Pressure and Rate Transient Analysis for Crossflow Test in Enhanced Geothermal Systems

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ABSTRACT

Using a semi-analytical solution for the pressure and rate transient response in multifractured enhanced geothermal systems, we developed a mathematical formulation to handle multiple wells with switching between flux control and pressure control for injector and producer. By decoupling well control, we could use a two-step approach to compute the solution effectively. We first solved the pressure and rate transient response with constant rate impulse in each well individually. Then, we combined them together to satisfy flux control and pressure control in each well. With this new semi-analytical solution, we estimated system parameters from inverse modeling for the crossflow tests in the Frisco pad of the Project Cape development, using both injection/production rate and wellhead/downhole pressure. The system parameters in consideration are fracture permeability, fracture area, rock matrix permeability, and initial reservoir pressure. Interestingly, one of the unique aspects of Frisco is that there are multiple injectors and multiple observers operating at the same time and their interactions are dependent on their connectivity through fractures – this is in distinction to the case of Utah FORGE which had only a single injector-producer pair.

INTRODUCTION

Hydraulic fracturing technology has been one of the key technologies in stimulation to increase well productivity or injectivity in unfavorable low permeability oil and gas formations (Clark 1949; Wilsey and Bearden 1954). By injecting fluid at high pressure into subsurface formation, we can create hydraulic fractures by overcoming minimum principal stress of the formation or induce shear stimulation to reactivate natural faults (McClure and Horne 2014). These newly created pathways may be held open with proppant, such as sand, to keep the fracture open upon releasing the pressure and act as a conduit for fluid flow from formation to well (Clark 1949). For very low permeability formations, a multifractured horizontal well, a horizontal well with multistaged fracturing, can be used to exploit the system. Their early applications were in unconventional oil and gas resources, to produce hydrocarbon trapped inside source rock with very low permeability compared to conventional resources in sandstone or carbonate formations (Jenkins and Boyer 2008).

This multifractured horizontal well technology also plays a crucial role in the recent resurgence of enhanced geothermal systems (EGS) due to the increase in production rates and reduction in drilling cost (Horne et al. 2025). Unlike unconventional hydrocarbon resources that are exploited by creating fluid pathways between formations and wells with hydraulic fractures, enhanced geothermal systems rather use hydraulic fracturing to create fluid pathways between wells in hot formations with very low permeability. The key idea in multifractured enhanced geothermal systems is to circulate water between injector and producer pairs to extract subsurface thermal energy through the engineered subsurface fracture network, which acts as a heat exchanger. Because the formation thermal conductivity is poor, the hydraulic fractures also provide a lot of surface area for efficient heat extraction in contrast to the very small wellbore surface area. With EGS, there is an opportunity for an additional 3,632 and 17,789 MWe of identified and undiscovered hydrothermal resources to become economically competitive with the industry baseline in the US (Aljubran and Horne 2025).

From a project viability perspective, the key challenges for multifracture enhanced geothermal systems are:

- Resources – uncertainty in heat initially in-place inside the targeted formation
- Investment cost – multifractured horizontal well costs and the effectiveness of their fracture network
- Safety – induced seismicity mitigation

Hence, system characterization and surveillance, both fracture-related and reservoir-related, play an important role in all project stages from exploration, development, and operation to understand subsurface system to design an efficient fracture network such as fracture conductivity, well connectivity, fracture surface area, and flow allocation. Well testing is one of the system characterization and surveillance techniques that infers system properties from system response (e.g., pressure, rate, temperature) using impulses (e.g., fluid injection and production) (Horne 1995). For testing in multifractured horizontal wells, our study focused on injection tests and crossflow tests after stimulation, corresponding to circulation tests as shown in Figure 1 and actual operations afterward for reservoir surveillance.
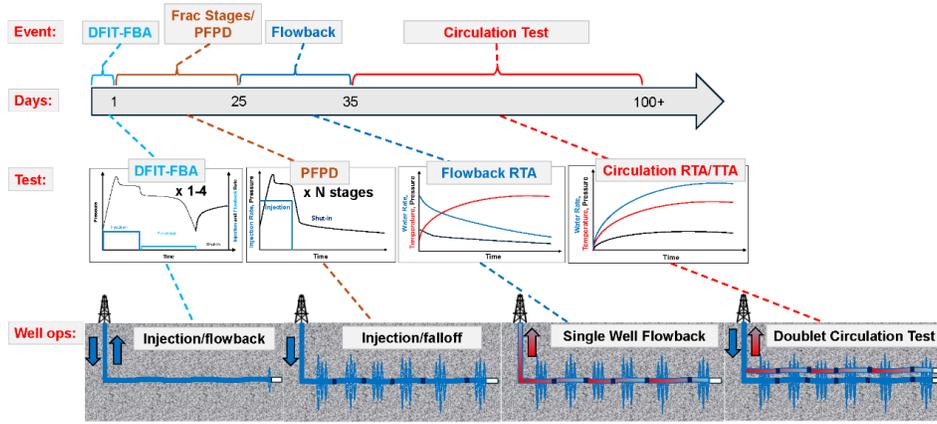
Figure 1: Testing performed on a multifractured horizontal well completed in an EGS at different periods (from Clarkson, Alkhayyali, and Zeinabady 2025)

