Numerical Simulation of Heat Extraction Performance in EGS with Cryogenic Fracturing

Hongyuan Zhang¹, Zhongwei Huang¹,*, Gensheng Li¹, Shikun Zhang¹, John D. McLennan²,*

¹State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum, Beijing, China
²EGI, University of Utah, Salt Lake City, UT

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ABSTRACT

Artificial fractures play an important role in improving heat extraction performance of an EGS. Cryogenic fracturing technology employs cryogenic liquid nitrogen as a stimulation fluid - causing severe thermal shock. This thermal shock leads to a well-connected fracture network in the native hot, low permeability reservoir. An experiment has been conducted to investigate the morphology of the fractures induced by thermal shock. Based on local thermal equilibrium theory, a coupled thermal-hydraulic model has been developed to simulate the heat extraction process from an EGS as a function of different fracture configurations. The reservoir is regarded as a fractured porous medium, consisting of rock matrix, porosity and fracture networks. The proposed model is validated against analytical solutions. With the validated model, the characteristics of fluid flow, temperature distribution and heat extraction performance in geothermal reservoirs are analyzed as a function of different fracture geometries. The results indicate that fracture networks created by cryogenic fracturing significantly improve the heat extraction performance of an EGS.

1. Introduction

Hot dry rock (HDR) formation is a sort of high temperature reservoir contains geothermal energy, with characteristics of low porosity and low permeability. Recently, enhanced (or engineered) geothermal system (EGS) is recognized as an effective and exercisable technology for HDR exploitation. EGS typically consists of one or more injection wells for cold water injection, and at least one production well through which hot water is produced carrying geothermal energy to the surface. Artificial fractures are also indispensable for EGS to form a heat recovery cycle together with injection wells and production wells, which offer fluid flow paths and heat exchange areas.
Except for drilling, the major challenge in EGS engineering is fracturing. Artificial fractures inside the reservoir, especially the fractures connecting the injection and production wells, are very important because they affect the heat extraction performance of an EGS directly. A high-efficiency fracture network must fulfill two requirements to ensure enough thermal power output (Hofmann H. et al. 2016). Firstly, the fractures are well connected to each other, and connecting the injection and production wells. Good connectivity enables high fluid flow rate through the stimulated reservoir under relatively lower cyclic pressure difference. Secondly, the residence time of working fluid in the fractures must be long enough for heat exchange. Long residence time enables working fluid heat up before it reaches the production wells, which helps reduce the risk of flow channeling.

To meet the requirements mentioned above, a complex (or branched) fracture network is needed, which is treated as a key for commercial heat production from an EGS (Hofmann H. et al., 2014; Tester et al., 2006). This is because complex fracture network is composed by many interlacing fractures, which disperses the injected cold water into a large area. With the advantage of increased heat exchange area and reduced local velocity of working fluid, heat extraction performance will be improved, economic mining time will be extended as well. Hence, finding a high-efficiency stimulation technology which is appropriate for HDR, evaluating the distribution and connectivity of artificial fractures and understanding its impacts on subsurface heat extraction performance together with hydro-thermal coupling process is of great importance to the heat mining from EGS.

