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Research Paper

Thermal interaction of multiple ground heat exchangers under different intermittent ratio and separation distance

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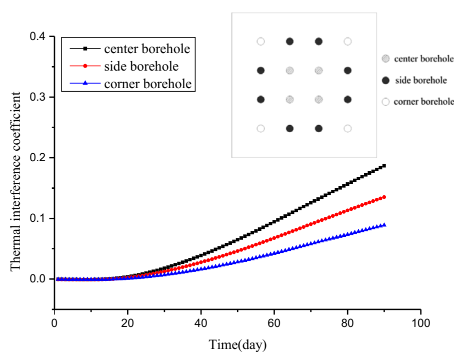
HIGHLIGHTS

- Multiple GHEs are classified as corner boreholes, center and side boreholes.
- The thermal interference coefficient is proposed.
- A model considering the difference of borehole wall temperature is developed.
- The effects of intermittent ratio and separation distance have been investigated.

GRAPHICAL ABSTRACT



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ABSTRACT

Heat transfer of multiple vertical ground heat exchangers (GHEs), the key component of ground source heat pump (GSHP) systems, should be paid more attentions in the soil temperature response, thermal interaction among boreholes and the consequences of heat exchange capacity decline. In this paper, based on their relative location, boreholes are firstly classified as corner boreholes, center boreholes and side boreholes, and then the thermal interference coefficient is proposed to evaluate the thermal properties under various intermittent ratios and separation distances. The calculation model consider the difference of borehole wall temperature, which is accurate and needs short calculation time because of combination analytic solution and numerical simulation. The results show that the heat transfer performance of each borehole remains almost the same until thermal interference emerges, the order of heat transfer flux over time is corner borehole > side borehole > center borehole. Increasing either the intermittent ratio or the separation distance can enhance the heat transfer over the same running time. The thermal interference coefficient increases with continued operation, increasing both the intermittent ratio and the separation distance can decrease the overall soil temperature, thus decreasing thermal interference. The coefficient can be reduced by nearly 1/3–1/2 under an intermittent mode compared with a continuous mode.

1. Introduction

Due to their high energy efficiency and environmental friendliness, ground-source heat pump (GSHP) systems have gained popularity in different regions and countries, including Europe [1], Australia [2], Korea [3], and China [4]. A ground heat exchanger (GHE) in a GSHP system rejects/extracts heat from the ground during cooling/heating periods and is obviously a key component that warrants significant attention. Many recent papers have focused on GHE calculations such as design methods [5], parameter

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estimations [6–8], and quasi-steady heat transfers around boreholes, and progress in conventional models for borehole GHEs [9,10].

Numerous analytical and numerical models for the heat transfer of GHEs have been proposed. Among the analytical models, typical solutions involve either line source theory [11] or cylindrical source theory [12,13]. Line source theory simplifies the GHE as a line source so that the heat transfer of the GHE is simplified as the temperature response in a semi-infinite medium with an infinite line heat source, then an improved finite-length linear heat source model in the same semi-infinite medium is proposed [14]. Whereas cylindrical source theory extends the line source to a cylindrical source with a constant radius. Numerous researchers have advanced analytical models based on these two theories [15–22]. The resulting analytical models can provide soil temperature response analyses with rapid solutions.

As for numerical models, Yavusturk and Spitler [23] presented a two dimensional model based on a fully implicit finite volume fraction and an automated parametric grid generation algorithm. Based on domain decomposition and state model reduction techniques, a three dimensional reduced model [24] was proposed. The domain decomposition was used to substructure and vary the time step values in each sub-domain, and state model reduction was then applied to each resulting sub-zone. Bauer et al. [25] presented the development and application of a 3D numerical simulation model for a single GHE. The proposed model included the thermal capacities of the borehole components, the fluid inside the tubes, and the grouting material, thus making it possible to consider the transient effects of heat and mass transports inside the borehole. In this approach, the use of simplified thermal resistance and capacity models provided accurate results while substantially reducing the number of nodes and computation time. Su et al. [26] built an explicit one dimensional transient numerical model for a single GHE while providing two computing algorithms with the quasi-steady-state assumption inside the borehole heat transfer. Luo et al. [27] developed a model based on experimental data to examine the thermal exchange of GHE in a layered subsurface. Two modeling approaches were implemented where ground properties were considered to be either homogenous or stratified. These numerical models can provide more accurate solutions than analytical models but the computation time is too long, particularly for long-term simulations over tens of years.

