International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 228

NUMERICAL SIMULATION AND FIELD TEST OF DOWNHOLE COAXIAL HEAT EXCHANGER GEOTHERMAL SYSTEM

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ABSTRACT

For downhole coaxial heat exchanger (DCHE), 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 numerical 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 flow in reservoir is presented. The effects of the key factors are studied. The field test is conducted to verify the feasibility of DCHE system. The simulation results depict that the increase of flow velocity in reservoir will increase the outlet temperature and thermal power. As the mass flow increases, the thermal power increases. As the inlet temperature decrease, the outlet temperature decreases and the thermal power increases. The simulation data are in good agreement with the test data, and the error is less than 12%. The findings can offer guidance for optimal design of DCHE.

Keywords: geothermal energy, DCHE, unsteady-state heat transfer numerical model, field test

1. INTRODUCTION

As a kind of clean and renewable energy, geothermal energy plays an important role in energy saving and emission reducing. In order to ensure the sustainable development of geothermal resources, avoid pollution and reduce costs, DCHE can be adopted. For this geothermal system, the working fluid is injected from the annulus and produced from the central insulated tubing, as shown in Fig 1. The great heat transfer area of DCHE cannot only enhance heat extraction performance, but also allow more fluid to extract heat.

For DCHE system, the heat transfer process includes heat convection of working fluid and subsurface water, heat conduction of tubing, casing, cement and rock, 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 one-dimensional quasi steady heat transfer model and assumed that the heat transfer mechanism in reservoir was heat conduction [1]. Then, Morita et al. used the explicit finite difference method to solve equations, in which the model ignored heat convection and axial heat transfer [2]. Morita et al. modified the model. The results showed that the insulated tubing can effectively improve the thermal power [3]. In 1992, Morita et al. conducted the field test in Hawaii. The results showed that the permeability of the reservoir was low, the heat transfer mechanism was mainly heat conduction. The DCHE had a great potential and a good application prospect of heat recovery [4-5].

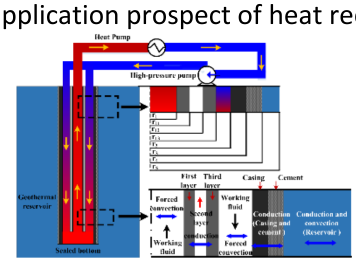

Fig 1 Downhole coaxial heat exchanger

The previous simulation and experiment studies have made contributions to comprehend the heat transfer process of DCHE. However, to the best of our knowledge, few of the numerical models consider the flow in reservoir. In this paper, an unsteady state numerical model is presented for the first time to consider flow in reservoir. The model describes the heat transfer in DCHE system. Then, influences of major parameters on DCHE performance are investigated. Finally, field test is used to analyze feasibility of DCHE. The key findings of this work can offer guidance for optimal design of DCHE geothermal system.

2. DESCRIPTION OF THE NUMERICAL MODEL

2.1 *Model assumption*

(1) Subsurface water flow in one direction; (2) Thermal conductive medium is isotropic and homogeneous, and its thermal properties are constant; (3) Water is considered as liquid state (pressure lower than 18 MPa, temperature lower than 59 ℃); (4) Viscous friction of the fluid is neglected; (5)Axial heat conduction of water is ignored.

2.2 *Heat transfer numerical model*

(1) Working fluid in insulated tubing

$$\rho_m C_m q \frac{\partial T}{\partial z} + 2\pi R_1 \Delta T = \rho_m C_m \pi r_1^2 \frac{\partial T}{\partial t} \tag{1}$$

Where T (℃) is the temperature of water in insulated tubing, q (m^3/s) is the mass flow of water, ρ_m (Kg/m^3) is the density of water, C_m (J/(kg·℃)) is the thermal capacity of water, t (s) is time, r_1 (m) is the inner radius of insulated tubing. R_1 ((m·℃)/W) is the thermal resistance of insulated tubing.

