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An investigation on thermal interaction coefficient for multiple borehole heat exchangers

Ahmet Gultekin, Murat Aydin, Altug Sisman*

Istanbul Technical University, Energy Institute, Istanbul, 34469, Turkey

Abstract

In large scale applications of ground source heat pump systems, multiple Borehole Heat Exchangers (BHE) are used and thermal interactions between BHE becomes an important issue. Thermal Interaction Coefficient (TIC) is a critical parameter to represent the dependency of total heat transfer ratio of multiple BHE on their spacing. For given thermal properties of application field, TIC depends on number of BHE, allocation geometry and operation duration. In this study, a rectangular allocation field having 64 BHE is considered. Dependencies of total heat transfer ratio (HTR) of the field and TIC on aspect ratios of allocation geometry are computationally investigated. Furthermore, the effects of number of BHE and operation duration on TIC are examined. The results can be used during the engineering design of a BHE field to maximize the time averaged total HTR value of a given application field.

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Keywords: Borehole configuration; thermal interaction coefficient; optimal borehole spacing.

1. Introduction

In recent years, Ground Source Heat Pumps (GSHPs), which use ground as a thermal energy storage, have received a significant attention due to their high energy efficiency, low emissions and low operation cost for heating and cooling applications [1-4]. A GSHP system consists of three main parts: heat pump unit, ground heat exchangers, and indoor heating/cooling units. To provide heat exchange between ground and working fluid through the pipes, ground heat exchangers are inserted into the ground either horizontally or vertically [5]. The vertical ground heat exchangers, commonly named borehole heat exchangers (BHE), are usually installed by using single or multi polyethylene U-tubes.

There are some parameters which affect the thermal performance of BHE such as; thermal properties of ground and grout, shank spaces between pipes, BHE depth, velocity of working fluid and operation duration [6-9]. There is a requirement to install more than one BHE in most of GSHP applications. In this case, thermal interaction between BHE has an adverse effect on total performance of BHE field [10, 11]. This adverse effect will become more vital with increasing operation duration [12]. Therefore, allocation of multiple BHE in an application field and borehole spacing between them become a key issue [13-15]. Different methods for the design of BHE field are available and the well-known method is ASHRAE's analytical method by Kavanaugh and Rafferty [16]. The sizing equation for the total BHE length is simply based on steady state heat transfer equation with artificially time dependent thermal resistance of ground. The ASHRAE method includes an important parameter called as Temperature Penalty (T_P) which is accounted for considering the thermal

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* Corresponding author. Tel.: +90 212 285 3939; fax: +90 212 285 38 84.
E-mail address: sismanal@itu.edu.tr

interactions between BHE for a given operating time. There are different contributions on temperature penalty approach [17-22]. Fossa and Rolando [22] have improved the ASHRAE method and examined the improved method for extensive set of 240 BHE configurations (including square, rectangular, in-line, L-shaped, U and O-shaped arrangements).

To investigate the thermal interaction and regeneration of multiple BHE, a mixed numerical/analytical method has been developed [23]. They considered a square 4x4 BHE field and classified the BHEs into three types as side, center and corner boreholes. Then, time dependencies of thermal performance loss and ground temperature regeneration are examined for various intermittent operation ratios and borehole spacing. The results show that the thermal performance loss increases with operation duration and decreases with increasing intermittent operation ratio and borehole spacing. Law et al. have numerically studied the effects of borehole configuration and thermal interaction with long term ground temperature modelling of GSHP [24]. The results indicate that 2x8 configuration is more suitable in comparison with 4x4 one when thermal performance is considered.

In our earlier work, we have computationally investigated the thermal performance loss of BHE due to thermal interaction in a borehole field for different number of BHE [25]. We considered four different configurations and studied the variation of average total HTR value with borehole spacing. We also proposed an analytical equation to predict total HTR value of a BHE field as a function of number of BHE, HTR value per unit depth of a single BHE, BHE spacing and the thermal interaction coefficient (TIC). TIC represents the magnitude of thermal interaction between multiple BHE. It has been shown that the proposed equation is in a very good agreement with the results of numerical simulations. In comparison with the temperature penalty method, the proposed simple equation provides a quick and overall prediction as long as TIC value is known. TIC depends on arrangement of BHE, operational duration as well as thermal properties of ground.