Cryogenic fracturing is a relatively new technology which employs ultralow temperature fluid as working medium. It rests on the idea that a sharp thermal shock caused by contacting with and vaporization of cryogenic fluid, can induce a complex fracture network when ultralow temperature fluid is injected into a much warmer formation under down-hole conditions (Alqatahni, N.B. et al., 2016). HDR is an ideal formation for cryogenic fracturing technology for its brittleness, high temperature and low permeability. Schematic diagram of cryogenic fracturing in HDR is illustrated in Fig. 1. Many field tests, experimental and numerical studies have been conducted to investigate the effects of cryogenic fracturing since 1980s. King and Lillies (King, S.R. 1982; Lillies, A.T., King, S.R. 1982) stimulated tight gas sand formations using gelled liquid carbon dioxide (233.2K to 244.3K), and all wells experienced an increase on production rates. McDaniel et al. (1997) conducted an experimental study to investigate the effects of thermal shock on coal samples. The experimental results show that the coal samples experienced a significant shrinkage when immersed in liquid nitrogen (77K). Repeated cycles of liquid nitrogen make the samples break into smaller pieces. Field tests are also conducted in 5 wells and the stimulation results are satisfactory. Grundmann, S.R., et al. (1998) stimulated a Devonian shale well with liquid nitrogen and gain an 8% increase on production rate. Alqutahni, N.B., et al. (2016) conducted series of experimental researches on cryogenic fracturing in different rock samples under true tri-axial confining stresses. Results show that liquid nitrogen promote the rock breakdown process with relatively lower injection pressure. Complex fracture networks are formed in all the specimens after confined cryogenic fracturing treatments. Zhao, B. et al. (2016) suggest that using liquid nitrogen as working fluid during re-fracturing process to improve the stimulation results over conventional hydraulic re-fracturing. Experimental research and theoretical analysis are taken to investigate the stimulation mechanism of cryogenic re-fracturing. The fractures induced by thermal shock on the surface of rock specimen are also presented.
For heat extraction process of EGS, the complexity involves convective and conductive heat transfer, fluid flow, rock matrix deformation, stress redistribution, and geochemical reactions, which is a multi-field coupling problem (Song, X.Z., et al. 2018). Accurate analytical solution is always impossible for these problems. Numerical simulation is an alternative way, and has been proved to be reliable in optimization of heat extraction in EGS (Franco, A. et al. 2014; Chen, J.L. et al. 2014; Li, M. et al. 2015). In previous numerical study, real discrete fracture network model or equivalent continuous porous media model is always adopted for natural and artificial fractures, local thermal equilibrium or local thermal non-equilibrium model is used to depict the heat transfer between rock and fluid (Kazuo, H., et al. 1999; O'Sullivan, MJ., et al. 2001; Botros, FE. et al. 2008; Blöcher, MG. et al. 2010; Kedziora, A. et al. 2013). Based on coupled thermo-hydraulic (TH) numerical model, parameters sensitivity analysis have been conducted, including flow rate, injection temperature, reservoir porosity, formation permeability well-type, local thermal non-equilibrium, to investigate their effects on the heat extraction performance of an EGS (Song, X.Z., et al., 2018; Jiang, F.M., et al., 2014; Cheng, W.L., et al., 2016; Aliyu, M.D., et al., 2017; Huang, W.B., et al. 2017; Feng, G.H., et al., 2017). Coupled thermo-hydro-mechanical (THM) models are also developed to investigate the effects of mechanical parameters, such as stress distribution and matrix deformation, on heat mining (Rutqvist, J., et al. 2001; Rawal, C., et al., 2014; Zhao, Y., et al., 2015; Cao, W., et al., 2016; Sun, Z., et al., 2017; Pandey, S.N., 2017).

Although substantial efforts have been made on numerical simulation of heat extraction process in EGS, a thorough investigation and detailed analysis on the heat extraction performances in EGS with thermal induced fractures is still lacking. The purpose of present work is to figure out the effects of cryogenic fracturing on the heat extraction performances of an EGS. An experimental study is made to acquire the morphology and features of thermal induced fractures. A 3D transient model is developed for fluid flow and heat extraction process in an EGS, and an analytical solution is adopted to validate it. Local thermal equilibrium model is used to depict the heat exchange, real discrete fracture network is installed in the physical model and Darcy flow model is used for fluid flow. Based on the simulation results, the characteristics of fluid flow, temperature distribution and heat extraction performance are analyzed as a function of different fracture geometries. The production temperature, thermal power output in EGSs with different...
fracture distributions are also presented as a function of time. This study demonstrate that the existing of thermal induced fractures improves the heat extraction performance of an EGS significantly.

2. Methodology

The aim of this study is to evaluate the effects of cryogenic fracturing on heat extraction performances of an EGS with thermal induced fractures. Hence, a reasonable fractures setting is of great importance because the spatial distribution and interconnectivity of active fractures play a decisive role on heat extraction and thermal power output of an EGS.

