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Heat Recovery from Multiple-Fracture Enhanced Geothermal Systems: The Effect of Thermoelastic Fracture Interactions

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8 ABSTRACT

9 This study investigates the effect of thermoelastic interactions between multiple parallel fractures on energy production from a multiple-fracture enhanced geothermal system. A 10 coupled thermo-hydro-mechanical finite element model has been developed that accounts for 11 non-isothermal fluid flow within the fractures, conductive heat transfer in the rock matrix, 12 and the mechanical deformation of the matrix. The model results show that the matrix 13 deformation significantly increases the interactions between the two adjacent fractures. 14 Matrix contraction due to the cooling of the matrix increases the fracture aperture in the 15 adjacent fracture, and facilitates the creation of favourable flow pathways between the 16 injection and production wells. These flow paths reduce the energy production from the 17 system. The effects of fracture spacing, reservoir temperature gradient and mechanical 18 properties of the rock matrix on the production temperature and the net production energy are 19 investigated. It is shown that the spacing calculated based on the assumption of rigid matrix 20 (constant uniform aperture) are too small, and in order to account for the thermoelastic 21 interactions, the spacing between fractures should be further increased to maximise the net 22 energy production from the system. Otherwise, the multiple-fracture system fails to improve 23 the energy recovery from the geothermal reservoir, as initially intended. 24

Keywords: Multiple parallel fractures; Enhanced geothermal systems; Thermoelasticinteraction; Fracture flow; Coupled formulation;

27

28 1. Introduction

Geothermal energy is the energy stored in the Earth's crust and is one of the promising and 29 clean renewable energy resources in the world (MIT, 2006). Geothermal energy can be used 30 widely for district heating utilising the ground source heat pumps – GSHP (), and for power 31 generation from conventional/enhanced geothermal systems. Based on the geological 32 knowledge and technology, it has been estimated that in 2016 only 6 to 7 % of the total 33 34 global potential had been extracted (GEA, 2016). Low reservoir permeability is a common challenge for energy exploitation from deep geothermal reservoirs, and hydraulic fracturing is 35 frequently utilised to improve the permeability within the reservoir. The stimulation has been 36 widely used in the oil and gas industry and was introduced to geothermal projects in 1974 at 37 Fenton Hill (MIT, 2006; Xie et al., 2015). In order to improve the heat extraction from the 38 low permeability geothermal reservoirs, multiple induced fractures are proposed to provide 39 40 multiple flow paths between the injection and production wells, and multiple contact surfaces for the heat exchange between the hot rock and the cold fluid (Bataille et al., 2006). Multiple 41 fractures can improve the productivity of the geothermal system for a relatively lower cost 42 (Schweitzer and Bilgesu, 2009). 43

In Enhanced Geothermal System (EGS), short-circuiting between the injector and producer 44 wells is a common issue that affects the energy recovery from the system. Short-circuiting 45 occurs due to the locally increased fracture aperture that creates a channel and prevent the 46 47 cold fluid from accessing the bulk rock. The local increase in the fracture aperture is a result of the coupled thermo-hydro-mechanical and chemical (THMC) effects (Ghassemi and Zhou, 48 49 2011; Pandey et al., 2014; Guo et al., 2016). For the case of multiple parallel fractures, the 50 mechanical interactions between the fractures further facilitate the creation of the unfavourable short-circuits between the injector and producer wells, reducing the fluid 51 residence time and thus, reducing the energy recovery. Numerous analytical and numerical 52 53 models have been proposed in the literature for studying the behaviour of enhanced geothermal systems. Due to very low permeability of the rock matrix in EGS, the fractures 54 are considered as the primary pathways for the flow of the circulating fluid. For single 55 fracture EGS, Bodvarsson (1969) derived an analytical solution for the problem of advective-56 diffusive heat transfer through a single one-dimensional fracture, while the heat is transferred 57 through the matrix only by diffusion in the direction normal to the fracture (1D diffusion). 58 Ghassemi et al. (2008) also proposed semi-analytical solution for a similar problem with 59 60 leakoff of the fluid into the matrix. The apertures of the fractures vary during the lifetime of the EGS, as the cooling of the matrix results in matrix contraction and perhaps reduction of 61 the contact stresses on the fracture surfaces (Salimzadeh et al., 2018a, b). The effect of 62 thermoporoelastic deformation of the rock matrix on the fracture aperture and geometry 63 evolution has been widely studied using numerical simulations for single fracture EGS 64 (Ghassemi and Zhou, 2011; Guo et al., 2016; Abu Aisha et al., 2016; Pandey et al., 2017). 65 The thermal contraction of the rock matrix together with the increased fluid pressure in the 66 fracture decreases the contact stresses on the fracture surfaces and increases the fracture 67 aperture. The reduction of the contact stresses promotes the shear deformation of the fracture 68 69 (McClure and Horne, 2014), while the increase in the fracture aperture promotes the creation of unfavourable short-circuits. Guo et al. (2016) have shown that heterogeneity can aggravate 70 the problem of short-circuiting. 71

The multiple-fracture EGS creates more flow paths, and gives access to a larger volume of rock. Gringarten et al. (1975) presented analytical solutions to parallel equidistant vertical fractures, highlighting the importance of the multi-fracture concept in the geothermal energy extraction. Recently, Wu *et al.* (2016) developed a mathematical model for the heat

extraction from multiple horizontal fractures in a rigid medium (constant uniform apertures). 76 Their results show that for the case of two parallel infinite rigid fractures, the thermal 77 interactions for a spacing larger than 60m-80m in the lifetime of a geothermal reservoir 78 (thirty years) are negligible. This is due to the very slow propagation of heat through the low-79 permeability rock. However, as proven by many researches for single-fracture EGS, the 80 fracture aperture varies during the heat production from an EGS, and the aperture variation 81 has negative effects on the lifetime of the EGS. For the case of multiple fractures, the 82 mechanical interaction between multiple fractures can be significant and it affects the 83 aperture and the geometry of the propagating fractures as shown by Kumar and Ghassemi 84 85 (2016) and Salimzadeh et al. (2017a) for multiple hydraulic fractures. In EGS, the thermal contraction of the matrix reduces the contact stress on the fractures in the vicinity of the cold 86 region, and that increases the aperture of the fractures. The increase in the aperture, 87 negatively affects the heat production from the EGS as shown by Salimzadeh et al. (2018a, b) 88 for a single fracture EGS. The importance of coupling mechanics to the flow and transport 89 has been demonstrated in other applications such as in CO₂ sequestration by Martinez et al., 90 (2013) and Dempsey et al. (2014), in nuclear waste disposal by Rutgvist et al. (2005) and 91 92 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 93 (2015) and Salimzadeh et al., (2017b). 94

