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Study on Integrated simulations of heat recovery and power generation of high temperature geothermal systems

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ABSTRACT

The underground heat recovery and aboveground heat utilization in high temperature geothermal systems are studied separately in common research methods. To be clear, the utilization of aboveground heat is based on the fluid production temperature, and the influence of reinjection temperature and pressure on underground heat recovery are not considered. Underground heat recovery is based on close to ambient temperature and relatively random pressure, and less consideration is given to the optimal matching of exploitable heat of underground heat recovery and surface heat utilization system, such as pump power, flow, and pressure. However, geothermal development and utilization is an above ground and underground integrated system project. Therefore, the coupling method of reservoir-wellbore flow heat transfer and ground power generation system is proposed, which realizes the integrated optimization design of heat exchange in reservoir and ground heat transfer process. Based on the thermal-hydraulic-mechanical-chemical coupling mechanism and MPI parallel computing platform, this study developed a numerical simulation software of geothermal reservoir and wellbore. The simulation geothermal power system software is developed by encapsulating the core algorithm of medium and high temperature geothermal water power generation system based on organic Rankine cycle. Simulator for Multi-physics-coupling Geothermal system (SMG) is developed by the Exploration & Production Research Institute, Sinopec. SMG is a numerical simulation software integrating fluid flow and heat transfer process in injection well, reservoir, production well and ground power generation system. The integrated software can be used for the coupling analysis of heat exchange in reservoir and ground heat conversion in power generation cycle. This software has been used for power generation potential prediction of hot dry rock in Gonghe Basin, Qinghai Province, China. The prediction of water production temperature and system power generation under different circulating flow rates conditions are carried out. It realizes the prediction of operation characteristics of enhanced geothermal system and strongly support the optimization of development and utilization scheme.

1. INTRODUCTION

In recent years, geothermal resources has become an important way for the healthy and sustainable development of national economy. Hot dry rock is buried 3-10 km away from the surface with rock temperature 150-650 °C and little water or steam in the rock layer. Its porosity and permeability are very low. The energy in hot dry rock are abundant in China. The amount of hot dry rock resources buried in 3-10 km is equivalent to 856 trillion tons of standard coal. Therefore, the development and utilization of hot dry rock resources can reduce environmental pollution and promote the healthy and sustainable development of the national energy.

As a technology of heat utilization from hot dry rock, enhanced geothermal system (EGS) transforms low permeability reservoirs by hydraulic fracturing and constructs heat exchange channels in reservoirs. And then working fluid, such as water or CO_2 can extract heat from reservoirs for power generation and other purposes (Tester et al., 2006). The enhanced geothermal system consists of four parts: the above-ground energy conversion system, injection well, artificial fracturing reservoir and production well. Working fluid is injected into the reservoir through injection well, flowing in high-temperature fractured reservoir and exchanging heat with surrounding strata. Heated fluid reaches the surface through production well for power generation or other applications. After the heat of the high temperature fluid is utilized, the temperature decreases, and it is pumped and reinjected into the injection well for recycling. Therefore, the flow resistance and heat transfer performance of the refrigerant in the thermal storage are directly related to the heat recovery and operation efficiency of the whole system.

