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Performance of Fractured Geothermal Reservoirs: Utilizing Water Jet Drilled Laterals

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ABSTRACT

Utilizing the Radial Jet Drilling (RJD) technology in the existing geothermal wells has been considered recently for improving the productivity or injectivity of the wells. In this study, the application of RJD in naturally fractured reservoirs with an injection well and a production well is explored using a coupled THM three-dimensional DFM (discrete fracture-matrix) model. To this end, several cases of fracture models with different fracture spacing are employed to explore the impact of the RJDs on the performance of the geothermal doublet. Results show that for most cases, the required pressure differences are decreased due to the application of RJD laterals. We also observe that the produced temperature is affected by the application of RJD in high and low fracture spacing. The observed adverse effect on the high fracture spacing cases can be attributed to linking the producer well to fractures between both wells by the RJD laterals. On the other hand, the favorable impact on the produced temperature observed in the low fracture spacing case is due to connecting the wells to the fractures outside the area between the wells. Different key performance indicators are considered for featuring the conditions under which the application of RJD is favorable. By comparing different injection rate, fracture spacing, and rock matrix permeability, we find that in order to gain the best performance of RJD it is important to direct RJD laterals in the direction outside the area between the wells aiming at increasing the effective volume of the reservoir.

1. INTRODUCTION

There is an increased interest in recovering geothermal energy from deep geological resources. Doublet systems, including injection and producer wells, are commonly utilized to harvest heat from subsurface media (e.g. Willems and Nick, 2019). Naturally fractured reservoirs are suitable media for the geothermal project since fractures can act as heat exchangers facilitating heat extraction from hot rocks. Fractures can also provide sufficient effective permeability to avoid unfavorable injection pump pressure for circulating the fluid in the reservoir between the injection and production wells (e.g. Vik et al., 2018). The fracture connectivity and spacing have a direct impact on the performance of the geothermal systems. For reservoirs with low matrix permeability, the well connections through the fractures are essential. Stimulation treatments could be applied to facilitate the connectivity.

Drilling multiple laterals from a single well bore is a way to improve the reservoir connectivity. Coiled tubing conveyed jet drilling assemblies have been investigated for multilateral drilling in reservoirs. Radial jet drilling (RJD) uses the power of a focused fluid jet with full control on the operational parameters such as the initial direction of the lateral and length. This method can be applied to drill multiple laterals of about 100 m length out of the main wells providing an alternative to conventional hydraulic stimulation treatments. This method has been applied for oil wells to improve injectivity or productivity (Cirigliano and Talavera Blacutt, 2007). Last years several studies have been performed on this technology (Reinsch et al., 2020). Reinsch et al., 2018 performing the jetting experience in a sandstone quarry observed that the jetted laterals can intersect fractures under varying angles; however, the laterals may not follow a straight path under the ambient condition. Medetbekova et al., 2019 studied the impact of *in-situ* stress conditions on the jetting performance in chalk. Stability of jetted holes has been also analyzed in several studies (Bakker and Barnhoorn, 2019; Medetbekova et al., 2018).

A coupled Thermal-Hydraulic-Mechanical numerical model has been developed to study the performance of geothermal doublet systems with fractures and the water jetted laterals. Salimzadeh et al., (2018a) employing the coupled model showed that in fractured geothermal doublet system, the creation of flow channeling due to the thermal volumetric contraction of the rock matrix is very likely. This is because the injected fluid interacts with the rock matrix resulting in cooling down of the matrix and ensuing volumetric deformation. This reduces the contact stress on the fracture surfaces and increases the fracture aperture locally and creates channelized flow in the middle of the fractures. Salimzadeh et al., (2019) performed numerical simulations to highlight the advantages of applying RJD in fractured rock. Their simulations were conducted on fracture geometries with different fracture density and length. They illustrated that the RJD laterals can improve injectivity, productivity, and heat production from fractured aquifers. They showed that utilizing RJD laterals to connect the main wellbore to the fractures in reservoirs with low fracture density is the most effective setting among different scenarios considered in their study.