As a single fracture system has limited exposed area for heat transfer to happen between the 95 cold fluid and the surrounding hot rock formation, a system with multiple fractures can be 96 implemented in order to improve the performance of the EGS. Increasing the number of 97 fractures provides several flow paths allowing the cold fluid to access a greater volume of 98 99 rock. 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 100 horizontal, and a temperature gradient is considered with the assumption that the initial 101 102 temperature at the bottom fracture is fixed. They have varied the spacing between fractures 103 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 104 105 of the fractures interacts. However, they suggested that when the spacing between fractures is more than 80m, the thermal interactions within the lifetime of the EGS (30 years) are 106 negligible. The contribution of the mechanical deformation in the response of a single-107 fracture EGS is already mentioned to be important, however, for a multiple-fracture EGS, to 108 the best knowledge of the authors, there is no studies on the thermoelastic interactions 109 between the fractures. 110

In this paper, a coupled thermo-hydro-mechanical (THM) finite element (FEM) model is 111 utilised to investigate the thermoelastic interactions between multiple fractures in an EGS. 112 Fractures are modelled as surface discontinuities in three-dimensional matrix. Flow through 113 fractures are modelled using cubic law, together with advective-diffusive heat transfer within 114 fractures. The matrix is considered impermeable and the heat is propagating through 115 conduction. The governing equations are solved numerically using Galerkin finite element 116 method (FEM). The model has been validated and used to simulate single-, two- and three-117 118 fracture EGS examples to demonstrate the importance of the mechanical coupling on energy production. 119

120 2. Methodology

In this study, a model of multiple-fracture EGS is built based on the simple geometry 121 suggested by Guo et al. (2016). In their model, a horizontal radial fracture is assumed that 122 connects the injection and production wells as shown in Figure 1. Such geometry is created 123 based on the geothermal field in the Cooper Basin, Australia (Chopra and Wyborn, 2003; 124 Baisch et al., 2009; Llanos et al., 2015). Similar geometries for the EGS simulations are used 125 126 by other researchers in this field (e.g. Ghassemi et al, 2011; Pandey et al., 2014). The aim is to study the extent of the mechanical interactions between multiple parallel fractures and 127 compare it with the thermal interactions. The model includes a horizontal fracture of radius 128 500 m. The domain is 3 km \times 3 km \times 3 km, the penny-shaped fracture is located in the 129 centre, and the injection and production wells are directly connected to the fracture, as shown 130 in Figure 1. The distance between the injection and production wells is set to 500 meters. The 131 initial pore pressure is set to 34 MPa, and the three principal in situ stresses (64, 70 and 100 132 MPa) are assigned to the faces of the box-shaped model. The initial reservoir temperature at 133 the depth of fracture is set to 200°C. The water is injected at a constant rate of 0.0125 m³/s 134 with a constant fluid temperature of 50°C. Production is defined by constant pressure at the 135 producer well; however, as the leakoff is assumed to be negligible in these simulations, the 136 production rate rapidly reaches to the injection rate as time elapses. As there is no flow within 137 the rock matrix, the heat propagates through conduction in the rock matrix, while within the 138 fracture the heat is transferred mainly by advection. The material properties are given in 139 Table 1. The fluid density is considered to be pressure- and temperature-dependant, using the 140 following function: 141

$$\rho_{f} = \rho_{r} e^{\left[\beta_{f}(p_{f} - p_{r}) - \alpha_{f}(T_{f} - T_{r})\right]}$$
(1)

143 where $\rho_r = 887.2 \text{ kg/m}^3$, $p_r = 34 \text{ MPa}$, and $T_r = 200^{\circ}\text{C}$ are the reference (initial) density, pressure 144 and temperature, respectively. The volumetric matrix thermal expansion coefficient of the 145 solid (β_s) is modified for a low permeability matrix using the expression given by McTigue 146 (1986) for undrained thermal expansion coefficient of a fluid-saturated rock

147

142

$$\beta_{\mu} = \beta_{s} + \phi B(\beta_{f} - \beta_{s}) \tag{2}$$

148 where β_u is the undrained thermal expansion coefficient of a fluid-saturated, and *B* is the 149 Skempton coefficient (Jaeger *et al.*, 2007). For the given bulk modulus, porosity, and fluid 150 compressibility used in this example, the undrained volumetric thermal expansion is $\beta_u =$ 151 3.0×10^{-5} /°C.

The proposed numerical model is validated against two analytical solutions and one numerical simulation. Additional validation examples are performed in other publications by the authors, *e.g.* hydraulic fracturing examples (Salimzadeh *et al.*, 2017a, b; Usui *et al.*, 2017).

156 **3. Computational Model**

The fully coupled poroelastic and thermoporoelastic models for discrete fractures in a deformable medium has been presented by Salimzadeh et al. (2017a, b) and Salimzadeh et al. (2016, 2018a, b), respectively. The fully coupled governing equations for non-isothermal flow through deformable matrix with discrete fractures can be found in Salimzadeh et al., 2018a. In this section, a short review of the governing equations for impermeable matrix is

presented. The fractures are modelled as discontinuous surfaces in the three-dimensional 162 matrix, and a contact model is utilised to compute the contact tractions on the fracture 163 surfaces under thermoelastic compression. Assuming impermeable rock matrix, the coupled 164 computational model consist of four sub-models: a mechanical deformation-contact model, 165 flow and heat transfer models for fracture, and heat transfer model for the rock matrix. The 166 flow and heat transfer models through the fractures are defined for two-dimensional discrete 167 fractures, while the conductive heat transfer in the rock matrix, as well as the mechanical 168 deformation-contact model are constructed for a three-dimensional body. To reduce the 169 computational cost, the mechanical deformation and contact tractions are solved in a 170 mechanical deformation-contact model (M) while the flow and heat transfers are solved in a 171 172 thermo-hydraulic (TH) model. The two models are coupled sequentially.

173 **3.1. 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

$$\operatorname{div} \boldsymbol{\sigma} + \mathbf{F} = 0 \tag{3}$$

where **F** is the body force per unit volume, and σ 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)

181
$$\boldsymbol{\varepsilon}_T = -\boldsymbol{\alpha}_s (\boldsymbol{T}_m - \boldsymbol{T}_0) \tag{4}$$

182 where α_s is a symmetric second-order tensor known as the thermal expansivity tensor of the 183 rock matrix. If the rock is isotropic then $\alpha_s = \frac{1}{3}\beta_s \mathbf{I}$, where the scalar coefficient β_s is known 184 as the coefficient of volumetric thermal expansion of rock matrix. The stress-strain 185 relationship for thermoelasticity can be written as (Khalili and Selvadurai, 2003)

186
$$\boldsymbol{\sigma} = \mathbb{D}\boldsymbol{\varepsilon} - \boldsymbol{\beta}_{s} K (\boldsymbol{T}_{m} - \boldsymbol{T}_{0}) \mathbf{I}$$
(5)