Field scale numerical simulation is an important tool to guide recovery resources assessment and heat extraction plan of hot dry rock reservoir. Analyzing the influence of various factors on the operation characteristics of the system can help design and predict the operation characteristics of EGS. There are two main numerical simulation models used to describe flow and heat transfer in an EGS reservoir: the fracture network model and the equivalent continuous porous media model. The fracture network model generates a discrete fracture network reservoir based on measured project data, such as fracture aperture and length distribution, orientation, and spacing. Fracture network model can better reflect the details of fluid flow in reservoirs. But it is difficult to establish the model and has a large amount of calculation for the complex interlacing of natural and artificial fractures. Therefore, many field-scale numerical studies of EGS heat extraction performance regard the fractured reservoir as a continuous porous medium and average the flow and thermal transport properties of individual fractures in the reservoir over a representative element volume. The governing equations of flow and heat transfer in porous media is used to describe the flow and heat transfer process of fluid flowing in the fractured reservoir, such as water-EGS and CO_2-EGS. The flow and heat transfer performance of working fluid in vertical fracture area of reservoir is studied numerically. The results show that the fluid production temperature will be greatly reduced without considering natural convection in fractured area with large permeability (Bataille et al., 2006). Based on the actual reservoir parameters of Groβ Schonebekc EGS in Germany, a three-dimensional reservoir heat extraction model is constructed. The model takes into account the variations of physical properties of water with mineral saturation, temperature and pressure. The simulation results show that thermal breakthrough occurs after 3.6 years of operation of the geothermal system (Blocher et al., 2010). Domestic research institutes includes Tsinghua University (Luo et al., 2010), Jilin University (Guo et al., 2016; Zhang et al., 2014), Guangzhou Institute of Energy (Zeng et al., 2013, 2016; Jiang et al., 2013, 2014; Chen et al., 2015) and Tianjin University (Huang et al., 2014, 2016). They have carried out field scale numerical simulation and power generation prediction of Groβ Schonebekc geothermal project in Germany, Desert Peak geothermal project in the United States, Yangbajing geothermal project in Tibet, and Xujiawei geothermal project in Daqing, Songliao Basin, respectively. The comparative studies of water-EGS and CO_2-EGS show that supercritical CO_2 has low viscosity, which can penetrate into the fracture pore of rock better and smaller flow resistance. The compressibility and expansibility of CO_2 are large, and thermal siphon effect is produced in the system under the influence of temperature and pressure, which reduces the pumping power of surface system. The solubility of CO_2 to rock minerals is low, thus the damage to ground equipment is small. The CO_2 storage effect caused by working fluid filtration has attracted extensive attention of researchers. Pruess (2006) points out that under certain reservoir pressure loss, the heat recovery of CO_2 as working fluid is 50% higher than that of water. The results of Luo (2014) show that the optimal mass flow rate of CO_2 is half of that of water, but the pressure loss of water flowing through reservoir is about twice that of CO_2, and the net heat absorbed is only about 11% higher than that of CO_2.

It is well known that there are two models to describe convective heat transfer in porous media: the local thermal equilibrium (LTE) model and the local thermal non-equilibrium (LTNE) model. In the former, the temperature of the rock and fluid are assumed to be the same: only one energy balance equation is solved. In contrast, the LTNE model uses two energy equations to describe heat transport of the solid matrix and the fluid individually, with consideration given to the temperature difference between them in a representative element volume. The internal heat transfer coefficient in this model is important for the overall performance of a geothermal system. The numerical simulation of EGS reservoir mostly assumes that the local temperatures of fluid in rock and fracture are the same. Some researchers have applied the LTNE model to the field scale numerical simulation of EGS in recent years. Chen (2013) used the local non-thermal equilibrium model to simulate the three-dimensional thermal extraction reservoir model. Three volumetric convection heat transfer coefficients (1 $W/m^3/K$, 2 $W/m^3/K$ and 5 $W/m^3/K$) are selected to simulate respectively. The results show that in the case of larger volumetric convection heat transfer coefficients, the working fluid output temperature is higher, and the operating life of the system increases slightly. Zhang (2014) established a numerical model for Groβ Schonebekc area, Germany. The local non-thermal equilibrium model is used to simulate the flow and heat transfer process, and the range of volume convection heat transfer coefficient is expanded. Figure 2 illustrates that with the volume convection heat transfer coefficient decreasing gradually, the fluid temperature at the reservoir outlet decreases, the thermal breakthrough time of the system is greatly advanced, and the operating life of the system is reduced. By comparing the site production parameters of hot dry rock in Fenton Mountains with the results of numerical simulations, the volume convection heat transfer coefficient in the reservoir is about 0.033 $W/m^3/K$ Gelet (2012, 2013).

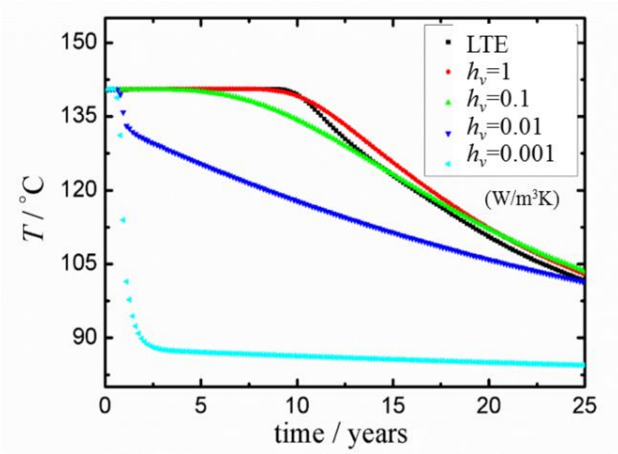


Figure 1: Fluid temperature at reservoir outlet with different volumetric heat transfer coefficients (Zhang, 2014)

In summary, there are still some shortcomings from the above researches on field scale numerical simulation of hot dry rock reservoir:

(1) Local thermal equilibrium model is mostly used in numerical model, with the assumption that there is no temperature difference between rock and fluid. Actual hot dry rock is compact. A few natural fractures and artificial fractures cannot achieve the same characteristics as conventional hydrothermal geothermal reservoir, so the local thermal non-equilibrium effect of heat exchange with reservoir cannot be neglected. The local thermal equilibrium model can help predict the outlet fluid temperature of reservoir and the operating year of the system more precisely.

