Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Theoretical Numerical Simulation of the Effect of Fracture Distribution Characteristics on EGS Heat Extraction

Haizhen Zhai, Guangrong Jin, Zheng Su, Lihua Liu, and Nengyou Wu

E-mail address: zhaihz@ms.giec.ac.cn

Keywords: Enhanced geothermal system (EGS); Reservoir stimulation; Fracture distribution; Preferential flow ratio; Preferential thickness ratio

ABSTRACT

The heat extraction from an enhanced geothermal system (EGS) strongly depends on the structure of fracture network of the reservoir. As the strong non-uniform distributed fracture networks are generally stimulated in EGS reservoir, a parallel multi-fracture non-uniformly distributed model is built to study the impact of fracture distribution characteristics on EGS heat extraction. Here, the concept of the preferential flow ratio and preferential thickness ratio are introduced to characterize the non-uniformity in fracture distribution. Theoretical simulation results show that the heat extraction performance for a non-uniformly stimulated reservoirs, will be co-affected by the number of fracture and the distribution characteristics of the fracture. The production temperature is in a loose positive relation to the number of fractures, and in a negative correlation to the preferential flow ratio and preferential thickness ratio. Moreover, it can enhance the heat extraction performance by blocking the preference fracture or narrowing the gap of fracture widths. To seal the inferior rock HTU or enhance the stimulation degree by increasing fracture number can also enhance the heat extraction efficiency. The results indicate that it is favorable to exploit the heat reservoir with the conditions of sufficient fractures and evenly distributed fracture width.

1. INTRODUCTION

Enhanced geothermal system (EGS) is a potential technique to substantially extract geothermal energy in deep hot rock formation which with low permeability and/or porosity. By stimulating fractures in the deep reservoir, a connected pathway networks can be created in low permeability and/or porosity reservoir for fluid flow and heat extract. In the EGS, therefore, the efficient heat extraction from a deep geothermal reservoir will involve a synergy of various scientific disciplines including geology, geophysics, seismology, and reservoir engineering [Aliyu et al., 2017; Breede et al., 2013; Tester et al., 2006].

In a deep geothermal system, reservoir rock parameters determine the value of accumulated heat and energy. The structure of the reservoir ascertains the quantity and quality of the energy which can be extracted [Huang et al., 2017; Tester et al., 2006]. Therefore, the construction of an EGS artificial thermal reservoir is the key link in the development of geothermal field. The idealized structure of an EGS reservoir is a sufficiently fractured volume with large heat exchange area and without severely preferential flow paths [Baria et al., 1999; Batchelor, 1986; Blanton, 1982; Pine and Batchelor, 1984]. However, the field stimulation of an EGS reservoir is a complicated process depending on the difference in rock structures, the existence of natural faults and cracks [Baria et al., 1999], and specific fracturing operations [Tester et al., 2006], fracture networks is inevitably created to be non-uniformity. Field and laboratory experiments have demonstrated strong evidence of the presence of the channels and highly preferential flow paths in individual fractures and fracture networks [Huang et al., 2017; Willis-Richards and Wallroth, 1995]. Fracture width and distribution characteristics are direct implications of the reservoir stimulation degree which are also closely related to water flow impedance, short circuit circulation, thermal efficiency and reservoir lifetime. Single vertical fracture model research [Hu et al., 2014; Zhai et al., 2016] showed that with the same fluid velocity, fracture width is positively correlated with reservoir temperature drop. While the operation of a geothermal field often adopts fluid flow controlling [Tester et al., 2006]. Under a certain fluid flow, fracture distribution determines the fluid velocity and the convective heat transfer effect within the rock mass, and also the time/ heat/fracture length that needed to heat fluid.

Strong non-uniformity generally exists in the engineered heat reservoirs of EGS and the influence of reservoir non-uniformity on EGS heat extraction are mainly focused. Aliyu et al. [2017] proposed the concept of triple porosity-permeability to better represent reservoir heterogeneity in naturally fractured and faulted reservoirs. Huang et al. [2017] simplified the reservoir as equivalent to a porous medium and conduct simulations with different porosity distributions to establish heterogeneous reservoirs. Finally, a method quantifying heat extraction performance of EGS in heterogeneous reservoirs was established using the seepage distribution data. Bakhsh et al. [2017] proposed a modified conceptual model of EGS that define the reservoir based on a multi-subdomain (the hydraulic fractures, a network of numerous smaller thermal cracks and the planar thermal fractures) flow model. Xu et al. [2015] proposed a new approach for flow and heat transfer modelling in complex fracture networks. Site application further demonstrated the efficiency of those proposed approach in industrial-scale EGS reservoirs. Recently, a THM coupling model, by which the reservoir is regarded as fractured porous media consisting of rock matrix blocks and discrete fracture networks, is presented for heat extraction process in EGS [Sun et al., 2017]. However, few study can deal with multi-fractured EGS reservoir and focuses on fracture distribution.

The accurate characterization of fracture network structure is difficult due to the thermal reservoir is buried underground in several kilometers. In order to study the effect of fractures on fluid flow and heat extraction of the reservoirs, a series of discrete fracture models had been developed [Cheng et al., 2001; Fox et al., 2013; Hu et al., 2014; Li et al., 2015; Wu et al., 2016], among which can be separated into single vertical fracture model and multiple parallel fracture model. Based on these models, the influence of fracture opening and spatial distribution on the heat extraction has been studied [Hu et al., 2014; Zhai et al., 2016], however, these models do not consider the heterogeneity in the fracture distribution. The numerical results of the production temperature and the reservoir lifetime are often higher than that in the field trial [Chen et al., 2015; Fox et al., 2013; Grant and Bixley, 2013; Huang et al., 2017] due to assumption that the fractures in reservoir are parallel equidistantly distributed.