Here we demonstrate how applying the radial jetting technology in both injection and production wells influence the performance of a geothermal doublet system in naturally fractured reservoirs. We achieve this by utilizing a novel discrete fracture generator (Welch and Luthje, 2018) and a coupled Thermal-Hydraulic-Mechanical (THM) model (Salimzadeh and Nick, 2019). The first provides fracture geometries and the second simulates flow and heat transfer in a reservoir for different conditions. We compute different key performance indicators of the system to examine the impact of the stimulation method. We further aim to discuss the conditions under which the stimulation method is favorable.

2. METHODOLOGY

We use the workflow presented in Salimzadeh et al., (2019) for simulating flow and heat transfer in the fractured reservoir. Figure 1 shows three examples of three-dimensional fracture networks (hereafter referred to as low, medium and high fracture spacing cases) employed for this study. The network covers an area of 3000 by 3000 m with 100 m thickness and contains 2023, 171 and 177 fractures in a highly-connected arrangement. P_{31} and P_{32} of the three cases are listed in Figure 1. Note that both medium and high spacing facture cases contain longer fractures compared to those in the low fracture spacing case. We consider a reservoir with an initial temperature of 80 ^{o}C, an initial fluid pressure of 20 MPa, and matrix porosity of 25%. Young's modulus and Poisson's ratio are set to 20 GPa and 0.25 with an isotropic *in situ* stress of 35 MPa. Solid ($_s$) and fluid ($_f$) heat capacities (C) and thermal conductivities (λ) are set to 790 and 4180 J/kgC 3.5 and 0.6 W/mC, respectively. The volumetric thermal expansion for solid and fluid of 2.4×10^{-5} and 7.66×10^{-4} 1/C and the fluid compressibility of 4.6×10^{-10} Pa^{-1} are assumed. We assume water as the working fluid with a density (ρ) of 1000 kg/m^3. The left, right, back and front boundaries are open for flow while the top and the bottom sides are assigned a no flow boundary condition. The Barton-Bandis model is used to express the fracture aperture in terms of the contact stress:

$$a_f = a_0 - 7.3\times 10^{-9}\sigma_n/(1+6.6\times 10^{-7}\sigma_n), \tag{1}$$

where σ_n is the normal component of the contact stress over the fracture and a_0 is the initial fracture aperture. We assume an initial aperture of 0.001 m for the simulations with rigid rock matrix and 0.01 m for the simulations with deformable rock matrix. Water viscosity (η) is also defined as a function of the fluid temperature:

$$\eta = e^{A+\frac{B}{C+T}} \tag{2}$$

This relation is valid for water temperature (T) between 273 and 373 K. The parameters A, B, and C are equal to -3.7188, 578.919, and -137.546, respectively. We conduct 36 simulations with the parameters summarized in Table 1. All the simulations are conducted for 50 years in this study. Both the injection and production wells are located in the rock matrix and intersect at least one fracture. The intersection is a point since the wells are verticals and all the fractures are inclined in depth. The distance between the wells are kept constant for all the simulations and is equal to 1017 m. For the model with RJD we apply four perpendicular laterals of 100 m at the middle of both wells.

