Study on the fracture propagation in geothermal during the hydraulic fracturing based on a coupled thermal-hydraulic-mechanical modeling

Zheng Heng
School of petroleum engineering, Yangtze University, Wuhan, Hubei, China
Key Laboratory of Drilling and Production Engineering for Oil and Gas, Wuhan, Hubei, China

Xu Ersi
Engineering technology research institute of Southwest Oilfield company, Chengdu, Sichuan, China

Li Jie
Engineering technology research institute of Xinjiang Oilfield company, Karamay, Xinjiang, China

Chen Jin
Engineering technology research institute of Xinjiang Oilfield company, Karamay, Xinjiang, China

ABSTRACT: In this paper, a coupled thermal-hydraulic-mechanical modeling was proposed based on the linear elastic fracture mechanics to understand the effect of thermal stress field on fracture propagation. Due to a cooling zone was formed in the matrix when the fracturing fluid injection, the rock had a shrink dramatically when the temperature reached the threshold value. The simulations indicated that when the temperature increased to 180°C from 155°C, the breakdown pressure and extension pressure decreased by 14.56% and 13.27%, and the total fracture length of multiple fractures propagation increased by 28.51%, which demonstrated that increasing the temperature difference can not only decrease the breakdown pressure and extension pressure, but also can offset the stress shadow caused in multiple fractures extension. This research was helpful for the hydraulic fracturing design when the horizontal well with multiple stage fracturing was adopted in the development of geothermal systems.

Keywords: thermal stress, hydraulic fracturing, thermal-hydraulic-mechanical, thermo-elastic deformation, volume shrinkage.

1 INTRODUCTION

Geothermal energy is an attractive renewable and clean energy which plays an important role to solve the global warming effect caused by fossil fuels[1-2]. Due to the low intrinsic permeability and porosity of HDR, it is intractable to circulate water through the high-temperature zone for recovering heat energy. Thus the hydraulic fracturing is an indispensable technology for the development of geothermal energy by which to create fracture network to improve the permeability.

The geothermal development in EGS is a complicated process involving the coupled multi-physical fields, including the stress-field, thermal field and flow field[3]. Numerical simulation is an essential tool to understand the fracture propagation in coupled multi-physical fields. Many researchers have conducted a serious of numerical simulation of the geothermal extraction process. The simulations indicated that triplet well can dramatically increase the heat productivity, and two horizontal well system can significantly enhance the water production rate and possibly improve the production efficiency[4-6].

From the survey above, it can be found that most researches were focused on the heat extractions in EGS, the effect of thermal stress field on fracture initiation and propagation has not been analyzed. Especially when the horizontal well was applied in the development of EGS, the propagation mechanism of multiple fractures was still unclear. In this paper, a coupled thermal-hydraulic-mechanical modeling was proposed based on the linear elastic fracture mechanics which considering the thermo-elastic deformation of geothermal reservoir, it was solved by the finite element method. The effect of temperature on fracture initiation and propagation was simulated in the modeling, and the mechanism of multiple fractures was analyzed.

2 MATHEMATICAL MODEL

Hydraulic fracturing in geothermal systems is a multi-physical field coupling problem, which involves three physical processes: (1) The initiation and propagation of hydraulic fracture induced by high pressure; (2) Heat conduction and heat transfer between fracturing fluid and rock; (3) The leak-off of fracturing fluid from fracture to rock matrix. In the hydraulic fracturing, the hydraulic fracture is created when the pressure reaches the breakdown pressure of rock, then the hydraulic keeps propagation when the pressure exceeds the extension pressure. The relationship between the three physical processed is shown as Fig. 1, and the coupled thermal-hydraulic-mechanical model involves stress equilibrium equation, Darcy's law, damage criterion and damage evaluation.