(2) Working fluid in annulus

$$\begin{aligned} &-\rho_m q C_m \frac{\partial T}{\partial z} + 2\pi R_1 \Delta T + 2\pi r_2 h_3 \Delta T \\ &= \rho_m C_m \pi \left(r_2^2 - r_{13}^2\right) \frac{\partial T}{\partial t} \end{aligned} \tag{2}$$

Where h_3 (W/(m²·℃)) is the convection coefficient between water and casing. r_2 (m) is casing inner radius.

(3) Casing

$$\begin{aligned} &\lambda_{ca} \pi \left(r_3^2 - r_2^2\right) \frac{\partial^2 T}{\partial z^2} + 2\pi r_2 h_3 \Delta T + \frac{2\pi \lambda_{34} \Delta T}{\ln \dfrac{r_3 + r_4}{r_2 + r_3}} \\ &= \rho_{ca} C_{ca} \pi \left(r_3^2 - r_2^2\right) \frac{\partial T}{\partial t} \end{aligned} \tag{3}$$

Where λ_{ca} (W/(m·℃)) is the thermal conductivity of casing, r_3 (m) is casing outer radius, ρ_{ca} (Kg/m^3) is casing density, C_{ca} (J/(kg·℃)) is casing thermal capacity, λ_{34} (W/(m·℃)) is the harmonic thermal conductivity of surface between casing and cement.

(4) Cement

$$\begin{aligned} &\lambda_{ce} \pi \left(r_4^2 - r_3^2\right) \frac{\partial^2 T}{\partial z^2} + \frac{2\pi \lambda_{34} \Delta T}{\ln \dfrac{r_4 + r_3}{r_3 + r_2}} + \frac{2\pi \lambda_{45} \Delta T}{\ln \dfrac{r_5 + r_4}{r_4 + r_3}} \\ &= \rho_{ce} C_{ce} \pi \left(r_4^2 - r_3^2\right) \frac{\partial T}{\partial t} \end{aligned} \tag{4}$$

Where r_4 (m) is cement outer radius. ρ_{ce} (Kg/m^3) is cement density. C_{ce} (J /(kg·℃)) is cement thermal capacity. λ_{45} (W/(m·℃)) is the harmonic thermal conductivity of surface between cement and reservoir.

(5) Reservoir

$$\begin{aligned} &\lambda_{eff} \left(\frac{\partial^2 T}{\partial z^2} + \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + \rho_m C_m v \frac{\partial T}{\partial x} \\ &= \rho_{eff} C_{eff} \frac{\partial T}{\partial t} \end{aligned} \tag{5}$$

Where v (m/s) is the subsurface water velocity. λ_{eff} (W/(m·℃)) is the equivalent thermal conductivity, ρ_{eff} (Kg/m^3) is the equivalent density, C_{eff} (Kg/(m³·K)) is the equivalent thermal capacity.

2.3 *Model solution*

The finite difference method with full implicit scheme is adopted to discrete these differential equations. The Gauss-Seidel iterations is employed to solve the above equations, and MATLAB serves as the programming language.

2.4 *Boundary and initial conditions*

(1) The initial temperature of thermal conductive medium is the original reservoir temperature.

(2) A Neumann boundary is imposed at the ground surface, where the adiabatic condition is applied

(3) The boundary temperature of reservoir in radial direction is the original reservoir temperature

2.5 *Model validation*

The experiment data of HGP-A well in Hawaii is shown in Fig 2 [4]. The simulation results agree with experiment data well, and the temperature difference at 7d is only 0.8 °C, which indicates the model proposed in this paper is quite reliable.

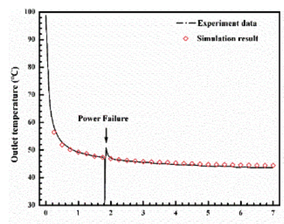

Fig 2 Simulation data and experiment data

2.6 *Model parameters*

In this paper, the research is based on geothermal field in Xiong'an New Area, which aims at exploiting geothermal resources with a depth of 1850 m. Well structure is shown in Table 1. The physical parameters of thermal conductive medium are shown in Table 2.

