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Transient numerical simulation of the coaxial borehole heat exchanger with the different diameters ratio

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ABSTRACT

In this paper, the thermal and hydrodynamic performance of the coaxial borehole heat exchanger (CBHE) with different diameters ratio, during heat injection into the ground are investigated. For this purpose, the energy and Reynolds Averaged Navier-Stokes (RANS) equations with SST k-ω turbulence model are numerically solved to simulate transient fluid flow and heat transfer. Numerical simulation results are validated with results of available experimental data. The reduction of heat transfer between the annular and central region and the increase of heat transfer between the annular region and ground is the main objective of this study to improve the thermal performance of the CBHE. The results show that the temperature difference between the inlet and outlet of the CBHE rises with the decrease of diameter ratio. In order to reduce costs, instead of using a CBHE with a high diameter ratio and more borehole depth, it is better to use a CBHE with a low diameter ratio and borehole depth. Also, the optimal diameter ratio is calculated for the lowest pumping power. Of course, due to the insignificance of the pumping power against the heat transfer at the different diameters ratio, the CBHE with a lower diameter ratio is recommended because it has better thermal performance and cooling.

1. Introduction

Green building control strategies use various concepts of natural heating and cooling, ventilation, and air conditioning (see Bayrak et al., 2013; Mardiana-Idayu and Riffat, 2012; Zuo and Zhao, 2014). Ground source heat pumps (GSHP) technique is one of them. The use of the earth rather than the ambient air provides a lower temperature sink for cooling, a higher temperature source for heating, and smaller temperature fluctuations, thereby yielding higher efficiency for the heat pump. Borehole heat exchangers (BHEs) are critical components of GSHP, which use the ground as a heat source or sink in winter and summer. BHEs have different geometries. Usually, they are designed as single U pipe and double U pipes or coaxial pipes. The distance between the ground and the outer pipe is filled with grout. In some cases, CBHEs are used without grout, and the outer pipe is directly connected to the ground. For example, Acuña and Palm (2013, 2011) evaluated non-grout CBHE with the flexible outer pipe. By changing the geometry of the CBHE as well as reducing the thermal conductivity of the central pipe, their thermal performance can be improved.

Many techniques and solutions on the heat transfer inside and around BHEs consist mainly of experimentation, numerical and analytical models in the literature. Although the analytical solution has the lower computational cost than a numerical solution. Of course, the low accuracy of the analytical solution makes it impossible to evaluate all of the BHEs phenomena.

In the experimental context, thermal response test (TRT) method (Gehlin, 2002; Lhendup et al., 2014; Wang et al., 2010) is used to calculate the thermal properties of the ground and to design a BHE. This method is based on the inlet and outlet temperature of the borehole heat exchanger. Until recently, measured temperature profiles during thermal response tests have not been available to verify the models. Acuña (2013) and Beier et al. (2013) have measured the entire vertical temperature profile of the circulating fluid during a thermal response test in U-tube and coaxial heat exchangers. In the present study, results are validated with experimental data. The experimental method is called the distributed thermal response test (DTRT) where the vertical temperature profile is measured.

Computational Fluid Dynamics (CFD) technique can be used to simulate different heat transfer problems (See e.g. Chen et al., 2016; Ermagan and Rafee, 2018; Oztop and Akpinar, 2008). In context of geothermal energy and borehole heat exchanger, Bouhacina et al. (2015) proposed the use of fin to improve heat transfer in U pipe BHE. In their work, they used the finite volume model to show that adding the fin to the inside of the polyethylene pipe would increase heat transfer. Saadi and Gomri (2017) studied the thermal interference in the CBHE using finite volume method. They have been able to predict

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Nomenclature

c_p	Specific heat [J/kg K]
f	Friction factor
D_h	Hydraulic diameter [m]
D_ω	Cross diffusion term [kg/m^{3}s^2]
G_k	Turbulent kinetic energy production rate [kg/ms^3]
G_ω	Production rate of the specific dissipation [kg/m^{3}s^2]
h	Convection heat transfer coefficient [W/m^2 K]
k	Turbulent kinetic energy [m^2/s^2]
L	Active borehole Length [m]
$\dot{m}$	Mass flow rate [kg/s]
Nu	Nusselt number
P	Pressure [Pa]
Pr	Prandtl number
Q	Heat input rate [W]
r	Radius [m]
T	Temperature [K]
t^*	Dimensionless time
$\vec{u}$	Velocity vector [m/s]
Y_k	Dissipation rate of turbulent kinetic energy [kg/ms^3]
Y_ω	Dissipation rate of ω [kg/m^{3}s^2]
z	Depth direction [m]

Superscript

*	Dimensionless values

Greek letters

ρ	Density [kg/m^3]
λ	Thermal conductivity coefficient [W/m K]
μ	Dynamic viscosity [kg/m s]
ν	Kinematic viscosity [m^2/s]
Γ	Diffusion Coefficient [kg/m s]
ω	Specific dissipation rate [1/s]

the start time of thermal interferences for a given heat load and borehole spacing in order to maximize energy extraction to occupy the lowest surface. Biglarian et al. (2017) studied the U-shaped borehole heat exchanger in short and long times. They provided a model that is able to estimate the thermal response in a period of one minute to 10 years.

