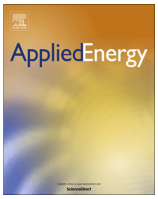
Applied Energy xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy



Numerical and analytical analysis of groundwater influence on the pile geothermal heat exchanger with cast-in spiral coils ☆

Deqi Wang [a], Lin Lu [a,*], Wenke Zhang [a], Ping Cui [b,c]

[a] *Renewable Energy Research Group, The Hong Kong Polytechnic University, Hong Kong, China*
[b] *Key Laboratory of Renewable Energy Utilization Technologies in Buildings, Ministry of Education, Jinan, China*
[c] *School of Thermal Energy Engineering, Shandong Jianzhu University, Jinan, China*

HIGHLIGHTS

- We have established a 3-D simulation model of pile geothermal heat exchangers.
- The effect of groundwater flow is investigated based on the simulation model.
- An improved analytical model was developed based on the simulation model.

ARTICLE INFO

Article history:
Received 6 November 2014
Received in revised form 8 April 2015
Accepted 9 April 2015
Available online xxxx

Keywords:
Ground-coupled heat pump
Energy pile
Groundwater flow

ABSTRACT

The effect of groundwater flow on the heat transfer performance of pile geothermal heat exchanger (PGHE) with spiral coils was simulated by a 3-D simulation model using finite element method. Different groundwater flow conditions were taken into consideration by applying different hydraulic gradients. Based on the moving ring-coils model and simulation results, an improved analytical model is developed by introducing a key parameter of effective dimensionless velocity. The calculation results shows that the improved model can better describe the heat transfer performance of PGHE with spiral coils. Both numerical and analytical results indicated that the groundwater flow has an enhancing effect on the heat transfer performance of the PGHE with spiral coils and can accelerate the heat transfer process into stability. When the groundwater flow mean velocity equal to 6.98E−06 m/s, the amount of heat exchange is higher than 26.72% than it of non-advection situation. The improved ring-coils analytical model can be used as a reliable tool for the design of pile geothermal heat exchanger with spiral coils under groundwater flow.

1. Introduction

Nowadays, the ground-source heat pump (GSHP) technology has been extensively used in residential buildings and commercial buildings, because of its high efficiency and environmental friendliness [1–3]. Generally, a typical GSHP system, shown in Fig. 1, consists of several components, such as geothermal heat exchangers (GHEs), heat pump units and heating/cooling terminal units The GHEs are usually constructed of high density polyethene pipes, through which water or anti-freezing liquid is circulated to inject heat into soil in summer and extract heat from soil in winter. Vertical borehole [4] is the most common GHEs layout in a GSHP system, but the high installation and drilling cost of borehole GHEs hinder its wider application. To overcome this problem, a new vertical GHEs system, pile geothermal heat exchangers (PGHEs) [5–7], are applied to residential and commercial buildings. Piles not only support the building structure, but also serves as heat exchangers. It is a combination of building piles and GHEs and can also be called as “Energy Pile”.

The performance of a GSHP system generally depends on arrangement types (single U-tube, double U-tube or spiral tube) and buried forms (horizontal type or vertical type) of GHEs [8], hence the heat transfer evaluation of GHEs is important and essential for the system design and operation [9]. The heat transfer research of GHEs has been going on for more than a century. Kelvin’s infinite line source (ILS) [10] model, one classical model,

---

☆ This article is based on a short proceedings paper in Energy Procedia Volume 161 (2014). It has been substantially modified and extended, and has been subject to the normal peer review and revision process of the journal. This paper is included in the Special Issue of ICAE2014 edited by Prof. J Yan, Prof. DJ Lee, Prof. SK Chou, and Prof. U Desideri.

* Corresponding author. Tel.: +852 3400 3596; fax: +852 2765 7198.
E-mail address: vivien.lu@polyu.edu.hk (L. Lu).

http://dx.doi.org/10.1016/j.apenergy.2015.04.037

Nomenclature

x,y,z	Cartesian coordinate (m)
X,Y,Z	dimensionless Cartesian coordinate
h_1, h_2	depth (m)
H	dimensionless depth
b	coils pitch
r_0	coil radius (m)
r	radial coordinate (m)
R	distance to heat source (m)
R_p	pile radius (m)
k	thermal conductivity (W $\mathrm{m^{-1}\,K^{-1}}$)
a	thermal diffusivity ($\mathrm{m^2\,s^{-1}}$)
ρ	density (kg $\mathrm{m^{-3}}$)
c	specific heat (J $\mathrm{kg^{-1}\,K^{-1}}$)
q_l	heating rate per length of source (W $\mathrm{m^{-1}}$)
t_0	initial temperature (K)
t	temperature (K)
u	speed in x-direction (m $\mathrm{s^{-1}}$)
L	dimensionless velocity
L_{eff}	effective dimensionless velocity
Greek symbols	
Θ	dimensionless excess temperature
θ	excess temperature
Fo	Fourier number
τ	time (s)
φ	angular coordinate (rad)
ξ, η, μ	moving Cartesian coordinates
Superscript	
$'$	integration parameter