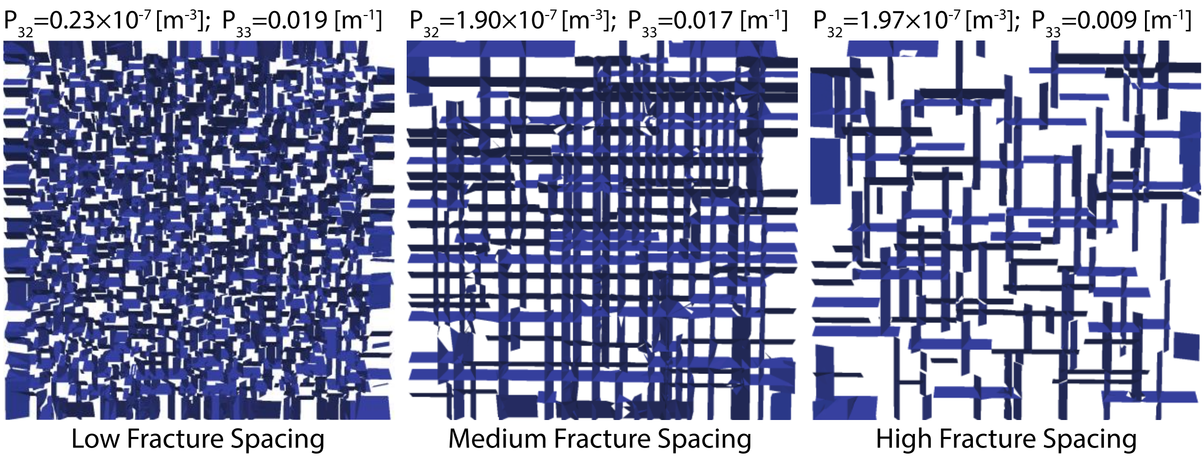

Figure 1: Top view of the fracture geometries of low, medium, and high fracture spacing cases together with the P_{31} and P_{32} values. The geothermal reservoir consists of a single layer of thickness 100 m and lateral extent of 3 km by 3 km.

Table 1: A summary of simulation varying parameters (total number of simulations are 36)

Parameter	*Fracture spacing ($1/P_{11}$)*	*Injection rate*	*Matrix permeability*	*Stimulation*
Magnitude	75, 150, and 300 m	0.05, 0.1, and 0.2 m^3/s	1 and 100 mD	no RJD and 4×100m laterals
Notation	L, M, and H	Q_1, Q_2, and Q_3	Km_1, Km_{100}	-, RJD
Number of cases	3	3	2	2

2.1 Key performance indicators

In order to measure the importance of different parameters the following parameters are defined:

1. Life time: LT_1 and LT_{10} of geothermal heat recovery defined as the time (in years) when the temperature of the production well decreases by 1 °C and 10 °C, respectively.
2. Net energy production: $E_{net}=E_{prod} - E_{pump}$
3. Coefficient of Performance: COP = E_{prod} / E_{pump}

4. Energy sweep: $S = E_{prod} / E_R$

where E_{prod} is the energy produced from production well and E_{pump} is an estimation of pump energy losses in which ε is the pump efficiency of 60%, and doublets. These are calculated for the life time of the system LT_n (n=1 or 10). E_R is the available reservoir energy of the entire domain.

$$E_{prod} = (\rho C)_f Q \int_{t=0}^{LT_n} (T_{prod} - T_{inj}) dt \tag{3}$$

$$E_{pump} = \frac{Q}{\varepsilon} \int_{t=0}^{LT_n} (P_{inj} - P_{prod}) dt \tag{4}$$

3. RESULTS

In this section, we first show the result of the simulations with rigid rock matrix for which the fracture aperture remains constant in time. The different cases vary in the spacing of the fractures, RJD laterals, matrix permeability, as well as the injection rate.

Figure 2 and 3 depict the temperature field for three geometries of Q_3 and Q_2, and for different matrix permeability and with and without RJD treatment. The following observations can be made:

1. By increasing the fracture spacing, the heat extraction from the matrix decreases due to less interaction between the matrix and fractures. This effect is more pronounced for lower fracture-matrix permeability ratio (k_f/k_m).

2. The impact of RJD laterals is limited to the area near the production and injection wells. For example, for the high fracture spacing case (H), the RJD laterals connect the production well to a fracture north of the producer. While this connection improves the well productivity, it may result in earlier produced temperature drop as the effective distance between the producer and injector becomes shorter.

3. The impact of fractures on the cold plume development becomes less distinct for higher matrix permeability. This results in the smaller cold plume.

