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A new solution for thermal interference of vertical U-tube ground heat exchanger for cold area in China

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A B S T R A C T

This paper presents a new solution to reduce the thermal interference of vertical U-tube ground heat exchanger (UGHE): pipe insulation installed on the upward branch pipe of the U-tube. 3-dimensional numerical models of the UGHE with and without pipe insulation were developed to simulate the heat transfer process around the UGHE. The models were verified with previously published data. The effects of pipe insulation on outlet temperature, soil temperature, heat exchange rate per unit length of borehole depth and soil temperature recovery ratio were investigated. The effects of inlet velocity of heat transfer fluid (HTF) and the thermal conductivity of backfill material were also studied to fully assess the effects of the insulation. The results indicate that the average outlet temperature of HTF, soil temperature near the upward branch pipe and soil temperature recovery ratio all increased and the thermal interference can be effectively weakened when pipe insulation was installed.

1. Introduction

Ground source heat pumps (GSHP) have attracted more attention as a renewable energy technology and have been used for space heating and cooling because the great thermal stability of the subsurface which can be used as a heat exchange medium (İnalli and Esen, 2004; Ozgener and Hepbasli, 2007; Lund et al., 2011). Recently, many studies have been performed to study the performance of ground source heat pump (GSHP) systems (Florides and Kalogirou, 2007; Esen et al., 2007; Yoon et al., 2014). Li et al. (2006) experimentally investigated the operation performance of a U-vertical ground coupled heat exchanger (GCHE). The variation of the ground temperature and heat balance of the system were numerically simulated and analyzed, and the results indicate that the ground source can be used as a heat source/sink for ground coupled heat pump system for higher efficiency and greater energy saving. Karabacak et al. (2011) experimentally investigated the cooling performance of a ground source heat pump system in Denizli, Turkey. They exactly indicated the relations of performance coefficients of ground source heat pump according to the meteorological data including solar radiation, wind speed, relative humidity and external temperature with this experiment. Michopoulos and Kyriakis (2009) and Michopoulos et al. (2007) studied the operational performance of a GSHP system installed in Northern Greece for heating and cooling modes. Ozyurt and Ekinci (2011) experimentally studied the vertical ground source heat pump performance for cold climate evaluation in Turkey and calculated the heat pump coefficient of performance (COP) and the system performance (COPs). Hwang et al. (2009) monitored the cooling performance of a ground source heat pump system installed in a school building in South Korea. They analyzed and discussed both the system operation and the effects of the outdoor ambient temperature. Comparing the COP to an air source heat pump (ASHP) system, the GSHP system is superior in energy efficiency.

The ground heat exchangers (GHEs) are important parts of ground source heat pump, and the performance of the vertical GHEs has great effect on the performance of GSHP (Yang et al., 2010; Lee et al., 2014; Luo and Rohna, 2015). The performance of the GHEs reduces gradually due to the heat buildup in the ground surrounding the heat exchanger during the long-term operation. Jalaluddin and Miyara (2012) numerically investigated the heat exchange rates of three types of GHEs with different operation modes such as a short operational period, 6 and 12 h discontinuous operation time over the course of a day, and continuous operation modes. The off-time period in the discontinuous operation and extracting heat from the ground during the heating process in the alternative operation mode contributed significantly to the increasing heat exchange rate.

Abbreviations: HTF, heat transfer fluid; UGHE, U-tube ground heat exchanger; GSHP, ground source heat pump; GHE, ground heat exchanger; COP, coefficient of performance; ASHP, air source heat pump; GCHE, ground coupled heat exchanger.

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Nomenclature

Symbols

T	Temperature (K)
t	Time (s)
$\vec{v}$	Velocity (m s^{-1})
S	Source term
$\dot{m}$	Mass flow rate: (kg s^{-1})
h	Enthalpy of HTF: (kJ)
p	Pressure: (Pa)
q_r	Source term
G_b	Generation term of turbulence energy
$c_{p,HTF}$	Specific heat of HTF: (kJ kg^{-1} K^{-1})
Q_{pl}	Heat exchange rate per unit length: (W m^{-1})
Q_p	Heat exchange rate (W)
L	Depth of borehole: (m)

Greek symbols

ρ	Density (kg m^{-3})
μ	Viscosity: (Pa s)
μ_t	Turbulence viscosity (Pa s)
u_{eff}	Effective viscosity coefficient (Pa s)
σ_t	Constant
$c_{\varepsilon 1}$	Constant
$c_{\varepsilon 2}$	Constant
λ	Thermal conductivity: (W m^{-1} K^{-1})
ϕ	Soil temperature recovery ratio
k	Turbulence kinetic energy

