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Numerical Simulation of the Temperature Field of Borehole Heat Exchanger Arrays Under Different Arrangement Configurations[#]

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ABSTRACT

Vertical borehole heat exchangers are the main method for utilizing shallow geothermal energy and are more suitable for small to medium-sized cities and town buildings with both heating and cooling demands. The imbalance of heating and cooling loads is a common issue during the operation of borehole heat exchanger systems, therefore, an appropriate arrangement of borehole heat exchanger arrays is crucial for alleviating thermal accumulation of the system. This paper constructs a heat transfer model for borehole heat exchanger arrays and selects Harbin, Tianjin, and Guangzhou as typical cities to discuss the differences in heating and cooling load ratios. Based on the analytical solution of the ground temperature field under dynamic loads, the study investigates the impact on the ground temperature field of sequentially arranged ground heat exchangers within square and rectangular areas. The results show that for a group of 16 borehole heat exchangers arranged in a 45 m × 45 m square configuration, after 10 years of system operation, the ground temperature in Guangzhou, which has a higher cooling demand, increased by 15.45°C; in Harbin, which has a higher heating demand, the ground temperature decreased by 18.55°C; and in Tianjin, where the heating and cooling loads are more balanced, the ground temperature fluctuated by about 2.06°C, showing relatively minor changes. When the borehole heat exchanger group is arranged in a rectangular configuration, the ground temperature in Guangzhou increased by 12.50°C, in Harbin, the ground temperature decreased by 15.45°C, and in Tianjin, the ground temperature changed by 1.55°C, which is significantly less than the changes observed with the square configuration. Therefore, the rectangular arrangement of ground heat exchangers is superior to the square arrangement. The research results can provide theoretical guidance for the arrangement of borehole heat exchangers in practical engineering applications.

Keywords: ground source heat pump system, borehole heat exchanger array, arrangement configurations

NONMENCLATURE

Abbreviations	
BHE	borehole heat exchanger
GSHPs	ground source heat pump systems
Symbols	
A	Year amplitude
B	deviation or average value within a period
t	operation time, day
q	heat flux at the borehole wall, W • m^{-1}
c_p	specific heat, J/kg°C
λ	thermal conductivity, W/(m • K)
K_1	a first-order modified Bessel function of the second kind
K_0	a zero-order modified Bessel function of the second kind
s	a complex
a	thermal diffusivity, m^2/s
r_w	borehole radius, mm
T_0	the original formation temperature, °C
i	well number
r_i	the distance from the spatial point to the i-th buried pipe, mm
(x, y)	coordinates of a point in the region
(x_i, y_i)	the position coordinates of the i-th BHE
ω	the frequency in a yearly cycle
φ	the phase angle
r	density, kg/m^3
ϑ	excess formation temperature, °C

1. INTRODUCTION

As a significant consumer of fossil fuels, China's commitment to the world "Dual Carbon" targets has presented both opportunities and challenges for the development and utilization of renewable energy. China has ranked first in the world in the geothermal direct utilization for many years, with shallow geothermal energy utilization accounting for 64% [1].

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Compare to air-source heat pumps, ground-source heat pump systems (GSHPs) exhibit higher performance coefficients and operational stability. However, in practical projects, it has been found that GSHP systems commonly experience thermal imbalance. This issue arises because the arrangement of the buried group pipes does not fully account for the uneven heating and cooling loads of buildings in some certain areas, directly affecting the long-term stable operation of the system. This paper proposes a method that can quickly and conveniently calculate the temperature of the stratum, thereby optimizing the arrangement of the buried pipe groups to minimize thermal imbalance effects as much as possible.

In the calculation of the temperature field of buried pipes, most numerical simulations are conducted using finite volume and finite difference methods (commercial software such as ANSYS and TRNSYS). However, proficiency in the software requires a certain level of expertise, and the simulation process can be time-consuming, posing significant inconvenience for engineering applications.Theoretical methods commonly used in the calculation of heat transfer models for a single buried pipe include an infinite line-source model [2], the infinite cylindrical model considering the influence of wellbore diameter [3] , and finite line or cylindrical models considering the effect of borehole depth [4]. To study the heat transfer effects among the buried pipes, Eskilson proposed dimensionless g functions [4], and Bernier et al. [5] utilized g functions with the principle of linear superposition to propose a method for calculating heat interference in the BHE array under the infinite cylindrical source model. Marcotte et al. [6] combined the principle of linear superposition, time convolution, and fast Fourier transform methods to propose a method for calculating formation temperature that can couple with “hourly” level variations in surface heat loads. In most analytical models, BHE has been treated as infinite line heat sources, infinite cylindrical heat sources, finite line heat sources, or finite column heat sources. The combination of line heat source g functions with the principle of linear superposition is a common method for solving the temperature field of BHEs under dynamic heat load. However, it has the following issues: the g function is based on the line-source model and does not consider the impact of the wellbore inner diameter. When the heat load varies significantly over time, it requires step g-functions with shorter intervals for different startup times to meet the calculation accuracy, consequently increasing the computational complexity.

