A Feasibility Study on Three Geothermal Designs: Deep Closed-Loop (with and without Conductive Fractures) and Open-Loop Circulation Between Multifractured Laterals

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Keywords

Modeling, fracture modeling, closed-loop, multistage, enhanced geothermal systems, EGS

ABSTRACT

We performed a modeling study to compare the feasibility of three geothermal designs: a closed-loop heat exchanger, a closed-loop heat exchanger with hydraulic fractures engineered to contain thermally conductive material, and an open-loop two-well doublet with multistage fracturing along horizontal laterals. The study was performed with a fully integrated hydraulic fracturing, reservoir, and wellbore simulator. Simulations were performed at a variety of temperatures and operating conditions. The findings show that the closed-loop heat exchanger designs yield very low energy production per foot of wellbore drilled. These designs would require a huge decrease in the cost of drilling to be economically competitive. In contrast, the simulations show that open-loop designs with horizontal laterals and multistage fracturing are capable of sustaining high energy production rates and temperatures over the long-term.

1. Introduction

Conventional geothermal energy production requires high permeability and high temperature to be available within reasonable drilling depth. In many locations, high temperatures are available at depth (Blackwell et al., 2011), but there is not sufficient permeability to sustain adequate production flow rate. Next-generation geothermal designs are being proposed with the goal of achieving economic production from these abundant, high temperature, low permeability formations.

In this paper, we perform analytical and numerical calculations to assess the energy production potential for three proposed next-generation geothermal designs: (a) a closed-loop heat exchanger, (b) a closed-loop heat exchanger with thermally conductive fractures, and (c) open-loop circulation between multifractured laterals.

In Configuration (a), a well is drilled in a U configuration – down, along a lateral, and then back up (van Oort et al., 2021). Fluid is injected on one side of the U, and produced on the other side. A closely related design uses a single vertical well with insulated tubing creating a tube-in-shell configuration (Wang et al., 2010). More complicated closed-loop configurations have been proposed, such as multiple horizontal laterals. In all 'closed-loop' designs, a working fluid is circulated down from the surface and then back up, never exiting the well(s). Energy is transported into the well(s) (and into the working fluid) through heat conduction with the surrounding formation.

In Configuration (b) – a closed-loop design with conductive fractures – multistage hydraulic fracturing is performed to create numerous fractures along a lateral. The fractures are filled with a solidifying material that has very high thermal conductivity.

In Configuration (c), the open-loop design with horizontal multifractured laterals, a horizontal well is hydraulically fractured, using a design similar to those used in shale (Gringarten, 1975; Cremer et al., 1980; Green and Parker, 1992; MacDonald et al., 1992; Jung, 2013; Glauser et al., 2013; Shiozawa and McClure, 2014; Lowry et al., 2014; Olson et al., 2015; Doe and McLaren, 2016; Li et al., 2016; Eustes et al., 2018). The fracturing could be performed with either 'plug and perf' or 'sliding sleeve' configurations. In either case, because of the unavailability of openhole packers/plugs at high temperature, it would probably be necessary to use a cemented liner.

Conventionally, hydraulic stimulation in geothermal (EGS) has been performed in openhole sections of vertical wells, without the use of mechanical isolation or proppant. With these designs, stimulation tends to localize into a small number of dominant flow pathways. The low number of flowing fractures limits the overall flow rate through the system and leads to early thermal breakthrough.

In shale, hydraulic stimulation with mechanical isolation and limited entry completion is used to place 100s to 1000s of conductive fractures along a horizontal lateral. If these technologies were applied in horizontal geothermal wells, they would create roughly two orders of magnitude more flowing fracture pathways than conventional EGS designs.

After fracturing the first well with multistage completion, a second well would be drilled, intersecting the fractures. Then fluid would be circulated between the wells – from injector to producer. At scale, an alternating series of injectors and producers could be used to increase productivity per well.

In this study, our goal is to assess the overall feasibility of these designs. We do not perform a detailed optimization. Also, we do not address the practical issues of how these designs would be implemented. Our goal is solely to perform 'proof of concept' assessments of whether these designs have the potential to be viable.

2. Methods

We perform numerical simulations with a fully coupled fracture, reservoir, and wellbore simulator (McClure et al., 2021). In every element during every timestep, the simulator implicitly calculates pressure and temperature using mass and energy balance. Also, flow velocity in the wellbore is calculated from momentum balance.

The fluid density, enthalpy, and viscosity are calculated using the correlations from the International Association for the Properties of Water and Steam (Cooper, 2007). The correlations account for the water/steam transition across the saturation line and accurately calculate properties under all conditions, even above the critical point.

The wells are meshed to the surface, and heat conduction with the surrounding formation is calculated using the semi-analytical method from Zhang et al. (2011). The fractures are meshed as discrete cracks, not zones of porous media. The matrix mesh is nonconforming to the fracture elements.

Fluid flow and conduction between the fracture elements and matrix elements is calculated using the method from McClure (2017). This method submeshes the matrix elements and calculates transport within the element using a high resolution mesh. This enables the calculations to be accurate, even if the 'radius of investigation' is small relative to the size of the element. This is critical for maintaining accuracy without requiring an extremely refined mesh.

3. Results

3.1 Analytical calculations

Before running the numerical simulations, we performed simple analytical calculations to build intuition and provide high-level guidance on what to expect from the numerical simulations.

3.1.1 Closed-loop heat exchanger

Regardless of the selection of working fluid, a closed-loop heat exchanger cannot produce energy to the surface faster than energy is transported into the well via conduction.