In this study, a parallel multi-fracture non-uniformly distributed model for the non-uniform reservoir stimulation is constructed. The non-uniform fracture network is constructed by adjusting the fracture width and distribution, rock HTU thickness and distribution. Furthermore, the concept of preferential flow ratio and preferential thickness ratio is proposed to quantify the non-uniformity of fracture distribution. The effect of stimulated non-uniformity in fracture on EGS heat extraction performance was studied under long-term production period. Our theoretical simulation results can serve as a basis for the future design and optimization of an EGS artificial reservoir.

2. METHODOLOGY

2.1 Physical Model

The multi-parallel fracture non-uniformly distributed model is built based on the ideal multi-parallel fracture model [Fox et al., 2013; Zhai et al., 2016], and the fractures with different widths are arranged in parallel non-equidistant arrangement (Fig.1). The reservoir heat transfer unit (HTU) of each fracture is asymmetric, but cannot be directly used to solve the whole reservoir fracture network due to the uneven width and distribution of the fractures. Therefore, it is necessary to solve the fluid outlet temperature of each fracture separately for the non-uniformity of the fracture distribution. The production temperature of the whole reservoir can be obtained through mixing all the fractured outlet fluid according to the flow rate of each fracture. The width of core fractures may range from 0.1 mm to 250 mm [Dezayes et al., 2010; Genter et al., 2007; Guo et al., 2014]. Here, the width of fracture is assumed to be range from 20 mm to 100 mm to simplify the calculation.

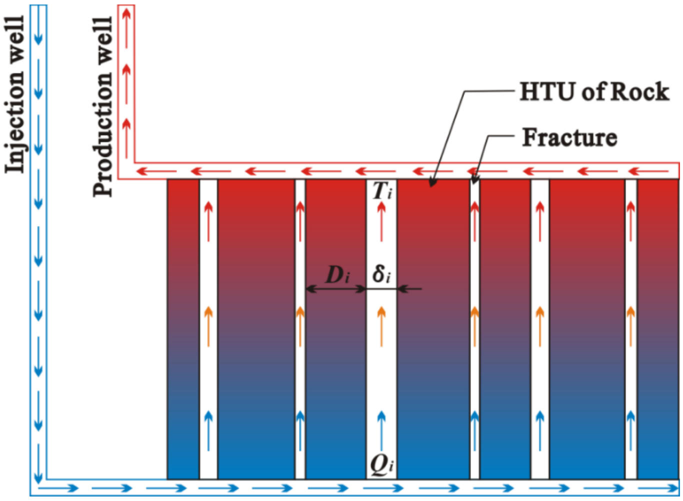

Figure 1: The multi-parallel fracture unevenly distributed conceptual model in EGS.

In this work, the following assumptions are made in order to formulate the mathematical model: (i) The rock mass in EGS reservoir is treated as a 2D fractured media consisting of rock matrix blocks and discrete fractures; the rock matrix blocks can be simplified as impermeable. The fractures created by hydraulic stimulation are the main flow pathways in the reservoir. (ii) The fractured geothermal reservoir is saturated with single-phase liquid, i.e., water. (iii) The heat exchange between water and rock matrix is achieved by advection and conduction process.

2.2 Governing Equations

The model is focused on modeling and analyses of the subsurface thermo-hydraulic process in EGS. The governing equations describing the conservation of energy are formulated as follows.

Mass continuity equation:

$$\frac{\partial \rho_{\mathrm{f}}}{\partial t} + \nabla\left(\rho_{\mathrm{f}} u_{\mathrm{f}}\right) = 0 \tag{1}$$

Energy equation in the fluid:

$$\rho_{\mathrm{f}} c_{\mathrm{f}} \frac{\partial T_{\mathrm{f}}}{\partial t} = -\rho_{\mathrm{f}} c_{\mathrm{f}} u_{\mathrm{f}} \nabla T_{\mathrm{f}} + \lambda_{\mathrm{f}} \nabla^2 T_{\mathrm{f}} + ha\left(T_{\mathrm{r}} - T_{\mathrm{f}}\right) \tag{2}$$

Energy equation in the rock matrix:

$$\rho_{\mathrm{r}} c_{\mathrm{r}} \frac{\partial T_{\mathrm{r}}}{\partial t} = \lambda_{\mathrm{r}} \nabla^2 T_{\mathrm{r}} - ha\left(T_{\mathrm{r}} - T_{\mathrm{f}}\right) \tag{3}$$

where, T is temperature, ρ is the density, c is the specific heat capacity, λ is the heat conductivity. The subscripts "r" and "f" mean rock and fluid respectively. The last terms of Eqs. (2) and (3), $\pm ha(T_r\text{-}T_f)$, describe the heat exchange between rock matrix and heat transfer fluid, where the parameter *ha* denotes the volumetric heat exchange coefficient between rock matrix and fluid in the fracture.

2.3 Case Setup

Geothermal energy in a reservoir, which buried 3 km deep to the ground, with a 500 m thickness and a horizontal area of 600 m×600 m is exploited in this study. The target reservoir rock mass is assumed to be homogeneous granite and the reservoir temperature is 200 °C. The injection rate and temperature of the injected fluid are 30 kg/s and 60 °C, respectively. The heat from each fracture and HTU of the reservoir are simulated first, and then the production temperature of the whole reservoir can be calculated after mixing, according to Eqs. (5). Both fracture and rock matrix are discretized using Gambit. The meshes are then mapped into FLUENT for the numerical calculations.

Here, the case with HTU in 100 m thickness, fracture in 10 cm width are explained in detail, the heat transfer unit and the fracture area are discretized separately (Fig.2). The grid size in z direction is uniformly 1 m for the rock HTU. The first grid size of the rock HTU is 2.5 cm and gird size increases with distance from the fracture; a total of 50 grid blocks is discretized in x direction, to save computation time and cost The grid size of the fracture area in x and z direction are uniformly 2.5 cm and 1 m, respectively. Finally, a total of 26,000 numerical elements are discretized. Moreover, grid-independence testes have been conducted prior to numerical simulation to guarantee the generated mesh could give satisfying accuracy.