(2) For EGS analysis, the conventional research method is to separate the underground heat extraction system and the ground energy conversion system. The ground energy conversion is based on production temperature and pressure, and the influence of injection temperature and pressure on underground heat recovery are not considered. Underground heat recovery is based on near-ambient temperature and relatively arbitrary pressure, and less consideration is given to the optimal matching of important parameters in the system, such as pump power, flow rate, pressure, etc., which has a great impact on the prediction of power generation and operation life of the whole system.

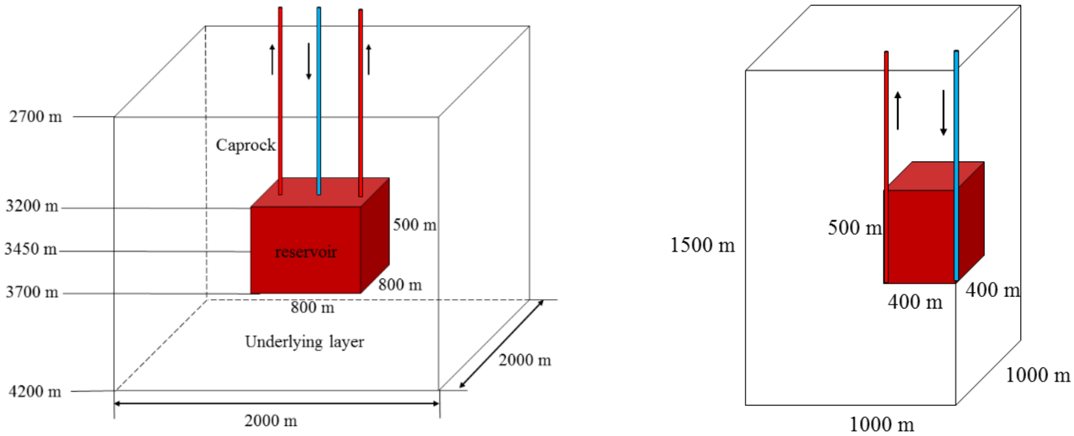
Therefore, based on the correlation of convection heat transfer in a rock fracture of hot dry rock, a local thermal non-equilibrium model of fluid flowing and heat production process of hot dry rock reservoir is proposed. The problem that no basis on the selection of convective heat transfer coefficient in the previous study is solved, and the accurate description of the heat exchange performance in reservoirs is realized. A mathematical and physical model of flow and heat transfer between reservoir and wellbore is established. Organic Rankine cycle is adopted in the ground power generation system. The integrated optimization analysis of underground heat exchange and ground heat transfer in reservoir is carried out. Based on the integrated model and the logging data of GR1 well in Gonghe Basin, Qinghai Province, water production temperature and pressure drop in the integrated system of dry-hot rock reservoir-wellbore-ground are analyzed. The effect of circulating flow rates on production temperature and power generation are obtained.

Local thermal non-equilibrium effect in reservoir is analyzed. The optimization design of water mass flow rates is completed under existing well groups and fracturing conditions, which provides technical support for hot dry rock power generation test in Gonghe Basin, Qinghai Province.

2. NUMERICAL APPROACH

2.1 Physical Model and Numerical Mesh

According to the logging data of GR1 well in Gonghe Basin, Qinghai Province, the target HDR reservoir is located at 3200-3700 m and the temperature is 200-236 °C. The temperature gradient of depth 0-1100 m is 0.049 °C /m, the geothermal gradient of depth 1100-3700 m is 0.075 °C /m. The pressure in the middle of the thermal reservoir is 37 MPa. Using the well group model of one injection and two production, the interval between injection well and production well is 400 m temporarily according to the site conditions. Considering the thermal supplement of surrounding rock in the process of thermal recovery, the model selects strata with a length of 2000 m, a width of 2000 m and a height of 1500 m in Figure 2(a). Due to the symmetry, the computational model is simplified to 1/4 computational region as shown in Figure 2(b). The heat transfer between fluid in injection well and production well and surrounding formation is considered in the model. Because the HDR reservoir in Gonghe Basin has not been hydro-fractured and cyclic test has not been carried out, the permeability parameters of reservoir in Gonghe Basin in this paper refer to foreign test data, and other thermal physical properties are measured from core test. Thus, the calculation results have guiding significance for fracturing design. The characteristic parameters of the wellbores and reservoir are listed in Table 1. Structured quadrilateral grids are used in two dimensional model of injection wells and production wells, and structured hexahedral grids are used in thermal reservoirs and the grids near wellbore are refined. After grid independence verification, the number of well grids is 1.09 million, and the number of thermal storage grids is 3.86 million, as shown in Figure 3.