The above models are applied to single GHE; several design tools for GSHP systems are commercially available and most utilize a "g-function" for multiple GHEs, including EED, GLHEPRO, and Energy Plus [28]. The g-functions have been pre-calculated in these tools and are included in a database containing a large number of bore field configurations. However, users are restricted to these configurations [29]. The concept of g-functions was initially introduced by Eskilson [30]. Eskilson's g-functions were numerically calculated under the assumption that the temperature along the wall of the boreholes was uniform and equal for all boreholes in a bore field. Considering the temperature differences surrounding each GHE, Katsura et al. [31] used the equivalent radius obtained by multiplying the ideal ground heat exchanger radius by a modification coefficient, to obtain the average surface temperature of the ground heat exchangers influenced by the heat transfer.

The thermal performances of multiple GHEs have been evaluated on the basis of analytic and numerical solutions. The effect of system parameters such as borehole spacing as well as heat flux from the borehole wall on the transient response of two neighboring boreholes are discussed by Koohi-Fayegh and Rosen [32], and found that the heat flux from the borehole wall and the time of system operation all affect directly the amount of thermal interaction between the systems. Cimmino and Bernier [29] calculated the individual normalized heat extraction of different boreholes in a 6×4 bore field. It should be noted that the extraction rate varied significantly as a function of the borehole position in the bore field. The normalized heat extraction rates were higher for boreholes located further away from the center of the bore field and at the top and bottom of the boreholes.

Adopting an appropriate intermittent operation strategy according to building load properties can improve the heat performance of GSHP systems. Based on five intermittent operation modes, Cao and Yuan [33] studied the effect of intermittent operation on the restoration performance of a vertical GHE by investigating the heat exchange flux, temperature difference, soil temperature distribution and thermal radius. Gao et al. [34] compared the energy efficiency between continuously controlled and intermittently controlled GSHP systems. They showed that the intermittent process not only changed the trend and the degree of ground temperature but also changed the balanced temperature. Furthermore, factors such as thermal inertia, temperature levels, and lag time were also considered to examine how they affected efficiency. Yang et al. [35] compared the highest average soil temperature under different intermittent operations, the result showed that the highest average soil temperatures of the three intermittent operating conditions were lower than those of the continuous operation, at 5.9%, 10.4%, and 14.5%, respectively, after 20 years of operation.

In summary, several aspects of GHEs heat transfer should be further studied due to the following aspects: the above studies most focus on heat exchange of a single borehole and do not investigate the thermal interaction among multiple boreholes. The heat performance difference of each borehole is affected by many factors, such as operation time, borehole spacing, but there is a little research on the effect of position. Considering the number and space of boreholes, thermal performance evaluation must involve boreholes at different positions, not just the entire GHEs heat exchange capacity. On the other hand, heat transfer calculation method of multiple GHEs are mostly based on the assumption that the temperature distribution are equal for all boreholes, which directly caused the simulation error of heat transfer.

The object this paper is to investigate the thermal interaction of multiple boreholes, the soil hear transfer properties of a large soil area is the focus. So a new model for multiple boreholes that consider the temperature difference of borehole wall is proposed. According to the relative location, the GHEs area have been classified as corner borehole, center borehole or side borehole, the thermal interference and heat performance restoration of different borehole are discussed respectively. Then the effect of borehole spacing as well as intermittent operation mode are investigated. This would be helpful for the GHEs design, site characterization and operation so that these systems minimally impact neighboring systems.

2. Numerical simulation and experiment verification

Due to the large borehole area and long operation time of GHEs heat transfer simulation, a mixed numerical/analytical method is developed. The calculation area is divided into two parts based on the boundary of the borehole walls: several boreholes and the soil. The calculation method for the borehole area is a steady analytical solution based on energy conservation; for the soil area, whereas the heat transfer is regard as a heat response under different heat fluxes boundary condition corresponding to each borehole, and the numerical simulation method is adopted. The two parts are coupled by the wall temperature and heat flux of each borehole. The simulation model and solution of borehole and soil are described in the Section 2.1.

2.1. Mathematical model and solution

For the borehole area, some acceptable heat transfer assumptions are as follows: (i) there is no contact resistance between