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On Tunable Facture Conductivity to Improve Heat Extraction from Fractured Geothermal Systems

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ABSTRACT

During the development of an enhanced geothermal reservoir (EGS), production efficiency may be significantly affected by the heterogeneity of fracture conductivity. To avoid any dominant flow path that may "short-circuit" the fluid flow between the injector and producer, we presented the idea of autonomous tunable fracture conductivity and explored its potential benefits in production. The presented technique can provide high hydraulic conductivity in fractures when the surrounding temperature is high and vice versa low conductivity at low temperatures. Results show that utilizing this technique could prevent an early appearance of the dominant flow path between injector and producer in an EGS. By applying this technique, the output thermal power after 50 years of production can be increased by over 30 %, which is considerable for the EGS production. Since other flow-control systems are mainly focused on the wellbore and near-wellbore areas, this technique can provide a more effective enhancement in heat extraction by controlling flow deep inside the reservoir.

1. INTRODUCTION

Geothermal energy could play a critical role in the decarbonization of the economy and is critical to address climate change, especially in areas where reliable solar or wind resources are not available. Geothermal energy is also a renewable source that can be used for power generation or direct heating purposes. In general, the development of a geothermal reservoir relies on circulating the working fluid to extract heat from subsurface reservoirs. Based on the method of heat extraction, geothermal systems can be divided into two categories: traditional geothermal (hydrothermal) systems and enhanced geothermal systems (EGSs) (Lu, 2018). Compared to conventional geothermal development systems, the EGS has the advantage of extracting heat at a higher rate by creating artificial fractures in the hot rocks and then circulating fluid through them. US Department of Energy has envisioned that with technology improvements, especially in areas relevant to enhanced geothermal systems (EGS), geothermal power generation could increase 26% from today by 2050 (Hamm et al., 2019). In recent years, EGSs are rapidly developed all over the world, especially in the U.S. Since the Fenton Hill project in 1970s, great amounts of EGS projects are developed or approved in the U.S, including Raft River in Idaho, Geysers and Coso in California, Milford in Utah, Brady and Desert Peak in Nevada (Olasolo et al., 2016).

EGS operators are naturally aiming to extract heat at the maximum rate from a given volume of the reservoir rock. In other words, they expect the circulation fluids could carry heat as much as possible from the reservoir and would like to avoid any "fast paths" that would "short-circuit" the fluid flow. However, the hydraulic fracturing in the EGS would generate several long and wide fractures between well doublet. These induced fractures with high conductivity could develop some dominant flow paths for fluid flow, which might lead to the problems like the early thermal breakthrough. Therefore, EGS requires the ability to control the flow of fluids through and throughout the created fracture network in the reservoir. One of the problems that is usually encountered in EGS development is the early thermal breakthrough (Li et al., 2016). Thermal breakthrough means that the cold water from the injection well breakthrough the hot reservoir environment and reaches the production well without sufficient heating. In general, after the EGS reaches the thermal breakthrough, production temperature would significantly decline and thus the EGS may not continue effectively extracting the heat from the reservoir, which is destructive for the whole system. Great amounts of field evidence and numerical results suggest that the fluid flow between well doublet of EGS tends to localize into few fractures and then "short-circuit" the flow of working fluid (Brown et al.,2012; Wyborn et al., 2004). In this situation, early thermal breakthrough is more likely to appear. In last few years, researchers have proposed different therapies to avoid thermal shortcut or flow "short-circuit" in EGS and tried to delay the thermal breakthrough. Fan et al. (2020) proposed a periodic operation scheme for the optimization of EGS. They suggested that periodical shut-in between each production of months could effectively delay the thermal breakthrough. However, the economic efficiency for this scheme highly depends on the balance between the shut-in time and operation time. Besides, Li et al. (2016) recommended larger well spacing and smaller fracture spacing for the EGS with MFHW. Although many optimization methods were proposed in recent years, all these methods mainly focused on the injection rate, well configuration and completion strategies and well spacing. None of these methods really touch the reservoir itself, especially for the fractures. The methods based on fracture flow control have great development potential and could be an alternative way for the optimization of EGS. Currently, there is no effective way to control the direction of fracture paths or alter the closure stress in the rock to engineer the geometry of induced fractures in the subsurface. However, it would be a big benefit to somehow control the hydraulic conductivity of these fractures autonomously.

