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Dynamics of Thermal Migration in Pressure-Propped Fractures During Huff-n-Puff Operations

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ABSTRACT

To harvest enough heat from the subsurface and produce profitable energy at surface, traditional Enhanced Geothermal Systems (EGS) methods include a large number of proppant-propped fractures and desire that the circulating fluid have an ideal uniform flow distribution among all the fractures. An alternative method for heat extraction from hot dry rock is to maintain the surface and subsurface systems pressurized above fracture opening pressure, not connecting wells in the subsurface, and cycling (via Huff-n-Puff) only a fraction of the system fluid stored in the fracture system.

In this alternative method, the number of fractures is lower by an order of magnitude compared to traditional EGS, making uniform split flow more manageable and not as critical. In each fracture, a large fluid volume always resides throughout the operations, absorbing significant amounts of heat. Then a smaller volume (relative to the residing hot fluid, but large enough for surface energy production) of cold fluid is injected into the fracture and the slightly larger volume is shut-in. During this process, fractures are maintained above fracture opening pressures but below the threshold that would initiate fracture propagation. After a pre-defined shut-in time, a volume (similar to that injected) of hot fluid is produced.

A model has been developed that characterizes the thermal migration dynamics occurring within a single fracture maintained above fracture opening pressure during Huff-n-Puff operations. Specifically, pressure, temperature and flow behaviors in the pressurized fracture are determined by a thermal-hydro-mechanical (THM) solver for varying fluid volumes. Emphasis is placed on exploring the competing processes of balancing small-cold/large-hot fluid volumes in a pressurized fracture and its relation to thermal energy production. The results demonstrate that this alternative approach of operating fractures offers an efficient and sustainable alternative method for heat extraction in hot dry rock.

1. INTRODUCTION

In Enhanced Geothermal Systems (EGS) comprised of multiple fractures connected by two or more wells, it is generally a challenge to achieve and maintain uniform split flow through a large set of fractures. A non-uniform flow distribution between fractures can cause the formation to cool faster. Colder formations shrink due to thermal contraction and may increase local fracture apertures and cause thermal breakthrough. For different modeling approaches on preferential fluid flow and thermal breakthrough for EGS, see Doe et al. (2014), Gong et al. (2020), Aliyu and Archer (2021), and McLean and Espinoza (2022) and references therein.

Huff-n-Puff Geopressured Geothermal Systems (GGS), as in Figure 1, are an alternative method for extracting geothermal energy from deep hot dry rock that (1) operates always above pore and fracture opening pressure (Geopressured Geothermal) (2) eliminates thermal breakthroughs since well laterals are disconnected in the subsurface; (3) dramatically reduces downhole impedance due to low friction/pressure loss through open un-propped fractures and (4) requires less fractures than EGS by an order of magnitude. This Huff-n-Puff method eliminates altogether the expensive task of connecting wells in the subsurface and does not require proppant placement treatments. The methodology of a general GGS, that includes the Huff-n-Puff GGS, is described in Rivas et al. (2024). That paper shows that these systems naturally have low impedance and significant lower parasitic energy losses while maintaining commercial flow rates (~100 kg/s). In the present paper, attention is given to the Huff-n-Puff GGS where fractures are maintained open only by fluid pressure above the minimum in-situ stress while cyclically injecting and producing from each well. That is, fractures are maintained pressurized while conducting *single well Huff-n-Puff operations*.

The Huff-n-Puff methodology that is widely used in the Oil and Gas (O&G) industry was first employed in the field for geothermal energy extraction (district heating) in the GeneSys Project; the project and learnings are well documented in Orzol et al. (2005), Tischner et al. (2010) and Tischner et al. (2013). Modeling by Wessling et al. (2009) provides a detailed analysis of the cyclic water injection/soaking/production (Huff-n-Puff) process performed in the GeneSys field tests. That work focused on the pressure analysis of the hydromechanical behavior of a single fracture, not on the fracture creation, and encouraged studying the thermal behavior/efficiency. Safari and Ghassemi (2011) developed a three-dimensional model that simulated the GeneSys Huff-n-Puff field tests as a numerical validation to analyze a version of field tests from the Soultz-souz-Forets geothermal project.

Recent modeling that investigated parameters for improving the GeneSys Project performance is given by Merzoug et al. (2023). However, they considered a combination of two GeneSys schemes (discussed in Tischner et al. 2010) where fluid is injected (at a wellhead flowrate below 3 bpm) down the tubing into the fracture where it leaks into a highly permeable formation and then subsequently, not concurrently, produced (at a wellhead flowrate about 0.25 bpm) through the annular of the well from an upper perforation. In a follow up work given by Sekar et al. (2024), the commercial code ResFrac (McClure et al. 2018) was used to model technical feasibility and the techno-economic analysis of implementing the Huff-n-Puff methodology in traditional EGS systems. In their EGS modeling, fractures are maintained opened by proppant, production pressures are constrained to be small, and injection-soak-production cycles are in the scale of days; production flowrates are not detailed but estimated to be very small. Thus, these assumptions are not applicable to the Huff-n-Puff GGS approach that involves maintaining fractures pressurized, operating with much higher flowrates and cycling in the scale of hours.