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

189

$$\boldsymbol{\varepsilon} = \frac{1}{2} (\nabla \mathbf{u} + \nabla \mathbf{u}^T) \tag{6}$$

190 where **u** denotes the displacement vector of the rock matrix. Hydraulic loading on the 191 fracture boundary are applied as a normal traction

192

$$\boldsymbol{F}_{\boldsymbol{c}} = \boldsymbol{\sigma}_{\boldsymbol{c}} - \boldsymbol{p}_{\boldsymbol{f}} \boldsymbol{n}_{\boldsymbol{c}} \tag{7}$$

where σ_c is the contact tractions on the fracture surfaces, p_f is the fluid pressure inside fracture, and \mathbf{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

197
$$\operatorname{div}(\mathbb{D}\boldsymbol{\varepsilon}) + \mathbf{F} = \operatorname{div}(\boldsymbol{\beta}_{s}K(\boldsymbol{T}_{m} - \boldsymbol{T}_{0})\mathbf{I}) + \delta(\mathbf{x} - \mathbf{x}_{c})(\boldsymbol{p}_{f}\mathbf{n}_{c} - \boldsymbol{\sigma}_{n})$$
(8)

198 where $\delta(\mathbf{x} - \mathbf{x}_c)$ is the Dirac delta function, and \mathbf{x}_c represents the position of the fracture (Γ_c). 199 Note that the contact tractions and hydraulic loadings exist only on the fracture surfaces (Γ_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).

207 3.2. Coupled Thermo-Hydro (TH) Model

208 Fracture Flow Model

211

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

$$\operatorname{div}(a_f \rho_f v_f) + \frac{\partial}{\partial t}(a_f \rho_f) = 0 \tag{9}$$

where a_f is the fracture aperture, ρ_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)

216
$$v_f = -\frac{a_f^2}{12\mu_f} \nabla p_f \tag{10}$$

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

219
$$\frac{\partial \rho_f}{\partial t} = \rho_f c_f \frac{\partial p_f}{\partial t} - \rho_f \beta_f \frac{\partial T_f}{\partial t}$$
(11)

where c_f is the fluid compressibility, T_f is the fluid temperature in the fracture, and β_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

225
$$a_f = a_0 - \frac{a\sigma_n}{1 + b\sigma_n}$$
(12)

where σ_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

231
$$\frac{\partial a_f}{\partial t} = \frac{1}{K_n} \frac{\partial p_f}{\partial t}$$
(13)

in which K_n is the fracture tangent stiffness, given by

$$K_n = -\frac{\partial \sigma_n}{\partial a_f} = \frac{\left(1 + b\sigma_n\right)^2}{a} \tag{14}$$

The governing equation for the laminar flow in the fracture is written as

235
$$\operatorname{div}\left(\frac{a_{f}^{3}}{12\mu_{f}}\nabla p_{f}\right) = \left(\frac{1}{K_{n}} + a_{f}c_{f}\right)\frac{\partial p_{f}}{\partial t} - a_{f}\beta_{f}\frac{\partial T_{f}}{\partial t}$$
(15)

236 Fracture Heat Transfer Model

233

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)

240
$$q_{fc} = -a_f \lambda_f \nabla T_m + a_f \rho_f C_f \mathbf{v}_f T_f$$
(16)

where λ_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

244
$$q_{fp} = a_f \beta_f T_f \frac{\partial p_f}{\partial t}$$
(17)

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

248
$$q_{mf} = \lambda_n \frac{\partial T}{\partial \mathbf{n}_c}$$
(18)

249 where λ_n is the thermal conductivity of the rock matrix along the direction normal to the 250 fracture (in the direction of \mathbf{n}_c). The rate of heat storage in the fluid is given by

251
$$q_{fs} = a_f \rho_f C_f \frac{\partial T_f}{\partial t}$$
(19)

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

253
$$\operatorname{div}(a_f \lambda_f \nabla T_f) = a_f \rho_f C_f \frac{\partial T_f}{\partial t} - a_f \beta_f T_f \frac{\partial p_f}{\partial t} + a_f \rho_f C_f \mathbf{v}_f \cdot \nabla T_f - \lambda_n \frac{\partial T}{\partial \mathbf{n}_c} \quad (20)$$

254 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

 $q_{mc} = -\lambda_m \nabla T_m \tag{21}$

where λ_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)

262
$$\lambda_m = (1 - \phi)\lambda_s + \phi\lambda_f$$
(22)

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

265
$$q_{ms} = \rho_m C_m \frac{\partial T_m}{\partial t}$$
(23)

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

$$\rho_m C_m = (1 - \phi) \rho_s C_s + \phi \rho_f C_f \tag{24}$$

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

270
$$\operatorname{div}(\boldsymbol{\lambda}_{m} \nabla T_{m}) = \left(\rho_{m} C_{m} - \beta_{s}^{2} K T_{m}\right) \frac{\partial T_{m}}{\partial t} + \delta(\mathbf{x} - \mathbf{x}_{c}) \lambda_{n} \frac{\partial T}{\partial \mathbf{n}_{c}}$$
(25)

Note that the heat leakoff only occurs through the fracture surfaces (Γ_c). To reduce 271 computational time, the mechanical contact model (M) is solved separately from the rest of 272 the TH model. However, they are still coupled iteratively, where the following process is 273 carried out in each timestep. Firstly, the TH model is run with contact stresses and fracture 274 aperture computed from the previous step (or initial values for the first step). The TH model 275 then sends the computed temperatures and pressures values to the mechanical contact model 276 so the results for the contact stresses and fracture aperture can be updated. Further, the TH 277 model is ran with the updated apertures. The contact model is run in the "stick" mode, which 278 means that sliding along the opposing fracture surfaces is not allowed. 279

280 **3.3.** Finite Element Approximation

268

289

290

291

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 **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 **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 $(\hat{\mathbf{u}}, \hat{p}_f, \hat{T}_f, \hat{T}_m)$ as

$$\mathbf{u} = \mathbf{N}\hat{\mathbf{u}} \tag{26}$$

$$p_f = \mathbf{N}_c \hat{\mathbf{p}}_f \tag{27}$$

$$T_f = \mathbf{N}_c \hat{\mathbf{T}}_f \tag{28}$$

 $T_m = \mathbf{N}\hat{\mathbf{T}}_m \tag{29}$

where **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

295
$$\frac{\partial X}{\partial t} = \frac{X^{t+dt} - X^t}{dt}$$
(30)

where X^{t+dt} and X^{t} are the values of X at time t + dt and t, respectively. The set of discretised equations can be written in matrix form as SX = F, in which S is the element's 298 general stiffness matrix, and \mathbb{F} is the vector of right-hand-side loadings. For the mechanical 299 deformation-contact model (M) the set of discretised equations may be written in matrix form 300 as

