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Comparison of EGS Thermal Performance with CO2 and Water as Working Fluids

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ABSTRACT

The primary objective of this investigation was to compare the thermal performance of an enhanced geothermal system (EGS) with supercritical carbon dioxide (CO2) and water as working fluids. A major consideration in this study is the possibility that fractures may have spatial variations in aperture and it is relevant to understand the impact of the heterogeneous aperture distribution on EGS performance using CO2 in place of water. The system being modeled is a doublet EGS system.

First a study was done to determine how the mass flowrates of CO2 and water could impact thermal performance. The fracture was considered to be parallel plates. The results showed that there was an optimal water mass flowrate above which the rate of heat extraction was constant. Such a deduction could not be made for CO2, as the mass flowrate was determined not to be a sufficient metric for comparing the two fluids.

By choosing a mass flowrate that ensured the same energy input for CO2 and water, a comparative study on the two fluids could be done. The study showed that if the fracture aperture is smooth i.e., modeled as parallel plates, for the same energy injected, CO2 results in higher energy produced compared to water. However, if the fracture has spatial variations in aperture, in the long term, water is a better working fluid for EGS. This is because as the temperature in the system drops, the viscosity of water increases much more than that of supercritical CO2. This is advantageous in that the mobility of water reduces, creating more contact with the hot rock and consequently more heat extracted from the rock. CO2 on the other hand is impacted more by channeling due to its low viscosity and higher mobility compared to water.

1. INTRODUCTION

Enhanced or Engineered Geothermal Systems (EGS) are emerging technologies that have the potential to increase the geothermal capacity in the US (Tester, et al, 2006) and consequently expand the reach to locations without natural geothermal resources. An Enhanced Geothermal System involves extracting heat from a hot subsurface rock, which lacks natural permeability sufficient for fluid flow, by creating a fracture system through which a cold fluid can be passed from injection wells to production wells. The fracture system creates permeable pathways that allow the injected cold fluid to be heated up by direct contact with the surrounding hot matrix. One or more production wells return the heated fluid to ground surface for electricity generation or for direct-use heating/cooling.

Enhanced Geothermal Systems are still in the research and demonstration phases. Most studies and field tests on EGS have used water as the working fluid. However, Brown (2000) proposed a novel renewable energy concept wherein supercritical CO2 could be used in place of water for both reservoir creation and heat extraction. The work by Brown (2000) highlighted the advantageous properties of CO2 over water including a higher density-to-viscosity ratio, a larger buoyancy force, and lower salt solubility. Since then, several studies (Pruess, 2006; Luo and Jiang,2014; Isaka et al., 2019; and Wu and Li, 2020) have built on the work of Brown (2000) with many studies confirming the findings that supercritical CO2 provides greater power output and can simultaneously sequester CO2. Moreover, the studies have shown that the use of CO2 minimizes parasitic losses from pumping and cooling, reduces the use of water, and could reduce scaling and corrosion of system components due to CO2 having a much lower tendency to dissolve minerals and other substances compared to water. On the other hand, (Pritchett 2009) considered multiphase flow effects during the heat mining and CO2 sequestration process and found that heat sweeping effectiveness can be maximized if water is used as a working fluid in place of CO2. This was cited as due to the development of an unstable material interface between the low-viscous injected CO2 and more viscous native water, resulting in the more mobile CO2 bypassing the relatively higher viscosity regions and reducing the overall thermal sweep efficiency.

Fractures are usually the main flow conduit in EGS, predominantly created through hydroshearing (Gischig and Preisig, (2015)). This leads to fractures that are self-propped due to mismatched asperities across the two fracture surfaces. Several studies (e.g., Abelin, et al., 1991; Hakami and Larsson, 1996; Tsang and Neretnieks, 1998; Tester, et al., 2006; Watanabe, et al., 2008; Co, Pollard and Horne, 2017, Mattson, et al., 2018; Hawkins, et al., 2018) have demonstrated at various scales that variation in fracture aperture can lead to flow channeling where the fluid moves along a preferential flowpath. In an EGS, cold injectate is circulated through one or more fractures in the hot rock reservoir and fluid collection at one or more producers returns the heated working fluid to ground surface. Therefore, heat is recovered only across the effective heat transfer area available between injectors and producers. Under channeled flow conditions, a relatively reduced heat transfer area can lead to inadequate heat transfer efficiency (e.g., Neuville, et al., 2010) and, as a consequence, cause premature thermal breakthrough and reduced energy recovery (Co, 2017; Hawkins, et al., 2017; 2018). These studies have considered water as the injected fluid and there are few studies describing the behavior of CO2 as a working fluid in the presence of fractures with spatial variations.

