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Effect of borehole short-time-step performance on long-term dynamic simulation of ground-source heat pump system

C.K. Lee

Division of Building Science and Technology, City University of Hong Kong, Tat Chee Avenue, Kowloon Tong, Hong Kong

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ABSTRACT

Despite many studies that were found in the literature regarding the modelling of the short-time-step (STS) behaviour of the borehole ground heat exchangers, reported investigations of its effect on the long-term dynamic simulation of a ground-source heat pump (GSHP) system were sparse. Hence, in this study, the dynamic performances of a GSHP system applied to an office zone in Hong Kong over a period of 10 years were compared with both the long-time-step (LTS) and STS approaches for the boreholes. It was found that with the adoption of the more appropriate STS approach, the simulated fluid temperature leaving the ground heat exchanger borefield was lower by at most 1.62 °C over a range of ground and grout thermal conductivities investigated. This also allowed the design borehole length to be reduced by at most 14.4% while the resulting energy consumption was still better than those based on the LTS approach. In this regard, the STS approach should be employed in the long-term dynamic simulation of GSHP systems.

1. Introduction

Ground-source heat pump (GSHP) systems, being considered as an energy-efficient and renewable option for sustainable development, have become popular in Europe and USA [1] as well as in China [2]. With the ground employed as the media of heat exchange with the surrounding through a system of borehole ground heat exchangers (or a borefield) as shown in Fig. 1, heat is injected to and extracted from the ground alternately between summer and winter. In this sense, the ground behaves like a thermal capacitor which acts as a heat source/sink during the heating/cooling mode operations, and the effectiveness depends on the system design although this possibility is inherently guaranteed by the large thermal capacity of the ground heat itself.

In view of its highly dynamic characteristic, the behaviour of the borehole heat exchanger depends strongly on the loading profile. For a GSHP without part-load control, the system tends to operate intermittently particularly during the low-load season, say within few minutes under the action of a thermostat control. Hence, the ground heat exchangers are also loaded intermittently. In this circumstance, the borehole performance is strongly influenced by the thermal capacitance effect of the grout and the circulating fluid inside the U-tube. Consequently, the more appropriate short-time-step (STS) modelling approach for the boreholes, which takes into account the dynamic response inside the boreholes, should be employed. Indeed, from the comparison of simulation results with test data according to Beier et al. [3] and Lee [4], the simulation results based on the short-time-step models agree well with the test data throughout the entire test period. On the other hand, the simulation results with the long-time-step (LTS) model for the borehole, which assume a steady state inside the borehole, depart more substantially from the test data during the first few hours of the loading period although the simulation results from both modelling approaches converge in the long run.

The evolution of the STS approach helps improve the simulated borehole performance at the early stage of a loading cycle. Indeed, in some common design tools for GSHP system like EED and GLEHEPRO, the STS approach is used to supplement the LTS approach when a short simulation time step is used. The load profile is transformed into a series of step loads. A STS response function is developed using the STS approach for the early loading period of each step load, say within several hours while a LTS response function determined from the LTS approach is employed to evaluate the borehole performance at the later loading period of each step load. In particular when the load aggregation technique is employed, the STS approach is used for the hourly step loads while the LTS approach is applied to the aggregated weekly, monthly and yearly step loads.

E-mail addresses: a8304506@graduate.hku.hk, avatarlee168@gmail.com

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Nomenclature

APD	Absolute percentage difference as defined in Eq. (1)
C_{gr}	Thermal capacitance of grout per unit length (J/mK)
COP	Coefficient of performance
k	Thermal conductivity (W/mK)
$\overset{\Delta}{R}$	Thermal interference coefficient based on the delta network in long-time-step model (mK/W)
$\overset{Y}{R}$	Thermal interference coefficient based on the star network in short-time-step model (mK/W)
tE_{gshpp}	Total energy consumption from GSHP and pump (kWh)
T_b	Temperature (°C)
$T_{fl,1}$, $T_{fl,2}$	Fluid temperature inside the U-tube of borehole (°C)
T_g	Ground temperature (°C)
T_{gr}	Grout temperature (°C)
T_o	Undisturbed ground temperature (°C)
x, *y*	Measurements in the transverse directions of the ground (m)
z	Measurement in the vertical direction of the ground (m)
Δt	Simulation time step (minute)
Subscripts	
bf	Borehole fluid inside U-tube
g	Ground
gr	Grout
i, j, m	Discretisation step of the ground in z-, x- and y-directions
max	Maximum
o	Outlet
Abbreviations	
AC	Air-conditioning
GHE	Ground heat exchanger borefield
GSHP	Ground-source heat pump
LTS	Long-time-step
STS	Short-time-step