4. Similar to increasing the matrix permeability, by reducing the injection rate more efficient heat exchange occurs between the fractures and the hot rock matrix. This improves the sweep for all the fracture geometries.

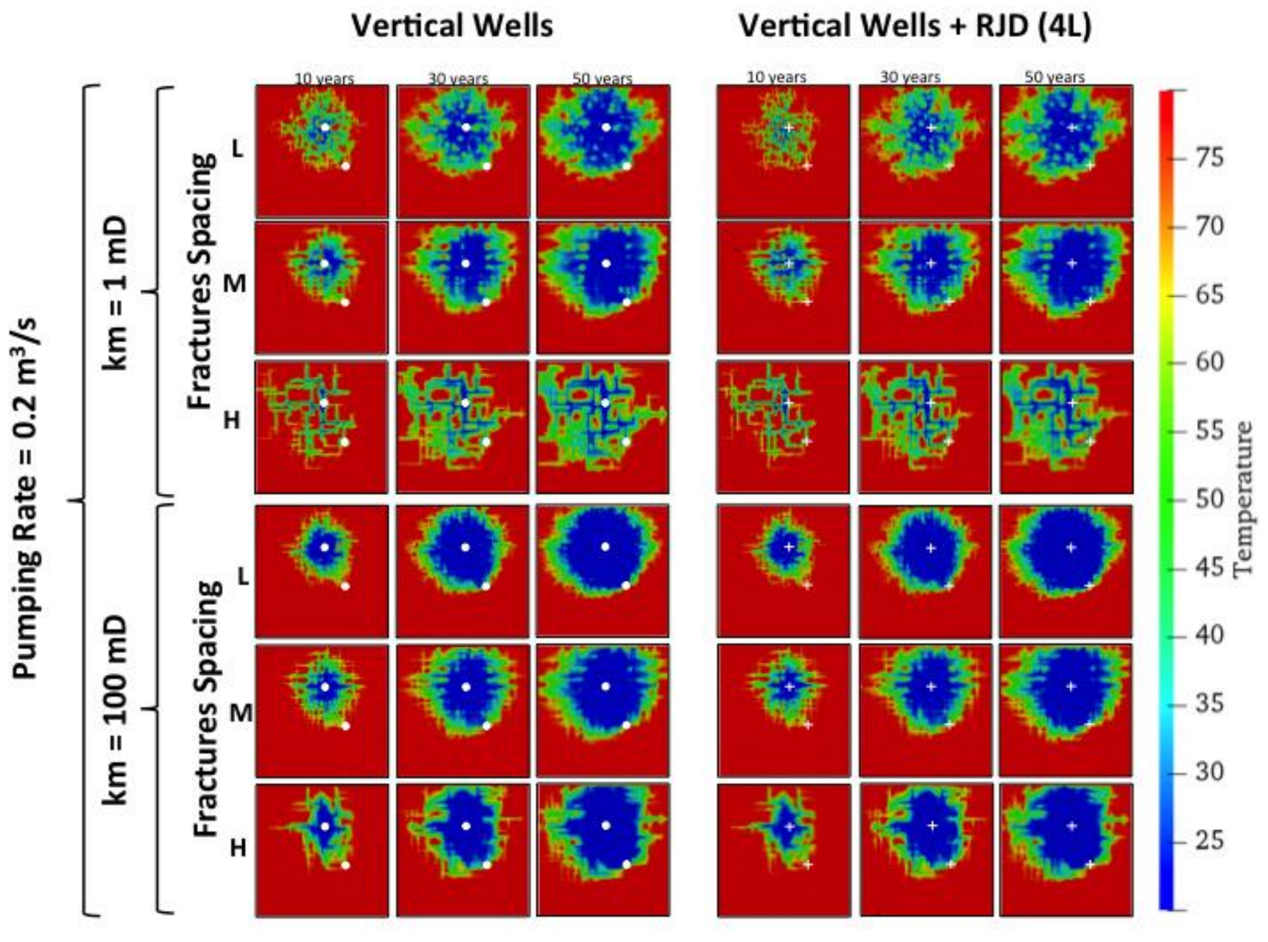

Figure 2: Temperature field after 10, 30, and 50 years of simulation for the case with and without RJD laterals for different matrix permeability values and Q_3. The location of the wells and four laterals are shown with white symbols.