To fill the current gaps, here we are proposing a new development method for the EGS, i.e., Fracture Conductivity Tunning Technique. To study the feasibility of this technique in the development of EGS, this research is organized as follows. First, the mathematical model and the principle of fracture conductivity tunning technique would be presented in section 2. Then, a numerical model is established and the results are presented in section 3 to evaluate the performance of this new method in the development of EGS. Since current approaches for the optimization of EGS are mainly focused on flow control near the wellbore, we are now looking to control the flow deep inside the reservoir. In this research, we expect to provide a new insight for clean, environmental, and highly efficient development of EGS

2. CONCEPT OF FCTT

Hydraulic conductivity of fractures after hydraulic stimulation (hydraulic fracturing and shearing) plays a dominant role in EGS production. However, the presence of "flow circuit" or "flow shortcut" may significantly decrease the production efficiency of the geothermal system. To make fluid flow in the geothermal reservoir more uniform and delay a possible thermal breakthrough, we explore a new concept, i.e., Fracture Conductivity Tuning Technique (FCTT). The idea of FCTT is to provide high fracture hydraulic conductivity at high temperatures and low hydraulic conductivity at low temperatures. Such tunable fracture hydraulic conductivity can be achieved in several ways, including the temperature-sensitive proppant which will soft expand or shrink according to the surrounding temperature.

The autonomous tunable fracture conductivity is important to EGS production since it can alter the flow distribution in the reservoir. let's assume that we have several fractures connecting the injection well to the production well as shown in **Figure 1** (a). In the absence of the tunable fracture hydraulic conductivity in the fractures, the flow rate in fracture III would be much larger than that in other fractures, since it has the shortest path (higher pressure gradient) and it might also have higher fracture hydraulic conductivity. Therefore, a dominant flow path would appear in this situation and more heat would be extracted from reservoir rocks around fracture III. Early thermal breakthrough tends to take place under this condition since the cold water could be fast delivered from the injector to the producer through fracture III without enough residence time to heat it up. By contrast, when the FCTT is applied in an EGS as shown in **Figure 1** (b), the flow rate in fracture III would significantly decline as the flow of cold water in this fracture could decrease the corresponding hydraulic conductivity. Then, more working fluid would have to flow through other fractures, i.e., fractures I, II, IV, and V. By applying the FCTT, the flow rate in each path would be adjusted to have the same residence time in the reservoir. In this situation, a thermal breakthrough can be effectively delayed and the existing heat in the areas near fractures I and V can also be effectively tapped.

