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Heat extraction performance of a downhole coaxial heat exchanger geothermal system by considering fluid flow in the reservoir

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ABSTRACT

The downhole coaxial heat exchanger (DCHE) is expected to exploit medium-deep geothermal resources because of its large heat transfer area. For this geothermal system, the working fluid is injected from the annulus and produced from the central insulated tubing. There have been many studies on the heat extraction performance of DCHE. However, to the best of our knowledge, most previous heat transfer models did not consider the fluid flow in the reservoir, which has a significant effect on DCHE performance. Thus, an unsteady-state heat transfer model considering heat conduction and heat convection of reservoir is presented. The finite difference method is employed to solve the mathematical model. The temperature distribution in the wellbore and nearby reservoir during the exploitation process are analyzed. Subsequently, the effects of the key factors, including flow velocity in reservoir, aquifer thickness, and thermal conductivity of cement on the heat extraction performance are studied. The simulation results depict that the temperature decreases sharply near the wellbore. The temperature impact scope in the reservoir without geothermal fluid is about 20 m, while it reaches 40 m in the aquifer. This indicates that the fluid flow in the reservoir can enhance the heat transfer of DCHE and improve the heat extraction performance. The increase of flow velocity in reservoir will increase the outlet temperature and thermal power. As the aquifer thickness increases, the outlet temperature and thermal power increase. Besides, the outlet temperature and thermal power have a remarkable decrease at the initial stage, but then remains relatively stable. The findings can offer guidance for optimal design of DCHE geothermal system.

1. Introduction

Since the twenty-first Century, with the development of the global economy, the world's energy demand is growing strongly, the contradiction between supply and demand is becoming increasingly tense. The competition for oil and coal, which is dominant in energy consumption, is more intense. At the same time, the problem of resource exhaustion and environmental pollution caused by traditional fossil energy is becoming more and more serious (Asif and Muneer, 2007; Sun et al., 2012). As a kind of clean and renewable energy, geothermal energy plays an important role in alleviating the contradiction of energy supply and demand and improving the ecological environment. Therefore, it is imperative to speed up the efficient development and utilization of geothermal resources (Shi et al., 2018; Song et al., 2017).

As the basic development mode of geothermal resources, the application range of exploiting geothermal fluid is limited. Exploiting geothermal fluid may cause the decline of groundwater level and ground subsidence, so it is necessary to re-inject geothermal fluid to the reservoir (Kaya et al., 2011; Valgar-đur Stefansson, 1997). However, due to the limitation of reservoir physical properties, there are many problems, such as the difficulty and low efficiency of the re-injection of geothermal fluid (Ungemach, 2003; Seibt and Kellner, 2003). At the same time, the number of hole required increases. It requires large area, inconvenient management and high initial investment, which restricts large-scale utilization of this system.

In order to ensure the sustainable development of geothermal resources, avoid geothermal fluid re-injection and reduce costs, single well closed loop geothermal system can be adopted. The typical development mode for shallow geothermal reservoir is ground source heat pump system. For this system, heat transfers between the working fluid in the U-tube and the aquifer, and the ground source heat pump is used to convert the low-grade heat energy into the high-grade heat energy. However, the small heat transfer area of ground source heat pump limits its utilization in middle and deep geothermal resources (Sarbu and Sebarchievici, 2014; Yang et al., 2010). In view of this situation, downhole coaxial heat exchanger geothermal system is put forward (Horne, 1980). For this geothermal system, the working fluid is injected from the annulus and produced from the central insulated tubing, as

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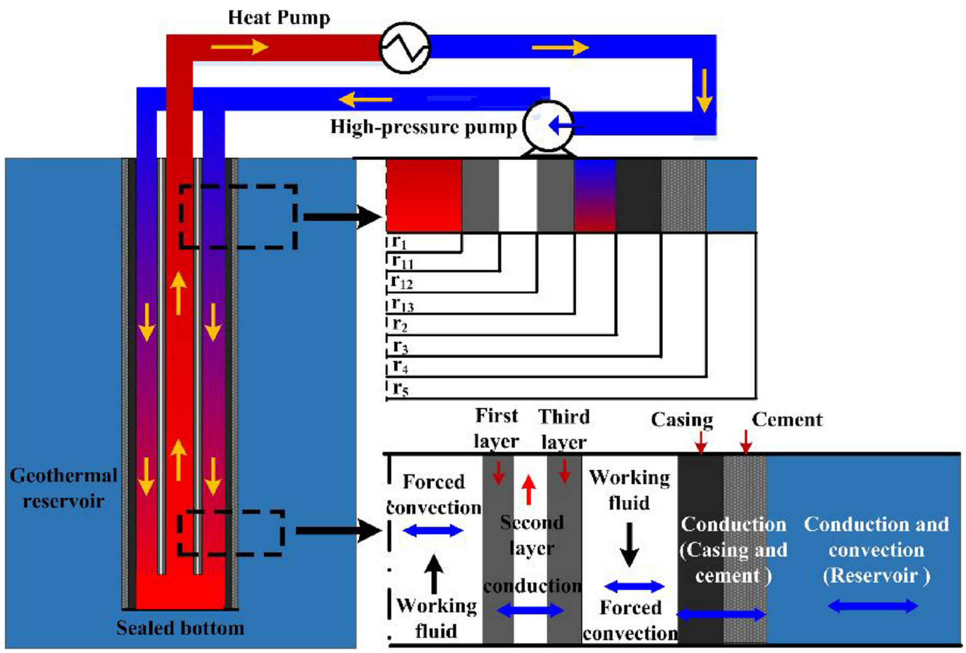