METHODOLOGY

Based on the original works in both finite conductivity fracture (Cinco L., Samaniego V., and Dominguez A. 1978) and horizontal well with multiple fractures (Chen and Raghavan 1997; Horne and Temeng 1995), the governing equation for multistaged fracture horizontal well can be written as

$$\begin{cases} \phi_{f,i} c_{t,f,i} \dfrac{\partial p_{f,i}}{\partial t} = \dfrac{k_{f,i}}{\mu} \nabla^2 p_{f,i} + q_{f,i}(\vec{x},t) + q_{w,i}(\vec{x},t), & i = 1, \dots, n_f \\[3mm] \phi_m c_{t,m} \dfrac{\partial p_m}{\partial t} = \dfrac{k_m}{\mu} \nabla^2 p_m + \displaystyle\sum_{i=1}^{n_f} q_{m,i}(\vec{x},t) \end{cases} \tag{1}$$

where:

- $\phi_{f,i}$ and ϕ_m are porosity of fracture i and rock matrix
- $c_{t,f,i}$ and $c_{t,m}$ are total compressibility of fracture i and rock matrix
- $k_{f,i}$ and k_m are rock permeability of fracture i and rock matrix
- μ is fluid viscosity
- $p_{f,i}$ and p_m are pressure of fracture i and rock matrix
- $q_{w,i}(\vec{x},t)$, $q_{f,i}(\vec{x},t)$, and $q_{m,i}(\vec{x},t)$ are source term for well and fracture-rock matrix connection at location $\vec{x}$ and time t
- n_f is number of fractures

which are the pressure diffusion equations for fracture and rock matrix, respectively. Before we describe the solution of this problem, we need to understand that this formulation is based on isothermal reservoir assumption, which is perfectly reasonable in unconventional resources systems (shale oil/gas) and geothermal systems without reinjection. For enhanced geothermal systems, we must consider that we will have thermal front propagation through the fractures from injector to producer and changing fluid properties over time as a result. Nevertheless, well testing solutions based on constant fluid properties may still be applicable during a given limited testing period as both thermal/flood front velocities are orders of magnitude slower than the pressure front. To find a specific solution, we need to define the corresponding initial conditions, inner boundary conditions (at the wells), and outer boundary conditions for this problem. From an initially unperturbed reservoir with either Dirichlet or Neumann outer boundary conditions in rock matrix, we have

$$\begin{cases} p_{f,i}(\vec{x},0) = p_0, & \vec{x} \in \Omega_{f,i} \\ \vec{n} \cdot \nabla p_{f,i}(\vec{x},t) = 0, & \vec{x} \in \Gamma_{f,i}^N \end{cases} \tag{2}$$

$$\begin{cases} p_m(\vec{x},0) = p_0, & \vec{x} \in \Omega_m \\ p_m(\vec{x},t) = p_0, & \vec{x} \in \Gamma_m^D \\ \vec{n} \cdot \nabla p_m(\vec{x},t) = 0, & \vec{x} \in \Gamma_m^N \end{cases} \tag{3}$$

where:

- p_0 is initial unperturbed pressure of the system in both fracture and rock matrix
- $\vec{n}$ is a unit normal vector at the outer boundary
- $\Omega_{f,i}$ and Ω_m are set of spatial domains of fracture i and rock matrix

- $\Gamma_{f,i}^N$, Γ_m^D, and Γ_m^N are subsets of boundary point of fracture i and rock matrix for corresponding Dirichlet and Neumann outer boundary conditions

We assume no flow across the outer boundary of each fracture to ensure that fluid is either flowing between wells inside the fracture or transported through the fracture-matrix connection via the source term. For inner boundary conditions at wells, we have either pressure-controlled or rate-controlled injection/production as

$$p_{f,i}(\vec{x}_{w,i,j}, t) = p_{w,j}(t) \tag{4}$$

$$\begin{cases} \sum_{i=1}^{n_f} q_{w,i}(\vec{x}_{w,i,j}, t) = q_{w,j}(t) \\ p_{f,i}(\vec{x}_{w,i,j}, t) = p_{f,k}(\vec{x}_{w,i,j}, t) \end{cases} \tag{5}$$

where:

- $\vec{x}_{w,i,j}$ is location of well j in fracture i
- $p_{w,j}(t)$ and $q_{w,j}(t)$ are specified well pressure and well flow rate for multistaged fracture horizontal well

Note that we assume no pressure drop along the horizontal section of the well between each fracture, resulting in a constant pressure value at all well locations within each fracture. To find a solution for these coupled equations, we can discretize the fracture-matrix connection sources as a piecewise-constant function in both spatial and temporal domains and assemble a pressure solution from a superposition in space with an individual solution from one source based originally from the Green's function (Gringarten and Ramey 1973). The detail of implementation as well as a useful technique to deal with computational complexity (exponential time stepping) and ill-conditioned matrix for the steady-state solution are highlighted in our previous work (Wongpattananukul, Horne, and Tartakovsky 2025). Concisely, we have pressure solution equations, continuity constraint equations, and well control equations for a simple system as in Figure 2 with equations as shown in Figure 3.
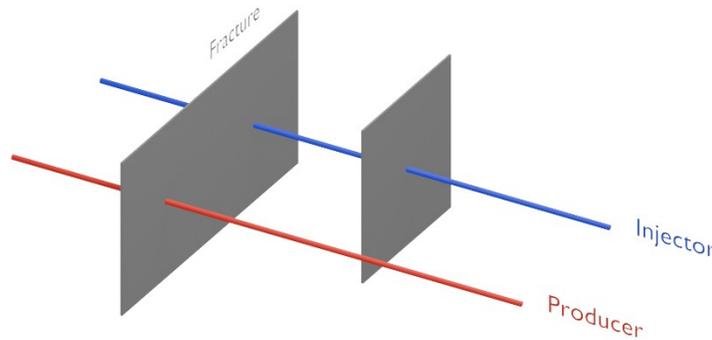

Figure 2: A schematic of a system with two multifractured horizontal wells (1 connected and 1 disconnected fracture network)

Figure 3: A linear system of equation for a coupled pressure diffusion equations for fractures and rock matrix

However, this formulation works efficiently only under unchanging well control, a constant pressure-controlled or rate-controlled injection/production, with exponential time stepping. Consequently, there are two main issues in modeling actual crossflow tests which are:

- Changing in well control value over time, e.g., adjusting injection/production pressure or rate

$$p_{w,j}(t) = \begin{cases} p_{w,j}^{(1)}, & 0 < t \le t_{b,1} \\ p_{w,j}^{(2)}, & t_{b,1} < t \le t_{b,2} \\ \quad \vdots \\ p_{w,j}^{(M)}, & t_{b,M} < t \end{cases} \tag{6}$$

$$q_{w,j}(t) = \begin{cases} q_{w,j}^{(1)}, & 0 < t \le t_{b,1} \\ q_{w,j}^{(2)}, & t_{b,1} < t \le t_{b,2} \\ \quad \vdots \\ q_{w,j}^{(M)}, & t_{b,M} < t \end{cases} \tag{7}$$

- Changing in well control type over time, e.g., switching between pressure-controlled and rate-controlled due to equipment limit or safety constraint

