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Heat Extraction Analysis of Multi-Stage Hydraulic Fracturing Doublet Horizontal EGS Wells

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ABSTRACT

Enhanced Geothermal System (EGS) are developed using various stimulation technologies to improve the production of heat energy from hot dry rock (HDR) that has ultra-low permeability. In this study, a horizontal EGS well design with partially bridging multistage hydraulic fractures is presented. Based on the proposed design, a semi-analytical model for temperature is derived assuming bi-linear heat transfer in the fractures and stimulated reservoir volume (SRV). The model considers heat conduction and advection in the SRV, and, depending on the number and spacing of fractures, can be used to optimize EGS design. A 3D numerical model is also developed to validate the semi-analytical model and test geometry effects. The numerical model is constructed in the COMSOL finite element solver and compared to a fully bridging hydraulic fracture design. The results show that the partially bridging design can obtain a longer period of high temperature production, delaying thermal breakthrough by forcing water to traverse the SRV.

1. INTRODUCTION

The heat stored in hot dry rock (HDR) at subsurface depths of 2-10 km depths is one of the most promising and clean renewable geothermal energy resources for electricity generation (Tester J., 2006). Enhanced geothermal systems (EGS) are being developed to accelerate the production of this heat energy from HDR in ultra-low permeability formations. This typically involves the application of stimulation technologies like hydraulic fracturing, shear, thermal or chemical stimulation. However, the technology is not mature and the thermal power achieved to date has not met economic standards (Jung, 2013). Although the conceptual model of multistage hydraulic fracture EGS was advanced by Gringarten et al. in 1975, this technology was never adopted due to technical limitations of the time, such as a lack of high temperature open-hole packers and advanced direction drilling technology. More recently, multistage hydraulic fracturing in horizontal wells is widely deployed in the development of unconventional oil and gas reservoirs. As the technology and tools have been developed to tolerate high temperature, some researchers have re-evaluated the availability of this technology for EGS development. Li et al. (2016) and Shiozawa & Mcclure (2014) studied the availability, optimization and sensitivity analysis of EGS design with horizontal wells and multiple fracturing stages. Their results showed that multiple stages significantly improves economic performance, delays thermal breakthrough and allows a higher flow rate to be circulated through the system.

Gringarten et al. (1975) proposed an analytical model for heat extraction from hot dry rock. In their model, geothermal wells are drilled in a direction perpendicular to the expected orientation of a series of parallel, vertical fractures that are created from a single well. The fractures are separated by blocks of homogeneous, isotropic, and impermeable rock, as shown in Fig. 1. One of the drawbacks of this model is that water only flows in the main fractures; the matrix is regarded as impermeable and the only heat transfer is conduction. Several researchers have studied and modified this design since. Abbasi et al. (2017) comprehensively reviewed the analytical model for advective and conductive heat transfer in fractured geothermal reservoirs. Radial advective transport in fractures and conduction from the matrix are considered in their model. In Abbasi et al. (2018), the effect of fracture boundary conditions on heat transfer shape factor was studied based on the same model. Also, Abbasi et al. (2019) investigated the same problem in Cartesian coordinate, providing an exact solution for the transient temperature distribution and advancement of the thermal front. However, all of these EGS well designs and models assumed the permeability of the matrix was zero, which will not be the case if there has been successful stimulation. Li et al. (2015) numerically investigated the heat extraction potential over 20 years of circulating water through horizontal wells with multiple transverse fractures connected to a permeable SRV. They noted that, compared with the classic HDR system (doublet or triplet vertical wells + single fracture), the combination of horizontal wells and multiple transverse fractures was an attractive approach for development of HDRs. Asai et al. (2018a, 2018b, 2019) evaluated the fluid distribution, performance and simulation workflow for multi-fractured EGS, assessing five dominant factors that would affect the performance of EGS with multiple stages, using the data from Utah FORGE site.

This paper proposes a new EGS well design that uses partially bridging hydraulic fractures to increase flow through the SRV. Semi-analytical and numerical models of this design are developed and used to explore the effect of fracture spacing and number on heat transfer. The heat extraction performances and temperature distribution in the stimulated reservoir volume are compared between three different analytical and numerical well design models. The simulation results of the proposed EGS well design provide some guidance on the application and optimization of multistage hydraulic fracturing in EGS development.