2.1 Fracture reconstruction

To get a realistic fracture morphology, an experimental study is conducted to obtain the distribution features of the fractures induced by thermal shock. After the treatment of liquid nitrogen, a fracture network is formed in the sample (As shown in Fig. 2(a)). Because the distribution of the 3D fractures are too complex to depict. The 2D fractures on the surface of the sample are used for the morphological features extracting of the thermal induced fractures.

![Image 1](image1.png)
(a) Thermal induced fractures

![Image 2](image2.png)
(b) Grid for features extraction

![Image 3](image3.png)
(c) 2D discrete fractures

![Image 4](image4.png)
(d) 3D model of EGS with fractures

**Figure 2: Reconstruction of fractures induced by cryogenic fracturing**

For the convenience of parameters statistics, the surface of the sample are segmented into 25 smaller areas (As shown in Fig. 2(b)). Statistic method of image is employed to obtain the morphological and location features of the fractures. The number of fractures, intersections points, minimum and maximum dimensionless length, intersection angles are calculated for each segment. Base on random fracture network generation method (Alghalandis, Y.F., 2017), a 2D discrete fracture network is formed (As shown in Fig. 2(c)). For the goal of 3D fracture network,
two orthogonal planes are selected for the generation of 2D discrete fracture networks (25 fractures for each), then the fracture networks are extruded (one for 90m, and another for 120m), and a staggered 3D fracture network is created.

2.2 Model description

2.2.1 Basic assumptions

In order to make the model more pragmatic, the Soultz geothermal system is selected as the prototype (Genter, A., et al., 1997; Spichak V., et al., 2015; Aliyu, M.D., et al. 2017), and the simulated area is idealized make up of an overburden layer, a bottom layer, a stimulated area, a HDR formation, an injection well, a production well and a natural fracture with 45° incline angle. It should be noted that in the models stimulated by cryogenic fracturing treatment, the physical model also contains a set of artificial fractures in the vicinity of injection or production well, or both of them. The schematic is illustrated in Fig. 3.

Because the joints and natural fractures in HDR formation are very complicate, the actual spatial distribution of active fractures can never be acquired. To simplify the physical model, the dominant flow paths provided by joints and natural fractures are degraded into a tilted fracture (Dimensions 560m × 300m, Tilt angle 45°). According to the previous studies, the main assumptions of this study are as follows:

- Four simulation domains (overburden layer, bottom layer, HDR reservoir, stimulated area) are simplified as homogeneous and isotropic continuous porous medium; (Sun, Z., et al. 2017; Song, X., et al. 2018)
- The stimulated area have the same porosity and slightly higher permeability compared with overburden layer and bottom layer, while fractures have relatively lower porosity and higher permeability; (Aliyu, A.D., et al. 2017)
- Water losses are assumed to be zero; (Shaik, A.R., et al 2011)
- The porous is saturated with single phase fluid, and local thermal equilibrium is assumed between the matrix and fluid; (Sun, Z., et al. 2017; Song, X., et al. 2018)
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- The fluid flow in the porous follows Darcy’s law;
- No chemical reaction between porous medium and injected fluid;
- Effect of thermal stress induced by circulation of fluid on the porous and fracture aperture is ignored.

2.2.2 Governing equations

This model focuses on the subsurface fluid flow and heat exchange process, the governing equations are formulated as follows.

Mass continuity equation for fluid in matrix:

\[
\frac{\partial (\rho_j \phi_s)}{\partial t} + \nabla \cdot (\rho_j u_s) = Q
\]

Mass continuity equation for fluid in fractures:

\[
d_j \frac{\partial (\rho_j \phi_f)}{\partial t} + \nabla_T \cdot (d_j \rho_j u_f) = d_j Q
\]

where \( \rho_j (\text{kg/m}^3) \) denotes the density of water, \( \phi_s \) and \( \phi_f \) denote the porosity of matrix and fracture, \( t (\text{s}) \) is the time, \( d_j (\text{m}) \) denotes the aperture of fracture, \( \nabla \) is hamilton operator, \( \nabla_T \) is Hamilton operator restricted to the fracture’s tangential plane, \( Q (\text{kg/m}^2 \cdot \text{s}) \) represents the mass exchange between rock and fractures, \( u_s \) and \( u_f \) denote Darcy velocity vector in rock and fracture.

