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Numerical Simulation of the Effect of Aquifer Permeability on the Heat Output of an Open Loop Geothermal Single Well System

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ABSTRACT

Deep geothermal single well system is one of the geothermal energy utilization mode that only takes heat without consuming water. Compared with the traditional mode, this system avoids the problem of difficult sandstone reinjection, which can greatly reduce drilling costs, and is applicable to a wide range of geological conditions. Geothermal single well system can be divided into close loop and open loop system. The latter exchanges heat with the aquifer by convection heat transfer and mass transfer, the heat output is higher than that of the close loop system through conduction heat transfer. In this paper, a three-dimensional unsteady flow and heat transfer model is established for the open loop coaxial casing of the geothermal deep single well with a packer, the effect of the density of geothermal water on the aquifer temperature distribution and heat output of the single well under different aquifer permeability is numerically simulated. The result shows that when the permeability of the aquifer is greater than 1.0E-12 m^2, the permeability has a great influence on the heat output of a single well, while when the permeability is less than 1.0E-12 m^2, the permeability has little effect the heat output too much. The permeability has little effect on the heat output of a single well. The results can be used for calculating the heat output of a single well in different aquifers.

Keywords: open loop, deep geothermal single well, aquifer, permeability, density, heat output

1. INTRODUCTION

Most of the geothermal resources in China are low temperature geothermal resources (Li, 2020), and the geothermal production and reinjection mode are the common way of geothermal utilization in north of China. However, the poor reinjection into sandstone formation has been the technical problem form many years, and for this reason, more than 1,000 geothermal wells were shut off in Hebei, China in 2021, thus the deep geothermal single well system has received extensive attention in recent years. This technology uses the geothermal single well mode, which does not have the problem of difficult reinjection and saves the drilling cost (Gioia, 2018), this system is applicable to a wide range of formation conditions (Collins MA, 2017). The deep geothermal single well system can be divided into close loop and open loop system, the heat output of the close system is low due to the conduction heat transfer with the aquifer (Wang, 2019). In contrast, the open loop system exchange energy with the aquifer by both convection heat transfer and mass transfer, the heat output of the well is much higher than that of the close loop system. Ma et al. (2017) conducted a field test of a geothermal single well system with a coaxial casing structure in UK, a system with 2 km deep well would achieve a delivery temperature of 69°C. Using the assumed return temperature of 40 °C, the well would deliver a peak load of 363 kW with 7 kW input: an equivalent COP of 52. Dai et al. (2017) conducted a field test of open loop single-well system in Tianjin, China, and the stable heat output of the system can reach 275kW after 3 days of operation, this is the first in-situ open loop geothermal single well system in China. Wang (2019) proposed an open loop single well heat exchanger structure, and the packer was used to separating the upper reinjection section and lower production section, the numerical simulation of the heat output with the aquifer permeability in the range of 5.0E-14 m^2 to 2.0E-13 m^2 was carried output. In this paper, a three-dimensional unsteady flow and heat transfer model in the aquifer was established for the open loop deep geothermal single well system with a packer, and the effect of aquifer permeability ranged from 1.0E-10 m^2 to 1.0E-13 m^2 on the heat output was numerically calculated.

2. MODEL

2.1 Initial and boundary conditions

In the deep geothermal single well heat extraction system, production and reinjection are in the same well. In order to avoid the thermal breakthrough caused by the mixing of reinjected cold water and produced hot water, it is necessary to set a packer at a suitable position in the well. As shown in Fig.1, the packer divides the geothermal wellbore into the upper water intake section and the lower reinjection section, so that the higher temperature geothermal water enters the upper section of the wellbore and flows to the wellhead for heat exchange, and the injected cold water entering the bottom of the wellbore, avoiding the drop of the water intake temperature caused by the mixing of cold water. The heat energy of this model mainly comes from the convective heat transfer of geothermal water in the aquifer, so this paper focuses on the fluid flow and heat transfer inside the aquifer. Since there is mass and energy exchange between the wellbore and the aquifer in the actual flow, in order to characterize the flow coupling between the wellbore and the aquifer, the reinjection section between the wellbore and the aquifer is set as the boundary of constant pressure and temperature, and the pumping section is set as the boundary of constant pressure and temperature. The temperature is determined according to the fluid mass average; the upper part of the aquifer is an insulating caprock, which is set as an adiabatic wall; the lower end of the aquifer is connected to a 20m thick low-permeability formation, and the bottom of the low-permeability formation is set to a constant temperature condition; the far end of the aquifer is a constant pressure boundary.