Table 1 Well structure parameters

Item	Surface casing	Intermediate casing	Production casing	Insulated tubing
D_{in} (mm)	339.7	228.6	161.7	62
D_{out} (mm)	320.4	244.5	177.8	114.3
Depth (m)	350	1395	1850	1800

3. ANALYSIS OF HEAT EXTRACTION PERFORMANCE

To achieve the best heat extraction performance, it is highly necessary to study the effects of the key factors, including velocity of subsurface water, mass flow, and thermal conductivity of insulated tubing.

3.1 *The effect of velocity of subsurface water*

By changing the velocity of subsurface water, the outlet temperature and the thermal power of DCHE are shown in Fig 3. With the increase of velocity, the outlet temperature and the thermal power of the system are significantly improved. The increase of subsurface water velocity can enhance strength of heat convection, and improve heat extraction performance.

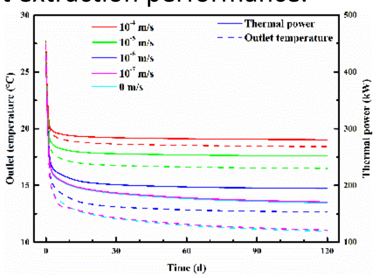

Fig 3 thermal performance with subsurface water velocity

3.2 *The effect of mass flow*

Fig 4 illustrates that thermal power decreases fast initially because of the great temperature gradient and insufficient heat compensation near the wellbore. Then, the decreasing rate of outlet temperature slows down gradually, and remains stable. The outlet temperature declines with the increase of mass flow. Due to the increase of the mass flow of water, the thermal power increases.

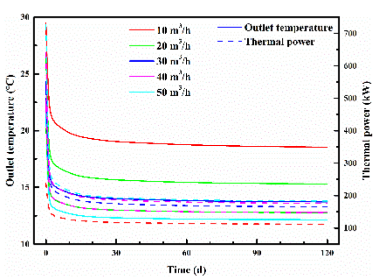

Fig 4 Thermal performance with mass flow

3.3 *The effect of insulated tubing*

Fig 5 illustrates that with the increase of thermal conductivity, the outlet temperature decreases. The thermal power declines linearly. Due to the enhancement of the forced convection heat transfer in the annular fluid and the insulated tubing under low thermal insulation, the heat transfer between the working fluid and reservoir becomes weak. Therefore, it is recommended that insulated tubing with low thermal conductivity material should be used.

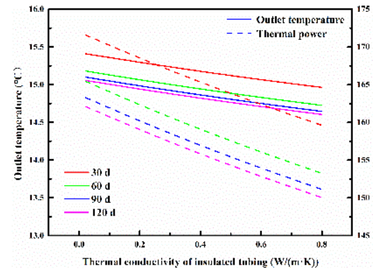

Fig 5 Thermal performance with insulated tubing

3.4 *The effect of insulated tubing*

Figure 6 illustrates that the outlet temperature increases with the increase of inlet temperature, but the thermal power declines linearly. This indicates that the smaller temperature difference between the reservoir and working fluid would weak heat extraction performance of DCHE system.

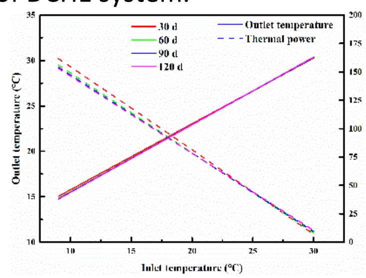

Fig 6 Thermal performance with inlet temperature

4. FIELD TEST

4.1 *Test scheme*

(1) Wellhead (as shown in Fig 7) and booster pump are installed.