The purpose of this study is to examine the effects of aspect ratio of allocation geometry on the thermal performance and interaction coefficient for a BHE field. The considered borehole field consists of 64 BHE with allocation geometries having different aspect ratios (AR). Four different aspect ratios, such as 8x8 (AR=1), 4x16 (AR=1/4), 2x32 (AR=1/16), 1x64 (AR=1/64), are computationally studied. Operation durations of 1800 h (75 days) and 2400 h (100 days) are chosen for a heating period as the worst case scenarios in a season, [26]. Variations of time averaged thermal performance with aspect ratio of allocation geometry and spacing for multiple BHE are examined. Effect of aspect ratio on thermal interaction coefficient (δ) is analyzed. A saturation behavior is observed for the dependency of δ on AR. It is seen that highly anisometric allocation geometry is the best one since δ and so the performance loss of BHE reaches to its minimum value in that case. In other words, for a given number of BHE, N, a rectangular arrangement of 1xN provides the highest total HTR value whereas the square one of $\sqrt{N}x\sqrt{N}$ has the minimum value. Furthermore, variation of δ with number of BHE (up to 400) for a square arrangement (AR=1) are studied for non-stop operation durations of 1800 h and 2400 h.

2. Computational Model

A sketch of a typical borehole with a single U-tube is shown in Fig.1. It consists of three domains; polyethylene pipes, grout and ground. The properties of grout and ground are assumed to be homogeneous and isotropic. Initial and undisturbed ground temperature is chosen as 17ºC. Only conductive heat transfer is considered by assuming insignificant groundwater movement. Also, temperature variation along the vertical axis is unimportant since the difference between input and output temperatures is very minor. This condition allows to ease 3D heat conduction problem into 2D one.

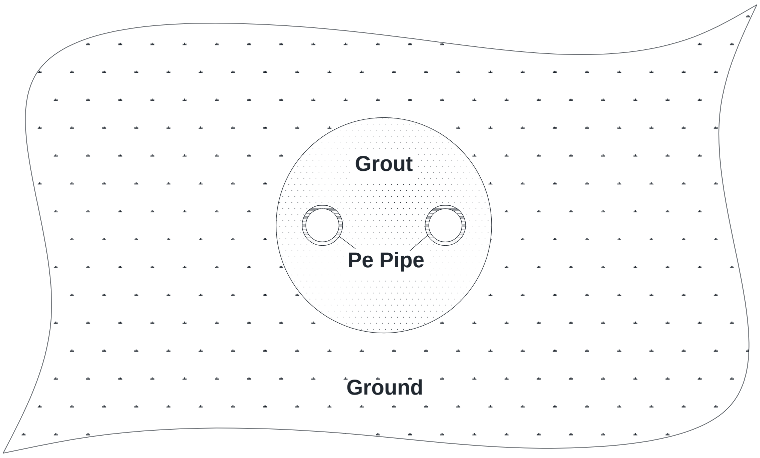

Fig. 1. Sketch of a single U-tube borehole cross section and its surrounding.

The values of geometrical and material parameters as well as working conditions used in the model are given in Table 1 and these parameters are taken from the Ref. [25]. Only domain size of ground is chosen large enough and different for each simulation to ensure that temperature distribution around BHE is not effected by domain size. Constant mean fluid temperature ($T_{ave} = 2\,^{o}\mathrm{C}$) for the inner surface of PE pipes and constant undisturbed ground temperature ($T_{\infty} = 17\,^{o}\mathrm{C}$) for far field are applied as boundary conditions.