There are several studies on coaxial borehole heat exchangers. For example, Daneshipour and Rafee (2017) studied the performance of CBHE in the presence of nanofluids and concluded that the use of nanofluids increases the heat transfer rate and pressure drop simultaneously. However, they evaluated the CBHE in steady state and with constant inlet temperature.

In some cases, CBHEs are used in power plants. For example, Mokhtari et al. (2016) obtained the optimal parameters of the geothermal Rankin cycle with a coaxial heat exchanger using the laws of thermodynamics and cost standpoints. They have optimized diameter ratio with respect to pressure drop decrement inside the heat exchanger and cycle thermal efficiency increment. They evaluated the heat exchanger in the heat extraction mode and they often investigated the performance of the Rankine cycle. Yekoladio et al. (2013) obtained the optimum diameter ratio minimizing the pressure drop. In addition, by minimizing the entropy generation, they obtained the optimal mass flow rate for minimum pumping power and maximum net power output of binary cycle. However, thermal properties are not considered in their analysis. These results are obtained by assuming the fully developed and no heat flux from the inner fluid and a high conductive outer pipe with negligible thermal resistance. Zanchini et al. (2010a,b) applied a finite element method to study the performance of two CBHEs in both winter and summer seasons. They increased the borehole diameter to increase heat transfer and improve the thermal performance of the CBHE. First, this is a clear result, moreover, increase of the borehole diameter will increase the costs. Also, they used available correlations to calculate the Nusselt number and heat transfer coefficient and used constant inlet temperature in their simulations. While in the GSHP, the inlet temperature of the BHE is not constant and changes over time. Also, Holmberg et al. (2016) increased the diameter and depth of borehole to improve the performance of the CBHE While these will increase the pressure drop and also the costs.

In the present study, a model is proposed to improve the thermal performance of the CBHE, which also reduces the costs. GSHPs are usually used cross-sectionally throughout the day. Therefore, it is very important to examine the transient state of the BHE. So far, researchers have not investigated the performance of the CBHE that is coupled to the GSHP, in the transient state and different diameters ratio at the same time. In addition, the proposed model reduces system startup costs. The accurate numerical solution of transient flow and heat transfer are carried out using the Reynolds Averaged Navier-Stokes (RANS) equations. The results of this study are validated with the available experimental data obtained from distributed thermal response test. All results are evaluated during heat injection into the ground.

2. Numerical model

2.1. Geometry of the problem

A schematic diagram and detail of the geometry of the CBHE are given in Fig. 1. As shown, the fluid enters the CBHE from the central region and exits from the annular region and the outlet fluid re-enters after the heat absorption from the condenser.

2.2. Governing equations

To simulate the fluid flow and heat transfer, RANS equations are used. The RANS equations include continuity, momentum, and energy equations.

$$\frac{\partial}{\partial x_i}(\bar{u}_i) = 0 \tag{1}$$

$$\rho\frac{\partial \bar{u}_i}{\partial t} + \rho\left[\bar{u}_j\frac{\partial \bar{u}_i}{\partial x_j}\right] = -\frac{\partial \bar{P}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial \bar{u}_i}{\partial \bar{x}_j}\right) - \rho \overline{u'_i u'_j}\right] \tag{2}$$

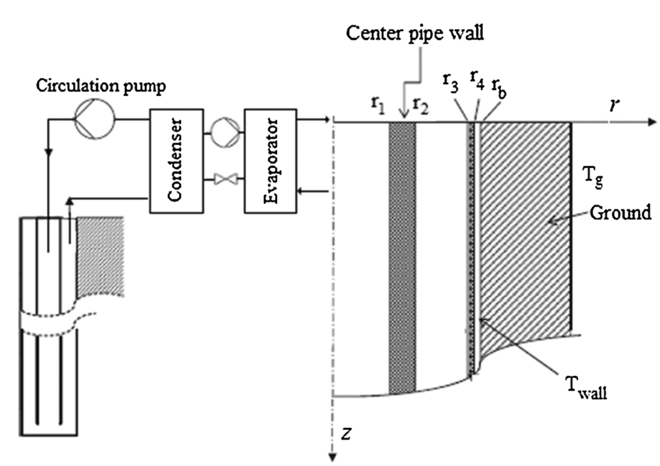

Fig. 1. Schematic figure of the CBHE with part name and flow directions.