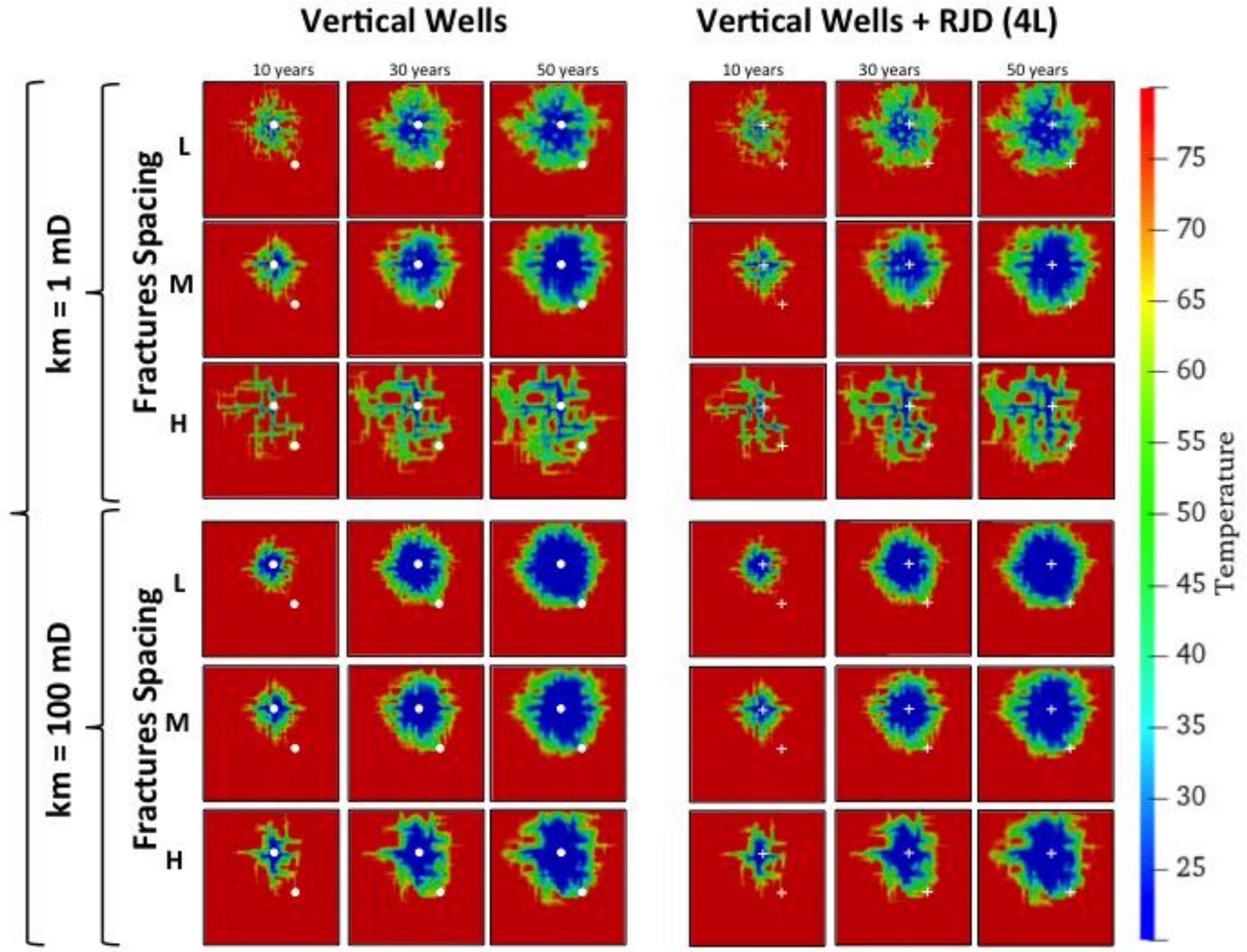

Figure 3: Temperature field (top view) after 10, 30, and 50 years of simulation for the case with and without the RJD laterals and for different matrix permeability values and Q_2. The location of the wells and four laterals are shown with white symbols.