Zhang, et al. (2017) carried out a lab scale investigation comparing the heat transfer behavior of supercritical CO2 on a rough fracture and a smooth fracture at different mass flow rates and different rock temperatures. The study showed that heat transfer in the rough fracture was hindered by channeling effects. Their study however does not compare how water would perform in a similar situation. Moreover, the behavior of fluids varies with factors such as temperature and pressure hence it is of interest to understand how the heat transfer on both rough and smooth fracture compares for CO2 and water on the field scale considering in-situ conditions.

Because channeling and short circuiting are common occurrences with water as a working fluid for EGS, this study contrasts the performance of CO2 with water, and evaluates the behavior of the fluids in the presence of rough fractures with spatial variations. The operating conditions modeled in this study ensured that CO2 remained in the supercritical state.

2. METHODS

2.1 Model Description

The system modeled is a hypothetical EGS doublet consisting of a single injector/producer well-pair circulating the working fluid through a single fracture contained within hot, impermeable rock. Relatively cold injectate is heated by the surrounding rock and then recovered at a single production well. The fracture is horizontal, measuring 1000 m x 1000 m at a depth of 1295.5 m below ground surface, and is embedded within the relatively impermeable bulk rock matrix. Horizontal wells, one injection and one production, are placed at the edges of the fracture. The numerical model is a 50 by 50 by 70 grid. In the X and Y directions, the individual cells are of uniform length of 20 m while in the Z direction, the thicknesses are very fine around the fracture and become coarser away from the fracture. Figure 1 shows a snapshot of the reservoir simulation domain.

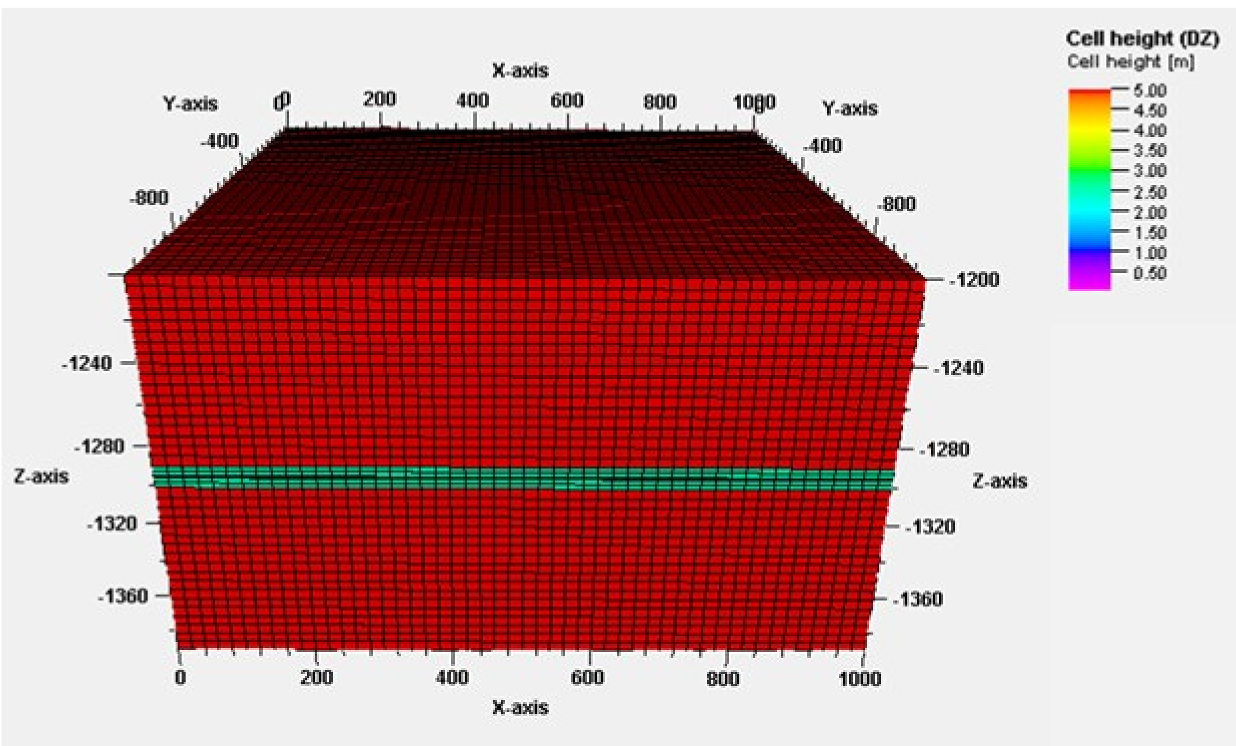

Figure 1: The hypothetical EGS model showing the grids. The height (Z-axis) is not to scale.

The coupled flow and heat transport mechanism are modeled with a three-dimensional compositional numerical simulator - ECLIPSE. ECLIPSE is a finite-difference simulator and was run in the fully implicit mode, using Cartesian block-center geometry in three dimensions for flow and heat transport. The simulator has been verified for geothermal applications by Stacey and Williams (2017) and Okoroafor and Horne (2018).