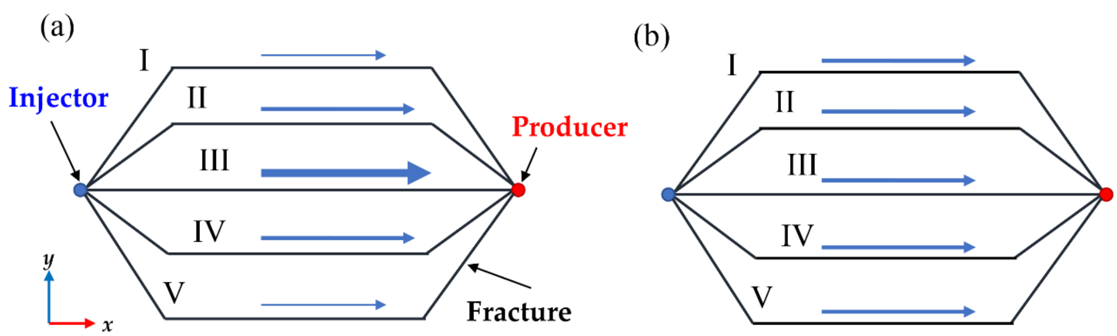
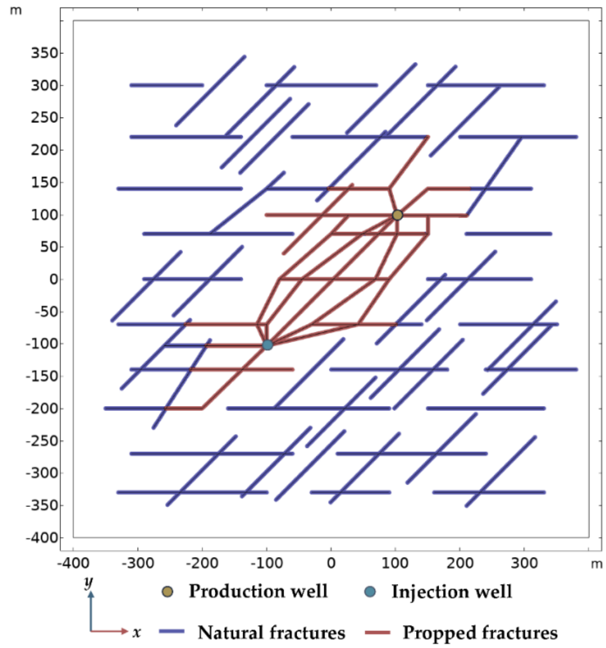


Figure 1:Illustrations of flow rates along each fracture in 2-D map view: (a) FCTT is not applied; (b) FCTT is applied. The arrow size represents the flow rate.

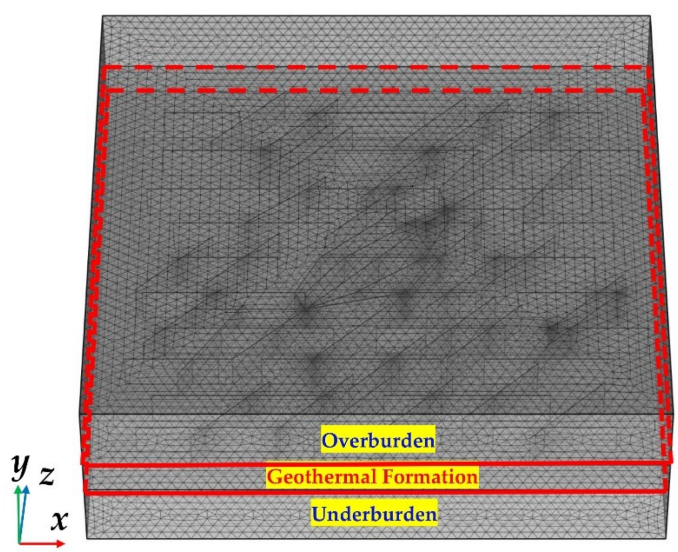
3. RESULTS AND DISCUSSION

3.1 Model Description

Based on the mathematical models presented in section 2, a field-scale model is constructed to see how FCTT can improve the heat extraction performance in an EGS. **Figure 2 (a)** shows a map view of a hypothetical naturally fractured geothermal formation. The size of the depicted model is 800 m × 800 m × 50 m. We assigned the origin of the coordinate system to the center of this geothermal formation. In this geothermal formation, two sets of fractures are created to represent natural fractures formed mainly in two different geological time, i.e., in-situ stresses. An injection vertical well located at (-100, -100, 0) and a production vertical well located at (100, 100, 0), are considered. Both wells are assumed to be hydraulically stimulated, thus a complicated fracture network is created near the wellbore. In this model, we assume that the FCTT is only applied in fractures that are directly connected to the wells shown as red lines in **Figure 2**. We assume that the proppants are uniformly placed in those fractures. The blue fractures in the figure are assumed to be unpropped natural fractures whose permeability can be calculated using the Cubic Law (Zhang and Dahi Taleghani, 2022). Besides, an overburden and an underburden are also incorporated into the model to consider the potential impacts of heat flux between layers and external heat support. **Figure 2 (b)** shows a 3-D rendering of the complete geometry model where the targeted geothermal formation is outlined by the red box.



