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Numerical investigation on the reservoir heat production capacity of a downhole heat exchanger geothermal system

Yu Shi, Xianzhi Song*, Gensheng Li, Ruiyue Yang, Zhonghou Shen, Zehao Lyu

State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum, Beijing 102249, China

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ABSTRACT

The downhole heat exchanger (DHE) geothermal system is commonly used for space heating in the residential and commercial buildings. The reservoir properties have significant effects on the reservoir heat production capacity of DHE geothermal system. However, to the best of our knowledge, few researches are conducted to study this problem. In this paper, an unsteady-state fluid flow and heat transfer model considering natural convection for DHE system is presented. Subsequently, the temperature and velocity fields are analyzed comprehensively to understand the thermal process in geothermal reservoir. The influences of key parameters, including reservoir porosity, permeability and thermal conductivity coefficient of rock, on the heat production capacity are studied. The simulation results depict that the natural convection velocity near the wellbore is the largest, and the temperature gradient keeps constant along the vertical direction with time. The impact scopes of velocity and temperature fields both remain in a small range within the heating period. The reservoir heat production capacity decreases with the increase of porosity, while it does not reveal obvious trends because of a variation in permeability. As rock thermal conductivity rises, reservoir heat production capacity is improved. As a result, it is inferred that if only natural convection exists in reservoir, DHE system could be more suitable for the geothermal field with smaller porosity. The key findings of this work can be used to provide guidance for choosing the appropriate geothermal reservoir for the DHE geothermal system.

1. Introduction

With the increasing concern on the environmental pollution due to the use of fossil fuels, the development of clean and renewable resources has attracted global attentions (Panwar et al., 2011; Moomaw et al., 2011; I.P.O.C. Change 2014). As one of the promising and clean renewable resources, geothermal energy merits many advantages, such as abundance, environmental friendly and easy exploitation. As a result, we should accelerate the development and utilization of geothermal energy to alleviate energy demand and air pollution.

Extracting groundwater from the geothermal reservoir is the most efficient method to develop geothermal energy. However, if a large amount of geothermal fluid is exploited, the subsurface water table will decline, which will cause land subsidence and other issues (Kaya et al., 2011; Valgar-đur, 1997). Therefore, the geothermal fluid should be re-injected into the reservoir to maintain the subsurface water table. At present, the re-injection technology of groundwater in limestone and other karst reservoirs is relatively mature. However, most of the geothermal resources are stored in sandstone reservoirs. As a result, the re-injection of geothermal fluid is quite difficult (Ungemach, 2003; Seibt and Kellner 2003).

In order to ensure the sustainable development and utilization of geothermal resources, DHE geothermal system was proposed several decades before, which absorbs heat only, without extracting any groundwater from the underground aquifer (Lund, 2003). The DHE geothermal system has been widely used for space heating in residential and commercial buildings (Lund, 1999a,b; Hepbasli and Canakci, 2003; Burnell and Kissling, 2005; White, 2006). The DHE system consists of a series of tubes or a single U-tube. The DHE is located in a single wellbore, which is full of geothermal fluid. The working fluid is circulated inside the DHE and then extracts heat from the surrounding geothermal fluid. Thus, the DHE system has a complicated heat transfer process, which includes natural convection of geothermal fluid induced by heat extraction of DHE, heat conduction of reservoir rock, and forced convection if the geothermal fluid flows naturally. The schematic diagram of heat extraction process for DHE geothermal system is shown in Fig. 1.

In the 1970s, researchers began to carry out a series of studies on the method of enhancing heat exchange as well as the fluid flow and heat transfer model for the DHE system (Allis and James, 1980; Carotenuto and Casarosa 2000; Tago et al., 2006; Gustafsson et al., 2010; Steins et al., 2012; Carotenuto et al., 1999; Carotenuto et al.,

* Corresponding author.

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Nomenclature

$c_{p,f}$	Geothermal fluid heat capacity, J/(kg °C)
$c_{p,s}$	Reservoir rock specific heat capacity, J/(kg °C)
CFD	Computational fluid dynamics
DHE	Downhole heat exchanger
F	Volume force, N/m^3
g	Gravitational acceleration, m/s^2
K	Reservoir permeability, m^2
P	Thermal power, kW
p	Pressure, Pa
q	Heat flow rate, W/m^2
S	Area of wellbore-wall, m^2
T	Temperature in kelvin degree, K
T_c	Temperature in centigrade degree, °C
T_r	Reference temperature, K
u	Geothermal fluid velocity, m/s

Greek symbols

ρ	Water density, kg/m^3
ρ_r	Reference density of geothermal fluid, kg/m^3
ρ_f	Geothermal fluid density, kg/m^3
ρ_s	Rock density, kg/m^3
μ	Water viscosity, Pa s
λ_{eff}	Effective thermal conductivity coefficient, W/(m °C)
λ_f	Geothermal fluid heat conductivity coefficient, W/(m °C)
λ_s	Rock heat conductivity coefficient, W/(m °C)
β	Coefficient of thermal expansion of geothermal fluid, 1/K
φ	Porosity