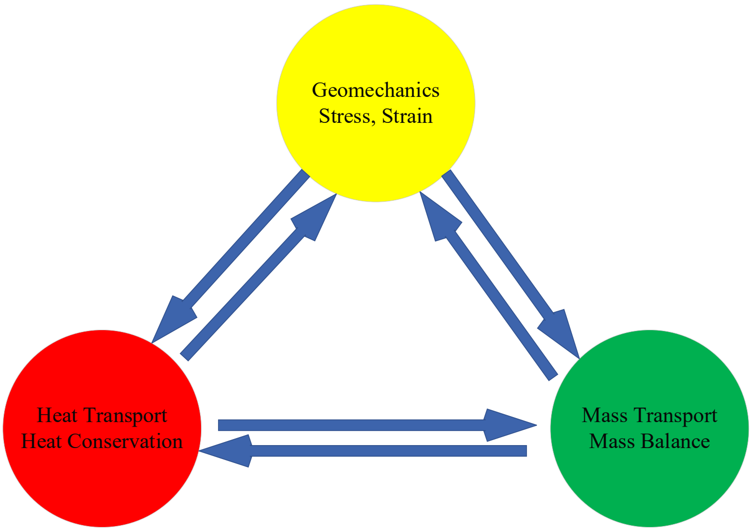

Figure 1. Schematic diagram of the THM coupling model.

2.1 Stress equilibrium equation

In this section, the thermo-elastic deformation of geothermal reservoir caused by hydraulic fracture is formulated and solved in terms of a finite element method. In the simulation, the fracture deformation in the THM process is basically caused by the external loads such as in situ stress, the thermal strain induced by the heat loss and the overpressure induced by the fluid flow inside the fracture. According to the principle of virtual work, the equilibrium equation can be expressed as

$$\int_{\Omega} \sigma : \delta\, \varepsilon d\Omega - \int_{\Gamma_t} t^* \cdot \delta u d\Gamma - \int_{\Omega} b \cdot \delta u d\Omega + \int_{\Gamma_d} (T + F_{hy}) \cdot \delta u \, d\Gamma = 0 \qquad (1)$$

Where σ is the Cauchy stress tensor; b is the body force; t^* is the force (such as the in-situ stress and fluid pressure) acting on the boundary Γ_t; ε is the strain tensor; $\delta\varepsilon$ is the virtual strain field; δu is the virtual displacement field; T and F_{hy} are the contact traction vector and the force vector contributed by the fluid pressure on fracture interfaces, respectively. δu is the virtual displacement jump over the fracture interface. The total strain ε can be expressed as

$$\varepsilon = \varepsilon_{elastic} + \varepsilon_{thermal} \tag{2}$$

In the simulation, the thermal part of the strain was calculated as follows.

$$\varepsilon_{thermal} = \alpha_T (T - T_{ini}) \tag{3}$$

Where $\varepsilon_{elastic}$ is the elastic part of the strain; $\varepsilon_{thermal}$ is the thermal part of the strain; α_T is the thermal expansion coefficient for the rock matrix; T and T_{ini} are the current temperature and initial temperature, respectively.

3 NUMERICAL SIMULATION

To understand the effect of thermal stress caused by the fracturing fluid injection on fracture propagation in geothermal reservoir stimulation, a 2D numerical model with the size of 100m×100m was established to understand the propagation characteristic of hydraulic fracture. The key parameters of the model was shown in Table 1.

Table 1. Key parameters of the geothermal reservoir in hydraulic fracturing model.

Parameter	Unit	Value
Young's Modulus	GPa	42.3
Poisson ratio	Dimensionless	0.31
Fracture toughness	$MPa \cdot m^{1/2}$	4.87
Tensile strength	MPa	6.32
Porosity	%	4.21
Permeability	10^{-3} μm^2	0.47
Maximum horizontal principle stress	MPa	38.42
Minimum horizontal principle stress	MPa	33.42
Vertical stress	MPa	47.53
Fracturing fluid viscosity	mPa·s	1.0
Injection rate	m^3/min	3.0
Temperature of fracturing fluid	℃	25