For this study, we compared the thermal performance of the EGS using water and CO2. The original reservoir fluid was considered to be water, and due to the low porosity and permeability of the matrix, the CO2 sequestration does not take place. For the case of water as the working fluid, the Thermal option of the simulator was used. The formulation of equations used to describe thermal processes can be found in Schlumberger (2016) and has three important differences from a general compositional simulator with the addition of an energy variable and an energy equation; the presence of a water component in the gas phase as well as the water phase; and temperature dependence of properties. The thermodynamic properties of water are based on the International Association for the Properties of Water and Steam (IAPWS-IF97) (Wagner, et al., 2000) using the keyword: THSTT97. For the case of CO_2 as the injected fluid, the Thermal CO2STORE option is used. The fluid properties are defined similarly to a standard thermal case, but the CO_2 component is allowed to dissolve in the aqueous phase. The CO_2: H_2O phase splitting, activity coefficient models and CO_2 density follow the procedure given by Spycher and Pruess (2005) and Spycher and Pruess (2009). CO_2 viscosity is calculated from the procedure outlined in Fenghour, et al. (1998). Other rock and fluid properties used in the model are presented in Table 1.

The initial reservoir conditions are 200 °C and 12 MPa while the injection conditions are 40 °C and 15 MPa. For CO_2, the bottom hole pressure of the producer does not go below 7.4 MPa throughout the simulation time to ensure the fluid in the reservoir remains in supercritical condition. Temperature and pressure losses within the wellbores were not modeled in this study.

Table 1: Rock and fluid properties, and other parameters used in the model

Symbol	Description	Value	Units
$\emptyset$	Porosity of the formation	0.01	-
k	Permeability of the formation matrix	9.86923266716E-21	m^2
K_r	Thermal Conductivity of rock	2.8	W/m/K
C_r	Specific heat capacity of rock	1600	J/kg/K
μ	Dynamic viscosity of water	0.00013	Pa*s
P	Reference pressure for water viscosity	12	MPa
T	Reference temperature for water viscosity	200	°C
C_w	Specific heat capacity of water	4200	J/kg/K
ρ_{ST}	Reference water density	1000	kg/m^3
P_{ref}	Reference pressure for water density	101.325	kPa
T_{ref}	Reference temperature for water density	15.6	°C
C	Fluid compressibility	5.00E-10	Pa^{-1}

2.2 Model Assumptions

The following assumptions were considered in setting up the system to be modeled with water as the working fluid: -

- The fluid circulating throughout the system is single-phase and remains in the liquid state throughout the duration of the simulation.
- Fluid flow is in the laminar regime with Reynold's number low enough to allow the application of Darcy's law.
- There is no gas trapped in the rock fracture.
- Fluid-rock interaction such as chemical dissolution/deposition is minimal and can be ignored.
- Thermal stresses and changes in aperture due to injection of cold water through hot rock were ignored.

For CO_2, the following assumptions were made: -

- The CO_2 is injected at supercritical conditions and remains above critical temperature and pressure through the duration of the simulation.
- When displacing water, the CO_2 is partially miscible according to the Spycher and Pruess equation of state (Spycher and Pruess, 2009).

2.3 Fracture Characterization

In this study, a comparison was made between the performance of a smooth fracture that is parallel-walled to a rough fracture that is considered to have spatial aperture variations. The fracture is treated as a porous medium with porosity set as 0.99 while the heterogenous permeability is defined by the local cubic law for a fracture with spatial variations (Oron & Berkowitz, 1998) which is represented by Equation 1. When computing the value for a homogeneous permeability field (i.e., smooth parallel-plate fracture), the aperture value was constant at 2 mm.

$$k_{f_{ij}} = \frac{b_{ij}^3}{12 \times H} \tag{1}$$

where kf, i, j, b, and H are the effective permeability, grid number in the x direction, grid number in the y direction, local fracture aperture and thickness of the fracture grid element respectively.

2.4 Determination of the Rough Fracture Aperture Distribution

The work by Ishibashi, et al. (2012) provides nonuniform aperture fields for sheared fractures. Co (2017) derived variogram model parameters of the heterogeneous aperture field from Ishibashi, et al. (2012), which were subsequently used to generate artificial aperture fields. This was done using Sequential Gaussian simulation (SGSIM) with the Stanford Geostatistical Modeling Software (SGeMS) (Remy, et al., 2009). A full discussion on the SGSIM method and variogram modeling can be found in Goovaerts (1997).

One of the artificially generated aperture fields was chosen for the purpose of this study. Figure 2 shows the selected aperture distribution. Considering that fractures could be self-similar or self-affine (Yavari, et al., 2002), the aperture distribution was upscaled as a self-similar surface from lab scale to field scale.