The equation describing thermal conduction into the wellbore is equivalent to the equation for single-phase flow through a hydrocarbon reservoir. In well test analysis the equation is called 'infinite acting radial flow' (IARF). The equation for IARF is (in metric units and assuming skin factor is zero):

$$\Delta P = \frac{Q\mu}{4\pi kh}(\ln\left(\frac{kt}{\mu\phi c_t r_w^2}\right) + 0.80907), \qquad (1)$$

where Q is flow rate, k is permeability, h is height, t is time, μ is viscosity, ϕ is porosity, c_t is total compressibility, and r_w is wellbore radius.

This equation can be modified to solve for heat conduction into a wellbore by replacing pressure with temperature, ϕc_t (porosity times compressibility) with ρC (density times heat capacity), and k/μ (permeability divided by viscosity) with K (thermal conductivity). We can rearrange the equation to calculate the heat production rate that would be required to achieve a specified thermal drawdown over a specified period of time. The equation is:

$$Q_t = \frac{4\pi K h \Delta T}{\ln\left(\frac{Kt}{\rho C r_w^2}\right) + 0.80907}. \qquad (2)$$

Typical horizontal laterals in shale are around 10,000 ft. Closed-loop heat exchangers have been proposed with longer laterals, and so for calculation purposes, we assume an exceptionally long

7 km lateral (h = 7000 m). Also, we assume: thermal conductivity is 3 W/(K-m), the wellbore radius is 10 cm, heat capacity is around 2000 J/(kg-K), density of 2650 kg/m^3, and that we want to achieve no more than a 100 degree Celsius (180 degrees Fahrenheit) thermal drawdown over the first year of production. Using these numbers, we can calculate how quickly it will be possible to extract heat from this system:

$$Q_t = \frac{4*\pi*3*7000*100}{\ln\left(\frac{3*365*24*3600}{2650*2000*0.1^2}\right)+0.80907} = 3.2\ MWth. \quad (3)$$

This is the thermal energy extraction rate. Zarrouk and Moon (2014) review performance from geothermal power plants and report efficiencies up to 17%, depending on the enthalpy of produced fluid. From 200’C or lower, typical efficiencies are no more than 10%. Assuming 10% efficiency, the electricity generation of the system will be 0.32 MWe.

3.1.2 Closed-loop heat exchanger with high-conductivity fractures

Let’s suppose that we are able to place 500 high thermal conductivity (zero hydraulic conductivity) fractures along the lateral. How much additional energy will be transported to the lateral by these fractures?

The equation for 1D heat conduction is:

$$Q_t = -KA\frac{dT}{dx} \quad (4)$$

For each high thermal conductivity fracture, heat will be conducting inward to the wellbore in radial flow. The temperature of the high thermal conductivity fracture will be supported by heat conduction inward from the surrounding rock. We can roughly approximate this process as being a steady-state thermal conduction process with a ΔT driving conduction into the well. The energy transport from the fractures can be approximated as:

$$Q_t = NKWG\Delta T, \quad (5)$$

where *N* is the number of fractures, *W* is crack aperture. The value *G* is a geometric term that represents the ‘perimeter of flow’ divided by ‘distance.’ For this problem, *G* can be roughly approximated as being 1.0. Plugging in thermal conductivity of 300.0 W/(m-K) (roughly equivalent to the thermal conductivity of a metal), ΔT of 100 degrees, and aperture of 0.002 mm, we can calculate:

$$Q_t = 300.0 * 0.002 * 1.0 * 100 = 60\ W \quad (6)$$

With 500 fractures along the well, the aggregate energy production contribution of the fractures will be 30 kWth. At 10% efficiency of conversion to electricity, this yields 3 kWe (0.003 MWe).

Because the simplification inherent to the use of Equation 5, this is only an approximate value. Section 3.2.2 provides more rigorous, detailed calculations. They yield qualitatively similar results.

3.1.3 Open-loop circulation between multifractured laterals

Let's assume that there are 500 flowing hydraulic fractures connecting an injector and producer; the well separation is 300 m, the fracture height is 200 m, the fracture conductivity is 50 md-ft (1.52e-14 m^2), and that the water viscosity is 0.15 cp; the bottomhole pressure at the injector well is 5 MPa greater than the bottomhole pressure at the production well. Then, assuming 1D flow, from Darcy's law, the energy production rate will be:

$$Q_t = \frac{NhC}{\mu D}\Delta P \rho H, \quad (7)$$

where N is the number of fractures, h is the height, C is the hydraulic conductivity of each fracture, D is the separation between the wells, ΔP is the bottomhole pressure difference between the wells, μ is the viscosity, ρ is the fluid density, and H is the specific enthalpy of the fluid. At 200°C, the density will be around 880 kg/m^3, and the specific enthalpy will be around 860 kJ/kg.

This works out to:

$$Q_t = \frac{500*200*1.52e{-}14}{0.15e{-}9*300} 5*880*860 = 128 \text{ MWth}. \quad (8)$$

At 10% efficiency of conversion to electricity, this would yield 12.8 MWe.

3.1.4 Recap

The electricity generation potential of the closed loop design (with very long 7 km lateral) was estimated to be 0.32 MWe. If 500 thermally conductive fractures were placed (with very high thermal conductivity of 300 W/(m-K)), the additional thermal energy contribution was calculated to be 30 kWth (roughly equivalent to 3 kWe, or 0.003 MWe). Circulating fluid between a pair of wells through an array of fractures was calculated to yield 12.8 MWe.