(a) Geometry model of geothermal formation with fracture networks in 2-D map view.



(b) The illustration of the geometry model and mesh generation.

Figure 2: Geometry model and mesh generation of the geothermal reservoir.

The parameters used for the simulation are listed in **Table 1**.

Table 1: Parameters used for the field-scale numerical model.

Parameters	Value	Unit
Dimensions of the reservoir	800×800×250	m^3
Thickness of geothermal formation	50	m
Permeability of the reservoir	0.5	10^{-3} μm^2
Permeability of overburden and underburden layers	0.05	10^{-3} μm^2
Initial porosity of the reservoir	10	%
Thermal conductivity of the reservoir rock	2.8	W/(m·K)

Specific heat capacity of the reservoir rock	1000	J/(kg·K)
Thermal conductivity of propped fractures	2.4	W/(m·K)
Specific heat capacity of propped fractures	850	J/(kg·K)
Initial reservoir pressure	3.0×10^7	Pa
Injection pressure	4.0×10^7	Pa
Production pressure	2.0×10^7	Pa
Initial reservoir temperature	473.15	K
Injection temperature	373.15	K
Simulation period	50	Year

In this section, we design two different simulation cases for comparison. For case 1, FCTT is not applied in the fracture system. For case 2, FCTT is applied in the fracture systems. **Figure 3** shows the comparison of temperature distribution between simulation cases 1 and 2 at the 10th year, respectively. We can observe from the figure that when the FCTT is not applied in the fracture system, i.e., Case 1, a dominant flow path can be easily identified. By contrast, when the FCTT is applied in the fracture system, i.e., Case 2, fluid from the injection well will flow to the production well evenly through each fracture. We cannot recognize any dominant flow path or "short-circuit" flow path in the reservoir. To sum up, When FCTT are not employed in the fracture systems, a dominant flow path can be clearly observed from the injector to the producer, which has a negative impact on the production efficiency from EGS and would decrease the effective life for the system.

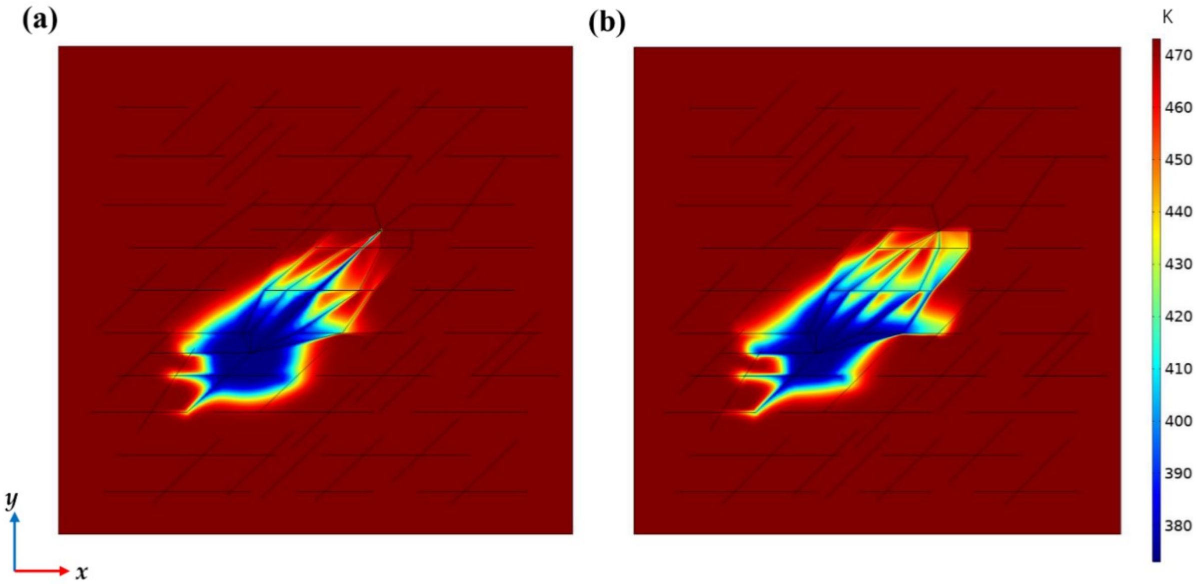


Figure 3: A comparison of temperature distribution between (a) case 1: without FCTT and (b) case 2: with FCTT at the 10th year of production.

