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Seepage-heat transfer coupling process of low temperature return water injected into geothermal reservoir in carbonate rocks in Xian County, China

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Abstract: Fracture seepage and heat transfer in the geothermal reservoir of carbonate rocks after the reinjection of low temperature geothermal return water is a complex coupling process, which is also the frontier of geothermal production and reinjection research. Based on the research of cascade comprehensive development of geothermal resources in Beijing-Tianjin-Hebei (Xian County), the carbonate geothermal reservoir of Wumishan formation in the geothermal field in Xian County is investigated. With the development of the discrete fracture network model and the coupling model of seepage and heat transfer, the numerical solution of seepage field and temperature field with known fracture network is reached using the finite element software COMSOL, and the coupling process of seepage flow and heat in carbonate rocks is revealed. The results show that the distribution of temperature field of fractured rocks in geothermal reservoir of carbonate rocks has strong non-uniformity and anisotropy. The fracture network is interpenetrated, which constitutes the dominant channel of water conduction, and along which the fissure water moves rapidly. Under the influence of convective heat transfer and conductive heat transfer, one of the main factors to be considered in the study of thermal breakthrough is to make the cold front move forward rapidly. When the reinjection and production process continues for a long time and the temperature of the geothermal reservoir on the pumping side drops to a low level, the temperature of bedrocks is still relatively high and continues to supply heat to the fissure water, so that the temperature of the thermal reservoir on the pumping side will not decrease rapidly to the water temperature at the inlet of reinjection, but will gradually decrease after a long period of time, showing an obvious long tail effect. The distribution of fractures will affect the process of seepage and heat transfer in carbonate reservoirs, which should be considered in the study of fluid thermal coupling in carbonate reservoirs.

Keywords: Carbonate reservoir; Geothermal reinjection; Fractured rock mass; Fluid thermal coupling

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Introduction

The thermal reservoirs of the bedrocks at middle and deep levels of the earth are favored by many countries due to their high temperature and large thermal reserves (LIN Wen-jing *et al*. 2013; WANG Gui-ling *et al*. 2017; LIU Yan-guang *et al*. 2017a; WANG Gui-ling *et al*. 2018; HONG

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Zeng-lin *et al*. 2019). However, many complicated technical problems have been encountered in the pumping and reinjection process, among which the most important is the multi-field coupling process in deep fractured rocks, mainly including water seepage, heat transfer, ion transmission, mechanical process, *etc*. (LIU Jiu-rong, 2013; CHEN Bi-guang *et al*. 2013; LIU Yan-guang *et al*. 2019a). Currently, numerical method has many advantages compared with on-site measurement and analytical method. It costs less and can better reflect the complex structure and physical process underground (WANG Xiao-xing *et al*. 2012; ZHAO Zhi-hong *et al*. 2017; CUI Han-bo *et al*. 2020). ZHAO Yang-sheng *et al*. (2002) established the block fractured medium model of high-temperature rock mass, which essentially simplified the rock mass into matrix and fractured medium, and carried out three-dimensional numerical simulation by using MFHDM100 analysis software to simulate the thermal-fluid-solid coupling process. ZHAO Yan-lin *et al*. (2010) developed a three-dimensional thermal-hydraulic-mechanical coupling model based on the dual medium hypo-thesis of continuous medium and discrete medium. Using the software DETHM, they analyzed the stress distribution of discontinuous surfaces and its influence on temperature field. SUN Zhi-xue *et al*. (2016) regarded fractured rock mass as a dual medium of discrete fracture network and matrix rocks, and reached the fully coupled solution of temperature field, seepage field and stress field of fractured rock mass by using COMSOL finite element software, and analyzed the distribution of seepage, temperature, stress and deformation in the reservoir of dry and hot rock formations. In view of the inhomogeneity and anisotropy of the distribution of fractures in the rock, CHEN Bi-guang *et al*. (2014) generalized the fracture network model by using the random fracture network method proposed by Leung & Zimmera (2012). Based on the methodology in solute transmission and exchange between fracture and matrix rock proposed by Zhang and Woodbury (2002), the governing equation describing seepage and heat transfer process of fractured rock was proposed. The above research provides a good methodology for studying thermal reservoir of fractured rocks, and the research on the inhomogeneity and anisotropy of fractures in carbonate rocks needs to be further carried out.