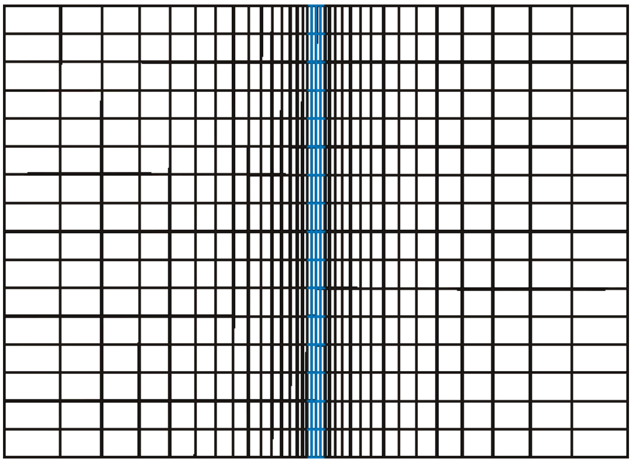

Figure 2: Schematic diagram of mesh discretization of the fracture (blue grids) and rock HTU (black grids).

Only heat transfer and fluid flow are considered and the related geo-mechanical responses is ignored. The fluid flow within the fracture is considered as low Reynolds number laminar, single-phase flow. Thermo-physical properties of fluid and rock are assumed temperature independent, as listed in Table 1 [Hu et al., 2014; Shaik et al., 2011].

Table 1: Thermo-physical properties of fluid and rock

	Density, ρ / $kg\cdot m^{-3}$	Heat Capacity, c / $J\cdot kg^{-1}\cdot K^{-1}$	Heat Conductivity, λ / $W\cdot m^{-1}\cdot K^{-1}$	Viscosity, μ / $Pa\cdot s$
Fluid	900	4200	0.609	0.0003
Rock	2820	1170	2.8	—

2.4 Definitions of Characteristic Parameters

To facilitate the analyses and discussions, five parameters, namely average production temperature, output electric power, preferential flow ratio, preferential thickness ratio, heat extraction ratio, are defined to characterize the heat extraction performance of the EGS.

Flow rate distributed in heat reservoir, flow rate Q_i of fracture i is given by:

$$Q_i = \frac{\delta_i}{\sum_{i=1}^{N} \delta_i} \cdot Q \tag{4}$$

where δ is the fracture width, Q is the total injection flow rate, N is the total number of fractures.

Average production temperature of heat reservoir T_{pro} is written as:

$$T_{\mathrm{pro}}=\frac{\sum_{i=1}^{N}\rho_{\mathrm{f}}c_{\mathrm{f}}Q_iT_i}{\rho_{\mathrm{f}}c_{\mathrm{f}}Q}=\frac{\sum_{i=1}^{N}Q_iT_i}{Q} \tag{5}$$

where T_i is the outlet temperature of fracture i.

For the closed binary power system with an injector and a producer, based on the second law of thermodynamics, the output electric power W_e is calculated as:

$$W_{\mathrm{e}}=\eta c_{\mathrm{f}}Q(T_{\mathrm{pro}}-T_{\mathrm{f0}})(1-\frac{T_0}{T_{\mathrm{pro}}}) \tag{6}$$

where $(\frac{T_0}{T_{\mathrm{pro}}})$ is calculated with absolute temperature, where T_0 is an assumed heat rejection temperature of 288.15 K, η is the utilization factor of the maximum useful work transferred to electrical power of 0.45 [Sanyal and Butler, 2005; Xu et al., 2018].

The preferential flow ratio η_{pref} represents the sum of the dominant rates of the fracture widths. It is calculated as the accumulative ratio of the difference between the dominant fracture width and the average fracture width to the average fracture width:

$$\eta_{\mathrm{pref}}=\sum_{i=1}^{N_{\mathrm{pref}}}\frac{\delta_{\mathrm{pref}}-\mu_\delta}{\mu_\delta} \tag{7}$$

where $\mu_\delta=\frac{\sum_{i=1}^{N}\delta_i}{N}$ is the average fracture width, δ_{pref} is the dominant fracture width, and N_{pref} is the number of dominant fractures, $\sigma_\delta=\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\delta_i-\mu_\delta\right)^2}$ is the standard deviation of fracture width.

The preference thickness ratio ξ_{pref} represents the sum of the dominant rates of rock HTU thickness relative to the average HTU thickness:

$$\xi_{\mathrm{pref}}=\sum_{i}^{M_{\mathrm{pref}}}\frac{D_{\mathrm{pref}}-D_{\mathrm{aver}}}{D_{\mathrm{aver}}} \tag{8}$$

where $D_{\mathrm{aver}}=\frac{\sum_{i=1}^{M}D_i}{M}$ is the average thickness of rock HTU, D_{pref} is the thickness of the dominant rock HTU, M is the number of heat transfer unit: M=N-1, M_{pref} is the number of the dominant rock HTU.

3. RESULTS AND ANALYSIS

3.1 Impacts of Fracture on Heat Extraction

The natural fractures originally contained in reservoir may be widened by reservoir stimulation and becoming a flow channel, result in a non-uniformly stimulated reservoir. The fracture distribution varies with specific natural fractures and the stimulation method. In this section, we characterize the fracture distribution by non-uniformly distributed fractures of different widths. The effect of the fracture distribution type on heat extraction is evaluated based on the reservoir with 7 fractures and HTU thickness of 100 m. Six types (Case 1-6) of fracture distribution system is built considering three fracture widths (2 cm, 6 cm and 10 cm). Based on this, cases of preference fracture and fracture width will be studied after. Part of the cases simulated in the present work are tabulated in Table 2.