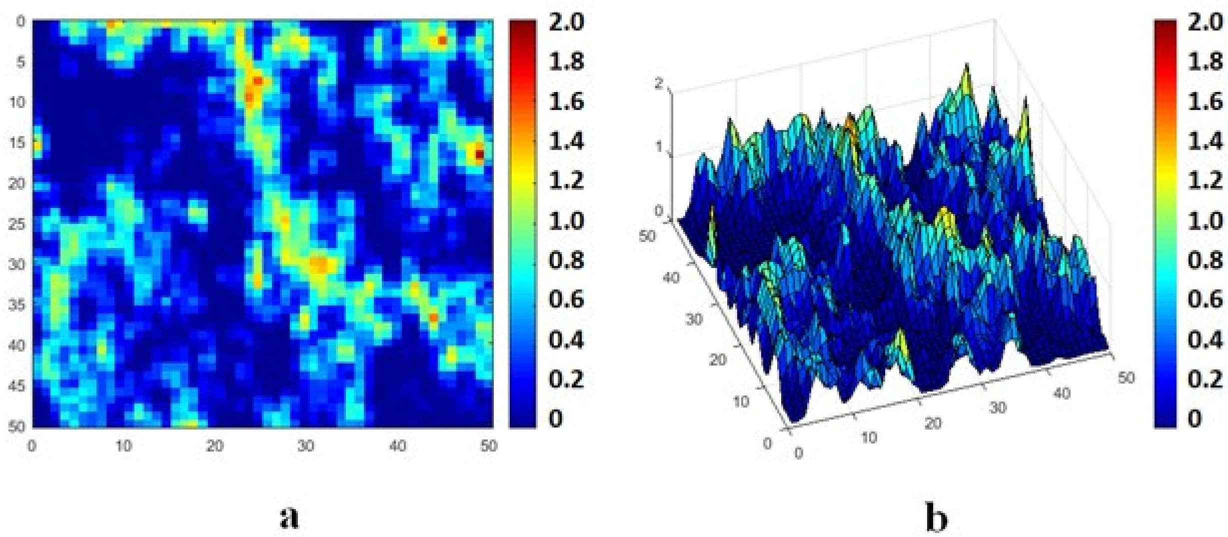

Figure 2: Selected aperture map used to characterize the spatial variations in fracture aperture. The aperture ranges from 0 - 2 mm. 2a is the planar view of the fracture while 2b is the isometric view of the fracture.

Figures 2a and 2b show areas with high aperture contrasted against areas of low aperture. These would result in preferential flow paths. If these preferential flow paths are connected, they may provide alternative flow paths for fluids.

2.5 Workflow and Metrics for Evaluation

To understand the value of CO_2 and water as working fluids, the numerical simulation was done at the same injection pressure and temperature as for the smooth fracture. Different mass flow rates were used ranging from 10 kg/s to 280 kg/s. The produced energy, energy production rate and Carnot efficiency were metrics used for analyzing the results.

Subsequently, a specific CO_2 injection rate was chosen to match the input energy of water at 40 kg/s. Using the same energy input for both fluids, a comparison of thermal output was done between the thermal performance of CO_2 and water for a smooth fracture and the rough fracture with spatial aperture variations. The cumulative produced energy and energy production rate were analyzed to deduce the performance of the fluids over the simulated time.

3. RESULTS AND DISCUSSION

3.1 Heat Extraction at Different Mass Flowrates

Presented in this section are the cumulative heat produced and net heat extracted after two years of circulating CO2 and water. For the given initial reservoir conditions and injection conditions, at each mass flow rate, water gives a higher heat produced and heat extracted. However, using the mass flow rate is not a suitable equivalent metric for comparing CO2 and water for the purpose of heat extraction. Though supercritical CO2 has some liquid-like properties, there is a large difference between the heat capacities of CO2 and water; and there are differences in phase behavior of the fluids at different temperatures and pressures.

From Figure 3, it can be seen that the net heat extracted for water does not follow a linear trend. Hence the mass flow rate for heat extraction from EGS needs to be selected optimally. The red lines indicate that the mass flowrate of CO2 needs to be about five times that of water to generate the same produced energy at the selected time under the given injection and reservoir conditions.

