DYNAMIC MODEL OF DISCRETE FRACTURE OPENING UNDER FLUID INJECTION

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ABSTRACT
A new, dynamic, fully-coupled, Thermal-Hydraulic-Mechanical-Chemical (T-H-M-C) numerical model is developed for simulating flows and transport in Enhanced Geothermal System (EGS) reservoirs. The model assumes the presence of a single, pressure-conducting planar fracture of unknown aperture and size or a system of such fractures in a geologic medium before the onset of fluid injection. The shape of each planar fracture both in aperture and lateral extension is determined by the dynamic balance of the hydrodynamic fluid pressure distribution over the fracture plane and the elastic compression resistance of the geologic rockmass surrounding the fracture. The non-isothermal, and time-dependent, planar, flow, pressure, temperature, and chemical species concentration distribution in the fracture is simulated with a Computational Fluid Dynamics (CFD) element in MULTIFLUX. The fracture aperture at each surface grid is adjusted iteratively, allowing for: (a) elastic deformation in the fracture system by hydrodynamic pressure; (b) thermal dilatation of the rock; and (c) geochemical precipitation and/or dissolution. The CFD model element in MULTIFLUX is coupled to the model of the host geothermal formation by importing the numerical, non-isothermal, time-dependent results from TOUGH2 and/or TOUGHREACT. Coupling of the T-H-M-C model of the fracture flow to the model of host rockmass applies the NTCF (Numerical Transport Code Functionalization) technique, a modeling accelerator of the iterations in MULTIFLUX. A model validation example is given comparing simulation results with published data for the Fenton Hill EGS experiments. The results prove the capabilities of the new model in dynamically controlling fracture shape including the development of fracture opening as well as lateral-transversal size evolution.

INTRODUCTION
A T-H-M-C model is described for “solid” EGS reservoirs with discrete flow and transport fracture(s) created in very low permeability rockmass. The best case for this type of EGS would be in a dry, hot rockmass with zero permeability. Examples of such reservoirs include the Fenton Hill Phase I arrangement with one flow and transport fracture, and the Phase II case with multiple fractures [Murphy et al, 1981]. These EGS systems are considered for low-permeability, dry hot rock reservoirs in which fluid loss to the rockmass is a nuisance and not the benefit. Other, “porous” EGS systems involve enhanced natural systems with a permeable rockmass in which there is cross-flow of coolant fluid in the natural system. The EGS component in such a system serves as a fluid distribution manifold to the rockmass to inject or collect fluid to and from a large volume of rockmass. The best case for this EGS manifold type would be a hot, fluid-saturated rockmass with high permeability. Example of such EGS reservoir would be an enhanced sedimentary system.

The heat exchanger EGS systems even with “leaky,” porous and fractured rockmass are different in working principle from the manifold EGS systems. The T-H-M-C models are also different. The shear flow and transport in the planar-type fractures are unlike the flow in a porous media. The geometry and the mechanical model for a planar-type fracture is also different from a cubic-type, permeable rock body. The same is true for the T-H-M-C models for the two different EGS systems.

Planar fracture flow and transport models have been published for the true EGS systems (Murphy et al, 1981, Danko, 2011, 2012). Murphy et al. successfully used analytical solution elements, combined with a numerical framework. Our new model is their continuation with commercially-tested numerical elements, such as TOUGH2 for flow and
heat, TOUGHREACT for chemical reaction, dissolution or deposition, 3DEC for mechanical response, and MULTIFLUX to couple all elements in one conjugate model solution (Danko and Bahrami, 2012). A brief review is in order to see the formation similarities as well as differences as compared to other EGS models.

Taron et al. (Taron, et. Al, 2009) describes a coupled T-H-M-C model for porous and fractured rockmass, assigning equivalent porosity and elasticity to the fractures, and simplifying the media to be of a dual-porosity, and equivalent elasticity. While this model applies general-purpose elements, i.e., TOUGHREACT for the solution of flow, heat, and chemical processes in the porous and fractured rockmass; and FLAC3D for the mechanical stress-induced deformations and porosity changes, it is not applicable to flows and transport in a planar EGS fracture. Such an EGS fracture does not follow a dual-porosity model with cubic geometry-elements. Similar poro-elastic rockmass concept is applied by Duang et al. (Deng et. al, 2011) in their new model for fracture development and permeability changes under hydraulic stimulation. For fracture propagation even along a plane, the assumptions of finite rock cells are the best to make, especially if the stochastic nature of the problem is recognized, such as by Wang and Gasshemi (Safari and Ghassemi, 2011). However, once the fracture plane with joints, bumps and islands is complete and a shear displacement is complete due to local stress relief and/or thermal strain, the planar fracture forms a layer of self-propped zone, representing a macro-mechanical system different from the rockmass before fracturing.