(a) Physical model of EGS reservoir

(b) 1/4 simulation model

Figure 2: Schematic diagram of an Enhanced Geothermal System and simulation physical model.

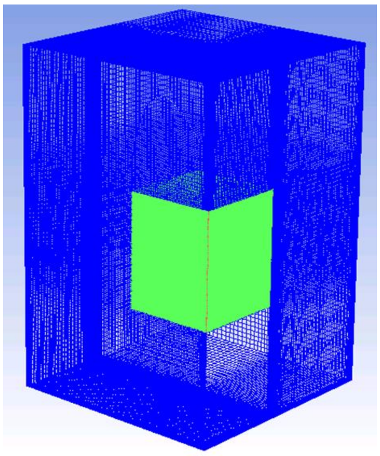


Figure 3: Mesh distribution.

Table 1: Characteristic parameters of the wellbores and reservoir.

Parameters	Value
Wellbore diameter	152 mm
Distance between injection and production wells	400 m
Wellbore depth	3700 m

reservoir dimensions	$800m \times 800m \times 500m$
Model dimensions	$1000m \times 1000m \times 1500m$
Horizontal permeability	30 mD
Vertical permeability	3 mD
Reservoir porosity	0.2
Reservoir rock density	2773 kg/m^3
Reservoir rock specific heat capacity	794 J/(kg·K)
Reservoir rock thermal conductivity	2.721 W(m·K)
Caprock permeability/porosity	0
Caprock density	2680 kg/m^3
Caprock specific heat capacity	750 J/(kg·K)
Caprock thermal conductivity	2.30 W(m·K)
Underlying Rock permeability/porosity	0
Underlying Rock density	2773 kg/m^3
Underlying Rock specific heat capacity	794 J/(kg·K)
Underlying Rock thermal conductivity	2.721 W(m·K)

2.2 Coupled Numerical Model

Equation (1) is the correlation of convection heat transfer in a rock fracture, which was obtained experimentally and numerically. The governing equations of heat extraction process in reservoir with LTNE model is established, as shown in Equation (2)-(5). Convection heat transfer coefficient *h* in Equation (4) and (5) is calculated by Equation (1), which fully considers the influence of flow rate, thermal properties of working fluid, fracture angle and other factors. The governing equations of water flowing in wellbores are listed and heat exchange with surrounding rock are considered (Equation (10)). The organic Rankine cycle is adopted in the ground power generation system. Therefore, a coupled numerical model of working fluid flow and heat transfer in reservoir and wellbore and heat conversion system is established. The parameter coupling method is adopted to realize the integrated optimization analysis of enhanced geothermal extraction and utilization systems.

$$Nu = 1.25Re^{0.308}Pr^{0.428}\left(\frac{\lambda_w}{\lambda_b}\right)^{-4.75}\left(\frac{\rho_w}{\rho_b}\right)^{-7.03}(1+0.0029sin\theta+0.0035sin^2\theta) \tag{1}$$

where $Nu=hd/\lambda_f$, $Re=\rho_f vd/\mu_f$, $Pr=\lambda_f/\rho_f c_p$ are dimensionless numbers, Nusselt number, Reynolds number and Prandtl number, respectively. *h* is convection heat transfer coefficient, *d* is rock fracture aperture, *v* is velocity, c_p *is fluid specific heat capacity*, λ_f is fluid thermal conductivity, ρ_f is fluid density, μ_f is fluid viscosity. Subscripts *w*, *b*, *s* represents rock fracture wall, water bulk and solid rock, respectively.

The governing equations of reservoir with LTNE and LTE model:

Continuity equation:

$$\frac{\partial \rho_f}{\partial t} + \nabla\cdot\left(\rho_f \vec{v}\right) = 0 \tag{2}$$

Momentum equation:

$$\frac{\partial\left(\rho_f \vec{v}\right)}{\partial t} + \nabla\cdot\left(\rho_f \vec{v}\vec{v}\right) = -\nabla p + \nabla\cdot\left(\mu_f\left[\left(\nabla\vec{v}+\nabla\vec{v}^{T}\right)-\frac{2}{3}\nabla\cdot\vec{v}I\right]\right)+\rho g-\frac{\mu}{k}\vec{v} \tag{3}$$