Subscripts

t	Turbulence
d	Discontinuous operation mode
c	Continuous operation mode
in	Inlet
out	Outlet
s	Soil

A discontinuous operation mode (i.e., 12 h on, 12 h off) can effectively increase the heat transfer performance of the GSHP. However, because of the small size of a borehole diameter and the temperatures difference between the two branch pipes of the UGHE, the downward and upward branch pipe not only exchange heat with the

soil and backfill material, but also exchange heat with each other. The thermal interference has a great impact on the overall heat transfer of the UGHE. Li et al. (2014b) analyzed different geometrical characteristics that influenced thermal short-circuiting and the heat transfer between the two branch pipes through 2-D modeling. They also evaluated the fluid temperature variations along the pipe and analyzed the effects of flow velocity, grout conductivity and borehole depth on the outlet temperature, average heat flux per unit length and thermal short-circuiting loss rate. Overall, a larger short-circuiting loss rate would cause greater error for effective subsurface conductivity estimation. Li et al. (2014a) numerically investigated the thermal performance of a borehole heat exchanger with different U-tube diameters and borehole parameters. As the borehole diameter increases or the borehole depth decreases, the influence of thermal interference is reduced. However, most studies weaken the thermal interference by changing the geometric dimension of the UGHE and borehole. Only few studies investigate the effects of pipe insulation. Basogul and Keçebas (2011) evaluated the economic and environmental impacts of insulation in district heating pipelines. Their results show that the insulation material installed at its optimum insulation thickness in the district heating pipelines will not only reduce the heat loss from the district pipeline but also has economic and environmental advantages. However, few researchers study the effects of pipe insulation on the thermal interference of UGHE. Therefore, the present computational study was undertaken.

In this paper, we propose a new method to reduce the thermal interference between the two branch pipes by installing insulation. The UGHE was fitted with a heat pump system for cold climate in China. 3-D numerical simulation models were developed in order to simulate and analyze the heat transfer process among soil, backfill material and UGHE with and without pipe insulation using ANSYS FLUENT, and the models were verified with previously published data. The effects of inlet velocity on heat transfer fluid (HTF), the conductivity of backfill material and the length of pipe insulation on soil temperature were studied. Finally, the effects of pipe insulation under continuous and discontinuous operation modes on outlet temperature, soil temperature, heat exchange rate per unit length of borehole depth and soil temperature recovery ratio were numerically investigated.

2. Simulation model

2.1. Physical model

The schematic diagrams of the UGHE with and without pipe insulation are shown in Fig. 1(a) and Fig. 1(b). The U-tube is a high density polyethylene pipe with an external diameter of 32 mm, a thickness of 3 mm and a length of 100 m. The height from the bottom of the elbow pipe to the bottom of the model was 100 mm and the center-to-center distance of the vertical tube lines is 80 mm. The upward branch pipe (outlet pipe) was insulated to protect heat exchange process from the downward branch pipe (inlet pipe) as shown in Fig. 1(b). The length of pipe insulation was 30 m and the thickness of the pipe insulation was 0.03 m. The U-tube was placed inside the borehole with a diameter 0.18 m. The backfill material was modeled around the U-tube, and the diameter of the soil was 5 m. Ethylene glycol aqueous solution was used as the heat transfer fluid (HTF) to avoid freezing of the HTF in the UGHE for the winter conditions.

2.2. Mathematical models

We developed 3-dimensional models for the UGHE with and without pipe insulation to simulate the heat exchange process among the U-tube, backfill material and soil in ANSYS Fluent. Finite-volume formulation was used to solve the Navier-Stokes equations. The SST $k-\omega$ model and standard $k-\omega$ model are used for compressible fluid, while heat transfer fluid (HTF) in our research is incompressible fluid, so the turbulent flow was described using the Realizable $k-\varepsilon$ model in this paper. The following Section 2.2.1 describes the governing equations.

The following Section 2.2.1 describes the governing equations.

2.2.1. Governing equations

This section describes in detail the conservation equations of mass, momentum and energy.

2.2.1.1. Continuity equation. The continuity equation is written as:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \vec{v}) = 0 \tag{1}$$

where $\vec{v}$ is velocity, and ρ is density.