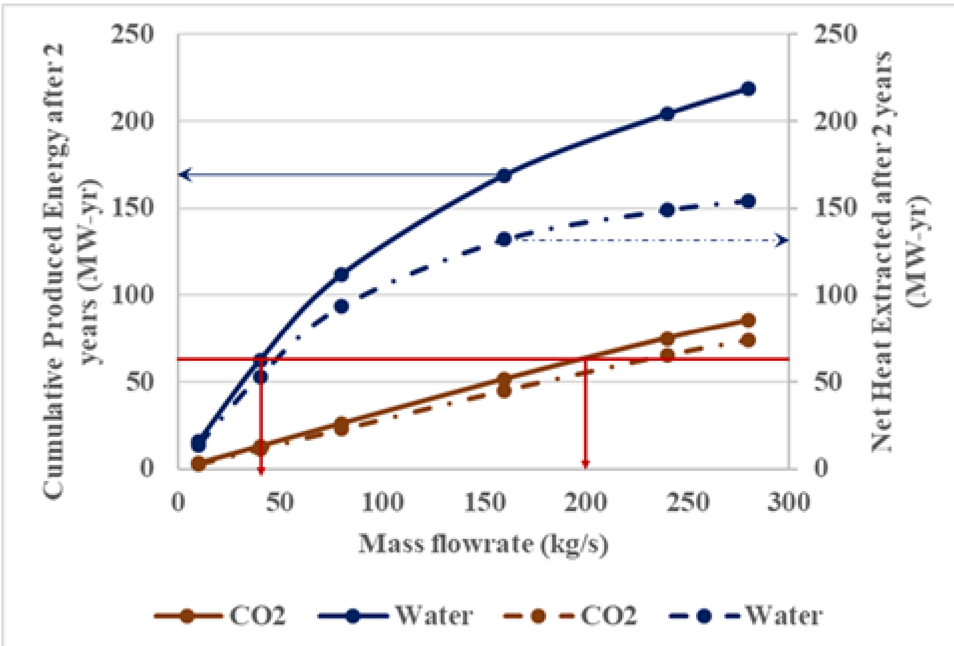

Figure 3: Cumulative energy produced (bold lines) and net heat extracted (dashed lines) for CO2 and water at different mass flowrates after two year of continuous fluid circulation.

Figure 4 shows the heat production rate and the net heat extraction rate measured after two years. The net heat extraction rate (in dashed lines) appears to plateau for water at high mass flow rates, supporting the need for optimal selection of injected mass flow rates. The CO2 curves do not show a similar trend although this may be because the presented mass flow rates are too small to give the equivalent behavior of water at the same rates.

The Carnot efficiency, which is the maximum theoretical efficiency of a hypothetical engine, is computed using the expression

$$\eta = 1 - \frac{T_C}{T_H} \qquad (2)$$

where T_C is the ambient temperature, 15.6 °C while T_H is the exit temperature of the fluid from the production well. The values were taken after two years of continuous fluid circulation and are presented in Table 2.

Table 2: Exit Temperature of the fluid from the production well

Exit Temperature after 2 years (°C)						
	10kg/s	40kg/s	80kg/s	160kg/s	240kg/s	280kg/s
CO2	200.0	200.0	200.0	197.0	184.4	176.3
Water	200.0	193.6	157.1	109.6	88.9	82.6

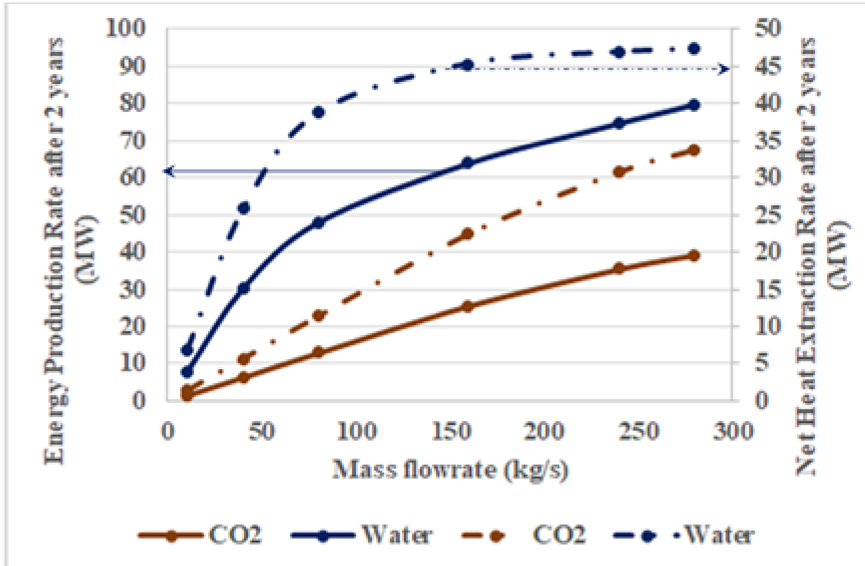

Figure 4: Energy production rate (bold lines) and net heat extraction rate (dashed lines) for CO2 and water at different mass flowrates after two year of continuous fluid circulation.