An EGS fracture is basically planar, the geometry of the flow system is two-dimensional (2D), and the aperture changes as a distance in normal direction to the fracture plane in its T-H-M-C interactions with the surrounding rockmass. Even if the rockmass is considered dual-porosity with poro-elasticity in an EGS site, the fluid dominantly flows in the discrete EGS fracture(s) and not in the surrounding rockmass. An application to EGS is promised by Taron and Elsworth (Taron and Elsworth, 2009) with a poro-elastic model previously published (Taron, et. al, 2009). The model is applied to an injection and extraction doublet, with two wells and two planar fractures, each extending separately from either well. The planar fractures are parallel, separated by 670 m of dual-porosity, poro-elastic rockmass. The dominant heat exchange, therefore, is in the porous and equivalent-fractured rockmass, and not between the injection fluid and the EGS fracture. The connection between the wells is representative of a natural system, or an enhanced natural geothermal reservoir but not an EGS reservoir with discrete flow and transport fracture(s).

Safari and Gasshemi (Safari and Gasshemi, 2011) presents a model application of a poro-elastic formulation to a planar EGS fracture with a pre-determined penny shape. The model prediction against injection pressure measurements in a huff-puff EGS test is found acceptable with the non-linear Goodman joint model instead of using linear stiffness. It is not clear, however, if the difference between measurements and simulation were rather due to thermal effects which were not modeled.

We pursue a new and improved T-H-M-C model for “solid” EGS systems with a conceptual, self-propped fracture and rock mechanics system. The model is developed to follow the evolution of a planar fracture aperture and lateral extension variation as a function of injection pressure, fluid and rock temperature, as well as time. The self-adjusting fracture size (both aperture and extension) can start from near-zero initial values at zero injection flow rate and follow the process of fracture development with time during either short-time or long-time pumping tests. The T-H-M-C model uses modular components (e.g., TOUGH2, 3DEC, TOUGHREACT) which can be individually adjusted and fine-tuned to match results from field measurements. The coupled model is iteratively solved in MULTIFLUX. A numerical accelerator called Numerical Transport Code Functionalization (NTCF) (Danko, 2006) is used in MULTIFLUX, allowing for minimizing the individual numerical runs on the individual model components.

THE COUPLED T-H-M-C MODEL

We described the coupled T-H-M-C model previously (Danko and Bahrami, 2012) with three sub-models, namely for (1) the T-H-M-C flow and transport in the discrete, planar fracture; (2) the T-H-M-C flow and transport in the surrounding rockmass; and (3) the mechanical system model for the self-propped fracture zone in the rockmass. Figure 1 shows the logic flow chart of the integrated T-H-M-C model. The new element in the paper is an expanded 3-D thermo-mechanical fracture aperture model.
MECHANICAL SYSTEM MODEL FOR THE SELF-PROPPED FRACTURE ZONE

We start with the review of the concept of a self-propped fracture zone, based on a previous publication (Danko and Bahrami, 2012). As explained in the foregoing, the creation of a fracture will likely separate the rockmass along a jointed plane with intact rock islands and flow channels between them, shown in Figure 2. These flow channels will form the conceptual, planar fracture for basically planar flow field for coolant transportation. Shear movement due to stress relief and/or thermal strain will shift the opposing surfaces from perfect match, therefore, the fracture will be pressed closed only imperfectly after the release of the injection pressure. The islands will help opening the fracture at the arrival of the fluid flow and pressure. The in situ stress normal to the fracture plane will oppose the opening and must be overcome by the hydrodynamic pressure and the opening forces on the islands.

It must be recognized that the mechanical system response from such a strained rock layer depends on the 3-D geometry of the fracture plane, the stiffness of the islands, and the shear slip of the fracture walls. It would be naïve to assume that this system may act as the rockmass with its equivalent fracture and pore elastic properties. To wit, the macro-islands should have no bearings and/or similarities of any discretization grids or shapes used in the numerical models such as in 3DEC or FLAC3D. In addition, there will be free-hanging wall stretches of void spaces of at least a few microns or even millimeters or more in fracture aperture at some patches and zero apertures along the close-pressed islands.