Fluid energy equation:

$$\begin{aligned}&\frac{\partial}{\partial t}(\varepsilon\rho_f E_f) + \nabla\cdot\left[\overline{V}\left(\rho_f E_f + P\right)\right]\\ &= \nabla\cdot\left[\varepsilon\lambda_f\nabla T_f + \mu\overline{V}\left(\nabla\overline{V}+\nabla\overline{V}^{T}-\frac{2}{3}\nabla\cdot\overline{V}I\right)\right] + h\cdot a\cdot(T_s-T_f)\end{aligned} \tag{4}$$

Solid energy equation:

$$\left(1-\varepsilon\right)\rho_s C_{ps}\frac{\partial T_s}{\partial t} = \nabla\cdot\left(\left(1-\varepsilon\right)\lambda_s\nabla T_s\right) - h\cdot a\cdot(T_s-T_f) \tag{5}$$

where ε, k, p, T are porosity, permeability, pressure and temperature, respectively. a is the specific surface area of porous media, which in the range 0.01-0.0001 for fractured reservoir of EGS.

The energy equations based on local thermal equilibrium model are the sum of equation (4) and (5), as shown in the following.

Energy equation (LTE):

$$\begin{aligned}&\frac{\partial}{\partial t}\left[\varepsilon\rho_f E_f+(1-\varepsilon)\rho_s E_s\right]+\nabla\cdot\left(\vec{v}\left(\rho_f E+p\right)\right)\\&=\nabla\cdot\left[(\varepsilon\lambda_f+(1-\varepsilon)\lambda_s)\nabla T_s+\mu_f\vec{v}(\nabla\vec{v}+\nabla\vec{v}^T-\frac{2}{3}\nabla\cdot\vec{v}I)\right]\end{aligned} \tag{6}$$

where E_f is the internal energy.

Considering the heat exchange with surrounding rock, fluid flows and heat transfer in the injection and production wells are described as follows:

Continuity equation:

$$\frac{\partial\rho_f}{\partial t}+\nabla\cdot\left(\rho_f\vec{v}\right)=0 \tag{7}$$

Momentum equation:

$$\begin{aligned}&\frac{\partial\left(\rho_f\vec{v}\right)}{\partial t}+\nabla\cdot\left(\rho_f\vec{v}\vec{v}\right)=-\nabla p+\nabla\cdot\left(\mu_f\left[\left(\nabla\vec{v}+\nabla\vec{v}^T\right)-\frac{2}{3}\nabla\cdot\vec{v}I\right]\right)+\rho g+\\&\nabla\cdot\left[0.09\rho\frac{K}{\omega}(\nabla\bar{v}+\nabla\bar{v}^T)-\frac{2}{3}\rho KI\right]\end{aligned} \tag{8}$$

$$\frac{\partial}{\partial t}\left(\rho_f E\right)+\nabla\cdot\left(\vec{v}\left(\rho_f E+p\right)\right)=\nabla\cdot\left\{\begin{aligned}&\lambda_f+0.09\rho_f\frac{K}{\omega}\frac{C_{pf}}{\Pr_f})\nabla T\\&+(\mu_f+0.09\rho_f\frac{K}{\omega}\bar{V})\bar{V}\left[\left(\nabla\vec{v}+\nabla\vec{v}^T\right)-\frac{2}{3}\nabla\cdot\vec{v}I\right]\cdot\vec{v}\end{aligned}\right\} \tag{9}$$

where K, ω are turbulent kinetic energy and turbulent dissipation rate, respectively.

$$q=\frac{-4\pi\lambda_s}{\ln(\frac{2.3089\alpha_s t}{r^2})}(T_f-T_{s,i}) \tag{10}$$

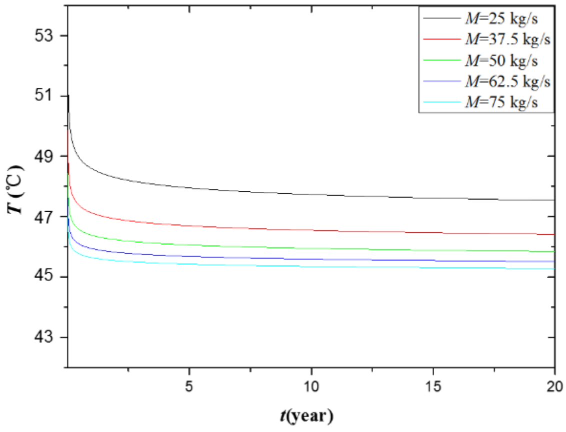
where q, t, α_s, r, $T_{s,i}$, T_f are heat flux from the surrounding rock, time, thermal diffusivity, wellbore radius, initial temperature distribution without no flow, fluid temperature in the wellbores, respectively.

