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Heat Recovery from Multiple-Fracture Enhanced Geothermal Systems: The Effect of Thermo-Hydro-Mechanical Interactions

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ABSTRACT
This study investigates the thermoelastic interactions between multiple parallel fractures and their effects on energy production in an enhanced geothermal system utilising a coupled thermo-hydro-mechanical finite element model. The model accounts for fluid flow within the fractures, advective-diffusive heat transfer in fractures and conductive heat in the rock matrix, and the mechanical deformation of the matrix. The effects of fracture spacing, reservoir temperature gradient and mechanical properties of the rock matrix on the production temperature and the net production energy are investigated for two geothermal reservoir rocks. The model results show that the matrix deformation significantly increases the interactions between the two neighbouring fractures. Matrix contraction due to the cooling of the matrix increases the fracture aperture in the adjacent fracture, and the increased aperture improves flow of cold fluid towards the production, hence reduces the production temperature. It is shown that the mechanical interactions are much more important than the thermal interactions and the optimum spacing, corresponding to maximum net energy production, in this study ranges between 150m to 300m which is much larger than the optimum spacing previously reported for the rigid matrix.

Keywords: Multiple parallel fractures; Enhanced geothermal systems; Mechanical interaction; Fracture flow; Coupled formulation;
1. INTRODUCTION

Geothermal energy is the energy stored in the Earth’s crust and is one of the promising and clean renewable energy resources in the world (MIT, 2006). Low reservoir permeability is a common challenge for energy exploitation from deep geothermal reservoirs, and hydraulic fracturing is frequently utilised to improve the permeability within the reservoir by creating conductive flow pathways. The thermoporoelastic contraction of the rock matrix, as well as the thermos-mechanical interactions between multiple fractures may undermine the efficiency of the fractures by creating shortcuts between the injector and producer wells (Ghassemi & Zhou, 2011; Guo et al., 2016; Wu et al., 2016).

Heat extraction from deep fractured geothermal reservoir requires a water circulation system in which heat is extracted from produced water and water with a temperature lower than the reservoir temperature is injected back into the reservoir (e.g. Xu et al., 2015). The economical productivity of such system in low permeability reservoirs relies on the conductive fractures to create the pathways (McClure & Horne, 2014). The performance of such system is therefore highly affected by the fracture surface area as well as the residence time of the fluid i.e. the time that fluid is in contact with the rock prior to production. Enhanced Geothermal System (EGS) is a concept where the rock has been artificially stimulated in order to increase the permeability in the rock formation. The stimulation has been widely used in the oil and gas industry and was introduced to geothermal projects in 1974 at Fenton Hill (MIT, 2006). The enhancement of the permeability can be conducted through either chemical enhancement or hydraulic fracturing. Hydraulic fracturing is achieved by injecting pressurized fluid into the reservoir formation until one or several fractures propagate into the formation. Cooled water injected in the reservoir through an injection well moves within the induced fractures and heats up by exchanging heat between the fluid in the fractures and the rock matrix before being produced through the production well. The thermal contraction that take place in the rock matrix causes the fracture aperture to open further, and the increase of fracture aperture affects propagation of the heat front in the fracture and the reservoir. This may results in preferential pathways. If these flow paths become too direct, the fluid will not have sufficient time to heat up and thermal short-circuiting might occur. This unwanted phenomenon is a major concern and challenge, as it can highly affect the reservoir lifetime and the total produced energy. The effect of thermoporoelastic deformation of the rock matrix on the fracture aperture and geometry evolution has been widely studied (Ghassemi & Zhou, 2011; Guo et al., 2016; Abu Aisha et al., 2016; Pandey et al., 2017). They have shown that the contact stresses over the fracture reduces due to the increased fluid pressure and due to the cooling of the matrix. The reduction in the contact stress increases the fracture aperture and promote the shear propagation of the fracture. Guo et al. (2016) have shown that heterogeneity can aggravate this problematic event.
The multiple hydraulic fractures have successfully been used in the oil and gas industry, where uneconomical shale formations have been the main target. For the same reason, to improve the transmissivity of the reservoir, multiple engineered fractures are used within EGS. Allowing fracturing in multiple stages creates a greater number of flow paths, which gives access to a larger volume of rock. In the case of multiple fractures, new issues arise that need to be investigated. A recent study by Wu et al. (2016) shows the effect of overlapping of the cold plume around the fractures results in lower heat extraction. They have shown that for the case of two parallel infinite rigid fractures if the spacing is larger than 60m-80m, then the thermal interactions are negligible. This is due to the very slow propagation of heat through the low-permeability rock. For the case of deformable rock matrix, the mechanical interaction between multiple fractures can be significant and it affect the aperture and the geometry of the propagating fractures as shown by Kumar and Ghassemi (2016) and Salimzadeh et al. (2017a) for multiple hydraulic fractures. In EGS, the thermal contraction of the matrix around each fracture affects the displacement field around the adjacent fractures and that affects the aperture field of the fractures. The importance of coupling mechanics to the flow and transport has been demonstrated in other applications such as in CO₂ sequestration by Martinez et al., (2013) and Dempsey et al. (2014), in nuclear waste disposal by Rutqvist et al. (2005) and Tsang et al. (2012), in solute transport by Nick et al. (2011), in geothermal reservoirs by McDermott et al. (2006), and in hydraulic fracturing process by Salimzadeh and Khalili (2015) and Salimzadeh et al., (2017b).

In this paper, a coupled thermo-hydro-mechanical (THM) finite element (FEM) model is utilised to investigate the thermoelastic interactions between multiple fractures in an EGS. Fractures are modelled as surface discontinuities in three-dimensional matrix. Flow through fractures are modelled using cubic law, together with advective-diffusive heat transfer within fractures. The matrix is considered impermeable and the heat is propagating through conduction. The governing equations are solved numerically using Galerkin finite element method (FEM). The model has been validated and used to simulate single-, two- and three-fracture EGS examples to demonstrate the importance of the mechanical coupling on energy production.