301
$$[\mathbb{S}_{uu}][\hat{\mathbf{u}}] = \left[\mathbf{F} + \mathbf{C}_{p_f}\hat{\mathbf{p}}_f + \mathbf{C}_{T_m}(\hat{\mathbf{T}}_m - \hat{\mathbf{T}}_0)\right]$$
(31)

and for the TH model

303
$$\begin{bmatrix} \mathbf{S}_{p_{f}p_{f}} & -\mathbf{C}_{p_{f}T_{f}} & \mathbf{0} \\ -\mathbf{C}_{T_{f}p_{f}} & \mathbf{S}_{T_{f}T_{f}} & -\mathbf{L}_{T_{f}T_{m}}dt \\ \mathbf{0} & -\mathbf{L}_{T_{m}T_{f}}dt & \mathbf{S}_{T_{m}T_{m}} \end{bmatrix} \begin{bmatrix} \hat{\mathbf{p}}_{f} \\ \hat{\mathbf{T}}_{f} \\ \hat{\mathbf{T}}_{m} \end{bmatrix} = \begin{bmatrix} \mathbf{M}_{p_{f}p_{f}} \hat{\mathbf{p}}_{f}^{t} - \mathbf{C}_{p_{f}T_{f}} \hat{\mathbf{T}}_{f}^{t} + \mathbf{Q}_{p_{f}}dt \\ \mathbf{M}_{T_{f}T_{f}} \hat{\mathbf{T}}_{f}^{t} - \mathbf{C}_{T_{f}p_{f}} \hat{\mathbf{p}}_{f}^{t} + \mathbf{Q}_{T_{f}}dt \\ \mathbf{M}_{T_{m}T_{m}} \hat{\mathbf{T}}_{m}^{t} - \mathbf{C}_{T_{m}p_{m}} \hat{\mathbf{p}}_{m}^{t} + \mathbf{Q}_{T_{m}}dt \end{bmatrix}$$
(32)

304 where

305
$$\mathbb{S}_{uu} = \int_{\Omega} \overline{\nabla} \mathbf{N}^T \mathbb{D} \overline{\nabla} \mathbf{N} d\Omega$$
(33)

306
$$\mathbf{C}_{p_f} = \int_{\Gamma_c} \mathbf{N}_c^T (p_f \mathbf{n}_c - \boldsymbol{\sigma}_n) \mathbf{N} d\Gamma$$
(34)

307
$$\mathbf{C}_{T_m} = \int_{\Omega} \mathbf{B}_2^{\mathrm{T}} \boldsymbol{\beta}_s K \mathbf{N} d\Omega$$
(35)

308
$$\mathbb{S}_{p_f p_f} = \left[\mathbf{H}_{p_f} dt + \mathbf{M}_{p_f p_f} \right]$$
(36)

309
$$\mathbb{S}_{T_f T_f} = \mathbf{H}_{T_f} dt + \mathbf{M}_{T_f T_f} + \mathbf{L}_{T_m T_f} dt$$
(37)

310
$$\mathbb{S}_{T_m T_m} = \mathbf{H}_{T_m} dt + \mathbf{M}_{T_m T_m} + \mathbf{L}_{T_m T_f} dt$$
(38)

311
$$\mathbf{H}_{p_f} = \int_{\Gamma_c} \nabla \mathbf{N}_c^T \frac{a_f}{12\mu_f} \nabla \mathbf{N}_c d\Gamma$$
(39)

312
$$\mathbf{M}_{p_f p_f} = \int_{\Gamma_c} \mathbf{N}_c^T (\frac{1}{K_n} + a_f c_f) \mathbf{N}_c d\Gamma$$
(40)

313
$$\mathbf{H}_{T_f} = \int_{\Gamma_c} \nabla \mathbf{N}_c^T a_f \boldsymbol{\lambda}_f \nabla \mathbf{N}_c d\Gamma + \int_{\Gamma_c} \mathbf{N}_c^T a_f \rho_f C_f \mathbf{v}_f \nabla \mathbf{N}_c d\Gamma$$
(41)

314
$$\mathbf{M}_{T_f T_f} = \int_{\Gamma_c} \mathbf{N}_c^T a_f \rho_f C_f \mathbf{N}_c d\Gamma$$
(42)

315
$$\mathbf{C}_{p_f T_f} = \int_{\Gamma_c} \mathbf{N}_c^T a_f \beta_f \mathbf{N}_c d\Gamma$$
(43)

316
$$\mathbf{C}_{T_f p_f} = \int_{\Gamma_c} \mathbf{N}_c^T a_f \beta_f T_f \mathbf{N}_c d\Gamma$$
(44)

317
$$\mathbf{L}_{T_m T_f} = \int_{\Gamma_c} \mathbf{N}_c^T \left(\lambda_n \frac{\partial}{\partial \mathbf{n}_c} \right) \mathbf{N}_c d\Gamma$$
(45)

318
$$\mathbf{H}_{T_m} = \int_{\Omega} \nabla \mathbf{N}^T \boldsymbol{\lambda}_m \nabla \mathbf{N} d\Omega$$
(46)

319
$$\mathbf{M}_{T_m T_m} = \int_{\Omega} \mathbf{N}^{\mathrm{T}} (\rho_m C_m - \beta_s^2 K T_m) \mathbf{N} d\Omega$$
(47)

where **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 S are populated with the

coupling matrices **C**, and **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 $\overline{\nabla}$ for three-dimensional displacement field is defined as

$$\overline{\nabla} = \begin{bmatrix} \frac{\partial}{\partial x} & 0 & 0 \\ 0 & \frac{\partial}{\partial y} & 0 \\ 0 & 0 & \frac{\partial}{\partial z} \\ 0 & \frac{\partial}{\partial z} & \frac{\partial}{\partial y} \\ \frac{\partial}{\partial z} & 0 & \frac{\partial}{\partial x} \\ \frac{\partial}{\partial y} & \frac{\partial}{\partial x} & 0 \end{bmatrix}$$
(48)

327

328

The components of the stiffness matrix are dependent upon the primary unknown variables, *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 S are updated using weighted average solution vector $X_{n+1}^{s+\theta}$ defined as

335
$$X_{n+1}^{s+\theta} = (1-\theta)X_{n+1}^{s-1} + \theta X_{n+1}^{s}$$
(49)

where X_{n+1}^{s-1} and 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

339 $X_{n+1}^0 = X_{n+1}^1 = X_n$ (50)

340 where X_n is the solution vector from previous timestep *n*. The iterations are repeated until 341 consecutive normalised values of X_{n+1}^{s} agree to within a specified tolerance ε

$$\frac{|\mathbf{x}_{n+1}^{s+1} - \mathbf{x}_{n+1}^{s}|}{|\mathbf{x}_{n+1}^{s+1}|} < \varepsilon$$
(51)

342
$$\frac{|X_{n+1} - X_{n+1}|}{|X_{n+1}^{s+1}|} < \varepsilon$$

The tolerance is set to 1%. The discretised equations are implemented in the Complex 343 Systems Modelling Platform (CSMP++), a finite element base code library (Matthäi et al., 344 2001) designed to simulate complex multi-physics problems of geological processes (e.g. 345 Matthäi et al., 2010; Nick and Matthäi, 2011; Paluszny and Zimmerman, 2011). Quadratic 346 347 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 348 349 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. 350 Fracture flow and fracture heat equations are accumulated only on one side of the fracture, 351 whereas, the heat leakoff is accumulated over both sides of the fracture. The ensuing set of 352

linear algebraic equations SX = F is solved at each timestep using the algebraic multigrid method for systems, SAMG (Stüben, 2001).

