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

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A B S T R A C T

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 Muneeer, 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-dur 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 (Sărbu 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
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, environmentally 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
of flow direction on thermal power decreased. In the deep well, the thermal power of DCHE system was more than that of the U-tube (Holmberg et al., 2016).

The previous simulation and experiment studies have made significant contributions to comprehend the heat transfer process of DCHE geothermal system. However, to the best of our knowledge, few of the numerical models consider the flow in reservoir. Besides, there is no comprehensive research about the influences of geothermal reservoir conditions on the heat extraction performance of DCHE system. In this paper, an unsteady state numerical model is presented for the first time to consider heat convection in reservoir. The model describes the heat transfer in DCHE system, including insulated tubing, working fluid, casing, cement and reservoir. Then, the entire temperature fields are analyzed comprehensively. Influences of major parameters, such as velocity of subsurface water, thickness of aquifer, mass flow, inlet temperature, cement thermal conductivity, ground temperature gradient, rock thermal conductivity, and depth of well on DCHE performance are investigated. The key findings of this work can offer guidance for optimal design of DCHE geothermal system.

2. Description of the numerical model

2.1. Heat extraction principle

For the DCHE geothermal system, casing and insulated tubing are located coaxially in the hole. The working fluid is injected into the annulus and produced from the insulated tubing. The heat extraction principle of DCHE system contains heat convection between working fluid and wellbore, heat convection and heat conduction between wellbore and reservoir. Through the heat exchanger, the heat energy carried by the high temperature working fluid can be used for heating or generating electricity. Then, the cooled working fluid is pumped again into the wellbore through high pressure pumps, so that the development of geothermal resources can be realized. The workflow of a single well DCHE system are shown in Fig. 2.

2.2. Model assumption

Based on the heat extraction principle of DCHE system, an unsteady state mathematical model considering heat conduction and heat convection of DCHE system is established. The assumptions include: (1) subsurface water flow in one direction; (2) the casing, cement and reservoir rock is considered as isotropic and homogeneous, and its thermal properties are regarded as constant which are independent of temperature; (3) water is served as the working fluid. According to the geothermal reservoir temperature and pressure conditions (the pressure ranges from 0 to 20 MPa, and the temperature ranges from 20 ℃ to 60 ℃), water does not vaporize, and is considered as liquid state (Thomson, 1946); (4) The viscous friction of the fluid is neglected; (5) the working fluid transfer heat mainly by convection, and the axial heat conduction of working fluid is ignored.

2.3. Heat transfer model of working fluid in insulated tubing

According to Fig. 1 the energy balance equation is established for the working fluid in insulated tubing. The second term on the left side refers to heat transfer from annular working fluid. The thermal process involves forced convection and heat conduction through insulated tubing. The expression is as follows:

\[ \rho_w C_w \frac{\partial T}{\partial t} + 2\pi R_i \Delta T = \rho_w C_w \pi r_1^2 \frac{\partial T}{\partial t} \]

Where \( T (°C) \) is the temperature of working fluid in insulated tubing, \( q \) (m³/h) is the mass flow of working fluid, \( \rho_w \) (Kg/m³) is the density of working fluid, \( C_w \) (J/(Kg·°C)) is the thermal capacity of working fluid. \( t \) (h) is the time of heat exchange. \( r_1 \) (m) is the inner diameter of insulated tubing. \( R_i \) ((m·°C)/W) is the thermal resistance between working fluid in insulated tubing and working fluid in annulus. It can be described as follow:

\[ R_i = \frac{1}{\frac{1}{r_1 R_i} + \frac{1}{\frac{\ln(\frac{r_1 + r_2}{r_1 + r_3})}{4\lambda_p}} + \frac{1}{\frac{\ln(\frac{r_3 + R_i}{r_1 + r_3})}{4\lambda_p}}} \]

Where \( \lambda_{12} \) is the harmonic thermal resistance between the first layer and the second layer of insulated tubing, which is described as follow:

\[ \lambda_{12} = \frac{r_2^2 - r_1^2}{4\lambda_p} + \frac{r_3^2 - r_2^2}{4\lambda_p} \]

Where \( \lambda_{23} \) is the harmonic thermal resistance between the second layer and the third layer of insulated tubing, which is described as follow:

\[ \lambda_{23} = \frac{r_3^2 - r_1^2}{4\lambda_p} + \frac{r_4^2 - r_3^2}{4\lambda_p} \]