By using the following fundamental equation, time dependent 2D heat conduction problem in BHE field is numerically solved by considering conductive heat transfer in PE pipes, grout and ground for each BHE simultaneously in COMSOL Multiphysics environment [27],

$$\rho c_p \frac{\partial T}{\partial t} = \lambda \nabla^2 T \tag{1}$$

where λ, ρ and c_p are thermal conductivity, mass density and specific heat capacity at constant pressure of a considered domain respectively. After solution of time dependent temperature field from Eq. (1), time variation of unit HTR value is calculated by

$$\dot{q}' = -2\pi r_b \lambda_{gr}^{eff} \left.\frac{\partial T}{\partial r}\right|_{r=r_b} \tag{2}$$

where r_b is the radius of BHE and λ_{gr}^{eff} is the effective thermal conductivity of ground. Since ground is a mixture of different materials as well as possible large or small cavities, effective quantities should be considered to represent the properties of this mixture.

Allocation of BHE becomes significant issue to minimize thermal interaction loss in large GSHP applications. A rectangular BHE field is considered as allocation of *K*x*L* BHE where *K* and *L* represent the number of BHE in transverse and longitudinal directions of the field respectively. Aspect ratio can be defined as *K/L*.

Table 1. Geometrical parameters, properties of solid materials and working conditions. [25]

Symbol	Value	Quantity
Geometrical data of U-tube		
r_i	13.3	Internal radius of PE tube [mm]
r_e	16	External radius of PE tube [mm]
r_b	88	Radius of borehole [mm]

Geometrical data of BHE field		
B	1, 2,…,10	Distance between boreholes [m]
l_W	30+K*d/2	Domain width [m]
l_L	30+L*d/2	Domain length [m]
Thermal properties of PE		
λ_{PE}	0.38	Thermal conductivity [W $m^{-1}K^{-1}$]
c_{PE}	1900	Specific heat capacity [$Jkg^{-1}K^{-1}$]
ρ_{PE}	958	Density [kg m^{-3}]
Thermal properties of grout		
λ_{gt}	0.85	Thermal conductivity [W $m^{-1}K^{-1}$]
c_{gt}	900	Specific heat capacity [$Jkg^{-1}K^{-1}$]
ρ_{gt}	1500	Density [kg m^{-3}]
Thermal properties of ground		
$\lambda_{gr,eff.}$	3.1	Thermal conductivity [W $m^{-1}K^{-1}$]
c_{gr}	800	Specific heat capacity [$Jkg^{-1}K^{-1}$]
ρ_{gr}	2130	Density [kg m^{-3}]
Working conditions		
T_{ave}	2	Average fluid temperature [ºC]
T_∞	17	Undisturbed ground temperature [ºC]

To reduce the simulation work and solution time, symmetric nature of the problem is considered and symmetry boundary conditions are applied. As shown in Fig.2, for 8x8, 4x16, 2x32 configurations, a quarter of BHE field is chosen to model. Symmetry boundary conditions are applied on both bottom and left sides while it is applied only on left side for 1x64 configuration. Similarly, undisturbed temperature conditions are applied as boundary condition for the other sides of ground domain. The domain size of ground is chosen big enough for each case to ensure that temperature distribution around BHE is not effected by the domain size.

To verify the number of grid independence of the results, different number of triangular mesh elements have been used for each configuration. It is found that optimum number of triangular elements varies from 2585 to 211855 depending on number of BHE and aspect ratio.

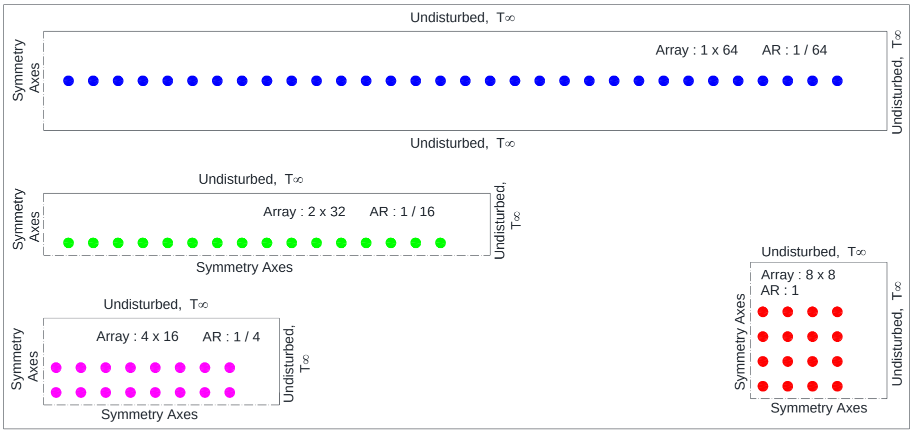

Fig. 2. Sketches of different configurations of 64 BHE with different aspect ratios (AR) and boundary conditions.

