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Investigation on heat transfer around buried coils of pile foundation heat exchangers for ground-coupled heat pump applications

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ABSTRACT

The application of ground heat exchangers (GHEs) has attracted much attention for its advantages in terms of energy-saving and emission-reduction. Therefore, it is significant to introduce heat transfer into investigation, the paper illustrated the existing heat transfer models in order to analyze the GHEs with buried coils. Line heat source, cylindrical heat source and ring-coil heat source are introduced step by step. For the present, the borehole GHEs are the mainstream, and in recent years pile foundation GHEs have been followed with interest on account of heat transfer superiority as well as lowering initial cost and saving land area. Concerning that groundwater flow exist in geological stratum sometimes, so that the thermal analysis about heat transfer should be composed of two cases, i.e. models under the condition of both pure conduction and combination that include conduction and advection. It is obvious that ring-coil model is on the verge of actual situation for pile foundation GHEs with buried coils from the academic research perspectives, nevertheless for some engineering computation problems which the result error can be permitted in the certain range, other heat transfer models can be chosen in order to simplify the calculation process.

1. Introduction

With the development of heat transfer research, heat conduction around a buried heat source has been a subject of study from academic as well as engineering perspectives [1]. Some recent focuses on this problem come from the applications of the ground-coupled heat pump (GCHP) systems, which have been used more and more for space cooling or heating of buildings due to its energy-efficient and environment-friendly features [2]. The GCHP system collects renewable ground heat or recovers building heat rejection that accumulated in the ground during the cooling season to heat the buildings in winter [3]. Consisting of a sealed loop of pipe buried in the ground, the ground heat exchangers (GHEs) are devised for extraction or injection of thermal energy from or into the ground[4]. The GHEs with vertical boreholes have been the mainstream for the GCHP systems up to now [5]. The wide application of the GCHP technology, however, has been hindered by its higher initial cost and substantial land areas required to install the borehole GHEs. The foundation piles of buildings have been used as part of the GHEs [6] in recent years in order to reduce the cost and the plot of land for the borehole field. Concerning the so-called "energy pile" technology [7], pipes may be buried in concrete piles in configurations of U-tubes or spiral coils. The spiral coil configuration has the advantage of more heat transfer area in a certain pile and better flow pattern without air chocking in the pipes compared with the serial or parallel U-tubes in the pile. The schematic diagram of a GCHP system with piles and spiral coils in them are illustrated in Fig. 1, the function of 3 and 8 can be converted by four-way valve in summer and in winter.

The work reported here tries to study the fundamental problem of heat transfer around buried coils in a more comprehensive and detailed way in view of their application in thermal analysis of the pile foundation GHEs as well as in other potential engineering problems. For application of the GCHP technology, it is vital to model the heat transfer of GHEs for the sake of proper design and energy analysis of the systems [8]. Whenever possible, it is often desirable to found out analytical solutions of physical models, because the explicit solutions are helpful to understand and simulate engineering problems for their simplicity and clarity as well as for their convenience of computation. During evolution of the modeling on the heat transfer of the GHEs, basic simple cases were studied first, the complications have been introduced by degrees to obtain an embedded understanding of the complex process. Following such a strategy, a few existing models and their analytical solutions are summed up, and new models with increasing sophistication are presented in a progressive way in this paper. The fundamental task for modeling the heat transfer of the GHEs is to

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Nomenclature

a	thermal diffusivity ($m^2\ s^{-1}$)
b	coil pitch (m)
c	specific heat ($J\ kg^{-1}\ K^{-1}$)
Fo	Fourier number
h_1, h_2	depth (m)
H	dimensionless depth
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
q	heating rate (W)
q_l	heating rate per length of source ($W\ m^{-1}$)
Q	instant heat pulse (J)
R	distance (m)
r	radial coordinate (m)
r_0	cylinder radius (m)
T	temperature in moving coordinates (K)
t	temperature (K)
t_0	initial temperature (K)
u	speed in x-direction ($m^{-1}s$)
U	equivalent speed ($m^{-1}s$)
V	velocity ($m^{-1}s$)
x,y,z	Cartesian coordinates (m)

Greek symbols

θ	temperature excess (K)
ρ	density ($kg\ m^{-3}$)
ξ,η,ζ	moving coordinates
τ	time (s)
φ	angular coordinate (rad)
ψ	integration variable

Subscripts

a	advection
c	conduction
f	finite length
i	infinite length
w	water
1	line source
2	cylindrical source
3	ring-coil source

Superscripts

'	coordinates and time for sources

grasp the heat dissipation process around a single borehole or pile. Heat transfer of multiple boreholes or piles can then be analyzed by the superposition principle.