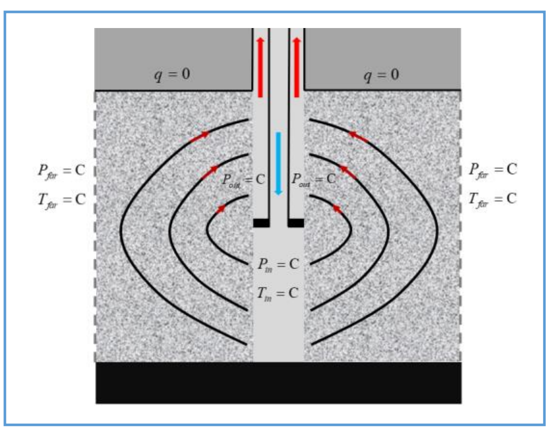


Fig. 1 Model description

In the mathematical model, it is assumed that the aquifer permeability is in the range of 1.0E-10 m^2 to 1.0E-13 m^2, the thickness is 100m, the isotropic uniform porous formation with the initial temperature is 60℃, the porosity is set to 0.35, and the thermal conductivity is 3.75 W/(m·K). The diameter of the geothermal wellbore is 180mm, and the calculation region is cylindrical with a radius of 150m. The outer boundary of the area is set as a constant pressure and constant temperature boundary with a pressure of 13.7 MPa and a temperature of 60 °C. The low permeability reservoir temperature below the aquifer is 60 °C. The simulated heat exchanger runs stably at 8.33kg/s for 120 days.

2.2 Governing equation

The flow of geothermal water in the aquifer satisfies the continuity Eq. (1), and Eq. (2) is the momentum equation of fluid flowing in the aquifer, where $-\frac{\mu}{k}\vec{v}$ is the Darcy term and k is the permeability. Eq. (3) is the energy equation, the three terms on the right side are heat conduction, diffusion and viscous dissipation, respectively. where γ is the porosity of the aquifer, and λ_{eff} is the effective thermal conductivity of the aquifer, defined in Eq. (4). The density of geothermal water varies with temperature, and its expression is shown in equation Eq. (5).

$$\nabla\cdot(\rho\vec{v})=0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho\vec{v})+\nabla\cdot(\rho\vec{v}\vec{v})=-\nabla p+\nabla\cdot(\bar{\bar{\tau}})+\rho\vec{g}-\frac{\mu}{k}\vec{v} \tag{2}$$

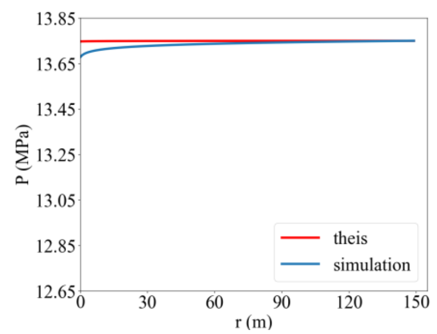
$$\begin{aligned}&\frac{\partial}{\partial t}(\gamma\rho_f u_f+(1-\gamma)\rho_s u_s)+\nabla\cdot(\vec{v}(\rho_f u_f+p))\\&=\nabla\cdot(\lambda_{eff}\nabla T-(\sum_i h_i J_i)+(\bar{\bar{\tau}}\cdot\vec{v}))\end{aligned} \tag{3}$$

$$\lambda_{eff}=\gamma\lambda_f+(1-\gamma)\lambda_s \tag{4}$$

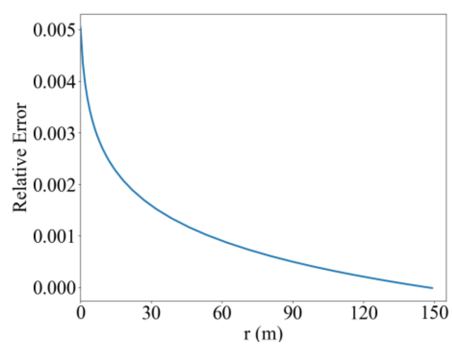
$$\rho=\begin{cases}1000\cdot(1-\frac{(T-273.13)^2}{503570}\cdot\frac{T+9.85}{T-205.89})\\ \qquad \text{for } 273.15\text{K}\le T<293.15\text{K}\\ 996.9\cdot(1-3.17\cdot10^{-4}\cdot(T-298.15)-\\ 2.56\cdot10^{-6}\cdot(T-298.15)^2)\\ \qquad \text{for } 293.15\text{K}\le T<523.15\text{K}\end{cases} \tag{5}$$