Li et al.[7] proposed a simplified analytical algorithm for calculating the formation temperature of BHEs under dynamic heat load. By applying the Fourier transform, this method approximates any dynamic load curve as a superposition of multiple periodic functions. Compared to existing analytical solutions, this method offers higher calculation accuracy, greater speed and convenience, making it suitable for calculating the formation temperature distribution in the BHE array under dynamic load in practical engineering.

The optimization of BHEs mainly focuses on the arrangement configurations of the BHE arrays. Bayer et al. [8] established an iterative procedure to optimize the combination of seasonal heating and cooling load for individual buried tube loads, discussing the maximum number of BHEs that can be reduced without incurring significant losses in efficiency. Chen et al. [9] established a numerical analysis model for groups BHEs to study the impact of load ratio, borehole configuration, and other factors. They pointed out that irrespective of rectangular or square configurations, the unevenness of the temperature field in the borehole array first increases and then decreases as the size of the borehole field expands.

This paper establishes a heat transfer model for the BHE array based on our existing analytical solution of the formation temperature distribution under the dynamic heat load of the BHE for a single BHE. The formation temperature distributions of the BHE arrays in three cities: Guangzhou, Tianjin, and Harbin, considering their different cooling and heating loads are calculated. The study investigates the thermal interaction between BHEs and the distribution of formation temperature under different pipe configurations, offering theoretical guidance for the optimization of BHE arrays arrangement configurations.

2. MODEL

2.1 *Establishment of BHE arrays heat transfer model*

Considering that buried pipes within a certain range will mutually influence each other, the formation temperature field for a group of buried pipes can be viewed as the superposition of the formation temperature of single buried pipes, as illustrated in Figure 1. This range is referred to as the thermal disturbance radius, defined as the area where the temperature difference from the original formation temperature exceeds 0.3°C.

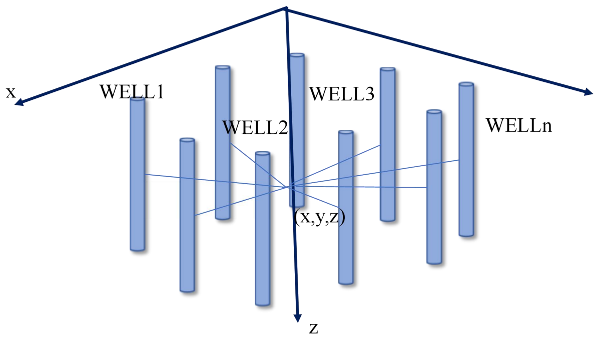


Fig. 1 Illustration of the superposition effect of the formation temperature distribution of the BHE arrays.

The following assumptions are as follows to simplify the model:

1. The radial heat conduction in the cylinder is axially symmetric.
2. Initial temperature of the formation is constant and uniform.
3. Groundwater seepage is ignored, and the formation properties are isotropic and constant.
4. The heat flux density on the wellbore wall varies sinusoidally or sinusoidally with time and can be expressed in the form of a sine function: $q(\mathrm{t}) = A \sin(\omega t + \phi)$.

Thus the temperature at a point (x, y) in the formation outside the BHEs at time *t* is represented as:

$$T(x,y,t)=T_0(x,y,t)+\sum_{i=1}^{n1}\theta_i(r_i,t)\quad i=1,2,3\cdots n \tag{1}$$

Based on the analytical solution of the formation temperature distribution under dynamic heat load of BHE proposed by Li et al.(2023), The excess temperature θ is expressed as:

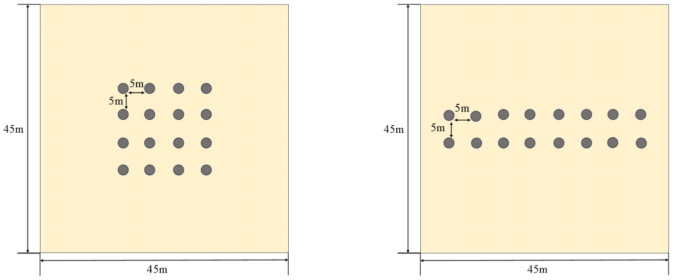
$$\theta(r_i,t)=T(x,y,t)-T_\infty \tag{2}$$