According to Darcy’s law, the Darcy velocity vector can be calculated by:

\[
u_s = -\frac{k_s}{\mu_f} (\nabla p - \rho_j g)
\]

\[
u_f = -\frac{k_f}{\mu_f} (\nabla_T p - \rho_j g)
\]

where \( k_s (\text{m}^2) \) and \( k_f (\text{m}^2) \) denotes permeability of rock and fracture, \( \mu_f (\text{Pa} \cdot \text{s}) \) denotes the viscosity of water, \( p (\text{Pa}) \) is the pressure of water, and \( g (\text{m/s}^2) \) is the gravity acceleration vector.

Local thermal equilibrium model is used as energy conservation equation in this study.

Energy conservation equation for rock matrix:

\[
\left( \rho c \right)_{eff} \frac{\partial T}{\partial t} + \rho_j c_s u_s \cdot \nabla T + \nabla \cdot q_s = Q_h
\]

Energy conservation equation for fracture:
\[ \frac{d}{dt} \left( \rho c \right)_{\text{eff}} \frac{\partial T}{\partial t} + d_f \rho_f c_f u_f \cdot \nabla T + \nabla \cdot \mathbf{q}_f = Q_h \]  

(6)

where \( (\rho c)_{\text{eff}} (J/\text{m}^3 \cdot \text{K}) \) represents effective volumetric thermal capacity of porous media or fractures, \( T(K) \) denotes temperature, \( c_s (J/(\text{kg} \cdot \text{K})) \) and \( c_f (J/(\text{kg} \cdot \text{K})) \) denotes thermal capacity of rock matrix and fracture matrix. \( \mathbf{q}_s \) and \( \mathbf{q}_f \) represent the conductivity heat transfer in rock matrix and fractures, \( Q_h (J/\text{m}^2 \cdot \text{s}) \) represents the heat transfer between rock and fractures.

\[ \mathbf{q}_s = -\lambda_{\text{eff}} \nabla T \]  

(7)

\[ \mathbf{q}_f = -d_f \lambda_{\text{eff}} \nabla T \]  

(8)

\[ \lambda_{\text{eff}} = (1-\varphi)\lambda_s + \varphi \lambda_f \]  

(9)

\[ (\rho c)_{\text{eff}} = (1-\varphi)\rho_s c_s + \varphi \rho_f c_f \]  

(10)

where \( \lambda_{\text{eff}} (W/\text{m} \cdot \text{K}) \) represents effective thermal conductivity. \( \lambda_s (W/\text{m} \cdot \text{K}) \) and \( \lambda_f (W/\text{m} \cdot \text{K}) \) denote the thermal conductivity of matrix and water, \( c_s (J/\text{kg} \cdot \text{K}) \) and \( c_f (J/\text{kg} \cdot \text{K}) \) denote the thermal capacity of matrix and water.

2.2.3 Model validation

Because the subsurface fluid flow and heat transfer process is extremely complex, and the accurate distribution of temperature and velocity can never be obtained. Comparing the numerical solution against an analytical solution of a simple problem is a less-than-ideal alternative for model validation, which has been adopted by many researchers (Aliyu, M.D. et al., 2017; Song, X., et al., 2018). Hence, we use analytical model for an idealized problem examine the reliability of the numerical model. An analytical solution presented by Barends, F.B.J., et al. (2010) is used for model validation in this study. The expression is show in equation (11).

\[ T_f = T_0 + (T_{in} - T_0) \text{erfc} \left( \frac{\lambda_s x / (\rho_s c_s d_f)}{\sqrt{u_{in} t (t-x) / \lambda_s / (\rho_s c_s)}} \right) \left( t - \frac{x}{u_{in}} \right) \]  

