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Modeling the interactions between the performance of ground source heat pumps and soil temperature variations

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ABSTRACT

The adoption of geothermal energy in space conditioning of buildings through utilizing ground source heat pump (GSHP, also known as geothermal heat pump) has increased rapidly during the past several decades. However, one problem in operating GSHPs is that collection or rejection heat from the ground alters the ground temperature, which can adversely affect the coefficient of performance (COP). In turn, the amount of heat that must be exchanged with the ground increases in order to satisfy a given heating or cooling load. This paper presents a novel model to calculate the soil temperature distribution and the COP of GSHP. Different scenarios were simulated to quantify the impact of different factors on the GSHP performance, including seasonal balance between heat collection and heat rejection, daily running mode, and spacing between boreholes. Our results show that greater loads and smaller distances between boreholes cause changes in soil temperature large enough to adversely affect the GSHP performance, even resulting in COPs less than those commonly achieved with air source heat pumps. However, shifting from heating to cooling on a seasonal basis can, in part, mitigate this problem. Long boreholes, additional space between boreholes and intermittent running mode could also improve the performance of GSHP, but large initial investment is required.

Introduction

The awareness of climate change and environmental pollution issues increased dramatically in the past decade. Interest in adopting alternative energies to improve energy efficiency and reduce environmental risks is growing rapidly. Geothermal energy utilized by ground source heat pumps (GSHP, also known as geothermal heat pump, includes systems that supply either heat or cooling to the end user) becomes a new and promising energy source lying right beneath our feet. It is environmentally friendly, low life-safety risk and has low maintenance cost (Bayer et al., 2012; Capozza et al., 2012; Kharseh et al., 2011; Lund et al., 2011; Staffell et al., 2012).

Heat pumps use work to transfer energy from a cold source to a warm sink. A GSHP typically uses the ground as a heat source during the heating season and a heat sink during the cooling season. Because of the relatively constant underground temperature (higher than the air temperature during winter and lower than the air temperature during summer), the GSHP theoretically has higher energy efficiency compared to the conventional air–air or air–water heat pumps. The ground heat exchanger (GHE) is an important part of the GSHP system. It could be soil or groundwater. For soil GSHP, the orientation of GHE can be either horizontal or vertical. Vertical GHEs occupy less area and can accommodate large air temperature fluctuation, while horizontal GHEs experience seasonal temperature cycles due to solar gains and transmission losses to ambient air at ground level (Capozza et al., 2012; Staffell et al., 2012; Yang et al., 2010; Yuan et al., 2012). In this study, we focus on vertical GHEs.

Heat and cold accumulations will excessively and adversely affect the GSHP system performance when the system is not properly designed. For the building located in warm areas where cooling load is larger than the heating load (referring to the load of the building space), heat will be injected into the ground leading to the increase of ground temperature and fluid temperature entering heat pumps. This makes the GSHP efficiency decrease, and eventually makes the heat pump halt. The cold accumulation may appear when the heating load is larger than the cooling load. Alternative heating and cooling can, in part, mitigate the accumulation. However, the frequent alteration is practical only on a multi-month basis. This drawback can be overcome by increasing the total length of the GHE and the space between boreholes. Some hybrid methods combined with solar energy or cooling tower were used to solve this problem (e.g. Qi et al., 2014). However, they increased the complexity of running and maintaining the GSHP.

The accurate prediction of long term soil temperature distribution when the GSHP is running can improve the design of the GHE. Previously, some models were developed to predict the soil temperature distribution, such as the analytical solution of line source theory, the analytical solution of cylindrical source theory and numerical solutions

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(Lu and Chen, 2010; Yang et al., 2010; Yuan et al., 2012). Analytical solutions can deliver accurate results in a timely manner. However, they only suit single boreholes. Numerical simulation methods are widely used in engineering projects to investigate long-term temperature distribution of soil for multiple boreholes and to predict the heat pump performance. There is still a lack of models to integrate both the GSHP performance and the soil temperature distribution. In this paper, we present a novel model integrating these two perspectives. We evaluate the performance of GSHP under different running modes and cooling/heating loads using this model.

Methods

Model description

This paper focuses on the vertical underground GHE, which is being widely used in China. Multiple boreholes were placed as array as shown in Fig. 1. Also the essential parts of the system are shown in Fig. 2. Boreholes were placed at the nodes of the rectangle mesh. The distance between boreholes was between 3 m and 6 m in accordance with the technical code for GSHP systems in China (MOHURD, 2009). There are a number of tube configurations (e.g. U-tube and double U tube). In this paper, we simplify each borehole as one single point as the heat source. The difference between different configurations is expressed by the different heat resistance shown as Rs in Eq. (5). Fig. 1 shows the layout of boreholes in two dimensions of 5 by 5 multiple pipes.

The heat transfer around vertical multi-pipe in soil is governed by soil thermal properties, distance between boreholes, cooling and heating loads, ambient air temperature. Assumptions made are listed below.