3. RESULTS AND DISCCUSSIONS

3.1 Reservoir-Wellbore Coupled Simulation Results

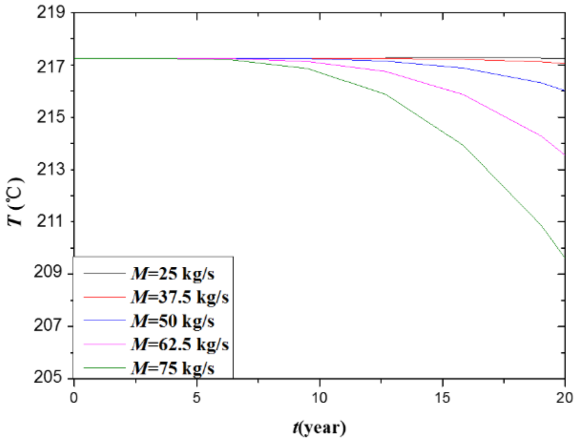
Firstly, based on the assumption of local thermal equilibrium, the transient numerical simulation of HDR reservoir-wellbore coupling system in Gonghe Basin of Qinghai Province were carried out for continuous production for 20 years. The ground energy conversion system uses organic Rankine cycle with isobutane as working medium. According to the requirements of power generation system, the water injection pressure at injection well is 50 MPa and the injection temperature is 45 °C.

Fig. 4 shows the variations of bottom hole temperature of injection well, reservoir outlet temperature and wellhead temperature of production well with time under mass flow rate of 25-75 kg/s. Figure 4 (a) shows that the surrounding rock have heating effect on the working fluid in the injection well. The heating effect is more obvious with smaller mass flow rates. The bottom water temperature of 75 kg/s mass flow rate is less than 3 °C higher than the wellhead fluid temperature. Fig. 4 (b) represents the simulation results show that the water temperature at the outlet of reservoir decreases rapidly once the thermal breakthrough of the working fluid occurs. The larger the flow rate, the greater the rate of decline, and the time of thermal breakthrough is inversely proportional to the mass flow rate. Under the combined influence of heat dissipation from production wells to surrounding rock and compressibility of fluid, the temperature of water flowing upward in production wells decreases. The larger the mass flow rate, the greater the pressure drop and the more the temperature decreases correspondingly, as shown in Fig. 4 (c). Figure 5 shows the pressure drop of the system with different water flow rates. With the increase of mass flow rate, the pressure drop of the system increases correspondingly. With the advance of heating time, the kinematic viscosity increases with the decreasing water temperature in the system, and thus the resistance of the system increases gradually. The calculation results have guiding significance for the design and selection of surface water pumps. In order to run the whole system steadily and efficiently for 20 years, it is necessary to ensure that the water temperature of production wells does not decrease dramatically and the pressure drop of the system is within the acceptable range of surface water pumps. In this case, it can be seen that the appropriate mass flow rate of water is 37.5 kg/s.



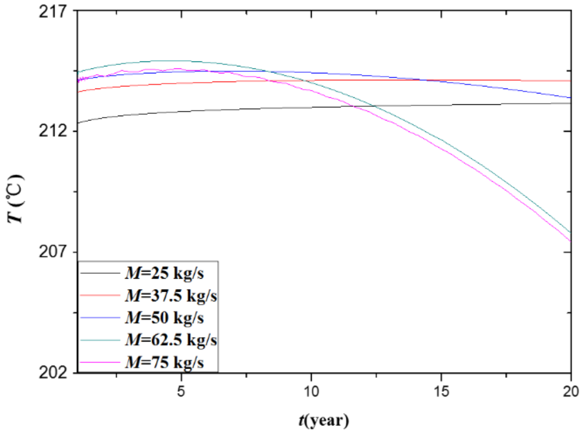
(a) fluid temperature at the bottom of injection well

(reservoir inlet)



(b) fluid temperature at reservoir outlet

(production well bottomhole)



(c) fluid temperature at the outlet of production well

Figure 4: Fluid temperature variations with under different fluid mass flow rates