Fig. 1. Downhole coaxial heat exchanger of geothermal single-well.

shown in Fig. 1. The great heat transfer area of single well closed loop geothermal system cannot only enhance heat extraction performance, but also allow more fluid to extract heat during the circulation. As a result, DCHE system merits the advantages such as low installation costs, environmental friendly and widely applicable.

For DCHE system, the heat transfer process includes heat convection of working fluid induced by heat extraction of DCHE, heat conduction of insulated tubing, heat conduction of casing, heat conduction of cement, heat conduction of reservoir rock, and heat convection of subsurface water, as shown in Fig. 1. Consequently, there have been tremendous studies on the heat transfer model of DCHE geothermal system. In the previous attempts, Roland N. Horne established a one-dimensional quasi steady heat transfer model and obtained the analytical formula of the outlet temperature. It assumed that the heat transfer mechanism in reservoir was heat conduction. It was found that reducing the radius of the inner tube and increasing the radius of the annular space could increase the thermal power. The thermal power of reverse circulation was higher than that of positive cycle. When the velocity of central tube fluid and the annular fluid were the same, the thermal power was maximum (Horne, 1980). Then, Morita et al. used the explicit finite difference method to solve the transient heat transfer equation, in which the model ignored the heat convection and axial heat transfer in the reservoir (Morita et al., 1984). Morita et al. modified the model of DCHE system and studied the sensitivity of the insulated tubing thermal conductivity, mass flow and inlet temperature. The insulated tubing uses heat insulation material to reduce the heat dissipation into the annulus. The results showed that the insulated tubing can effectively improve the thermal power. The thermal power increased with the increasing of ground temperature gradient, and the thermal power increased with the increasing of well depth. With the increase of the inlet temperature, the outlet temperature was higher. When the entrance temperature exceeded the surface temperature, the heat insulation of the insulated tubing was not obvious. Hydraulic fracturing was helpful to improve reservoir permeability and enhance heat transfer between wellbore and reservoir (Morita et al., 1985). Due to the heat convection in the hot and humid rocks, the effective thermal conductivity was introduced by Morita et al., the effect of the inlet temperature and flow rate on the outlet temperature and pressure drop was simulated. The results showed that there was a significant increase of thermal power in the reservoir existing heat convection (Morita et al., 1989). However, the heat convection cannot be equal to heat conduction considering effective thermal conductivity. The model should be validated. In 1992, Morita et al. conducted the field test in HGP-A well in Hawaii. The results showed that the permeability of the reservoir was low, the heat transfer mechanism was mainly heat conduction. The inlet temperature, outlet temperature and pressure drop is simulated. The simulation result was basically consistent with the experimental data, which verified the accuracy of the heat transfer model. The DCHE had a great potential and a good application prospect of heat recovery (Morita et al., 1992a,b). In 1993, the commercial operation of the DCHE system was carried out in Weissbad, Switzerland, but its outlet temperature was much lower than simulated temperature. In view of this problem, Kohl T et al. established a two-dimensional axisymmetric transient heat transfer model. The results showed that non-ideal contact between cement and casing increase thermal resistance. The steel inner tube dissipated heat to the annulus also caused outlet temperature lower than expected temperature (Kohl et al., 2000). In 1996, Morita et al. introduced the use of the DCHE generating electricity in Hawaii. The study demonstrated the feasibility of the insulation central tube in the geothermal well; the magma has great potential for geothermal energy; the combination of the downhole coaxial heat exchanger and the ORC power generation system is technically feasible. Combined with DCHE, the single well geothermal system can make use of shallow geothermal resources for heating and cooling of roads and buildings (Morita et al., 1989). In order to improve the heat transfer performance of the shallow DCHE system, E. Zanchini et al. established a two-dimensional axisymmetric transient heat transfer model and solved it using COMSOL. Two different thermal conductivity cements and two different insulated tubing were compared. The simulation well depth was 100 m and simulation time was 5d. It is clear that the thermal conductivity of cement had a great influence on the thermal power. Increasing the diameter of the insulated tubing can increase the outlet temperature (Zanchini et al., 2010). There is a contradiction with the study of Roland N. Horne, which may be caused by the difference of simulation well depth and simulation time. In 2014, Richard A. Beier et al. studied the temperature profile of DCHE system. The results show that the temperature profile depends on the thermal resistance of the insulated tubing and the flow direction of working fluid (Beier et al., 2014). In 2016, Henrik Holmberg et al. evaluated the thermal power of DCHE. The study showed that with the decrease of well depth, the effect