Table 2: Simulate cases

Case	Number of Fractures			μ_δ	σ_δ	η_{pref}
	δ=2cm	δ=6cm	δ=10cm			
1	0	0	7	10	0	0
2	1	2	4	7.71	2.91	1.19
3	4	2	1	4.29	2.91	2.13
4	2	4	1	5.43	2.56	1.26
5	3	1	3	6.00	3.70	2
6	2	3	2	6.00	3.02	1.33
7	4	2	0	3.33	1.44	0.40

3.1.1 Fracture distribution type

The effect of fracture distribution on the fluid production temperature and flow distribution are shown in Fig. 5. It can be observed that the production temperature is the highest when the all fracture widths are equal (Case 1). While with different fracture distribution, the production temperature and the output electric power decreases, which denotes that fracture distribution type will affect the influence of fracture number of non-uniformly stimulated reservoir. This is because the fracture width distribution will affect the fluid flow distribution, and the outlet temperature of each fracture is different, large fracture width relates to large fluid flow, which leads to low outlet temperature and decreases in production temperature. With the largest number of fracture with width of 10 cm of 4, the production temperature of Case 2 is quite high with 180.9℃ with a electric power of 2.5MW after 50 years extraction. With the largest number of fracture with width of 2cm of 4, the production temperature of Case 3 is the lowest which decreases to 166.1℃ with the lifetime decreases to 16.7 years.

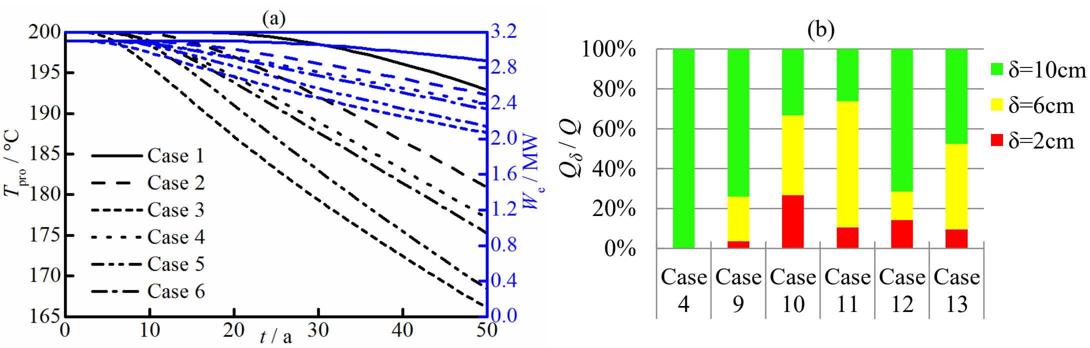

Figure 3: Production temperature and fluid flow distribution of different fracture distribution types under non-uniform stimulation.

Combining Fig. 3 with Table 2, it can be found that there is no significant correlation between the mean value and standard deviation of fracture width and the production temperature. The preferential flow ratio is negatively correlated with the fluid production temperature. This is because the standard deviation is a representation of the dispersion degree of the fracture width. While preferential flow ratio represents the sum of the dominant rates of the fracture widths. In heat extraction process the dominant fracture with wider width is more valued. Wide fracture relates to large fluid flow, low outlet temperature, which decreases the production temperature. On the contrary, narrow fracture relates to small fluid flow, high outlet temperature, which contributes little to the production temperature.

The distribution of the fracture width determines the arrangement of the fluid flow in the reservoir, which affects the evolution of the temperature field of the rock mass and the fluid during heat extraction. Fig. 4 shows the rock matrix temperature distribution of Case 6 after 20 years heat mining. It can be observed that when the width of the fracture on both sides of the rock HTU is the same, the same flow rate in the fractures and the fluid output temperature from fractures is obtained. The temperature distribution of the rock matrix is symmetrical. When the fracture widths on both sides of the rock mass are different, the fluid flow within the fracture is different, differences in the fluid output temperature is obtained and the temperature distribution of the HTU is asymmetrical. The performance of fluid flow and heat extraction increase with fracture width, as a consequence, the HTU temperature decreases more. Therefore, the temperature field of the whole reservoir will be a non-uniformity state due to the distribution of the fracture width. The preference flow channel dominantly lead the front of the thermal breakthrough and affect the reservoir lifetime.

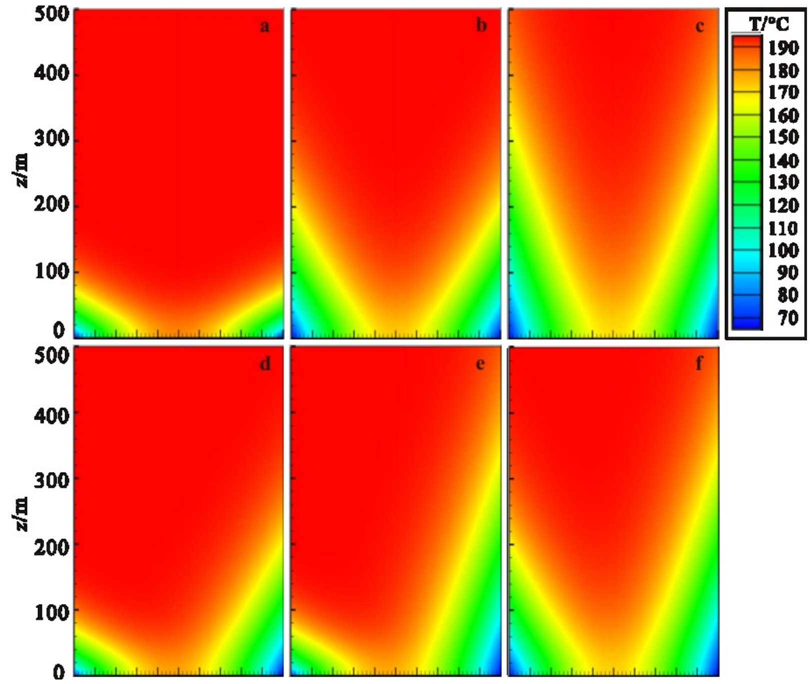

Figure 4: The temperature distribution of rock matrix of Case 6 after 20 years. The fracture widths on left and right side of the rock HTU are: a. 2cm, 2cm; b. 6cm, 6cm; c. 10cm, 10cm; d. 2cm, 6cm; e. 2cm, 10cm; f. 6cm, 10cm.