$$p_{w,j}(t) = \begin{cases} p_{w,j}^{(1)}, & 0 < t \le t_{b,1} \\ p_{w,j}^{(3)}, & t_{b,2} < t \le t_{b,3} \\ \quad \vdots \\ p_{w,j}^{(M-1)}, & t_{b,M-1} < t \le t_{b,M} \end{cases} , \qquad q_{w,j}(t) = \begin{cases} q_{w,j}^{(2)}, & t_{b,1} < t \le t_{b,2} \\ q_{w,j}^{(4)}, & t_{b,3} < t \le t_{b,4} \\ \quad \vdots \\ q_{w,j}^{(M)}, & t_{b,M} < t \end{cases} \tag{8}$$
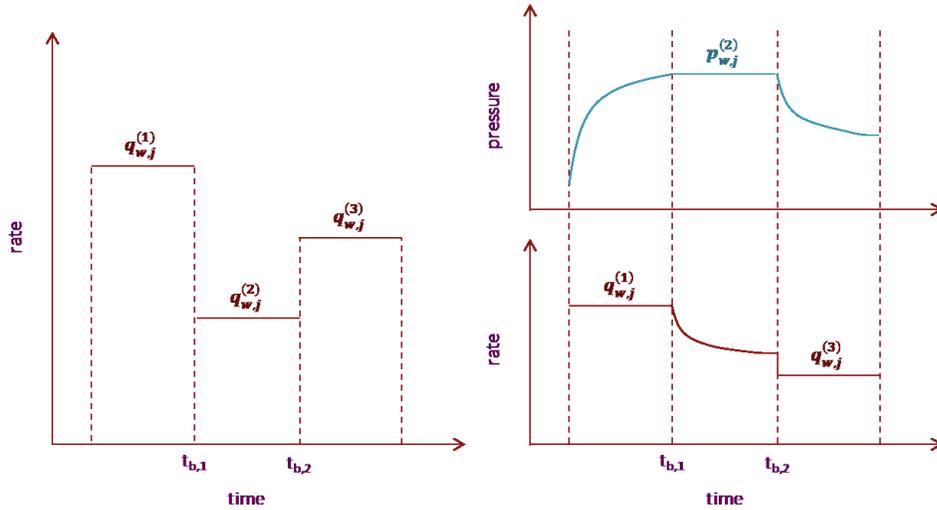

Figure 4: Examples of well control (a) changing in well control value over time; (b) changing in well control type over time

Figure 4 shows examples of changing in well control over time that can be purely rate-controlled but non-constant injection/production rate or mixing between rate-controlled and pressure-controlled injection/production due to maximum pressure limit. At any given point in time, we can only prescribe either pressure-controlled or rate-controlled for well control and the remaining value is solved from our system of equations. Given that we have breakpoints in time at $t_{b,1}, t_{b,2}, \dots, t_{b,M}$ for changing in well control over time, we need to restart the exponential time stepping at every breakpoint to represent the solution accurately. To illustrate, we use exponential time stepping with a power of 10 and our set of discrete time points for unchanging and changing well control are

$$A = \{0.0, 10^{-3}, 10^{-2}, 10^{-1}, \dots\} \tag{9}$$

$$A^* = \{0.0, 10^{-3}, 10^{-2}, 10^{-1}, \dots, t_{b,1}, t_{b,1} + 10^{-3}, t_{b,1} + 10^{-2}, t_{b,1} + 10^{-1}, \dots, t_{b,2}, t_{b,2} + 10^{-3}, t_{b,2} + 10^{-2}, t_{b,2} + 10^{-1}, \dots\} \tag{10}$$

respectively. By restarting exponential time stepping at every breakpoint, we can accommodate changes in well control over time with minimal modification to our formulation. However, the resultant linear system of equations is scaled with $O(N^2 K^2 M^2)$ where N is number of sources, K is number of exponential time stepping points per breakpoint, and M is number of breakpoints. This can be prohibitively expensive as both number of sources and number of breakpoints are large. One way to combat this issue is to split computation into two steps as:

1. Solve individual constant rate-controlled injection/production for each well

$$\begin{cases} \vec{q}_{w,1} = \vec{1}, \vec{q}_{w,2} = \vec{0}, \dots, \vec{q}_{w,L} = \vec{0} \Longrightarrow \Delta\vec{p}_{w,11}, \Delta\vec{p}_{w,21}, \dots, \Delta\vec{p}_{w,L1} \\ \vec{q}_{w,1} = \vec{0}, \vec{q}_{w,2} = \vec{1}, \dots, \vec{q}_{w,L} = \vec{0} \Longrightarrow \Delta\vec{p}_{w,12}, \Delta\vec{p}_{w,22}, \dots, \Delta\vec{p}_{w,L2} \\ \qquad\qquad\qquad\vdots \\ \vec{q}_{w,1} = \vec{0}, \vec{q}_{w,2} = \vec{0}, \dots, \vec{q}_{w,L} = \vec{1} \Longrightarrow \Delta\vec{p}_{w,1L}, \Delta\vec{p}_{w,2L}, \dots, \Delta\vec{p}_{w,LL} \end{cases} \tag{11}$$

where $\vec{q}_{w,j} = \left(q_{w,j}^{(1)}, q_{w,j}^{(2)}, \dots, q_{w,j}^{(K)} \right)$ is the vector of rate-controlled at all discrete time intervals for well j and $\Delta\vec{p}_{w,jj'}$ is the vector of pressure drop at all discrete time intervals for well j from well j'

