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Thermal performance analysis of multiple borehole heat exchangers

Ahmet Gultekin, Murat Aydin, Altug Sisman *

Istanbul Technical University, Energy Institute, 34469 Istanbul, Turkey

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ABSTRACT

Effect of borehole spacing on Heat Transfer Rate per unit borehole length (unit HTR) is computationally investigated for multiple Borehole Heat Exchangers (BHE). Experimentally verified computational model is used to analyze different configurations consisting of various number of BHE. To determine the performance loss due to mutual thermal interactions of BHE, the averaged unit HTR value of the most critical borehole in each configuration is compared with that of a single borehole alone for various borehole spacing and operation durations of 1800 and 2400 h. Effect of thermal conductivity of ground on the relation between performance loss and borehole spacing is also examined. Furthermore, variations of total HTR values of a borehole field with borehole spacing are compared with each other for different configurations. It is seen that 4.5 m spacing is enough to keep the total performance losses less than 10% even for 2400 h non-stop operation. An analytical formulation is proposed for total HTR value which depends on thermal interaction coefficient (δ) as well as spacing and number of BHE (N). Dependence of δ on N is also examined for different operation durations. Variations of dimensionless HTR value with borehole spacing are analyzed for different values of N. The results can be used during the engineering design stages of a BHE field to predict the variation of total HTR value of the field with borehole spacing and number of boreholes.

1. Introduction

Because of high efficiency and low operational cost, Ground Source Heat Pump (GSHP) systems are becoming increasingly popular due to growing energy costs. A GSHP system has three main parts: heat pump unit, ground heat exchangers, and indoor heating/cooling units. Ground heat exchangers are embedded to the ground to obtain heat exchange between ground and working fluid through the pipes, and they can be either horizontal or vertical [1]. The vertical ground heat exchangers, generally called Borehole Heat Exchangers (BHE), are usually composed of a drilled hole with one or multi polyethylene U-tubes and grout. Time dependent heat transfer analysis of BHE is an essential effort to calculate the required total length of BHE [2,3]. To investigate BHE's heat transfer rates, some analytical and numerical models have been proposed in literature, these models are summarized in a comprehensive review [4]. There are so many parameters which affect the thermal performance of even a single BHE such as; thermal properties of ground and grout, shank spaces between inlet and outlet pipes, the depth of the BHE, flow velocity of the working fluid and operation duration [5,6].

In large-scale applications of GSHP, there is a requirement to use more than one BHE. In this case, thermal interaction between BHE has an adverse impact on total performance of BHE field [7,8]. Therefore, allocation of large-scale BHE in application field and determination of the optimal borehole spacing become important issues [9,10]. Comprehensive reviews about the recent studies on research challenges in modeling and optimal design of BHE can be found in Refs. [11,12].

Koohi-Fayegh et al. have been developed analytical and numerical models to analyze the thermal interaction between two boreholes, by assuming constant heat flux from boreholes [13,14]. The results show that borehole spacing, heat flux from borehole and operation duration affect directly the intensity of thermal interaction between BHE. The long-term performance of BHE field with different heat loads and the life time of BHE fields have been predicted by considering the lowest allowed temperature for working fluid were studied with negligible ground flow by Priarone et al. and by Lazzari et al. [15,16], with groundwater flow by Fujii et al. and Zanchini et al. [9,17]. The effects of allocation of BHE on long term performance has been studied for regular allocation by Zanchini and Lazzari [18], and for irregular one by Teza et al. [19].

It is important to secure the thermal balance of ground to sustain a long-term GSHP operation [20]. Simulated variations and

* Corresponding author.
E-mail address: sismanal@itu.edu.tr (A. Sisman).

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Nomenclature

c_p	specific heat capacity at constant pressure (J/(kg K))
d	borehole spacing (m)
$\dot{q}'$	unit heat transfer rate (W/m)
r	radial distance (m)
R_d	radius of domain (m)
T	temperature (°C)
t	time (s or h)
Greek letters	
λ	thermal conductivity (W/(m K))
ρ	density (kg m^{-3})
δ	thermal interaction coefficient (m)
Subscripts	
ave	average
b	borehole
∞	undisturbed, far field
gr	ground
gt	grout
PE	polyethylene
Abbreviations	
BHE	borehole heat exchangers
CB	critical borehole
GSHP	ground source heat pump
HTR	heat transfer rate
MAPE	mean absolute percentage error
PL	performance loss (%)
SB	single borehole
TRT	thermal response test

distributions of temperature around BHE have been compared between GSHP systems with and without water heater for dominant cooling load by Li et al. [21]. Yu et al. suggested that using two different operation modes (one for heating and one for cooling due to dehumidification) in winter season could keep the ground temperature more stable compared with the conventional operations in a large BHE field [22]. By this method, performance loss of BHE due to thermal interaction could be minimize, and BHE spacing could be taken as short as 4–5 m in Shangai.