To understand the effect of thermal stress field on fracture propagation, the reservoir temperature with 25℃, 120℃,140℃,160℃,180℃,200℃,220℃ were simulated. From the simulation results (Fig. 2 and Fig. 3), it can be found that a main fracture was formed when the temperature was 25℃ which propagated along the maximum horizontal principle stress, and the breakdown pressure and average extension pressure was 54.21MPa and 39.41MPa, respectively. When the reservoir temperature was 120℃, only a main fracture was created, and the breakdown pressure and extension pressure was 51.32MPa and 37.44MPa, respectively. When the temperature increased to 140℃, there was still a main fracture created, and the breakdown pressure and extension pressure had a slightly change compared with the reservoir temperature was 120℃, the breakdown pressure and extension pressure was 50.68 MPa and 36.84 MPa. When the temperature jumped to 180℃, a main fracture with two branch fractures were formed in the situation, and a fracture was created in the inner of rock. In addition, the breakdown pressure and extension pressure dramatically decreased to 43.85MPa and 32.47MPa. As the reservoir temperature increase to 200℃, a main fracture with three branch fractures were created, and two fractures were formed in the inner of rock. The breakdown pressure and extension pressure decreased to 42.15 MPa and 31.16MPa. When the temperature went to 220℃,there was still a main fracture with two fractures were formed, and the breakdown pressure and extension pressure were similar to that the temperature was 200℃. The simulations also indicated the fracture propagated along the maximum horizontal principle stress when the temperature was 25℃, while the extension of hydraulic fracture gradually deviates from the direction of maximum horizontal principal stress when the temperature was 140℃, and the deviation degree increased with the formation temperature rising. The main reason was that due to the increase of formation temperature, the temperature difference gradually increased, and the thermal stress field caused by heat exchange in the formation became more serious . Under the joint action of geostress field and thermal stress field, deflection occurred in fracture propagation.

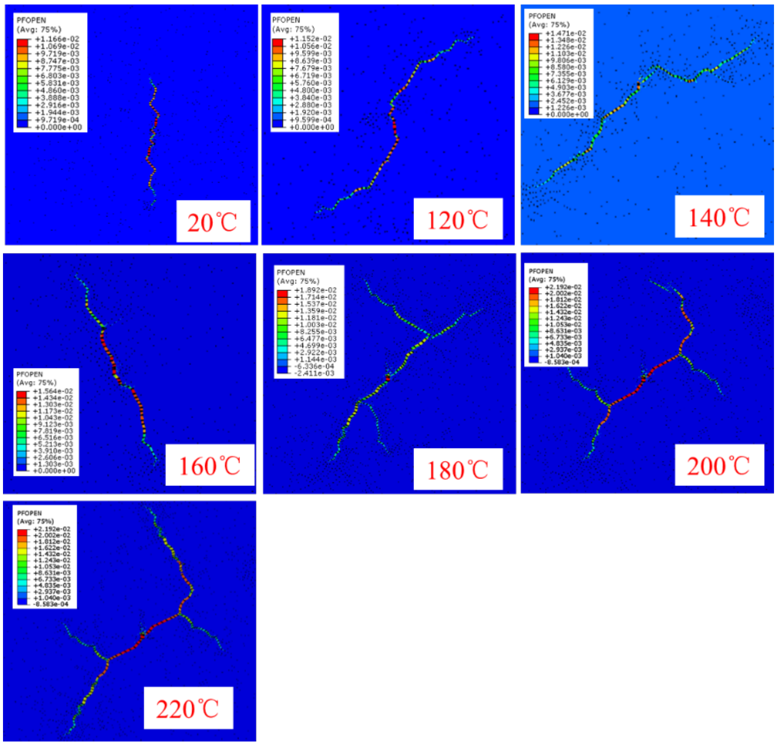

Figure 2. Change of fracture geometry under different temperature.