In early 2023, Huff-n-Puff techniques were employed for mechanical energy storage in deep hydraulic fractures field tests in South Texas. See Simpkins et al. (2023) for a description of the geosystem as well as field results, and modeling, that demonstrated the successful Huff-n-Puff operations of a fracture with pressures between the minimum in-situ stress and the pressure that would initiate fracture propagation. The Huff-n-Puff GGS is an incremental geothermal technology built upon the tested mechanical energy storage approach that requires fluid temperatures at surface to be less than 95 °C upon entering the impulse turbine to maintain practical efficiencies. This paper considers the Huff-n-Puff technique utilized for extracting heat from hot dry rock so that temperatures of the produced water are above 150 °C at surface (wellhead).

Mathematical modeling in this paper supplements our previous modeling on (1) energy storage that was validated and calibrated against real-time field data (Simpkins et al. 2023), and (2) general Geopressured Geothermal Systems (Rivas et al. 2024) both of which focused on the strongly coupled hydraulic and mechanical processes arising from operating the subsurface system above the minimum in situ stress. The current study analyzes the Thermal-Hydro-Mechanical (THM) behavior of a single fracture to understand, at the fracture level, the thermal behavior of a Huff-n-Puff GGS as a system for heat extraction in hot dry rock. In particular, the long-term effects on production temperature (at the fracture/well interface) as a result of inclusion or exclusion of a soaking time is investigated. This work is not meant to be an exhaustive study, but to demonstrate capability of the THM solver for varying parameters; detailed calibration of the solver against collected field data is required before making further parametric analyses.

2. BACKGROUND

2.1 The Huff-n-Puff Geopressured Geothermal System

The framework of a Huff-n-Puff GGS is shown in Figure 1. This version of the system comprises a binary-cycle surface power plant that is capable of handling high pressures and is linked at surface to wells reaching low-permeability hot dry rock where the wells have their own sets of created hydraulic fractures. The fractures do not contain proppant, have an effective upper geologic seal, and are created away from major faults and high-permeability formations (potential pressure leak zones). Fractures of one well do not connect with fractures of the other well and each engineered reservoir attached to the first well operates independently of the fracture system attached to the second well

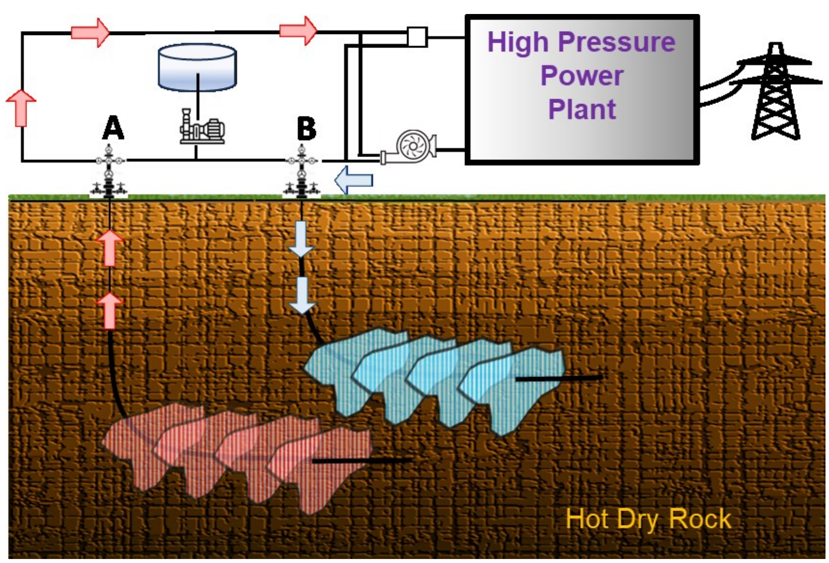

Figure 1: Framework of a Huff-n-Puff Geopressured Geothermal System operating from Well A to Well B. Flow is reversed in the second half of the cyclic, or Huff-n-Puff, operation, and fractures are always maintained pressurized.

Initialization of this Huff-n-Puff GGS begins by pressurizing each well with a pump that inflates the fractures with fluid from the surface and stores mechanical energy through the elastic deformation of the rock surrounding the created fracture system. The fracture fluid pressure in each well is raised and maintained above the minimum in-situ stress during initiation and throughout the heat extraction process; fluid pressures are always maintained below that which would initiate fracture propagation. Well A fractures (red in Figure 1) are given more fluid than the (blue) Well B fractures, and the wells are shut-in when the appropriate fluid volumes are met as calculated beforehand to achieve the desired duration of power production demand.

The initial shut-in allows the fluid in each fracture of both wells to pick up a significant amount of heat while downhole, and power production operations commence as follows. A percentage (about 10-20%) of the pressurized hot fluid in Well A is produced to surface and fed into the high-pressure power plant; this 10-20 percent of fluid is called the *operating volume* of the Huff-n-Puff operation. The cooler fluid exiting the heat exchanger is then injected into Well B. This injected fluid mixes with the already hot fluid in place and the injection further pressurizes the fractures of Well B. Both wells are shut-in when the operating volume that was in Well A is moved completely to Well B, so that now Well B has a larger fluid volume (and higher pressure) than Well A. It is emphasized here that all fractures in each well have pressurized hot fluid, and the fracture fluid volumes in the two wells are in the opposite state compared to when operations commenced. This shut-in time after having moved the operating volume from one well to the other is called the *soak time* of the Huff-n-Puff operation.