The excess formation temperature is shown in Eq.(3)

$$\theta(r_i,t)=\frac{1}{2\pi R_w\lambda}\frac{1}{2\pi i}\int_{s-i\infty}^{s+i\infty}\frac{K_0(\varepsilon r_i)}{\varepsilon K_1(\varepsilon R_w)}\left(A\frac{s\sin\varphi+w\cos\varphi}{s^2+w^2}+B\frac{1}{s}\right)e^{st} \tag{3}$$

2.2 *Simulation of formation temperature distribution under different arrangement configurations of BHE arrays*

The pipe spacing of 5 m is commonly used in the practical engineering of BHEs. Therefore, this paper discusses the changes in the formation temperature field in three cities with representative hot and cold load ratios—Harbin, Tianjin and Guangzhou, three cities with representative cold and heat load ratios, under the condition of a 5 m pipe spacing. Within an area of 45 m × 45 m, 16 boreholes are arranged in square and rectangular arrays with 5 m pipe spacing in each of the three cities. The arrangement configurations of the BHEs are shown in Fig.2.



(a)square array (b)rectangular array

Fig. 2 Schematics of different BHE arrays

The parameters used for the simulation are shown in Table 1.

Table 1. Parameters given in the simulation

Parameters	Value
λ_s (W/(m·K))	3.5
(ρcp)s($\mathrm{J\cdot m^{-3}\cdot K^{-1}}$)	2.16×10^6
r_w (m)	0.055

To observe significant changes in the formation temperature field, the simulation duration is set to 10 years. The buried pipe system begins operation from the cooling season of the first year, and the changes in the formation temperature field after 10 years of system operation are analyzed.

As mentioned above, this paper selects Harbin, Tianjin, and Guangzhou with representative cold and heat load ratios. Harbin, a cold region, primarily has a heating load; Tianjin, with balanced cooling and heating loads; and Guangzhou, a hot region, primarily has a cooling load. By analyzing the environmental temperature variations in these three cities, the total periodic power per meter at the buried pipe wall for each city can be calculated as follows.

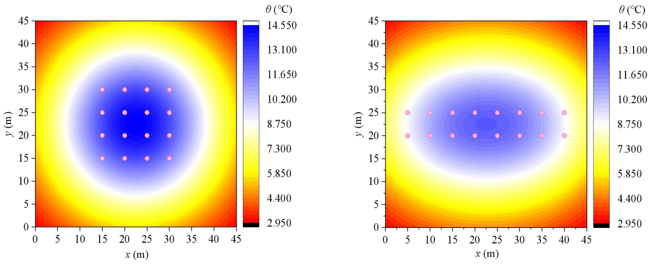
$$q_{\mathrm{gz}}(t)=\begin{cases} q=50\sin\left(\frac{\pi}{6}t\right) & 0\le t< 6\mathrm{month}\\ q=0 & 6\le t<8\mathrm{month}\\ q=10\sin\left(\frac{\pi}{2}t+\pi\right) & 8\le t<10\mathrm{month}\\ q=0 & 10\le t<12\mathrm{month}\end{cases} \tag{4}$$

$$q_{\mathrm{tj}}(t)=\begin{cases} q=30\sin\left(\dfrac{\pi}{4}t\right) & 0\le t<4\text{month} \\ q=0 & 4\le t<6\text{month} \\ q=30\sin\left(\dfrac{\pi}{4}t-\dfrac{\pi}{2}\right) & 6\le t<10\text{month} \\ q=0 & 10\le t<12\text{month} \end{cases} \tag{5}$$

$$q_{\mathrm{hb}}(t)=\begin{cases} q=10\sin\left(\dfrac{\pi}{2}t\right) & 0\le t<2\text{month} \\ q=0 & 2\le t<4\text{month} \\ q=50\sin\left(\dfrac{\pi}{6}t+\dfrac{\pi}{3}\right) & 4\le t<10\text{month} \\ q=0 & 10\le t<12\text{month} \end{cases} \tag{6}$$

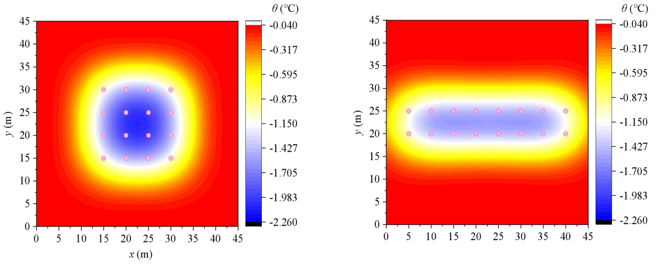
3. RESULTS AND DISCUSSION

The formation temperature distribution after 10 years of operation of two configurations in the above three cities was calculated, as shown in Figure 3.