355 4. Model Validation

360

381

356 One-dimensional flow through a rigid fracture

In this example, a fracture of length 1 km is considered between injection and production wells, as shown in Figure 2a. Plane-strain conditions are assumed, in order to validate the model results against the analytical solution given by Bodvarsson (1969) as

$$T_{d}(x,y,t) = \operatorname{erfc}\left[\left(\frac{\lambda_{s}x}{q\rho_{w}C_{w}} + \frac{y}{2}\right)\sqrt{\frac{\rho_{s}C_{s}}{\lambda_{s}t}}\right]$$
(52)

in which, $T_d = (T_0 - T)/(T_0 - T_{inj})$, T_0 is the initial temperature, and T_{inj} is the temperature 361 of the injected fluid. Injection of cold water at temperature 20°C, at constant rate q = 0.0001362 m²/s is assumed, while production is simulated through constant zero pressure in the 363 production well. The initial temperature of the rock matrix is set to 100 °C. Water has a 364 density of $\rho_f = 1000 \text{ kg/m}^3$, a heat capacity of $C_f = 4200 \text{ J/kg} \circ \text{C}$, and the matrix rock has 365 density $\rho_s = 2820 \text{ kg/m}^3$, heat capacity of $C_s = 1170 \text{ J/kg} \,^\circ\text{C}$, and thermal conductivity of $\lambda_s =$ 366 2.88 W/m °C. Constant matrix temperature is assumed at the far boundaries of the simulation 367 region, while the matrix is assumed impermeable to the flow, so the injected fluid remains 368 inside the fracture, while the heat is transferred through conduction in the matrix. A box 369 model of size $5000 \times 1000 \times 10000$ m is built and spatially discretised using 25,248 quadratic 370 tetrahedral and triangular elements. The results for the fluid temperature at production are 371 shown in Figure 2b. Included in these figure is the solution proposed by Bodvarsson (1969) 372 for comparison. The temperature of the cold water in the fracture increases as it exchanges 373 heat with the hot rock matrix. Very good agreement is found between the present model 374 results and the solution proposed by Bodvarsson (1969). 375

376 *Radial flow through a rigid fracture*

In this example, an infinite fracture is modelled, and the cold water is injected into the centre of the fracture. The matrix is assumed impermeable to the flow, so the heat is being transferred only through conduction in the matrix. Ghassemi et al. (2003) presented the analytical solution for the temperature of the matrix as

$$T_{d}(x,y,t) = \operatorname{erfc}\left[\left(\frac{\pi\lambda_{s}x^{2}}{Q\rho_{w}C_{w}} + \frac{y}{2}\right)\sqrt{\frac{\rho_{s}C_{s}}{\lambda_{s}t}}\right]$$
(53)

A fracture of 3000 m × 3000 m is modelled in a block of 3 km × 3 km × 3 km as shown in Figure 2c. The model is discretised spatially using 32,984 quadratic tetrahedral and triangular elements. The injection rate is set to Q = 0.01 m³/s, water has a density of $\rho_f = 1000$ kg/m3, a heat capacity of $C_f = 4200$ J/kg °C, the matrix rock has density $\rho_s = 2700$ kg/m3, heat capacity of $C_s = 1000$ J/kg °C, and thermal conductivity of $\lambda_s = 2.0$ W/m °C. The results for the temperature profile at three timesteps: $t = 10^7$, 10^8 , and 10^9 s are shown in Figure 2d. Very good match is observed between the present model and the analytical results.

389 4.1. A Single-fracture EGS

For further validation, the example given by Guo et al. (2016) is adopted and the results of 390 the present model is compared against their results for the homogenous aperture field. In this 391 example, heat is produced from a horizontal penny-shaped fracture in a low-permeability hot 392 crystalline rock, which roughly resembles the Habanero project in the Cooper Basin, 393 Australia (Chopra and Wyborn, 2003; Baisch et al., 2009; Llanos et al., 2015). The fracture 394 395 aperture is defined as a function of the contact stress, using the Barton-Bandis model (Eq. 12). Two reference points are assumed to evaluate the model parameters a and b, where the 396 fracture aperture at zero contact stress a_0 is assumed equal to a/b. The two reference points 397 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, 398 the model parameters a and b are 1.6×10^{-10} /Pa and 1.333×10^{-7} /Pa, respectively. The domain 399 is discretised spatially using 39,957 quadratic tetrahedra and triangles for matrix volume and 400 fracture surface, respectively. The mesh is refined at the injection and production points as 401 shown in Figure 3a. The first timestep is set to 1 day, and in each step the timestep is 402 increased by a factor of 1.1 until the prescribed maximum timestep of 0.25 years is reached. 403 The cold plume around the fracture at the end of simulation is shown in Figure 3b. The 404 temporal variation of the temperature of the water produced at the production well is shown 405 in Figure 3c. A very good agreement is found between the results from the present model and 406 the results by Guo et al. (2016), which validates the accuracy of the present model and the 407 choice of mesh. 408

The given parameters in Table 1 are for a crystalline rock, so sensitivity analyses are 409 performed in which the Young's modulus and the matrix porosity have been altered to 20 410 GPa and 0.2 to represent a sandstone reservoir. The results for the aperture evolution within 411 the fracture at time 5, 15 and 30 years of simulation, together with its temperature at 30 years 412 are plotted for three various scenarios in Figure 4. Lower Young's modulus reduces the 413 stresses developed during the contraction of the matrix, and results in lower fracture aperture, 414 and thus slower drawdown of the production temperature as the cold fluid gets access to a 415 larger area of the fracture. For a stiffer rock on the other hand, higher fracture aperture is 416 417 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 418 produced water. For the softer rock (E = 20 GPa), however when the porosity in the rock 419 matrix is increased to 0.2, the fracture aperture increases compared to the case with lower 420 porosity. This is related to the higher undrained thermal expansion coefficient for the higher 421 matrix porosity. Higher undrained thermal expansion coefficient improves the mechanical 422 effects and as a result, the rock contracts more and aperture increases more as shown in 423 Figure 4. Higher aperture provides improved flow path between the injector and producer 424 wells and the cold fluid reaches the producer well faster. The produced temperature and 425 aperture distribution for the case of sandstone reservoir with a high porosity (0.2) is similar to 426 those of the granite reservoir with a very low porosity (0.01). Not that there is no flow in the 427 428 matrix, and the effect of the change in porosity is applied through the undrained thermal expansion coefficient of the matrix. 429

