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Applicability of the pipe structure and flow velocity of vertical ground heat exchanger for ground source heat pump

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ABSTRACT

This paper builds three-dimensional heat transfer model of single- and double-U type vertical ground heat exchanger (GHE). The heat transfer and pressure loss of vertical GHE is simulated with different flow velocities, pipe diameters and well depths. Moreover, the value engineering (VE) is used to evaluate the tech-economic performance of the buried pipe. The value coefficient of each scheme is compared with selecting five functional indicators. The objective of this paper is to obtain the recommended structures for the GHE in engineering applications. The results show that single-U32, double-U25 and double-U32 have their own advantages in the aspects of the heat transfer, outlet temperature, pressure loss and material consumption. The recommended velocity ranges of single-U32, double-U25 and double-U32 are 0.4–0.6, 0.4–0.5, 0.3–0.4 m/s respectively. Finally, the recommended well depth ranges of double-U25 and double-U32 are 80–100 m and 90–110 m respectively.

1. Introduction

Ground source heat pump (GSHP) has been developing quickly since the middle of the last century [1–3]. By 2009, the GSHP systems had obtained more than 1,000,000 units, with an annual growth rate of about 15% [4]. The applications of the GSHP in Europe are also widespread. The market growth rate in Austria and Germany reached 45% and 120% by 2006 [5,6]. Geothermal energy is an ideal low-grade energy, which not only realizes the efficient running of GSHP, but also reduces the consumption of conventional energy as the cooling and heat source of GSHP. This kind of clean resource has significant environmental benefits and great popularities under the current of growing tensions in energy and deteriorating environment [7].

In recent years, the heat transfer model of ground heat exchanger (GHE) and the tech-economic evaluation of the GSHP system are still the research hot-spots. Researchers have achieved fruitful results on the heat transfer models of GHE, design scheme of GSHP, system installation, operation and management [8–10]. Hikmet et al. [11] compared three well depths of single-U pipe and found that soil temperature has little correlation with the well depth. Lamarche et al. [12] found that thermal resistance of the one-dimensional model is 1.5 and 0.7 times to that of the two-dimensional and three-dimensional models, respectively. Jalaluddin [13] studied the flow velocity on the heat transfer of GHE, and result is that the thermal efficiency of double-U pipe is the highest, and the following is the multi-pipe and single-U pipe. Chulbo et al. [14] found that the heat transfer performance of the new tubular exchanger is more excellent than the traditional ring exchanger. Jung and Choi [15] conducted a three-dimensional heat transfer model of vertical GHE and simulated the system performance under the continuous and intermittent working conditions and the intermittent operation is preferable.

From the above-mentioned analysis, there are rare studies focusing on energy consumption reduction and the factors of affecting the heat transfer and pressure loss quantitatively. The pipe diameter, well depth, flow velocity and the type of buried pipe are crucial to system performance, which are often determined by engineering experiences and lack theoretical basis. Therefore, this paper focuses on applicability of the different structures for GHE through numerical simulation and theoretical analysis.

2. Physical model

The heat transfer of the GHE is often divided into two parts, namely in drilling hole and out of drilling hole, which is coupled by the wall of drilling hole. There are the working fluid, PE pipe and backfill material in the drilling hole.

The geometries contain: the vertical-U pipe, fluid, backfill material and soil [16–18]. The drilling hole and soil around are regarded as a cylinder, and the U-type pipe is placed in the drilling hole. The structures and horizontal sections of typical single- and double-U type buried pipe are shown in Figs. 1 and 2.

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Nomenclature

Abbreviations

GHE	Ground heat exchanger
VE	Value engineering
GSHP	Ground source heat pump
AHP	Analytic hierarchy process
tech	Technological
COP	Coefficient of performance
EER	Energy efficiency ratio Symbols
t	Time (s)
p	Pressure (Pa)
T	Temperature (°C)
υ	Kinematic viscosity (m^2/s)
ρ	Density (kg/m^3)
V_i	Value coefficient (–)
μ	Dynamic viscosity (Pa·s)
F_i	Function coefficient (–)
α	Thermal diffusion coefficient (m^2/s)
C_i	Cost coefficient (–)
ε	Dissipation rate (%)
γ	Bulk density (N/m^3)
k	Kinetic energy (J)
G	Flow rate (m^3/s)
U	Temporal average velocity (m/s)
η	Efficiency (–)
S	Modulus (–)
H	Lift (m)
t_j	Weight coefficient (–)

In the paper, the diameter of the drilling hole is 200 mm; the pin spacing is 100 mm; the adjacent drilling spacing is 5 m; the soil is a cylinder of 5 m diameter, which has the same circle center with the drilling hole. The geometry structures are listed in Table 1 and the thermophysical properties of material are listed in Table 2.