From the simulation above, it can be found that a higher reservoir temperature contributed to a more complex fracture network, and the breakdown pressure and extension pressure also decreased with the increase of reservoir temperature. When the reservoir temperature exceeded to 180℃, the fractured area was much bigger, and the breakdown pressure and extension pressure experienced a huge decrease. Compared with the reservoir temperature was 120℃, the breakdown pressure and extension pressure decreased by 14.56% and 13.27% when the temperature reached to 180℃ (Tab.3). It also can be found that when the temperature exceeded to 180℃,the decline gradually moderates, and the change of fracture morphology became less.

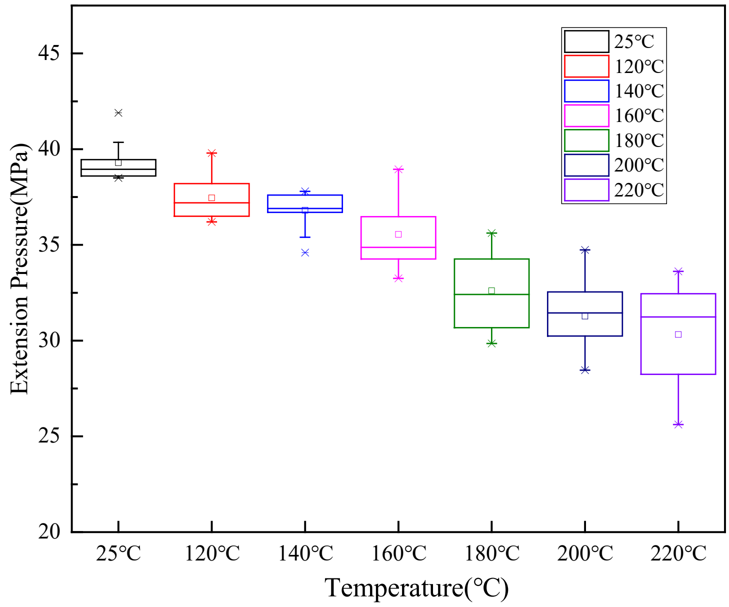

Figure 3. The change of extension pressure under different temperature.

To further understand the effect of thermal stress field on fracture propagation, another model was established to understand the effect of "stress shadow" on fracture propagation. In the modeling, a model with three fractures was investigated, the fracture space was 20m, and the temperature with 25℃,120℃,180℃,220℃on fracture propagation were investigated. From the simulation (Fig. 4), it can be found that the middle fracture was seriously confined when the temperature was 25℃, the propagation length of adjacent fracture was much longer than that of middle fracture, and fracture width of adjacent fractures was much narrower than that of middle fracture. When the temperature difference was 95℃ with the reservoir temperature was 120℃, the propagation length of middle fracture had an obvious increase, but still shorter than that of adjacent fracture, the fracture width of middle fracture had a decrease. When the temperature difference increased to 175℃,the propagation of three fractures reached balance, and the fracture length was longer than that of above models, and the fracture width of three fractures also reached balance. When the temperature difference continuously to increase to 195℃, the fracture length continuously to increase, but the fracture width had a slightly decrease. As shown in Tab. 4, the adjacent fracture length increased from 65.3m to 75.3m as the temperature climbed from 25℃ to 180℃, increased by 15.31%, and the length of middle fracture increased by 53.78%. While the average adjacent fracture width decreased by 12.35% from 1.62mm to 1.42mm, and the average middle fracture width decreased from 2.41mm to 1.44mm, decreased by 40.25%. From the simulations, it can be concluded that with the temperature difference increase, the effect of "stress shadow" on fracture propagation was weakened. When the temperature was 25℃ and the temperature difference was 0 ℃, an obvious "wrapped phenomenon" can be found caused by effect of "stress shadow". With the temperature increase, the limitation of middle fracture from adjacent fracture was released, and the propagation length of middle fracture increased from 65.3m to 75.3m, which was nearly equal to the length of adjacent fracture. Compared with the total length when the temperature was 25℃,the fracture propagation length increased by 28.51%. The main reason was that when the fracturing fluid was injected, a cooling zone was formed in the matrix, which caused the rock to shrink dramatically. The greater the temperature difference was, the more serious the shrinkage of rock volume was. When the temperature was 180℃, the stress caused by rock shrinkage was sufficient to offset the stress shadow caused by fracture extension, thus the fracture length were uniform. Meanwhile, the injection of fracturing fluid was a certain value in the simulation, due to the damage caused by rock shrinkage, which caused the net pressure decreased in the fracture, so the fracture width had a decrease.

