_b$	mean temperature along the borehole wall [K]
v	volume corresponding to a segment [m^3/m]
$\dot{V}$	circulation flow rate in a pipe [m^3/s]

Subscripts

b	borehole
c	casing
i	inside or time index
j	node or segment index
k	index of nodes surrounding node j
o	outside
f	fluid
g	peripheral portion of grout (sheath)
gg	central portion of grout (core)
n	neighbour
p	pipe material
r	number of sub-resistances or residence time
s	soil
0	initial condition

emanating from interacting heat sources kept at a constant temperature (Pasquier and Marcotte, 2013).

Although convolution in the spectral domain is not limited to a transfer function deducted from analytical model, no attempt has yet been made to use a thermal resistance and capacity model (TRCM) to generate a normalized transfer function. The objectives of this paper are three fold: 1) present a TRCM designed to reduce model error for short, as well as long-term simulations, 2) demonstrate that joint use of TRCM and spectral approach can rapidly lead to very accurate results, and 3) present a detailed validation of the model to reassure potential users on the approach proposed in this work.

Firstly, Section 2 describes the quasi-3D TRCM used as response model to generate a set of transfer functions. Then, the section presents the strategy used to construct an input function consistent with the response model. Sections 3 and 4 compare the solution given by the method proposed in this work to the solution coming from a 3D finite element model, to the medium scale laboratory experiment conducted by Beier et al. (2011) and, to the long duration TRT performed by Pasquier and Groleau (2009).

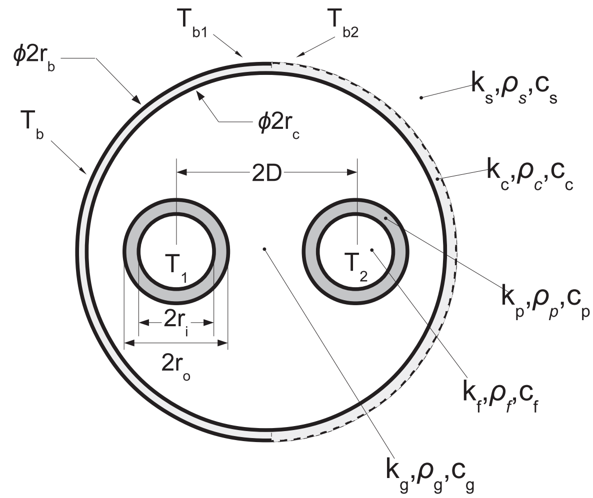

Fig. 1. Horizontal cross-section of a single U-tube BHE showing the thermal conductivity and capacity of each component. T_b represents the mean temperature along the borehole wall while T_1 and T_2 represent respectively the temperature of the downward and upward fluid in each pipe.

2. Methodology

2.1. TRCM used to generate the transfer functions

The variation of temperature (T) over time (t) can be modelled in space by a network of interconnected thermal resistances (R) and capacities (C). Such network represents a system of ordinary differential equations (ODE) subject to initial conditions (T_0). For a network of n nodes, heat conservation at node j allows writing of

$$C_j \frac{dT_j}{dt} = \sum_{k=1}^{n_j} \frac{T_k - T_j}{R_k} \quad \forall j = 1 \ldots n \tag{1}$$

where n_j is the number of neighbouring nodes to node j and where k is the index of the neighbouring nodes. Integrating a system of ODEs allows simulation of the system dynamics at some discrete times, providing known R and C values.

In Eq. 1, R and C are closely related to the discretization scheme and should ensure a sufficient accuracy without increasing too much the number of nodes and its associated computation time. For this purpose, Bauer et al. (2010) proposed a simple 2D model for two pipes BHE and later extended the model to include vertical fluid advection in the pipes (Bauer et al., 2011). To enhance the simulation of BHE for initial times, better take into account the pipe skank spacing, and integrate fluid and pipe thermal capacities, Pasquier and Marcotte (2012) improved the original model proposed by Bauer et al. (2010) by suggesting a refinement to the discretization scheme. Their modifications led to a significant accuracy improvement over the original model for short-term simulation.

In the following section, the modified TRCM is pushed two steps further by (1) extending the model to account for vertical fluid advection through a quasi-3D model and by (2) including the metal casing of a BHE (whose function is to keep pulverulent soils outside the open borehole). A brief overview of the initial 2D model will be done to allow the reader to understand the development presented hereinafter. The reader, is however, referred to the initial paper for points of detail.

2.1.1. Resistances

The BHE components and its associated nomenclature are illustrated in Fig. 1. The conductive and geometrical characteristics of each component illustrated in Fig. 1 are accounted for through a set of six main resistances, namely R_f, R_p, R_g, R_{gg}, R_c, R_s. These