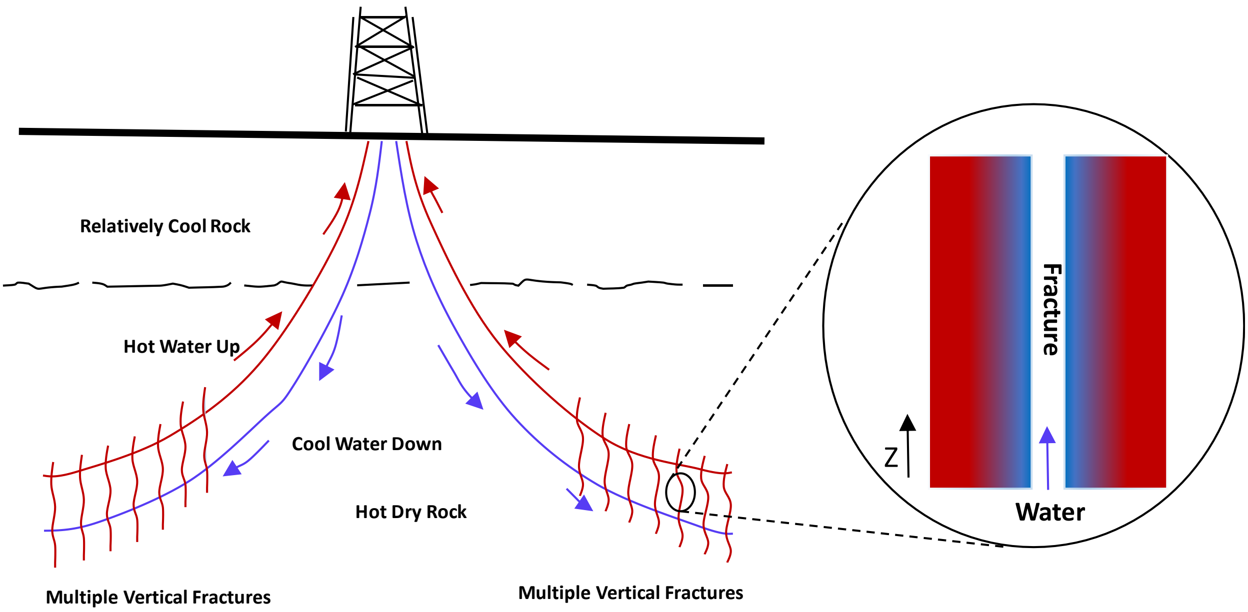


Figure 1: Schematic diagram of multi-stage fracture EGS (Gringarten et al., 1975).

2. EGS WITH PARTIALLY BRIDGING HYDRAULIC FRACTURES

The commonly used concept model of multi fractured horizontal well EGS doublet is shown in Figure 2(a). The main fractures are assumed to be created by high pressure injection into a section of the well that has been isolated and perforated, with fracture growth terminating when it intersects the other well. The fractures are termed fully bridging, as they directly connect the two wells. During this process, the volume between the two main fractures may also be stimulated, usually by the accumulation of poroelastic stresses, and its permeability may have increased. Therefore, in this design, a portion of the injected water will enter the SRV, absorb heat from the rock matrix, and then exit back into the main fractures. However, this flow scheme might still cause early thermal breakthrough; the size of the heat extraction zone will be limited by the penetration length of injected water into the SRV.

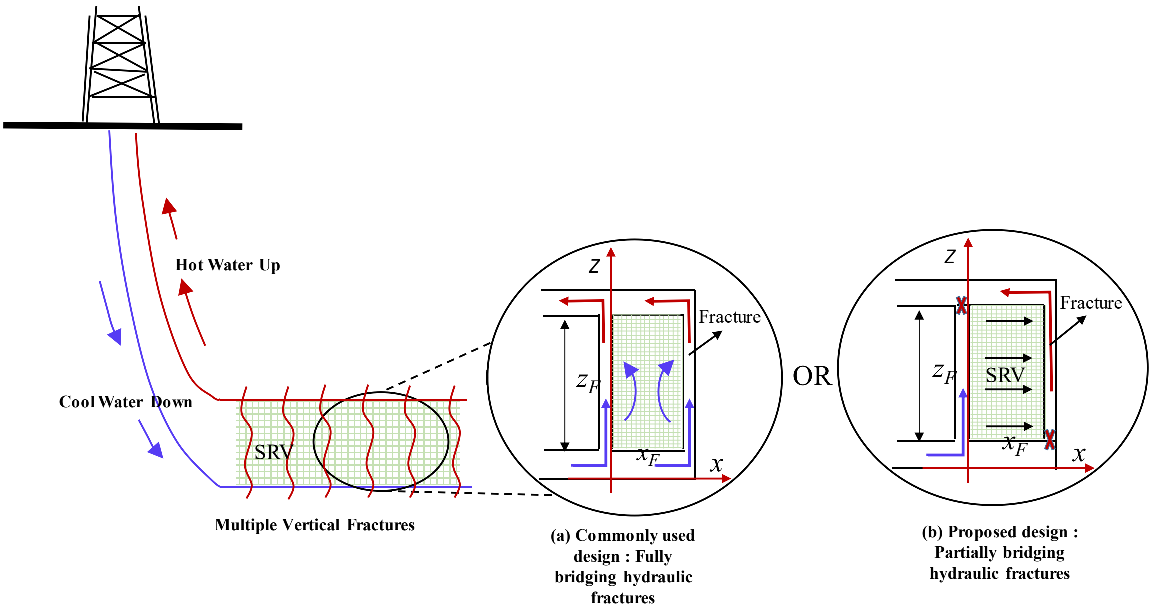


Figure 2: Schematic diagram for the commonly used conceptual model and proposed conceptual model of the enhanced geothermal system (EGS).