2.3 Model verification

The model is verified by the calculation results of the Theis model after 120 days of system operation, under a constant flow rate of 8.33kg/s and a formation permeability of 10-12 m2, as shown in Fig.2, where Fig.2(a) is the pressure distribution in the aquifer, and Fig.2(b) is the relative error between the two results. It can be seen that the relative error within the radius of 150 m is less than 0.5%, and the relative error of the remote aquifer pressure is less than 0.1% This is because the well diameter is neglected in the Theis model, resulting in a large difference in the aquifer pressure around the well in the two models.



(a) Aquifer pressure distribution



(b) Relative error

Fig. 2 Model validation

3. RESULTS AND DISCUSSIONS

In this paper, when the circulating fluid flow rate was 8.33kg/s and the system ran for 120 days, the aquifer permeability (1.0E-10 m^2 to 1.0E-13 m^2) and geothermal fluid density affect the temperature distribution of the aquifer and the heat output of a single well. As shown in Fig. 3, considering that the heat output of a single well under the condition that density vary with temperature is greater than that of a single well under the condition of constant water density. When the aquifer permeability is 1.0E-12 m^2, the heat output considering the density change is 8.53kW, which is 0.68% higher than that of the condition of constant density; When the aquifer permeability is 1.0E-11 m^2 and 1.0E-10 m^2, respectively, the difference of heat extraction rate between constant density and thermo-induced density is 129.29kW and 436.03kW, respectively, which are 10.39% and 35.42% of the heat output under the condition of constant density. When the permeability of the aquifer is greater than 1.0E-12 m^2, with the increase of the permeability, the difference of the single well heating power taking into account the change of density with temperature gradually increases.

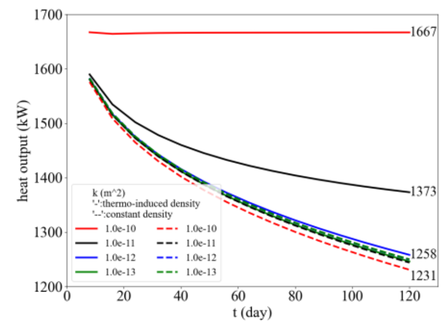
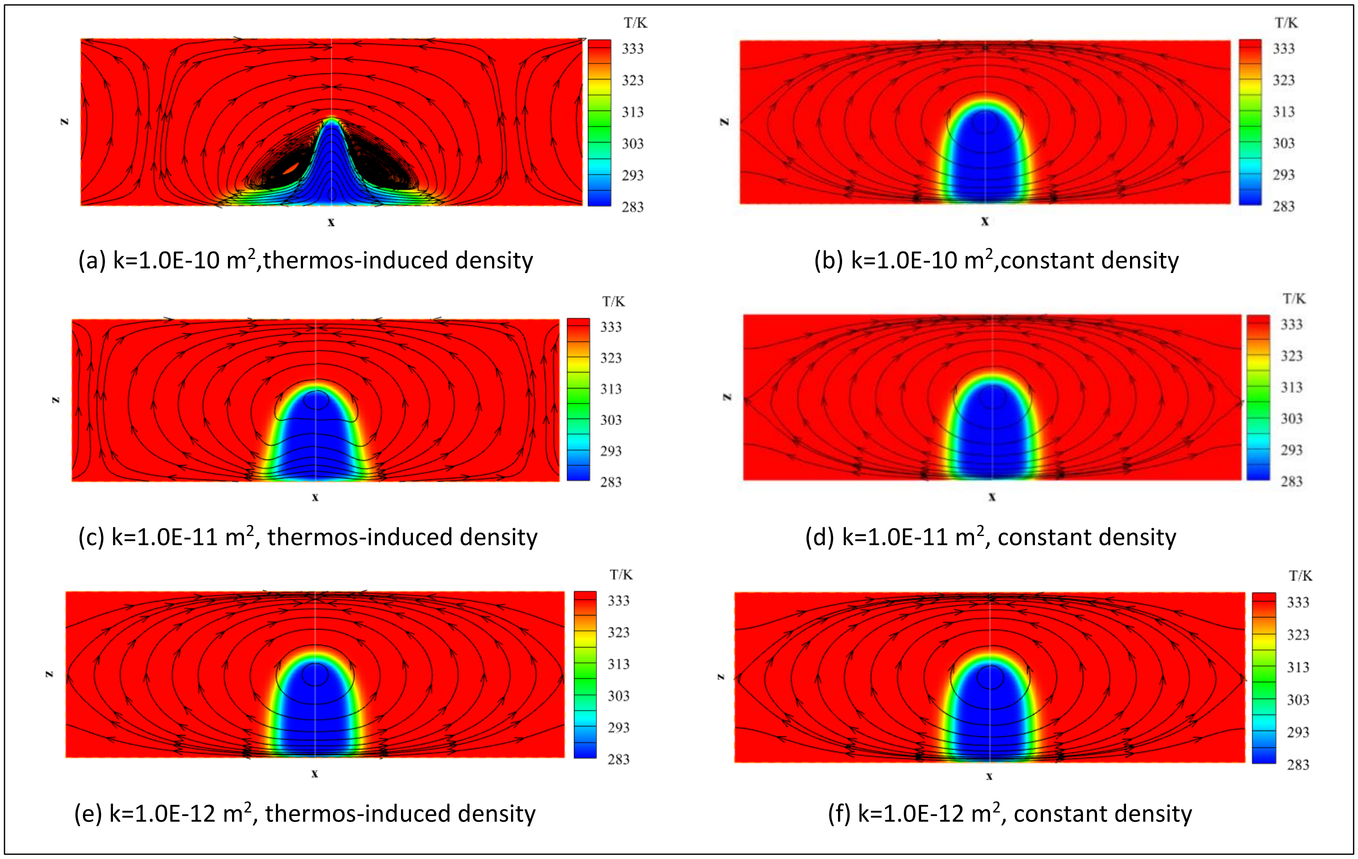