Thus, it is apparent that the open-loop circulation designs have roughly two orders of magnitude greater potential for energy generation than closed-loop designs (even though they would use shorter laterals). Creating thermally conductive fractures around a closed-loop system has minor impact on the overall energy production.

The difference in heat production rate arises from the difference between thermal conduction and heat convection. Thermal conduction is an inherently slow process. Even materials with relatively high thermal conductivity do not transport energy very rapidly, compared with the thermal convection.

3.2 Numerical simulations

Following the analytical calculation, numerical simulations of the three scenarios were run under a variety of conditions to assess power output.

3.2.1 Closed-loop heat exchanger

A closed-loop system is setup as a 12 km loop (3 km deep, 6 km lateral) as shown in Figure 1.

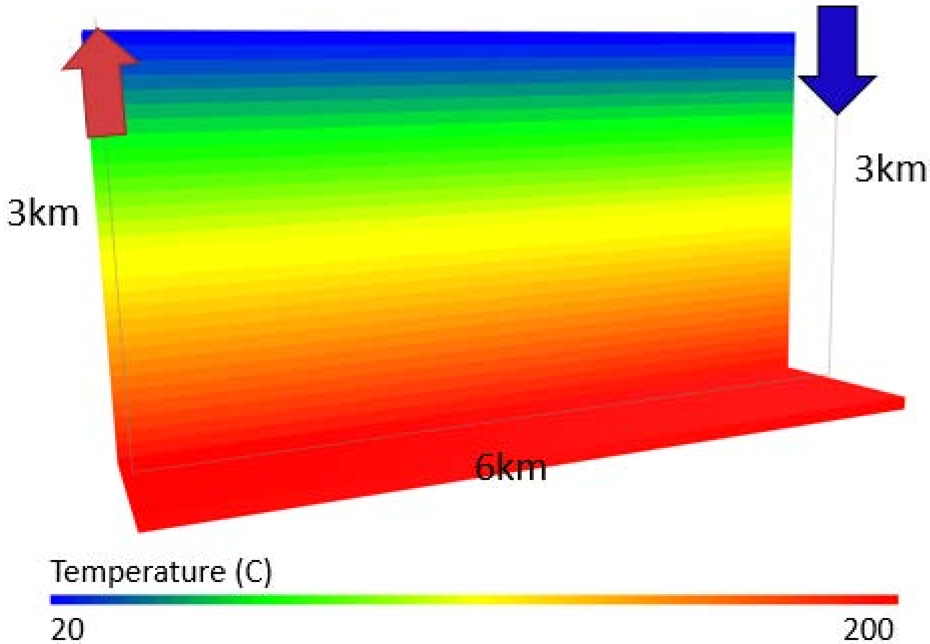

Figure 1: Closed-loop setup.

The matrix is homogenous rock with 5% porosity, 50 nd permeability, and initialized at 100% water saturation. The well is a 7” monobore with an ID of 6.25”.

Water is injected at 110’ C and 30 MPa into the loop. We compare simulations varying reservoir temperature and flow rate. Cases are compared on the basis of produced enthalpy.

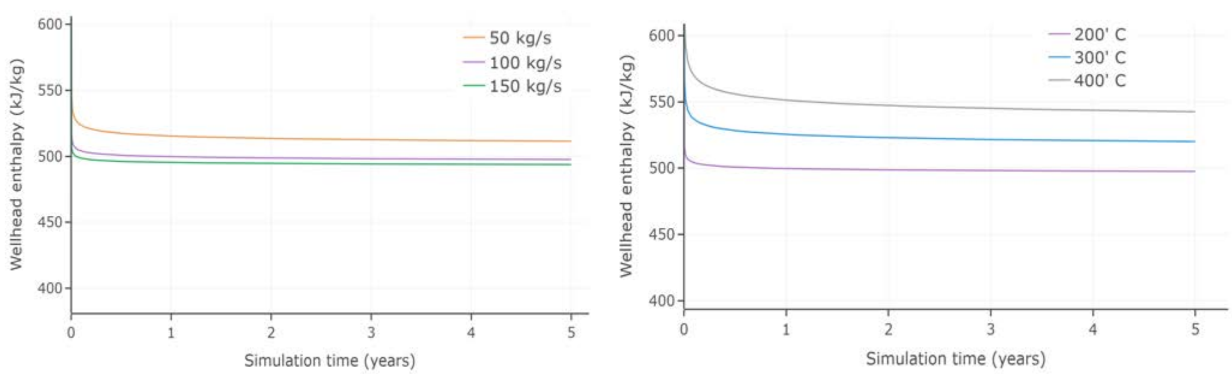

Figure 2. a. Enthalpy output of closed-loop system in 200’ C rock at different flow rates. b. Enthalpy output of closed-loop system circulating 100 kg/s at different reservoir temperatures. The purple trend in the two charts is the same case.

Figure 3 shows the isobaric properties of water at 30 MPa.