Where \( h_i \) (W/(m²·°C)) is the convection heat transfer coefficient between working fluid and insulated tubing. \( r_1 \) (m) is the outer diameter of the first layer insulated tubing. \( r_2 \) (m) is the outer diameter of the second layer insulated tubing. \( r_3 \) (m) is the outer diameter of the third layer insulated tubing. \( \lambda_{23} \) (W/(m·°C)) is the thermal conductivity of the first and the third layer insulated tubing. \( \lambda_{23} \) (W/(m·°C)) is the thermal conductivity of the second layer insulated tubing. \( h_i \) (W/(m²·°C)) is the convection heat transfer coefficient between working fluid and casing. The convection heat transfer coefficient represents the strength of heat convection, which depends on the physical properties of the fluid, velocity of the fluid, the shape of the heat transfer surface and area of the heat transfer surface. It can be described as follow:

\[ h = \frac{N_u \lambda_{23}}{D} \]

Where, \( \lambda_{23} \) (W/(m·°C)) is the thermal conductivity of working fluid. \( D \) (m) is the inner diameter of pipe. \( N_u \) is Nusselt number which represents the dimensionless characteristic number of two similar convective phenomena. It can be calculated by Gnielinski (Gnielinski, 1975) formula:

\[ N_u = \frac{\left( \frac{h_i}{h} \right) (Re - 1000) - Pr}{1 + 12.7 \sqrt{\frac{Pr}{Re}} \left( \frac{Pr^{2/3}}{Re} - 1 \right)} \]

Where Re is Reynold number. Pr is Prandl number. \( f \) is the turbulence drag coefficient in tube, which can be calculated by Filonenko (Filonenko, 1954) formula:
\[ f = \frac{1}{(1.82\lg Re - 1.64)} \quad (7) \]

Applicable conditions of Eq. (7) are:

\[ Re = 2300 \sim 10^3, \quad Pr = 0.6 \sim 10^3, \quad L/D > 10, \quad \text{where} \ L/D \ is \ the \ ratio \ of \ length \ and \ diameter. \] The flow in the annulus usually corresponds to the flow in tube, and the hydraulic diameter is introduced as follow:

\[ D_{eq} = 2(r_2 - r_1) \quad (8) \]

Where \( D_{eq} \) (m) is hydraulic diameter. \( r_1 \) (m) is the inner radius of annulus. \( r_2 \) (m) is the outer radius of annulus.

### 2.4. Heat transfer model of working fluid in annulus

The energy balance equation is established for the working fluid in annulus. The third term on the left side refers to heat transfer from casing. The thermal process involves forced convection and heat conduction through annulus. The expression is as follows:

\[ - \rho_m q C_m \frac{\partial T}{\partial z} + 2 \pi r_1 h_1 \Delta T + 2 \pi r_2 h_2 \Delta T = \rho_m c_m \pi (r_2^2 - r_1^2) \frac{\partial T}{\partial t} \quad (9) \]

Where \( h_1 \) (W/(m²·K)) is the convection heat transfer coefficient between working fluid and casing. \( r_2 \) (m) is the inner diameter of the casing.

### 2.5. Heat transfer model of casing

The energy balance equation is established for the casing. The third term on the left side refers to heat transfer from cement sheath. The thermal process involves forced convection and heat conduction through casing. The expression is as follows:

\[ \lambda_{ca} \pi (r_3^2 - r_4^2) \frac{\partial T}{\partial z} + 2 \pi r_3 h_3 \Delta T = \rho_c c_c \pi (r_3^2 - r_4^2) \frac{\partial T}{\partial t} \quad (10) \]

Where \( \lambda_{ca} \) (W/(m·K)) is the thermal conductivity of casing. \( r_4 \) (m) is the outer diameter of casing. \( \rho_c \) (Kg/m³) is the density of casing. \( C_c \) (J/(K·m³)) is the thermal capacity of casing. \( \lambda_{ca} \) (W/(m·K)) is the harmonic thermal conductivity of surface between casing and cement sheath, which can be described as follow:

\[ \lambda_{ca} = \frac{r_3^2 - r_4^2}{\lambda_{ca}} + \frac{r_3^2 - r_4^2}{\lambda_{ca}} \quad (11) \]

Where \( \lambda_{ca} \) (W/(m·K)) is the thermal conductivity of cement.