2. COMPUTATIONAL MODEL

The fractures are modelled as discontinuous surfaces in the three-dimensional matrix, and a contact model is utilised to compute the contact tractions on the fracture surfaces under thermoelastic compression. Assuming impermeable rock matrix, the coupled computational model consist of four sub-models: a mechanical deformation-contact model, flow and heat transfer models for fracture, and heat transfer model for the rock matrix. The flow and heat transfer models through the fractures are defined for two-dimensional discrete fractures, while
the conductive heat transfer in the rock matrix, as well as the mechanical deformation-contact model are constructed for a three-dimensional body. To reduce the computational cost, the mechanical deformation and contact tractions are solved in a mechanical deformation-contact model (M) while the flow and heat transfers are solved in a thermo-hydraulic (TH) model. The two models are coupled sequentially.

2.1. Mechanical Deformation-Contact (M) Model

The thermoelastic mechanical deformation model is based on the stress equilibrium for a representative elementary volume of porous medium. The linear momentum balance equation may be written as

$$\text{div } \sigma + F = 0 \quad (1)$$

where $F$ is the body force per unit volume, and $\sigma$ is the total stress. Assuming linearity, the thermal strain within the solid rock, when the rock matrix undergoes a temperature change from initial temperature $T_0$ to a new value $T_m$, is given by Zimmerman (2000)

$$\varepsilon_T = -\beta_s(T_m - T_0) \quad (2)$$

where $\beta_s$ is a symmetric second-order tensor known as the thermal expansivity tensor of the rock matrix. If the rock is isotropic then $\beta_s = \beta_s I$, where the scalar coefficient $\beta_s$ is known as the coefficient of volumetric thermal expansion of rock matrix. The stress-strain relationship for thermoelasticity can be written as (Khalili & Selvadurai, 2003)

$$\sigma = \mathbb{D}\varepsilon - \beta_s K(T_m - T_0)I \quad (3)$$

in which $\mathbb{D}$ is the stiffness matrix and $K$ is bulk modulus of rock. Assuming infinitesimal deformations, strain is related to displacement by

$$\varepsilon = \frac{1}{2}(\nabla u + \nabla u^T) \quad (4)$$

where $u$ denotes the displacement vector of the rock matrix. Hydraulic loading on the fracture boundary are applied as a normal traction

$$F_c = \sigma_c - p_f n_c \quad (5)$$

where $\sigma_c$ is the contact tractions on the fracture surfaces, $p_f$ is the fluid pressure inside fracture, and $n_c$ is the outward unit normal to the fracture surface (on both sides of the fracture). The governing differential equation for mechanical deformation-contact is thus given by

$$\text{div}(\mathbb{D}\varepsilon) + F = \text{div}(\beta_s K(T_m - T_0)I) + \delta(x - x_c) \left(p_f n_c - \sigma_n\right) \quad (6)$$

where $\delta(x - x_c)$ is the Dirac delta function, and $x_c$ represents the position of the fracture ($\Gamma_c$).

Note that the contact tractions and hydraulic loadings exist only on the fracture surfaces ($\Gamma_c$). A sophisticated algorithm is used for the treatment of frictional contact between the fracture
surfaces, based on isoparametric integration-point-to-integration-point discretisation of the contact contribution. Contact constraints are enforced by using a gap-based Augmented Lagrangian (AL) method developed specifically for fractured media (Nejati et al., 2016). In this model, penalties are defined at each timestep as a function of local aperture. The original contact model has been extended to incorporate thermoporoelastic loadings (Salimzadeh et al., 2017c).

2.2. Coupled Thermo-Hydro (TH) Model

Fracture Flow Model

A laminar flow is considered for fracture discontinuities. The mass balance equation for slightly compressible fluid can be expressed as (Salimzadeh and Khalili, 2016)

$$\text{div}(a_f \rho_f v_f) + \frac{\partial}{\partial t}(a_f \rho_f) = 0$$

(7)

where $a_f$ is the fracture aperture, $\rho_f$ is the density of fluid and $v_f$ is fluid velocity in the fracture. Fluid flow through a fracture is governed by the cubic law, which is derived from the general Navier-Stokes equation for flow of a fluid between two parallel plates (Zimmerman and Bodvarsson, 1996)

$$v_f = -\frac{a_f^2}{12\mu_f} \nabla p_f$$

(8)

where $\mu_f$ is viscosity. The fluid density is a function of both fluid pressure and temperature and may be written as

$$\frac{\partial \rho_f}{\partial t} = \rho_f c_f \frac{\partial p_f}{\partial t} - \rho_f \beta_f \frac{\partial T_f}{\partial t}$$

(9)

where $c_f$ is the fluid compressibility, $T_f$ is the fluid temperature in the fracture, and $\beta_f$ is the volumetric thermal expansion coefficient of the fluid. When two surfaces of a fracture are in partial contact at the micro-scale, the mean aperture of the fracture can be written as a function of the normal contact stress. In this study, the classic Barton-Bandis model (Bandis et al., 1983; Barton et al., 1986) is used to calculate the fracture aperture under contact stress

$$a_f = a_0 - \frac{a \sigma_n}{1 + b \sigma_n}$$

(10)

where $\sigma_n$ is the normal component of the contact stress, $a_0$ is the fracture aperture at zero contact stress, and $a$ and $b$ are model parameters. The normal contact stress is directly computed in the mechanical deformation-contact model (M). In the fracture flow model, the change in aperture can be approximated from the change in the fluid pressure in the fracture as

$$\frac{\partial a_f}{\partial t} = \frac{1}{K_n} \frac{\partial p_f}{\partial t}$$

(11)

in which $K_n$ is the fracture tangent stiffness, given by
The governing equation for the laminar flow in the fracture is written as

$$\text{div}\left(\frac{a_f}{12 \mu_f} \nabla p_f\right) = \left(\frac{1}{K_n} + a_f C_f\right) \frac{\partial p_f}{\partial t} - a_f \beta_f \frac{\partial T_f}{\partial t}$$

(13)

**Fracture Heat Transfer Model**

The heat transfer model in the fracture is achieved by combining Fourier’s law with the energy balance for fluid. The advective-diffusive heat transfer flux through the fracture fluid may be written as (Salimzadeh et al., 2016)

$$q_{fc} = -a_f \lambda_f \nabla T_m + a_f \rho_f C_f v_f T_f$$

(14)

where $\lambda_f$ is the thermal conductivity tensor of the fluid, $T_f$ is the fluid temperature, $C_f$ is the specific heat capacity of the fluid. The heat energy change due to thermal power in the course of the bulk deformation of fluid can be expressed as

$$q_{fp} = a_f \beta_f T_f \frac{\partial p_f}{\partial t}$$

(15)