The Institute of Hydrogeology and Environmental Geology, Chinese Academy of Geological Sciences, relying on the research base of cascade comprehensive development and utilization of geothermal resources in Beijing, Tianjin and Hebei (Xian County), developed the production and reinjection system, and carried out the tracing experiment with the reinjection of geothermal reservoir in the Wumishan formation (LIU Yan-guang *et al*. 2019b). Based on the reinjection test, this paper puts forward the coupling model of seepage and heat transfer according to discrete fracture network model. In the finite element software COMSOL, the fully coupled solution of seepage field and temperature field of fractured rock mass with known fracture network is reached, and the coupling process of flow and heat in fractures of carbonate rocks is revealed. The findings lay a scientific foundation for the exploitation and reinjection of geothermal resources under similar geological conditions in the county and other regions in Beijing, Tianjin, and Hebei.

1 Seepage-heat transfer model based on fracture element

Darcy’s law is used to describe the seepage process, which can be used to simulate the low speed flow with low permeability and porosity, in which pressure is the main driving force. The governing equations are as follows:

(1) Governing equation of seepage field in porous media

Combining Darcy’s law with continuity equation (LIU Gui-hong *et al*. 2019):

$$\frac{\partial}{\partial t}(\varepsilon_s \rho_f)+\nabla\cdot(\rho_f u)=Q_m \tag{1}$$

In the equation: t is time; ε_s is the porosity of porous media; ρ_f is fluid density; Q_m is the mass source of the fluid; u is the Darcy velocity, which can be expressed as (only considering two dimensions, excluding gravity):

$$u=-\frac{k_s}{\mu}\nabla P \tag{2}$$

In the equation: k_s is the permeability of porous media; μ is the hydrodynamic viscosity; p is the fluid pressure in pores; the water storage model can be expressed as:

$$\frac{\partial}{\partial t}(\varepsilon_s P_f) = P_f S \frac{\partial P}{\partial t} \quad (3)$$

Where: S is the storage coefficient of porous media; the compressibility of the introduced fluid (χ_f) can be expressed as:

$$S=\varepsilon_s \chi_f \quad (4)$$

Combining the above formula, the governing equation can be expressed as follows:

$$\rho_f S\frac{\partial p}{\partial t} + \nabla\cdot\rho_f(-\frac{ks}{\mu}\nabla p) = Q_m \quad (5)$$

(2) Governing equation of seepage field in discrete fracture network:

$$d_{fr}\frac{\partial}{\partial t}(\varepsilon_{fr}P_f) + \nabla_T\cdot(P_f q_{fr}) = d_{fr}Q_m \quad (6)$$

In the Equation 6: d_{fr} is the fracture width; ε_{fr} is the porosity of fracture; ∇_T is the gradient operator restricted to the fracture section; q_{fr} is the discharge per unit length in the fracture, which can be expressed as (only considering two dimensions, excluding the gravity):

$$q_{fr}=d_{fr}\,u=-\frac{k_{fr}}{\mu}d_{fr}\nabla_T p \quad (7)$$

In the Equation 7: k_{fr} is discrete fracture permeability.

(3) Governing equation of temperature field in porous media:

The heat transfer process in porous media is described by convective diffusion equation, and the thermodynamic properties are averaged by volume to consider the solid matrix and pore fluid. The governing equations are as follows (ZHAO Zhi-hong *et al*. 2020):

$$(\rho C_p)_{eff}\frac{\partial T}{\partial t} + \rho C_{p,f}u\cdot\nabla T + \nabla\cdot q = Q \quad (8)$$

Where: q is the conductive heat vector, expressed as:

$$q=-K_{eff}\nabla T \quad (9)$$

In the Equation 9: T is temperature; $C_{p,f}$ is the specific heat capacity of the fluid at constant pressure; Q is the heat source; K_{eff} is the effective thermal conductivity of porous media, which is given through the weighted average of thermal conductivity of porous media K_s and thermal conductivity of fluid K_f; $(\rho C_p)_{eff}$ is the effective volume heat capacity of porous media, expressed as:

$$(\rho C_p)_{eff}=\theta_s\rho_s C_{p,s}+(1-\theta_s)\rho_f C_{p,f} \quad (10)$$

In the Equation 10: θ_s is the volume fraction of porous medium; ρ_s is the density of porous media; $C_{p,s}$ is the specific heat capacity of porous media at constant pressure;

(4) Governing equation of temperature field in the discrete fracture network:

$$d_{fr}(\rho C_p)_{eff}\frac{\partial T}{\partial t} + d_{fr}\rho_f C_{p,f}u\cdot\nabla_t T + \nabla_t\cdot d_{fr}q_{fr} = d_{fr}Q_f \quad (11)$$

In the Equation 11: Q_f is the heat source of fractures.