In order to demonstrate the impact of the laterals on the performance of the doublet system, the heat production and the pressure difference between the wells are shown in Figures 4 and 5. The following features are observed:

1. For most cases, the required pressure differences are decreased due to adding the RJD laterals. This effect is more evident for the reservoir with low fracture spacing.

2. The temperature dependence of the viscosity clearly influences the well pressures. As the cold plume progresses, higher pump pressure is required for injection of the cold water.

3. Viscose cross flow also creates conductive flow path inside the rock matrix. This effect is noticeable in the reservoirs with higher matrix permeability.

4. The produced temperature is affected by the application of RJD in the high and low fracture spacing. The observed adverse effect in the high and low fracture spacing cases can be attributed to linking the producer well to fractures between both wells by the RJD laterals. The favorable impact on the produced temperature observed in the medium fracture spacing case is due to connecting the wells to the fractures outside the area between the wells.

5. The impact of RJD on the produced temperature is limited for the cases with higher permeability. The effect is more important for the cases with the highest injection rates.

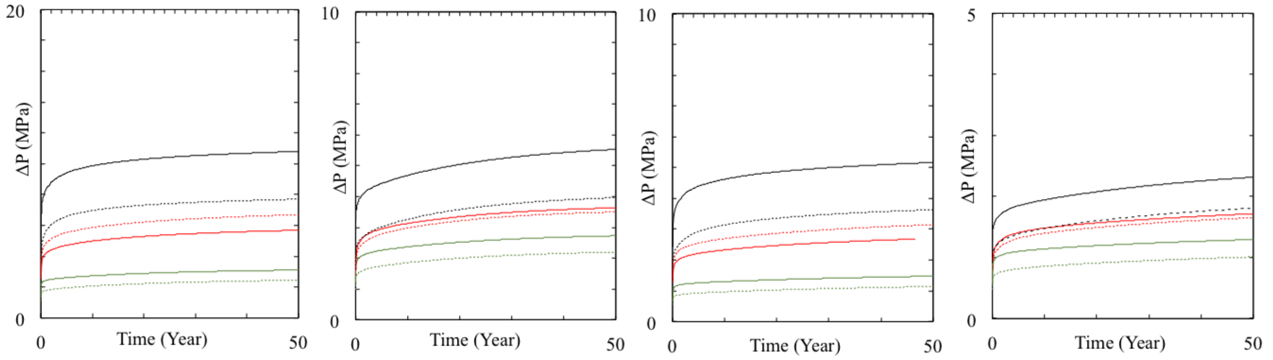

Figure 4: The pressure difference between injector and producer wells during 50 years of simulation for low (L), medium (M), and high (H) fracture spacing examples. The plots from left to right are: a) Q_3 Km_1, b) Q_3 Km_{100} , c) Q_2 Km_1 , and d) Q_2 Km_{100} . The solid lines show cases without RJD laterals; the cases with RJD laterals are shown with dashed lines. Black, green, and red lines are for H, M, and L cases, respectively.

