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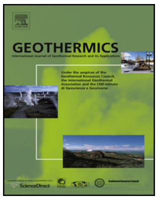

Restoration performance of vertical ground heat exchanger with various intermittent ratios

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ABSTRACT

Based on five intermittent operation modes with the intermittent ratios of 0.7, 1, 1.4, 2 and 3, the effect of intermittent operation on restoration performance of vertical ground heat exchanger in Ground Source Heat Pump was investigated in terms of heat exchange flux, temperature difference, soil temperature distribution and thermal radius. Meanwhile, a heat transfer model of the GHE has been developed by combining the analytical solution and numerical solution, whose calculation area has been divided into two parts by the boundary of the borehole wall. For the area in the borehole, the calculation method is steady analytical solution based on energy conservation, whereas for the soil area, the finite volume method is adopted, and the two parts are coupled by the temperature and heat flux of the borehole. The simulation results indicate that intermittence operation modes can improve the heat exchange performance of ground heat exchanger. Furthermore, when the intermittent ratio is 3, the restoration performance is the best due to the longest stopping time. With the operation proceeding, the enhancement of the heat flux arising from the intermittence becomes more obvious while the restoration ratio of average temperature of borehole decreases simultaneously.

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1. Introduction

As a renewable energy technology, ground source heat pump (GSHP) systems are increasingly attracting attention for their high energy efficiency and environmental friendly. GSHP system rejects or extracts heat from ground by ground heat exchanger (GHE) in the cooling and heating periods respectively, and thus obviously the heat exchange capacity between GHE and the ground is a focus. With the widespread use of GSHP systems, the heat accumulates around the GHE because the cooling and heating load imbalance throughout the year prohibits the development of the GSHP technology, which will gradually decrease the system efficiency.

Many models for analyzing the heat transfer of GHE have been developed with analytical or numerical methods. And the typical analytical solutions are line source theory (Ingersoll and Plass, 1948) and cylindrical source theory (Ingersoll et al., 1954; Carslaw and Jaeger, 1959). The line source theory simplifies the GHE to be a line source with the same axis of the borehole, so the heat transfer of the GHE is simplified as a line heat source in a infinite medium, and the cylindrical source theory extends line source to a cylindrical source with a constant radius. On the basis of the above two theories, plenty of researchers (Michopoulos and Kyriakis, 2009; Mostafa Sharqawy and Said, 2009; Liu et al., 2009; Yu et al., 2010) have advanced the analytical models. For instance, Yavuzturk and Spitler (2001) introduced the term "load aggregation" to describe the effect of historical heat flux on the current temperature distribution; Bernier (2001) developed the cylindrical source model with varied heat flux via load dividing method to resolve the variations of heat flux around the borehole, and any load varying with time is regarded as the superposition of the thermal effect on the borehole caused by several piecewise linear.

With the rapid development of computer techniques, three dimensional numberical simulations on the GHE(s) and GSHP system throughout one year and even several years have been realized. Due to huge grid numbers and long-playing simulation, how can the accurate results be provided while substantially reducing the number of nodes and the computation time have been the focus of our study (Yuan et al., 2012). By introducing a double two-dimensional cylindrical coordinate system, Lei (1993) converted the heat transfer of heat exchangers into a two-dimensional transient heat transfer issue that the heat transfer along the depth of soil was neglected and the temperature of the same section in the pipe was supposed to be same during the simulation. Then, a three-dimensional heat exchanger model based on finite difference method was proposed (Rottmayer et al., 1997), whereas during the calculation, the authors assumed that there was no axial conduction

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Nomenclature

T	temperature (°C)
T_0	initial soil temperature (°C)
k	thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)
c_p	constant pressure specific heat ($\mathrm{J\,kg^{-1}\,K^{-1}}$)
m	the mass flux of circulating fluid in pipe ($\mathrm{kg^{-1}\,s}$)
T_b	average temperature of borehole wall (°C)
H	depth of borehole (m)
R	thermal resistance
ql	heat transfer rate per unit length (W/m)
$\bar{t}_f$	average temperature of circle fluid (°C)
X_r	thermal radius (m)
r	the distances from borehole wall (m)

Greek symbols

ρ	density ($\mathrm{kg\,m^{-3}}$)
τ	time (s)

Subscripts

f	fluid
1	left pipe of the ground heat exchanger
2	right pipe of the ground heat exchanger
in	inlet of the ground heat exchanger
out	outlet of the ground heat exchanger

and the temperature of the same section was the same. And in order to simplify the model, the circular tubes were approximated as non-circular sections. Meanwhile, Al-Khoury et al. (2010) presented a finite element modeling technique for double U-tube borehole heat exchangers (BHE) and the surrounding soil mass. Here, geothermal problems can be simulated using coarse meshes with hundreds to thousands elements. After that, based on domain decomposition and state model reduction techniques, a three-dimensional reduced model (3D-RM) (Kim et al., 2011) was proposed to reduce computation time and computer memory. The domain decomposition was used to sub-structure and to vary the time-step values in each sub-domain, and then state model reduction was applied to each resulting sub-zone.