The partially bridging fracture design is shown in Fig. 2(b). Half of the hydraulic fractures are generated from the production well but these stop short of the injection well. The other half are generated from the injection well and stop short of the production well. The position of production and injection fractures alternates down the length of the wells. The goal is for the fractures to provide connectivity to the SRV while preventing injected water directly flowing to the production well. Instead, the water in the injection fractures must enter and flow through the SRV, exiting in fractures connected to the production well. Compared with the well design of Gringarten et al. (1975) (Fig. 1) and its extension to a permeable SRV (Fig. 2a), the proposed design should delay thermal breakthrough and result in more heat extraction over the production lifetime.

There are several practicalities to consider with the new EGS design. First, the hydraulic fracturing operation must proceed with careful monitoring to avoid the growing fracture intersecting and damaging the casing of the neighboring well. In addition, as a commonly used stimulation method in oil and gas industry, the order of fractures should be performed as a "zipper fracking" operation, which can improve stimulation of the surrounding rock by accumulation of poroelastic stresses.

2.1 Semi-analytical model of proposed EGS well design

As the elements separated by the main fractures are symmetric, here, only one representative element is analyzed (Fig. 2b). The following assumptions are made to develop the semi-analytical model (Abbasi et al., 2019).

(1) Single-phase water flows in a steady-state both in the fractures and SRV.

(2) Vertical temperature gradients in the rock are ignored. The SRV is considered at a constant initial temperature.

(3) There is local thermal equilibrium between fluid and the rock matrix.

(4) Thermal properties (density and heat capacity) of the fluids and rock matrix are constant.

(5) Heat conduction of the overburden and underburden rock are ignored.

The principle flow and heat transfer processes occur in the SRV zone. The principle flow direction is perpendicular to the fractures and hence we neglect flow or temperature variations in the y and z directions. The differential equation governing temperature evolution in the SRV is derived from the energy balance for a control volume:

$$\left(\rho c\right)_{SRV}\frac{\partial T_{SRV}}{\partial t}+\rho_w c_w v_{SRV}\frac{\partial T_{SRV}}{\partial x}-\lambda_{SRV}\frac{\partial^2 T_{SRV}}{\partial x^2}=0 \tag{1}$$

$$\left(\rho c\right)_{SRV}=\phi_{SRV}\rho_w c_w+\left(1-\phi_{SRV}\right)\rho_r c_r \tag{2}$$

$$\lambda_{SRV}=\phi_{SRV}\lambda_w+\left(1-\phi_{SRV}\right)\lambda_r \tag{3}$$

where T_{SRV} is the temperature in the SRV; ρ_r, and ρ_w are the density of rock and water, c_r, and c_w are the heat capacity of rock and water, λ_r, λ_w, and λ_{SRV} are the thermal conductivity of rock matrix, water, and continuum, x_F is the fracture spacing, φ_{SRV} is the porosity of the SRV, v_{SRV} is the velocity of water in the SRV, which is obtained by dividing the injection rate by the number of fractures and area of each fracture.

Assuming local thermal equilibrium, the initial condition is expressed:

$$T_{SRV}\left(x,z,t=0\right)=T_0 \tag{4}$$

where T_0 is the initial rock temperature. Eq. (1) is solved subject to the boundary conditions that fluid temperature at $x = 0$ is the injected fluid temperature, T_i:

$$T_{SRV}\left(x=0,z,t\right)=T_i \tag{5}$$

and that the temperature of water approaches the initial rock temperature T_0 as x tends to infinity.

$$T_{SRV}\left(x\rightarrow+\infty,z,t\right)=T_0 \tag{6}$$

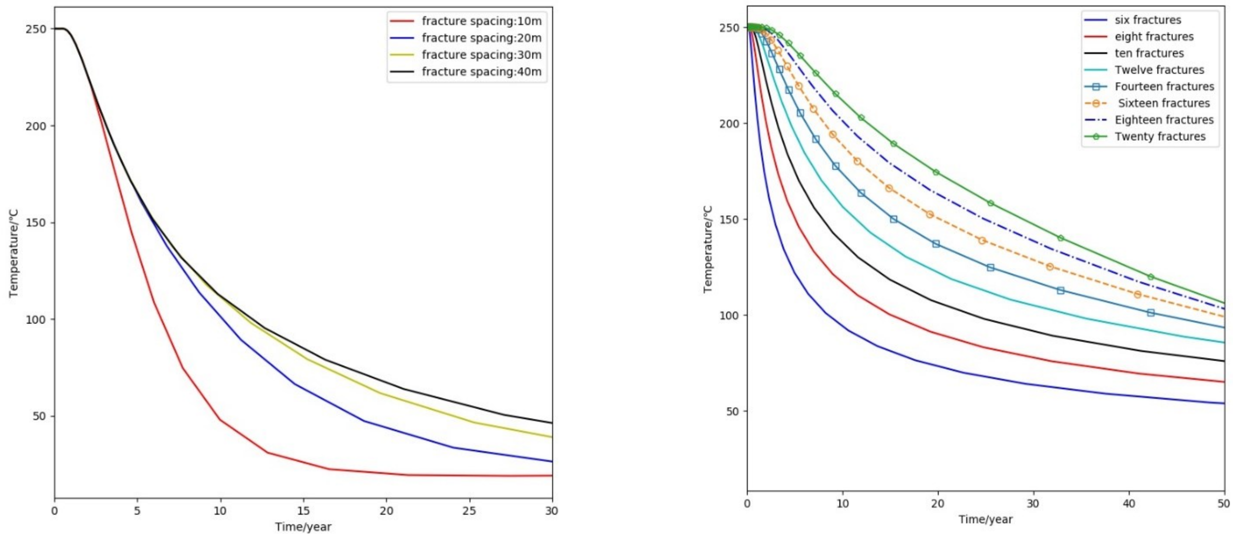
Several dimensionless parameters were defined and the equations were solved analytically in the Laplace domain (Appendix A). The temperature solution for the SRV in the Laplace domain is:

$$\overline{T_{DSRV}}\left(x_D,z_D\right)=\frac{1}{s}e^{r_2 x_D} \tag{7}$$

where s is the Laplace variable corresponding to t. This solution is transformed into the time-space domain using the Stehfest numerical inversion algorithm (Stehfest, 1970; Stehfest & Harald, 1970).

2.2 Sensitivity analysis of the proposed model

Solutions to (1) for a range of fracture spacing and fracture number are shown in Fig. 3. For one representative element (one injection and production fracture separated by an SRV), increasing the fracture spacing increases the produced water temperature at a given time. As more fractures are added to the system, each SRV accommodates less water, so the degree of cooling is reduced and the produced water temperature remains higher for longer. In this model, a target zone of 1000m×200m×50m at an initial temperature of 250°C with injection rate of 600 m^3/d can sustain high temperatures for many years. Adding additional stages increases the production life of the EGS.



(a) The effects of fracturing spacing on produced water temperature for one representative element (T_0=250 ℃, T_i=20℃, Q_{inj}=30 m^3/d).

(b) The extracted water temperature for different numbers of fractures in a specific target zone.

Figure 3: The influence of fracture spacing and fracture numbers on extracted water temperature.

3 NUMERICAL VALIDATION AND COMPARISON WITH THREE CASES OF EGS WELL DESIGN

3.1 Computational model

Here, we compare the heat extraction ability of the proposed EGS design to previous configurations, and evaluate the effect of simplifying geometry assumptions by validation against a numerical flow simulation. We have chosen to compare against the Gringarten analytical model (fully bridging fractures, impermeable SRV, denoted Model A) and a numerical simulation of fully bridging fractures with a permeable SRV (Fig. 2a, denoted Model B). Model C is a 3D numerical model of the partially bridging hydraulic fractures which relaxes the geometric assumptions introduced in the previous section.

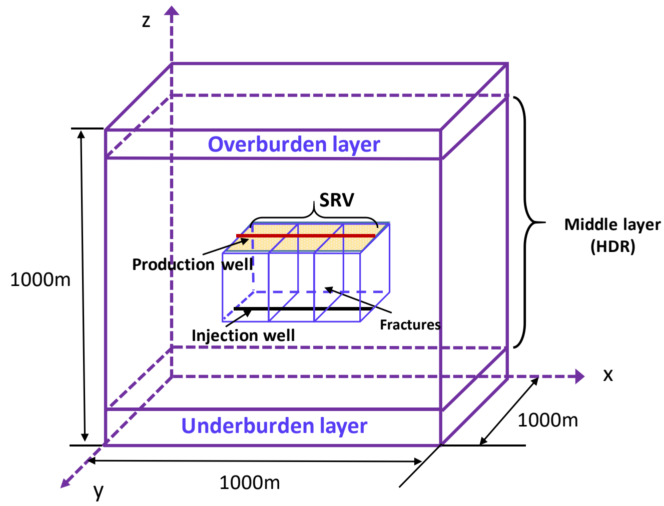


Figure 4: Schematic of the numerical model.

Numerical simulations were performed using the finite element solver COMSOL. Fig. 4 illustrates the schematic of the computational model for a doublet EGS horizontal well with four fractures. The model includes an overburden layer, a HDR layer enclosing the SRV and fractures, an under-burden layer, four hydraulic fractures, one horizontal injection well and one production well. The parameters of this model are adopted from Aliyu & Chen (2017), Song et al. (2018), and Shi et al. (2019a, 2019b). The computational domain is located at a depth of 4500-5500m with the size of 1000m×1000m×1000m. The SRV is 400m×100m×150m located at the center of the computational domain. For the injection and production well, previous researchers (Song et al., 2018, Shi et al., 2019a, 2019b) have modelled these as heat and mass line sources, which is inaccurate and delayed thermal breakthrough in their models. Here, the injection and production wells are point sources, representing the intersection of the production/injection wells with the main fractures. The key physical properties of the model are listed in Tables 1 and 2.

Table 1: Reservoir and fracture properties.