Heat is also exchanged between matrix and fracture fluid by conduction through the fracture surfaces. The heat leakoff can be defined as a function of the thermal conductivity of the matrix and the temperature gradient at the fracture surfaces

$$q_{mf} = \lambda_n \frac{\partial T}{\partial n_c}$$

(16)

where $\lambda_n$ is the thermal conductivity of the rock matrix along the direction normal to the fracture (in the direction of $n_c$). The rate of heat storage in the fluid is given by

$$q_{fs} = a_f \rho_f C_f \frac{\partial T_f}{\partial t}$$

(17)

The governing equation for the heat transfer through the fluid in the fracture can be written as

$$\text{div}(a_f \lambda_f \nabla T_f) = a_f \rho_f C_f \frac{\partial T_f}{\partial t} - a_f \beta_f T_f \frac{\partial p_f}{\partial t} + a_f \rho_f C_f v_f \nabla T_f - \lambda_n \frac{\partial T}{\partial n_c}$$

(18)

**Matrix Heat Transfer Model**

The matrix is assumed to be impermeable so the heat transfer occurs only through conduction. The conductive heat flux can be written as

$$q_{mc} = -\lambda_m \nabla T_m$$

(19)

where $\lambda_m$ is the thermal conductivity tensor of the matrix, and $T_m$ is the matrix temperature. The thermal conductivity tensor for the medium saturated by a fluid is calculated as a function of the fraction between solid and fluid (for more accurate models of the effective thermal conductivity see Zimmerman, 1989)
\[ \lambda_m = (1 - \phi)\lambda_s + \phi\lambda_f \]  

(20)

The rate of heat storage in the matrix is a function of the average density and specific heat capacity of the saturated matrix, and it may be written as

\[ q_{ms} = \rho_m C_m \frac{\partial T_m}{\partial t} \]  

(21)

where \( \rho_m C_m \) can be computed (exactly) from the density and specific heat capacity values of rock solid \((\rho_s, C_s)\) and fluid \((\rho_f, C_f)\) as

\[ \rho_m C_m = (1 - \phi)\rho_s C_s + \phi\rho_f C_f \]  

(22)

The governing equation for heat transfer within the matrix is thus given by

\[ \text{div}(\lambda_m \nabla T_m) = (\rho_m C_m - \beta_s^2 K T_m) \frac{\partial T_m}{\partial t} + \delta(x - x_c)\lambda_n \frac{\partial T}{\partial n_c} \]  

(23)

Note that the heat leakoff only occurs through the fracture surfaces \((\Gamma_c)\). To reduce computational time, the mechanical contact model \((M)\) is solved separately from the rest of the TH model. However, they are still coupled iteratively, where the following process is carried out in each timestep. Firstly, the TH model is run with contact stresses and fracture aperture computed from the previous step (or initial values for the first step). The TH model then sends the computed temperatures and pressures values to the mechanical contact model so the results for the contact stresses and fracture aperture can be updated. Further, the TH model is run with the updated apertures. The contact model is run in the “stick” mode, which means that sliding along the opposing fracture surfaces is not allowed.

2.3. Finite Element Approximation

The governing equations are solved numerically using the finite element method. The Galerkin method and finite difference techniques are used for spatial and temporal discretisation, respectively. The displacement vector \( \mathbf{u} \) is defined as the primary variable in the mechanical deformation-contact model \((M)\), whereas the fluid pressure \( p_f \), and fracture fluid and matrix temperatures \( T_f \) and \( T_m \), are defined as the primary variables in the TH model. Using the standard Galerkin method, the displacement vector \( \mathbf{u} \), fluid pressure \( p_f \) and fluid and solid temperatures \( T_m \) and \( T_f \) within an element are defined as a function of their nodal values \( (\mathbf{u}, p_f, T_f, T_m) \) as

\[ \mathbf{u} = \mathbf{N} \hat{\mathbf{u}} \]  

(24)

\[ p_f = N_c \hat{p}_f \]  

(25)

\[ T_f = N_c \hat{T}_f \]  

(26)

\[ T_m = N \hat{T}_m \]  

(27)

where \( \mathbf{N} \) and \( N_c \) are the vector of shape functions for matrix \((3D)\) and fracture \((2D)\), respectively. Using the finite difference technique, the time derivative of \( X \) is defined as
\[
\frac{\partial \mathbf{X}}{\partial t} = \frac{\mathbf{X}^{t+dt} - \mathbf{X}^t}{dt} \quad (28)
\]

where \(\mathbf{X}^{t+dt}\) and \(\mathbf{X}^t\) are the values of \(\mathbf{X}\) at time \(t + dt\) and \(t\), respectively. The set of discretised equations can be written in matrix form as \(\mathbf{S} \mathbf{u} = \mathbf{F}\), in which \(\mathbf{S}\) is the element’s general stiffness matrix, and \(\mathbf{F}\) is the vector of right-hand-side loadings. For the mechanical deformation-contact model (M) the set of discretised equations may be written in matrix form as

\[
[S_{uu}] [\tilde{\mathbf{u}}] = \begin{bmatrix} \mathbf{F} + C_{pf} \tilde{\mathbf{p}}_f + C_{Tm}(\tilde{\mathbf{T}}_m - \mathbf{T}_0) \end{bmatrix} \quad (29)
\]

and for the TH model

\[
\begin{bmatrix} S_{pfP_f} & -C_{pfT_f} & 0 \\ -C_{TfP_f} & S_{TfT_f} + L_{TfT_m} dt \\ 0 & -L_{TmT_f} dt & S_{TmT_m} \end{bmatrix} \begin{bmatrix} \tilde{\mathbf{p}}_f \\ \tilde{\mathbf{T}}_f \\ \tilde{\mathbf{T}}_m \end{bmatrix} = \begin{bmatrix} M_{pfP_f} \tilde{\mathbf{p}}_f^t - C_{pfT_f} \tilde{\mathbf{T}}_f^t + Q_{pf} dt \\ M_{TfP_f} \tilde{\mathbf{T}}_f^t - C_{TfP_f} \tilde{\mathbf{p}}_f^t + Q_{Tf} dt \\ M_{TmT_m} \tilde{\mathbf{T}}_m^t - C_{TmP_m} \tilde{\mathbf{p}}_m^t + Q_{Tm} dt \end{bmatrix} \quad (30)
\]