3. Results and Discussions

Fig. 3 shows temperature distributions around boreholes for different configurations after 2400 h non-stop operation when borehole spacing is 3 m. The figures indicate that magnitude of thermal interaction and temperature drop around BHE reaches to a minimum for highly anisometric allocation geometry. It is clearly seen that the lowest thermal interaction occurs for a rectangular arrangement of 1x64 while 8x8 arrangement has the highest interaction.

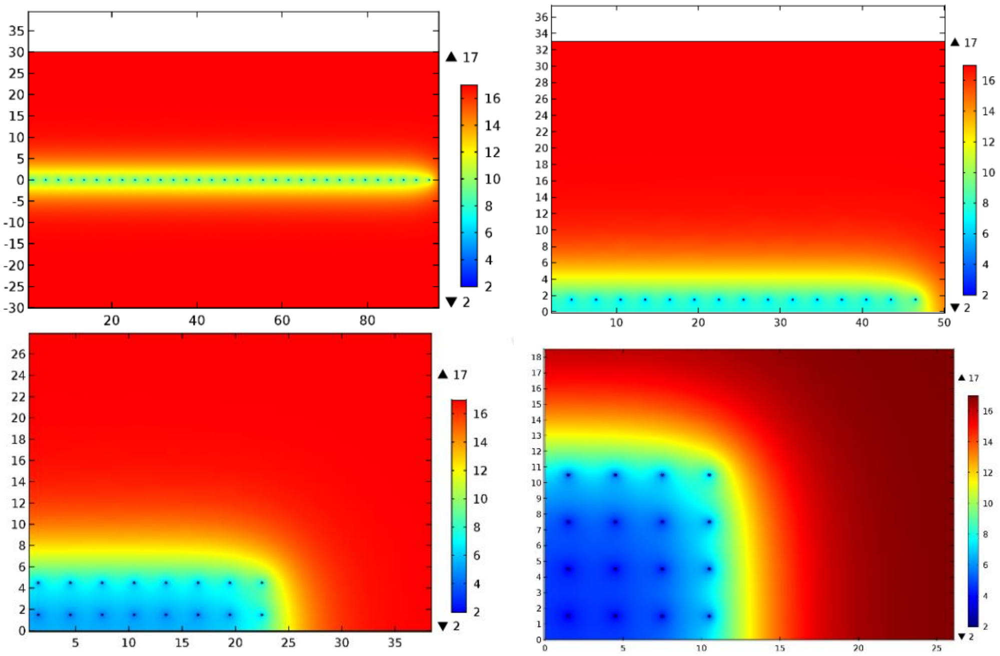

Fig. 3. Temperature distributions around BHE for different aspect ratios after 2400 hours non-stop operation when borehole spacing is 3 m.

Total HTR value of a BHE field is one of the most significant quantities for the engineering design procedure. Hence, allocation of BHEs is vital to maximize total unit HTR value. When borehole spacing goes to infinity, each borehole behaves like a single borehole alone, so total HTR value goes to the multiplication of $\bar{q}'_{SB}$ with number of boreholes, N. On the other hand, when borehole spacing goes to zero, all boreholes behave like a single borehole, so total HTR value goes to $\bar{q}'_{SB}$. Therefore, Gultekin et al. have proposed the following expression to predict the dependency of time averaged total unit HTR value of a vertical BHE field on BHE spacing [25].

$$\bar{q}'_{tot} = \sum_{i=1}^{N} \bar{q}'_i = \bar{q}'_{SB} N \left[1 - \frac{N-1}{N} \boldsymbol{exp}(-B/\delta)\right] \tag{3}$$

where N is number of boreholes, B is borehole spacing, δ is thermal interaction coefficient and $\bar{q}'_{SB}$ is the averaged unit HTR value over the operation duration of a single borehole. When the average fluid temperature is 2°C for 2400 h non-stop operation, $\bar{q}'_{SB}$ is 41.8 W/m.