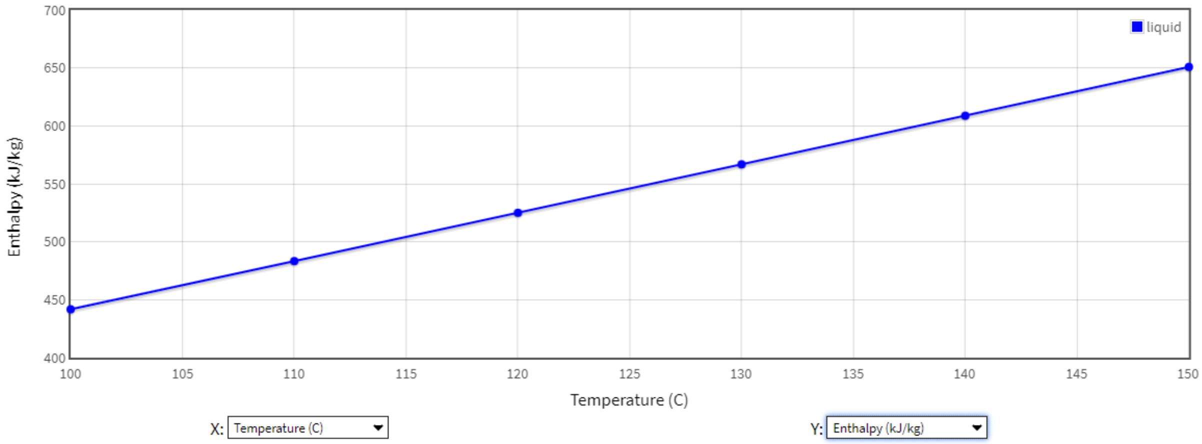

Figure 3. Isobaric properties of water at 30 MPa. Source: www.webbook.nist.gov

The 110' C injection stream has an enthalpy of 485 kJ/kg. An production stream enthalpy of 500 kJ/kg, corresponds to a water temperature of 115' C, just 5' C warmer than the injection. Figure 4, below, confirms that the fluid heats up minimally in the closed-loop system.

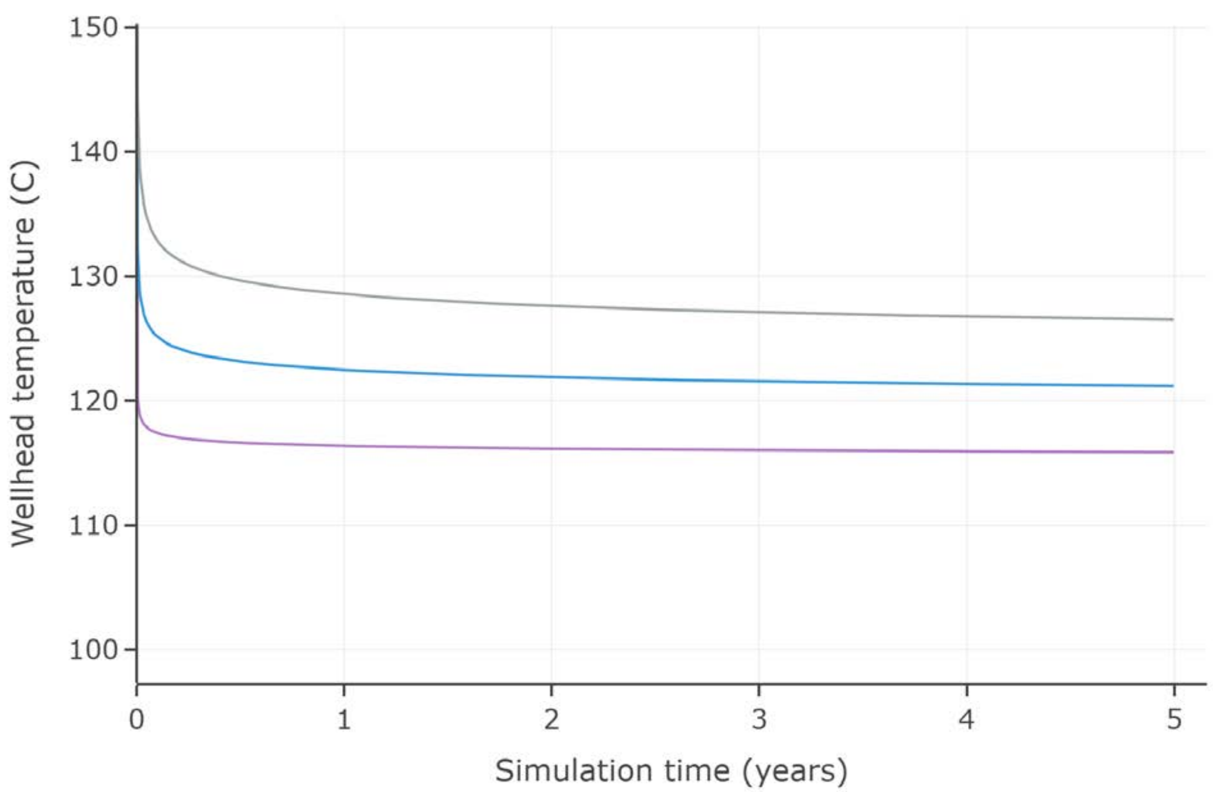

Figure 4. Producing temperature of closed-loop system circulating 100 kg/s of water with an initial temperature of 110' C at different reservoir temperatures.

3.2.2 Closed-loop heat exchanger with high-conductivity fractures

The 400’ C closed-loop heat exchanger is then augmented with 400, thermally conductive fractures along the 6 km lateral section. Each fracture is 500 m long and 100 m tall. Reservoir parameters such as permeability, porosity, and water saturation are the same as in Section 3.2.1. The is no fluid exchange with the fractures; the only heat exchange between the fractures and the fluid in the wellbore is through conduction.

The thermally conductive fractures increase the heat transfer into the working fluid by 3-10 kJ/kg. Figure 5 shows the produced enthalpy difference between the heat exchanger in 3.2.1 and the same case augmented with the conductive fractures with a thermal conductivity of 1000 W/(m-K) and aperture of 2.5 mm when flow rate is 100 kg/s.

