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Field test and numerical investigation on the heat transfer characteristics and optimal design of the heat exchangers of a deep borehole ground source heat pump system

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ABSTRACT

Deep borehole ground source heat pump (DBGSHP) is a new type of heat pump heating system which extracts deep geothermal energy through heat exchange and can be applied for space heating in winter. To date, the development of deep borehole heat exchangers (BHEs) is limited to the cognized structure design and there is a lack of the experimental studies. This paper presents the investigation of the heat transfer characteristics of the heat exchanger of a DBGSHP heating system through both field test and numerical simulation. A field test was first carried out based on the DBGSHP implemented in a demonstration project. A numerical model was then developed to facilitate the evaluation of the heat extraction capacity and the outlet temperature of the coaxial deep BHEs. Based on the numerical model developed, a sensitivity study was further performed to examine the effect of the primary parameters including the inlet velocity, inlet temperature, flow pattern (one was that the circulating fluid flowed from the inner pipe to the annular space and the other was that the circulating fluid flowed from the annular space to the inner pipe) and pipe diameter on the performance of deep BHE. The results from the field test indicated that the average heat transfer capacity of each single borehole, the average COP of the heat pump unit and the DBGSHP heating system COP were 286.4 kW, 6.4 and 4.6, respectively. The simulation results matched well with the field test data, and showed that the inlet fluid velocity between 0.3 m/s and 0.7 m/s as well as the circulating fluid flowed from the annular space to the inner pipe can result in a better performance for the system of concern. The results from this study could be used as a reference basis for optimal design of coaxial deep BHE and to promote the utilization of deep geothermal energy.

1. Introduction

Nowadays, energy demand and environment impact have drawn increasing attention due to non-renewable energy utilization and environmental deterioration such as greenhouse gas emissions and global warming resulting from the combustion of conventional energy sources such as fossil fuels and coal [1–3]. The use of clean and renewable energy resources is being considered as one of the primary choices to replace conventional energy sources. Geothermal energy, as a renewable energy source, is becoming more and more attractive with local availability, low operational cost and low CO_2 emissions [4–7].

Geothermal resources have been exploited for space heating and sanitary hot water, mainly using the shallow geothermal energy limited to 300 m [8–10]. Borehole heat exchangers (BHEs) which can extract heating and cooling from the shallow ground, has been rapidly developed over the recent decades. However, the performance of the shallow BHEs gradually degrades as a function of the operating time due to the disequilibrium between heating demand in winter and cooling demand in summer [11,12].

Deep geothermal energy has been used for electricity generation and other functional purposes such as space heating and cooling [13]. A deep drilling project (over 1.3 km depth) for district heating showed that deep boreholes exhibited good performance in the western suburbs of Dublin [14]. An Enhanced Geothermal System (EGS) that cools the fluid through the injection well was proposed to extract the heat from low permeable and high temperature rock at thousand meters underground (usually considered as "artificial thermal reservoir") [15]. Up to 2012, nine countries in Europe established the geothermal power stations with an installed capacity of 1847.9 MW, annual generation capacity of 12158.3 GWh, and annual energy utilization coefficient 75%

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Nomenclature

C_p	specific heat capacity [J/(kg·K)]
I	turbulence intensity
Gr	Grashof number
Nu	Nusselt number
L	characteristic length (m)
N_1	electric power consumption of compressor for high area (kW·h)
N_2	electric power consumption of compressor for low area (kW·h)
N_3	electric power consumption of circulating water pump (kW·h)
Pr	Prandtl number
Q_1	heat transfer capacity for deep borehole heat exchanger (kW)
Q_2	heat transfer capacity for user (kW)
Q_3	total heat capacity (kW·h)
Re	Reynolds number
T_1	average inlet temperature of borehole heat exchanger (°C)
T_2	average outlet temperature of borehole heat exchanger (°C)
T_3	average outlet temperature for users (°C)
T_4	average inlet temperature for users (°C)
V_1	flow rate of borehole heat exchanger (m^3/h)
V_2	flow rate for users (m^3/h)
$\overline{X}$	arithmetic square root
h	convective heat transfer coefficient [W/(m^2·K)]
u	fluid velocity (m/s)

Greek letter

α_v	volume expansion coefficient (1/K)
δ	viscous boundary-layer thickness (m)
ζ	local resistance coefficient
λ	thermal conductivity [W/(m·K)]
λ'	friction coefficient
μ	dynamic viscosity coefficient (Pa·s)
ν	kinematic viscosity coefficient (m^2/s)
σ	standard deviation
ρ	density (kg/m^3)

Abbreviations

COP	coefficient of performance
BHE	borehole heat exchanger
DBGSHP	deep borehole ground source heat pump
GSHP	ground source heat pump
HDPE	high density polyethylene pipe

[16]. Compared with the data in 2010, the installed capacity of geothermal generation increased 212.9 MW [17]. Although EGS has been extensive applied, there are some problems such as underground configuration change, area restriction and low thermoelectric efficiency [18–20] that need to be solved.