The variation of total unit HTR value with borehole spacing for different aspect ratios of allocation geometry is shown in Fig.4. The solid lines symbolize the results of Eq. (3) while the marks symbolize the deterministic computational results. It is clearly seen that they are in very good agreement and they have the smallest values when AR equals to unity and their values rise for smaller AR. Moreover, total unit HTR values increase when borehole spacing increases because of weaker thermal interactions as expected.

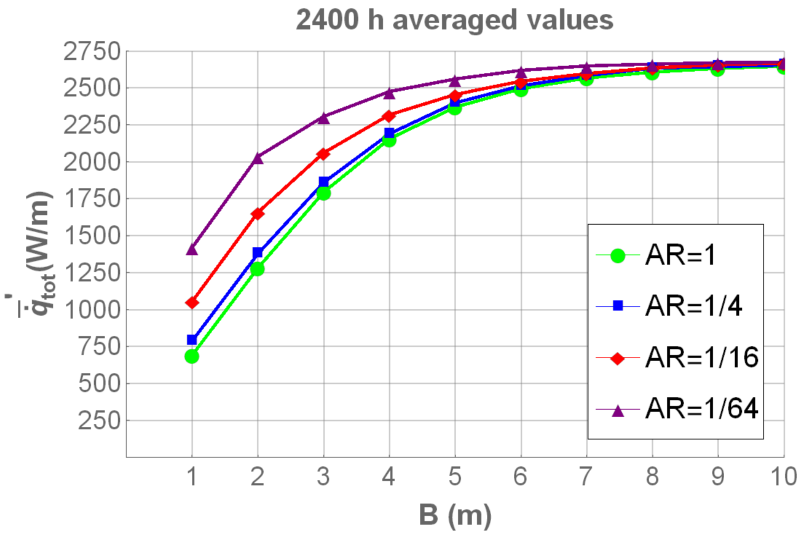

Fig. 4. Variation of total unit HTR with borehole spacing for different aspect ratios in case of 2400 h non-stop operation duration.

Fig. 5 shows the variation of total unit HTR value with aspect ratios for different borehole spacing. It is seen that aspect ratio dependency of total unit HTR value becomes more significant in case of shorter BHE spacing. In other words, it is important to choose smaller aspect ratio if BHE spacing has to be small. On the other hand, in case of large application field possibility, longer spacing opportunity for BHE field makes the aspect ratio dependency negligible. The figure also show that thermal interaction increases with increasing aspect ratio and causes lower total unit HTR values. This behavior can be seen more clearly when borehole spacing is very close.

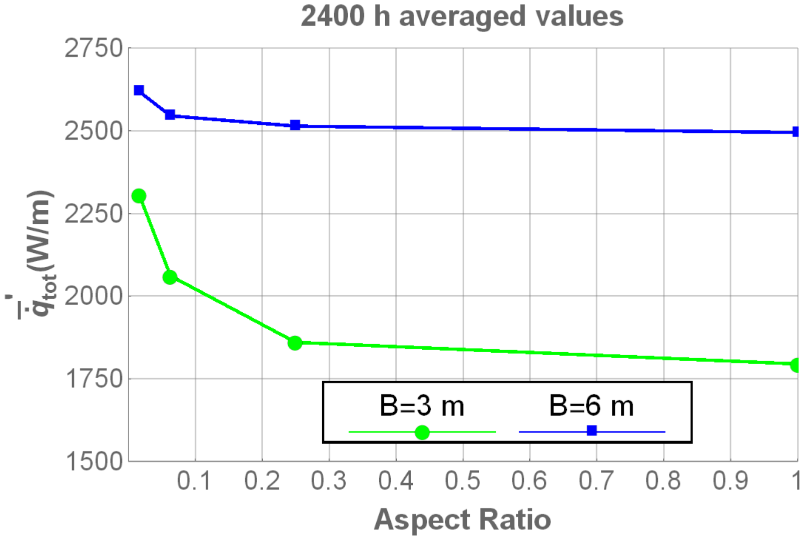

Fig. 5. Variation of total unit HTR value with aspect ratio for different borehole spacing.