For seasonal heating and cooling periods, strategic optimization of BHE field has been studied by Bayer et al. [23,24]. They numerically showed that removing the critical BHE one by one in a field reduces the investment cost while its effect on total performance is limited.

Most of the studies are based on constant heat flux assumption for each borehole. In real working conditions, however, working fluid is distributed to all boreholes at nearly the same temperature. Therefore, it is clear that heat flux or similarly unit HTR values of BHE are not the same in multiple borehole applications since each BHE has different thermal interaction value as a result of its geometrical position in the field. Consequently, a constant temperature model is also needed for a comprehensive analysis of BHE performance loss.

In the application field, boreholes thermally interact with each other. Nevertheless, some boreholes have higher thermal interaction with others and they can be called as the critical boreholes (CB). Temperature of ground surrounding CB approaches to the temperature of working fluid more rapidly due to its strong thermal interaction with other BHE. Consequently, CB has the smallest unit HTR value, which means the highest performance loss. In other words, these boreholes will have bigger performance loss than those of others. This performance loss changes mainly with number of boreholes, borehole spacing, allocation geometry, duration of operation and thermal properties of ground. Moreover, variation of total HTR value of BHE field with spacing and operation duration provides critical information for engineering design. Therefore, during the design process, taking the CB's performance and total HTR value of BHE field into account leads to more reliable system designs.

The aim of this study is to investigate the effects of different parameters (such as spacing and number of BHE, operation duration and thermal conductivity of ground) on the performance loss of CB and total HTR value of BHE field. First, 2D finite element model is built and experimentally verified. Then four different configurations consisting of 2, 3, 5 and 9 boreholes are computationally studied. Averaged unit HTR value of the most CB in each configuration is compared with that of a single BHE alone (SB) to determine the performance loss of CB. Operation durations of 1800 h (75 days) and 2400 h (100 days) are considered for a heating season [25]. Variations of performance loss of CB and total HTR value of BHE field with both spacing and operation duration are analyzed. During these investigations, temperature distributions around CB as well as effect of thermal conductivity of ground on performance loss are also examined.

2. Computational model

A typical single U-tube borehole is shown in Fig. 1. Model consists of three domains; namely polyethylene pipes, grout and ground.

The following assumptions are made:

- Initial and undisturbed uniform ground temperature is 17 °C.
- Grout and ground properties are isotropic and homogeneous.
- Groundwater movement is insignificant.
- There is no contact resistance between borehole and ground.
- Mean temperature of working fluid in PE tubes is nearly constant.
- Temperature variation along the vertical axis is negligible since the difference between input and output temperatures is very

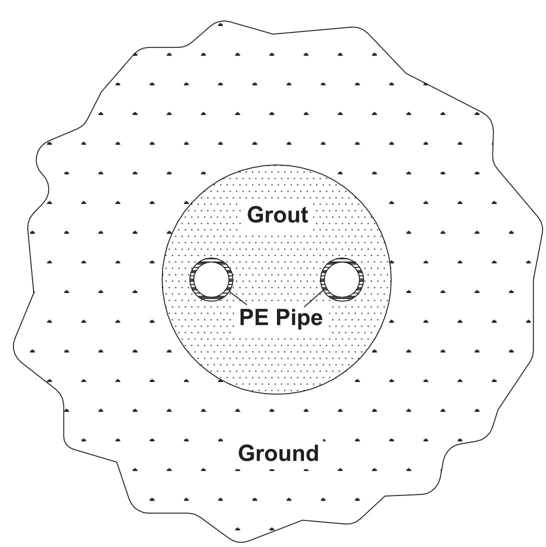

Fig. 1. Sketch of a single U-tube borehole cross section.