2 Geothermal and geological characteristics of the research area

The investigated geothermal field is located in Xian County, Hebei Province. It crosses two grade III structural units, *i.e*. an uplift in Cang County and a depression in central Hebei Province. It is at the intersection of depression in Raoyang, uplift in Xian County, depression in Fucheng and uplift in Qing County. The main fault in Xian County is the boundary fault of the aforementioned two grade III structural units in the area, which has affected the deposition of strata, resulting in the absence of Guantao formation and Paleogene deposits in the uplift area of Xian County, a grade IV structural unit. The depth of bedrock is about 1 300~1 500 m, while in the depression in Raoyang, a grade IV structural unit belonging to the area of depression in central Hebei has the depth of more than 4 000 m (LIU Yan-guang *et al*. 2019b; QIN Xiang-xi *et al*. 2019; WANG Jun-ke *et al*. 2020). Geothermal reservoirs can be pore type or karst fractured type (FENG Jian-yun *et al*. 2019). Among them, the thermal reservoir in matrix rock is mainly associated with Wumishan formation of Jixian system in the Middle Proterozoic. The main lithology is dolomite, and the temperature is in the range of 80~107°C. The research area is located in Meizhuangwa farm in the east of Xian County, which is the research base for cascade comprehensive development and utilization of geothermal resources in Beijing, Tianjin and Hebei (Xian County) (Fig. 1). The karst fractured geothermal reservoir of Wumishan formation has been developed here, which has a single well with the inflow of 120 m^3/h. The buried depth of the reservoir is 1 326 m, and the thickness is 2 003 m (Fig. 2). The lithology is mainly dolomite and chert banded dolomite (LIU Yan-guang *et al*. 2019b; LI Ting-xin *et al*. 2020).