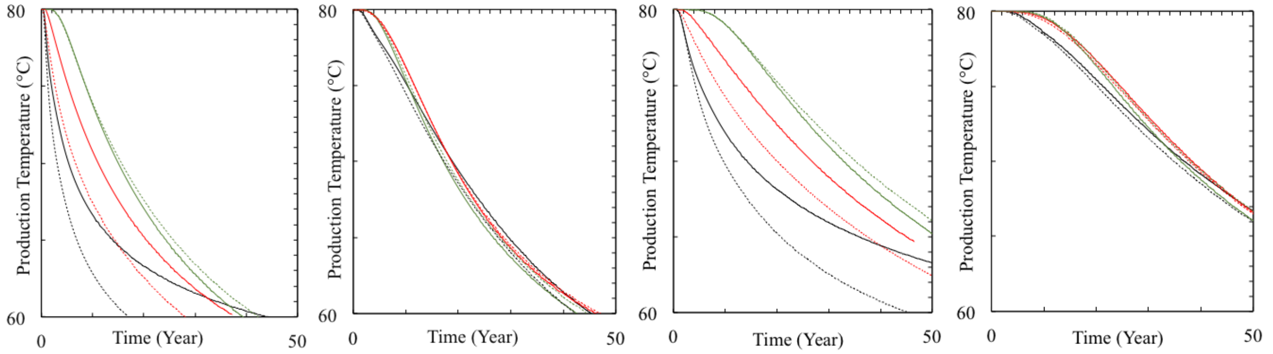

Figure 5: Temperature breakthrough curves during 50 years of simulation for low (L), medium (M), and high (H) fracture spacing examples. a) Q_3 Km_1, b) Q_3 Km_{100} , a) Q_2 Km_1 . The solid lines show cases without RJD laterals, the cases with RJD laterals are shown with dashed lines. Black, green, and red lines are for H, M, and L cases, respectively. The plots from left to right are: a) Q_3 Km_1, b) Q_3 Km_{100} , c) Q_2 Km_1 , and d) Q_2 Km_{100} .

Figure 6 shows the normalized changes of Coefficient of Performance (CoP) Energy Sweep (S), E_{pump}, E_{net}, and lifetime (LT) as a function of injection rates for different matrix permeability and fracture geometries caused by the application of RJDs. The values are normalized against the result of cases without RJD. As mentioned before for most cases the RJD improves the energy required for the pump. This also has a direct impact on the E_{net} and COP. While the same trend is observed for COP the net energy is influenced by the RJD differently. The life time is decreased for many of the low and high fracture spacing cases. The adverse effect of RJD on sweep is also evident which can be mainly attributed to the reduced lifetime. The impact of RJD on the performance indicators is more significant for the cases with lower matrix permeability. Increasing the injection rate is more effective in changing E_{net} . In summary RJDs have positive impact on both COP and E_{pump} but negative impact on the lifetime which also influences E_{net} and S. These results suggest that in order to gain the best performance of RJD it is important to direct RJD laterals in the direction outside the area between the wells aiming at increasing the effective volume of the reservoir.

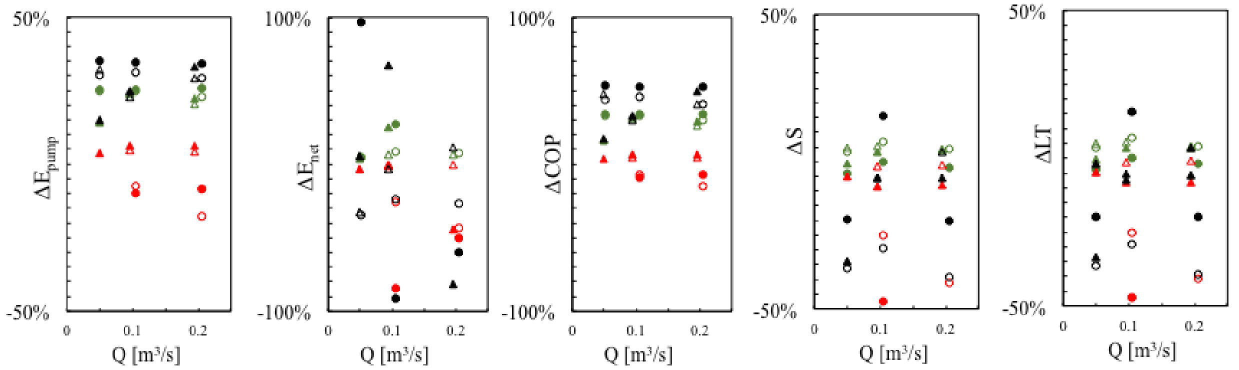

Figure 6: The normalized differences of COP, E_{pump}, E_{net}, LT, and S between the RJD and no RJD cases for Km_1 (circle symbols) and Km_{100} (triangle symbols). The filled symbols represent the results at LT_1, and the empty symbols represent the results for LT_{10} . Black, green and red colors are for H, M, and L cases, respectively.