To quantitatively evaluate the improvement caused by the proposed FCTT in EGS heat extraction, we present a comparison of typical indicators of EGS performance. **Figure 4** shows the evolution of production temperature over the 50 years of operation according to different simulation cases. It could be seen from the comparison that when the FCTT is not adopted in the EGS, i.e., case 1, the temperature of the produced fluid would drop rapidly over the 50 years of production, from 473.15 K to 396.91 K. By contrast, when the FCTT is adopted in the fracture system, i.e., case 2, the production temperature after 50 years of development could reach 406.52 K, which is around 20 K higher than the production temperature in case 1. In other words, the application of autonomous fracture conductivity allows for maintaining a higher production temperature during long-term production.

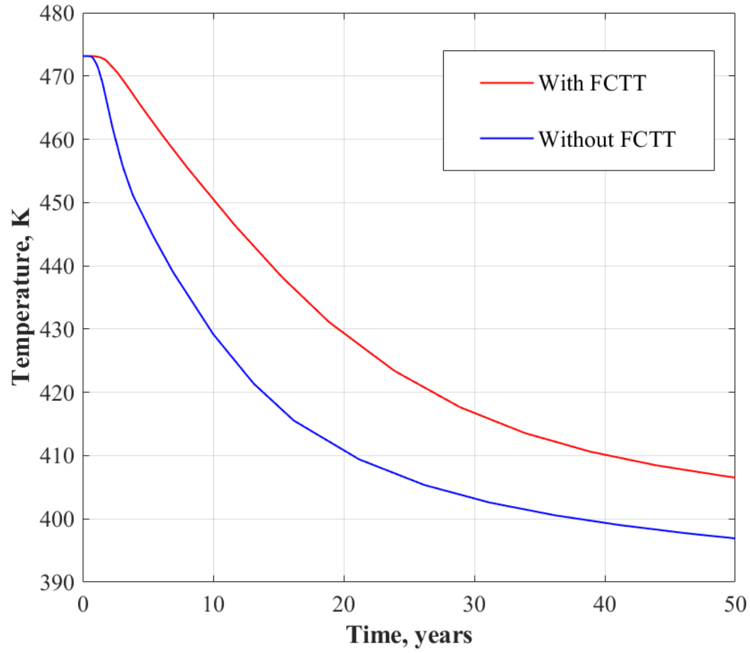


Figure 4: A comparison of fluid temperature at the production well between different cases.

To evaluate the performance of an EGS, the temperature of the circulated fluid should not be the only variable to consider. Instead, the maximum output thermal power from the geothermal systems should also be considered. It is essential to evaluate the improvement in energy extraction from EGS when of the proposed FCTT is adopted. To quantitatively evaluate the benefits of the application of FCTT in heat extraction from EGS, a dimensionless heat extraction index fold of increase I is defined as following

$$I = \frac{Q_p}{Q_i} \cdot \qquad (1)$$

where Qp is the thermal power output when FCTT is utilized during production. Qi is the thermal power output when the FCTT is not applied but have the same fracture geometry propped. For the field-scale simulation model presented in this section, the heat extraction index fold of increase I equals thermal power from case 2 divided by that from case 1.