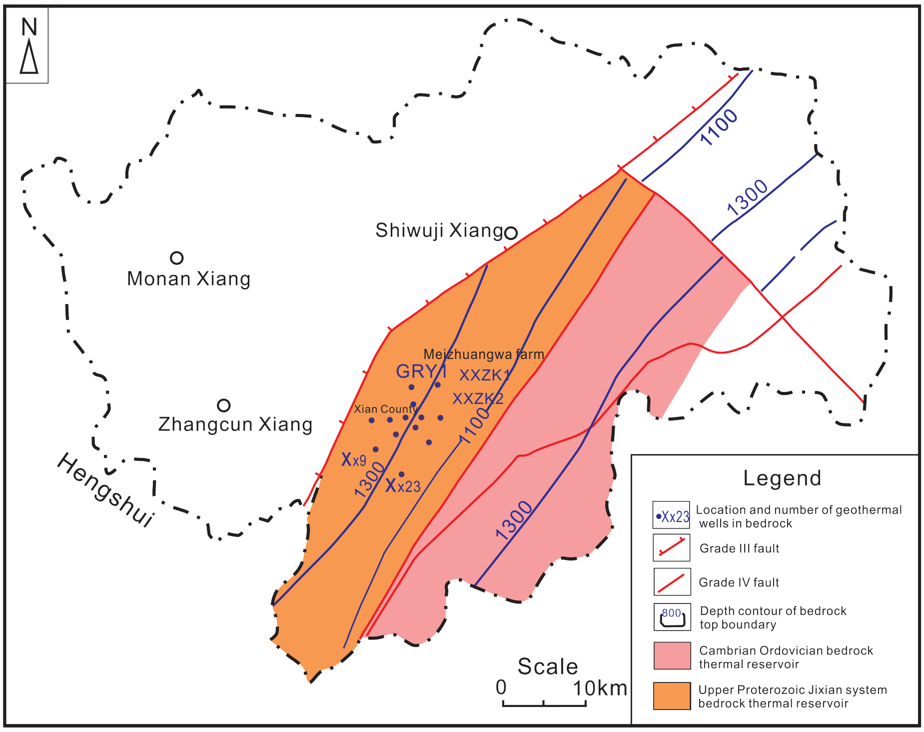


Fig. 1 Distribution map of bedrock thermal reservoir in Xian County

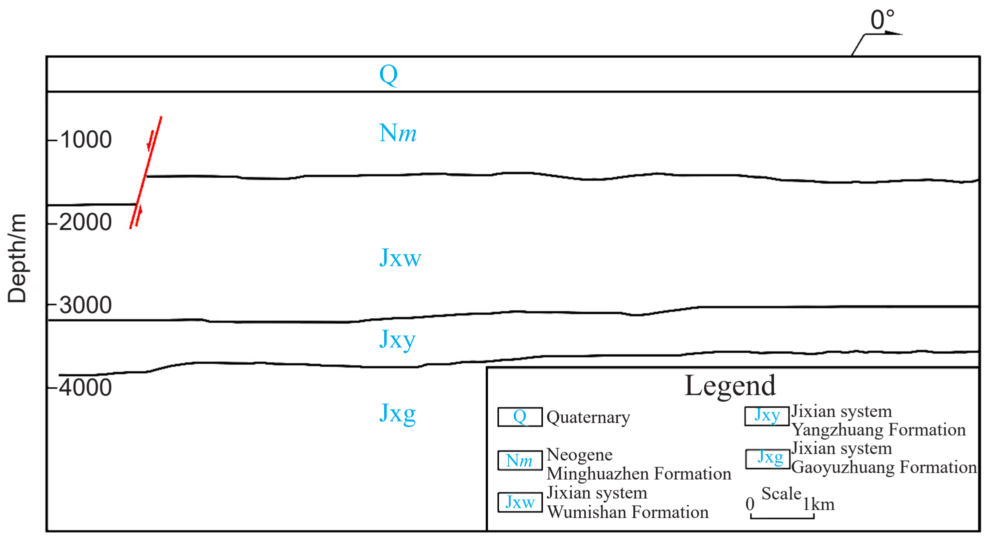


Fig. 2 Geological profile in the research area

3 Establishment of two-dimensional fracture network model

Based on the geological survey, borehole hydraulic test, tracer test and statistical parameters of fractures from borehole core logging in the research area, this paper adopts the method of generating random fracture network proposed by Leung and Zimmerman (2012), CHEN Bi-guang *et al* (2014), and uses the finite element software COMSOL to generate the fracture network, capture the endpoint coordinates of fractures, and then do the calculation. In order to reduce the influence on the boundary, the fractures in the range of 30 m × 30 m are generated, and the fractures in 20 m × 20 m are intercepted for analysis. Finally, two groups of fractures with obvious anisotropy are generated. The average trace length of the fracture is 2 m and the variance is 1 m, which follows normal distribution. The fracture width is 0.4 mm and the density is 1 m/m^2.