3.1.2 Preference fracture

In this section, we optimized Case 3 by blocking the preference flow channel (Case 7), the production temperature is shown in Fig. 5a. It shows that the production temperature increased by 3℃ after 50 years extraction. After shutting down the preference fracture, the fluid flow distribution will be more uniformly rearranged although the number of fracture is decreased (see Fig. 5b). The preference flow phenomenon will be weakened to some extent. In actual EGS project, for those reservoirs with serious preference flow channel or fluid leakage, it should be properly blocked of the preference flow channel to ensure the effective fluid flow and heat transfer in the reservoir.

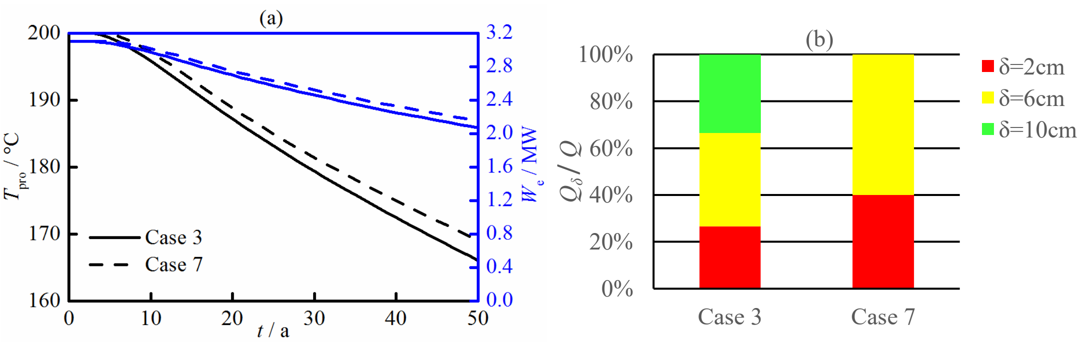

Figure 5: Comparison of the production temperature and fluid flow distribution of Case 3 and 7.

3.1.3 Fracture width

The fracture distribution not only made up the different number of fracture, but also the specific assembly of fracture widths of under same numbers of fracture. Here, the effect of fracture width on EGS heat extraction in the same fracture distribution type is studied by changing the fracture width in Case6. In this section, nine widths of fractures are combined to construct five types of fracture width combinations, and the detailed case setup is shown in Table 3, which characterized by an average value of the fracture widths of 6 cm.

Table 3: Case setup of fracture width combinations

Case	Fracture Width			μ_δ	σ_δ	η_{pref}
	n=2	n=3	n=2			
6	δ=2cm	δ=6cm	δ=10cm		3.02	1.33
8	δ=3cm	δ=6cm	δ=9cm	6cm	2.27	1
9	δ=4cm	δ=6cm	δ=8cm		1.51	0.67

10	δ=5cm	δ=6cm	δ=7cm	————	0.76	0.33
11		δ=6cm			0	0

The effect of fracture width on the fluid production temperature is shown in Fig6. It apparently shows that the combination of other fracture widths strengthened the heat extraction performance. Compared to Case6, the production temperature increased by 3.6 ℃, 7.2 ℃, 10.7 ℃ and 17.7 ℃ in 50 years by narrowing the gap of fracture widths. The average value of the fracture widths of the above combinations are the same of 6 cm. The standard deviation of the fracture width is positively correlated with the preference flow ratio, and the fluid production temperature is inversely proportional to the standard deviation of fracture widths and the preference flow ratio. A smaller the standard deviation means a more uniform the fluid flow distribution. The outlet temperature of each fracture tend to be more uniform, because of the weak preference flow channel. Consequently, the higher overall reservoir production temperature is obtained.

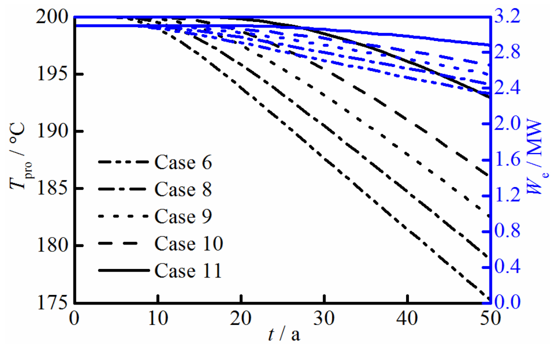

Figure 6: Effect of fracture width on EGS heat extraction under non-uniform stimulation.

3.2 Impacts of HTU on Heat Extraction

The number of fractures and the fracture density and distribution directly reflect the degree of the reservoir stimulation, which in turn affects the distribution of heat in the reservoir rock mass and the evolution of the temperature field during the heat mining process. In this section, the heat extraction effect of the reservoir with different stimulation degree is simulated by changing the combination form of rock HTU with different thickness (20 m, 40 m and 100 m) respectively. Corresponding fracture width equally assumed to be 10cm. Case setup is shown in Table 4.

Table 4: Simulation cases

Case	Number of fractures N	Number of HTU			μ_D	σ_D	ξ_{pref}
		D=20m	D=40m	D=100m			
12	9	1	2	5	75.00	32.79	1.67
13	10	3	1	5	66.67	37.71	2.50
14	11	5	0	5	60.00	40.00	3.33
15	12	4	3	4	54.55	35.26	3.33
16.1		6	2	4		36.06	4.00
16.2	13	3	6	3	50.00	30.00	3.00
16.3		0	10	2		22.36	2.00
17	14	8	1	4	46.15	36.28	4.67

3.2.1 HTU distribution type

Fig7 shows the effect of HTU distribution type on production temperature and electric power. Previous studies have shown that the production temperature is positively correlated with fracture number when the thermal reservoir is uniformly stimulated. When the fracturing of thermal reservoirs is not uniform, fracture number is still the main influencing factor of production temperature. However, due to the non-uniformity of the reservoir stimulation, the production temperature does not show a strictly proportional relationship with the number of fractures. In particular, with the progress of heat extraction, the correlation between production temperature and fracture number is gradually weakened, while the influence of HTU distribution type gradually appears.