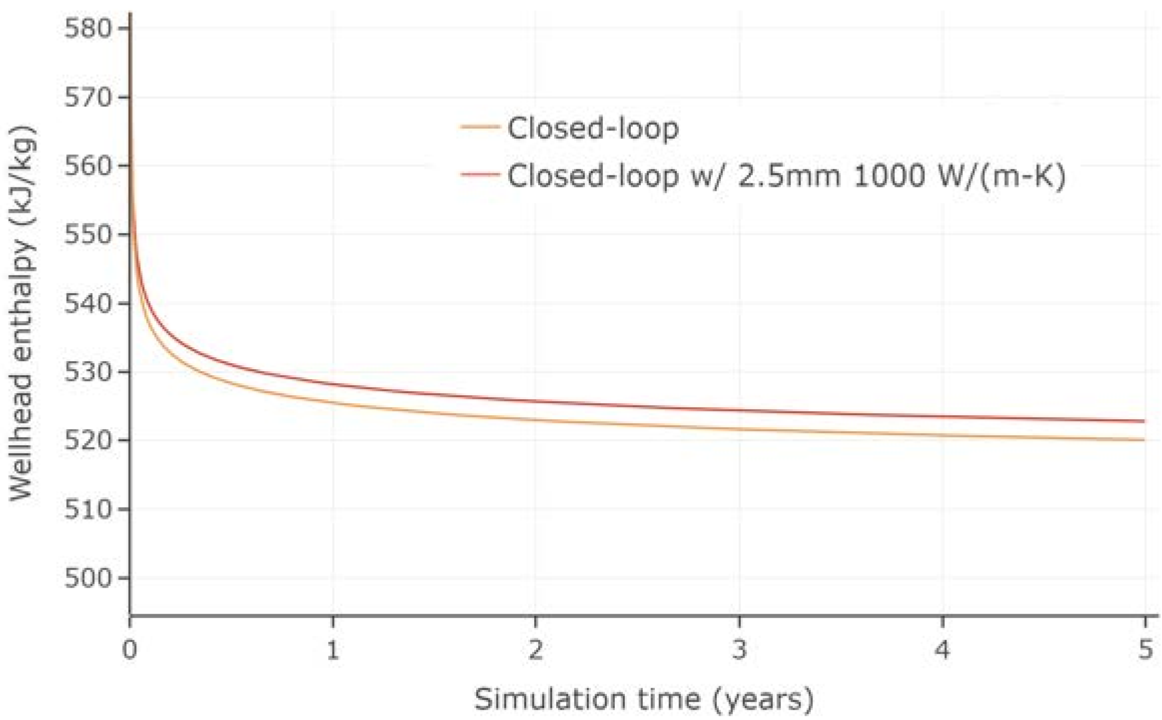

Figure 5. Produced enthalpy of a closed-loop vs closed-loop with thermally-conductive fractures in 300’ C rock.

This 3-10 kJ/kg increase in enthalpy is same ‘order of magnitude’ as the approximate calculation from Section 3.1.2. From Equation 5, we can calculate:

$$Q_t = NKWG\Delta T$$
$$Q_t = 400 * 1000 \frac{W}{m-K} * 0.0025m * 1 * 300C = 300\ kW \quad (9)$$
$$\frac{Q_t}{Q_m} = \frac{300\ kW}{100\ kg/s} = 3\ kJ/kg$$

The 3 kJ/kg calculated analytically for the system is in the 3-5 kJ/kg range seen in the simulation.

At 50 kg/s, a 5 kJ/kg increase yields an additional 0.25 MWth of power, a small increase over the case without fractures. Conductive heat transfer can be increased by increasing the aperture of the fractures. Figure 6 shows the impact on enthalpy of the produced fluid when fractures of increasing aperture are added to a closed-loop system.