Parameters	Overburden/ Underburden layer	Middle layer	SRV	Fracture
Density (kg/m^3)	2800	2700	2700	n/a
Heat conductivity (W/(m·K))	2	2.8	2.8	n/a
Heat capacity (J/(kg·K))	1000	1000	1000	n/a
Porosity (%)	0.01	0.08	Model A: 8% Model B: 20% Model C: 20%	1
Permeability (m^2)	10^{-18}	5×10^{-17}	Model A: 5×10^{-17} Model B: 4×10^{-14} Model C: 4×10^{-14}	2×10^{-11}

For the initial and boundary conditions, the initial temperature and pressure on the top boundary are 200℃ and 45 MPa. A temperature gradient of 0.04 °C/m and pressure gradient of 8.5 kPa/m is used to set the initial conditions and the lateral boundary conditions. No heat or mass flow are applied at the top and bottom boundaries. The temperature and pressure of side boundaries remain constant at the initial reservoir temperature and pressure. The geometry shown in Fig. 4 is constructed and meshed in COMSOL. A finer mesh is developed in the SRV where the dominant heat and mass flows occur. The segregated solution method is selected to solve the flow and heat transfer coupling equations. Water is injected at 20°C at a rate of 7.5 kg/s, and the production well pressure was set as 35 MPa for a period of 60 years. The properties of water are a function of pressure and temperature and are computed internally by COMSOL.

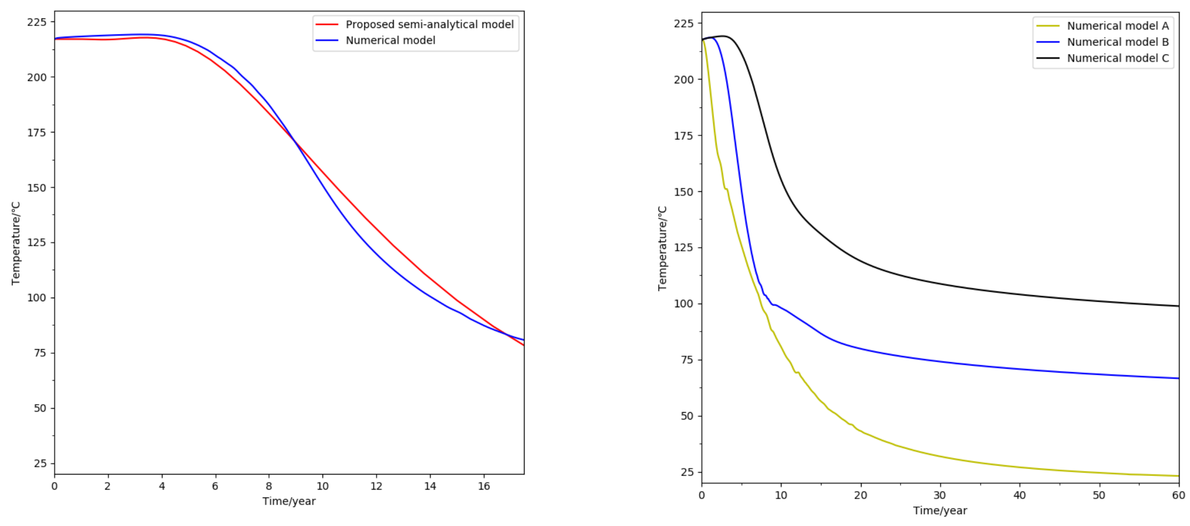
Table 2: Geometrical parameters of the model.

Parameters	Values
Well diameter	0.1 m
Well length	400 m
Fracture aperture	0.002 m
Fracture width	100 m
Fracture height	150 m
Fracture spacing	400/3 m
Well spacing	150 m

3.2 Simulation results

Fig. 5(a) compares the semi-analytical model developed in Section 2 to the COMSOL Model 3. The models broadly agree, both in the timing and rate of production temperature decline, after about 5 years and at a rate of 15° per year. There are small differences between the two models and these can be attributed to: (1) the assumption of linear steady-state flow in the analytical model; (2) constant fluid properties in the analytical model; and (3) geometric effects related to finite fracture dimensions in the numerical model. Nevertheless, the semi-analytical model is a useful first order tool for quickly assessing and optimizing EGS design across a range of different parameters.

The extracted water temperature over 60 years was compared for numerical models A, B and C, described in the previous section. The worst performing model in terms of production temperature is the Gringarten model (A), in which the only mode of heat exchange with the rock matrix is conduction. In this case, thermal breakthrough occurs almost immediately after production begins, and the production temperature rapidly drops to an uneconomic level. Model B is an improvement, delaying thermal breakthrough by several years due to the advective heat exchange of injected water with the surrounding rock. However, once it begins, temperature decline is very rapid. The best configuration is model C, with partially bridging fractures, which delays thermal breakthrough by about five years. Overall, this model has the longest thermal breakthrough time, the lowest rate of temperature decline post breakthrough, and the highest long-term stabilized temperature.