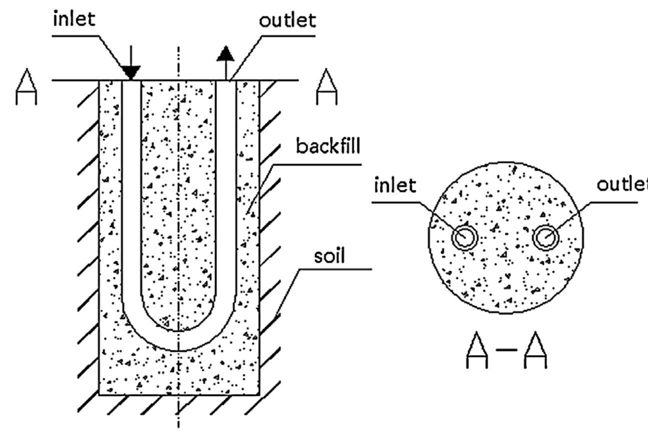

Fig. 1. Single-U GHE.

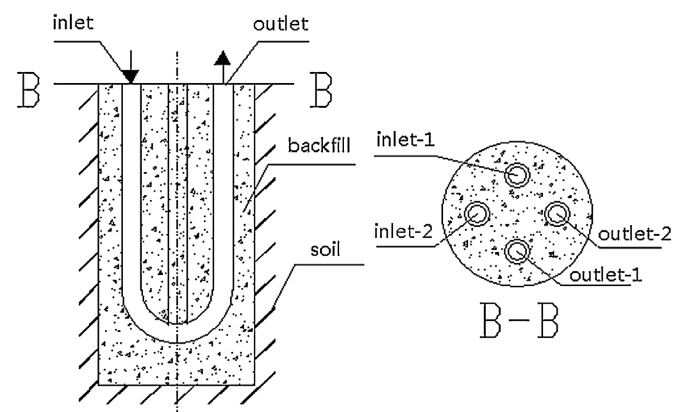

Fig. 2. Double-U GHE.

3. Mathematical model

3.1. Assumptions [19–21]

1) GHE maintains the vertical and symmetrical in the drilling hole and the pipe spacing is invariable;
2) The Soil is uniform. The thermophysical property of the soil, backfill material, fluid and buried pipe is considered constant. The initial temperature of the soil is assumed to distribute uniformly;
3) It is considered that close contact between the pipe wall and backfill material, backfill material and soil. And their thermal contact resistance is neglected;
4) The spacing between two drillings is large enough so that the thermal interference is not considered;
5) It is not considered that the groundwater seepage and the heat and moisture transfer have influences on the heat transfer. Pure thermal conduction is considered between the soil and buried pipe.

3.2. Governing equations

The fluid temperature, velocity inside the pipe and the soil temperature surrounding the pipe are simulated. The fluid water flowing in the pipes satisfies the conservations of mass, momentum and energy. By using FLUENT, the conservations of mass and energy are fixed, which are expressed: [22]

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad (1)$$

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial z}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \quad (2)$$

where x, y, z are the coordinate components of three directions in rectangular coordinate system, m; u, v, w are the velocity components of three coordinate directions, m/s; t is the time, s; ρ is the density, kg/m^3; μ is the dynamic viscosity, Pa·s; α is the thermal diffusion coefficient, m^2/s; p is the pressure, Pa; T is the temperature, °C.

For the conservation of momentum, modified k-ε model with high Reynolds is used [2], which make assumptions for the fluid near wall region and the model apply a finer grid in the vicinity of the wall so that more accurate results can be obtained. The equation is expressed [23]:

$$\frac{\partial \varepsilon}{\partial t}+U_j\frac{\partial \varepsilon}{\partial x_j}=\frac{\partial}{\partial t}[(\upsilon+\frac{\upsilon_t}{\partial x_i})\frac{\partial \varepsilon}{\partial x_i}]+C_1 S+C_{1\varepsilon}C_{3\varepsilon}\frac{\varepsilon}{k}\upsilon_t(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i})\frac{\partial U_i}{\partial x_j}-C_2\frac{\varepsilon^2}{k+\sqrt{\upsilon\varepsilon}} \quad C_1=\max\left[0.43\times\frac{\eta}{\eta+5}\right] \quad \eta=S\frac{k}{\varepsilon} \quad (3)$$