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A three-dimensional numerical model of borehole heat exchanger heat transfer and fluid flow

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ABSTRACT

Common approaches to the simulation of borehole heat exchangers assume heat transfer within the circulating fluid and grout to be in a quasi-steady state and ignore axial conduction heat transfer. This paper presents a numerical model that is three-dimensional, includes explicit representations of the circulating fluid and other borehole components, and so allows calculation of dynamic behaviours over short and long timescales. The model is formulated using a finite volume approach using multi-block meshes to represent the ground, pipes, fluid and grout in a geometrically correct manner. Validation and verification exercises are presented that use both short timescale data to identify transport delay effects, and long timescale data to examine the modelling of seasonal heat transfer and show the model is capable of predicting outlet temperatures and heat transfer rates accurately. At long timescales borehole heat transfer seems well characterized by the mean fluid and borehole wall temperature if the fluid circulating velocity is reasonably high but at lower flow rates this is not the case. Study of the short timescale dynamics has shown that nonlinearities in the temperature and heat flux profiles are noticeable over the whole velocity range of practical interest. The importance of representing the thermal mass of the grout and the dynamic variations in temperature gradient as well as the fluid transport within the borehole has been highlighted. Implications for simplified modelling approaches are also discussed.

1. Introduction

Single pairs of pipes formed in a 'U' loop and grouted into vertical boreholes are probably the commonest form of ground heat exchanger found in ground source heat pump systems, and are known as borehole heat exchangers (BHEs). The components of such a heat exchanger are illustrated in Fig. 1. BHEs of this type are not only used in building heating and cooling systems but in large thermal storage schemes also. The primary physical phenomena of interest in the study of heat exchanger performance are the dynamic conduction in the pipe, grout and surrounding ground as well as convection at the pipe wall. In reality, the heat transfer in the surrounding ground may be enhanced by groundwater flow through porous and possibly fractured rock. If interaction with the heat-pump system and its controls is to be considered then it becomes necessary to consider the physics of variable flow and diffusion of heat in the circulating fluid.

It is not common, nor always necessary, to include representation of all these physical processes in BHE models. This may be partly a practical consideration of what physical parameter data are available (or measurable) as well as the level of detail required to meet the modelling objective. Models of BHEs have three principle applications namely (i) design of BHEs – determining the required borehole depth, number of boreholes, etc.; (ii) analysis of in situ ground thermal response test (TRT) data; and (iii) integrated building and system simulation i.e. with the model coupled to HVAC and building thermal models to study overall system performance.

A number of analytical, numerical and hybrid models exist and the features of a number are reviewed here. These models differ mostly according to whether they consider three spatial dimensions, multiple boreholes, groundwater convection and buoyancy effects, heterogeneous thermal properties, grout and pipe thermal capacity and explicit representation of transport of heat by the circulating fluid.

The question of dimensionality and to what level of detail the gout, pipe and fluid components are represented bears a relationship to both the timescales and length scales that have to be considered. At short timescales, being able to resolve the dynamic changes in temperature gradient within the borehole is essential to determining fluid temperatures. At long timescales (a number of years), it is necessary to consider conduction in the surrounding ground in the axial (third) dimension. This is because – particularly if an array of boreholes is considered – conduction below the borehole, and towards the ground surface further from the borehole, become more significant after a number of years of operation.

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Nomenclature

C_P	specific heat (kJ/(kg K))
D	diameter (m)
E	east
F	cell face flux (W/m^2)
h	convection heat transfer coefficient (W/(m^2 K))
L	length (m)
$\mathbf{n}$	surface normal vector
P	point (in mesh)
Q	heat transfer rate per unit length (W/m)
r	radius (m)
R	thermal resistance ((m K)/W)
$\mathbf{S}$	surface area (m^2)
t	time (s)
T	temperature (°C)
$\mathbf{v}$	surface velocity vector (m/s)
$\dot{v}$	volume flow rate (m^3/s)
$\mathbf{V}$	volume (m^3)

Greek symbols

α	thermal diffusivity (m^2/s)
ξ	local coordinates (m)
ρ	density (kg/m^3)
Γ	thermal conductivity (W/(m K))
τ	non-dimensional time