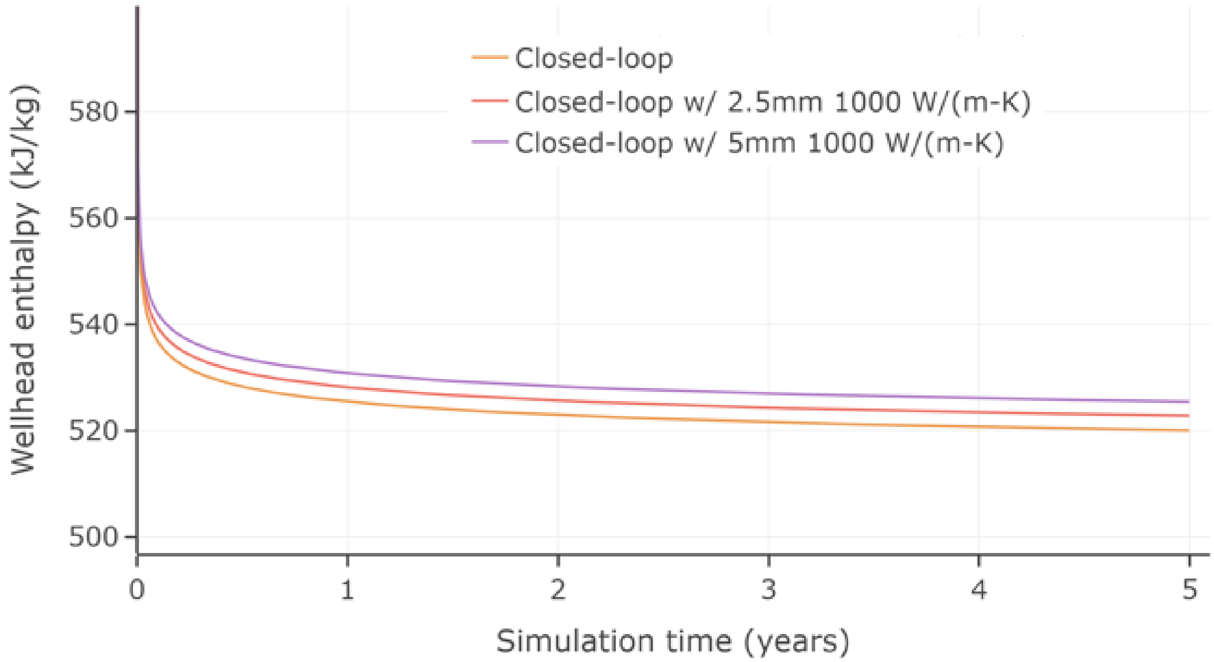

Figure 6. Enthalpy of the producing fluid in different closed-loop geothermal systems (with and without thermally conductive fractures).

Doubling the aperture from 2.5 mm to 5 mm approximately doubles the increase in enthalpy of the produced fluid to 10 kJ/kg more than the fractureless closed-loop system. However, even doubling the energy input from the thermally conductive fractures does not increase the power output by more than 1 MWth.

As a thought experiments, simulations were performed with unrealistically high values of thermal conductivity. Diamond is one of the most thermally conductive materials in existence, with a thermal conductivity around 2000 W/(m-K). We performed simulations using even higher values of thermal conductivity – 10,000 and 100,000 W/(m-K). These values are not physically possible. The simulations were performed solely for sensitivity analysis.

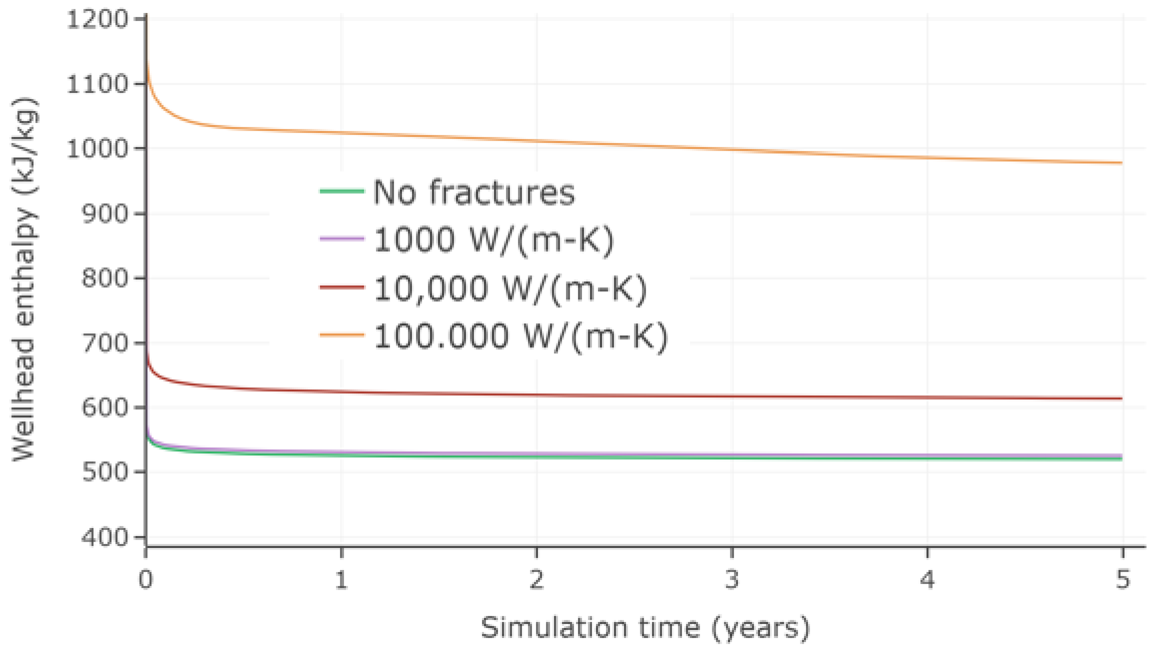

Figure 7. Produced enthalpy at 50 kg/s at different fracture thermal conductivities

Even when thermal conductivity of the fractures is increased to 10,000 W/(m-K), the increase in enthalpy of the produced fluid is modest. Thermal conductivity must be increased to 100,000 W/(m-K) to achieve large changes in produced enthalpy.

Heat conduction is a slow process, and the rate of energy transfer from the reservoir to the wellbore is limited by the thermally conductivity and connection to the wellbore (fracture aperture). In Figure 8, the fractures have been hidden and the temperature of the reservoir is compared after five years of circulation between the 1000 W/(m-K) and 100,000 W/(m-K) cases (note the different temperature scales on the two images).

