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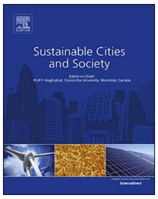

Effects of load optimization and geometric arrangement on the thermal performance of borehole heat exchanger fields

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ABSTRACT

In this work, the effects of load optimization and geometric arrangement on borehole heat exchanger (BHE) fields have been studied. A ground source heat pump (GSHP) system model is introduced, and validated against both the experimental and modelling results from literature. Based on the GSHP system model, optimization strategies are applied on the BHE fields. The results show that, compared with the single BHE, thermal interaction in BHE fields is obvious when the pipe spacing is limited and the building load is unbalanced. Improving the side BHEs' load helps in enhancing the performance of BHE fields, whereas slightly inferior results are achieved by improving the middle BHEs' load. When the groundwater flow is considered, optimized-load BHE fields can keep the maximum outlet fluid temperature 7.99% lower than that for the BHE fields with equal loads. For the geometric arrangement, increasing the number of side BHEs and downstream BHEs contributes to the spreading of released heat, which improves the efficiency of the system.

1. Introduction

Compared with the conventional heating and cooling methods, ground source heat pump (GSHP) systems are an environment friendly alternative (Capozza, Carli, & Zarrella, 2012; Yuan, Cao, Wang, & Sun, 2016). These systems use the relatively constant ground temperature as the heat reservoir, and therefore, can offer higher energy efficiency for air-conditioning and lower greenhouse gas emissions to benefit the ecosystem. Generally, GSHP systems can be divided into two categories, namely the open and closed loop systems. Based on the configuration of ground heat exchangers, closed loop systems can be further classified into horizontal and vertical systems (Gabrielli & Bottarelli, 2016; Florides, Theofanous, Iosif-Stylianou, & Tassou, 2013). Compared with the horizontal type, vertical systems are used more widely, especially in the crowded urban areas due to their higher efficiency and lower land use (Carotenuto, Ciccolella, Massarotti, & Mauro, 2016).

Generally, the energy demand is higher than what a single borehole heat exchanger (BHE) can provide. As a result, multiple BHEs are often arranged as BHE fields (Emad Dehkordi, Schincariol, & Olofsson, 2015; Geng, Li, Han, Lian, & Zhang, 2016; Kurevija, Macenić, & Borović, 2017). A common approach is to arrange the BHEs in a rectangle to optimize the land use (Bayer, 2015; Zhang, Yang, Lu, & Fang, 2015). As the land area is limited, thermal interaction among the BHEs becomes inevitable. However, in the current planning practices, interactions between adjacent BHEs are rarely considered (Koohi-Fayegh & Rosen, 2012). In recent years, more and more researchers have started paying attention to this discrepancy. However, consistent conclusions have not been reached so far. As an example, when suitable pipe spacing of BHE fields is considered, Signorelli, Kohl, and Rybach (2004) recommend a distance of 7–8 m, which is considered adequate to avoid substantial interactions among neighboring installations. However, in practical application, even smaller distances (around 5 m) have been observed (Fossa & Minchio, 2013; Gultekin, Aydin, & Sisman, 2016). Lazzari et al. (Lazzari, Priarone, & Zanchini, 2010) studied the long-term performance of double U-tube BHE fields under six-time periodic heat loads using finite element simulations. Different distances between the adjacent BHEs in BHE fields were examined. However, the effect of groundwater flow was ignored in their study. Choi et al. (Choi, Park, & Lee, 2013) investigated the influence of groundwater flow on the performance of various types of BHE arrays using a two-dimensional coupled heat conduction-advection model. It turned out that, when Peclet number was less than 0.05, the influence of groundwater flow on the performance of the system can be neglected, regardless of the array type and the flow direction.

Abbreviations: BHE, borehole heat exchanger; COP, coefficient of performance; GSHP, ground source heat pump
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Nomenclature

A_0	Highest magnitude of the load (W)
A_p	Cross-sectional area of the pipe (m^2)
a	Coefficient of COP function
a_{eff}	Effective ground thermal diffusivity [$m^2\ s^{-1}$]
a_s	Soil thermal diffusivity [$m^2\ s^{-1}$]
b	Coefficient of COP function
$C_{p,f}$	Circulating fluid heat capacity ($J\ kg^{-1}\ °C^{-1}$)
$C_{p,w}$	Groundwater heat capacity ($J\ kg^{-1}\ °C^{-1}$)
c	Coefficient of COP function
d_h	Hydraulic pipe diameter (m)
f_D	Darcy friction factor
h_{eff}	Equivalent convective coefficient of pipe wall ($W\ m^{-2}\ °C^{-1}$)
h_i	Convection coefficient inside pipe ($W\ m^{-2}\ °C^{-1}$)
k_{eff}	Effective ground thermal conductivity ($W\ m^{-1}\ °C^{-1}$)
k_f	Fluid thermal conductivity ($W\ m^{-1}\ °C^{-1}$)
k_p	Pipe thermal conductivity ($W\ m^{-1}\ °C^{-1}$)
Nu	Nusselt number
n	Total number of BHEs
Pr	Prandtl number
Q_{BHE}	Thermal load of BHE (W)
$Q_{Building}$	Thermal load of building (W)
Q_{wall}	Heat flux through pipe wall ($W\ m^{-2}$)
Re	Reynolds number
r_i	Pipe internal radius (m)
r_o	Pipe external radius (m)
T_{amp}	Amplitude of annual temperature (°C)
T_{ext}	Temperature outside the pipe (°C)
T_f	Temperature of circulating fluid (°C)
$T_{f,i}$	Inlet fluid temperature (°C)
$T_{f,o}$	Outlet fluid temperature (°C)
T_{mean}	Annual average temperature (°C)
T_s	Soil temperature (°C)
t	Time (s)
t_0	Period of one year (s)
t_c	Coldest day of a year (s)
u	Circulating fluid velocity ($m\ s^{-1}$)
u_w	Groundwater flow velocity ($m\ s^{-1}$)
V_f	Volumetric flow rate ($m^3\ s^{-1}$)