Subscripts

i	cell index
e	east
w	west
n	north
s	south
t	top
b	bottom

Superscripts

C	convection
D	diffusion
n	convection correlation exponent

Numbers

Nu	Nusselt number
Re	Reynolds number
Pr	Prantl number

Acronyms

BHE	borehole heat exchanger
BiCGSTAB	bi-conjugate gradient stabilized solver
CARM	capacitance resistance model
CFD	computational fluid dynamics
DST	duct storage model
EWS	Erdwärmesonden
GEMS3D	General Elliptical Multi-block Solver 3D
HVAC	heating ventilation and air-conditioning
RMSE	root mean square error
RTD	residence time distribution
TRCM	thermal resistance capacitance model
TRNSYS	transient system simulation tool
TRT	thermal response testing

This was demonstrated in the early work of Eskilson (1987) who applied an axial-radial 2D numerical model to capture axial conduction effects and an analytical superposition method to consider interaction between neighbouring boreholes in the horizontal direction. The importance of axial heat transfer has been commented upon by Marcotte et al. (2010) and has also been recognised in more recent application of analytical finite line source models (Zeng et al., 2002; Molina-Giraldo et al., 2011) although in these models interaction between neighbouring boreholes is neglected.

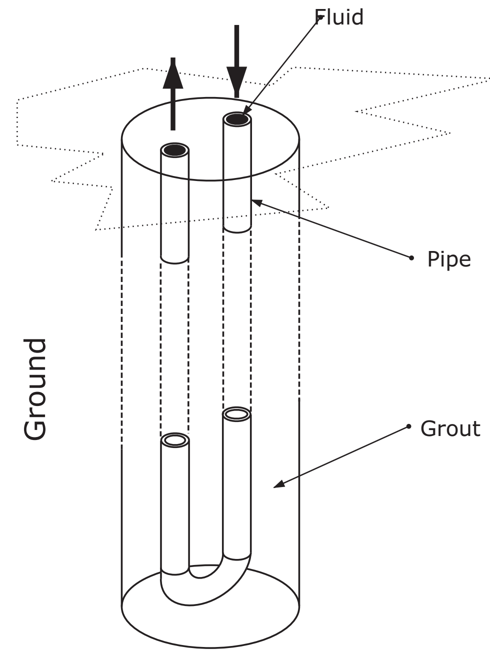

Fig. 1. A single U-tube borehole heat exchanger. Depths are typically 50–150 m and bore diameters 100–150 mm.

If only medium and long timescales are considered – as they are in the 'g-function' response factor models of Eskilson (1987) and Hellström (1991) – then the borehole can be considered a single resistive element. This can be argued to be sufficient for applications of the model for design purposes where it is more important to consider long-term responses, particularly where annual heating and cooling demands are not well balanced. Eskilson stated that g-function data derived using his approach should only be applied at timescales such that $t > 5r_b^2/\alpha$. This limit may amount to a number of days. If shorter timescales are to be considered – as they need to be where system simulation is the objective – it may be sufficient to consider heat transfer in two-dimensions, and possibly only the radial direction. At shorter time scales, behaviour is strongly dependent on the dynamic behaviour of the borehole pipe, grout and fluid components. Hybrid approaches whereby different models are applied depending on time scale can be devised to treat the whole range of timescales. For example, a one-dimensional numerical model was added to the response factor approach in the DST model (Hellström, 1991) to allow simulation in the TRNSYS simulation environment (SEL, 1997).

Yavuzturk and Spitler (1999) used a two-dimensional numerical model of a borehole (Yavuzturk et al., 1999) to calculate short timescale responses and subsequently extend g-function response data to allow short simulation time steps (as short as a few minutes) to be simulated. Several studies have been carried out using this 'short time step g-function' model (Gentry et al., 2006; Sankaranarayanan, 2005) and the model has been implemented in the EnergyPlus simulation environment (Fisher et al., 2006). Yavuzturk's numerical model (1999) represented the pipes as 'pie sector' shapes and did not include an explicit representation of the circulating fluid. Young (2004) sought to address this by applying a 'buried cable' analogy to include the effect of the fluid's thermal capacity. Xu and Spitler (2006) sought to simplify the derivation of