### 2.6. Heat transfer model of cement sheath

The energy balance equation is established for the cement sheath. The third term on the left side refers to heat transfer from reservoir. The thermal process involves heat conduction through cement. The expression is as follows:

\[ \lambda_{es} \pi (r_5^2 - r_6^2) \frac{\partial T}{\partial z} + \frac{2 \pi r_5 h_5 \Delta T}{\ln \frac{r_5}{r_6}} + \frac{2 \pi r_6 h_6 \Delta T}{\ln \frac{r_5}{r_6}} = \rho_e c_e \pi (r_5^2 - r_6^2) \frac{\partial T}{\partial t} \quad (12) \]

Where \( r_6 \) (m) is the outer diameter of cement sheath. \( \rho_e \) (Kg/m³) is the density of cement sheath. \( C_e \) (J/(K·m³)) is the thermal capacity of cement sheath. \( \lambda_{es} \) (W/(m·K)) is the harmonic thermal conductivity of surface between cement sheath and reservoir, which can be described as follow:

\[ \lambda_{es} = \frac{r_5^2 - r_6^2}{\lambda_{es}} + \frac{r_5^2 - r_6^2}{\lambda_{es}} \quad (13) \]

Where \( \lambda_{es} \) (W/(m·K)) is the thermal conductivity of reservoir rock.

### 2.7. Heat transfer model of outside reservoir

The energy balance equation is established for outside reservoir. The terms on the left side refer to heat transfer in z-direction, x-direction, y-direction and heat transfer from subsurface water. The thermal process involves heat conduction and heat convection through reservoir. The expression is as follows:

\[ \lambda_{ef} \left( \frac{\partial^2 T}{\partial z^2} + \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + \rho_m C_m \frac{\partial T}{\partial x} = \rho_m C_m \frac{\partial T}{\partial t} \quad (14) \]

Where \( v \) (m/s) is the velocity of subsurface water. \( \lambda_{ef} \) (W/(m·K)) is the equivalent thermal conductivity of reservoir, which can be described by formula:

\[ \lambda_{ef} = (1 - \phi) \lambda_f + \lambda_m \quad (15) \]

Where \( \phi \) is the porosity of reservoir. \( \rho_f \) (Kg/m³) is the equivalent density of reservoir, which can be described as follow:

\[ \rho_f = (1 - \phi) \rho_f + \rho_m \quad (16) \]

Where \( \rho_f \) (Kg/m³) is the density of reservoir rock. \( C_f \) (Kg/(m³·K)) is the equivalent thermal capacity, which can be described as follow:

\[ C_f = (1 - \phi) C_f + C_m \quad (17) \]

Where \( C_f \) (Kg/(m³·K)) is the thermal capacity of reservoir rock.

### 2.8. Model solution

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

### 2.9. Boundary and initial conditions

(1) The initial temperature of working fluid, insulated tubing, casing and cement sheath are the original reservoir temperature.

\[ Q_{out} = q \rho_m c_m T_{in} \quad (18) \]

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

\[ \frac{\partial T}{\partial z} \bigg|_{z=0} = 0 \quad (19) \]

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

\[ T = T_i + a \cdot j \cdot \Delta z \quad (20) \]

Where \( T_i \) (°C) is the ground surface temperature. \( a \) (°C/m) is the geothermal gradient. \( \Delta z \) is the axial grid length. \( j \) is the number of grid cells in axial direction.

### 2.10. Model validation

To determine the accuracy of mathematic model, the experimental data of HGP-A well in Hawai is adopted, and the outlet temperature is shown in Fig. 3 (Morita et al., 1992a,b). It should be noted that there was a power failure during the experiment in Fig. 3, but the temperature variation trend remains basically unchanged and the influence can be neglected. Consequently, the data obtained from the experiment is reasonable. It is clear that 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.
3. Model parameters

In this paper, the research is based on geothermal field in Xiong’an New Area, Hebei Province, China, which aims at exploiting geothermal resources with a depth of 2000 m. And it is intended to employ DCHE for its cleanliness and efficiency. Based on the Technical specification for geothermal well drilling released the People’s Republic of China, DCHE is designed as the second spudging structure, and its specific parameters are shown in Table 1. Table 2 lists the physical parameters of heat conduction medium.

Based on the geological data of Xiong’an geothermal reservoir, the ground surface temperature is 20 °C, and the geothermal gradient is 0.03 °C/m. The velocity of subsurface water is $1.27 \times 10^{-7}$ m/s, the thickness of aquifer is 1000 m, and the porosity is 0.2. Additionally, due to the climatic conditions in the north of China, the heating time is usually from November to March of the next year. Hence, the computation time in our model is set as 4 months.