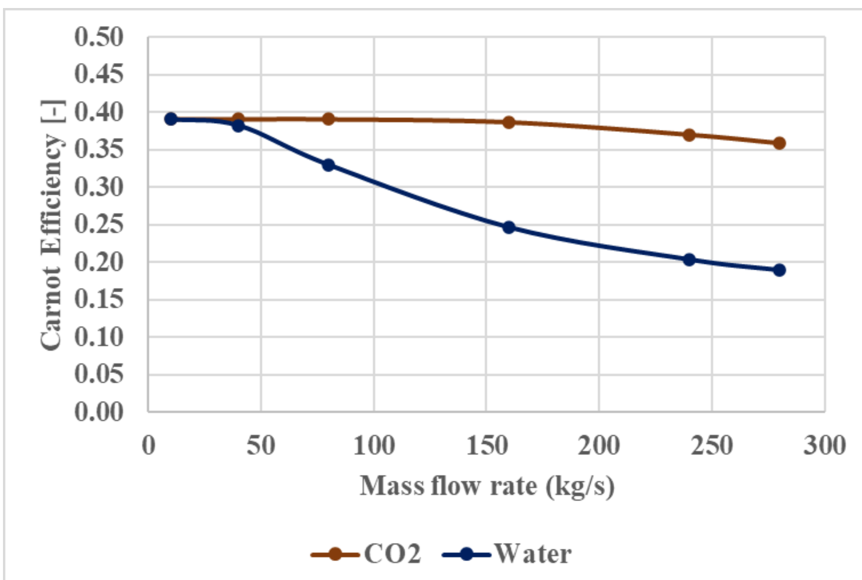

Figure 5: Carnot efficiencies for CO2 and water at different mass flowrates after two years of continuous fluid circulation.

3.2 Heat Extraction at a Fixed Energy Input

In order to compare the performance of CO2 and water as EGS working fluids, the volumetric throughput for water at 40 kg/s was matched with a CO2 mass flowrate of 235 kg/s which gave the same input energy required to push the fluids through the system at the specified injection conditions. The fracture was treated as a smooth parallel-walled fracture. Figure 6 shows the cumulative input energy and cumulative produced energy of the fluids over a five-year period. For the same energy input, CO2 gives a higher energy output over the simulated life of the reservoir. This is consistent with findings of previous works.

Having established the CO2 mass flowrate that would give the same energy input for water at 40 kg/s, the thermal performance was evaluated for a rough fracture with heterogeneous aperture distribution.

Figure 7 shows the temperature at the production well for the cases of a smooth fracture and a rough fracture for both CO2 and water. For the smooth fracture, while the thermal drawdown for CO2 is larger than that of water, the cumulative heat extracted is also more (Figure 6) due to the high mass flowrate. For the rough fracture, the thermal drawdown of CO2 is disproportionately larger than that of water. It is not only the high mass flowrate that contributes to the thermal drawdown. The low viscosity of CO2 and consequently its higher mobility compared to water makes it more susceptible to channeling. As the temperature of the reservoir drops with continuous fluid circulation, water becomes more viscous and its mobility is reduced, a similar temperature drop has only a negligible effect on the mobility of CO2. There is a stable contact interface between the injected water and the in-situ water, which allows for a good thermal sweep efficiency. The higher viscosity of the water on the cooler paths enables the water to move through alternative flowpaths. Over time, the water will contact more area of the rock to an extent the mobility changes act to create a more balanced sweep. The CO2, however, has much higher initial mobility and as a pathway cools, it remains high mobility relative to alternatives, hence the flow from injector to producer tends to remain in the more permeable paths and is more affected by channeling due to heterogeneity. Figure 8 shows the impact of channeling for CO2 and water on the thermal sweep efficiency at selected time periods.

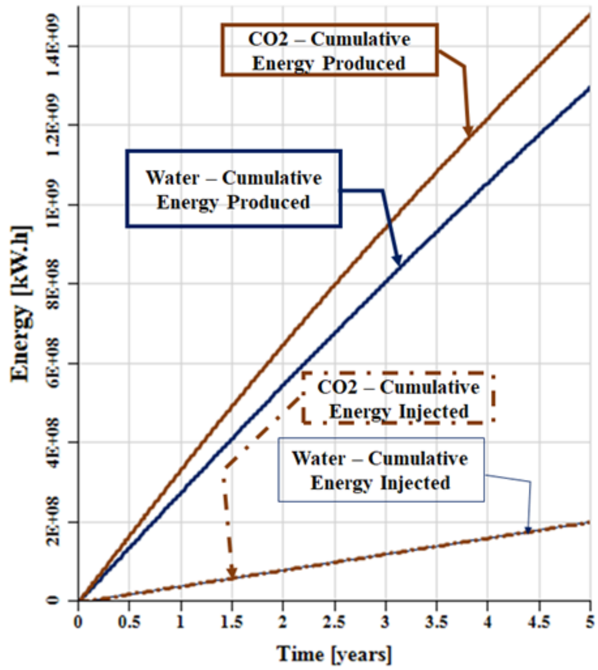

Figure 6: Cumulative energy produced vs. cumulative energy injected for CO2 and water over a five-year period in a smooth fracture.