Various STS models for the vertical ground exchanger are found in the literature which can be grouped as 2-D and 3-D approaches. For 2-D models, some [5–7] approximated the U-tube by a single tube using the equivalent pipe approach which converted the borehole into a composite cylinder in order to account for the thermal capacitance effects of the grouting, the pipe and the circulating fluid. Others [8,9] evaluated the transient heat transfer inside the borehole based on the exact layout of the pipes. For 3-D models, some [10–13] adopted quasi-3D approach in which the interior of the borehole was not discretised and the heat transfer inside the borehole determined from a thermal resistance and capacitance network. These models employed a cylindrical coordinate system to discretise the ground surrounding the borehole for calculating the conductive heat transfer only. Other 3-D models [14–16] adopted full discretisation both inside and outside the borehole. With very small grid size employed inside the borehole, a very short simulation time step should be used in order to enhance the computational stability which resulted in long simulation time particularly when long-term system simulation was to be performed.

Lee [4] recently proposed a modification of a previous 3-D numerical model developed by Lee and Lam [17] to handle the short-time-step behaviour of the borehole. The new STS model was validated against the test results from Beier [18]. With the avoidance of using very small grids inside the borehole as shown in Fig. 2, a longer simulation time step can be adopted without deterioration of the iteration stability particularly during the early stage of the loading cycle which helps reduce the computation time. Lee [4] also remarked that the borehole performance could differ substantially under an intermittent load as compared to that based on the LTS approach. Besides, the derivation was affected by the type of grout employed. However, same as other studies as listed in [5–16], the main concern was still on the model development. Indeed, very few reported researches could be found which discussed the effect of the borehole short-time-step behaviour on the detailed long-term dynamic simulation of a GSHP system. In particular, the impact of adopting the STS approach on the simulated long-term overall energy consumption of the GSHP system needs further investigation. Hence, in the study, the dynamic performance of a GSHP system based on both the LTS and STS approaches for the boreholes are investigated and compared under the weather conditions of Hong Kong. Attention will also be paid on the effect of the ground and grout thermal conductivities on the system performance derivation under the two modelling approaches for the boreholes, and how the borehole designs can be affected by the adoption of the STS model.

2. System description

2.1. Ground heat exchanger

According to Fig. 2, a 3-D rectangular discretization grid scheme for the ground and the borehole is adopted for both the LTS and STS models according to Lee and Lam [17] and Lee [14]. Here, each borehole is represented by a square column circumscribed by the borehole radius. Finite volume method is employed to calculate the heat transfer with the ground volume. To determine the heat transfer inside the borehole, an equivalent resistance matrix approach is adopted as shown in Fig. 3 for both the LTS and STS models with a single U-tube inside the borehole.

With the LTS model as shown in Fig. 3a, a steady state is assumed inside the borehole which neglects the thermal capacitance effect of the circulating fluid and the grout. Hence, the heat transferred from the circulating fluid inside the borehole is the same as that exchanged through the borehole surface. A delta resistance network is adopted according to Hellstrom [19] with the formulations for the various thermal resistances ($\overset{\Delta}{R}$) also given. For the STS model as shown in Fig. 3b, the thermal capacitance effect of the grout has to be taken into account. Hence, the delta resistance network is transformed to a star network with a hypothetical grout temperature (T_{gr}) calculated according to Lee [4]. The thermal capacitance of the grout (C_{gr}) is then employed to determine the change of T_{gr} within each simulation time step. As a 3-D model, the borehole surface temperature (T_b), fluid temperature inside the U-tube ($T_{fl,1}$ and $T_{fl,2}$) and T_{gr} are assumed to vary along the borehole length.

2.2. Building zone

A reference office building zone of size 14 m (W) × 14 m (D) × 3.6 m (H) as adopted by Fong et al. [20] is employed in this study. The various internal loads are based on the design guidelines from EMSD [21] as summarised in Table 1. The wall-to-window ratio on the four sides of the boundary walls is taken as 2. All occupants are assumed to be seated with very light writing work. The fresh air requirement is 0.008 m^3/s per occupant as specified in EMSD [21].

The respective operating schedules of each type of internal loads also follow those recommended in EMSD [21] as depicted