1997; Carotenuto et al., 2012; Carotenuto et al., 2001; Dai et al., 2011; Lyu et al., 2017). For example, Allis and James (1980) found that a convection promoter tube installed in a borehole could improve the natural convection in the wellbore, and then enhance the heat extraction performance. The installation position and size of the convection promoter had a significant influence on the DHE performance. Subsequently, Carotenuto and Casarosa (2000) proposed a lumped parameter model to describe the characteristics of fluid flow and heat transfer in wellbore and reservoir matrix in the DHE system, and validated the reliability of this model by experiments. Tago et al. (2006) established a fluid flow and heat transfer model of a U-tube DHE with rectangular cross-section, and investigated the influences of working fluid flow rate and DHE materials on the output thermal power of the system. Gustafsson et al. (2010) established a 3D steady-state numerical model for a U-tube DHE, and analyzed the characteristics of temperature and velocity fields for the natural convection in the wellbore. Steins et al. (2012) pointed out that airlifting technique in the DHE system could enhance geothermal fluid movement and improve the performance of DHE, which obtained a 125% increase in output heat. Carotenuto et al. (2012) utilized a single domain numerical approach to establish a fluid flow and heat transfer model for the DHE geothermal system, and optimized the position of the tube casing slotted section to obtain the best heat extraction performance. Lyu et al. (2017) used a computational fluid dynamics (CFD) software to study the influences of working fluid flow rate, DHE length and inlet temperature on the thermal power of a U-tube DHE.

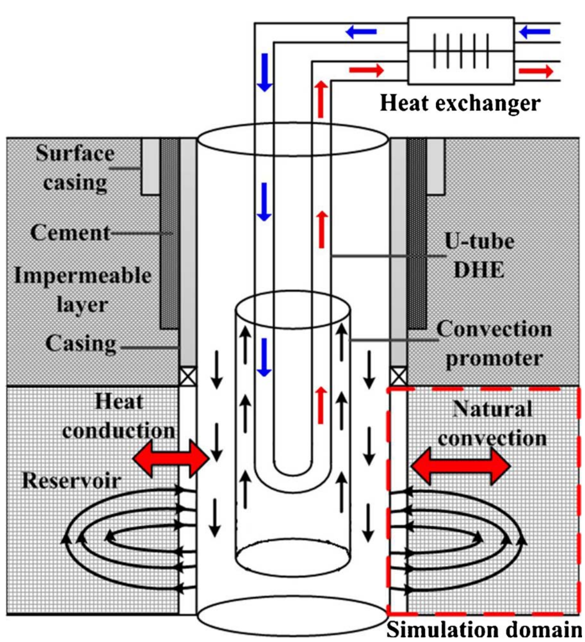

Fig. 1. Schematic diagram of DHE geothermal system with a convection promoter.

Previous researches have made significant contributions to the understanding of the thermal process in DHE geothermal system, and the optimization of the heat transfer performance. However, to the best of our knowledge, few investigations are conducted to analyze the influences of reservoir properties on the reservoir heat production capacity of the DHE system. In addition, it is significant to study the influences of reservoir properties on the maximum heat production capacity of reservoir (Allis and James, 1980) and analyze the adaptation of DHE geothermal system. In this paper, an unsteady-state fluid flow and heat transfer model by considering the natural convection is established. Then, based on the geothermal reservoir properties in Bazhou, Hebei, China, the velocity and temperature fields are analyzed comprehensively. The influences of key factors, including temperature difference, porosity, permeability and heat conductivity coefficient of rock, on reservoir heat production capacity are studied. The simulation results in this paper can be used to provide guidance for choosing the appropriate geothermal reservoir for the DHE system.

2. Numerical model description

2.1. Physical model

The natural convection and heat conduction are the main heat transfer forms for DHE geothermal system. The bottom hole of DHE system is full of geothermal fluid, from which the working fluid circulated in DHE extracts heat. During this thermal process, the geothermal fluid in the wellbore is cooled down, which results in the density difference between the fluid in the wellbore and geothermal reservoir. Then, buoyancy effect and natural convection are induced. As a result, the cooled geothermal fluid flows out of the borehole, and the hot fluid in the reservoir flows into the borehole. In addition, in order to promote the heat extraction performance of the geothermal system, a convection promoter made of thermal insulation material is often installed at the bottom of the well. The top and bottom of the promoter pipe are open-ended. Because of heat extraction process of DHE, density difference is generated between the inside and outside of the promoter, which enhances the natural convection intensity. Moreover, under the temperature difference between working fluid in DHE and surrounding ground, heat is transferred from reservoir to wellbore through heat conduction. The heat transfer principles of DHE system is shown in Fig. 1. Well-wall is set as the computational boundary in this model. The region marked by the red dotted lines is the simulation domain. In the following section, we will present the influences of reservoir properties on the reservoir heat production capacity of the DHE system.