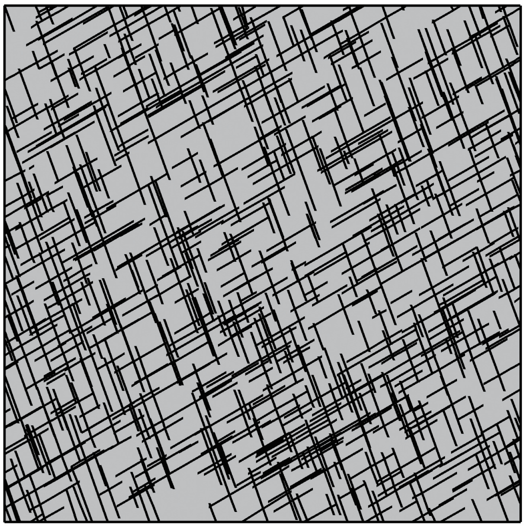


Fig. 3 Numerical model schematics

In this simulation, the working condition of XXZK2 well with final holes in 2 000 m in the research base of Xian County is taken as the initial condition. The pressure difference between reinjection and production is 0.5 Mpa, with 19.5 Mpa on the pumping side, and 20 MPa on the reinjection side. The temperature of the injected geothermal return water is 30°C and the average reservoir temperature is 90°C. The influence of upper and lower boundaries is excluded in this two-dimensional model, so the upper and lower boundaries are taken as no-flow boundary and always in adiabatic boundary conditions. The computational parameters are shown in Table 1. In order to better reflect the influence factors of temperature field change, the fracture permeability is increased by 10 times. The finite element grid is shown in Fig. 3. A total of 271 372 domain elements and 31 862 boundary elements are generated. The transient solver is used in calculation which involves 30 days and the step size is 1 day.