The compression-only mode-element

We model this self-propped zone with a self-similarity compression-only model first according to the arrangement depicted in Figure 3.
Figure 2. Self-propped fracture with flow channels and support islands.

Figure 3. Thermal-hydraulic conceptualization of the fracture aperture change

Notations:
δ: Hydrodynamic fracture aperture under load, pressure, flow, and thermal effects
δ_p: Fracture aperture under hydrostatic (no-flow) pressure
S: Static deformation of L due to in situ stress
ΔL(T): Total, integrated thermal contraction of the rock strata of thickness L, function of temperature, T
σ: In situ stress normal to the fracture plane
p: Hydrodynamic pressure in the fracture
E_f: Self-propped fracture layer elastic modulus
E_R: Rockmass elastic modulus
L: Affected distance into the strata
k_R: Spring constant for the rockmass
k_s: Spring constant for the self-propped layer

The self-propping islands, when compressed together by the in situ stress, increase the resultant stiffness of the system and reduce the deformation caused by both the hydrodynamic pressure in the fracture as well as the thermal contraction in the rockmass. This effect is conceptualized for a dx by dy surface element by a model of springs and a changing dimension due to thermal dilatation in the z direction. Figure 3 shows half of the model, assuming symmetry around the center plane of the fracture, under in situ load as well as in an unloaded, assumed state. The loaded and unloaded states of the spring and thermal dilatation model are also shown in Fig. 3. The unloaded aperture, δ/2, is compressed by the in situ stress, σ, to δ_p/2, which is opened by the hydrodynamic injection pressure, p, as well as the 1D thermal contraction of the rockmass, ΔL.

The force of the rock layer over a unit area, σ, equals the sum of the compression stress of the fractured, self-propped rock layer and the hydrodynamic
pressure in the fracture applied in between the self-propped islands:

\[ \sigma = p + \left( \frac{\delta p}{2} - \frac{\delta}{2} \right) \frac{E_F}{\delta_p} \]  

(1)

The in situ stress may be accounted for by the deformation of the rock strata, where \( E_F \) is the bulk modulus of the fractured zone and \( E_R \) is the one of the rockmass:

\[ \sigma = \left( L - \left( S + \frac{\delta p}{2} - \frac{\delta}{2} + \Delta L(T) \right) \right) \frac{E_R}{L} \]  

(2)

The self-propped fracture aperture can be expressed from Eqs. (1) and (2). After some simplifications by eliminating small terms involving \( \delta/L \sim 0 \) and \( \delta_p/L \sim 0 \), it reads:

\[ \delta = \delta_0 \left( 1 - \frac{E_R}{E_F} + \frac{E_R S}{E_F L} + \frac{p}{E_F} + \frac{E_R \Delta L(T)}{E_F L} \right) \]  

(3)

Equation (3) may be used in a differential form relating the change in \( \delta \) to the changes in the hydrodynamic pressure, \( p \), and the free thermal dilatation, \( \Delta L(T) \):

\[ d\delta = \frac{\delta_p E_F}{E_F} dp + \frac{\delta_p E_F}{E_F L} d\Delta L(T) \]  

(4)

The advantage of Eq. (4) is its independence from \( S \), the unknown in situ compression strain of the strata, as well as other unknown constants in Eq. (3). Integration of Eq. (4) gives back the finite fracture aperture, conglomerating all unknown constants into one value which can be expressed from the initial condition for the fracture aperture. It is advantageous to include in this initial condition an initial fracture aperture, \( \delta_0 \), which may represent an open conduit in the fracture at the hydrostatic pressure at zero injection flow rate. With these in mind, as well as with the assumption of linearity of the elastic deformation system, the integration of Eq. (4) gives:

\[ \delta = \delta_0 + \frac{\delta_p E_F}{E_F} (p - p_0) + \frac{\delta_p E_F}{E_F L} \Delta L(T - T_0), \]  

(5)

where \( p_0 \) and \( T_0 \) are pressure and temperature at in situ condition.