Fig. 3 Outlet water temperature under different aquifer permeability

In formations with different permeability, the temperature contour and streamlines diagram of the aquifer when the single-well heat extraction system operates for 120 days is shown in Fig. (4). It can be seen that when the permeability of the aquifer is 1.0E-10 m^2 and 1.0E-11 m^2, respectively, the low temperature water flow line of the reinjection is shifted to the direction of gravity, and this phenomenon is more obvious when the permeability is 1.0E-10 m^2. This is because the low-temperature water in the reinjection has a high density and flows downward under the action of gravity, which makes the cold water flow to the bottom of the aquifer and drives the high-temperature water in the aquifer to migrate to the pumping port while moving away from the pumping port. The system has higher outlet water temperature and stable heat output. When the permeability of the aquifer is small (<1.0E-12 m^2), according to the Darcy term $\left(-\frac{\mu}{k}\vec{v}\right)$ in Eq. (2), the permeability introduces a large resistance and the natural convection phenomenon inside the aquifer is weak. The permeability of the aquifer has little effect on the temperature distribution of the aquifer and the heat output of a single well.

4. CONCLUSIONS

In this paper, we proposed an open loop deep geothermal single well system with the packer, the effect of aquifer permeability and fluid density on the aquifer temperature distribution and heat output of the single well is numerically simulated. The results show that the permeability of the aquifer affects the heat extraction power of a single well within a certain range. When the permeability of the aquifer is greater than 1.0E-12 m^2,



(a) k=1.0E-10 m^2,thermos-induced density

(b) k=1.0E-10 m^2,constant density

(c) k=1.0E-11 m^2, thermos-induced density

(d) k=1.0E-11 m^2, constant density

(e) k=1.0E-12 m^2, thermos-induced density

(f) k=1.0E-12 m^2, constant density

Fig. 4 Contour temperature and streamlines

the heat output of a single well increases as the permeability increase, while when the permeability is less than 1.0E-12 m^2, the change of the permeability has little effect on the heat output. In addition, the change of water density has little effect on the heat output of a single well. Therefore, if the permeability of the aquifer is less than 1.0E-12 m^2, the effect of permeability and geothermal water density on the heat output can be ignored in the calculation.

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