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Numerical analysis of characteristics of a single U-tube downhole heat exchanger in a geothermal well

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ABSTRACT

Heat extraction from a geothermal reservoir using a single U-tube in a reservoir has been applied in the field. The advantages include extracting only heat instead of water. Based on the geological data of Bazhou geothermal field, China, a three-dimensional steady state numerical model, including the U-tube, wellbore and reservoir is established to analyze the entire flow field comprehensively. The performance of the exchanger is studied through investigation on the influences of four important geological parameters of depth, porosity, permeability and heterogeneity of the formation. Simulation values are validated by results obtained from field tests. Results indicate that the overall flow velocity in the geothermal reservoir is relatively low compared with the flow in the wellbore mainly due to the high flow resistance. In addition, the mass flow rate can hardly affect the flow in the reservoir. Under the conditions of this study, the depth of the geothermal field, the reservoir porosity and the heterogeneity of the geothermal formation may hardly affect the performance of the U-tube. However, if it is possible, it is better to install the single U-tube in the homogeneous area of the reservoir, which may obtain better heat extraction effect. The results in this paper could provide implications for further study of geothermal energy exploitation.

1. Introduction

Geothermal energy has been considered as one of the most promising renewable and clean energy resources for the last several decades (Nasruddin et al., 2016; Lund et al., 2010). Downhole heat exchanger (DHE) is the most common form used to extract heat from the ground for space conditioning in residential and commercial buildings (Rees, 2015; Lee and Lam, 2008). DHE consists of a system of tubes or a U-tube located in a single wellbore, through which the working fluid is circulated to extract heat as shown in Fig. 1. The vertical DHEs are usually constructed by inserting one or two high-density polyethylene U-tubes in vertical boreholes to serve as the ground loops (Zeng et al., 2003). Compared with other exploitation methods, such as Engineered (Enhanced) Geothermal System, the U-tube only extracts heat from the geothermal reservoir instead of water (Carotenuto et al., 2001). This feature gives DHE some unique advantages, including low installation costs and minimized damage to the environment, etc.

A large number of investigations have been carried out on heat extraction by DHE. In summary, the study can be divided into two parts: the solid rock outside the borehole and the region inside the borehole. For the first part, Carotenuto et al. used a single domain numerical approach to describe the heat and fluid flow through saturated geothermal reservoir of DHE system (Carotenuto and Casarosa, 2000). Furthermore, since the borehole depth is much larger than its diameter, this process is often formulated by a 1D line-source (Ingersoll et al., 2009) or cylindrical-source theory (Carslaw et al., 1959; Kavanaugh, 1985; Deerman, 1991; Bernier, 2001). Zeng et al. have presented a 2D model of a finite line-source to consider axial heat flow in the ground for longer durations (Zeng et al., 2002). For the second part, the main objective is to determine the entering and leaving temperatures of the circulating fluid in the exchanger. The temperature variation inside the borehole is usually slow and minor. Thus, the heat transfer in this region is approximated as a steady-state process, which has been proved to be suitable and described by a constant borehole thermal resistance, except for analysis dealing with dynamic responses within a few hours (Yavuzturk et al., 1999). Eskilson et al. calculated the ground temperature around a single borehole using the finite-difference method and proposed a g-function to describe the performance of borehole and developed g-functions curves based on selected borehole field configurations (Eskilson, 1987). Li and Zheng developed a 3D unstructured finite-volume model for a vertical ground heat exchanger and used Delaunay triangulation to mesh the computational domain. The surrounding soil or rock was divided into several layers to evaluate the effect of fluid temperature with depth on the thermal process (Li and Zheng, 2009). In addition, a transient finite-volume model was developed by Kaltreider et al. specifically for modeling the thermo-

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Nomenclature

ρ	Density of water, kg/m^3
C_p	Specific heat of water, $J/(kg\,k)$
Nu	Nusselt number
d_0	Internal diameter of the U-tube, m
Re_f	Reynolds number
Pr_f	Prandtl number
h	Convection heat transfer coefficient
l	Length of the U-tube, m
f	Darcy drag coefficient
m	Mass flow rate, kg/s
Q	Heat extraction rate, kW
C_{p1}	Specific heat capacity of the inlet fluid, $J/(kg\,K)$
C_{p2}	Specific heat capacity of the outlet fluid, $J/(kg\,K)$
∇p	Pressure difference, Pa
μ	Geothermal fluid viscosity, $kg/m/s$
$1/\alpha$	Coefficient of viscous impedance
v	Reservoir flow velocity, m/s
Δn	Thickness of the porous media, m
k	Reservoir permeability, m^2
r_e	Radius of the entire reservoir, m
r_w	Wellbore radius, m
r	Radial distance to the wellbore, m