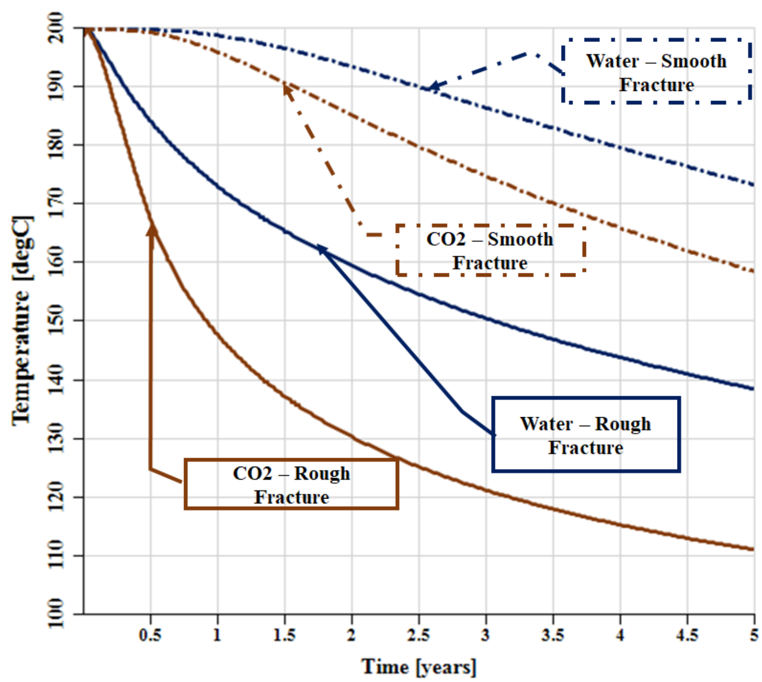

Figure 7: CO2 and water temperature at the producer for flow over a smooth fracture and a rough fracture.

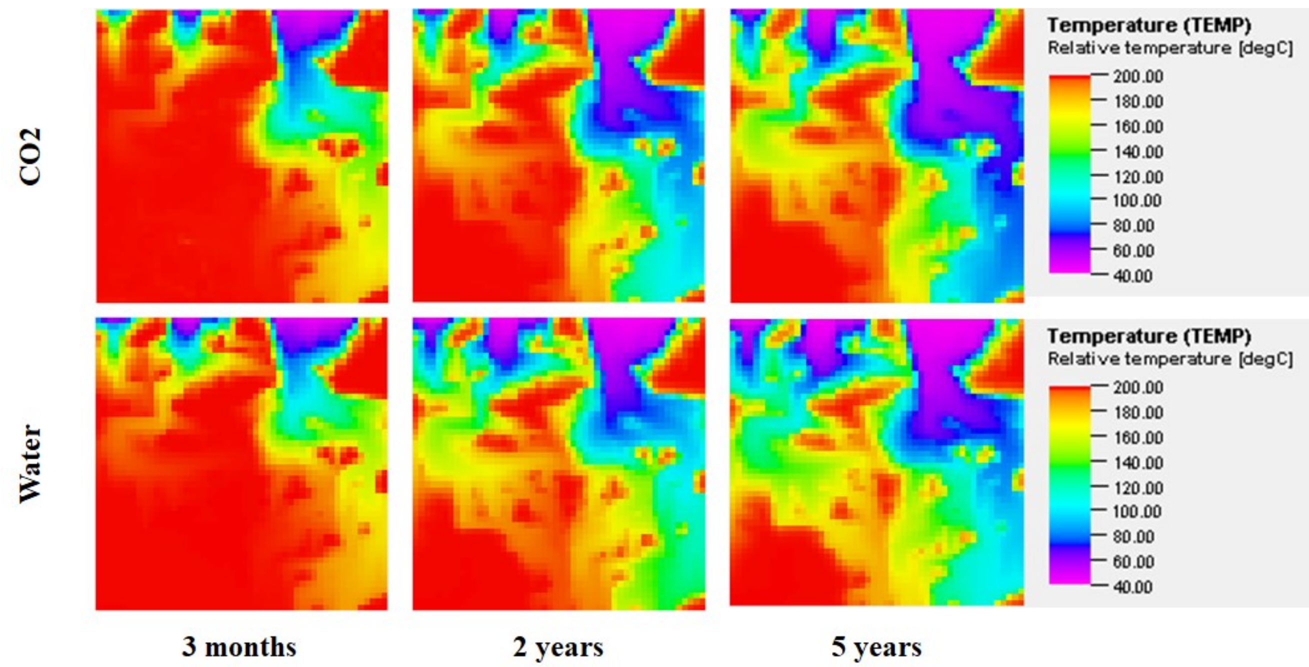

Figure 8: Evolution of the temperature distribution at the fracture plane for CO2 and water at selected time periods.