where

\[
S_{uu} = \int_\Omega \bar{\nabla}\mathbf{N}^T \bar{\nabla}\mathbf{N} d\Omega \quad (31)
\]

\[
C_{pf} = \int_{I_c} \mathbf{N}_c^T (p_f \mathbf{n}_c - \sigma_n) \mathbf{N} dI \quad (32)
\]

\[
C_{Tm} = \int_\Omega \mathbf{B}_2^T \beta_s \mathbf{K} \mathbf{N} d\Omega \quad (33)
\]

\[
S_{pfP_f} = \left[ \mathbf{H}_{pf} dt + \mathbf{M}_{pfP_f} \right] \quad (34)
\]

\[
S_{TfT_f} = \mathbf{H}_{Tf} dt + \mathbf{M}_{TfT_f} + L_{TfT_m} dt \quad (35)
\]

\[
S_{TmT_m} = \mathbf{H}_{Tm} dt + \mathbf{M}_{TmT_m} + L_{TmT_f} dt \quad (36)
\]

\[
\mathbf{H}_{pf} = \int_{I_c} \bar{\nabla}\mathbf{N}_c^T \frac{1}{2} \kappa_n^f + a_f c_f \nabla dI \quad (37)
\]

\[
\mathbf{M}_{pfP_f} = \int_{I_c} \mathbf{N}_c^T \frac{1}{2} \kappa_n^f + a_f c_f \mathbf{N} dI \quad (38)
\]

\[
\mathbf{H}_{Tf} = \int_{I_c} \bar{\nabla}\mathbf{N}_c^T a_f \lambda_f \mathbf{N} dI + \int_{I_c} \mathbf{N}_c^T a_f \rho_f c_f \mathbf{N} dI \quad (39)
\]

\[
\mathbf{M}_{TfT_f} = \int_{I_c} \mathbf{N}_c^T a_f \rho_f c_f \mathbf{N} dI \quad (40)
\]

\[
\mathbf{C}_{pf} = \int_{I_c} \mathbf{N}_c^T a_f \beta_f \mathbf{N} dI \quad (41)
\]

\[
\mathbf{C}_{TfP_f} = \int_{I_c} \mathbf{N}_c^T a_f \beta_f T_f \mathbf{N} dI \quad (42)
\]

\[
L_{TmT_f} = \int_{I_c} \mathbf{N}_c^T \lambda_m \frac{\partial}{\partial n_c} \mathbf{N} dI \quad (43)
\]

\[
\mathbf{H}_{Tm} = \int_\Omega \bar{\nabla}\mathbf{N}^T \lambda_m \bar{\nabla} d\Omega \quad (44)
\]

\[
\mathbf{M}_{TmT_m} = \int_\Omega \mathbf{N}^T (\rho_m C_m - \beta_s^2 K T_m) \mathbf{N} d\Omega \quad (45)
\]

where \(\mathbf{Q}\) represents the flow and heat rate vectors, superscript \(t\) represents the time at the current time step, superscript \(t + dt\) represents time at the next time step, and \(dt\) is the timestep.
The non-diagonal components of the stiffness matrix $\mathbb{S}$ are populated with the coupling matrices $\mathbb{C}$, and $\mathbb{L}$. Note that the leakoff term only exists for matrix elements (volume elements) connected to a fracture; it is evaluated over the surface of the volume element that is shared with the fracture, and is equal to zero for other faces of that element. The gradient matrix $\nabla$ for three-dimensional displacement field is defined as

$$
\nabla = \begin{bmatrix}
\frac{\partial}{\partial x} & 0 & 0 \\
0 & \frac{\partial}{\partial y} & 0 \\
0 & 0 & \frac{\partial}{\partial z} \\
0 & \frac{\partial}{\partial z} & \frac{\partial}{\partial y} \\
\frac{\partial}{\partial z} & 0 & \frac{\partial}{\partial x} \\
\frac{\partial}{\partial y} & \frac{\partial}{\partial x} & 0
\end{bmatrix}
$$

(46)

The components of the stiffness matrix are dependent upon the primary unknown variables, \textit{i.e.} conductance, capacitance and coupling coefficients of the fracture are all dependent on the fracture aperture; therefore, a Picard iteration procedure is adopted to reach the correct solution within acceptable tolerance. For current iteration $s + 1$ in current step $n + 1$, the solution-dependent coefficient matrices in the stiffness matrix $\mathbb{S}$ are updated using weighted average solution vector $\mathbb{X}_{n+1}^{s+\theta}$ defined as

$$
\mathbb{X}_{n+1}^{s+\theta} = (1 - \theta)\mathbb{X}_{n+1}^{s-1} + \theta\mathbb{X}_{n+1}^{s}
$$

(47)

where $\mathbb{X}_{n+1}^{s-1}$ and $\mathbb{X}_{n+1}^{s}$ are the solution vectors of the two most recent iterations in the current timestep $n + 1$, and $\theta = 2/3$ is the weighting coefficient. For the first iteration $s = 1$, the previous timestep solution is used as

$$
\mathbb{X}_{n+1}^{0} = \mathbb{X}_{n+1}^{1} = \mathbb{X}_{n}
$$

(48)

where $\mathbb{X}_{n}$ is the solution vector from previous timestep $n$. The iterations are repeated until consecutive normalised values of $\mathbb{X}_{n+1}^{s}$ agree to within a specified tolerance $\varepsilon$

$$
\frac{\|\mathbb{X}_{n+1}^{s+1} - \mathbb{X}_{n+1}^{s}\|}{\|\mathbb{X}_{n+1}^{s+1}\|} < \varepsilon
$$

(49)

The tolerance is set to $1\%$. The discretised equations are implemented in the Complex Systems Modelling Platform (CSMP++), a finite element base code library (Matthäi \textit{et al.}, 2001) designed to simulate complex multi-physics problems of geological processes (e.g. Matthäi \textit{et al.}, 2010; Nick & Matthäi 2011, Hardebol \textit{et al.} 2015, Fowler \textit{et al.} 2016, Bisdom \textit{et al.} 2017). Quadratic tetrahedra are used for spatial discretisation of volumes and quadratic triangles for surfaces. For the fracture, the triangles on the two opposite surfaces match to each other, while
the nodes are not shared but rather duplicated for the two sides. The triangles are matched with faces of the tetrahedra connected to the fractures, where they also share the same nodes. Fracture flow and fracture heat equations are accumulated only on one side of the fracture, whereas, the heat leakoff is accumulated over both sides of the fracture. The ensuing set of linear algebraic equations $\mathbf{S}\mathbf{X} = \mathbf{F}$ is solved at each timestep using the algebraic multigrid method for systems, SAMG (Stüben, 2001).