The computational results for the variation of δ with aspect ratio are shown in Fig. 6 for different operational durations. Thermal interaction coefficient increases with increasing aspect ratio. The arrangement of $\sqrt{N}$x$\sqrt{N}$ leads to maximum thermal interaction while the minimum interaction occurs for 1xN. One of the important factors which affect the values of thermal interaction coefficient is operation duration. For AR=1, for example, δ is 2.3 m and 2.7 m for 1800 h and 2400 h non-stop operations respectively.

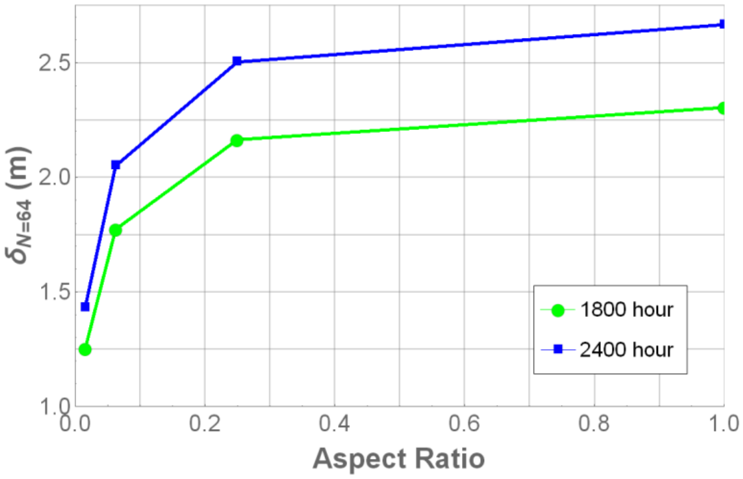

Fig. 6. Variation of thermal interaction coefficient with aspect ratio for non-stop operation durations of 1800 h and 2400 h.

Isometric allocation geometry (AR=1) is the worst one since the performance loss of BHE field reaches to its maximum value due to the highest value of thermal interaction coefficient. For AR=1, the variation of thermal interaction coefficient with number of BHE is examined and the results are given in Fig.7 for non-stop operation durations of 1800 h and 2400 h. Number of BHE dependency of δ can be approximated by the following expression

$$\delta(N) = C\boldsymbol{exp}(-D/N) \tag{4}$$

where *C* and *D* are constants. It is seen that there is a saturation of δ for large number of BHE and dependency of this saturation on operation duration seems to be weak although the saturation values are different. Minimum and maximum values of δ are obtained when N goes to unity and infinity respectively. Therefore relative change in δ can be expressed as

$$\mathrm{R}_{\delta} = \frac{\delta(N)-\delta(N{=}1)}{\delta(N\rightarrow\infty)-\delta(N{=}1)} = \frac{\boldsymbol{exp}(-D/N)-\boldsymbol{exp}(-D)}{1-\boldsymbol{exp}(-D)} \tag{5}$$

Number of BHE corresponding to the relative change of R_{δ} can be calculated from Eq.(5) as

$$N = -\frac{D}{\boldsymbol{ln}[R_{\delta}+\boldsymbol{exp}(-D)(1-R_{\delta})]} \tag{6}$$

The critical number of BHE corresponding to the saturation of δ can then be found as follows by considering R_{δ} □ 1 and $\boldsymbol{exp}(D) \gg 1$ in Eq.(6)

$$N_c \cong \frac{D}{(1-R_{\delta})} \tag{7}$$

For 95% and %98 saturation, N_c are approximately 72 and 180 for 1800 h operation duration and 73 and 183 for 2400 h operation respectively. Therefore, thermal interaction coefficient can be approximated by $\delta \cong C$ for number of BHE greater than N_c and its dependency on N can be neglected. On the other hand, in case of $N << N_c$, a strong dependency of δ on N is observed.