Although the energy input remains the same for the smooth fracture and the rough fracture, with the rough fracture, the energy extracted is reduced. This occurs for both the water and CO2 injection fluids and is due to channeling of the flow by heterogeneity of the fracture aperture. Figure 9 shows the net energy extracted for CO2 and water when used in a smooth fracture and a rough fracture. Despite the high mass flowrate of CO2, it is more impacted by channeling, which causes the net heat extracted to become less than that of water after about a year and a half. Hence, CO2 may not be beneficial in the long term with a heat mining strategy of continuous CO2 circulation where fractures have spatial variations in their apertures.

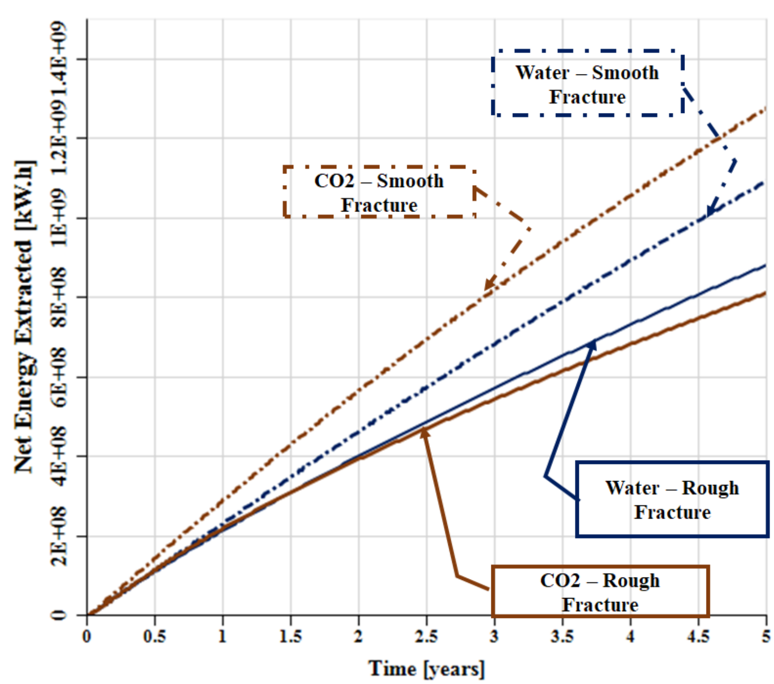

Figure 9: Net energy extracted from the EGS for a smooth fracture and a rough fracture using CO2 and water.

4. CONCLUSIONS

An investigation of CO_2 as an alternative working fluid to water for enhanced geothermal systems has been performed. Various thermal performance metrics have been evaluated for different mass flowrates of CO_2 and water. It has been demonstrated that the mass flowrate is not necessarily an appropriate equivalence for evaluating the thermal performance of CO_2 compared to water. Based on mass flow rate, water will appear to give superior thermal performance, but this is due to it being delivered through the system in a liquid state and does not account for the energy required to do this. Because the phase behavior of CO_2 and water differ at varying temperatures and pressures, the energy input was used as the metric for evaluating the thermal performance of the working fluids.

CO_2 at the injected condition of 40 °C and 150 bars, and at the reservoir condition of 200 °C and 120 bars, is a supercritical fluid with thermophysical properties that make it quite attractive for heat mining. On comparing CO_2 with water for the same energy input and assuming a smooth fracture, CO_2 resulted in more energy extracted from the reservoir.

Compared to the thermal performance with a smooth fracture, the temperature at the production well and the cumulative energy produced is reduced for both CO_2 and water when spatial variations in the aperture are accounted for in the model. The gas-like viscosity of supercritical CO_2 is however a disadvantage when the flow and heat extraction is modeled with a heterogenous fracture aperture and over realistic time periods for heat extraction. CO_2 is affected by channeling due to viscous fingering and fracture aperture heterogeneity. The channels persist over time leading to a very inefficient thermal sweep. Water at low temperatures is more viscous than the background reservoir water and so cooler pathways become less preferential and the sweep is able to contact more area of the rock over time. Thus, the net energy extracted from the reservoir became more than that of CO_2 after about a year and half into the simulation.

This study spurs further questions such as: What might be an optimal strategy for harnessing heat from an enhanced geothermal system? It is worth investigating if a water alternating supercritical CO_2 cycle injection might be optimal in order to take the advantages of both fluids when trying to extract heat through fractures with heterogenous apertures, for example using the water to vary the sweep pattern and then using CO_2 at the same injected energy rate to more efficiently exploit that sweep until it cools.

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