4. Analysis of temperature field

Fig. 4 displays that the impact scope is limited by comparison with the size of reservoir in radial direction, which also indicates the computational domain adopted in our model is reasonable. Apparently, a much larger temperature gradient appears around the borehole, and that’s why the thermal process from the reservoir to working fluid mainly occurs along radial direction. Besides, a local enlargement is carry out to distinguish the wellbore from the surrounding reservoir.

According to different thermal insulation conditions, we investigate the temperature distribution of working fluid in wellbore at 120d. Fig. 5 shows that the temperature in annulus increases gradually with well depth, while the temperature in insulated tubing only has a little reduction, which proves its well thermal insulation. However, for the DCHE without thermal insulation, the temperature in wellbore changes sharply, which indicates that the heat transfer between the insulated tubing and annulus is strong. But this would cause smaller temperature difference between the working fluid and reservoir, which is not beneficial to heat transfer. Thus, the difference of outlet temperature can even reach 15 °C. Additionally, if we employ partial thermal insulation, the outlet temperature also has a remarkable increase in Fig. 5.

The heat extraction radius refers to the radial influence distance of the DCHE system on the geothermal reservoir during the process of heat extraction. The study of heat extraction radius can be used to obtain the impact scope of geothermal development on the reservoir. It can guide for optimization design of well spacing and rational development of the geothermal reservoir. Fig. 6 is the variation curve of the temperature difference near wellbore and temperature of well bore at different depth. The result shows that the temperature difference near wellbore is large. With the increase of the radial distance, the temperature difference rapidly decreases. It is known that the radius of heat extraction increases with the increase of well depth. Because the increase of well depth increases the temperature difference between working fluid and reservoir, which can enhance the heat exchange. After 4 months, the impact radius of the upper reservoir is about 20 m, the impact radius of deep aquifer influenced by heat convection is about 40 m. There is a water source in the upstream direction to supply heat to the wellbore continuously while the heat in downstream direction cannot be supplemented in time, which leads to the asymmetry of reservoir temperature distribution in radial direction.

5. 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, thickness of aquifer, inlet temperature, mass flow, geothermal gradient, thermal conductivity of cement and reservoir conditions, etc. And the formula for thermal power is as follows:

$$Q_{out} = 0.001q(c_{p,in}c_{out}T_{out} - \rho_{in}c_{in}T_{in})$$  \hspace{1cm} (21)

Where $Q_{out}$ (Kw) is the thermal power. $\rho_{in}$ (Kg/m³) is the density of inlet working fluid. $c_{p,in}$ (J/(Kg·°C)) is thermal capacity of inlet working fluid. $T_{in}$ (°C) is the temperature of inlet working fluid. $c_{p,out}$ (J/(Kg·°C)) is thermal capacity of outlet working fluid. $T_{out}$ (°C) is the temperature of outlet working fluid.

5.1. The effect of velocity of subsurface water

By changing the velocity of subsurface water, the outlet temperature and the thermal power of DCHE are calculated as shown in Fig. 7. With the increase of velocity, the outlet temperature and the thermal power of the system are significantly improved. Because the increase of subsurface water velocity can enhance strength of heat convection between wellbore and reservoir, and improve heat extraction performance. For the geothermal reservoir existing fluid flow, the influence of the fluid flow on the heat extraction performance needs to be considered.

Changing the thermal conductivity of the reservoir and geothermal gradient, the outlet temperature and the thermal power under different subsurface water velocity are shown in Figs. 8 and 9 respectively.

As shown in Fig. 8, with the increase of reservoir thermal conductivity, the difference of the outlet temperature and the thermal power under different subsurface water velocity gradually expands. It

### Table 1: Well structure parameters.

<table>
<thead>
<tr>
<th>Structure parameter</th>
<th>Surface casing</th>
<th>Production casing</th>
<th>Insulated tubing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner diameter (mm)</td>
<td>228.6</td>
<td>161.7</td>
<td>62</td>
</tr>
<tr>
<td>Outer diameter (mm)</td>
<td>244.5</td>
<td>177.8</td>
<td>114.3</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>300</td>
<td>2000</td>
<td>1950</td>
</tr>
</tbody>
</table>