In order to check the performance of intermittent operation of GSHP, the system (Li and Zeng, 2009) adopted an intermittent operation mode, operating from 9:00 am to 9:00 pm every day but stopped at the rest of the time. As a validation of the numerical model, the authors only concerned about the inlet and outlet water temperatures of the GHE (the water flow rate of the GHE was kept constant during the entire period of operation). Additionally, the hourly inlet water temperatures were considered as the input variable of the model, and the measured outlet water temperatures were used to verify the predicted value. Cui et al. (2008) developed a finite element numerical model for the GHEs in alternative operation modes. The authors found that the variation of the wall temperature of U-tube pipes illustrated that the discontinuous operation mode and the alternative cooling/heating modes can effectively alleviate the heat accumulated in the surrounding soil, as well as the operation modes possess the ability to improve the system performance ultimately. However, in the simulation, the operation time varied from 26 min to about 4 h, and the period was short and optional. Li et al. (2006) simulated a system operated from Monday to Friday in intermittent operation mode from 8:00 am to 5:00 pm, and stopped at night. Unfortunately, in the work, the heat flux in the pipe was treated as a constant value, so the simulation could not reflect the effect of intermittence on heat flux of heat exchanger. Gao et al. (2010) made a comparison on the energy efficiency between continuous control system and intermittent control system, in which factors such as thermal inertia, temperature levels and lag time were taken into account to observe how they affect the efficiency. Shang et al. (2011) presented a three-dimensional model to calculate the influencing factors including thermal conductivity, porosity, backfill material, air temperature, solar radiation and wind speed in the soil recovery process, which eventually reachead a conclusion that the soil properties had great impacts on the heat recovery.

Table 1
The daily time schedule of 5 intermittent operation modes.

Intermittent ratio	Stopping time	Operating time
0.7	10	14
1	12	12
1.4	14	10
2	16	8
3	18	6

This paper develops a heat transfer model of the GHE by combining the analytical solution and numerical solution. And futherly, the investigations on heat exchange capability of the GHE and the soil heat accumulation around the GHE are proceeding with different intermittent ratios, which refers to the ratio of stopping time to operation time every day. The daily time schedule of these intermittent operation modes is shown in Table 1.

2. The heat transfer model of GHE

2.1. The heat transfer model of soil outside borehole

The heat transfer process of the soil outside borehole is simplified as a two-dimensional transient heat conduction with varied heat flux boundary, the detail calculation area is displayed in Fig. 1, and energy equation is described as follows.

$$\rho c \frac{\partial T}{\partial \tau} = k\frac{\partial^2 T}{\partial x^2} + k\frac{\partial^2 T}{\partial y^2} \tag{1}$$

Boundary conditions:

$$\mathrm{AB}: \quad \left.\frac{\partial T(x,y,\tau)}{\partial x}\right|_{\mathrm{AB}} = 0; \tag{2}$$

$$\mathrm{BC}: \quad \left.\frac{\partial T(x,y,\tau)}{\partial x}\right|_{\mathrm{BC}} = 0; \tag{3}$$

$$\mathrm{HA}: \quad \left.\frac{\partial T(x,y,\tau)}{\partial x}\right|_{\mathrm{HA}} = 0; \tag{4}$$

$$\mathrm{CD,\ GH}: \quad T(x,y,\tau) = T_0; \tag{5}$$

$$\begin{aligned} \mathrm{DE,\ FG}: \quad & \text{operation}: -\left.\frac{\partial T(x,y,\tau)}{\partial x}\right|_{\mathrm{DE,FG}} = q_l(\tau); \\ & \text{stop}: -\left.\frac{\partial T(x,y,\tau)}{\partial x}\right|_{\mathrm{DE,FG}} = 0; \end{aligned} \tag{6}$$

$$\text{Initial conditions}: \quad T(x,y,0) = T_0 \tag{7}$$

The governing equation is discretized using the finite volume method with the diffusion term of the first-order central differencing scheme and the time term of the fully implicit differencing scheme. Meanwhile, the TDMA method is adopted to solve the discretized equation. The number of the mesh cell adopted in the simulation is 31680 and the mesh independent solution has been

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