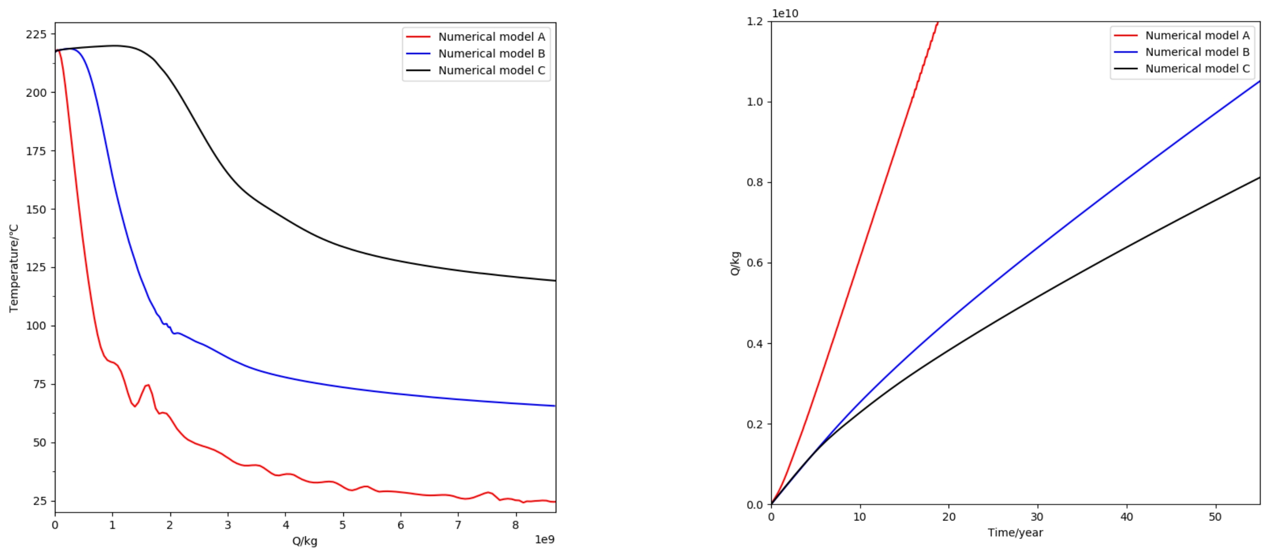


(a) model validation with numerical results

(b) numerical model results comparison

Figure 5: Model validation and numerical simulation results comparison of three cases.

Because the three model configurations have different flow connectivity, water is not produced at the same rate in all cases. Therefore, a fairer comparison of the three regimes is obtained by comparing temperature as a function of total produced mass, Q. This confirms the results of Fig. 5(b), that the EGS design with partially bridging fractures delays thermal breakthrough for longer, and has the highest stabilized temperature.



(a) the relationship between extracted water temperature and produced water mass

(b) the relationship between produced water mass and production time

Figure 6: The relationship of extracted water temperature and produced water mass as well as production time.

Advancement of temperature fronts through the SRV and fractures were also analyzed for the three numerical models (Fig. 7). For Model A (Fig. 7, top row), cooling is limited to the near fracture region accessible by conductive cooling, and is largest adjacent to the injection point. Thermal breakthrough occurs almost immediately, when cool water in the fractures reaches the production well.

In contrast, for model B (Fig. 7, middle row), injected water percolates within the SRV adjacent to the fracture. As the permeability of the SRV is much smaller than the fracture, this exchange is limited and the majority of injected water flows in the fracture. In cooling in the fracture is larger than in the SRV. Although model B delays thermal breakthrough to some extent compared with model A, this well design still does not efficiently extract heat from the SRV.

In contrast to models A and B, temperature changes in model C (Fig.7, bottom row) are limited to alternating fractures connected to the injection well. The thermal front does not reach the production fractures until it has first passed through the SRV, hence increasing the efficiency of the heat sweep. In all models, cooling of the SRV is largest near the injection well, which is a geometric effect not resolved by the semi-analytical model introduced in Section 2.