2. Convolve the constant rate-controlled injection/production to account for changing in well control over time.

$$\begin{bmatrix} H_{w,11} & H_{w,12} & \cdots & H_{w,1L} & -I & 0 & \cdots & 0 \\ H_{w,21} & H_{w,22} & \cdots & H_{w,2L} & 0 & -I & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ H_{w,L1} & H_{w,L2} & \cdots & H_{w,LL} & 0 & 0 & \cdots & -I \\ P_{w,1} & 0 & \cdots & 0 & I-P_{w,1} & 0 & \cdots & 0 \\ 0 & P_{w,2} & \cdots & 0 & 0 & I-P_{w,2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & P_{w,L} & 0 & 0 & \cdots & I-P_{w,L} \end{bmatrix} \begin{bmatrix} \vec{q}_{w,1} \\ \vec{q}_{w,2} \\ \vdots \\ \vec{q}_{w,L} \\ \Delta\vec{p}_{w,1} \\ \Delta\vec{p}_{w,2} \\ \vdots \\ \Delta\vec{p}_{w,L} \end{bmatrix} = \begin{bmatrix} \vec{0} \\ \vec{0} \\ \vdots \\ \vec{0} \\ \vec{d}_1 \\ \vec{d}_2 \\ \vdots \\ \vec{d}_L \end{bmatrix} \tag{12}$$

where $H_{w,jj'}$ is a discrete convolution matrix for $\Delta\vec{p}_{w,jj'}$, $P_{w,j}$ is the well control indicator matrix with diagonal component equal to 1 when it is a rate-controlled injection/production in that discrete time interval for well j, and $\vec{d}_j$ is the well control value for appropriate well control type at all discrete time intervals for well j

Using this two-steps approach, we can reduce time complexity from $O(N^2K^2M^2)$ to $O(N^2K^2L + L^2K^2M^2)$ where L is number of wells. In general, multifractured horizontal wells have $L \ll N$ and this two-step approach is worthwhile for changing in well control over time. Now, we can use this procedure to predict pressure responses at any location inside fracture and rock matrix from given system parameters.

For parameter estimation from a given injection and/or crossflow test, we can define a nonlinear regression problem as:

$$\text{minimize} \quad \frac{1}{2}\sum_{j=1}^{L} \rho\left(\frac{\Delta\vec{p}_{w,j,\text{measurement}} - G_1\Delta\vec{p}_{w,j}}{\left\| \Delta\vec{p}_{w,j,\text{measurement}} \right\|} \right) + \rho\left(\frac{\vec{q}_{w,j,\text{measurement}} - G_2\vec{q}_{w,j}}{\left\| \vec{q}_{w,j,\text{measurement}} \right\|} \right)$$

$$\text{subject to} \quad \begin{bmatrix} H_{w,11} & H_{w,12} & \cdots & H_{w,1L} & -I & 0 & \cdots & 0 \\ H_{w,21} & H_{w,22} & \cdots & H_{w,2L} & 0 & -I & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ H_{w,L1} & H_{w,L2} & \cdots & H_{w,LL} & 0 & 0 & \cdots & -I \\ P_{w,1} & 0 & \cdots & 0 & I-P_{w,1} & 0 & \cdots & 0 \\ 0 & P_{w,2} & \cdots & 0 & 0 & I-P_{w,2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & P_{w,L} & 0 & 0 & \cdots & I-P_{w,L} \end{bmatrix} \begin{bmatrix} \vec{q}_{w,1} \\ \vec{q}_{w,2} \\ \vdots \\ \vec{q}_{w,L} \\ \Delta\vec{p}_{w,1} \\ \Delta\vec{p}_{w,2} \\ \vdots \\ \Delta\vec{p}_{w,L} \end{bmatrix} = \begin{bmatrix} \vec{0} \\ \vec{0} \\ \vdots \\ \vec{0} \\ \vec{d}_1 \\ \vec{d}_2 \\ \vdots \\ \vec{d}_L \end{bmatrix} \tag{13}$$

$$\theta_{i,\text{lb}} \le \theta_i \le \theta_{i,\text{ub}}, \qquad \forall i$$

where:

- $H_{w,jj'}$ is a discrete convolution matrix between wells that has a nonlinear relationship with system parameters
- $\rho(z) = \begin{cases} z^2, & z < 1 \\ 2|z| - 1, & z \ge 1 \end{cases}$ is a Huber penalty function
- G_1, G_2 are time-interpolation matrix to map value from exponential time stepping to measurement time
- θ_i, $\theta_{i,\text{lb}}$, and $\theta_{i,\text{ub}}$ are targeted system parameters and their lower/upper bound

Then, we utilize a nonlinear least square module in SciPy (Virtanen et al. 2020) to solve our parameter estimation problem iteratively from a given initial guess using appropriate well control scheme. Note that we utilize Huber penalty function for a robust least-squares that is tolerant to outliers in measurements (Boyd and Vandenberghe 2004).