Flow is then reversed so that 10-20 percent of the Well B fluid, i.e. the operating volume, is produced to surface, fed into the high-pressure power plant and re-injected into Well A. One full *cycle* of the Huff-n-Puff operation is complete when Well A has again the larger volume as when operations commenced. Repeated cycles of this heat extraction system give rise to the Huff-n-Puff operations that, from the subsurface perspective, are the same as in O&G operations as the wells are disconnected in the subsurface.

2.2 Modeling Considerations

The fully coupled solver in this paper solves temperature, pressure and displacement equations, and modeling considerations include the following. Although the number of fracs in a Huff-n-Puff GGS is already small by design (less than EGS by an order of magnitude), the modeling in this paper is restricted to a single fracture. The solver does not deal with the fracture propagation mechanism since it was included in our previous studies (Simpkins et al. 2024, Rivas et al. 2023) and the focus is on the thermal behavior of the already created hydraulic fracture in a Huff-n-Puff GGS that is operated below fracture propagation pressure. That is, it is assumed here that the injected fluid during Huff-n-Puff operations re-opens parts of the already created fracture but does not break new rock. It is worth noting that Detournay et al. (2008) showed theoretically and experimentally that most hydraulic fractures propagate in the viscosity-dominated regime.

As the footprint of a hydraulic fracture is sensitive to changes in confining stress across layer interfaces, a simple layered confining stress is also considered in the modeling. Different works have modeled hydraulic fracture propagation in layered reservoir; see for example Adachi et al. (2006) that modeled hydraulic fracturing treatments and compared with real field data (from hydrocarbon reservoirs). That work also provides a nice brief historical background on the related hydraulic fracturing modeling work prior to that time. For a current and open-source solver that simulates the propagation of 3D fluid-driven fractures, see Zia and Lecampion (2020) that is based on the implicit level set algorithm developed by Peirce and Detournay (2008). These works influenced our previous modeling, but we note that they do not model pressurized fractures operated with Huff-n-Puff techniques.

3. METHODS AND MATERIALS

3.1 Model and Governing Equations

Model Geometry. The three-dimensional geometry for modeling a Huff-n-Puff GGS at the fracture level is shown in Figure 2. The model consists of a reservoir block with dimensions $4{,}000 \times 1{,}000 \times 2{,}000$ meters, with the fracture/well interface located at a true vertical depth of $4{,}000$ m in the subsurface; numerical scales in the axes give distance, in meters, with respect to the fracture/well interface.

In the equations, the reservoir block is denoted by Ω, and the plane of symmetry (given by $y = 0$) is denoted by Γ which contains a single vertical hydraulic fracture, $\Gamma_{fracture}$, whose dimensions are $3{,}600 \times 300$ meters. The boundary, or walls, of the domain Ω are given by $\partial\Omega_{walls} \coloneqq \partial\Omega \setminus \Gamma$ so that the plane of symmetry is excluded.

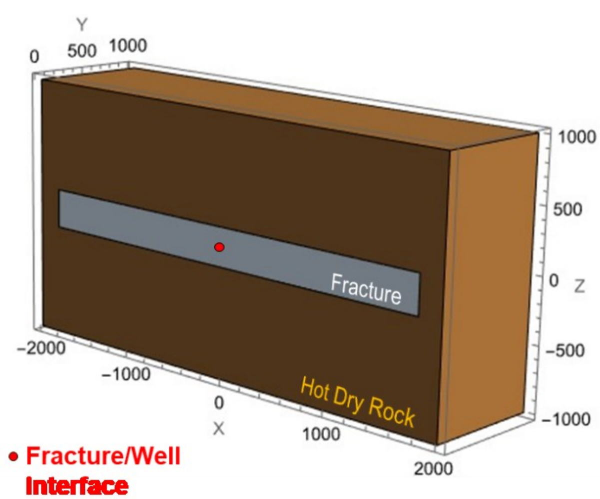

Figure 2: Three-dimensional computational domain for modeling a Huff-n-Puff GGS.

The reservoir is a porous rock with isotropic properties assumed to be 'dry rock' matrix containing both a solid, denoted in equations by a subscript *r* for rock, and pore space filled with a single-phase fluid, denoted by a subscript *f* for fluid. Porosity values are assumed less than two percent with isotropic permeability $\mathcal{K}_r$ less than 1 millidarcy. It is assumed here that the pore space is fixed. All source/sink terms are contained in the fracture assuming the fracture is connected to a wellbore type structure (only the rock and fracture are modeled here).

The reservoir block is under a stress state assumed to be in a normally faulted regime. Principal stresses are denoted as $\sigma_v \geq \sigma_{Hmax} \geq \sigma_{hmin}$, corresponding to the overburden, maximum and minimum horizontal stresses; σ_{hmin} is normal to the fracture plane. Pore pressure is assumed to be geo-pressured and is denoted by P_p. The solid is considered deformable, elastic and of a sedimentary structure with thermophysical properties assumed to be uniform.

The fluid in the rock is assumed to be water and thermophysical properties of the reservoir fluid are determined by thermophysical properties of water as derived from NIST's database/software REFPROP; see Lemmon et al. (2018). Thermophysical properties are assumed here to depend on pressure and temperature.