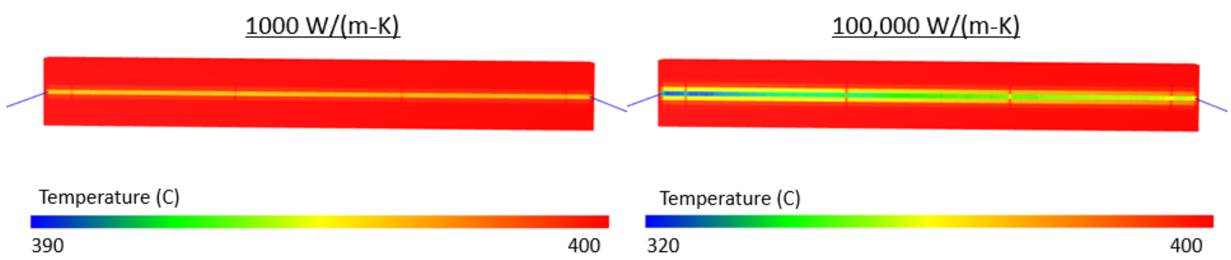

Figure 8. Temperature of the reservoir after five years of circulation in the closed-loop scenario augmented by thermally-conductive fractures (fractures have been hidden). Color scales are different between the two images.

3.2.3 Open-loop circulation between multifractured laterals

In an open-loop system, fluid is transported into the production well by convection. Relatively cool fluid is injected into the injector and heats up as it flows through the fractures in the reservoir. Using the same geologic setup as in Sections 3.2.1 and 3.2.2, we replace the single closed-loop with two 3 km laterals spaced at 200 meters (Figure 9).

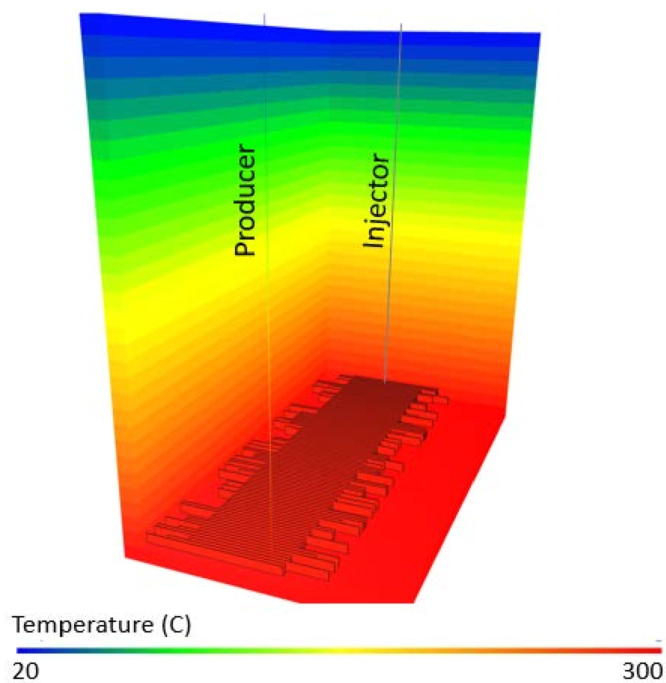

Figure 9. Open-loop multifractured lateral setup

The injector well is fully cased and perforated every 30 meters. At each perforation cluster there is a fracture with variable length between 400 and 600 meters and conductivity of 7.5e-14 m^3 (250 md-ft).

Injection in each case is constant rate at 110’ C, and the production wellhead pressure is constant at 3 MPa.

Figure 10 shows the produced enthalpy over time for a circulation rate of 100 kg/s and different reservoir temperatures.

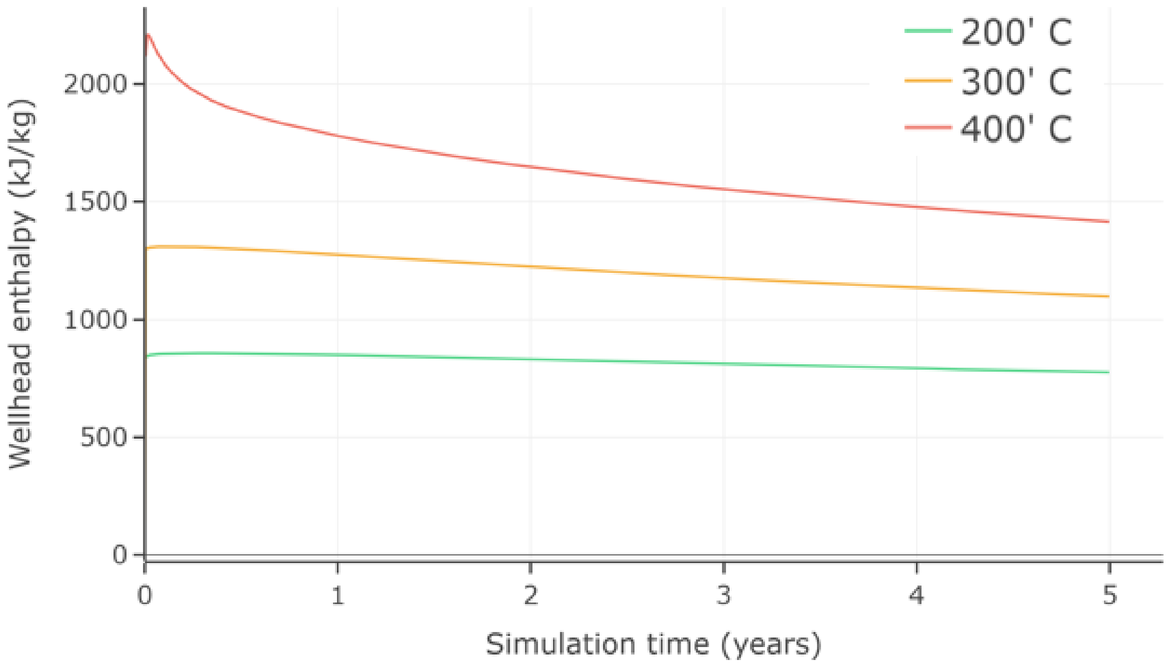

Figure 10. Produced enthalpy for multifracture lateral system circulating 100 kg/s at different reservoir temperatures.