FIELD EXAMPLES

Fervo Energy completed injection and crossflow tests for their Frisco pad in September 2024 at Project Cape. These tests were carried out in order to investigate the engineered fracture network in various aspects of mass and energy transport. Our interest in this study lay in pressure and flow rate measurement for mass transport using combined pressure and rate transient analysis. Figure 5 shows the well schematics for Frisco in contrast to Utah FORGE. In Frisco, we have multiple multifractured horizontal wells with multiple injectors, observers, and producer while Utah FORGE only has two deviated well with one producer and one injector. Additionally, Utah FORGE

is an experimental EGS project that was used to test different stimulation techniques across multiple stages which resulted in nonuniform flow across the different stages during production tests (McLennan et al. 2025).
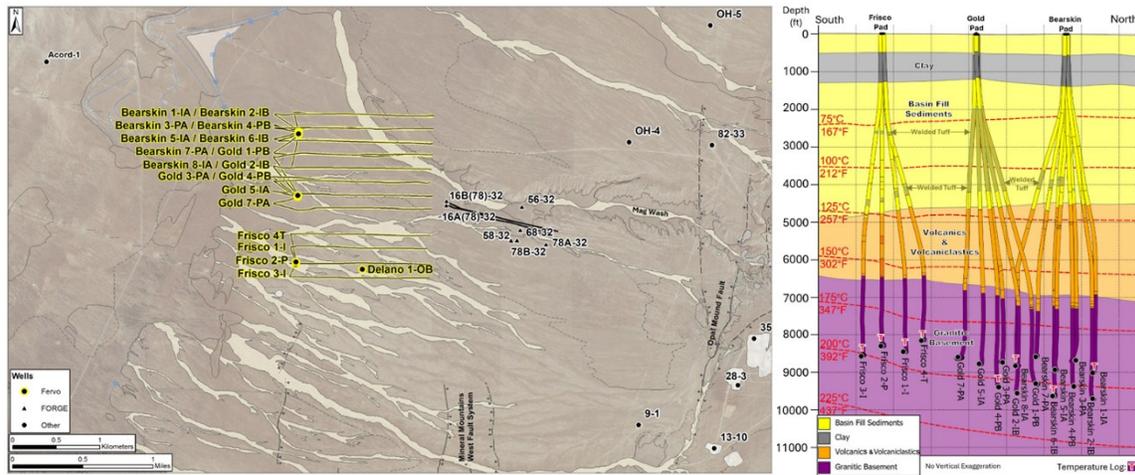

Figure 5: Top view and cross sectional view of Frisco pad at Project Cape (Fercho et al. 2025)

For the Frisco crossflow test, we have one producer (Frisco 2P), two injectors (Frisco 1I and Frisco 3I), and two observers (Frisco 4T and Delano) with measurement of surface flow rate (Frisco 1I, Frisco 2P, and Frisco 3I), wellhead pressure (Frisco 1I, Frisco 2P, Frisco 3I, and Frisco 4T), and downhole pressure (Delano), as shown in Figure 6. Note that Delano is a vertical observation well. The data were up-sampled to 6-minute frequency and bounded to remove outliers. For conventional well test analysis, we can extract transients from the injection test, falloff test, and build-up test and plot the pressure and its derivative in log-log diagnostic plot using Bourdet's derivative (Bourdet, Ayoub, and Pirard 1989) as shown in Figure 7. We observed wellbore storage (unit slope) at early time then linear flow (half slope) in the injection/fall-off/build-up test. Although we also observe a zero slope characteristic in the falloff/build-up test as well as in their corresponding interference responses at the observation wells, it is unlikely that this is a radial flow inside the fracture behavior. Conventional well test analysis would only apply to a few transients from a single-well perturbation. To utilize the whole dataset, we need a combined pressure and rate transient analysis that takes account of all interference responses.
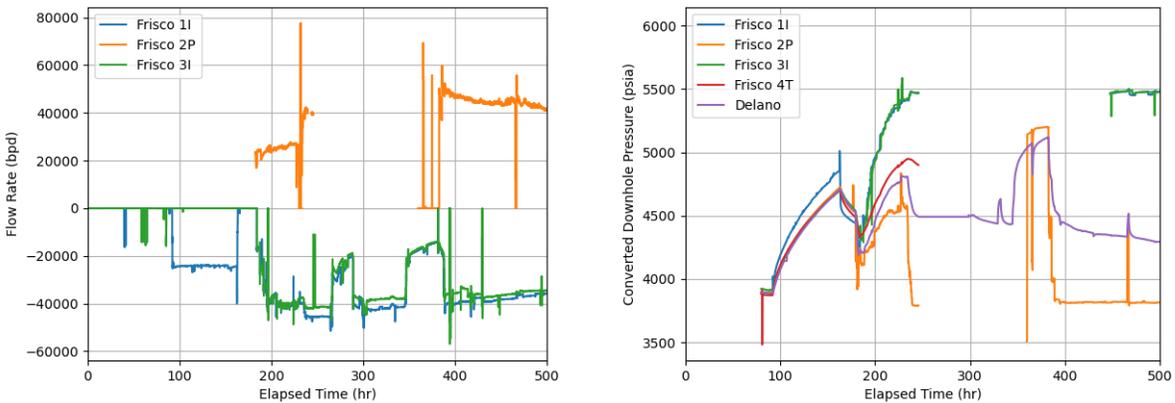

