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Heat transfer analysis of ground heat exchangers with inclined boreholes

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Abstract

Consisting of closed-loop of pipes buried in boreholes, ground heat exchangers (GHEs) are devised for extraction or injection of thermal energy from/into the ground. Evolved from the vertical borehole systems, the configuration of inclined boreholes is considered in order to reduce the land plots required to install the GHEs in densely populated areas. A transient three-dimensional heat conduction model has been established and solved analytically to describe the temperature response in the ground caused by a single inclined line source. Heat transfer in the GHEs with multiple boreholes is then studied by superimposition of the temperature excesses resulted from individual boreholes. On this basis, two kinds of representative temperature responses on the borehole wall are defined and discussed. The thermal interference between inclined boreholes is compared with that between vertical ones. The analyses can provide a basic and useful tool for the design and thermal simulation of the GHEs with inclined boreholes.

Keywords: Ground-coupled heat pump; Inclined borehole; Ground heat exchanger; Heat conduction

1. Introduction

Due to reduced energy consumption and maintenance costs, ground-coupled heat pump (GCHP) systems, which use the ground as a heat source/sink, have been gaining increasing popularity for space conditioning in buildings [1,2]. The efficiency of the GCHP systems is inherently higher than that of air source heat pumps because the ground maintains a relatively stable temperature throughout the year. The system is environment-friendly, producing less CO_2 emission than the conventional alternatives. The ground heat exchanger (GHE) is devised for extraction or injection of heat from/into the ground. These systems consist of a sealed loop of pipes, buried in the ground and connected to a heat pump through which water/antifreeze is circulated. The GCHP systems require a certain plot of ground for installing the GHEs, which often becomes a significant restriction against their applications in densely populated cities and towns. The vertical GHE is the most popular design of GCHP systems currently employed, since it requires less ground area than the horizontal trench systems. These boreholes should be separated by certain distances to ensure long term operation of the system. Evolved from the vertical borehole systems, inclined boreholes are considered as a favorable alternative to further reduce the land areas required for the GHEs. The inclined boreholes can alleviate the thermal interference among them in the ground while occupying less land area on the ground surface than the vertical GHEs.

Despite all the advantages of the GCHP systems, commercial growth of the technology has been hindered by higher capital cost of the system, of which a significant

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Nomenclature

a	ground thermal diffusivity ($m^2 s^{-1}$)
B	space between boreholes (m)
H	borehole depth (m)
k	ground thermal conductivity ($W m^{-1} K^{-1}$)
l	variable of the depth of borehole (m)
P	temperature at point P
q_l	heat flow per unit length of borehole ($W m^{-1}$)
r_b	borehole radius (m)
t	temperature (°C)
s	integral parameter in Eq. (1)
t_0	ground far field temperature (°C)
x	axial coordinate (m)
y	axial coordinate (m)
z	axial coordinate (m)

Greek symbols

α	inclined angle of borehole
β	direction angle of borehole
ω	angle in cross-section circle
Θ	dimensionless temperature
τ	time (s)

Subscripts

c	mean temperature of cross-section circle
e	temperature of borehole wall in ground heat exchangers
i	base borehole
j	adjacent borehole
L	mean temperature over borehole depth L
r	representative temperature
ω	temperature at the angle ω of a cross-section

portion is attributed to the GHEs. Thus, it is crucial to work out appropriate and validated tools, by which the thermal behaviour of the GCHP systems can be assessed and then, optimised in technical and economical aspects. However, the thermal analysis on the GHE with inclined boreholes is extremely difficult for engineering applications, for it has to be treated as transient and three-dimensional. Few studies, therefore, have been carried out on the GHE with inclined boreholes due to complexity of its heat transfer analysis, except some qualitative discussions from a Swedish researcher [3] who did some numerical simulation on the heat conduction of inclined boreholes in a specific GHE. However, the numerical solution of transient three-dimensional heat transfer is too computationally intensive to be applied generally in engineering designs.

On the basis of our previous studies on heat transfer of GHEs with vertical boreholes, a model has been established and solved analytically to describe the temperature response in the ground caused by a single inclined line source. Heat transfer in the GHE with multiple boreholes can then be studied by superimposition of the temperature excesses resulted from individual boreholes. The main objective of this paper is to provide a practical algorithm for engineers to design or analyze the GCHPs with inclined boreholes.

2. Heat transfer analysis of an inclined line source of finite length

In order to develop the theoretical model of inclined GHEs, a basic and simple case is to study a single inclined borehole and introduce other complications step by step. In a similar way to the vertical borehole analysis [4–7], the inclined borehole buried in the ground can be approximated as an inclined line source of finite length in a semi-infinite medium. In the model, the ground is regarded as a homogeneous semi-infinite medium; and its thermophysical properties do not change with temperature; the boundary of the medium, i.e. the ground surface, keeps a constant temperature all the time t_0 as its initial one throughout the period concerned.

A diagram of the physical model for a single inclined line source is illustrated in Fig. 1. The coordinate of the top of the line source at the ground surface is (x_0, y_0); its length is H; the inclined angle of the line source with the z-axis is denoted by α; the direction of the inclination is β; and the heating rate per length of the line source is q_l. In order to solve this problem, a virtual line-sink with

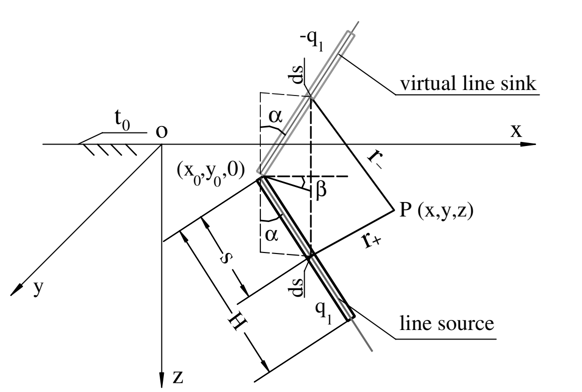

Fig. 1. The geometry of a finite line source in a semi-infinite medium.