(1) The initial soil temperature is uniform;
(2) The soil properties are constant;
(3) The influence of ambient air temperature and subsurface seepage flow is negligible because the impact of ambient air temperature is insignificant for vertical pipes (Yang et al., 2010);
(4) The vertical heat transfer is excluded. The problem can be simplified as two dimensions.
(5) The temperature of fluid inside a vertical pipe is constant throughout the entire length of pipe.

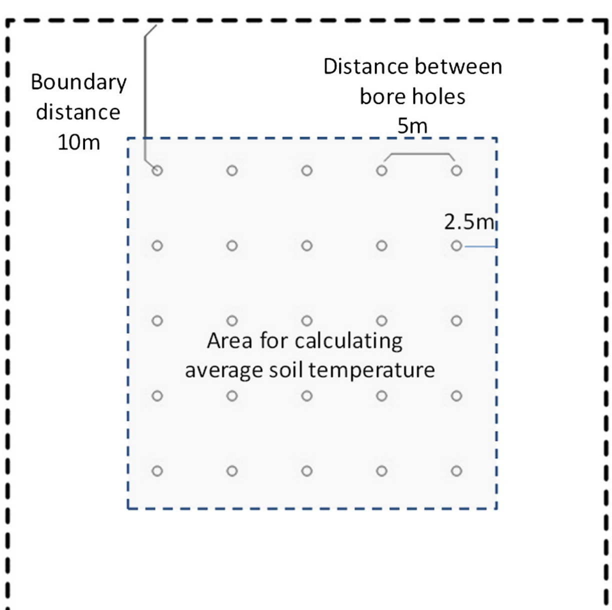

Fig. 1. The demonstration of computation area and array of boreholes. The uniform mesh was employed to discretize of Eq. (1), the grid size is 0.1 m × 0.1 m for both directions.

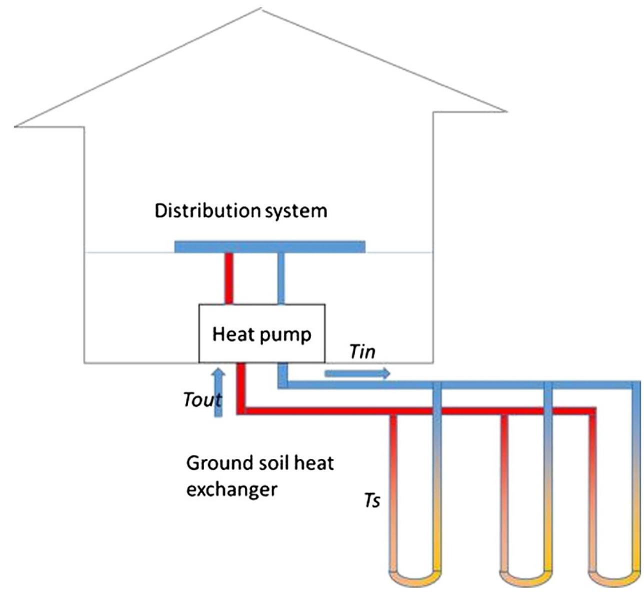

Fig. 2. The essential parts of the system.

Based on the above assumptions, the governing equation is described as shown below.

$$\frac{\partial T_s}{\partial \tau} = \alpha\left(\frac{\partial^2 T_s}{\partial x^2} + \frac{\partial^2 T_s}{\partial y^2}\right) + \frac{q}{\rho c} \tag{1}$$

in which T_s is the soil temperature (°C), τ is time (s), α is the soil thermal diffusivity (m^2/s), ρ is the density of the soil (kg/m^3), c is the specific heat capacity (J/(kg ∗ °C)), and q is the heat source (W/m^3). Note that soil thermal diffusivity is the thermal conductivity divided by density and specific heat capacity.

Initial condition:

When $\tau = 0$, t (x,y,τ) = t_0, where t_0 is the initial soil temperature (°C), τ is time (s). Eq. (1) can be discretized in space and time. The implicit algorithm was employed to discretize time to make results insensitive to time step (Holman, 1986).

Boundary conditions.

(1) The constant temperature was set as the measured soil temperature at the boundary of computing domain (see Fig. 1). The distance between the outside borehole and the computing boundary is 10 m, which is twice of the distance between boreholes.
(2) At the borehole node, the heat source q (W/m^3) was set to $\frac{\varphi}{\Delta x \Delta y}$, where $\Delta x \Delta y$ is the grid distance of the node where the borehole is located (both Δx and Δy = 0.1 m in this study), φ is set as the heat exchange per meter between circulating water and soil (W/m). At other locations, q is set to 0. It can be obtained based on the cooling or heating load and the performance of GSHP shown in Eqs. (2) and (3) below.

For cooling load:

$$\varphi = \left[CL^*\left(1 + \frac{1}{COP}\right)\right]/\ . \tag{2}$$

For heating load:

$$\varphi = \left[HL^*\left(1 - \frac{1}{COP}\right)\right]/ \tag{3}$$

where CL is the cooling load (W) in the summer and HL is the heating load (W) in the winter,   is total length of boreholes (m), COP is the