Figure 5 shows the evolution of the heat extraction index fold of increase I over 50 years of production. It could be seen from the figure that the utilization of the FCTT would significantly improve the heat extraction from the geothermal reservoir. From the beginning to the 20th year of production, the utilization of FCTT can rapidly improve heat extraction from the EGS. The reason behind this observation is that in this stage the utilization of such technique can significantly prevent the appearance of dominant flow paths and delay the cold water "short-circuit" from the injector to the producer. Then, at the 21th year of production, the improvement in heat extraction caused by adopting FCTT reaches its peak value, which is a 41.2% increase in the thermal power extracted from EGS. After that, the heat extraction index fold of increase I will gradually decrease and then stabilize. Finally, after 50 years of production, the application of FCTT could bring 31.4 % extra heat extraction from the EGS, which is highly considerable for the EGS production. In simple words, as time goes on, the heat extraction index fold of increase I will keep increasing and then stabilize. The utilization of FCTT could bring more heat extraction increment in the late period of production. This characteristic is important because for a typical EGS, no matter whether we apply the FCTT, we could still have a good heat extraction performance in the early period of production. The heat extraction increment in the late period means that the effective operation duration would be significantly extended. To sum up, the application of FCTT could help to harvest more heat energy from the EGS and significantly elongate the span of life of EGS.

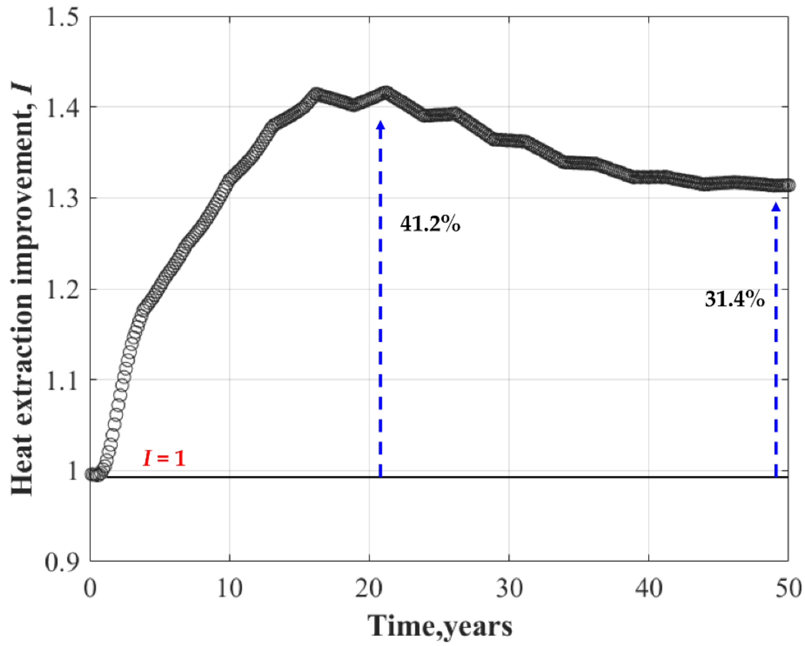


Figure 5: A Heat extraction index fold of increase *I* over 50 years of production

4. CONCLUSIONS

The development of a geothermal reservoir relies on circulating the working fluid to extract heat from subsurface reservoirs. Field results suggest that, during the development of EGS, fluid flow in the reservoir tends to be highly localized and unbalanced. To avoid any "fast flow paths" that would short-circuit the water and prevent the early thermal breakthrough in the enhanced geothermal systems (EGS), in this study, we presented a new EGS development method. i.e., Fracture Conductivity Tunning Technique. The aim of the utilization of this new method is to provide high fracture conductivity in high temperatures and low fracture conductivity in low temperatures.

Simulation results show that, for the well doublet with complex fracture networks, utilization of the fracture conductivity tunning method would avoid the appearance of dominant flow paths between wells and could enable to maintain high production temperature. When this new method is adopted in the development of EGS, the production temperature could 20 K higher than that without utilizing this method. By comparing the generated power according to different simulation scenarios, it could be known that, after a continuous production of 50 years, output thermal power with this new method could be over 30% higher than the scheme without it, which is significantly considerable in the development of EGS. Since standard approaches for altering flow are mainly focused on near-wellbore areas, we are now looking to control the flow far away inside the reservoir. In this research, we expect to provide a new insight for clean, environmental, and highly efficient development of EGS.

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