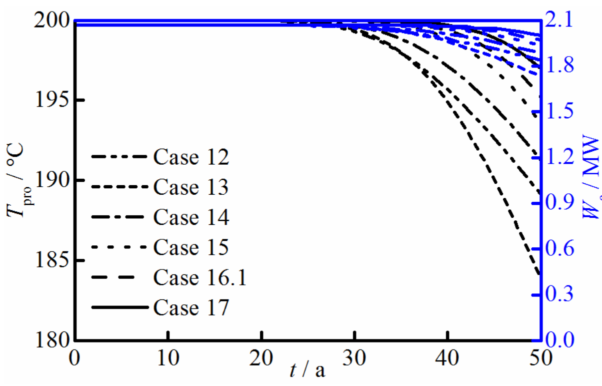

Figure 7: Effect of HTU distribution type on EGS heat extraction.

Among them, the production temperature of Case12 is higher than Case13, but the number of fractures is less than Case13. Fig.8 shows the variation of the fracture outlet temperature and the total production temperature versus time for Case12 and Case13 reservoirs. Compared with the outlet temperature of the fractures of the two groups of rock HTU combinations, it can be seen that the Case13 fracture outlet temperature is higher than the Case12 under the same HTU thickness, which is due to the number of fractures of Case13 is 10, which is higher than that of Case12 of 9. The fluid flow is smaller in each single fracture, the fracture outlet temperature is higher. But the total production temperature of the reservoir is the average temperature after mixing. In Case13, the number of fractures of D=20 m is 3, which is higher than Case12, and the fluid output temperature of D = 20 m is the lowest. So that after mixing, the production temperature is the same as Case 12 in the early stage, and lower than Case 12 in the later stage of heat extraction. Therefore, the fracture between narrow inferior HTU can be blocked to delay the early thermal breakthrough and enhance heat extraction performance.

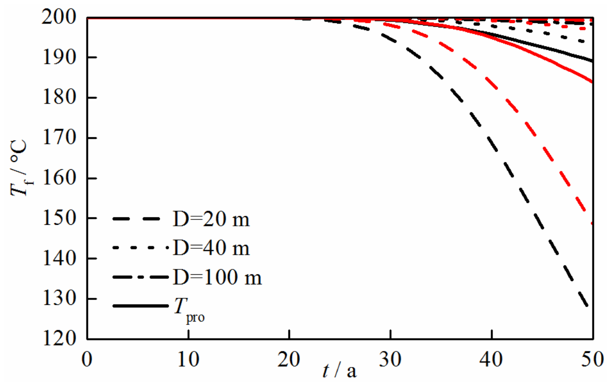

Figure 8: Production temperature of Case12(black) and Case13(red) cases.

3.2.2 HTU thickness

The effect of rock HTU thickness on the fluid production temperature is shown in Fig. 9. It can be seen that the fluid production temperature of Case16.3 is the highest which kept at the initial reservoir temperature for 40 years. The fluid output temperature is reduced by only 0.15℃ after 50 years heat extraction. The other two combinations decrease significantly in later extraction process. Combined with Table 4, there is a negative correlation between the production temperature and the standard deviation of the rock HTU thickness and the preference thickness ratio. The mean values of the thickness of the rock HTU of three cases are the same of 50 m. The standard deviation and the preference thickness ratio were positively correlated. The standard deviation of the HTU thickness describes the dispersion of the thickness of the rock HTU. The smaller the standard deviation, the more uniform the HTU thickness, the more homogeneous heat distribution, and the fluid can be uniformly heated to a higher temperature. The overall output temperature of the reservoir is high.

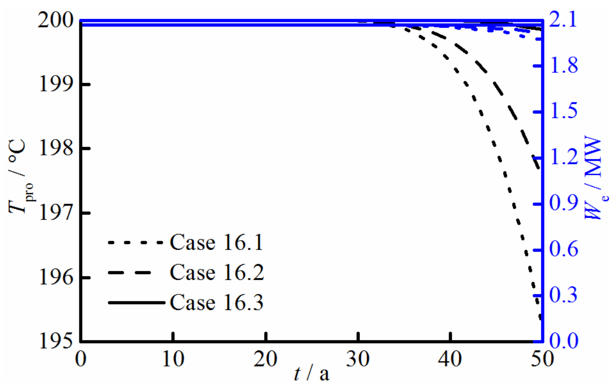

Figure 9: Effect of HTU thickness on EGS heat extraction.

Fig.10 shows the HTU temperature distribution of Case 16 after 20 years heat extraction. The rock mass temperature field presents symmetry when the thickness of the rock mass on both sides of the fracture is the same (see Label a, b, c). With the increase of the HTU thickness, the proportion of the temperature drop zone is shrinking, and the cooling zone (represented in blue) is gradually shrinking either. While when the thickness of rock mass on both sides of the fracture is different, the temperature field of rock mass is asymmetric (see Label d, e, f). Taking the thickness of HTU on both sides of the crack as 20 m and 40 m respectively, for example, compared with the symmetrical HTU, the temperature field on the side of D=20 m is higher, and the temperature field on the side of D=40 m is lower, tending to the average result of both. Therefore, the smaller the thickness of HTU, the less the internal heat storage, and the earlier thermal breakthrough under the same fracture flow, will finally affect the reservoir life.