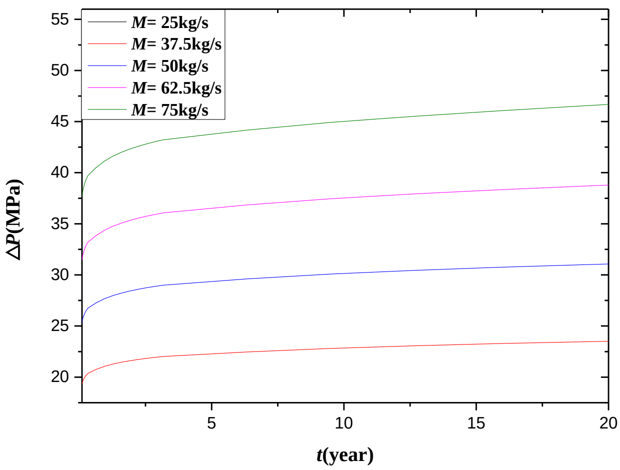
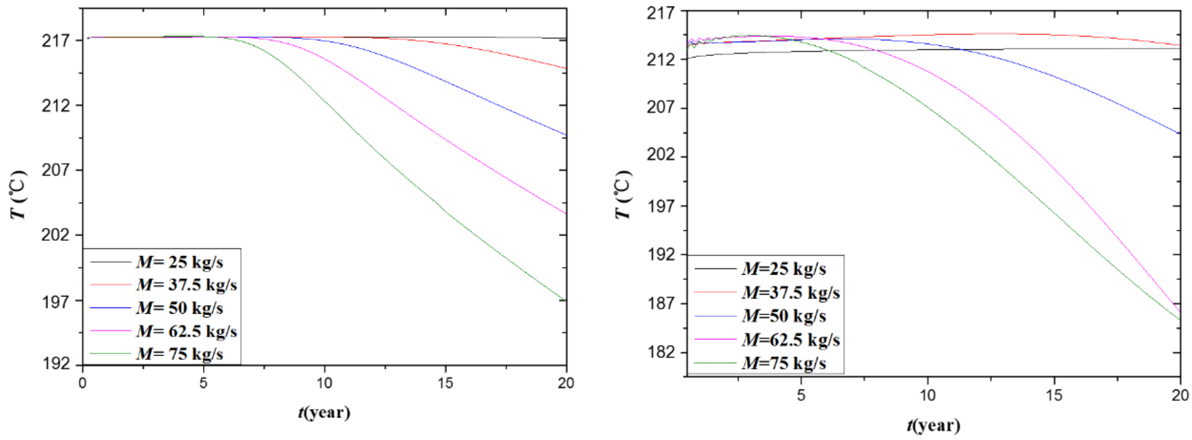


Figure 5: Pressure drop variations with time under different fluid mass flow rates (LTE)

3.2 Local Thermal Non-Equilibrium in EGS Reservoir

The local thermal non-equilibrium model is used to simulate the flow and heat transfer in reservoir and fluid temperature at wellhead of production well are re-calculated. From Figure 6, it can be seen that the results with LTNE model advance the time of thermal breakthrough. When the mass flow rate of water is 75 kg/s, the time of thermal breakthrough of reservoir is 2-3 years earlier than that of LTE model. Moreover, the rate of water temperature decrease at the reservoir outlet is larger than that calculated by LTE model.

This is because that there is temperature difference between solid and fluid in representative volume elements and heat exchange between fluids and hot rocks in LTNE. LTE model considers that the heat transfer coefficient between fluid and solid is infinite and fluid and rock instantaneously reach the same temperature. This assumption is valid in hydrothermal reservoirs, such as sandstone with fine porosity and permeability characteristics and large specific surface area of solid. But it is not suitable for hot dry rock reservoirs with fewer fractures and smaller heat transfer area. Therefore, the numerical simulation results of hot dry rock reservoir production based on LTE model are too optimistic.



(a) fluid temperature at reservoir outlet (b) fluid temperature at the outlet of production well

Figure 6: Fluid temperature variations with under different fluid mass flow rates

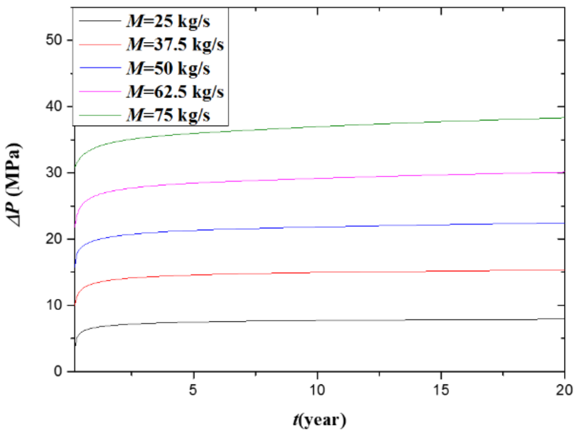


Figure 7: Pressure drop variations with time under different fluid mass flow rates (LTNE)

3.3 Coupling Analysis of Reservoir-Wellbore-Energy Conversion system

Based on the above field scale numerical simulation results of reservoir and wellbore, the integrated analysis of enhanced geothermal system is carried out by coupling the ground energy conversion system. In the organic Rankine cycle shown in Fig. 8, the temperature, pressure and mass flow rates at wellhead of production well are taken as input parameters of the ground system, i.e. state 1. State 4 are the temperature and pressure of reinjection water. The working fluid of organic Rankine cycle is isobutane. The temperature of isobutane after heat transfer from evaporator to water is set as 110 °C, i.e. state 5. Based on the above results of reservoir-wellbore simulation based on LTNE model, the power generation of the enhanced geothermal system varies with operation time under different flow rates, as shown in Fig. 9.