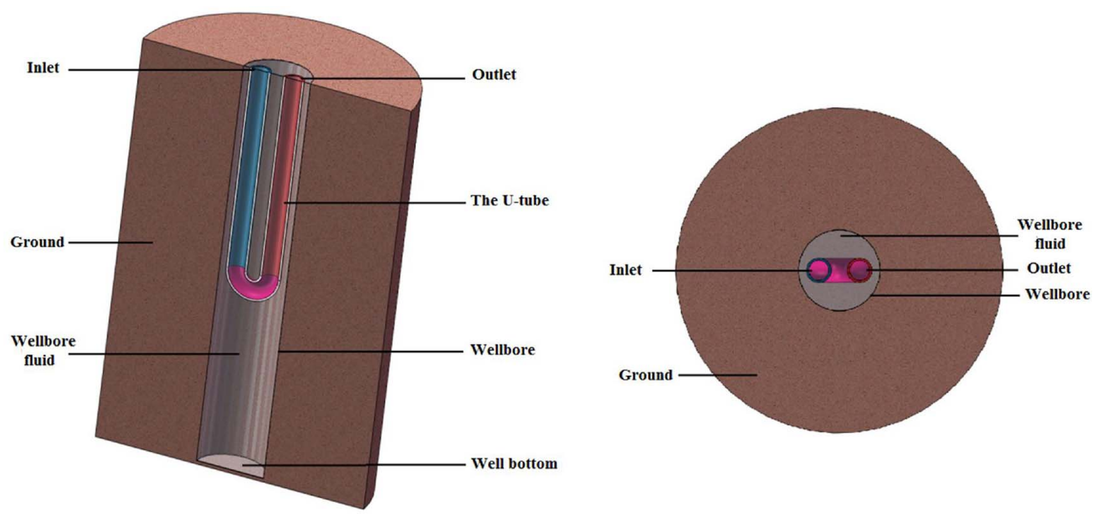

Fig. 1. Schematic diagram of a single U-tube DHE geothermal system.

active foundation (Kaltreider et al., 2015). Rees and He used a multi-block mesh to establish a 3D model to investigate the effects of fluid transport and diffusion on the fluid flow physical phenomenon (Rees and He, 2013). Lyu et al. proposed a steady-state numerical model, which coupled working fluid in DHE with geothermal fluid inside wellbore, to investigate the influences of key parameters on heat extraction performance of a U-tube DHE (Lyu et al., 2017).

In view of the complexity of the heat transfer in DHE, Computational Fluid Dynamics (CFD) has been widely used in the studies as listed above (Bhutta et al., 2012). Xie et al. evaluated the Nu and friction factor for three types of fin and tube heat exchangers. Study was conducted to observe the difference between laminar and turbulent heat transfer for larger diameter of tubes (Xie et al., 2009). Starace and Congedo evaluated horizontal GSHPs (Ground Source Heat Pumps) based on experiments and simulations. The main parameters affecting the performance of horizontal ground heat exchangers were investigated by the CFD code Fluent (Starace et al., 2005; Congedo et al., 2012). Gustafsson et al. studied the performance of a U-pipe in a groundwater-filled heat exchanger in Scandinavia using a 3D steady state CFD model. The results show that the induced natural convection significantly decreases the thermal resistance inside the borehole (Gustafsson et al., 2010). Habchi et al. observed heat transfer parameters and turbulent mixing in the multi-functional heat exchanger under three different configurations. Laser Doppler analysis and the CFD approach were used to determine the consequences of the vorticity produced by the trapezoidal tabs (Habchi et al., 2010).

However, to the best of our knowledge, there is no comprehensive study on the coupled flow field of working fluid in a single U-tube DHE, geothermal fluid inside the wellbore and flow in the reservoir. In this paper, Bazhou geothermal field in China is taken as a case to be studied. First, a three-dimensional steady state numerical model has been established to combine the entire flow field, including the working fluid flow in the U-tube, geothermal fluid flow inside the wellbore and the flow in the reservoir. Second, the flow field is analyzed comprehensively considering characteristics of the working fluid emphatically. Simulation values are validated by comparing with results obtained from field tests. Finally, influences of four important geological parameters, including depth, porosity, permeability and heterogeneity of the formation, on the performance of a single U-tube DHE are investigated. Results in this paper can provide guidance for the field application of vertical DHE.

2. Model development

2.1. Physical model

The simulation model is based on a small field scale case. For the heat extraction of a single U-tube well, the entire simulation model consists of three parts: the U-tube, the borehole and the ambient geothermal reservoir. Consequently, a three dimensional model is established as shown in Fig. 2. In this paper, the geological parameters of Bazhou geothermal field in China are taken as an example for simulation. The working fluid is water, which is injected from the inlet of the U-tube to exchange heat with the borehole fluid and extracted upwards back from the outlet. When the borehole fluid temperature varies because of the heat transfer, changes in the density occur. Dense fluid will start to sink and less dense fluid will rise, resulting in the natural convection within the entire downhole wellbore, which leads to a better