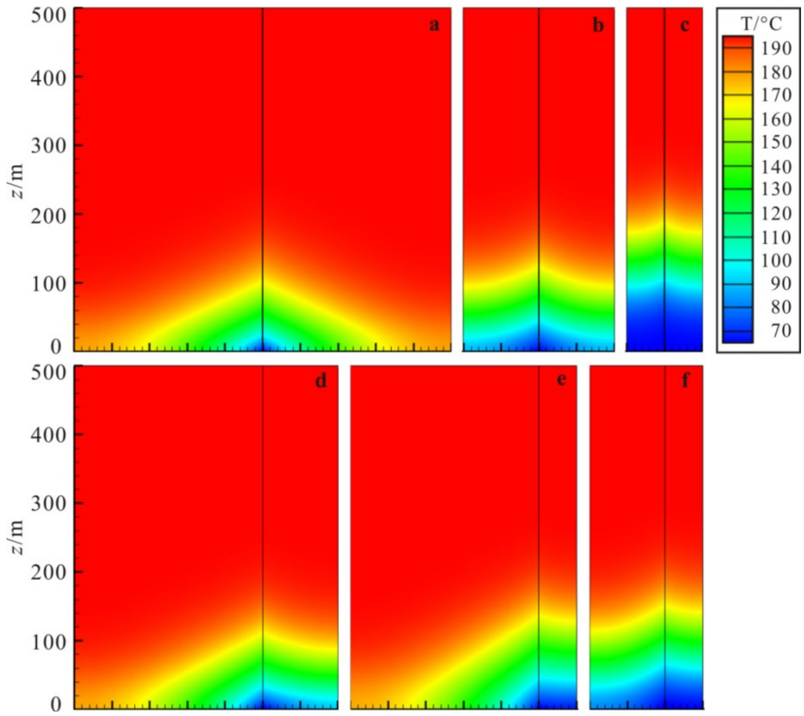

Figure 10: HTU temperature distribution of Case 16 after 20 years heat extraction. HTU thickness of both sides of the fracture are: a.100 m, 100 m; b.40 m, 40 m; c. 20 m, 20 m; d. 100 m, 40 m; e.100 m, 20 m; f.40 m, 20 m.

Fig. 11 shows the fluid temperature distribution within the fracture after 20 years heat extraction of Case16. It can be seen that the fracture outlet temperature is closely related to the adjacent rock HTU thickness. When the thickness of the HTU is the same on both sides of the fracture, the outlet temperature of the fracture increases with the increase of the HTU thickness. While when the thickness of the HTU on both sides of the fracture is different, the outlet temperature tends to the average value of the outlet temperature of the fracture corresponding to the two HTU.

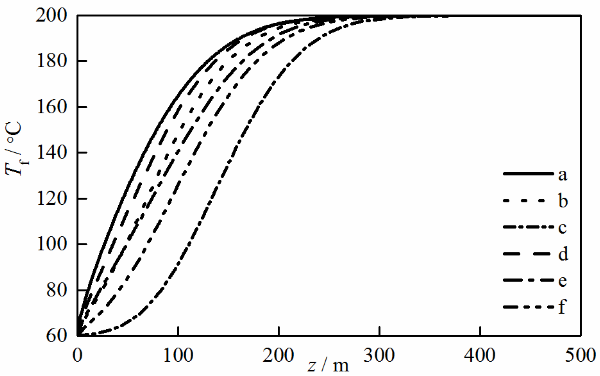

Figure 11: Fluid temperature distribution within the fracture after 20 years heat extraction.

Combined with Fig. 4, the distribution of fluid flow and reservoir heat will be affected by the combination of fracture width and rock HTU thickness. Different arrangement of fractures and rock HTU will affect the evolution of temperature field during heat extraction. The more fully the reservoir stimulated, the better the heat extraction performed and the longer the reservoir life. Especially for the multi-well system heat extraction-recovery process, the reservoir stimulation situation will affect the heat recovery of the reservoir. For non-uniformly stimulated reservoir, strong non-uniformity will intensify the cooling effect of the cold fluid which will make the heat recovery process cannot effectively recover the overall temperature field. Therefore, it is necessary to improve the reservoir stimulation technology, optimize the reservoir stimulation strategy, reduce the inhomogeneity of reservoir stimulation, and realize the fully uniformly reservoir stimulation to improve the efficiency of heat extraction and extend the reservoir life.

4. CONCLUSION

In this study, we proposed a multi-parallel fracture non-uniformly distributed model. For this model, the fracture and the rock HTU is not averagely distributed to accomplish the non-uniformity of EGS reservoir. Based on the model, the temperature field of non-uniformly distributed fracture system was analyzed, which provided a great understanding of the heat extraction process of non-uniformly stimulated reservoir. The key findings of this study were as follows.

The production temperature and rock mass temperature filed are strongly affected by the distribution characteristics of the fracture. The production temperature is in a negative correlation to the preferential flow ratio. To block the preference fracture, or to enhance the stimulation degree by narrowing the gap of fracture widths can enhance the heat extraction efficiency.

The number of fracture is still the main affecting factor of the production temperature. However, owing to the non-uniformity, the production temperature is not strictly positively correlated with fracture number, but also affected by the distribution characteristics of rock HTU. Under the same fracture number, the production temperature is negatively correlated with the preferential thickness ratio, which means that it is favorable for production from the heat reservoir in the conditions of sufficient fractures with uniformly distributed fracture width. To seal the inferior rock HTU or enhance the stimulation degree by increasing fracture number can enhance the heat extraction efficiency.

The proposed model of multi-parallel non-uniformly distributed fracture had been demonstrated to be an efficient tool for non-uniformly stimulated reservoir study. The simulation results provided great suggestions for reservoir stimulation and fracture system design. Based on the model, the operational and geometrical parameters of the actual EGS site, such as injection temperature, fluid flow, fracture density, fracture distribution, could be further optimized to obtain the greatest heat extraction performance for the field application, which is also the major point of our future studies.

REFERENCES

Aliyu M D, Chen H P, Harireche O, et al. Numerical Modelling of Geothermal Reservoirs with Multiple Pore Media[C]//PROCEEDINGS, 42nd Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 13-15, 2017.