3. Simulation Results and Discussions

3.1. Model Setup and Validation

The base case used in this study, shown in Figure 1, is adopted from Guo et al. (2016), and the present model has been validated against their results. The model includes a horizontal fracture of diameter 1000m. The domain is 3 km × 3 km × 3 km, the penny-shaped fracture is located in the centre, and the injection and production wells are directly connected to the fracture. The distance between the injection and producer wells is set to 500 meters. The initial pore pressure is set to 34 MPa, and the three principal in situ stresses (64, 70 and 100 MPa) are assigned to the faces of the box-shaped model as shown in Figure 1a. The initial reservoir temperature at the depth of fracture is set to 200°C for all simulations. The water is injected at a constant rate of 0.0125 m$^3$/s with a constant fluid temperature of 50°C. Production is defined by constant pressure at the producer well; however, as the leakoff is assumed to be negligible in these simulations, the production rate reaches to the injection rate as time elapses. As there is no flow within the rock matrix, the heat propagates through conduction in the rock matrix, while within the fracture the heat is transferred mainly by advection. The material properties are given in Table 1. For all simulations, the first timestep is set to 1 day, and in each step the timestep is increased by a factor of 1.1 until the prescribed maximum timestep of 0.25 years is reached. The fluid density is considered to be pressure- and temperature-dependant, using the following function:

$$\rho_f = \rho_r e^{[\beta_f (p_f - p_r) - a_f (T_f - T_r)]}$$

(50)

where $\rho_r=887.2$ kg/m$^3$, $p_r=34$ MPa, and $T_r=200$°C are the reference (initial) density, pressure and temperature, respectively. The fracture aperture is defined as a function of the contact stress, using the Barton-Bandis model. Two reference points are assumed to evaluate the model parameters $a$ and $b$, where the fracture aperture at zero contact stress $a_0$ is assumed equal to $a/b$. The two reference points are: $a_f = 0.24$ mm for $\sigma_n = 30$ MPa, and $a_f = 0.72$ mm for $\sigma_n = 5$ MPa. For these given data, the model parameters $a$ and $b$ are $1.6 \times 10^{-10}$/Pa and $1.333 \times 10^{-7}$/Pa, respectively. The volumetric matrix thermal expansion coefficient of the solid ($\beta_s$) is modified for a low permeability matrix using the expression given by McTigue (1986) for undrained thermal expansion coefficient of a fluid-saturated rock.
\[ \beta_u = \beta_s + \phi B (\beta_f - \beta_s) \]  

(51)

where \( \beta_u \) is the undrained thermal expansion coefficient of a fluid-saturated, and \( B \) is the Skempton coefficient (Jaeger et al., 2007). For the given bulk modulus, porosity, and fluid compressibility used in this example, the undrained volumetric thermal expansion is \( \beta_u = 3.0 \times 10^{-5} /\degree C \). The domain is discretised spatially using 39,957 quadratic tetrahedra and triangles for matrix volume and fracture surface, respectively. A very good agreement is found between the results from the present model and the results by Guo et al. (2016) as shown in Figure 1, which validates the accuracy of the present model. Sensitivity analyses are performed in which the Young’s modulus and the matrix porosity have been altered to 20 GPa and 0.2 (e.g. a sandstone reservoir), respectively, from the original values of 50 GPa and 0.01 as an example of a granite reservoir rock. The results for the aperture evolution within the fracture, together with its temperature at 30 years is plotted for three various scenarios in Figure 2. Lower Young’s modulus reduces the stresses developed during the contraction of the matrix, and results in lower fracture aperture, and thus slower drawdown of the production temperature as the cold fluid gets access to a larger area of the fracture. For a stiffer rock on the other hand, higher fracture aperture is observed near the injection well and towards the production well, which advances the channelling between the two wells, resulting in a faster reduction in the temperature of the produced water. For the softer rock (\( E = 20 \) GPa), however when the porosity in the rock matrix is increased to 0.2, the fracture aperture increases compared to the case with lower porosity. This is related to the higher undrained thermal expansion coefficient for the higher matrix porosity. Higher undrained thermal expansion coefficient improves the mechanical effects and as a result, the rock contracts more and aperture increases more as shown in Figure 2. Higher aperture provides improved flow path between the injector and producer wells and the cold fluid reaches the producer well faster. The produced temperature and aperture distribution for the case of sandstone reservoir with a high porosity (0.2) is similar to those of the granite reservoir with a very low porosity (0.01).

3.2. Multiple-Fracture EGS

As a single fracture system has limited exposed area for heat transfer to happen between the cold fluid and the surrounding hot rock formation, a system with multiple fractures can be implemented in order to improve the performance of the EGS. Increasing the number of fractures provides several flow paths allowing the cold fluid to access a greater volume of rock. The contribution of the mechanical deformation in the response of a single-fracture EGS is already mentioned to be important, however, for a multiple-fracture EGS, to the best knowledge of the authors, there is no studies on the thermoelastic interactions between the fractures. Recently, Wu et al. (2016) presented a semi-analytical thermo-hydro (TH) model for an EGS system with multiple fractures. In their model, fractures are considered to be infinite and horizontal, and a temperature gradient is considered with the assumption that the initial
temperature at the bottom fracture is fixed. They have varied the spacing between fractures from 5 to 120 m, and the number of fractures up to 13, and have shown that when the spacing between fractures reduces, the two neighbouring fractures communicate and the heat plume of the fractures interacts. However, when the spacing between fractures is more than 80m, the thermal interactions within the lifetime of the EGS (30 years) are negligible. An optimum number of fractures (N) and spacing (d) have been found and reported as $6 \leq N \leq 13$ and $30 \text{ m} \leq d \leq 90 \text{ m}$, respectively.