evaluate the heat transfer performance of vertical borehole GHEs by considering borehole as an infinite line source. Due to the simplification of infinite length, large calculation error exists in short/long time evaluation. Then, several improved models have been established, such as finite line source (FLS), the “hollow” cylindrical-source model and “solid” cylindrical source model [11–13]. To better estimate the heat transfer process of PGHEs, different analytical methods has been proposed, such as ring-coils source model [14] and composite cylindrical-source model [15]. These analytical models are established based on ideal simplifications, such as zero volume heat source, homogenous heat transfer medium and no-groundwater advection interference. A simulation model, proposed by Zarrella et al., successfully takes the thermal short-circuit process of PGHE and the difference of thermal properties between pile and ground into consideration [16,17], but also fail to consider the influence of groundwater flow. However, many researchers point out that the groundwater flow do enhance the heat transfer performance of GHEs [18–20].

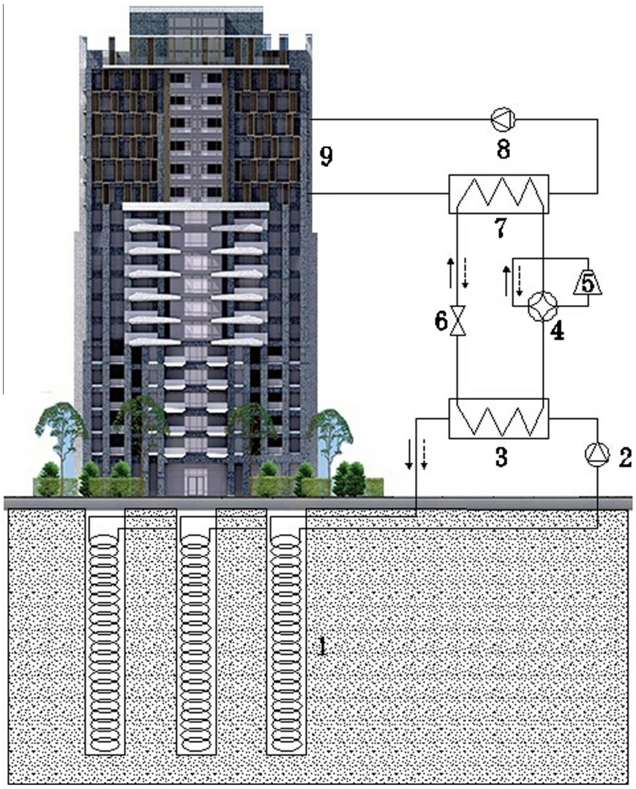


Fig. 1. Schematic diagram of a GCHP system with PGHEs (1. PGHE with spiral coils; 2, 8 circulation pump; 3, 7 condenser and evaporator; 4 reversing valve; 5 compressor; 6 expansion valve; 9 terminal units).

If groundwater flow exists in the installation area, water flow will transport heat released by GHEs from upstream to downstream. This effect of borehole GHEs has been widely discussed, but few studies have focused on PGHEs. Based on infinite moving line source model, Sutton et al. [21] established an analytical solution to evaluate the effects of groundwater flow of borehole GHEs. A similar approach was also presented by Diao et al. [22]. They concluded that the groundwater flow can provide an additional sink/source to greatly change the temperature of borehole and soil ground. Taking the axial effects into consideration, a moving finite line source model is established by Giraldo et al. [23]. The analysis results suggested that the increasing velocity of groundwater flow can accelerate the heat transfer process into steady stage and decrease the temperature plume. Signorelli et al. [24] developed a 3-D simulation model based on the FRACTure code for single U-tube borehole GHEs system. A 24% of heat transfer enhancement has been found when ground flow velocity is 1 m/day.

Previous studies of groundwater advection are mainly focus on borehole GHEs, little attention has been paid to research on PGHEs considering the groundwater flow, especially for PGHE with spiral coils. Compared with borehole GHEs, PGHEs are larger in radial dimension and more complicated in pipe structure. The length–width ratio of vertical U-tube is usually larger than 800. But, for PGHE with spiral coils, in general, the diameter is larger than 0.8 m and its depth is shorter. Thus, the heat transfer process under groundwater flow of PGHEs with spiral coils is quite different from that of a borehole GHEs. Based on moving spiral coil source model [25], the effect of groundwater on PGHEs in lone-term operation was investigated by Go et al. [26]. Comparison results between moving infinite line source model and moving spiral coil source model suggested there is no great difference in long-term operation. However, this study failed to evaluate the heat transfer performance of PGHEs in short-term operation and have not provided a method to predict temperature response of pipe wall, which plays a key role in GSHP design.

Hence, the objective of this study is to develop an improved analytical model to better estimate the heat transfer process of PGHE with spiral coils under the disturbance of groundwater flow, especially the temperature rise of pipe wall. Besides, based on finite element methods, a 3-D simulation model is established to

Please cite this article in press as: Wang D et al. Numerical and analytical analysis of groundwater influence on the pile geothermal heat exchanger with cast-in spiral coils. Appl Energy (2015), http://dx.doi.org/10.1016/j.apenergy.2015.04.037