Bakhsh K J, Nakagawa M, Arshad M, et al. An Innovative Computational Approach for Modeling Thermo-hydro Processes within Enhanced Geothermal System[C]// PROCEEDINGS, 42nd Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 13-15, 2017.

Baria R, Baumgärtner J, Rummel F, et al. HDR/HWR reservoirs: concepts, understanding and creation[J]. Geothermics, 1999, 28(4–5):533-552.

Batchelor A S. Reservoir Behaviour in a Stimulated Hot Dry Rock System[C]// PROCEEDINGS, Eleventh Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, January 21-23, 1986.

Blanton T. An Experimental Study of Interaction Between Hydraulically Induced and Pre-Existing Fractures[J]. Soc. Pet. Eng. AIME, Pap.; (United States), 1982, spe/doe 10847.

Breede K, Dzebisashvili K, Liu X, et al. A Systematic Review of Enhanced (or Engineered) Geothermal Systems: Past, Present and Future[J]. Geothermal Energy, 2013, 1(1): 4.

Chen J, Jiang F. A numerical study of EGS heat extraction process based on a thermal non-equilibrium model for heat transfer in subsurface porous heat reservoir[J]. Heat & Mass Transfer, 2015, 52(2):1-13.

Cheng A H D, Ghassemi A, Detournay E. Integral equation solution of heat extraction from a fracture in hot dry rock. International Journal for Numerical and Analytical Methods in Geomechanics, 2001, 25: 1327-1338.

Dezayes C, Genter A, Valley B. Structure of the low permeable naturally fractured geothermal reservoir at Soultz. Comptes Rendus Geoscience, 2010,342: 517-530

Doe T, McLaren R, Dershowitz W. Discrete Fracture Network Simulations of Enhanced Geothermal Systems[C]// PROCEEDINGS, Thirty-Ninth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 24-26, 2014.

Fox D B, Sutter D, Beckers K F, et al. Sustainable Heat Farming: Modeling Extraction and Recovery in Discretely Fractured Geothermal Reservoirs[J]. Geothermics, 2013, 46: 42-54.

Genter A, Cuenot N, Dezayes C, et al. How a better characterization of a deep crystalline reservoir can contribute to improve EGS performance at Soultz[C]//1st European Geothermal Review. Mainz. Germany: Geothermal Energy for Electric Power Production, 2007: 34-40.

Grant M A, Bixley P F. Geothermal Reservoir Engineering, Elsevier, 2013.

Guo J, Chen J L, Cao W J, et al. Research review on enhanced geothermal system[J]. Electric Power Construction(in Chinese), 2014, 35(4): 10-24.

Huang W, Cao W, Jiang F. Heat extraction performance of EGS with heterogeneous reservoir: A numerical evaluation[J]. International Journal of Heat & Mass Transfer, 2017, 108:645-657.

Hu J, Su Z, Wu N Y, et al. Analysis on temperature fields of thermal- hydraulic coupled fluid and rock in Enhanced Geothermal System. Progress in Geophysics (in Chinese), 2014, 29(3): 1391-1398.

Hu J, Su Z, Wu N Y, et al. Numerical simulation of vertical fractures heat mining process of the enhanced geothermal system. Renewable Energy Resources (in Chinese), 2014, 32(6): 829-835.

Li M, Gou Y, Hou Z, et al. Investigation of a new HDR system with horizontal wells and multiple fractures using the coupled wellbore-reservoir simulator TOUGH2MP-WELL/EOS3[J]. Environmental Earth Sciences, 2015, 73: 6047-6058.

Liu M L, Zhuang Y Q, Zhou C, et al. 2016. Application of chemical stimulation technology in enhanced geothermal system: theory, practice and expectation[J]. Journal of Earth Science and Environment (in Chinese), 2016, 38(2):267-276.

Pine R J, Batchelor A S. Downward migration of shearing in jointed rock during hydraulic injections[J]. International Journal of Rock Mechanics & Mining Sciences & Geomechanics Abstracts, 1984, 21(5):249-263.

Sanyal S K, Butler S J. An analysis of power generation prospects from enhanced geothermal systems. Geotherm. Resour. Counc. Trans. 2005;29:131e8.

Shaik A R, Rahman S S, Tran N H, et al. Numerical Simulation of Fluid-Rock Coupling Heat Transfer in Naturally Fractured Geothermal System[J]. Applied Thermal Engineering, 2011, 31: 1600-1606.

Song X, Shi Y, Li G, et al. Numerical simulation of heat extraction performance in enhanced geothermal system with multilateral wells[J]. Applied Energy, 2018, 218:325-337.

Sun Z X, Zhang X, Xu Y, et al. Numerical simulation of the heat extraction in EGS with thermal-hydraulic-mechanical coupling method based on discrete fractures model[J]. Energy, 2017, 120:20-33.

Tester J W, Anderson B, Batchelor A, et al. The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century[J]. Massachusetts Institute of Technology. 2006.

Willis-Richards J, Wallroth T. Approaches to the modelling of hdr reservoirs: A review[J]. Geothermics, 1995, 24(3):307-332.

Wu B, Zhang X, Jeffrey R G, et al. A simplified model for heat extraction by circulating fluid through a closed-loop multiple-fracture enhanced geothermal system[J]. Applied Energy, 2016, 183:1664-1681.

Xu C, Dowd P A, Tian Z F. A simplified coupled hydro-thermal model for enhanced geothermal systems[J]. Applied Energy, 2015, 140:135-145.

Xu T F, Yuan Y L, Jia X F, et al. Prospects of power generation from an enhanced geothermal system by water circulation through two horizontal wells: A case study in the Gonghe Basin, Qinghai Province, China[J]. Energy, 2018, 148:196-207.

Zhai H Z, Su Z, Ling L L, et al. Impact of heat transfer unit on EGS heat extraction in the multi-parallel fracture model. Progress in Geophysics (in Chinese), 2016, 31(3): 1399-1405.