Figure 6: Injection and crossflow test data in Frisco (a) flow rate; (b) converted downhole pressure
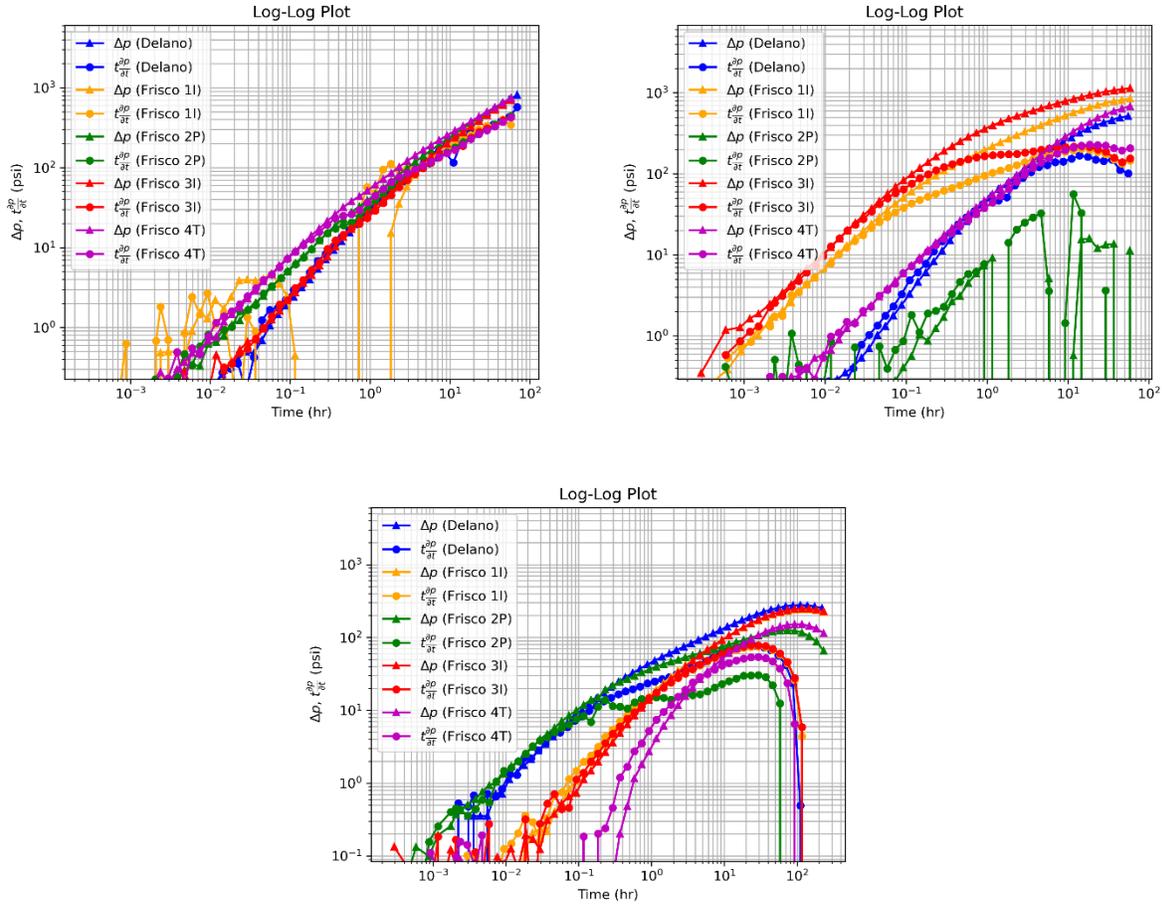
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Figure 7: Pressure transient response from (a) Frisco 1I injection test; (b) Frisco 1I and 3I fall-off test; (c) Frisco 2P build-up test