### Table 2: Physical parameters of heat conduction medium.

<table>
<thead>
<tr>
<th>Physical parameters</th>
<th>Casing</th>
<th>Insulated tubing</th>
<th>Cement</th>
<th>Air</th>
<th>Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>8060</td>
<td>8060</td>
<td>2140</td>
<td>25</td>
<td>2200</td>
</tr>
<tr>
<td>Thermal capacity</td>
<td>400</td>
<td>400</td>
<td>1900</td>
<td>1380</td>
<td>850</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>43.75</td>
<td>43.75</td>
<td>0.8</td>
<td>0.022</td>
<td>3</td>
</tr>
</tbody>
</table>

$ρ (Kg/m^3)$ is the density of inlet working fluid. $c_{p,in} (J/(Kg·°C))$ is thermal capacity of inlet working fluid. $T_{out}$ (°C) is the temperature of outlet working fluid.
Fig. 4. Temperature contours of the wellbore and surrounding formation at 120d.

Fig. 5. Temperature distribution of working fluid in wellbore at 120d.

Fig. 6. Temperature difference distribution at 900 m, 1200 m, 1500 m, 1800 m.

Fig. 7. Outlet temperature and thermal power with production time under different subsurface water velocity.

Fig. 8. Outlet temperature and thermal power with reservoir thermal conductivity under different subsurface water velocity at 120d.
shows that the increase of reservoir thermal conductivity will enhance the influence of subsurface water velocity on DCHE system. The influence of subsurface water velocity on the heat extraction performance of DCHE system is defined as follow:

\[
W = \frac{\Delta Q_{\text{later}} - \Delta Q_{\text{initial}}}{\Delta Q_{\text{initial}}} \times 100\% \tag{22}
\]

Where \( \Delta Q_{\text{initial}} \) (kW) is thermal power difference among different subsurface water velocity under the lowest reservoir thermal conductivity. \( \Delta Q_{\text{later}} \) (kW) is thermal power difference among different subsurface water velocity under the highest reservoir thermal conductivity. \( W \) (%) is an influence factor of subsurface water velocity on thermal power. The calculation results of \( W \) (%) are shown in Table 3.

In Table 3, \( W \) between \( 10^{-6}\text{m/s} \) and \( 10^{-7}\text{m/s} \) is 4.60\%, \( W \) between \( 10^{-5}\text{m/s} \) and \( 10^{-7}\text{m/s} \) is 35.43\%, and \( W \) between \( 10^{-4}\text{m/s} \) and \( 10^{-7}\text{m/s} \) is 57.09\%. The increase of reservoir thermal conductivity can enhance the influence of subsurface water on heat extraction performance.

Similarly, in Table 4, \( W \) between \( 10^{-6}\text{m/s} \) and \( 10^{-7}\text{m/s} \) is 100.14\%, \( W \) between \( 10^{-5}\text{m/s} \) and \( 10^{-7}\text{m/s} \) is 100.04\%, and \( W \) between \( 10^{-4}\text{m/s} \) and \( 10^{-7}\text{m/s} \) is 100.03\%. The results show that the increase of geothermal gradient may not enhance the influence of subsurface water on heat extraction performance.

### 5.2. The effect of aquifer thickness

By changing the aquifer thickness, the outlet temperature and the thermal power of DCHE are calculated as shown in Fig. 10. With the increase of aquifer thickness, the outlet temperature and the thermal power of the system are significantly improved. Because the increase of aquifer thickness can enhance strength of heat convection between wellbore and reservoir, and improve heat extraction performance. For the geothermal reservoir existing fluid flow, the influence of the fluid flow on the heat extraction performance needs to be considered.

In Fig. 10, it is known that the outlet temperature and the thermal power increase with the increase of the aquifer thickness. When the thickness exceeds 1000 m, the capacity increase of the DCHE system tends to be stable, and the increase relation is approximately linear. The slope of curve at 30d, 60d, 90d and 120d are 2.63 kW/100 m, 3.51 kW/100 m, 3.98 kW/100 m and 4.28 kW/100 m respectively. The thickness of aquifer will significantly affect the heat extraction performance of DCHE system. For the geothermal reservoir existing fluid flow, the influence needs to be considered.