Greek letters

ρ_f	Fluid density ($kg\ m^{-3}$)
ρ_w	Groundwater density ($kg\ m^{-3}$)
$(\rho c_p)_{eff}$	Effective volumetric heat capacity ($J\ m^{-3}\ °C^{-1}$)
Φ	Phase angle (rad)
ω	Angular frequency of annual temperature variations (1/s)

BHEs are commonly operated for long time periods. When the heat injection and heat extraction are not seasonally balanced, accumulation of ground heat will occur, especially in the interior of BHE fields, which will cause a decline in the heat pump's operational efficiency (Law & Dworkin, 2016; Zhou, Cui, Li, & Liu, 2016). Several approaches including seasonal thermal energy storage and hybrid GSHP system, have been applied to solve this problem. Seasonal thermal energy storage involves the storage of heat or cold for several months. Therefore, the energy demand can be balanced between the summer and winter seasons (Verma & Murugesan, 2017; Templeton, Hassani, & Ghoreishi-Madiseh, 2016). Hybrid systems use auxiliary equipment, such as cooling towers or solar collectors, which deal with the same problem (Sayyadi & Nejatolahi, 2011; You, Wu, Shi, Wang, & Li, 2016). So far, several researchers have studied the applications of these two methods. Although promising, these systems are characterized by an increased complexity when run and maintained (Qi, Gao, Liu, Yan, & Spitler, 2014). Besides, it is believed that the two methods are economical only when thermal imbalance is seriously large.

When thermal imbalance is small, optimizing energy extraction strategies (Jalaluddin, 2012; Retkowski, Ziefle, & Thöming, 2015) and geometric arrangement (Beck, Bayer, de Paly, Hecht-Méndez, & Zell, 2013; Hecht-Méndez, de Paly, Beck, & Bayer, 2013) of BHE fields can obtain better results. Through optimization, the discharged heat/cold can easily be transferred to surrounding soil, which improves the operational characteristics of BHE fields. de Paly et al. (2012) developed an optimization method to impose variable energy load on BHEs. The results show that optimized BHE fields can keep the maximum temperature change in the subsurface lower than that observed with equal load for all BHEs. Recently, a zoning operational strategy, in which only the central part of the BHE fields runs during the low load season, was proposed by Yu et al. (2016) to alleviate the accumulation of ground heat. Compared with the optimization of energy extraction, most researchers have focused their attention on the geometric arrangement. Kurevija, Vulin, and Krapec (2012)) simulated the long-term operation of a GSHP system with multiple boreholes in various geometrical arrays, and investigated the influence of borehole spacing on the required borehole length. Furthermore, Cimmino and Bernier (2014) studied the effect of BHE positioning for a given land surface area on the circulating fluid and ground temperature. In their work, the performances of BHE fields with equal and unequal borehole spacing were compared.

BHEs are always utilized as part of GSHP systems (Koohi-Fayegh & Rosen, 2014; Yang, Chen, Shi, & Zhang, 2013). Therefore, after the addition of a heat pump, the thermal load of BHEs depends on both the building load and the heat pump's coefficient of performance (COP) (Capozza, Zarrella, & Carli, 2015). In the heating mode, the thermal load of BHEs is lower than that of the building, whereas in the in cooling mode, the thermal load of BHEs is higher. Besides, the heat pump's COP is not constant, and depends on factors including the condition of the heat pump, and the condensation and evaporation temperatures. In some recent studies, most authors have presented optimization methods by minimizing the maximal ground temperature changes. However, in these studies, the influence of heat transfer inside the borehole, building load and heat pump's COP are neglected. It would have been more accurate, had these factors been taken into consideration.

In the current work, firstly, a GSHP system model is introduced, which consists of a BHE model and a heat pump model. The model considers the geothermal gradients, groundwater flow, and the dynamically-changing loads due to the COP characteristics of the heat pump. In addition, thermal interactions among BHEs are also analyzed. The outlet fluid temperature is regarded as the optimization target to study the effects of load distribution and geometric arrangement on the performance of BHE fields. The results provide useful information for better design and operation of BHE fields.

2. Methodology

GSHP systems mainly consist of two parts, namely the BHEs and the heat pumps. The optimization objective of BHE fields is to minimize the outlet fluid temperature (in cooling mode), while maximizing the heat pump's COP. The heat transfer processes considered include two parts: Heat transfer within the BHEs and heat transfer in the surrounding ground (Go, Lee, Yoon, & Kim, 2016; Han & Yu, 2016). The coupling of heat pump and BHEs is achieved through the inlet and outlet fluid temperatures. Inlet fluid temperature is calculated using the outlet fluid temperature from the preceding time step under BHE load, which is the