430 5. Multiple-Fracture EGS

431 **5.1. Two-Fracture EGS**

In this section, we aim at investigating the effect of the mechanical interactions betweenfractures on the response of the EGS system. As shown in Figure 5a, a model with two

parallel fractures is built by adding a second fracture to the model presented in the previous 434 section. The spacing between the two fractures ranges from 50m to 1000m, and the 435 temperature at the bottom fracture is fixed at 200 °C. The model is discretised spatially using 436 between 58,413 and 74,813 quadratic elements (depending on the geometry). The fixed 437 temperature at the bottom fracture enables the comparison of the two-fracture system with the 438 single-fracture system presented in the previous section. When the vertical thermal gradient is 439 considered, the temperature reduces as the top fracture moves up. Constant flow rate of 440 $0.0125 \text{ m}^3/\text{s}$ is applied to each fracture. Note that the life time is determined for a minimal 441 production temperature of 140 °C. Depending on the usage of the produced hot water and if 442 we take future technical development into consideration the minimal production temperature 443 could be lower (Willems et al., 2017). 444

445 *Uniform initial temperature*

Firstly, a system with uniform temperature at 200 °C is simulated to identify when the 446 mechanical interaction starts to affect the output temperature. As the fractures are positioned 447 448 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 449 experienced in the middle of the two fractures for the system with E = 50 GPa (white line in 450 Figure 5b) is plotted for fracture spacing of 1000m, 750m and 500m in Figure 5c. The areas 451 not affected by the mechanical interaction has a value equal to the initial vertical stress, 64 452 MPa. For a spacing of 1000 m, the minimum effective stress in the centre of the model is 453 found to be 61.56 MPa, indicating a stress change of 2.44 MPa (3.81% decrease). The 454 minimum vertical stress at this location reduces to about 53 MPa for spacing of 500m (17%) 455 reduction in vertical stress). The changes in the vertical stresses affect the aperture in the 456 fractures and lower vertical stress results in higher aperture. The contours for the vertical 457 stress around the fractures are shown in Figure 5d. It can be observed that the mechanical 458 interactions have already started between the two fractures with 500m spacing, while the 459 thermal interactions are almost negligible at these spacing. 460

The production temperature for two cases of Young's modulus E = 50 GPa and E = 20 GPa 461 (granite and sandstone reservoirs) are shown in Figure 6. A good fit is observed between the 462 fracture spacing of 750m for E = 50 GPa and the single fracture model, indicating that the 463 mechanical interactions between the two fractures at this spacing are negligible. For the softer 464 465 rock with E = 20 GPa, the spacing of 500m also shows a good fit with the single fracture 466 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 467 468 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 469 apertures and as such reducing the residence time of the fluid in fracture. The consequence of 470 reducing the spacing can be observed through the descending slope in the production 471 temperature in Figure 6. As the two fractures gets closer to each other, the fracture aperture 472 473 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 474 the production temperature. As the area below the temperature graph represent the amount of 475 heat produced, it is easily seen that a spacing of 50m results in a sharp reduction at the 476 477 production temperature and thereby the least energy produced. Included in Figure 6a, are the simulation cases without the mechanical interactions. It can be seen that the thermal 478 interactions between the two fractures start when the spacing decreases to less than 100 m. 479 Such spacing is compatible with the maximum spacing reported by Wu *et al.* (2016). 480

481 *Initial temperature gradient*

The fractures are considered horizontal in these simulations, so to achieve more realistic 482 results, a temperature gradient is introduced to the system. As the output temperature (at the 483 production well) is different for the two fractures, an average value of these two is selected as 484 the new production temperature. Ideally, the distance between the fractures should be large 485 enough to prevent thermal and mechanical interaction from the neighbour fracture. However, 486 the fracture spacing cannot be too wide either as the initial temperature for the top fracture 487 reduces by increasing the spacing. In this section, a temperature gradient of 47 °C/km is 488 introduced to the system with E = 50 GPa, where the initial temperature at the bottom 489 fracture is kept constant at 200 °C. However, lower temperature gradients may be observed in 490 other cases (e.g. 27 °C/km used by Saeid et al., 2015). Figure 7 shows the temperature profile 491 492 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 493 50m, while the other two cases show no such interactions. This is compatible with the results 494 by Wu et al. (2016) which indicated that the spacing of larger than 80m is too large for 495 thermal (and not the mechanical) interactions. As the spacing increases, the initial 496 temperature at the top fracture reduces. In Figure 8a, the temperature profile for different 497 spacing is plotted. Due to the initial temperature gradient, the initial average temperature 498 reduces with increasing spacing. As the initial temperature at the bottom fracture is kept 499 constant and equal to 200 °C for all cases, the initial temperature of the top fracture, for 500 instance in the spacing of 1000 m, reduces to153 °C. So, the case with minimum spacing of 501 50m shows higher initial production temperature of 198.8 °C, while the case with 1000m 502 spacing shows an initial production temperature of 176.5 °C. However, as the mechanical 503 interactions affect the apertures, the cases with lower spacing show higher reduction in the 504 505 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 140 506 °C in about 7 years, while the case with 1000m spacing reaches this temperature after 11.5 507 508 years. The case of 500m spacing shows longer production time. The fracture aperture at the injection well is plotted in Figure 8b for spacing of 50m, 150m, 300m and 1000m. Lower 509 spacing shows higher aperture due to the mechanical contraction of the neighbour fracture. 510 Due to the initial temperature gradient, the top fracture undergoes lower temperature 511 drawdown and thus shows lower aperture. The difference between apertures in bottom and 512 top fractures increases with increasing spacing. 513

Another case with lower initial temperature gradient of 30 °C/km (e.g West Netherlands 514 Basin, Bonté et al., 2012; Willems et al. 2017) is simulated where all other parameters are 515 kept the same. The results for production temperature for different spacing are shown in 516 Figure 9 for both temperature gradients. The initial temperature at the bottom fracture for 517 both cases is set at 200 °C. The effect of the change in temperature gradient increases as the 518 fracture spacing increases. A big difference is seen for the spacing of 1000m, while the effect 519 is negligible for the spacing of 50m. The difference in initial production temperature between 520 two temperature gradients for the spacing of 50m is only 0.4 °C, while a spacing of 1000m 521 will experience a temperature difference of 8.5 °C. Lower temperature gradient increases the 522 energy extraction from the system for higher spacing as the top fracture would have higher 523 initial temperature compared to the higher temperature gradient case. 524