In this section, we aim at investigating the effect of the mechanical interactions between fractures on the response of the EGS system. A model with two parallel fractures is built by adding a second fracture to the base model presented in the previous section as shown in Figure 3a. The spacing between the two fractures ranges from 50m to 1000m, and the temperature at the bottom fracture is fixed at 200°C. The fixed temperature at the bottom fracture enables the comparison of the two-fracture system with the single-fracture system presented in the previous section. When the vertical thermal gradient is considered, the temperature reduces as the top fracture moves up. Constant flow rate of $0.0125 \text{ m}^3/\text{s}$ is applied to each fracture. Note that the life time is determined for a minimal production temperature of 140 °C. Depending on the usage of the produced hot water and if we take future technical development into consideration the minimal production temperature could be lower (Willems et al., 2017b).

Uniform Initial Temperature

Firstly, a system with uniform temperature at 200°C is simulated to identify when the mechanical interaction starts to affect the output temperature. As the fractures are positioned symmetrically in the domain, both fractures show equal aperture when the system has a uniform in situ temperature. To look at the mechanical interactions, the vertical stress experienced in the middle of the two fractures for the system with $E = 50 \text{ GPa}$ (white line in Figure 3b) is plotted for fracture spacing of 1000m, 750m and 500m in Figure 3c. The areas not affected by the mechanical interaction has a value equal to the initial vertical stress, 64 MPa. For a spacing of 1000 m, the minimum effective stress in the centre of the model is found to be 61.56 MPa, indicating a stress change of 2.44 MPa (3.81% decrease). The minimum vertical stress at this location reduces to about 53 MPa for spacing of 500m (17% reduction in vertical stress). The changes in the vertical stresses affect the aperture in the fractures and lower vertical stress results in higher aperture. The contours for the vertical stress around the fractures are shown in Figure 3d. It can be observed that the mechanical interactions have already started between the two fractures while the thermal interactions are almost negligible at these spacing.

The production temperature for two cases of Young’s modulus $E = 50 \text{ GPa}$ and $E = 20 \text{ GPa}$ (granite and sandstone reservoirs) are shown in Figure 4. A good fit is observed between the fracture spacing of 750m for $E = 50 \text{ GPa}$ and the single fracture model, indicating that the
mechanical interactions between the two fractures at this spacing are negligible. For the softer rock with \( E = 20 \) GPa, the spacing of 500m also shows a good fit with the single fracture results. Therefore, the extent of mechanical interactions reduces for lower Young’s modulus, however, this spacing is still much higher than the extent of the thermal interactions reported by Wu et al. (2016). When the spacing is further reduced, a change in the breakthrough curve is realised which indicate that the mechanical interactions between fractures are affecting the apertures and as such reducing the residence time of the fluid in fracture. The consequence of reducing the spacing can be observed through the descending slope in the production temperature in Figure 4. As the two fractures gets closer to each other, the fracture aperture increases due to the stress relaxation it receives from the neighbour fracture. An increase in fracture aperture leads to higher fluid velocity within the fracture, thus a faster drawdown in the production temperature. As the area below the temperature graph represent the amount of heat produced, it is easily seen that a spacing of 50m results in a sharp reduction at the production temperature and thereby the least energy produced.

*Initial Temperature Gradient*

The fractures are considered horizontal in these simulations, so to achieve more realistic results, similar to Saeid et al. (2015) a temperature gradient is introduced to the system. As the output temperature (at the production well) is different for the two fractures, an average value of these two is selected as the new production temperature. Ideally, the distance between the fractures should be large enough to prevent thermal and mechanical interaction from the neighbour fracture. However, the fracture spacing cannot be too wide either as the initial temperature for the top fracture reduces by increasing the spacing. In this section, a temperature gradient of \( 47^\circ\text{C}/\text{km} \) is introduced to the system with \( E = 50 \) GPa, where the initial temperature at the bottom fracture is kept constant at \( 200^\circ\text{C} \). Figure 5 shows the temperature profile after 10 years of production on a vertical cross section for the spacing of 50m, 300m and 1000m. The interaction between the temperature plumes is only observed for the spacing of 50m, while the other two cases show no such interactions. This is compatible with the results by Wu et al. (2016) which indicated that the spacing of larger than 80m is excessively large for thermal (and not the mechanical) interactions. As the spacing increases, the initial temperature at the top fracture reduces. In Figure 6a, the temperature profile for different spacing is plotted. Due to the initial temperature gradient, the initial average temperature reduces with increasing spacing. So, the case with minimum spacing of 50m shows higher initial production temperature of \( 198.8^\circ\text{C} \), while the case with 1000m spacing shows an initial production temperature of \( 176.5^\circ\text{C} \). However, as the mechanical interactions affect the apertures, the cases with lower spacing show higher reduction in the production temperature. The mechanical interactions in the case of 50m spacing causes a rapid reduction in the output temperature such that it reaches the reference temperature of \( 140^\circ\text{C} \) in about 7 years, while the case with 1000m spacing reaches this temperature after 11.5 years. The case of 500m spacing shows longer production time. The
fracture aperture at the injection well is plotted in Figure 6b for spacing of 50m, 150m, 300m and 1000m. Lower spacing shows higher aperture due to the mechanical contraction of the neighbour fracture. Due to the initial temperature gradient, the top fracture undergoes lower temperature variation and thus shows lower aperture. The difference between apertures in bottom and top fractures increases with increasing spacing.

Another case with lower initial temperature gradient of 30°C/km (e.g West Netherlands Basin, Bonté et al., 2012; Willems et al. 2017a) is simulated where all other parameters are kept the same. The results for production temperature for different spacing are shown in Figure 7 for both temperature gradients. The initial temperature at the bottom fracture for both cases is set at 200 °C. The effect of the temperature gradient increases as the fracture spacing increases. A big difference is seen for the spacing of 1000m, while the effect is negligible for the spacing of 50m. The difference in initial temperature for the spacing of 50m is only 0.425 °C, while a spacing of 1000m will experience a temperature difference of 8.5 °C. Lower temperature gradient increases the energy extraction from the system for higher spacing as the top fracture would have higher initial temperature compared to the higher temperature gradient case.