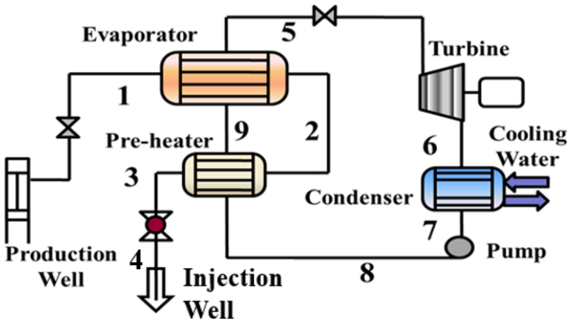


Figure 8: Systematic diagram of ground power generation system-organic rankine cycle

When the mass flow rate is 75 kg/s, the power generation has maintained at 5.5 MW for the first five years. When the thermal breakthrough occurs, the power generation of the system decreases rapidly, and after 20 years of operation, the power generation is less than 3 MW. When the mass flow rate is 25 kg/s and 37.5 kg/s, the power generation has been relatively stable since no thermal breakthrough occurred in 20 years. The larger the mass flow rate, the larger the power generation capacity. Hot dry rock power generation test in Gonghe Basin of Qinghai Province requires continuous power generation of 2 MW for 20 years. Considering the power generation capacity, power generation stability and system resistance, the water circulation flow rate is 37.5 kg/s under the target reservoir with fractured volume and permeability, and well group model built in this paper.

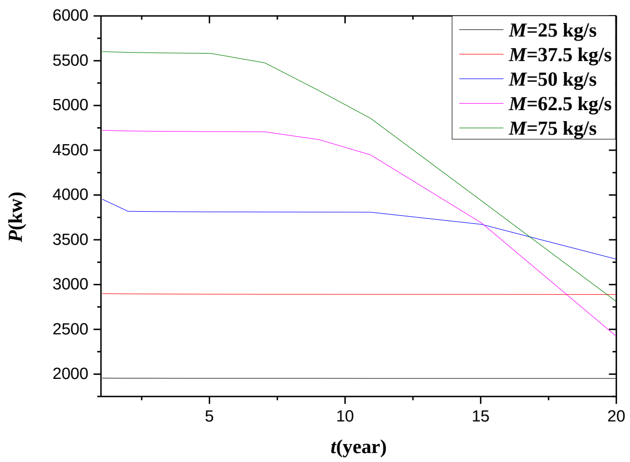


Figure 9: Variation of system power generation with time under different mass flow conditions

4. CONCLUSIONS

In this paper, the coupling numerical simulation model of injection well, reservoir, production well and ground energy conversion system is established, and the integrated simulation of enhanced geothermal system is realized. The numerical simulations of field scale are carried out for one injection and two production well group with water as working fluid in Gonghe Basin, Qinghai Province. Some conclusions are obtained.

(1) Before thermal breakthrough occurs in thermal storage, the production water temperature is relatively stable. After thermal breakthrough occurs, the water temperature at the production wellhead drops rapidly. The earlier the time of thermal breakthrough occurs in the reservoir, and the faster the production water temperature drops with larger mass flow rates of working fluid. In the case of certain reservoir characteristics and well group model, the optimization of flow rate of thermal working fluid needs to take into account many factors such as installed capacity, power generation stability and surface pump head.

(2) The local thermal equilibrium model considers that the heat transfer coefficient between fluid and solid is infinite, and they instantaneously reach the same temperature. The simulation results of heat extraction from reservoir based on the local thermal equilibrium model are too optimistic. Based on the correlation of convection heat transfer coefficient in a fracture of hot dry rock, a local thermal non-equilibrium model of fluid flow and heat transfer in enhanced geothermal reservoir is established, which accurately describes heat exchange performance in reservoir.

(3) The integrated model of enhanced geothermal system established in this paper can be used for the coulping analysis of heat exchange in reservoir and ground heat conversion in power generation cycle. It realizes the prediction of operation characteristics of enhanced geothermal system and strongly support the optimization of development and utilization scheme.

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