As well control switched between rate-control and pressure-control throughout the circulation test, we needed to prescribe the well control to be either constant-rate control or constant-pressure control then to predict the remaining parameter (pressure or flow rate respectively) to fit the measurements. Due to ambiguity in modeling fracture permeability (k_f) and fracture aperture (w) from a radial flow inside the fracture, we enforced a cubic rule dictating that $k_f = \frac{w^2}{12}$ to obtain a realistic estimate of a fracture aperture in the system. Additionally, we also reduced the injection and production rate to one thirtieth to match with one thirtieth of the horizontal section of the multifractured well for the estimates with reasonable order of magnitude value. Figure 8 and Table 1 show the result with the dashed line from the semi-analytical model. Note that the greyed-out parameters in the table were predefined and fixed for the parameter estimation. Because we observed that a consistent relationship between flow rate and pressure of injection well was almost identical between Frisco 1I and Frisco 3I, all fractures were modeled to be homogeneous. In general, we can model a system with a set of fractures that intersect only subsets of horizontal wells to provide preferential fluid pathway between injectors and producers.
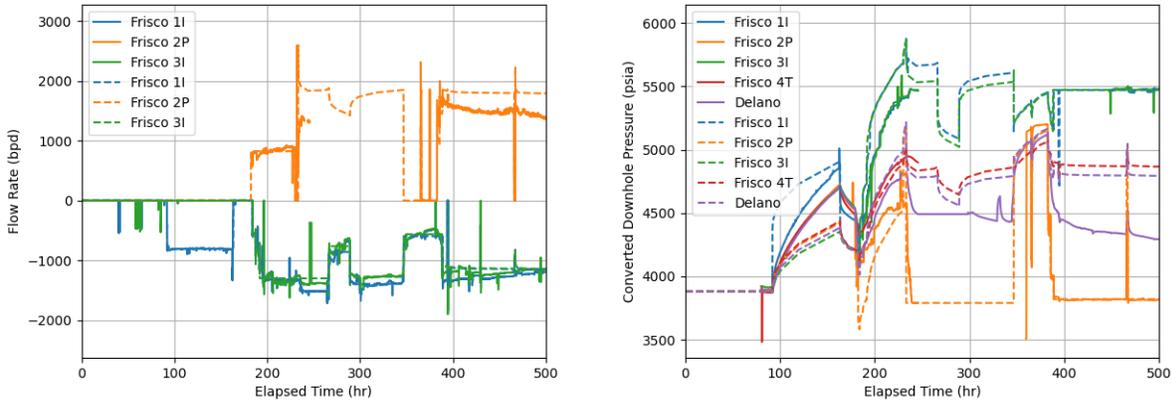
Figure 8: Model prediction in dashed line for Frisco crossflow test (a) flow rate; (b) converted downhole pressure

Table 1: Model parameter and their estimates from Frisco crossflow test

Parameter	SI Unit	Oil Field Unit
Rock matrix thickness	300.0 m	984.3 ft
Rock matrix permeability	1.829×10^{-20} m^2	1.853×10^{-5} md
Fracture geometry	1421.6×300.0 m	4663.9×984.3 ft
Fracture aperture	0.0572 mm	1.877×10^{-4} ft
Fracture permeability	2.728×10^{-10} m^2	2.764×10^5 md
Number of fractures	5	
Number of discretized elements	10	
Fracture spacing	12.5 m	41.0 ft
Modeling proportion	1/30 of total length with 1/30 of flow rate	
Number of wells	1 producer, 2 injectors, and 2 observers	
Well separation	150 m	492.1 ft
Well control schemes	Combination of pressure-controlled and rate-controlled as appropriate	
Initial pressure	26.75 MPa	3880.0 psia

CONCLUSIONS

In this study, we extended a time-domain semi-analytical formulation for a pressure transient solution in a multifractured enhanced geothermal system to accommodate changing well control value and type over time. We introduced a two-step approach to compute solutions with lower time complexity by solving individual constant rate-controlled injection/production for each well and then convolving them together with changes in well control over time. Using a robust least-squares method, we set up a nonlinear regression problem for parameter estimation of the enhanced geothermal system with combined pressure and rate transient analysis. From Frisco injection and crossflow test data, we showed that we could observe characterisitic flow behavior from conventional well test analysis and extract system parameters from a nonlinear regression given proper initial guesses and bounds.

ACKNOWLEDGEMENT

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