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A modified three-dimensional numerical model for predicting the short-time-step performance of borehole ground heat exchangers

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ABSTRACT

A modified three-dimensional numerical model for the borehole ground heat exchangers was proposed which took into account the effect of grout thermal capacitance and fluid circulation period inside the U-tube in a short-time-step analysis. The present model was validated by experimental data from others. It was found that the fluid temperature along the U-tube changed abruptly at the interface between the entering and the existing fluid inside the borehole. Before the entering fluid travelled to the bottom of the U-tube, the borehole was only partly-loaded. The difference in the simulated fluid leaving temperatures between the long- and short-time-step approaches could be up to 3 °C when a periodic intermittent load, common during the low-load season, was applied. This implied that a short-time-step model should be used in a long-term dynamic system simulation.

1. Introduction

With the urge for the reduction in carbon dioxide emission, the quest for energy saving has become an important direction of research and development. In a modern city, buildings usually contribute to more than half the total energy demand. In particular, the air-conditioning systems which provide space cooling and/or heating to the buildings, account for the majority of electricity demand from the buildings. Hence, the development and adoption of more energy-efficient air-conditioning systems is crucial. Ground-source heat pump (GSHP) systems have been deemed to be energy-efficient, particularly in regions with a very cold winter in which the ground is employed as a media of heat exchange with the surrounding [1]. Vertical borehole ground exchangers are commonly used. With U-tubes installed inside, heat transfer to/from the ground can be achieved by circulating a fluid around the closed-loop pipework. Fig. 1 shows the general arrangement of a ground heat exchanger borefield.

The performance of a GSHP system depends readily on the behaviour of the boreholes which is highly dynamic. Hence, the proper modelling of the boreholes is important. Various analytical models have been proposed, namely the line source model from Ingersoll et al. [2], the cylindrical source model from Carslaw and Jaeger [3], the finite line source model from Zeng et al. [4], the moving infinite line source model from Molina-Giraldo et al. [5], the moving finite line source model from Molina-Giraldo et al. [6] and superimposed borefield with groundwater advection from Hecht-Mendez [7]. These analytical models assume that the interior of the boreholes reach a quasi-steady condition which is only valid with a long simulation time step (usually hourly). In an actual dynamic system simulation, the GSHP may be on and off intermittently especially during the low-load period if there is no part-load control for the GSHP. In this circumstance, it is necessary to adopt a short time step (down to a minute) in order to analyse the performance of the system more precisely. Various analytical models have been developed [8–11] to investigate the short-time-step behaviour of the borehole by approximating the U-tube by a single tube using the equivalent pipe approach, thus forming a composite cylinder inside the borehole in order to account for the thermal capacitance effects of the grouting, the pipe and the circulating fluid. The main problem with the equivalent pipe approach is that in case double U-tubes are used inside the boreholes, the pipe connection configuration of the double U-tubes will have no effect on the performance of the boreholes. This clearly does not comply with the findings from Zeng et al. [12] in which the borehole thermal resistance varies with the pipe connection configuration of the double U-tubes. Pasquier and Marcotte [13] modified the thermal network inside the borehole to take into account the thermal capacitance effects of the grout, the pipe and

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Nomenclature

ALFTR	average leaving fluid temperature ratio
C	thermal capacitance per unit length (J/mK)
CP	thermal capacitance rate (W/K)
c_p	specific heat capacity (J/kgK)
D	distance between tube centre and borehole centre (m)
d	insulated length of borehole (m)
dz	grid separation in the *z*-direction (m)
H	borehole effective length (m)
k	thermal conductivity (W/mK)
m	mass flow rate (kg/s)
n_t	number of tubes inside the borehole
n_v	number of tube segments travelled in each simulation time step
n_z	number of discretisation segments along the effective length of borehole
q	specific load (W/m)
$\overset{\Delta}{R}$	thermal resistance for the delta matrix as shown in Fig. 4a (mK/W)
$\overset{\Delta}{R}_a$	total tube-to-tube thermal interference coefficient (mK/W)
$\overset{\curlyvee}{R}$	thermal resistance for the star matrix as shown in Fig. 4b (mK/W)
r	radius (m)
T	temperature (°C)
v	fluid velocity inside the U-tube (m/s)
x, y	measurements in the transverse directions of the ground (m)
z	measurement in the vertical direction of the ground (m)
Z′	normalized depth defined by $Z' = (z - d)/H$
Δt	simulation time step (s)
λ	dimensionless parameter as defined in Eq. (18)
$\Re$	parameter as defined in Eq. (26) (W/mK)
ρ	density (kg/m^3)