Changing the thermal conductivity of the reservoir and geothermal gradient, the outlet temperature and the thermal power under different aquifer thickness are shown in Figs. 11 and 12 respectively. As shown in Fig. 11, with the increase of reservoir thermal conductivity, the difference of the outlet temperature and the thermal power under different aquifer thickness gradually expands. It shows that the increase of the thermal conductivity of reservoir will enhance the influence of aquifer thickness on DCHE system. The influence of aquifer thickness on the heat extraction performance of DCHE system is defined as follow:

### Table 3

Calculation results of \( W \) in Fig. 8.

<table>
<thead>
<tr>
<th>Item</th>
<th>( 10^{-6}\text{m/s} ) and ( 10^{-7}\text{m/s} )</th>
<th>( 10^{-5}\text{m/s} ) and ( 10^{-7}\text{m/s} )</th>
<th>( 10^{-4}\text{m/s} ) and ( 10^{-7}\text{m/s} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta Q_{\text{initial}} ) (kW)</td>
<td>54.40</td>
<td>168.28</td>
<td>214.16</td>
</tr>
<tr>
<td>( \Delta Q_{\text{later}} ) (kW)</td>
<td>56.90</td>
<td>227.90</td>
<td>336.42</td>
</tr>
<tr>
<td>( W ) (%)</td>
<td>4.60%</td>
<td>35.43%</td>
<td>57.09%</td>
</tr>
</tbody>
</table>

### Table 4

Calculation results of \( W \) in Fig. 9.

<table>
<thead>
<tr>
<th>Item</th>
<th>( 10^{-6}\text{m/s} ) and ( 10^{-7}\text{m/s} )</th>
<th>( 10^{-5}\text{m/s} ) and ( 10^{-7}\text{m/s} )</th>
<th>( 10^{-4}\text{m/s} ) and ( 10^{-7}\text{m/s} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta Q_{\text{initial}} ) (kW)</td>
<td>39.24</td>
<td>150.28</td>
<td>222.62</td>
</tr>
<tr>
<td>( \Delta Q_{\text{later}} ) (kW)</td>
<td>78.53</td>
<td>300.61</td>
<td>445.30</td>
</tr>
<tr>
<td>( W ) (%)</td>
<td>100.14%</td>
<td>100.04%</td>
<td>100.03%</td>
</tr>
</tbody>
</table>
Where $\Delta Q_{\text{initial}}$ (kW) is thermal power difference among different aquifer thickness under the lowest reservoir thermal conductivity. $\Delta Q_{\text{later}}$ (kW) is thermal power difference among different aquifer thickness under the highest reservoir thermal conductivity. $W$ (%) is an influence factor of aquifer thickness on thermal power. The calculation results of $W$ (%) are shown in Table 5.

In Table 5, $W$ between 800 m and 1000 m is 14.32%, $W$ between 800 m and 1200 m is 16.25%, and $W$ between 800 m and 1400 m is 18.36%. The increase of reservoir thermal conductivity can enhance the influence of aquifer thickness on heat extraction performance.

Similarly, in Table 6, $W$ between 800 m and 1000 m is 100.14%, $W$ between 800 m and 1200 m is 100.04%, and $W$ between 800 m and 1400 m is 100.03%. The results show that the increase of geothermal gradient may not enhance the influence of subsurface water on heat extraction performance.

### 5.3. The effect of mass flow

Fig. 13 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 working fluid, the thermal power increases. The outlet temperature of DCHE needs to be kept at about 30 °C to meet the requirement of heat pump. This means that the flow rate should be less than 20 m$^3$/h, as shown in Fig. 13, and its outlet temperature is approximately 32 °C at 120d. The mass flow is set as 20 m$^3$/h in following analysis.

According to Fig. 14, the outlet temperature declines with the increase of mass flow, and the thermal power increases with the increase of mass flow. Because the increase of mass flow leads to a faster flow rate, which reduces the time of heat transfer between working fluid and reservoir, thereby reducing the outlet temperature.

### 5.4. The effect of inlet temperature

Fig. 15 illustrates that the outlet temperature increases with the increase of inlet temperature, but the thermal power declines linearly, and its curve slope is approximately $-7.28842$ kW/°C at 120d. This indicates that the smaller temperature difference between the reservoir and working fluid would weak heat extraction performance of DCHE system. Accordingly, the inlet temperature should be as low as possible if the outlet temperature meets the heating requirements. Thus, the inlet temperature is set as 20 °C in following analysis.

