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Study on the representative borehole in ground heat exchanger design

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Abstract

In view of the fact that the large-scale projects of the ground-coupled heat pump systems become more popular, a new concept is proposed that a representative borehole takes the place of the least-favorable borehole in thermal analysis of the ground heat exchangers so that more precise designs and simulations may be achieved. Borehole temperatures and their average are calculated in fields with multiple boreholes, and the mean square error coefficient is devised in order to analyze the imbalance between the boreholes. Conclusions are obtained to locate the representative borehole in different configurations of the borehole fields.

Keywords: Ground-coupled heat pump, Ground heat exchanger, Design, representative borehole, thermal imbalance

1. Introduction

A number of large-scale ground coupled heat pump (GCHP) projects have been established in commercial buildings for space heating and cooling in China because of their higher efficiency, lower maintenance cost and environmental friendliness [1]. Many of these GCHP systems currently in operation in China were inadequately designed only according to the rules of thumb. The rules of thumb can serve well for specific localities where the building load, soil and weather conditions are fairly uniform because design specifications are based on the

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experience with related installations [2]. However, the rules of thumb cannot properly assess the effect of varied design parameters, such as shallower burial depth, lower shank spacing between U-tube legs, and larger borehole space in ground surface. As a result, these ground heat exchangers (GHEs) were either oversized, which lead to unnecessarily high capital costs, or undersized which result in system malfunction.

Recently, a simulation-based program named GEOSTAR has been developed by our research group for the design and simulation of GHEs [3]. The superposition principle was employed to deal with the thermal inference among the multi-boreholes, which was proposed by [4,5]. Actually, the temperature response of each borehole is different from the other boreholes because of the different location and the thermal interference. Therefore, it is necessary to find a representative temperature of the borehole wall in order to calculate the inlet/outlet temperature of the circulating fluid during the design process. The accurate method is to calculate the temperature response of each borehole and obtain the average temperature among all the boreholes. However, this method may cause a tedious calculation process especially for the cases with a large number of boreholes, which is not suitable for engineering design. To simplify the calculation process and also to obtain a conservative design result, the least-favorable borehole with the highest thermal resistance among the multi-boreholes is generally chosen as the representative borehole in most design/simulation programs. Meanwhile, it is quite easy to search the location of the least-favorable borehole in the borehole configuration.

During the last decade, more and more large-scale GHE systems have been installed in China, which usually include hundreds or even thousands of boreholes. For the cases with large-scale boreholes, the temperature response of the least-favorable borehole may cause a severe deviation from the average temperature among the multi-boreholes. Accordingly, this method may result in an over-sized borehole length and increase the capital cost. Therefore, the primary objective of this study is to search the most optimal borehole to represent the average temperature response of the multi-boreholes and to further optimize the design method of GHE systems. The borehole configuration can be varied according to the actual available ground area, such as the "L" shape, double L, and matrix. Currently, the matrix has become the main borehole configuration in projects with multi-boreholes. Therefore, the following study focuses on the matrix configuration.

2. The thermal imbalance of multi-boreholes

In most heat transfer models of the GHE, the heat transfer process may usually be analyzed into two separated regions. One is the soil/rock outside the borehole, where the heat conduction must be treated as a transient process. Another sector often segregated for analysis is the region inside the borehole, including the grout, the U-tube pipes and the circulating fluid inside the pipes. The analyses on the two spatial regions are interlinked on the borehole wall. One of the typical heat transfer model for the heat transfer outside the borehole is the finite line source, i.e. the borehole with a constant heating rate is assumed to be a finite line source. Temperature rises that occur at any time τ on the wall of the borehole can then be calculated in the following manner [6]:

$$T_b - T_0 = \frac{q_l}{4k\pi}\int_0^H \left\{ \frac{\operatorname{erfc}\left(\frac{\sqrt{r_b^{\,2} + (0.5H - h)^2}}{2\sqrt{a\tau}}\right)}{\sqrt{r_b^{\,2} + (0.5H - h)^2}} - \frac{\operatorname{erfc}\left(\frac{\sqrt{r_b^{\,2} + (0.5H + h)^2}}{2\sqrt{a\tau}}\right)}{\sqrt{r_b^{\,2} + (0.5H + h)^2}} \right\} \mathrm{d}h \tag{1}$$

where, T_0 is the initial temperature of the soil, i.e. the annual mean temperature of the soil; k and a denote the thermal conductivity and thermal diffusivity of the soil, respectively; H and r_b are the borehole length and the radius, respectively; and q_l is the heating rate per length of the line source.

For each borehole, its temperature response on the borehole wall basically consists of two parts: the primary temperature rise due to the line source (U-tube) in the borehole itself (see equation 1) and the second one caused by the rest boreholes in the GHE. It should be noticed that the heat transfer rate per borehole is assumed to be constant. Thus, the heat transfer in a field with multiple boreholes can then be analyzed on the basis of the superposition principle, as shown in Equation (2).