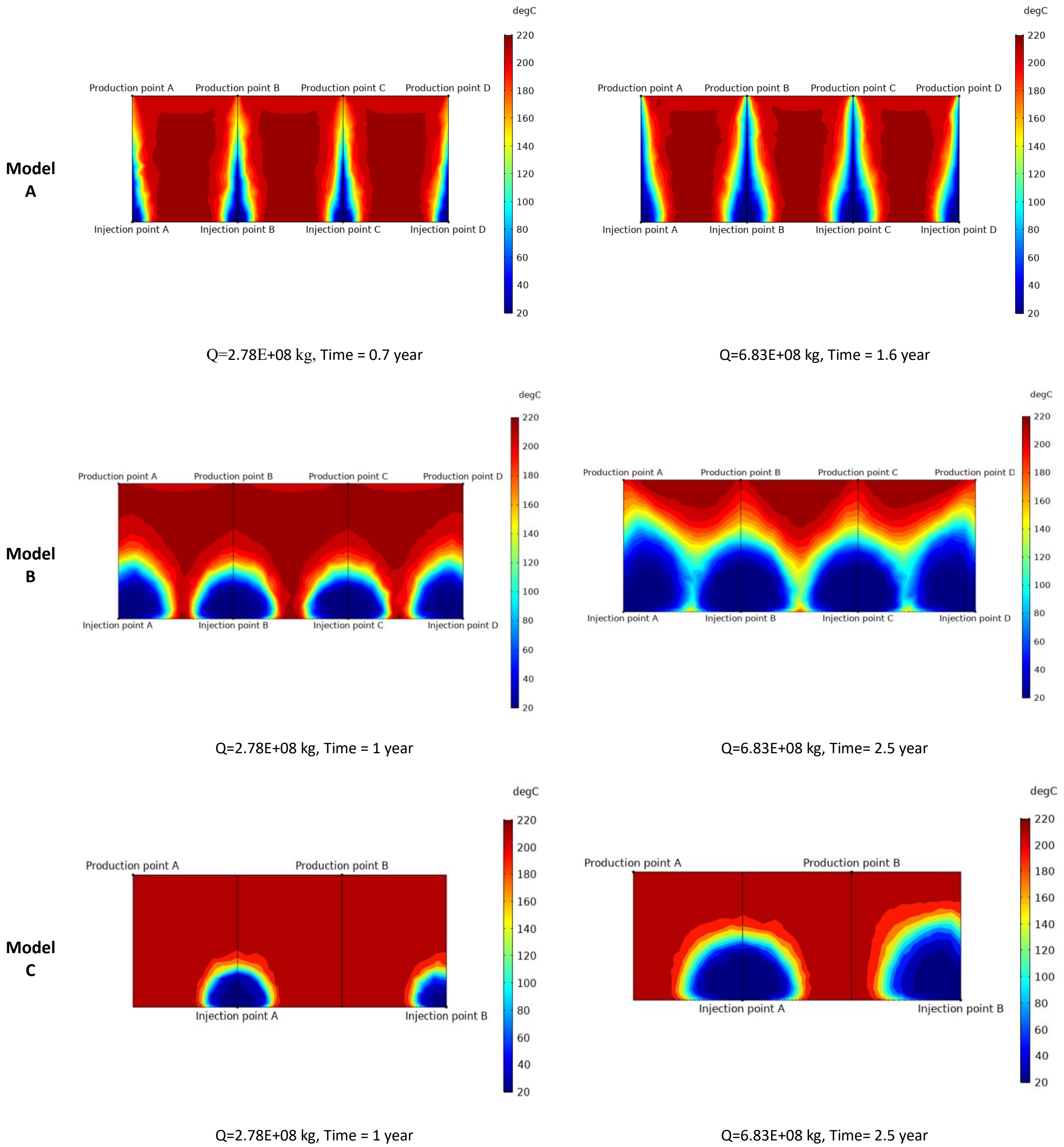


Figure 7: comparison of temperature contours in the SRV at equivalent production masses. (first row) model A, (middle row) model B, (bottom row) model C.

4. CONCLUSION

In this study, we introduced a new horizontal EGS well design that utilizes partially bridging multi-stage hydraulic fractures. A semi-analytical 1D model and a 3D numerical model were developed to illustrate the new design and compare its heat extraction performance to other design. The design model with partial bridging fractures was shown to maintain higher production temperatures over a longer period of time than fully-bridging designs. The improvement derives from the new design forcing water to flow through the SRV rather than potentially short-circuiting through the fracture. This increases the size of heat exchange zone and hence the overall performance of the system. A sensitivity analysis of fracture parameters indicates that long term performance is improved for more fracture stages and at large spacing. These models can be used in conjunction with an economic model to optimize the performance of future EGS projects.

APPENDIX A

In order to solve the governing equations, the following dimensionless parameters T_{DSRV}, t_D, x_D, δ are defined:

$$T_{DSRV} = \frac{T_{SRV} - T_0}{T_i - T_0} \qquad x_D = \frac{x}{z_F}$$

$$t_D = \frac{\lambda_{SRV} t}{\left[\phi_{SRV}\rho_w c_w + \left(1-\phi_{SRV}\right)\rho_r c_r\right] z_F^{\,2}} \qquad \delta = \frac{\rho_w c_w v_{SRV} z_F}{\lambda_{SRV}}$$

The dimensionless parameters are substituted into the governing equations, boundary conditions, and initial conditions yielding a corresponding set of dimensionless equations. The governing equations in the SRV become:

$$\begin{cases} \dfrac{\partial T_{DSRV}}{\partial t_D} + \delta \dfrac{\partial T_{DSRV}}{\partial x_D} - \dfrac{\partial^2 T_{DSRV}}{\partial x_D^2} = 0 \\ T_{DSRV}\left(x_D, z_D, t_D = 0\right) = 0 \\ T_{DSRV}\left(x_D = 0, z_D, t_D\right) = 1 \\ T_{DSRV}\left(x_D \to +\infty, t_D\right) = 0 \end{cases} \tag{A1}$$

Applying Laplace transformation for Eqs. (A1), we obtain:

$$\begin{cases} \dfrac{\partial^2 \overline{T_{DSRV}}}{\partial x_D^2} - \delta \dfrac{\partial \overline{T_{DSRV}}}{\partial x_D} - s\overline{T_{DSRV}} = 0 \\ \overline{T_{DSRV}}\left(x_D = 0\right) = \dfrac{1}{s} \\ T_{DSRV}\left(x_D \to +\infty\right) = 0 \end{cases} \tag{A2}$$