Flow in the Matrix. The fluid flow in the rock matrix is governed by conservation of mass and energy. In this study, thermal equilibrium transport is assumed between the solid and the fluid so that temperatures of the solid and fluid are equal at any point in space and time. Denoting by p_f, T_f the fluid pressure and temperature, respectively, the conservation of mass is given by

$$(\rho\phi)_f \left[c_{t,f}\frac{\partial p_f}{\partial t} + \alpha_{t,f}\frac{\partial T_f}{\partial t}\right] + \nabla\cdot\left(\rho_f \boldsymbol{u}_r\right) = 0 \tag{1}$$

where ρ is fluid density, ϕ the porosity of the rock, $c_{t,f}, \alpha_{t,f}$ the compressibility and thermal expansion coefficient of the fluid, and $\boldsymbol{u}_r$ the Darcy velocity. The fluid velocity is related to the pressure gradient by Darcy's law:

$$\boldsymbol{u}_r = -\frac{\mathcal{K}_r}{\mu_f}\left(\nabla p_f + \rho_f \boldsymbol{g}\right) \tag{2}$$

where $\mathcal{K}_r$ is the intrinsic permeability of the matrix, μ_f the dynamic viscosity of the fluid, and $\boldsymbol{g}$ is the gravitational acceleration. The conservation of energy is given by

$$\left(\rho C_p\right)_m \frac{\partial T_f}{\partial t} + \rho_f C_{p,f}\, \boldsymbol{u}_r \cdot \nabla T_f + \nabla\cdot \boldsymbol{q}_f = 0 \tag{3}$$

where the effective heat capacity of the matrix $\left(\rho C_p\right)_m := \phi\rho_f C_{p,f} + (1-\phi)\rho_r C_{p,r}$ sums the densities and heat capacities of the fluid and rock, and $\boldsymbol{q}_f$ is the conductive heat flux that is related to the temperature gradient by Fourier's law

$$\boldsymbol{q}_f = -k_{th,m}\nabla T_f \tag{4}$$

where $k_{th,m} := \phi k_{th,f} + (1-\phi)k_{th,r}$ is the effective thermal conductivity of the matrix

Interfacial Fracture Flow. The flow in the fracture is a sub-manifold 'interface' to the Darcy flow in the rock matrix. Similarly to the reservoir, fracture flow is governed by conservation of mass and energy but one dimension lower than in the rock domain. Due to the reduction in dimension, the fracture is considered a 'thin' structure with aperture $w = w(x,z)$ defined over the fracture plane. As an interface, the first condition that holds is that the fluid pressure and temperature in the rock matrix in $\Gamma_{fracture}$ is equal to the fluid pressure and temperature in the fracture. The fracture is assumed to be proppant free and composed of fluid. Porosity of the fracture is therefore unity. It is assumed that there is a subregion $A_0 \subset \Gamma$ that contains a source/sink term governed by mass-flowrate $\dot{m} = \dot{m}(t)$. A source is considered positive and a sink is considered negative. The conservation of mass in this case is expressed as

$$w\rho_f \left[c_{t,f}\frac{\partial p_f}{\partial t} + \alpha_{t,f}\frac{\partial T_f}{\partial t}\right] + \rho_f\frac{\partial w}{\partial t} + \nabla\cdot\left(\rho_f\boldsymbol{u}_f\right) - 2\left(\boldsymbol{u}_r\cdot\boldsymbol{n}_y\right) = \frac{\dot{m}}{A_0} \tag{5}$$

The heat transfer in the fluid is assumed to be convective dominated so that conduction has a minor effect ($k_{th,f} < 1$). Heat transfer related to $\dot{m}$ are driven by enthalpy differences due to external influences (such as temperature in a wellbore, considered external to the reservoir/fracture domain). The conservation of energy is expressed as

$$w\rho_f C_{p,f}\left(\frac{\partial T_f}{\partial t} + \boldsymbol{u}_f\cdot\nabla T_f\right) + 2k_{th,m}\boldsymbol{n}_y\cdot\nabla T_f = \frac{\dot{m}}{A_0}\left(H_{ext} - H\right) \tag{6}$$

where H is specific enthalpy. Within the fracture, the Darcy's field velocity is related to the pressure gradient by the 'cubic law':

$$\boldsymbol{u}_f = -\frac{w^2}{12\mu_f}\left(\nabla p_f + \rho_f\boldsymbol{g}\right) \tag{7}$$

The fracture is considered deformable, and aperture is related to the difference in pressure and minimum principal stress in the rock. For regions of the fracture that are in contact, a contact constraint is activated by enforcing a minimum aperture w_c with corresponding traction $\tau_c = p_f - \sigma_{hmin}$, otherwise, $\tau_c = 0$ for regions where the fracture is considered 'open.'

$$\left(p_f - \sigma_{hmin} + \tau_c\right)(\boldsymbol{x}) = -\frac{E}{8\pi(1-\nu^2)}\int_{\Gamma_{fracture}} \frac{w}{\|x-x'\|_2^3}\, d\Gamma(\boldsymbol{x}'), \quad \text{for } \boldsymbol{x} \in \Gamma_{frature} \tag{8}$$

Initial Condition. The temperature of the matrix and fracture fluid is assumed to be equal to static temperature that varies with depth z, so that

$$T_f = T_{static}(z) \tag{9}$$

The aperture of the fracture is initialized to be equal to the minimum aperture (closed-state). The pressure in the fracture will be initialized to satisfy equation (8). The reservoir pressure is assumed to be solved by a steady-state version of the equation by assuming pore-pressure holds on the walls of the block:

$$p_f(\boldsymbol{x}) = p_p(\boldsymbol{x}), \quad \text{for } \boldsymbol{x} \in \partial\Omega_{\text{wall}} \tag{10}$$

Static Geothermal Reservoir Properties. Thermophysical properties of the solid are assumed to be uniform with values given as in Table 1. During the Huff-n-Puff operations of the pressurized fracture, the fluid injected into the fracture is assumed to be at 90 °C and the reservoir temperature is assumed to be 200 °C at the depth of 4 km.