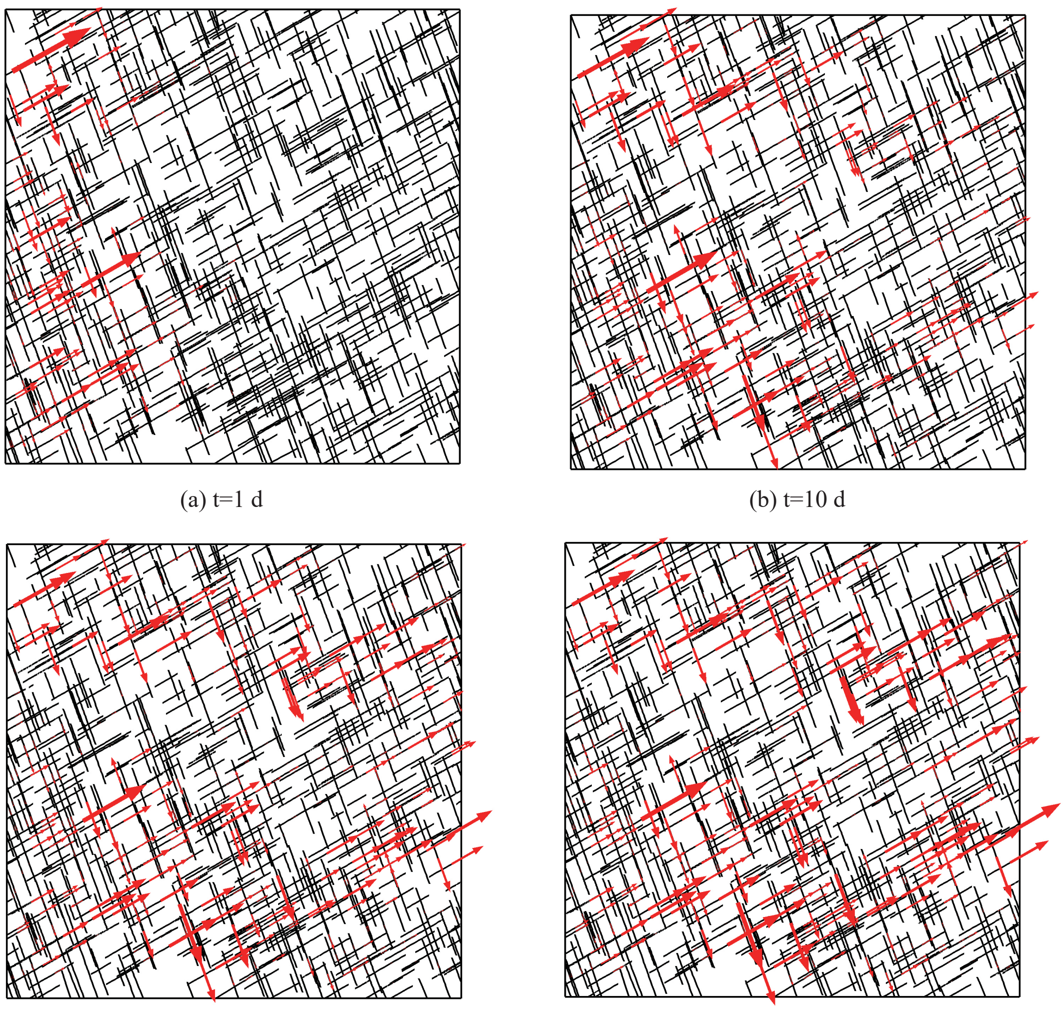
Table 1 Computational parameter

Name of parameter		Sign	Numerical value	Unit
Fracture	Porosity	ε_{fr}	0.5	-
	Permeability	k_{fr}	1.0×10^{-8}	m^2
Porous media	Density	ρ_s	2 800	kg/m^3
	Specific heat capacity at constant pressure	$C_{p,s}$	920	J/(kg·K)
	Thermal conductivity	K_s	5	W/(m·K)
	Porosity	ε_s	0.25	-
	Permeability	k_s	1.0×10^{-14}	m^2
Water	Density	ρ_f	1 000	kg/m^3
	Thermal conductivity	K_f	0.68	W/(m·K)
	Specific heat capacity at constant pressure	$C_{p,f}$	4 200	J/(kg·K)
	Fluid compressibility	χ_f	0.000 1	1/Pa
	Dynamic viscosity	μ	0.001	Pa·s
	Specific heat rate	γ	1	-
Boundary conditions and initial conditions	Temperature of reinjection side	T_in	30	°C
	Pressure of reinjection side	P_in	20	MPa
	Pressure of mining side	P_out	19.5	MPa
	Initial temperature of reservoir	T_str	90	°C
	Initial pressure of reservoir	P_str	19.5	MPa
	Boundary conditions	The upper and lower boundaries are thermally insulated and fixed without flow		

4 Results analysis

4.1 Change of seepage field

Fluid flow is an important factor affecting the temperature field. It is of great significance to study the change of seepage field in the reservoir after the reinjection of low-temperature return water (LIU Yan-guang *et al*. 2017b; 2019c). It can be seen from Fig. 4 that at the initial stage, on the reinjection side low-temperature water flows into the fracture under high pressure, and flows along the fracture network to the pumping side. Low-temperature return water in the reservoir flows preferentially along two well-connected fracture networks (WANG Gui-ling *et al*. 2019). According to the fluid pressure distribution at different times in Fig. 5, a high-pressure zone is formed on the reinjection side at the initial stage, which moves to the pumping side as time goes by. The distribution of pressure in the reservoir tends to be stable after about 20 days, and it is considered that the seepage field is also stable. When the high-pressure zone is moving, the pressure front is irregularly shaped with higher conductivity along the fracture networks. The fluid pressure in the fractures increases rapidly, while the fluid pressure in the bedrock mass increases gradually, but consistent with the fluid pressure in the fracture (WANG Shu-fang *et al*. 2013; SUN Zhi-xue *et al*. 2017).



(a) t=1 d (b) t=10 d

(c) t=20 d (d) t=30 d

Fig. 4 Schematic diagram of reservoir seepage velocity

4.2 Change of temperature field

The distribution of temperature field at different times is shown in Fig. 6. At the initial stage, low-temperature return water is injected into the reservoir, an irregular cold front rapidly forms on