525 The effect of matrix deformability

526 The matrix deformability affects the mechanical interactions between the two fractures as 527 shown for the uniform temperature case in Figure 6. Softer rock shows lower mechanical

interactions and therefore, produces hotter fluid for an extended period. When the initial 528 temperature gradient is considered, it is shown that for lower spacing cases there is a 529 competition between high mechanical interactions with higher initial temperature. So, the 530 system with lower spacing starts producing water at a higher temperature, but due to the 531 higher mechanical interactions the temperature at the production decreases faster. In this 532 section, the case with lower Young's modulus of E = 20 GPa is simulated with initial 533 temperature gradient of 47 °C/km. The plume of the stresses around the fractures for both 534 Young's moduli of 20 GPa and 50 GPa, and spacing of 300m and 500m are shown in Figure 535 10. Interactions between two fractures can be seen by the interference of the stress plume. For 536 the stiffer fracture, the two fractures are interacting when the spacing is 500m while for the 537 softer rock that spacing is large enough to neglect the interactions. When the spacing is 538 reduced to 300m, the stress interactions are considerable even for the softer rock. The bottom 539 540 fracture also shows higher stress reduction due to higher temperature variation. The production temperatures for different spacing are shown in Figure 11a. As the mechanical 541 interactions are lower for the E = 20 GPa, the simulations for spacing of 40m and 35m are 542 added. For the softer rock, the mechanical interaction between two fractures reduces 543 544 therefore, this system produces hotter fluid for longer time. However, as shown in Figure 11a, the lower spacing induces higher mechanical interactions and therefore higher aperture in the 545 fracture and faster reduction of the production temperature, while higher spacing shows lower 546 547 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 548 temperature for two cases of Young's moduli with spacing of 50m and 1000m are compared 549 in Figure 11b. Lower Young's modulus reduces the mechanical interactions so the case with 550 50m spacing crosses the curve with 1000m spacing after 15 years of production, while for the 551 stiffer rock, the crossing occurs much earlier (around 6 years). The slope of the production 552 temperature for the case of stiffer rock is also higher than the softer rock for the 1000m 553 spacing. Although, for spacing of 1000m, it is shown earlier that the mechanical interactions 554 between two fractures are negligible for both Young's moduli, so the higher temperature drop 555 is the result of the ability of the stiff matrix in sustaining higher aperture as shown in Figures 556 11c and 11d. The aperture in the softer rock is much less than the stiff rock for all spacing. 557 When the spacing is reduced in softer rock, the aperture initially increases, however, due to 558 the redistribution of stresses, the soft rock is not able to sustain high apertures and therefore 559 the aperture approaches to a maximum value. Due to lower fracture aperture in the softer 560 rock, the cold fluid can access to higher area of the fracture as shown before in Figure 4a for 561 single fracture case. The vertical stress reduces over a larger area of the fracture in softer rock 562 563 compared with stiffer rock as shown in Figure 12. The stiffer rock sustains higher reduction in the vertical stress (and higher aperture) and the additional load is carried by the area 564 around the cooled area in the fracture shown in darker colour in Figure 12. 565

The results from the simulator highlights the importance of the thermoelastic interaction 566 between two fractures and neglecting such interactions results in much lower optimum 567 spacing as reported by Wu et al. (2016). The present observations conclude that the aperture 568 variation highly affects the output temperature in the fracture, and the variation in the fracture 569 570 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 571 interaction is neglected. Since the effects of mechanical interaction have been observed in a 572 much greater spacing than the thermal interaction, the mechanical affects seems to be the 573 most critical and the optimum spacing is rather dictated by the thermoelastic deformations. 574

575 *The effect of fracture size*

In this section, the radius of the fracture is reduced to R = 250 m, to investigate how the size 576 of the fracture affects the mechanical interactions between the two parallel fractures. The 577 flow rate is also proportionally reduced to $Q = 0.00625 \text{ m}^3/\text{s}$ to avoid early breakthrough of 578 the cold fluid at production. A uniform temperature of 200 °C is assumed throughout the 579 model. A set of simulations with different spacings: D = 25 m, 50 m, 75 m, 150 m, and 250 m 580 are performed with and without the mechanical interactions (using TH and THM models). 581 The results for the temperature breakthrough at the production are shown in Figure 13 for 582 different cases. Again, in the absence of the mechanical interactions (TH model), the two 583 fractures are thermally interacting when the spacing decreases to less than 100 m, while in the 584 585 presence of the mechanical interactions (THM model) the thermal interactions between the two fractures affect the produced temperature from a spacing of D = 250 m. In the TH model, 586 a spacing of D = 150 m returns the temperature same as the single fracture case, indicating no 587 thermal interactions between the two fractures. In the THM model, from a spacing of 250 m, 588 the two fractures are mechanically interacting, resulting in higher aperture in each fracture 589 and thus, faster drawdown in the temperature of the produced water. Comparing with the case 590 with bigger fracture (R = 500 m) it can be seen that the mechanical interactions between the 591 two fractures are dependent on the size of the fractures, as larger fracture creates larger 592 disturbance area around it. However, as the spacing decreases to the fracture radius $(D \leq R)$, 593 the mechanical interactions start to affect the temperature drawdown. 594

595 5.2. Three-Fracture EGS

In this section, a third fracture is added to the model shown in Figure 5a. This is just to show 596 how the mechanical interactions increase as the number of fractures increases. Two cases are 597 simulated where the uniform spacing between the three fractures are set to 500m and 300m, 598 and the temperature at the bottom fracture is again fixed at 200 °C. The initial temperature 599 gradient is set at 47 °C/km, and the flow rate is kept constant at 0.0125 m³/s for all fractures. 600 The aperture distribution on each fracture for both cases are shown in Figure 14a. For the 601 spacing of 150m, the middle fracture undergoes highest aperture increase due to the matrix 602 contraction it receives from both sides, while the top fracture has the lowest aperture increase 603 due to the lower initial temperature. However, for the spacing of 300m, the bottom fracture 604 shows higher aperture due to higher temperature variation, and again the top fracture shows 605 the lowest aperture variation. So, for the spacing of 300m, the mechanical contractions 606 received by the middle fracture are lower to compensate for the lower initial temperature, 607 608 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-609 fracture system in Figure 14b. The three-fracture results show lower initial production 610 611 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 612 exerted on the middle fracture. Whereas for the spacing of 300m, the slope of the three-613 fracture case is slightly lower than that of two-fracture case, perhaps due to having access to 614 larger volume of the rock. The apertures along the horizontal line passing through the 615 injection and production points of each fracture are plotted in Figure 14c. Lower spacing 616 results in higher aperture around the injection point and towards the production point. For the 617 spacing of 150m, middle fracture shows the highest aperture developed due to the combined 618 thermal and mechanical contractions. For the spacing of 300m, the bottom fracture shows 619 620 highest aperture due to the highest thermal contractions.