(11)

where \( T_f (K) \) denotes the fracture temperature, \( T_0 (K) \) denotes initial temperature, \( T_{in} (K) \) denotes the injection temperature of cold water, \( \lambda_s (W/\text{m} \cdot \text{K}) \) denotes thermal conductivity of rock, \( x (m) \) is the distance along the fracture from the inlet, \( \rho_s (kg/\text{m}^3) \) and \( \rho_f (kg/\text{m}^3) \) denote the density of rock and injected fluid, \( c_s (J/\text{kg} \cdot \text{K}) \) and \( c_f (J/\text{kg} \cdot \text{K}) \) denote the density of rock and injected fluid, \( t (s) \) is time. All the values of the parameters used in validation of the numerical model are listed in Table 1.
### Table 1. Parameters for model validation (Song, X., et al. 2018)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock density $\rho_s$</td>
<td>kg/m³</td>
<td>2700</td>
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<tr>
<td>Rock thermal capacity $c_s$</td>
<td>J/(kg⋅K)</td>
<td>1000</td>
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<tr>
<td>Rock thermal conductivity $\lambda_s$</td>
<td>W/(m⋅K)</td>
<td>2.8</td>
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<tr>
<td>Fluid density $\rho_f$</td>
<td>Kg/m³</td>
<td>1000</td>
</tr>
<tr>
<td>Fluid heat capacity $c_f$</td>
<td>J/(kg⋅K)</td>
<td>4200</td>
</tr>
<tr>
<td>Darcy velocity $u_{in}$</td>
<td>m/s</td>
<td>0.01</td>
</tr>
<tr>
<td>Injection temperature $T_{in}$</td>
<td>K</td>
<td>360</td>
</tr>
<tr>
<td>Initial temperature $T_0$</td>
<td>K</td>
<td>300</td>
</tr>
<tr>
<td>Fracture aperture $d_f$</td>
<td>m</td>
<td>0.001</td>
</tr>
<tr>
<td>Fracture permeability $k_f$</td>
<td>m²</td>
<td>$8.33 \times 10^{-8}$</td>
</tr>
<tr>
<td>Injection and production pressure difference $\Delta p$</td>
<td>Pa</td>
<td>$2.4 \times 10^4$</td>
</tr>
</tbody>
</table>

For the numerical solution, a finite rectangular 200m × 400m domain is modeled for the rock matrix, and a fracture with 0.001m aperture is set through the center. A heat extraction period of 300d is solved. Fig. 4 compares the numerical and analytical solutions.

![Figure 4: Comparison of results solved by analytical and numerical models](image)

**Figure 4:** Comparison of results solved by analytical and numerical models

Fig. 4(a) shows the temperature profile along the fracture at different times. Fig. 4(b) presents the temperature evolution at four different positions along the fracture. Apparently, the numerical solution is in good agreement with the analytical solution, except for a slight deviation. This difference may be attributed to restrictions from the finite boundary conditions. In conclusion, this numerical model is reliable, and can be used to investigate the heat extraction process in an EGS.

### 2.3 Model parameters

#### 2.3.1 Domain, parameters and grid

In this study, an idealized model is established based on the Scoultz geothermal system (Genter, A., et al., 1997; Spichak V., et al., 2015; Aliyu, M.D., et al., 2017). The computational domain is consist of an overburden layer, a bottom layer, a stimulated area, a HDR reservoir, an injection well, a production well and a natural fracture with an incline angle (45°). The dimensions of the
domain is 1000m×1000m×1000m, and a stimulated area (600m×600m×400m) is located at the center of the domain. A 506m×300m inclined fracture (45°) with aperture of 0.005m is located in the stimulated area. If the injection or production well is stimulated by cryogenic fracturing, a set of fractures will be distributed around the well. The parameters used in this study are listed in Table 2.

### Table 2. Basic parameters for numerical model

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Values</th>
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<tr>
<td>Computational domain</td>
<td>km</td>
<td>1×1×1</td>
</tr>
<tr>
<td>HDR formation</td>
<td>km</td>
<td>1×1×0.6</td>
</tr>
<tr>
<td>Stimulated area</td>
<td>km</td>
<td>0.6×0.6×0.4</td>
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<tr>
<td>Geothermal gradient</td>
<td>K/m</td>
<td>0.04</td>
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<tr>
<td>Temperature at top boundary</td>
<td>K</td>
<td>450</td>
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<tr>
<td>Injection temperature</td>
<td>K</td>
<td>310</td>
</tr>
<tr>
<td>Injection mass flow rate</td>
<td>kg/s</td>
<td>40</td>
</tr>
<tr>
<td>Production mass flow rate</td>
<td>kg/s</td>
<td>40</td>
</tr>
<tr>
<td>Fracture aperture</td>
<td>m</td>
<td>0.005</td>
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**Matrix**