Fig 7 Wellhead

(2) Insulated tubing and cable are installed downhole. The structure of insulated tubing is a double layer tubing, with inner layer of 2-7/8'' and outer layer of 4-1/2'', filled with air in the middle layer. In order to reduce cost, insulated tubing is installed from surface to 900 m, and 2-7/8'' tubing is installed from 900 m to bottom.

(3) inlet temperature is controlled at 9 ℃, and displacement is controlled at 23 m^3/h. During the test, the simulation data are compared with test data to verify technical feasibility of DCHE system.

4.2 *Test results*

Temperature data are shown in Fig 8-11. The descending region of test data and simulation data are all about 2 days, and the coincidence is high. The stable regions are concentrated between 2 days and 22 days. The error between simulation data and test data is less than 12%, which shows that the simulation data is accurate and reliable.

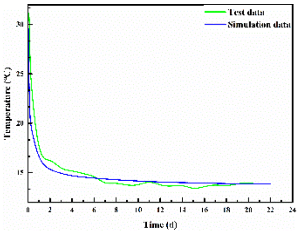

Fig 8 Temperature at 900 m in annulus

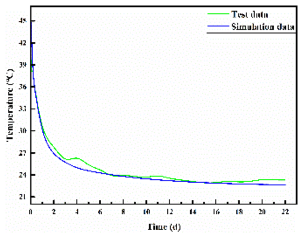

Fig 9 Temperature at 1800 m

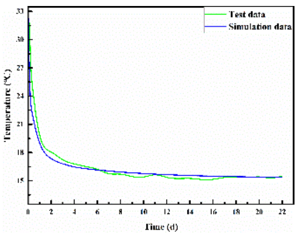

Fig 10 Temperature at 900 m in tubing

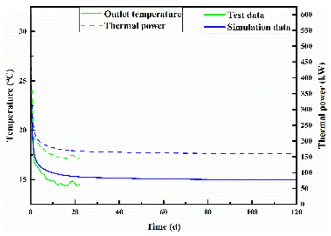

Fig 11 Temperature at outlet

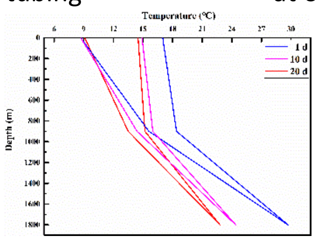

Fig 12 Test temperature in wellbore

The temperature data in wellbore is shown in Fig 12. It revealed that the temperature of the 900 m uninsulated section (from 1800 m to 900 m in the tubing) decreases by 7.6 C, and the 900 m insulated section (from 900 m to the outlet) decreases by 0.7 C. It indicates that the insulated tubing has good thermal insulation performance, and further verifies the reliability of the simulation results.

5. CONCLUSION

In this paper, an unsteady-state heat transfer model is proposed for DCHE. The influences of key parameters on heat extraction performance of DCHE are analyzed. The field test is used to verify the feasibility of DCHE system. The main conclusions are as follows:

(1) With the increase of velocity of flow in reservoir, the outlet temperature and the thermal power of the system are significantly improved. Because the increase of velocity of subsurface water can enhance strength of heat convection between wellbore and reservoir.

(2) The outlet temperature and thermal power have a remarkable decrease at the initial stage, but then remains relatively stable. Moreover, a higher mass flow leads to the decline of outlet temperature, but the thermal power would increase.

(3) With the decrease of insulated tubing thermal conductivity, the outlet temperature and thermal power increase. With the decrease of inlet temperature, the outlet temperature decreases and the thermal power increases.

(4) The simulation data are in good agreement with the test data, and the error is less than 12%, which verifies the reliability of the numerical model. The outlet temperature of the test well is stable at about 15 ℃, and the thermal power is stable at 160 kW.

ACKNOWLEDGEMENT

The authors would like to acknowledge the Program of Introducing Talents of Discipline to Chinese Universities (111 Plan) (Grant NO. B17045). Besides, support from the National Key Research and Development Program of China (Grant No. 2016YFE0124600) is appreciated.

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