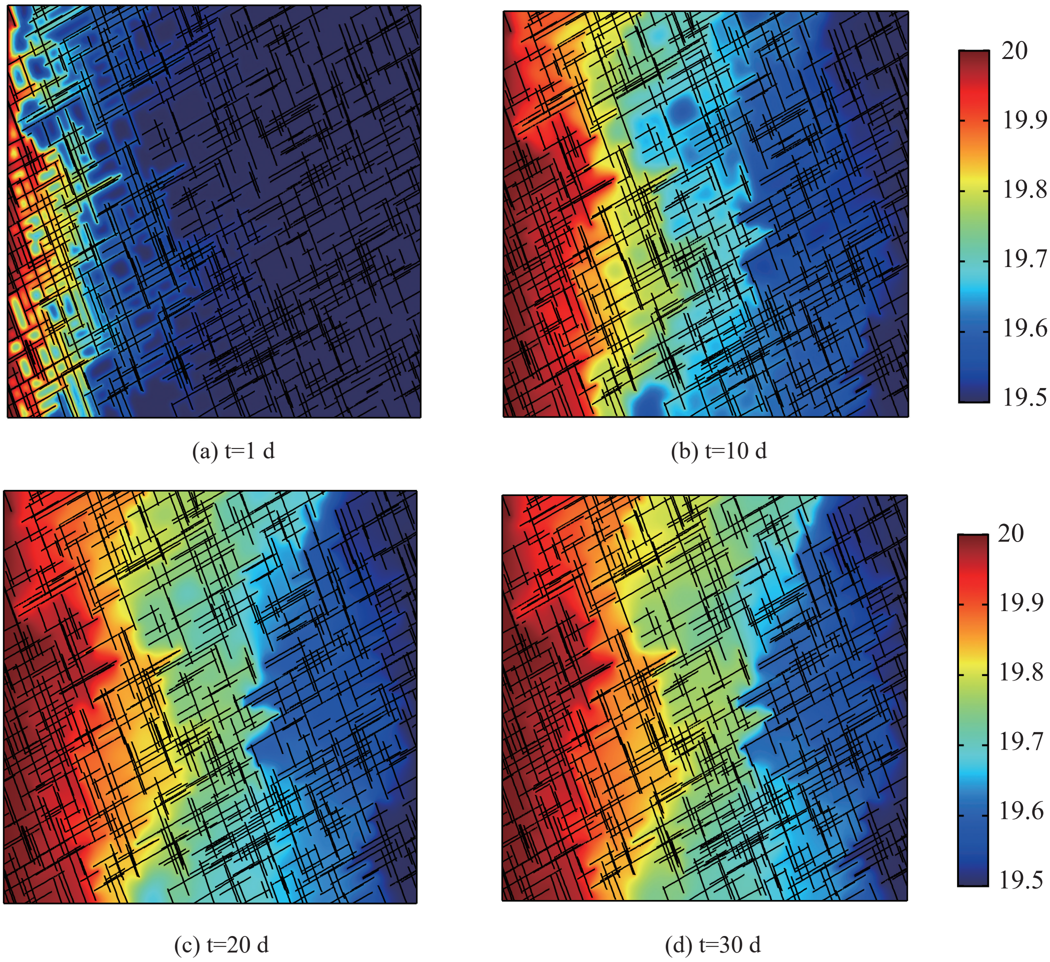


Fig. 5 Reservoir pressure distribution at different times (unit: MPa)

the injection side in the bedrocks, and with time passing, the cold front gradually moves from the injection side to the pumping side. This process shows obvious convective heat transfer (CHEN Bi-guang *et al*. 2014; LIU Yan-guang *et al*. 2015; SUN Zhi-xue *et al*. 2016).

After the low-temperature geothermal return water is injected into the reservoir fissures, heat exchange occurs between the water and the bedrocks. As a result, the water temperature increases and the rock temperature decreases. The temperature drop of the rock mass near the fissure surface is greater than that far from the fissure surface. The temperature change of carbonate rock matrix is closely related to the distance of fissure surface, which is mainly determined by the heat conduction between the fissure water and bedrock. Meanwhile, it is obvious that the temperature change of rocks near some densely distributed fracture network is relatively rapid. This is largely due to the strong inhomogeneity and anisotropy of the fractured rock mass in carbonate geothermal reservoir. The existence of interconnected fracture network constitutes the dominant channel of water flow, and the forward-moving fissure water pushes the cold front to move forward rapidly under the dual mechanism of convective heat transfer and conduction heat transfer, from which the irregularly-shaped cold front is formed (ZHANG Shu-guang *et al*. 2011; ZHAO Zhi-hong *et al*. 2017). It is easy to cause early thermal breakthrough under such circumstance, which is disadvantageous to the sustainable utilization of geothermal resources. When the reinjection process circulates for a long time and the temperature of the thermal reservoir on the pumping side drops to a low level, the temperature of some bedrocks is still high and continues to supply heat to the fissure water, so that the temperature of the thermal reservoir on the pumping side will decrease gradually other than rapidly to the inlet water temperature of the injection side. This is the so-called long tail effect. When studying seepage and heat transfer, we found if the fracture distribution and heat transfer mechanism are not considered and the rock is represented as equivalent continuum, the calculation results can not reflect these two main characteristics.