### 5.5. The effect of thermal conductivity of cement

Because of the lower thermal conductivity of cement compared to that of reservoir, so it may hinder the heat transfer between the reservoir and working fluid. Obviously, the outlet temperature and thermal power have a significant change when the thermal conductivity

\[
W = \frac{\Delta Q_{\text{later}} - \Delta Q_{\text{initial}}}{\Delta Q_{\text{initial}}} \times 100\% \tag{23}
\]
rise from 0.1 W/(m·K) to 1.2 W/(m·K) in Fig. 16. From 0.1 W/(m·K) to 0.7 W/(m·K), the thermal power and outlet temperature increase rapidly. From 0.7 W/(m·K) to 1.2 W/(m·K), the growth rate of thermal power and outlet temperature are slow. And the thermal power at 1.2 W/(m·K) can increase by 92.65% compared to that at 0.1 W/(m·K) after 120 days. Note that if the well cementing operations is not carried out, the subsurface water (0.569 – 0.687 W/(m·K)) would fill its space, which can result in worse performance.

5.6. The effect of insulated material

Fig. 17 illustrates that with the increase of thermal conductivity, the outlet temperature decreases. The thermal power declines linearly, and its curve slope is approximately −50.2234 kW/(0.1 W/(m·K)) at 120d. 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.

5.7. The effect of geothermal gradient

Fig. 18 illustrates that the outlet temperature and thermal power increase linearly with geothermal gradient, and the curve slope can even reach 3.60 °C/(°C/100 m) and 83.85 kW/(°C/100 m) at 120d, respectively. Consequently, the thermal conductivity of reservoir rock have remarkable impact on the heat extraction performance.

5.8. The effect of reservoir thermal conductivity

Fig. 19 shows that the outlet temperature and thermal power increase with the reservoir thermal conductivity, and this trend slows...
6. Conclusion

In this paper, an unsteady-state heat transfer model is proposed for the development of geothermal resources with high reservoir thermal conductivity.

5.9. The effect of well depth

Fig. 20 depicts that the growth rate of outlet and thermal power increase with well depth because of the heat transfer enhancement between the reservoir and working fluid. And if we employ a well depth of 2000 m, the outlet temperature difference can reach over 40°C compared to the outlet temperature at 5000 m. Hence, the DCHE system has great superiority in exploiting the middle-deep geothermal resources.

6. Conclusion

In this paper, an unsteady-state heat transfer model is proposed for DCHE geothermal system. The finite difference method is employed to solve the heat transfer model. Subsequently, the temperature field in reservoir is analyzed. And the influences of key parameters on heat extraction performance of DCHE are analyzed. The main conclusions are as follows:

(1) The temperature field analysis shows that there is a significant large gradient around the wellbore, indicating the heat transfer mainly occurs in the radial direction. The result shows that with the increase of the radial distance, the temperature difference decreases. It is known that the radius of heat extraction will increase with the increase of well depth. Because the increase of well depth increases the temperature difference between working fluid and reservoir, which can enhance the heat exchange. After 4 months, the impact radius of the upper reservoir is about 20 m, the impact radius of deep aquifer influenced by heat convection is about 40 m. There is a water source in the upstream direction to supply heat to the wellbore continuously while the heat in downstream direction cannot be supplemented in time, which leads to the asymmetry of reservoir temperature distribution in radial direction.

(2) 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, and improve heat extraction performance. For the geothermal reservoir existing fluid flow, the influence of the fluid flow on the heat extraction performance needs to be considered. Furthermore, the increase of reservoir thermal conductivity can enhance the influence of subsurface water on heat extraction performance, while the increase of geothermal gradient may not enhance the influence of subsurface water on heat extraction performance.

(3) 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. As the inlet temperature increases, the outlet temperature declines and the thermal power increases. This depicts that larger temperature difference between the reservoir and working fluid could enhance the strength of heat transfer. With the increase of cement thermal conductivity, the outlet temperature and thermal power increase. It indicates that cement sheath with high thermal conductivity could enhance the heat transfer from reservoir to working fluid. With the decrease of insulated tubing thermal conductivity, the outlet temperature and thermal power increase. It indicates that insulated tubing with low thermal conductivity could enhance the strength of heat transfer from reservoir to working fluid.

(4) The increase of reservoir thermal conductivity and geothermal gradient can enhance the heat exchange between reservoir and working fluid. It indicates that DCHE geothermal system may suitable for exploiting geothermal resources with high thermal conductivity and temperature gradient. Additionally, the growth rate of outlet temperature and thermal power increase with the increase of well depth. The findings can offer guidance for optimal design of DCHE geothermal system.

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