The universal solution of Eq. (A2) is:

$$\overline{T_{DSRV}}\left(x_D, z_D\right) = c_1 e^{r_1 x_D} + c_2 e^{r_2 x_D} \tag{A3}$$

$$r_1 = \frac{\delta}{2} + \frac{1}{2}\sqrt{\delta^2 + 4s} \tag{A4}$$

$$r_2 = \frac{\delta}{2} - \frac{1}{2}\sqrt{\delta^2 + 4s} \tag{A5}$$

$$c_1 = 0; c_2 = \frac{1}{s} \tag{A6}$$

Therefore, the expression of temperature in the stimulated reservoir volume is:

$$\overline{T_{DSRV}}\left(x_D, z_D\right) = \frac{1}{s} e^{r_2 x_D} \tag{A7}$$

The above analytical solutions could be numerically transformed into time-space based on the Stehfest numerical inversion algorithm (Stehfest, 1970; Stehfest & Harald, 1970).

REFERENCES

Abbasi, M., Khazali, N., & Sharifi, M. Analytical model for advection-conduction heat transfer during water injection in fractured geothermal reservoirs with variable rock matrix block size. *Geothermics*, **69**, (2017) 1–14.

Abbasi, M., Madani, M., Keshavarz Moraveji, M., & Sharifi, M. Effects of Advection and Fracture Boundary Conditions on Heat Transfer Shape Factor in Fractured Geothermal Reservoirs. *Transport in Porous Media*, **125(2)**, (2018), 357–375.

Abbasi, M., Mansouri, M., Daryasafar, A., & Sharifi, M.. Analytical model for heat transfer between vertical fractures in fractured geothermal reservoirs during water injection. *Renewable Energy*, **130**, (2019a), 73–86.

Abbasi, M., Mansouri, M., Daryasafar, A., & Sharifi, M.. Analytical model for heat transfer between vertical fractures in fractured geothermal reservoirs during water injection. *Renewable Energy*, **130**, (2019b), 73–86.

Aliyu, M. D., & Chen, H.-P. Sensitivity analysis of deep geothermal reservoir: Effect of reservoir parameters on production temperature. *Energy*, **129**, (2017),101–113.

Asai, P., Panja, P., McLennan, J., & Moore, J. Performance evaluation of enhanced geothermal system (EGS): Surrogate models, sensitivity study and ranking key parameters. *Renewable Energy*, **122**, (2018), 184–195.

Asai, P., Panja, P., McLennan, J., & Moore, J. Efficient workflow for simulation of multifractured enhanced geothermal systems (EGS). *Renewable Energy*, **131**, (2019), 763–777.

Asai, P., Panja, P., Velasco, R., McLennan, J., & Moore, J. Fluid flow distribution in fractures for a doublet system in Enhanced Geothermal Systems (EGS). *Geothermics*, **75**, (2018), 171–179.

Gringarten, A. C., Witherspoon, P. A., & Ohnishi, Y. Theory of heat extraction from fractured hot dry rock. *Journal of Geophysical Research*, **80(8)**, (1975), 1120–1124.

Jung, R. EGS — Goodbye or Back to the Future (2013).

Li, M., Gou, Y., Hou, Z., & Were, P. Investigation of a new HDR system with horizontal wells and multiple fractures using the coupled wellbore–reservoir simulator TOUGH2MP-WELL/EOS3. *Environmental Earth Sciences*, **73(10)**, (2015), 6047–6058.

Li, T., Shiozawa, S., & McClure, M. W. Thermal breakthrough calculations to optimize design of a multiple-stage Enhanced Geothermal System. *Geothermics*, **64**, (2016), 455–465.

Shi, Y., Song, X., Li, J., Wang, G., YuLong, F., & Geng, L. Analysis for effects of complex fracture network geometries on heat extraction efficiency of a multilateral-well enhanced geothermal system. *Applied Thermal Engineering*, **159**, (2019), 113828.

Shi, Y., Song, X., Wang, G., Li, J., Geng, L., & Li, X. Numerical study on heat extraction performance of a multilateral-well enhanced geothermal system considering complex hydraulic and natural fractures. *Renewable Energy*, **141**, (2019), 950–963.

Shiozawa, S., & Mcclure, M. EGS Designs with Horizontal Wells, Multiple Stages, and Proppant. *Proceedings,* 39th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (2014).

Song, X., Shi, Y., Li, G., Yang, R., Wang, G., Zheng, R., Lyu, Z. Numerical simulation of heat extraction performance in enhanced geothermal system with multilateral wells. *Applied Energy*, **218**, (2018), 325–337.

Stehfest, H. Algorithm 368: Numerical inversion of Laplace transforms [D5]. *Communications of the ACM*, **13(1)**, (1970), 47–49.

Stehfest, H., & Harald. Remark on algorithm 368: Numerical inversion of Laplace transforms. *Communications of the ACM*, **13(10)**, (1970),624.

Tester J. *The Future of Geothermal Energy in the 21 Century Impact of Enhanced Geothermal Systems (EGS) on the United States st* (2006).