Advancing from our previous studies on the borehole [9] and pile GHEs, this paper presents more sophisticated ones which take into account the impact of the GHEs geometry as well as the groundwater movement on the heat transfer of the buried coils. According to their heat transfer mechanism assumed, the models discussed in this paper are composed of two groups, i.e. the heat conduction models which assume conduction to be the only mechanism for heat dissipation from the source, and the combined models which consider both the conduction and water advection through the porous medium. The heat source of the buried coils is simplified into different shapes with varying fidelity from the simplest line source to the ring-coils.At the same time, all the models are studied on the premise of both the infinite-length and finite-length sources. For the finite-length sources, it consider the impacts of ground surface and limited length of borehole or pile GHEs, especially for their long-term operations, the axis of these models is supposed to be perpendicular to the ground surface, stretching from depth h_1 to depth h_2, different shapes of finite-length sources, which are used to represent the buried coils, are shown in Fig. 2.

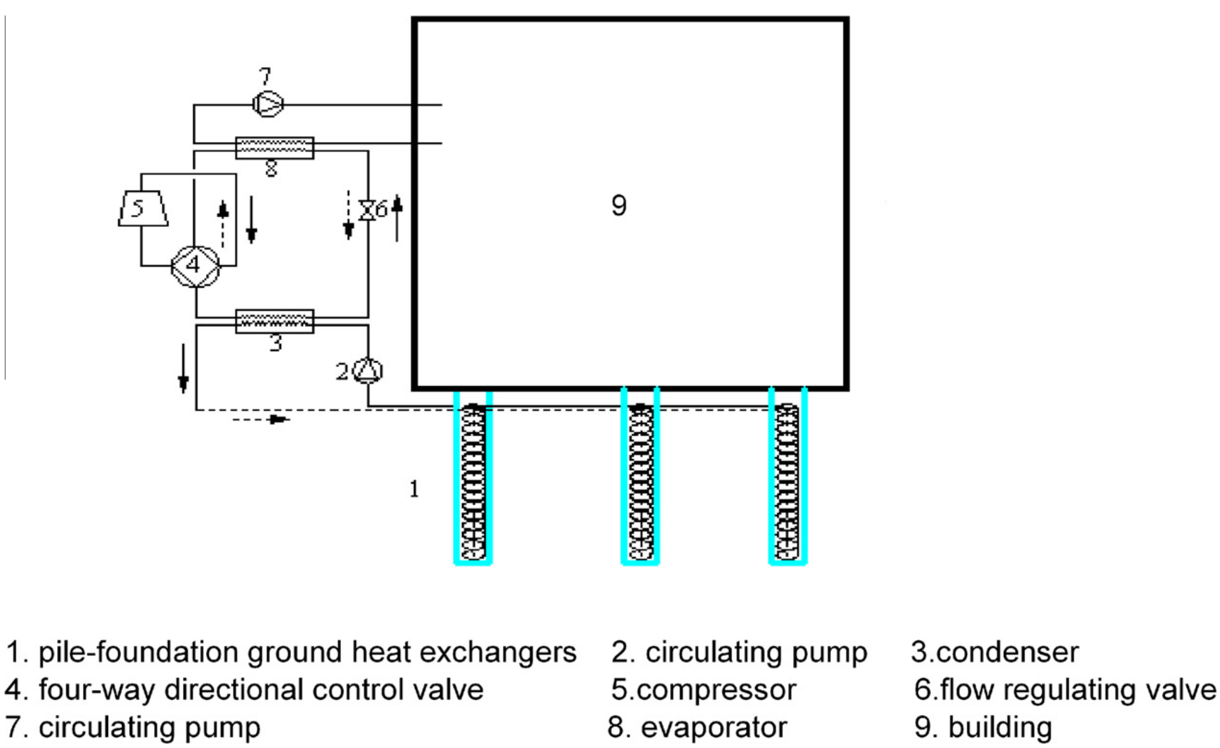

Fig. 1. Schematic diagram of a GCHP system with energy piles.