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<tbody>
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<td>Porosity $\varphi_s$</td>
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<td>Permeability $k_s$</td>
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<td>Thermal conductivity $\lambda_s$</td>
<td>W/(m·K)</td>
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<tr>
<td>Density $\rho_s$</td>
<td>Kg/m³</td>
<td>2600</td>
</tr>
<tr>
<td>Thermal capacity $c_s$</td>
<td>J/(kg·K)</td>
<td>1000</td>
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</table>

**Fracture**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity $\varphi_f$</td>
<td></td>
<td>0.1%</td>
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<tr>
<td>Permeability $k_f$</td>
<td>m²</td>
<td>$1\times10^{-11}$</td>
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<tr>
<td>Thermal conductivity $\lambda_f$</td>
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<tr>
<td>Density $\rho_f$</td>
<td>Kg/m³</td>
<td>300</td>
</tr>
<tr>
<td>Thermal capacity $c_f$</td>
<td>J/(kg·K)</td>
<td>4200</td>
</tr>
</tbody>
</table>

Figure 5: Computational mesh and grid refinements
Fig. 5 shows the grid configuration used in this study. Unstructured tetrahedral meshing method is employed to discretize the whole domain. The meshing process is elaborately controlled to obtain a rational grid, fine meshes are used in the stimulated area, especially the areas near fractures and the wellbores. Coarse meshes are used in the overburden layer, bottom layer and HDR formation. In all, nearly 400,000 elements are formed in the numerical model. Grid independence test is also conducted to guarantee the accuracy of the numerical result.

2.3.2 Initial and boundary conditions
The initial temperature of the numerical model is determined by geothermal gradient (0.04K/m) and top boundary temperature (450K). The initial temperature of the formation increases linearly with depth along the vertical direction. As the basic assumptions described in 2.2.1, all porous are initially saturated with working fluid. During the heat extraction process, constant mass flow rate (40 kg/s) is set as boundary conditions for injection and production wells. A Dirichlet boundary condition of 310K (injection temperature) is applied on the injection well.

2.4 Cases study
In this study, four physical models with different artificial fracture distributions, as shown in Fig. 6, are calculated and the influences of fractures on the heat extraction performances of EGSs are also compared. Case 1 only contains one natural fracture connecting the injection and production wells, which is treated as a basic case without cryogenic fracturing operation. Case 2 have 50 fractures distributed in the vicinity of injection well, which implies cryogenic fracturing has been operated in injection well. It is worth noting that the setting of the fractures follows the method depicted in 2.1. The fractures around the production well in Case 3 implies that the implementation of cryogenic fracturing in the production well. The existing of fractures in the vicinity of injection and production wells in Case 4 means both conduits have been stimulated. All the parameter values used in these models are same with those in Table2.
3. Results and discussions

In this section, the temperature distributions and thermal production performances of four Cases are compared.

![Temperature distribution at different times](image)