Deep BHE is a new type of heating systems, in which the indirect heat exchange mode extracts deep geothermal energy for district heating and domestic hot water, usually through a pipe embedded in an abandoned oil or gas drilling. Many projects using deep BHE systems have been carried out in Germany, Switzerland and other countries. For instance, in the Prenzlau research project in Germany, a deep BHE with 2786 m depth in sandstone was used to supply space heating and domestic hot water [21]. In the Weggis research project in Switzerland, a deep BHE with 2300 m depth in a rebuilt abandoned oil drilling was used to extract heat over 200 kW [22]. Another project in Germany, a deep BHE with 2500 m depth in a sandstone was used to provide for heating and cooling for the buildings in RWTH-Aachen University [21]. The heat transfer characteristics of deep BHEs have been discussed in many studies. Kujawa [23] investigated the utilization of deep geological wells for extracting geothermal energy. The result showed that the insulation and flow rate significantly affected the heat transfer process. Davis [24] demonstrated the influence of geothermal gradient and drilling depth on the heat extraction. The result indicated that the maximum heat extraction was dependent on the bottom temperature of drilling and inlet fluid pressure. Bu [25] studied the heat extraction capacity of an abandoned oil drilling through numerical simulations. It was found that the fluid flow rate and geothermal gradient were the primary parameters influencing the performance of the oil drilling and the deep BHE heating system could stably operate for a long period. Cheng [26] presented that the outlet fluid temperature of the deep BHE heating system would decrease with the increase of the operation time and eventually will reach stable.

A 3D numerical simulation method was used by Noorollahi [27] to analyze the heat transfer characteristic of an oil drilling in Iran. The result indicated that the geothermal gradient, fluid flow rate and size structure were significant for heat extraction capacity. Huchtemann [28] experimentally studied the heat transfer characteristics of a deep BHE heating system used in an office building. It was shown that the fluid flow rate in the inner pipe was a vital parameter and the change of the inner pipe diameter could contribute to a high outlet temperature.

Despite the use of deep BHE has shown great benefits, the deep BHE has not been widely applied. The previous research on deep BHE was primarily restricted to numerical simulations probably due to the high capital costs. The heat transfer model used was developed based on the shallow boreholes and there is a lack of experimental verification.

In the past several decades, many borehole heat transfer models have been proposed and applied in various engineering applications [29–31]. Ingersoll et al. [32], for instance, presented a line source model by assuming that borehole was an infinite line source and soil was the infinite homogeneous medium with constant thermal properties. A finite line source model of BHE was developed by Eskilson [33] to obtain the soil temperature responses around BHEs. Zeng [34] and Lamarche [35] generalized the finite line source model by providing a virtue heat source to examine the temperature distribution of the soil around BHEs. Teza et al. [36] investigated the temperature responses of soil around BHEs under various operation modes by using a pure conduction model. Beck et al. [37] optimized the heat transfer performance of a pipe-group BHE using the principle of superposition. Fossa et al. [38] proposed a more accurate calculating method to determine the BHE field length and geometry based on ASHRAE method. For numerical modelling of BHEs, the Finite Difference Method [39], the Finite Volume Method [40] and the Finite Element Method [41,42] have been adapted in order to analyze the optimum operation mode of BHEs, by taking the heat transfer mechanism between BHE sand soil into account. Chen [43] used the finite volume method to establish a three-dimensional, unsteady, and numerical model for a vertical ground heat exchanger (GHE) (< 150 m) to evaluate the effects of different parameters such as inlet temperature and inlet flow on the heat flux of the GHE. Zhao et al. [44] concluded that the spiral-shaped pile ground heat exchanger (PGHE) outperformed the U-shaped and W-shaped GHEs by using the finite element method. Marcotte et al. [45] presented a new method to acquire the thermal response by Fourier transform code and multiple curve interpolation Code, leading to a compromise between calculating time and modelling accuracy. A quasi-3D BHE heat transfer numerical model was established by Pasquier [46] by using spectral analysis code and response model code. However, the aforementioned