The Effect of Matrix Deformability

The matrix deformability affects the mechanical interactions between the two fractures as shown for the uniform temperature case in Figure 4. Softer rock shows lower mechanical interactions and therefore, produces hotter fluid for an extended period. When the initial temperature gradient is considered, it is shown that for lower spacing cases there is a competition between high mechanical interactions with higher initial temperature. So, the system with lower spacing starts producing water at a higher temperature, but due to the higher mechanical interactions the temperature at the production decreases faster. In this section, the case with lower Young’s modulus of E = 20 GPa is simulated with initial temperature gradient of 47°C/km. The plume of the stresses around the fractures for both Young’s moduli of 20 GPa and 50 GPa, and spacing of 300m and 500m are shown in Figure 8. Interactions between two fractures can be seen by the interference of the stress plume. For the stiffer fracture, the two fractures are interacting when the spacing is 500m while for the softer rock that spacing is large enough to neglect the interactions. When the spacing is reduced to 300m, the stress interactions are considerable even for the softer rock. The bottom fracture also shows higher stress reduction due to higher temperature variation. The production temperatures for different spacing are shown in Figure 9a. As the mechanical interactions are lower for the E = 20 GPa, the simulations for spacing of 40m and 35m are added. For the softer rock, the mechanical interaction between two fractures reduces therefore, this system produces hotter fluid for longer time. However, as shown in Figure 9a, the lower spacing induces higher mechanical interactions and therefore higher aperture in the fracture and faster reduction of the production temperature, while higher spacing shows lower initial production temperature and lower
reduction of the temperature versus time. As a result, the curves for lower spacing cross the ones for higher spacing. The production temperature for two cases of Young’s moduli with spacing of 50m and 1000m are compared in Figure 9b. Lower Young’s modulus reduces the mechanical interactions so the case with 50m spacing crosses the curve with 1000m spacing after 15 years of production, while for the stiffer rock, the crossing occurs much earlier (around 6 years). The slope of the production temperature for the case of stiffer rock is also higher than the softer rock for the 1000m spacing. Although, for spacing of 1000m, it is shown earlier that the mechanical interactions between two fractures are negligible for both Young’s moduli, so the higher temperature drop is the result of the ability of the stiff matrix in sustaining higher aperture as shown in Figures 9c and 9d. The aperture in the softer rock is much less than the stiff rock for all spacing. When the spacing is reduced in softer rock, the aperture initially increases, however, due to the redistribution of stresses, the soft rock is not able to sustain high apertures and therefore the aperture approaches to a maximum value. Due to lower fracture aperture in the softer rock, the cold fluid can access to higher area of the fracture as shown before in Figure 2a for single fracture case. The vertical stress reduces over a larger area of the fracture in softer rock compared with stiffer rock as shown in Figure 10. The stiffer rock sustains higher reduction in the vertical stress (and higher aperture) and the additional load is carried by the area around the cooled area in the fracture shown in darker colour in Figure 10.

The results from the simulator highlights the importance of the thermoelastic interaction between two fractures and neglecting such interactions results in much lower optimum spacing as reported by Wu et al. (2016). The present observations conclude that the aperture variation highly affects the output temperature in the fracture, and the variation in the fracture aperture is a result of the thermo-mechanical interaction within the system. By assuming a constant fracture aperture, the deformation due to thermal contraction and mechanical interaction is neglected. Since the effects of mechanical interaction have been observed in a much greater spacing than the thermal interaction, the mechanical affects seems to be the most critical and the optimum spacing is rather dictated by the thermoelastic deformations.

Energy Balance

The net energy production in the system is crucial as it estimate the performance of the EGS, and is determined by the sum of the energy produced minus the energy consumed by injection pump

\[ E_{\text{net}} = E_g - E_p \]  

(52)

The energy produced from the production well may be written as (Willems et al., 2017b)

\[ E_g = \rho C_f Q \int_{t=0}^{LT} (T - T_{\text{min}}) \, dt \]  

(53)
where $Q$ is the production flow rate, $T_{min}$ is the minimum temperature the plant sees it economical to produce, and $LT$ is the lifetime for when the produced temperature reaches to $T_{min}$. Energy used to pump in the injection fluid may be written as

$$E_p = \int_{t=0}^{LT} \frac{Q \Delta P}{\epsilon} dt$$  

(54)

where $\Delta P$ is the pressure change between injector and producer, and $\epsilon$ is the energy conversion efficiency factor, that is assumed to be 0.7. The coefficient of performance (COP) express the efficiency of the system by comparing the heat output with the power consumed as

$$\text{COP} = \frac{E_g}{E_p}$$  

(55)

The production energy is the area between the production temperature and the chosen value for the reference temperature (140°C), while the pumping energy is the area between the injection pressure and the production pressure (34 MPa). The reference temperature, representing the lifetime of the EGS, set to 140°C, indicating that the system allows a 30% drop in temperature. The net energy production is shown in Figure 11a for three cases: (i) $E = 50$ GPa and thermal gradient of 47°C/km, (ii) $E = 50$ GPa and thermal gradient of 30°C/km, and (iii) $E = 20$ GPa and thermal gradient of 47°C/km. The lower Young’s modulus results in higher energy production due to the lower fracture aperture induced in the system. Lower initial temperature gradient also increases the amount of the energy produced, specifically when the spacing increases. This is due to the higher initial temperature at the top fracture. However, a local maximum in the net energy production exists for all cases. The optimum spacing for case (i) is between 150m and 300m; for case (ii) is 300m; and for case (iii) is 150m. The optimum increases with reducing initial thermal gradient, and reduces with reducing Young’s modulus. However, these values are much more than the values reported by Wu et al. (2016) for rigid matrix. In Figure 11b the evolution of COP is plotted for spacing of 50, 150 and 300 m for case (i): $E = 50$ GPa and thermal gradient of 47°C/km. The lower spacing shows higher initial COP, but as time elapses the production temperature reduces faster and the production energy reduces. Although that the increase in the aperture improves the injectivity of the system and reduces the pumping energy, however, the overall COP shows a sharp reduction for lower spacing.

