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Periodic heat flux composite model for borehole heat exchanger and its application

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HIGHLIGHTS

- We present a model of a periodic cylinder heat source in composite media and give its solution in frequency domain.
- A frequency decomposition hybrid algorithm is specially designed for the periodic composite model.
- The equivalent relationship between constant heat flux model and periodic heat flux model is illustrated.
- The periodic model is applied on the data analysis of oscillatory thermal response test.

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ABSTRACT

Most existing borehole heat exchanger models are based on constant heat flux solutions. This paper first proposes a periodic heat flux composite model for a borehole heat exchanger to reproduce the periodic nature of real loads. An explicit analytical solution of a periodic cylinder-source in composite media is derived using a harmonic method. The periodic thermal response factor is defined to characterize the thermal behaviour of a borehole subjected to a periodic heat flux. The periodic thermal responses factors for high- and low-frequency periodic heat flux are dominantly determined by the thermal properties of the content inside the borehole and the ground outside the borehole, respectively. A frequency decomposition hybrid algorithm is specially designed according to the frequency response characteristic of borehole. The proposed periodic heat flux model is verified through an inter-model comparison with existing constant heat flux models and the comparison indicates an equivalent relationship between the two types of models. An annual simulation is performed using the hybrid algorithm and the accuracy of the algorithm is verified. The paper also presents a new method to analyse the data of an oscillatory thermal response test by using the periodic composite model. The effective heat capacities of the ground and grout are estimated. The simulation results of the periodic composite model are in good agreement with the experimental data.

1. Introduction

A ground-coupled heat pump (GCHP) is an economical system that provides heating and cooling to buildings while reducing environmental impact. GCHPs have seen rapid development in recent years. A critical component of the GCHP system is the borehole heat exchanger (BHE), through which the GCHP system rejects heat to or absorbs heat from the ground. The BHE consists of a number of vertical boreholes, each containing one or two U-pipes and filled with grout. A typical vertical borehole is shown in Fig. 1. Modelling heat transfer processes between the fluid circulating in pipes and the ground is a key issue in GCHP applications. Various analytical and numerical models have been put forward for BHE design and research [1]. In this paper we focus on analytical models. The heat transfer process in a borehole is usually separated into two processes: those in the regions inside and outside the borehole, which have different thermal properties. These two heat transfer processes can be explained using classical homogeneous models based on a decoupled approach or composite models based on a coupled approach.

In homogeneous models, the transient thermal responses of the ground regions outside the borehole are evaluated to obtain the temperature of the borehole wall. Three well-known analytical models are currently available for evaluating the heat transfer of the ground region: the infinite line heat source model [2], finite

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Nomenclature

k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
α	thermal diffusivity ($m^2\,s^{-1}$)
ω	frequency (s^{-1})
τ	time (s)
T	excess temperature over the undisturbed ground temperature (K)
r	radial distance from the borehole centre (m)
a	equivalent pipe radius (m)
b	borehole radius (m)
q	heat rate per unit borehole length ($W\,m^{-1}$)
A_1, A_2, B_1, B_2	coefficients
R	thermal resistance ($m\,K\,W^{-1}$)
C	heat capacity per unit borehole length ($J\,m^{-1}\,K^{-1}$)
h	convective heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
c	volumetric heat capacity ($MJ\,m^{-3}\,K^{-1}$)
PG	periodic thermal response factor, the unit of magnitude and angle of PG are $m\,K\,W^{-1}$ per borehole length and rad
$S1, S2$	stage asymptotes

Subscripts

b	borehole
f	fluid
gt	grout
gd	ground
p	pipe
j	region, 1 for inner-layer, 2 for outer-layer
o	outer
i	inner
tm	two-layer media
hm	homogeneous medium
equ	equivalent

line heat source model [3], and infinite cylinder heat source model [4]. In these three models, the heat transfer process outside a borehole is assumed to be based on an internal heat source with constant heat flux embedded in an infinite homogeneous medium. The infinite line heat source model is the simplest model but is a very useful analytical model, particularly for thermal response test (TRT) [5]. The finite line heat source model is suitable for mid- and long-term processes, whereas the infinite line heat source model is only suitable for mid-term processes [6]. The infinite cylinder heat source model involves the complicated calculation of integrating the Bessel function from zero to infinity, but its accuracy is not greater than those of the other two models [7]. In these homogeneous models, the heat transfer process inside the borehole is usually assumed to be in a steady-state. A steady-state equivalent borehole thermal resistance is employed to calculate the temperature difference between the fluid and borehole wall. Several methods have been proposed to estimate the equivalent borehole thermal resistance, such as the multi-pole method [8], equivalent diameter method [9], and shape factor method [10]. Recently, a quasi-three-dimensional steady-state model for the heat transfer process inside the borehole has been developed [11,12]. The temperature of each pipe is individually evaluated along the borehole length by using corresponding thermal resistances of the pipe-to-pipe and pipe-to-borehole walls, rather than the mean temperature of the inlet and outlet pipes which corresponds the total borehole thermal resistance. This method reveals the variation in the vertical fluid temperature and the impact of the thermal interference between U-pipes on heat transfer.

However, to analyse the short-term response of a borehole with a large diameter and heat capacity, the steady-state borehole thermal resistance is less suitable because the thermal inertia inside the borehole is ignored in the calculations. Lamarche [7] compared two classical homogeneous models: the infinite line heat source model and the infinite cylinder heat source model, and discussed their overestimations of the mean fluid temperature due to the simplification of heat transfer inside the borehole.

To avoid employing the frequently-used assumption that the region inside borehole is in a steady-state, several coupled composite models were developed that treat the borehole as a multi-layer composite coaxial cylinder. As the heat capacity inside the borehole is considered, composite models are particularly suitable for short-term response calculation. For example, Li and Lai [13,14] presented a composite line-source model based on Jaeger's solution and provided several analytical solutions for a composite hollow cylinder subjected to various boundary conditions by using Laplace transform method. Recently, Li et al. [6] developed a full-scale model by combining the composite model and classical homogeneous models. Furthermore, a comparative study between composite line-source model and numerical model was carried out by Yang and Li [15]. Javed and Claesson [16] developed a thermal network model for a borehole in the Laplace domain and found the time-domain solution using inversion integrals. Hu et al. [17] developed a composite cylindrical model based on the composite line-source model and cylindrical model, and applied the model to a TRT for an energy pile.

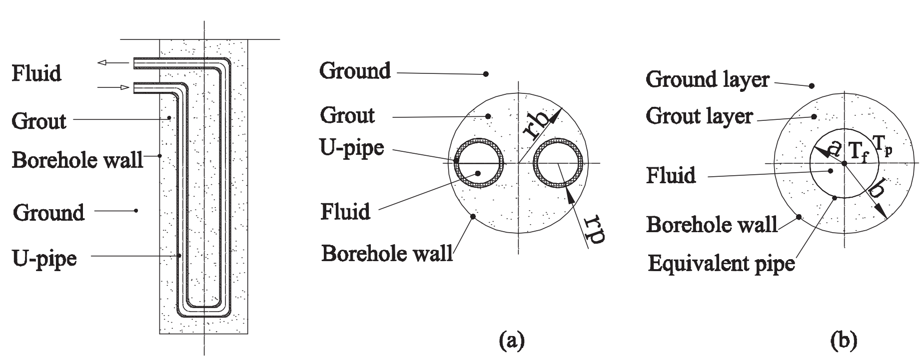

Fig. 1. Scheme of a single U-pipe borehole: (a) geometry of actual borehole (vertical and horizontal section); (b) composite cylinder-source model.