Change of aperture due to reservoir fluid pressure behave as if it were from a thin layer of rock only with a layer thickness of the self-propped fracture area, \( \delta_0 \), with a presumably softened modulus of elasticity, \( E_F < E_R \). Change of aperture due to thermal dilatation is scaled by a small fraction of \( \frac{\delta_p E_F}{E_F L} \ll 1 \) relative to the change for a free-hanging rock layer, which were \( \Delta L(T - T_0) \). Therefore, Eq. (5) is essentially and significantly different from other, similar-looking models in the literature but lacking the self-propped scale factors for pressure and temperature effects. These scale factors may be called pressure and thermal aperture coefficients, \( C_p \), and \( C_T \), respectively:

\[ C_p = \frac{\delta_p E_F}{E_F} \text{ and } C_T = \frac{C_p E_F}{L} \]  

(6)

Equation (5) is used assuming self-similarity within one planar EGS fracture, i.e., for each pixel of the planar fracture in 3-D with the same, constant \( C_p \), and \( C_T \) coefficients as well as initial aperture:

\[ \delta(X) = \delta_0 + C_p [p(X) - \bar{p}_0(X)] + C_T \Delta L(T(X) - T_0(X)) \]  

(7)

In Eq. (7), \( X = (x,y,z,t) \) denotes any point over the planar fracture at a grid of \( \Delta A \) and at any instant in the simulation time interval. The bars in Eq. (7) indicate grid averaged values in the \( (x,y,z) \) plane at any point over a \( \Delta A \) surface. Term \( \delta_0 \) is a small initial aperture which remains open under hydrostatic pressure when \( \bar{p}(X) = \bar{p}_0(X) \).

The thermal dilatation/contraction is modeled with a temperature-dependent displacement generator, TDL, in the spring-load model shown in Fig. 3. The free \( \Delta L(T) \) thermal contraction may be expressed by the integral of the changes over the depth of the rockmass affected by the temperature change due to thermal drawdown. The temperature change in the affected rockmass is calculated from the T-H-C model of the rockmass. For practical implementation, the NTCF technique is used for mapping the time-dependent temperature field \( T(x,y,z,t) \) over the planar fracture at any \( (x,y,z) \) point and over the \( z \) direction normal to the fracture surface. Only a few TOUGH2 runs are needed to establish the NTCF temperature mapping model for this task (Danko, 2011). With \( T(x,y,z,t) \), the \( \Delta L(T) \) distance is calculated by the following integral:

\[ \Delta L(T) = \Delta L(x,y,t) = \beta L_0 \int_0^T [(T(x,y,z,t) - T_0(x,y,z))] dz \]  

(8)

In Eq. (8), \( x, y, z \) are distances in 3D; \( \beta \) is thermal expansion; \( L \) is model length; and \( T \) is temperature.

**The combined shear-stress and compression model-elements**

The second step is to add the neighbor effects with shear-stress components to the normal stress model in the self-propped mechanical system model. Figure 4 shows the conceptualization of fracture opening at node \( i \) due to fluid pressure and the effect of the neighboring elements due to shear resistance perpendicular to the fracture plane. Node \( j, k, l \) and \( m \) are neighboring nodes of node \( i \).
Figure 4. The conceptualization of fracture opening due to fluid pressure at node $i$ (a) and the effect of neighboring elements (b); and the pressure-shear resistance model perpendicular to the fracture plane (c).

**Notations:**
- $\delta_i$: $i$th node aperture
- $\delta_{j,k,l,m}$: $i$th neighbor’s aperture
- $L$: rock influence zone due to pressure
- $\Delta x, \Delta y$: fracture discretization length
- $G$: rock shear modules
- $C^P$: Self-propped pressure coefficient
- $C^T$: Self-propped thermal coefficient
- $P_i$: Fluid pressure
- $P_0$: Ambient fluid pressure
- $T$: Fluid temperature
- $T_0$: Virgin rock temperature
- $R_s$: shear resistance
- $R$: Pressure resistance

The shear stress is explained by Hooke’s Law as follows:
$$ \tau = G \gamma $$  \hspace{1cm} (9)

where:
- $G$ is the shear modulus and
- $\gamma$ is the shear strain defined as the ratio of shear displacement to fracture length as follows:
$$ \gamma = \frac{\Delta \delta}{\Delta x} $$  \hspace{1cm} (10)

where:
- $\Delta \delta$ is the shear displacement and
- $\Delta x$ is the grid width in the fracture plane.

The shear force, $F$, is calculated as follows:
$$ F = \Delta y L \tau $$  \hspace{1cm} (11)

where:
- $L$ is the distance into the rockmass and
- $\Delta y$ is the grid width in the fracture plane.