While the fracture apertures were constant in previous simulations, another set of simulations with a deformable matrix in which the fracture apertures follow the Barton-Bandis model given in Eq. (1), are performed. The results for the pressure, pressure difference (Δp) and production temperature for the deformable matrix are illustrated in Figure 5. Better injectivity is observed for the deformable case, compared to the constant aperture cases (rigid matrix). This is due to the increase in the fracture apertures due to the reduction in the contact stress around the injection well (Salimzadeh et al., 2018b). Both the poroelastic and thermoelastic deformation of the matrix and fracture contribute in the reduction of the contact stress. The deformability of the matrix has less influence on the heat production with a negative effect on the heat production in this case. This is mainly because of adverse induced channeling for the deformable case.

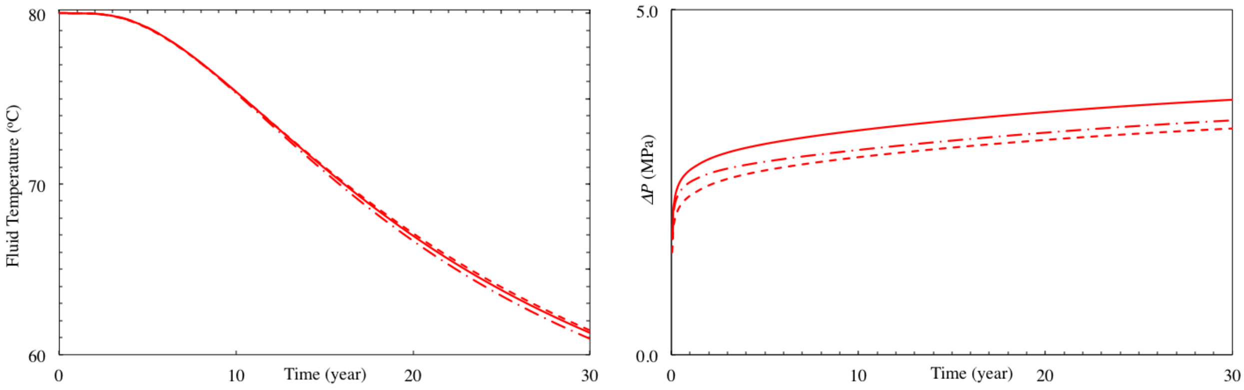

Figure 7: Low fracture spacing example: Left) Production fluid temperature evolution and Right) the pressure difference between injector and producer wells during 30 years of simulation for without RJD and rigid matrix (solid line), without RJD and deformable matrix (dotted dashed line), with RJD and rigid matrix (dashed line).

4. CONCLUSIONS

This paper reports results of coupled THM simulations for fractured reservoirs. We investigate the role of utilizing radial jet drilling technology as a stimulation method on improving performance of the geothermal doublets. The following conclusion arising from this analysis can be drawn:

1. The fracture distribution, spacing, and connectivity around the wells dictate whether application of RJD in fractured rock with low matrix permeability cause a negative or positive impact on the produced energy and the doublet lifetime.
2. Reduction of the distance between the wells by applying RJD laterals reduces the lifetime of the system. Thorough design of the direction of the RJD laterals is therefore important for improving the performance of the system.
3. The produced energy is less sensitive to the application RJD laterals for the reservoirs with high matrix permeability.
4. The well injectivity and productivity improvements by the laterals are evident for almost all cases. The best performances are observed for the cases with the highest fracture spacing.

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