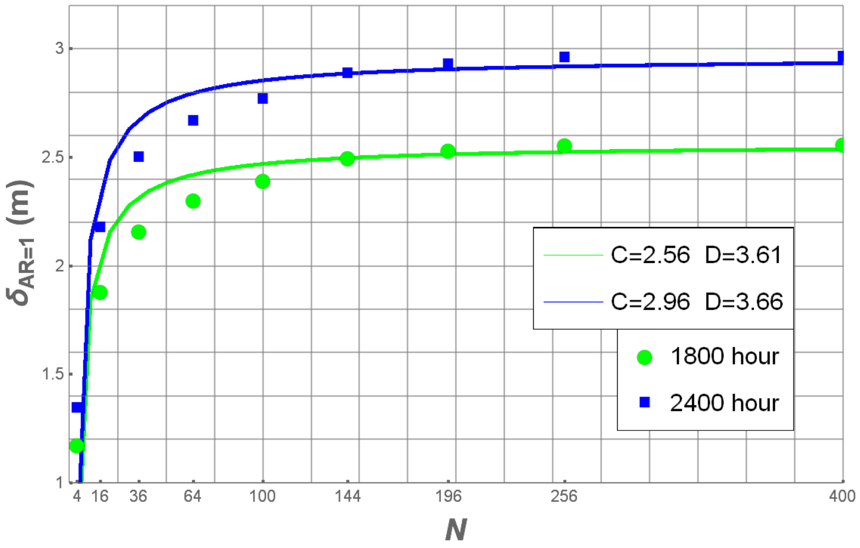

Fig. 7. Variation of thermal interaction coefficient with number of boreholes when AR=1 for non-stop operation durations of 1800 h and 2400 h. Symbols represent computationally calculated values while solid curves represent fitted exponential expressions for these data.

4. Conclusions

For the dependency of total unit HTR value of a BHE field on BHE spacing, the previously proposed analytical equation based on thermal interaction coefficient, δ, is considered [25]. When this simple equation is compared with the temperature penalty approach, it provides a quick and overall prediction as long as dependencies of δ on AR, N and operation duration are known. The effects of aspect ratio of allocation geometry on δ and thermal performance of a BHE field are investigated. An experimentally verified numerical model [25] is used in this study. For a BHE field, variations of total unit HTR value with aspect ratio of allocation geometry and spacing are examined. The analysis showed that highly anisometric allocation geometry is the best one since the performance loss of BHE reaches to its minimum value due to the lowest value of thermal interaction coefficient, δ. It is seen that there is a saturation of aspect ratio dependency of δ when AR approximately greater than 1/3. Similar saturation is observed for number of BHE dependency of δ. It is shown that saturation appears when $N>N_c$ for AR=1. In other words, number of BHE dependency of δ is important only in case of $N<<N_c$. The proposed formulas and the results can be helpful for the design stage of a BHE field to maximize total thermal performance and minimize field allocation.

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Nomenclature

B	Borehole spacing (m)
c_p	Specific heat capacity at constant pressure (J/(kg K))
K	number of BHE in transverse direction
L	number of BHE in longitudinal direction
l	Length (m)
N	Number of BHE
$\dot{q}'$	Unit heat transfer rate (W/m)
r	Radial distance (m)
T	Temperature (°C)
t	Time (s or h)

Greek Letters

λ	Thermal conductivity (W/(mK))
ρ	Density (kg/m^3)
δ	Thermal interaction coefficient (m)

Subscripts

ave	Average
b	Borehole
c	Critical
gr	Ground
gt	Grout
L	Length
P	Penalty
PE	Polyethylene
SB	Single borehole
W	Width
∞	Undisturbed, far field

Abbreviations

BHE	Borehole Heat Exchangers
GSHP	Ground Source Heat Pump
HTR	Heat Transfer Rate