Table 1: Simulation input parameters.

Parameter	Value	Unit
ρ_r	2890	kg/m^3
$C_{p,r}$	800	$\frac{\text{J}}{\text{kg}\cdot\text{K}}$
$k_{th,r}$	3.5	$\frac{\text{W}}{\text{m}\cdot\text{K}}$
E	25	GPa
ν	0.25	-
$\frac{dP_p}{dz}$	13.57	MPa/km
$\frac{d\sigma_{hmin}}{dz}$	15.83	MPa/km

4. RESULTS

An example of the subterranean GGS in Figure 2 in operation is shown in Figure 3. First, the system is initialized by injecting a large volume into the fracture and is provided an initial shut-in that brings the pressurized fracture fluid temperature to 200 °C as measured at the fracture/well interface. Then the schedule of flowrates shown in Figure 3 is used, where positive/negative flowrates, respectively, indicate injection/production of fluid through the fracture/well interface. For the first 10 hours, cold water is injected at a rate slightly above 8 kg/s into the fracture that already has hot pressurized fluid; next, the fracture is shut-in for 10 hours (so that the cold fluid *soaks* in the hot fracture fluid); for the next 10 hours, the hot pressurized fluid is produced at the rate of 8 kg/s from the fracture/well interface and this completes one Huff-n-Puff cycle; immediately thereafter cold fluid is injected for 10 hours; then the injected cold fluid soaks for 10 hours with the hot fluid already in the fracture; the hot pressurized fluid is produced for the next 10 hours. The slight difference in injection and production flowrate compensates for thermal fluid changes. Note that this model represents only one out of 12 fractures needed for commercial rates (~100 kg/s).

In this schedule, it is observed that the temperature measured at the frac/well interface decreases from 200 °C to 188 °C during the injection of the cold fluid, rebounds to 198 °C during the soaking time, and continues to increase above 199 °C by the end of the production, which is the end of the first cycle shown. A similar temperature trend occurs in the second cycle shown in Figure 3.

During the entirety of the schedule shown, the fracture is maintained pressurized above the minimum in-situ stress and the *net-pressure Pnet* in the middle plot of Figure 3 refers to the difference in fracture fluid pressure and the minimum fluid pressure observed during the two Huff-n-Puff cycles (both measured at the frac/well interface). The results show that at the given injection flowrate the net-pressure increases; then during the soaking time, the net-pressure slightly decreases and stabilizes as the fluid re-distributes in the fracture; finally, the net-pressure decreases when the hot pressurized fluid is produced from the fracture/well interface. This pressure behavior repeats in the second cycle shown.

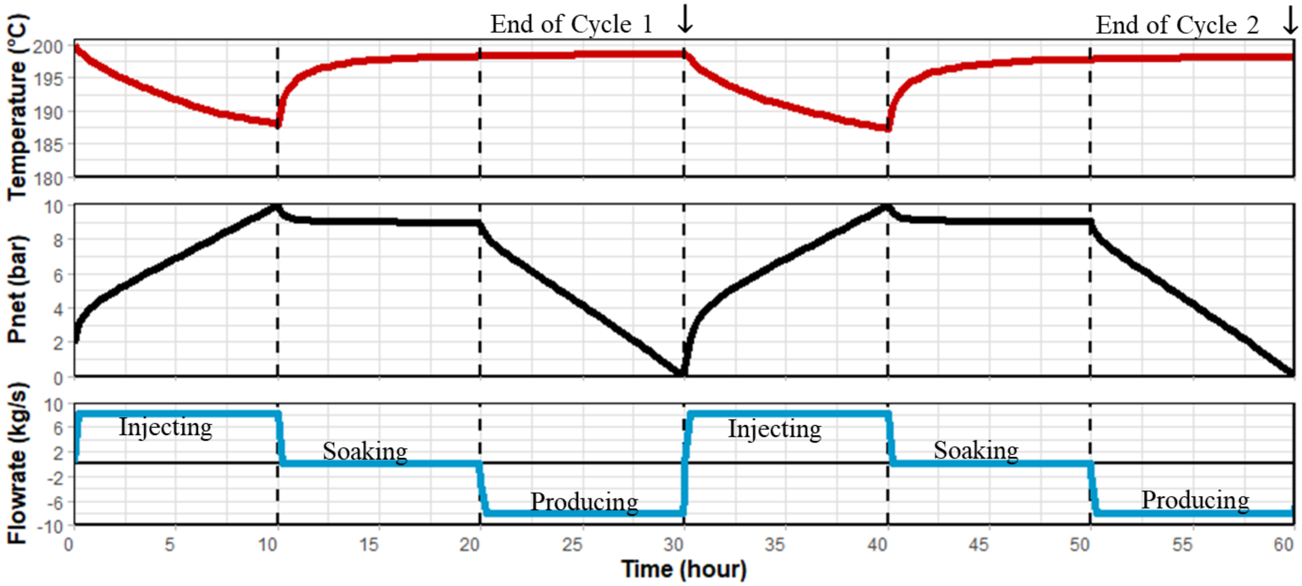

Figure 3: Two cycles of the Huff-n-Puff GGS with temperature and flowrate sampled at the fracture/well interface.