The effective shear pressure is defined as the shear force from Eq. (11) applied on the fracture surface, ($\Delta x \Delta y$), as follows:
$$ P_{\tau} = \frac{F}{\Delta A} = \frac{\Delta L G \Delta \delta /2}{\Delta x \Delta y} = \frac{L G \delta /2}{\Delta x^2} = \frac{L G}{2 \Delta x^2} \Delta \delta $$  \hspace{1cm} (12)

The effective shear pressure is also defined as the product of shear resistance, $R_s$, and shear displacement, $\Delta \delta$, as follows:
$$ P_{\tau} = R_s \Delta \delta $$  \hspace{1cm} (13)
Equating Eqs. (12) and (13) yields the definition of shear resistance as follows:

$$R_s = \frac{\alpha G}{2\Delta x^2} \quad (14)$$

The total aperture at node \( i \) due to pressure, temperature, and neighboring nodes shear resistances is determined as follows:

$$\delta_i = \frac{P_i - P_0}{R} - (\delta_i - \delta_j) \frac{R_{ij}}{R} - (\delta_i - \delta_k) \frac{R_{ik}}{R} - (\delta_i - \delta_l) \frac{R_{il}}{R} - (\delta_i - \delta_m) \frac{R_{im}}{R} + C^T[[\Delta L]](T_i - T_0) \quad (15)$$

For all nodes in the planar fracture, a set of equations must be used. In matrix-vector notation, the set of equations for all fracture nodes is as follows:

$$[R_c P] \cdot \delta = \left( [P_i - P_0] + C_T[[\Delta L]](T_i - T_0) \right) \quad (16)$$

where the \([R_c P]\) matrix is composed from the shear and compression resistances as an \( n \times n \) array, according to a structure as follows:

$$R_c P = \begin{bmatrix}
1 & \cdots & j & \cdots & k & \cdots & i & \cdots & l & \cdots & m & \cdots & n \\
1 + \frac{\sum R_{ij}}{R} & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
\cdots & \frac{R_{ij}}{R} & \cdots & \frac{R_{ik}}{R} & \cdots & 1 + \frac{\sum R_{il}}{R} & \cdots & \frac{R_{ij}}{R} & \cdots & \frac{R_{im}}{R} & \cdots & \cdots & \cdots \\
\cdots & \cdots & 1 + \frac{\sum R_{mn}}{R} & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
\end{bmatrix} \quad (17)$$

The other variables in Eq. (16) are as follows:

- \([\delta]\) is an \( n \)-vector of the fracture apertures at \( n \) nodes over the planar fracture surface at any time instant.
- \([P_i - P_0]\) is an \( n \)-vector of time-variable fluid pressure, and
- \([T_i - T_0]\) is an \( n \)-vector of time-variable fluid temperature.

The inverse of Eq. (16) must be solved for all \( \delta_i \) (\( i = 1 \ldots n \)) apertures along the fracture plane simultaneously for the inclusion of all shear and compression stress connections:

$$[\delta] = \left( [R_c P] \right)^{-1} \cdot \left( [P_i - P_0] + C^T[[\Delta L]](T_i - T_0) \right) \quad (17)$$

The model in Eq. (17) is solved in MULTIFLUX together with the other coupled model-elements. The pressure over the outer edge of the fracture is compared against fracture propagation strength or fracture opening fluid pressure. If the peripheral pressure is greater than the fracture propagation strength, the lateral fracture size would increase to a new size by one discretization length until the fluid pressure at the fracture tip falls below the fracture opening pressure.

**APPLICATION OF THE T-H-M MODEL TO INTERPRET INJECTION TEST RESULTS**

Fracture aperture variation according to Eq. (17) is tested using the coupled T-H-M model in MULTIFLUX against injection pressure, flow and thermal drawdown measurement results for the Fenton Hill Phase I measurements.

The first step in the model application is the identification of FOUR model parameters: \( \delta_0, C^p, C^T, \) and \( D(t) \). These are the model parameters that affect the time-dependent functions of (1) pressure field along the planar fracture and (2) the temperature field and the exit production temperature (or thermal drawdown) for a given injection flow rate. Two of these parameters are scalar constants, \( C^p \) and \( C^T \), and one is a time dependent function, the lateral extent (diameter) of the planar fracture, \( D(t) \). The initial fracture aperture, \( \delta_0 \), may be near-zero, just enough for passing through the opening pressure to new fracture nodes. We have established a model which self-generates the \( D(t) \) parameter, leaving only two
unknowns. These two unknowns can be inverse-evaluated for a given EGS site from the time-dependent injection pressure curve for a given flow rate and the production thermal drawdown for the same time period. We are experimenting with this inverse evaluation against the Fenton Hill, Phase I measurement results.