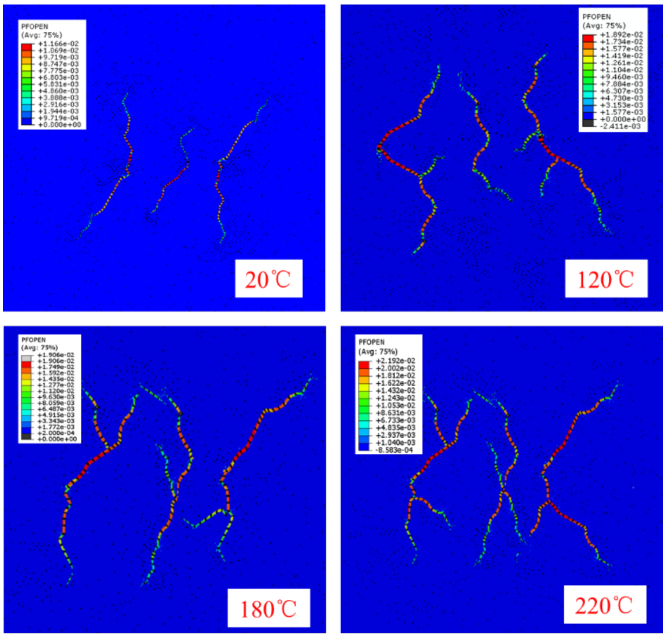

Figure 4. Change of fracture geometry when multi-fracture propagated under different temperature.

CONCLUSION

To understand the thermal effect on fracture propagation, a numerical model coupled temperature-hydraulic-mechanics (THM) was established, and the effect of temperature on fracture initiation and propagation were analyzed. It can be concluded as follows. When the temperature difference increased to a threshold value, the stimulated volume by hydraulic fracturing increased greatly, the number of branch fractures increased. Meanwhile, the breakdown pressure and extension pressure had a decrease with the increase of temperature difference.

REFERENCES

[1] Zheng, H.; Pu, C.; Xu, E.; Sun, C., Numerical investigation on the effect of well interference on hydraulic fracture propagation in shale formation. Engineering Fracture Mechanics 2020, 228,106932.

[2] Clarke, P.L. and Abedi, R., 2018. Modeling the connectivity and intersection of hydraulically loaded cracks with in situ fractures in rock. International Journal for Numerical and Analytical Methods in Geomechanics, 42(14): 1592-1623.

[3] Shaik AR, Rahman SS, Tran NH, Tran T. Numerical simulation of Fluid-Rock coupling heat transfer in naturally fractured geothermal system. Applied Thermal Engineering. 2011;31(10):1600-6.

[4] Xu C, Dowd P, Li Q. Carbon sequestration potential of the Habanero reservoir when carbon dioxide is used as the heat exchange fluid. Journal of Rock Mechanics and Geotechnical Engineering. 2016;8(1):50-9.

[5] Zhao Y, Feng Z, Feng Z, Yang D, Liang W. THM (Thermo-hydro-mechanical) coupled mathematical model of fractured media and numerical simulation of a 3D enhanced geothermal system at 573 K and buried depth 6000–7000 M. Energy. 2015;82:193-205.

[6] Zheng H, Pu C, Sun C. Study on the interaction between hydraulic fracture and natural fracture based on extended finite element method. Engineering Fracture Mechanics. 2020;230:106981.