To understand the long-term thermal behavior of the subterranean system in Figure 2, the simulation is extended to one year, where each cycle injects cold fluid for 10 hours; the cold fluid soaks with the hot fluid for the next 10 hours; and then the pressurized hot fluid is produced for 10 hours; as in the two-cycle case, the injections are at a slightly higher than 8 kg/s flowrate. The one-year simulation result is shown in Figure 4.

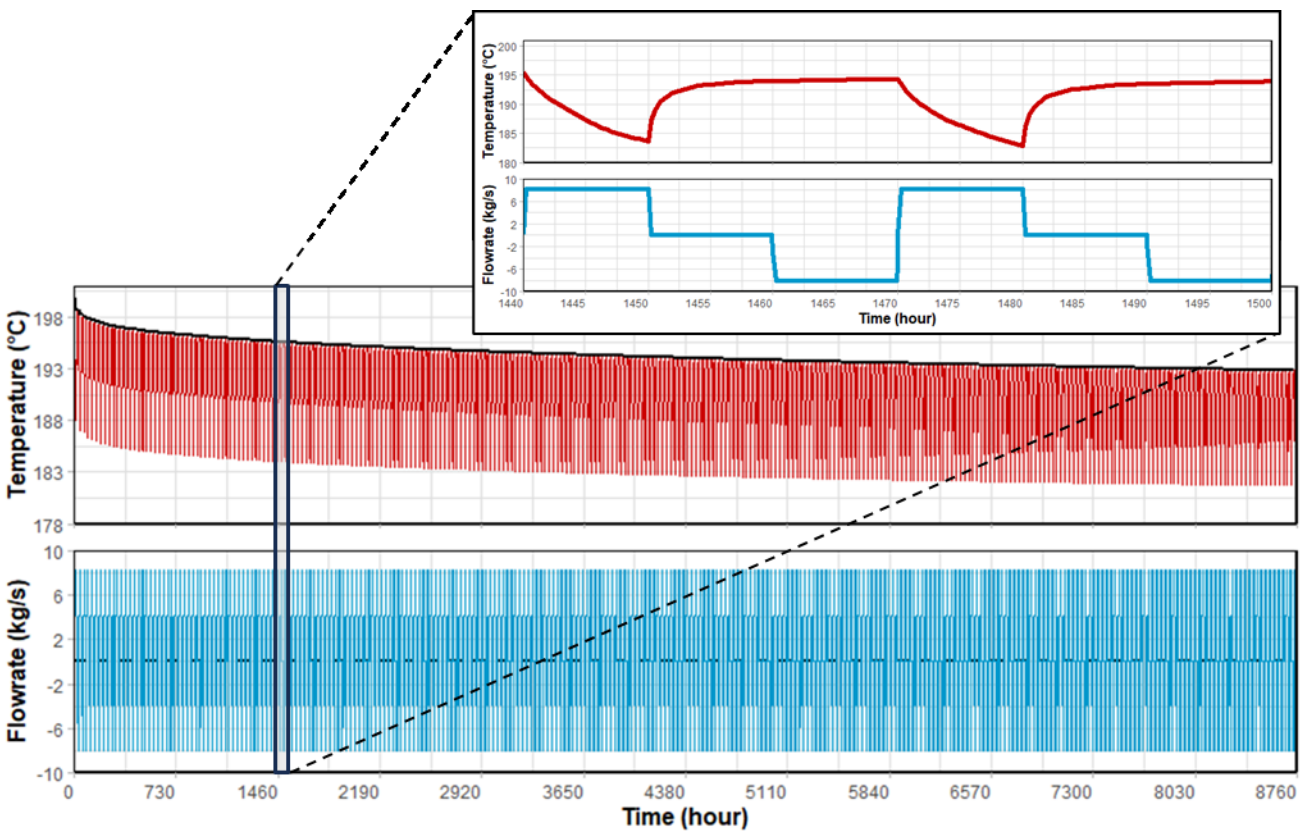

Figure 4: Operating the Huff-n-Puff GGS for one year where each cycle is of the form (10hr inject, 10hr soak, 10hr produce).

The temperature is again measured at the fracture/well interface, and a trend similar to that of Figure 3 is observed for each cycle. In the temperature plot of Figure 4, the black curve traces the temperature at the end of each cycle (i.e. end of production) so that this black envelope records the maximum temperature from each cycle. This envelope shows that the temperature has a minuscule decline that is steeper in the beginning of the year but flatter at the end. After one year of operating this Huff-n-Puff GGS fracture, the initial 200 °C temperature drops to 193 °C, which amounts to a 3.5% decrease in thermal power produced after one year from this fracture.

This result is now compared with the extreme case of no soaking time so that each cycle injects cold fluid for 10 hours and then immediately produces the fracture fluid for 10 hours; all other parameters are the same as in the previous 1-year simulation. Figure 5 shows the results from operating this Huff-n-Puff GGS, at the fracture level, with no soaking time. The maximum temperature of each cycle measured at the fracture/well interface is recorded in this case by the dashed black envelope (curve).