Numerical results provide proof of the concept. The hydro mechanical parameters of the first measurement segment for an injection flow rate of 7.5 kg/s are first matched against the measured pressure which appears to be constant during the first 4 days of the testing measurement, shown in Figure 5. The value of $C^P$ was determined to be $2.55\times10^{-12}$ with no appreciable thermal drawdown and a minimum lateral fracture size of 108 m in diameter.

The initial value of $C^T$ was calculated to be 0.0156 according to Eq. (6) assuming $L=30$m of affected distance into the rockmass.

Three variations of model parameters are summarized in Table 1 as Cases 1 through 3 for the increased injection rate of 15 kg/s between days 24 and 75 for the measurement results published for Fenton Hill Phase I. Case 3 provides the best match with $\delta_0=0.108$ mm initial fracture aperture. These model parameters are subject to further refinement.

Table 1. Summary of three sets of model parameter trial values.

<table>
<thead>
<tr>
<th>Trials</th>
<th>$C^P$</th>
<th>$C^T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case1</td>
<td>6.50E-12</td>
<td>0.016</td>
</tr>
<tr>
<td>Case2</td>
<td>2.48E-12</td>
<td>0.024</td>
</tr>
<tr>
<td>Case3</td>
<td>4.48E-12</td>
<td>0.020</td>
</tr>
</tbody>
</table>

Figure 5 depicts the pressure matching at the injection point of the Fenton Hill Phase I single fracture model for Cases 1 through 3. Figure 6 shows the variations of the simulated and measured thermal drawdowns for the three cases. Figure 7 depicts the fracture diameter variable from an initial fracture size of 108 m to 150m. The results show that the fracture diameter varies modestly with time and more rapidly with an increased injection flow rate.

Figure 8 shows the fracture aperture distribution over the fracture plane at Day 23 before the end of the injection period of low flow rate of 7.5 kg/s. Figure 9 shows the results at Day 36 at the end of transition from the flow rate to double flow rate of 15 kg/s. The fracture aperture clearly shows an increase in the open surface as the result of the mechanical model response to the increased flow rate and pressure.
Numerical model matching calculations will continue. The identification of the $\delta_o$, $C^p$ and $C^T$ model parameters is a three-dimensional optimization task using the objective function of minimizing the difference between measured and simulated curves for injection pressure and thermal drawdown. These parameters should be constants forever for the Fenton Hill Phase I fracture as $T$-$H$-$M$ system parameters.

A previously study (Danko, 2011) reported the numerical results of model matching for the Fenton Hill Phase I measurements. Only the thermal contraction sub-model was active, assuming a fix fracture diameter of 120m, which was manually increased to a final size of 150m as a hypothesis test for matching thermal drawdown. The results are shown here for comparison. Figure 10 depicts two model cases. Case 1 is modeled with a monolithic TOUGH2 model using a penny-shaped fracture with a constant aperture. Case 2 uses MULTIFLUX for a penny-shaped, 120m diameter fracture.

Figure 11 depicts the results for Cases 3, 4 and 5 using MULTIFLUX with self-propelled fracture with and without water loss from production. Case 3 is however, with constant diameter size at 120m of a lense-shaped fracture. Fracture size in cases 4 and 5 was hypothesized to increase from 120m to 150m in diameter (Danko, 2011). This fracture size variation is verified with the self-adjusting, active fracture size in the new model.

Re-running the Fenton Hill Phase I test with the self-opening and self-adjusting fracture model regarding both $\delta_o$ and $D(t)$ is underway, together with the inverse-modeling task of evaluation the best parameters for $\delta_o$, $C^p$ and $C^T$. 
CONCLUSIONS

The following conclusions can be made based on the numerical results:

• A new T-H-M-C model is presented that provides converging results for a self-propped fracture with self-similarity over the entire fracture envelope. The model describes the fracture aperture and lateral size variations as they evolve under the injection pressure as well as thermal self-enhancement automatically.

• The fracture aperture model parameters, such as initial, open aperture, as well as pressure and thermal coefficients can be identified from the measurement data of a single injection test by finding matches with the numerical simulation results. A trial-and-error search is needed as an optimization task, minimizing the matching error.

• The lateral extent of the fracture diameter along its plane is numerically evaluated by the model, governed by the force and mass balance of the T-H-M system.

• The MULTIFLUX model with the new fracture aperture model-element can match excellently published results for Fenton Hill, Phase I.

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