Subscripts

1	Tube 1
11, 22	tube-to-borehole surface
12	tube-to-tube
2	Tube 2
b	borehole surface
bo	borehole outlet
f	fluid inside tube
f1	fluid in Tube 1
f2	fluid in Tube 2
fl	fluid at centre of tube segment
g	ground
gr	grout
i, j, m	discretisation step of the ground in z-, x- and y-directions
o	far field condition
pi	tube inner surface
po	tube outer surface
t	tube surface

Superscript

n	discretisation step in the time domain

Abbreviations

DFT	downward-flowing tube
GSHP	ground-source heat pump
IN	borehole inlet
PRESENT	present short-time-step model
OLD	old long-time-step model from Lee and Lam [22].
OUT	borehole outlet
TEST	test data from Beier [29].
UFT	upward-flowing tube

the circulating fluid in accordance with the exact layout of the pipes inside the borehole. Li and Lai [14] proposed a composite-medium line source model which also excluded the use of the equivalent pipe approach. However, these modelling approaches only consider one or two-dimensional variations of the ground temperature and that the borehole load was assumed to be evenly distributed along the entire effective length. This will not be the case when considering the fact that the fluid needs time to circulate along the U-tube inside the borehole. In this regard, the borehole specific load profile (q_b) becomes stratified or the borehole may only be partly-loaded. Zarrella et al. [15], Bauer et al. [16], Pasquier and Marcotte [17] and Ruiz-Calvo et al. [18] developed quasi-3D methodology to handle this problem. However, the capability of employing their models in a laminated ground with groundwater flow is in doubt as these models are only applicable to pure conductive heat transfer in the ground.

To overcome these limitations, three dimensional numerical models have to be employed [19–21]. However, these numerical models usually adopt very fine grids to discretise the interior of the borehole. This necessitates the use of very short time step (probably down to a few seconds) in order to maintain the stability and convergence of the iterative calculation which leads to a very long computation time. Lee and Lam [22] previously proposed a three-dimensional implicit finite difference model for the ground heat exchanger as shown in Fig. 2. The entire ground volume in the borefield was discretised in one numerical scheme with the temperatures at the ground surface and those at the far ends of the ground volume assumed to be unchanged during the whole simulation period. They further modified their model [23] to account of the inhomogeneity in the ground properties and groundwater conditions. They employed a rectangular coordinate system to discretise the ground in which each borehole was represented by a square column circumstanced by the borehole radius. The full details of the formulations of the numerical model including the calculation algorithm of the heat transfer between the borehole and the ground are given in Lee and Lam [22]. By avoiding the use of very fine grids, the computation time becomes much less. In calculating the heat transfer inside the borehole, the fluid temperature along the U-tube is assumed to be fully coupled along the fluid flow direction. This requires that the fluid should completely pass through the borehole within each simulation time step. In case of a short-time-step analysis, such assumption cannot be fulfilled. To overcome the problem, the previous long-time-step model from Lee and Lam [22] is modified in this study so that the short-time-step performance of the borehole, which takes into account the effect of grout thermal capacitance and fluid circulation period inside the U-tube, can be investigated. By employing the modified model, the fluid temperature variation inside the borehole and hence the load stratification along the borehole effective length can be investigated.