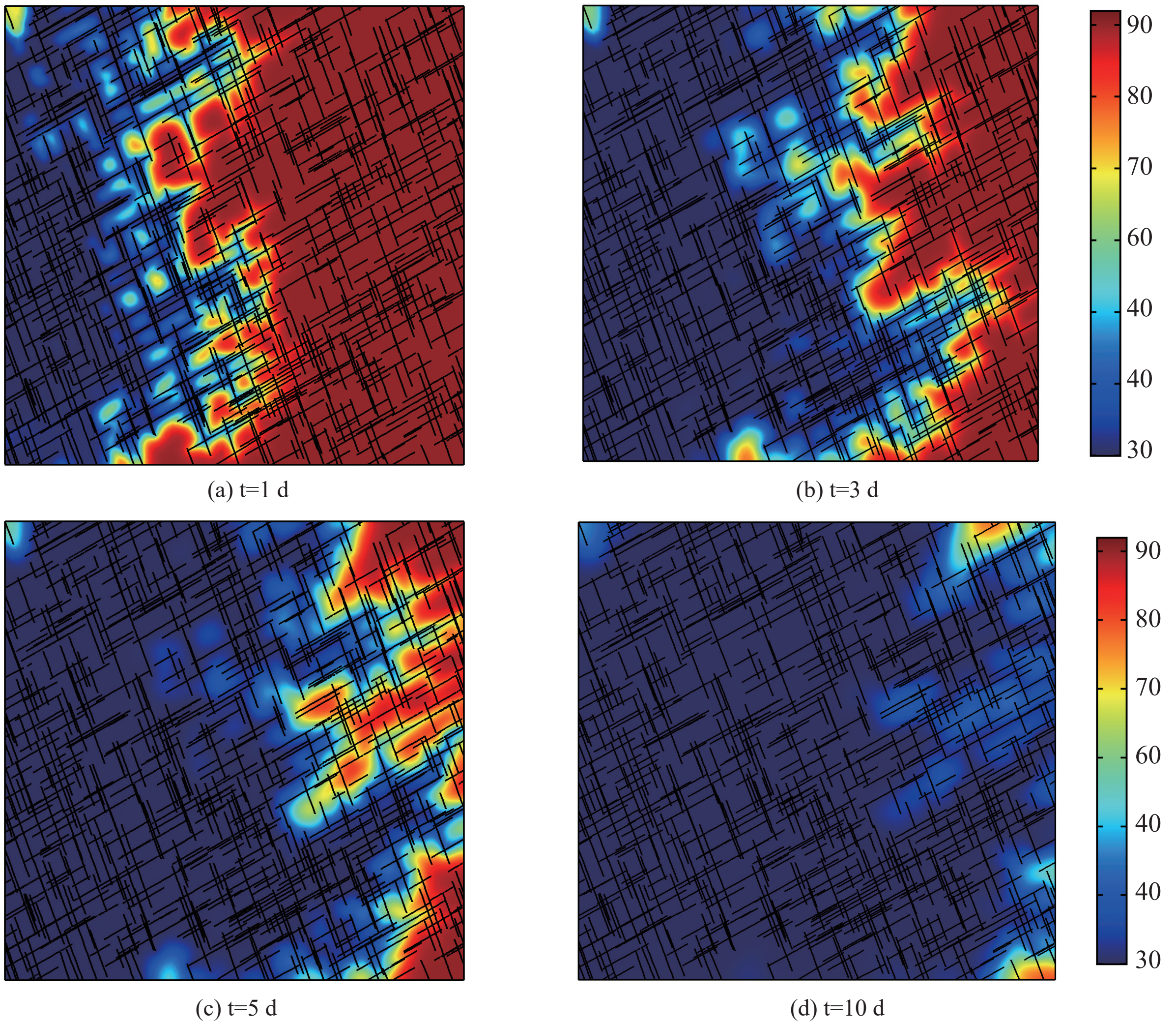


Fig. 6 Temperature distribution of reservoir at different times (unit: °C)

5 Conclusions

Based on the discrete fracture network model and the coupling model of seepage and heat transfer, a fully coupled solution of seepage field and temperature field of fractured rock with known fracture network in COMSOL is reached. According to the actual conditions of geothermal wells in the research base of Xian County, a two-dimensional fracture network model of carbonate rock is established to simulate the coupling process of the reinjection of low-temperature return water into geothermal reservoir. The temperature field distribution of fractured rock mass in carbonate geothermal reservoir has strong inhomogeneity and anisotropy. The interconnected fractures constitute the dominant channel of water flow, and the forward-moving fissure water pushes the cold front to move forward rapidly under the dual mechanism of convective heat transfer and conductive heat transfer. This is one of the main factors to be considered in the study of thermal breakthrough. When the reinjection process circulates for a long time and the temperature of the geothermal reservoir on the pumping side drops to a low level, the temperature of some bedrocks is still high and continues to supply heat to the fissure water, so that the temperature of the reservoir on the pumping side will decrease gradually other than rapidly to the temperature of inlet water on the injection side.

It is suggested that the coupling process of fracture distribution and heat transfer should be taken into consideration in the study of seepage and heat transfer in carbonate reservoir. Besides, if the rock is represented as an equivalent continuum, the typical conditions of actual reservoir should be considered.

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