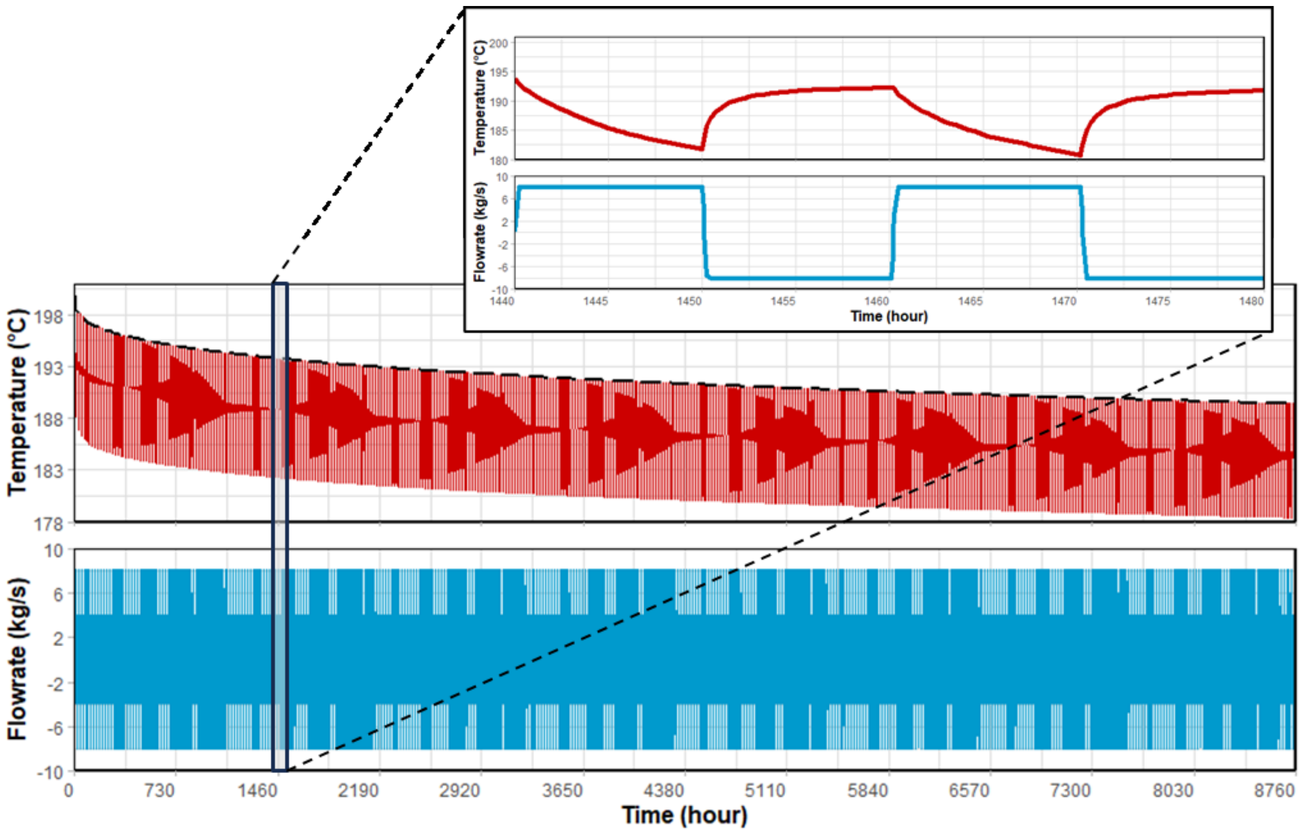

Figure 5: Operating the Huff-n-Puff GGS for one year with no soaking time; each cycle injects for 10 hrs, produces for 10 hrs.

In this case of no soaking, the maximum cycle temperature envelope follows a similar decay trend with a sharp slope at the beginning and nearly flat at the end. However, the 200 °C temperature measured at the fracture/well interface drops to 189.5 °C at the end of the year. This results in a 5.25% decrease in temperature.

The effect that soaking time has on maximum cycle temperature is best seen in Figure 6 that displays the envelopes of the two 1-year simulations from Figures 4 and 5. From Figure 6, it is observed that having a time period in which the injected cold fluid *soaks* with the hot fluid already in the fracture slows down the thermal decay in this subterranean system. Scheduling with soaking time, therefore, provides an action for extending the life of this HDR heat extraction system.

These 1-year results on maximum cycle temperature, are now extrapolated to provide a 5-year thermal performance, at the fracture level, of the Huff-n-Puff GGS fracture; this is shown in Figure 7. With this extrapolation, the difference in thermal decay in the subterranean system, when not incorporating a soaking time, is profound.