Fig. 7 shows temperature contours of four Cases after different production times. It can be observed that at 5 years and 15 years, the temperature drop region (Blue) in Case 1 and Case 3 is larger than that of the rest two Cases. This is because in Case 1 and Case 3, natural fracture is the dominant and only flow path for the cold water around the injection well at early stage, so the temperature drop region extend along the natural fracture rapidly. While for Case 2 and Case 4, the fractures created by cryogenic fracturing share the injected water. So, the cold water is dispersed by the fractures into a spatial region instead of flowing along the natural fracture. After produce for 30 years and 45 years, the cooled area around production wells in Case 1 and Case 2 is larger than Case 3 and Case 4. For the same reason, the heat extraction areas in Case 3 and Case 4 are expanded by the fracture networks, and the fluid flow velocity is also decreased. So, the cold breakthrough is delayed.
Fig. 8 presents the temperature distributions along the natural fracture between injection and production wells. It can be observed that the temperature in the vicinity area of injection wells drop to 310K rapidly. After 5 years production, the cold edges of Case 1 and Case 2 expand to 150m, while that for Case 2 and Case 4 are around 100m. After the injection and production cycling operate for 30 years, the temperature near the production well in Case 1 decreases to 388K, while the temperature for the other three Cases are still over 400K, the exact values are 406K for Case 2, 440K for Case 3 and 468K for Case 4. Apparently, the artificial fractures delayed the occurrence of cold breakthrough, which means the economic mining lifetime of EGS are extended. After producing for 50 years, all cold edges reach production wells in four Cases. It worth noting that the temperature distribution along the natural fractures in Case 1 and Case 2 tend to be the same, while the temperature profile for Case 3 is similar to that for Case 4. In Fig. 8(c) and Fig. 8(d), there are fluctuations at the tail ends of some curves, this is because some fractures around the production wells form a dominant flow path for cold fluid, and form a sharp temperature change around it. From the analysis above, it can be concluded that the artificial fractures can retard the occurrence of cold breakthrough and prolong the economic heat mining time of an EGS.
Fig. 9 illustrate the production temperature evolutions in 60 years. In the first 14 years, the production temperatures of all Cases are almost the same, and equal to the in situ temperature of the HDR formation (470K). The production temperature of Case 3 and Case 4 at early stage is slightly lower than 470K. It can be contributed to thermal gradient, because the artificial fractures channels the production wells with upper and lower formation with different temperatures. After 20 years, the temperature differences between four Cases become wider. At the end of each curve, the production temperature after 60 years are listed. After producing hot water for 60 years, the production temperatures for Case 1 and Case 2 reduced below 395 K, while those for Case 3 and Case 4 are still higher than 420K. Around 44 years, there is an intersection point between the temperature curves for Case 1 and Case 2, which means after 44 years, the production temperature of Case 2 become the lowest. This is because after the fractures around the injection well are filled with cold water, they aggravate the occurrence of cold breakthrough in production well.

Fig. 10: Thermal power output versus time

Thermal power output is one of the most effective parameters to evaluate the heat extraction performance of an EGS. Fig. 10 depict the variation of thermal power with time in four Cases. It’s not difficult to find that the sharp of the curves are very similar to the production temperature
curves in Fig. 9. This is because the amount of energy carried by the working fluid mainly depending on its temperature. The thermal power of Case 1 decreases 24.7% in 30 years, from 28.7MW to 21.6MW. 19.9% and 7.0% thermal power decreases occurred in Case 2 and Case 3, respectively. In Case 4, only 0.3MW thermal power is subtracted from this EGS in 30 years. After 50 years, the thermal power output of Case 1 and Case 2 decrease to 16.0MW and 15.6MW, respectively, while Case 3 and Case 4 can still operate with 21.2MW and 24.8 MW thermal output.

From the analysis above, we may safely draw the conclusion that fracture network induced by cryogenic fracturing around the injection or production well plays an important role on the heat extraction performance of an EGS. Fracturing treatment conducted in production well can yield a better result than in injection well.

4. Conclusions

In this study, we introduced cryogenic fracturing as a stimulation method for EGS. An experimental study is conducted to investigate the features of thermally induced fractures. Based on the experimental results and random fracture generation method, a 3D fracture network is generated and set around the injection or production well, which stand for a stimulation operation in it. A 3D transient fluid flow and heat transfer model is established for the simulation of heat extract process in an EGS. Based on the numerical model, the temperature distributions in EGSs with different fracture network are analyzed, the production temperature and thermal power output are compared as well. Under the basic assumptions and modelling parameters used in this study, there are three main findings:

- Cryogenic fracturing is an effective method for improving the heat extraction performance in an EGS. Because the local thermal stress induced by cryogenic fracturing can form a complicate fracture network in HDR reservoir, which can improve the heat extraction performance of an EGS significantly.

- Fractures around injection and production wells guide the cold working fluid into a large area, which can delay the cold breakthrough process between the injection and production well. Hence, cryogenic fracturing is an effective method to solve the channeling problem.

- Implement cryogenic fracturing in both injection and production wells can yield a better response than in a single well.

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REFERENCES