621 6. Net Energy Production

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

$$E_{net} = E_a - E_n \tag{54}$$

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

627
$$E_{g} = \rho C_{f} Q_{t=0}^{LT} (T - T_{min}) dt$$
(55)

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} . So, the production energy is basically the area between the production temperature and the minimum temperature. The minimum temperature is set to 140 °C, indicating that the system allows a 30 % drop in temperature. Energy used to pump in the injection fluid may be written as

$$E_p = \int_{t=0}^{LT} \frac{Q\,\Delta P}{\dot{\epsilon}}\,dt \tag{56}$$

where ΔP is the pressure change between injector and producer, and $\dot{\epsilon}$ is the energy 635 conversion efficiency factor, that is assumed to be 0.7. The pumping energy is basically the 636 area between the injection pressure and the production pressure (34 MPa). The net energy 637 production for the two-fracture EGS is shown in Figure 15a for three cases: (i) E = 50 GPa 638 and thermal gradient of 47 °C/km, (ii) E = 50 GPa and thermal gradient of 30 °C/km, and (iii) 639 E = 20 GPa and thermal gradient of 47 °C/km. The lower Young's modulus results in higher 640 641 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 642 spacing increases. This is due to the higher initial temperature at the top fracture. However, a 643 local maximum in the net energy production exists for all cases. The optimum spacing for 644 case (i) is between 150m and 300m; for case (ii) is 300m; and for case (iii) is 150m. The 645 optimum increases with reducing initial thermal gradient, and reduces with reducing Young's 646 modulus. However, these values are much larger than the values reported by Wu et al. (2016) 647 for rigid matrix. 648

The coefficient of performance (COP) express the efficiency of the system by comparing the heat output with the power consumed as

651

$$COP = \frac{E_g}{E_p}$$
(57)

In Figure 15b the evolution of COP is plotted for spacing of 50, 150 and 300 m for case (i): E 53 = 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.

657 7. Conclusions

In this study, a coupled THM model is developed to investigate the effect of mechanical interactions between multiple parallel fractures on heat recovery from multiple-fracture EGS. 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 between fractures enhance the flow locally and reduces
 the efficiency of the system
- The mechanical interactions are affecting the outcome of the system as soon as the spacing between two fractures decreases to less than the fracture radius
- The fracture spacing calculated based on the assumption of rigid matrix, i.e. constant
 fracture aperture, is not realistic and those spacing should be increased to maximise
 the net energy recovery
- The optimum spacing for the two-fracture case with the geometry given in this study,
 varies between 150m to 300m which is much larger than the proposed values for rigid
 fractures.

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Figure 1. The geometry of the model used for the EGS simulations.



Figure 2. Validation of the present model against the analytical solutions: (a and b) A one-dimensional flow through a single fracture between injection and production wells proposed by Bodvarsson (1969). (c and d) Radial flow through an infinite fracture proposed by Ghassemi *et al.* (2003). Normalised temperature is defined as $T_D = \frac{(T_0 - T)}{(T_0 - T_{inj})}$



Figure 3. a) The mesh used for the fracture. b) Vertical cross section showing fracture with its dimensions and connected wells. Temperature field is shown at 30 years. c) Comparison between the results of the studied model and results from Guo et al. (2016).



Figure 4. The effect of varying Young's modulus and the matrix porosity on the fracture responses: (a) The aperture and temperature distributions over the fracture for the three cases.(b) Aperture profile along the line passing through the injection and production points after 30 years. (c) The temperature breakthrough curves for the three cases.



Figure 5. (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, on a vertical plane passing through the injection and production points, for fracture spacing of 1000, 750 and 500m.



Figure 6. The temperature breakthrough curves for various spacing (D) within an initial uniform temperature of 200°C for (a) E = 50 GPa and (b) E = 20 GPa. The case without mechanical interaction (TH model) is shown in (a)

50 m	
300 m	
_	Q-
	S
1000 m	Temperature 260.
	- 165. 103.
	50.0

Figure 7. 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 8. (a) The temperature breakthrough curve where a temperature gradient of 47°C/km is introduced. (b) Aperture evolution for bottom (solid lines) and top (dashed lines) fracture for different fracture spacing. As the bottom fracture experience a higher temperature variation, the aperture tends to increase more



Figure 9. The temperature breakthrough curves for two temperature gradients: 47°C/km (dashed lines) and 30°C/km (solid lines), in the two-fracture EGS with different spacing.



Figure 10. 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





= 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

GPa



Figure 12. 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 13. The temperature breakthrough curves for the case with two small fractures (R = 250m) with different spacings (D = 25m to 250m)



Figure 14. (a) Aperture distribution at 10 years for the bottom, middle and top fractures. (b) Production temperature versus time for two- and three-fracture cases. (c) Aperture profile along the line passing through the injection and production wells at 10 years.



Figure 15. (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 0.047° C/m

Highlights

- Thermoelastic interactions between multiple fractures are modelled
- Fractures are modelled as discontinuous surfaces within 3D matrix
- Thermoelastic interactions improves the conductivity of the fracture
- The optimum spacing is rather dictated by the thermoelastic deformations
- The optimum fracture spacing are higher for deformable matrix

Parameter Matrix porosity (ϕ) Matrix permeability (k_m) Solid density (ρ_s) Young's modulus (E)	Value 0.01 1×10 ⁻²⁰ 2500	- m ²
Matrix porosity (ϕ) Matrix permeability (k_m) Solid density (ρ_s) Young's modulus (E)	0.01 1×10 ⁻²⁰ 2500	- m ²
Matrix permeability (k_m) Solid density (ρ_s) Young's modulus (E)	1×10 ⁻²⁰ 2500	m ²
Solid density (ρ_s) Young's modulus (<i>E</i>)	2500	
Young's modulus (<i>E</i>)		kg/m ³
	50	GPa
Poisson's ratio (ν)	0.25	-
Specific heat capacity of the solid (C_s)	790	J/kg°C
Specific heat capacity of the fluid (C_f)	4460	J/kg°C
Volumetric thermal expansion coefficient of the solid (β_s)	3.03×10 ⁻⁵	/°C
Volumetric thermal expansion coefficient of the fluid (β_f)	7.66×10-4	/°C
Fluid dynamic viscosity (μ_f)	1.42×10 ⁻⁴	Pa s
Fluid compressibility (c_f)	5.11×10 ⁻¹⁰	Pa ⁻¹
Thermal conductivity of the solid (λ_s)	3.5	$W/m^{\circ}C$
Thermal conductivity of the fluid (λ_f)	0.6	$W/m^{\circ}C$

Table 1-	The rock and	l fluid m	ronerties	used in	the simula	tions
	The rook and	i nunu pi	opernes	useu m	the sinnula	uons