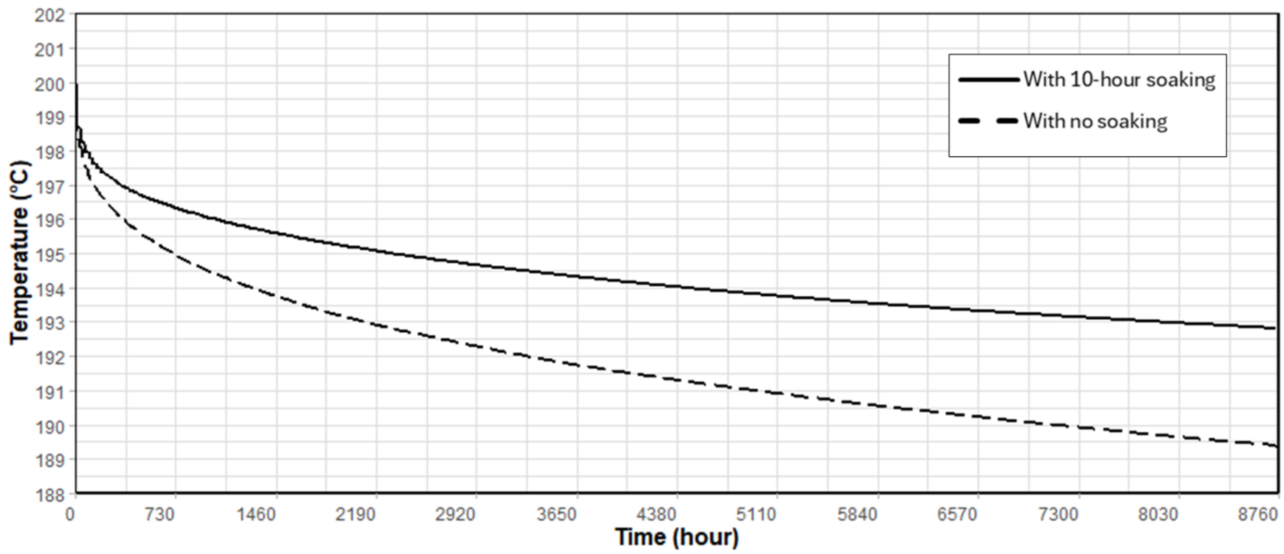

Figure 6: Maximum cycle temperature at fracture/well interface when operating the Huff-n-Puff GGS for one year with or without soaking.

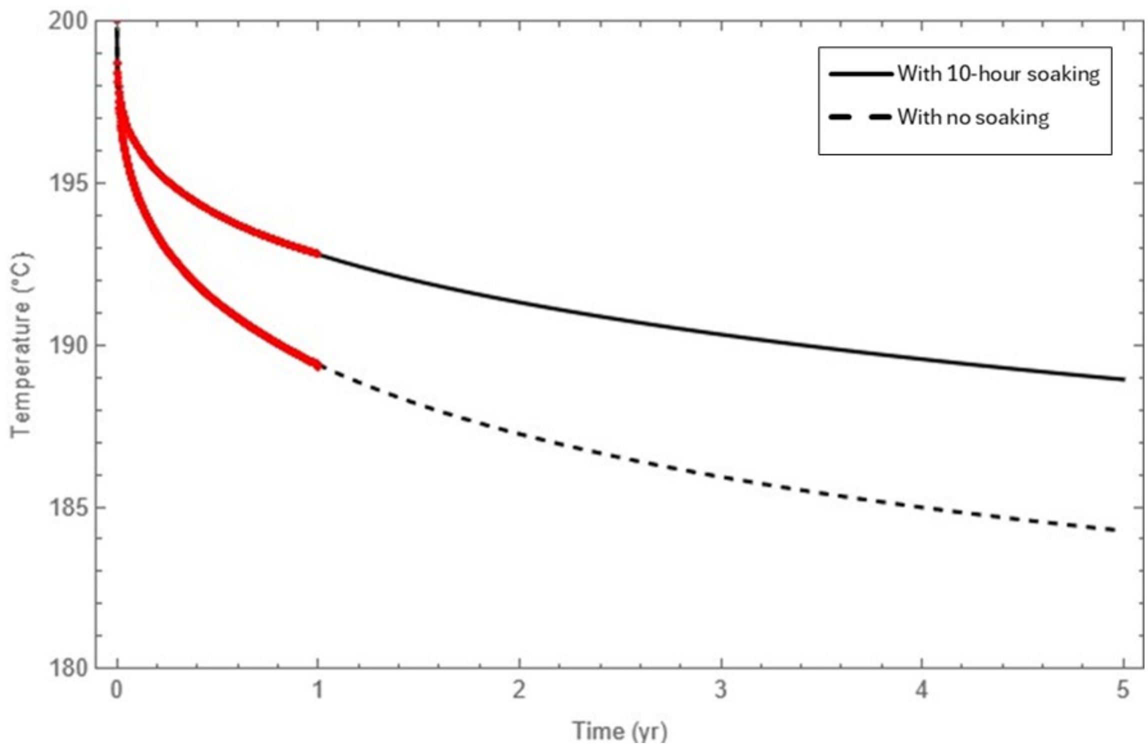

Figure 7: Five-year projection (in black) of maximum cycle temperature at fracture/well interface when operating the Huff-n-Puff GGS with or without soaking; red is the 1-year data seen in Figure 6.

5. CONCLUSION

The work presented here demonstrates the numerical capabilities of a highly coupled thermal, hydraulic and mechanical (THM) solver for modeling, at the fracture level, the Huff-n-Puff Geopressured Geothermal Systems (GGS). During heat extraction operations, these systems maintain each fracture with fluid pressure above the minimum in-situ stress but below that which would initiate fracture propagation, and Huff-n-Puff cycles are in the scales of hours. The initial simulations presented here show that the soaking of the cold injected fluid with the hot fluid already in the fracture has a significant influence on the thermal behavior of the heat extraction system. Specifically, with no soaking time the overall temperature of the fracture fluid drops by 3.5 °C more in one year than when operating with a 10-hour soaking time. That is, soaking reduces the rate of cooling of the reservoir that arises from heat extraction by Huff-n-Puff operations.

Interpreting this from the subsurface perspective and at the fracture level, the Huff-n-Puff single-well approach minimizes thermal breakthrough by a pressure- and time-management process. The solver presented here is to be calibrated with collected field data before utilizing it to further investigate the design of cycle schedules with this solver.

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