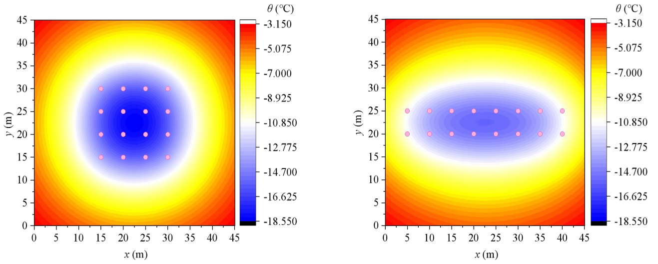
(a) Guangzhou square configuration

(b) Guangzhou rectangular configuration



(c) Tianjin square configuration

(d) Tianjin rectangular configuration



(e)Harbin square configuration

(f)Harbin rectangular configuration

Fig. 3 Formation temperature distribution after 10 years of operation of BHEs under different arrangement configurations.

It can be seen from Figure 3 that when 16 buried pipes are arranged in rectangular and square arrays respectively with 5-meter spacing, the excess ground temperatures at the center points of the study area after 10 years of system operation are as follows:

Guangzhou: 12.24°C and 14.52°C

Tianjin: 1.55°C and 2.06°C

Harbin: -15.45°C and -18.55°C

It is obvious that the rectangular array configuration is superior to the square array configuration. Additionally, it can be seen that Tianjin, with balanced cold and heat loads, has a smaller thermal disturbance area, followed by Guangzhou. However, in Harbin, which primarily has a heating load, the thermal disturbance area exceeds the set study area, indicating the need to extract heat from a more distant part of the formation to meet the heat demand. In this case, increasing the pipe spacing or the depth of the buried pipes should be considered.

Figure 4 shows the distribution of excess formation temperature at the center point of the study area (x=22.5, y=22.5) after 10 years of system operation with different arrangements of buried pipes. Figure 5 compares the radial excess formation temperature at y=22.5 as it changes over time during system operation.

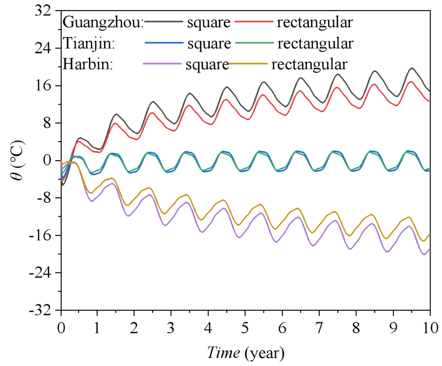


Fig.4 Excess formation temperature changes at the center point (x=22.5, y=22.5) of the study area under different arrangement configurations.

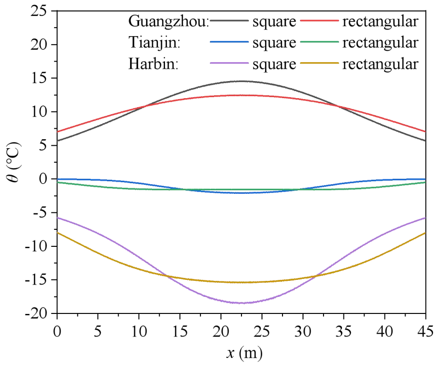


Fig.5. Radial excess formation temperature (y=22.5) changes over time under different arrangement configurations

4. CONCLUSIONS

This paper establishes a model for solving the formation temperature distribution of BHEs based on the analytical solution of formation temperature distribution under dynamic heat load. The formation temperature distributions in Guangzhou, Tianjin, and Harbin, three cities with representative cold and heat load ratios were analyzed, under square and rectangular arrangements of buried pipes. The results show that, under the configuration of 16 heat pipes of 45 m × 45 m square meters, after 10 years of operation, the heat accumulation effect under square arrangements is more severe compared to rectangular arrangements. The temperature differences between the two arrangements are 2.95°C (Guangzhou), 0.51°C (Tianjin), and 3.10°C (Harbin). It is recommended to use a rectangular configuration. Furthermore, for Harbin, where the thermal disturbance radius is larger, increasing the pipe spacing or borehole depth can also alleviate thermal accumulation. The research findings can provide theoretical reference for optimizing the design of buried pipe systems in practical engineering applications.

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