Three-Fracture System

In this section, a third fracture is added to the model shown in Figure 3a. This is just to show how the mechanical interactions increase as the number of fractures increases. Two cases are simulated where the uniform spacing between the three fractures are set to 500m and 300m, and the temperature at the bottom fracture is again fixed at 200°C. The initial temperature gradient is set at 47°C/km, and the flow rate is kept constant at 0.0125 m³/s for all fractures. The aperture distribution on each fracture for both cases are shown in Figure 12a. For the
spacing of 150m, the middle fracture undergoes highest aperture increase due to the matrix contraction it receives from both sides, while the top fracture has the lowest aperture increase due to the lower initial temperature. However, for the spacing of 300m, the bottom fracture shows higher aperture due to higher temperature variation, and again the top fracture shows the lowest aperture variation. So, for the spacing of 300m, the mechanical contractions received by the middle fracture are lower to compensate for the lower initial temperature, while for the spacing of 150m, the mechanical contractions are quite strong for the middle fracture. The average production temperature for both cases are compared with the two-fracture system in Figure 12b. The three-fracture results show lower initial production temperature due to lower initial temperature for the top fracture, also the temperature declines faster for the three-fracture case with spacing of 150m, due to higher mechanical interactions exerted on the middle fracture. Whereas for the spacing of 300m, the slope of the three-fracture case is slightly lower than that of two-fracture case, perhaps due to having access to larger volume of the rock. The apertures along the horizontal line passing through the injection and production points of each fracture are plotted in Figure 12c. Lower spacing results in higher aperture around the injection point and towards the production point. For the spacing of 150m, middle fracture shows the highest aperture developed due to the combined thermal and mechanical contractions. For the spacing of 300m, the bottom fracture shows highest aperture due to the highest thermal contractions.

4. Conclusions

In this study, a coupled THM model is utilised to investigate the mechanical interactions between multiple parallel fractures during heat extraction from a multiple-fracture EGS. Multiple fractures increase the number of flow paths and provide access to a larger volume of rock, however, interactions between the fractures may lead to higher apertures and higher fracture conductivity, thus a faster drawdown of the production temperature. Additionally, as the temperature of the rock matrix varies with depth, the higher spacing means lower initial temperature for fractures in shallower depths. Simulations for various cases are carried out for a system with two and three fractures, where key parameters such as spacing between fractures, Young’s modulus of the rock matrix, and the initial temperature gradient are varied and their effects on the production temperature of the system is studied. Results show that the mechanical interactions are quite strong compared to the thermal interactions and the mechanical interactions begin to affect the results through increasing fracture aperture at much larger spacing. As the matrix deformability increases (Young’s modulus decreases), the mechanical interaction decreases, however, they are still much more influential than the thermal interactions. Due to low permeability of the matrix in EGS, the heat propagates through the rock by relatively slow diffusion, so for the lifetime of an EGS (30 years) the propagation of the cold front is on the order of tens of meters. Thus, as shown by Wu et al. (2016) the thermal
interactions are negligible for spacing higher than 60-80m. This is not the case when the mechanical deformations are accounted for. Results show that the optimum spacing for the two-fracture case with the geometry given in this study, varies between 150m to 300m. The optimum spacing may increase for three or more fractures.

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References


Figure 1. a) The geometry of the model for the EGS example. b) Vertical cross section showing fracture with its dimensions and connected wells. Temperature field is shown at 30 years. c) The mesh used for the fracture. d) Comparison between the results of the studied model and results from Guo et al. (2016).
Figure 2. (a) Fracture aperture and temperature at the fracture. (b) Aperture along the fracture at 30 years. (c) Breakthrough curve.
Figure 3 – (a) The geometry used for multiple-fracture EGS simulations. The two fractures are symmetrically situated within the domain. (b) Vertical stress distribution over a centralized vertical cross section for a system with fracture spacing of 1000m. (c) The vertical stress along the white line shown in (b) is plotted. (d) 3D contour of the vertical stresses around the two fractures for fracture spacing of 1000, 750 and 500m.
Figure 4 – Breakthrough curves for various spacing within an initial uniform temperature of 200°C for (a) $E = 50 \text{ GPa}$ and (b) $E = 20 \text{ GPa}$
Figure 5 – Vertical cross section of the temperature field at 10 years for fracture spacing of 50m, 300m and 1000m for a temperature gradient at 47°C/km. The initial temperature at the bottom fracture is fixed at 200°C for all cases.
Figure 6 – (a) Breakthrough curve where a temperature gradient of 47°C/km is introduced. (b) Aperture evolution for bottom (solid lines) and top (dashed lines) fracture. As the bottom fracture experience a higher temperature variation, the aperture tends to increase more
Figure 7 – Breakthrough curve for two temperature gradients. Dashed lines indicate a temperature gradient of 47°C/km and the solid lines for 30°C/km.
Figure 8 – Vertical stress distribution around two parallel fractures. (a) $E = 20$ GPa, spacing = 500m, (b) $E = 50$ GPa, spacing = 500m, (c) $E = 20$ GPa, spacing = 300m, (d) $E = 50$ GPa, spacing = 300m
Figure 9 – (a) Breakthrough curve for E = 20 GPa for different spacing. (b) Comparison between production temperature for cases of 50m and 1000m spacing with E = 50 GPa (solid lines) and E = 20 GPa (dashed lines). Aperture evolution at the injection point at the bottom fracture during the lifetime of the EGS for (c) E = 20 GPa and (d) E = 50 GPa
Figure 10 – Horizontal cross section through bottom fracture for a system with fracture spacing of 300 m. (a) Young’s modulus is 20 GPa, (b) Young’s modulus is 50 GPa
Figure 11 – (a) The net energy for all spacing is shown for the three different scenarios for a system with two parallel fractures. (b) The COP for $E = 50$ GPa and temperature gradient of $47^\circ$C/km
Figure 12 – (a) Aperture distribution at 10 years for all (bottom, middle and top) fractures. (b) Production temperature versus time for two- and three-fracture cases. (c) Aperture along the line passing through the injection and production wells at 10 years.