Figure 11 shows the produced enthalpy over time for a reservoir temperature of 300' C.

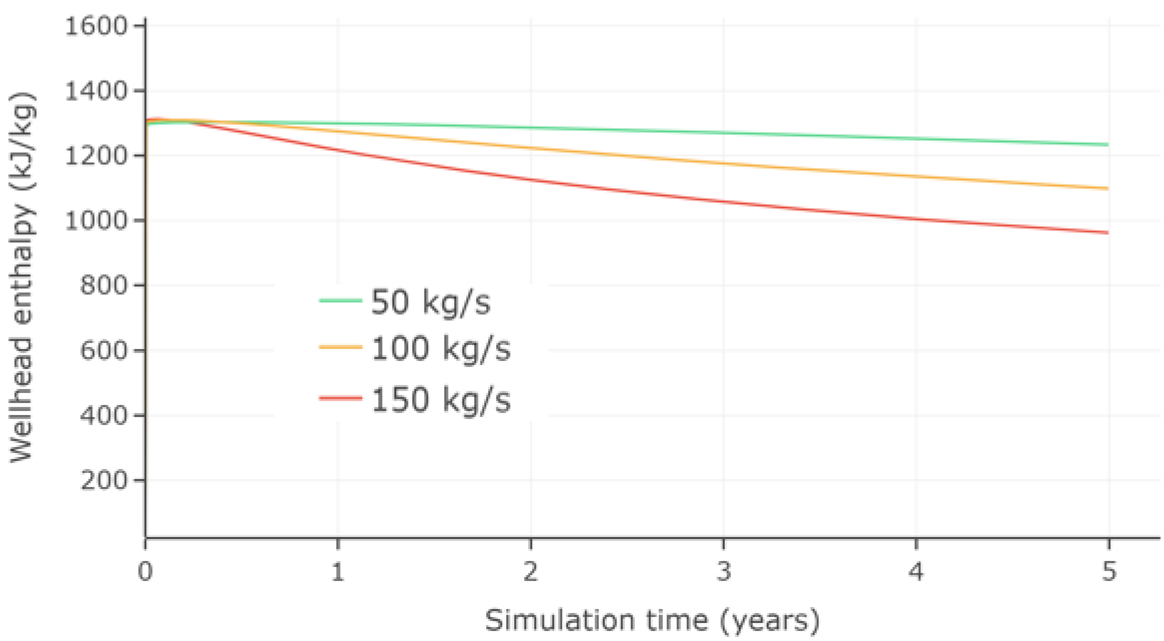

Figure 11. Energy output of the three geothermal systems investigated at 100 kg/s and 300' C reservoir temperature.

As expected, higher flow rates increase the rate of reservoir cooling. In the base case of 100 kg/s, energy produced decreases by 15% over the first five years of circulation. The rate of cooling will decrease with greater fracture surface area, and increase with higher flow rates. Figure 12 shows the temperature depletion in the reservoir after five years of circulating at 150 kg/s.

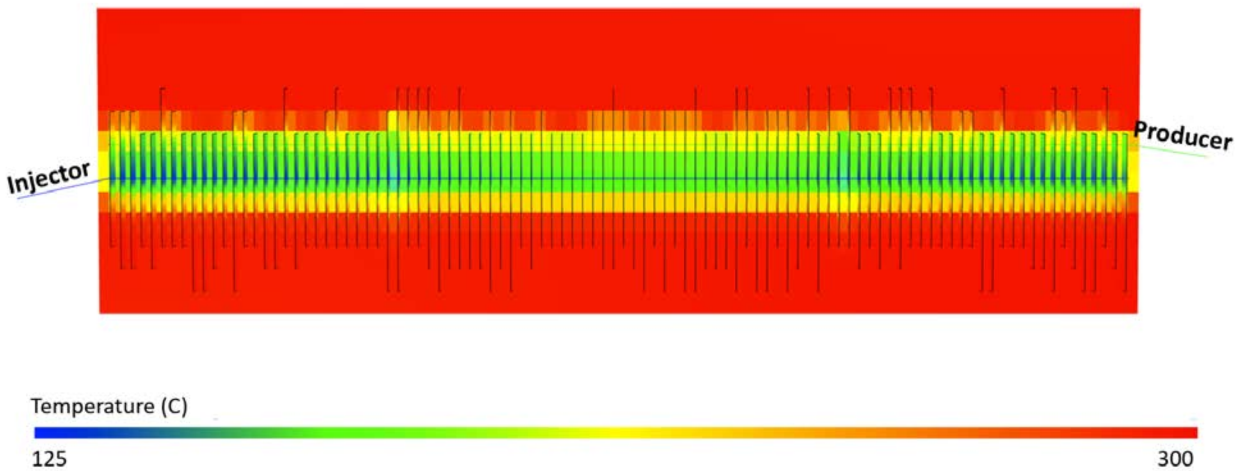

Figure 12. Temperature in the reservoir and fractures after five years of circulating at 150 kg/s

The temperature of the reservoir between the wells has decreased from 300' C to less than 200' C. Some temperature decrease is observed to the outside of the two wellbores, but to a lesser extent given limited fluid flow in those regions. Figure 13 compares the temperature and enthalpy in the fracture networks of the three different injection rates at five years.

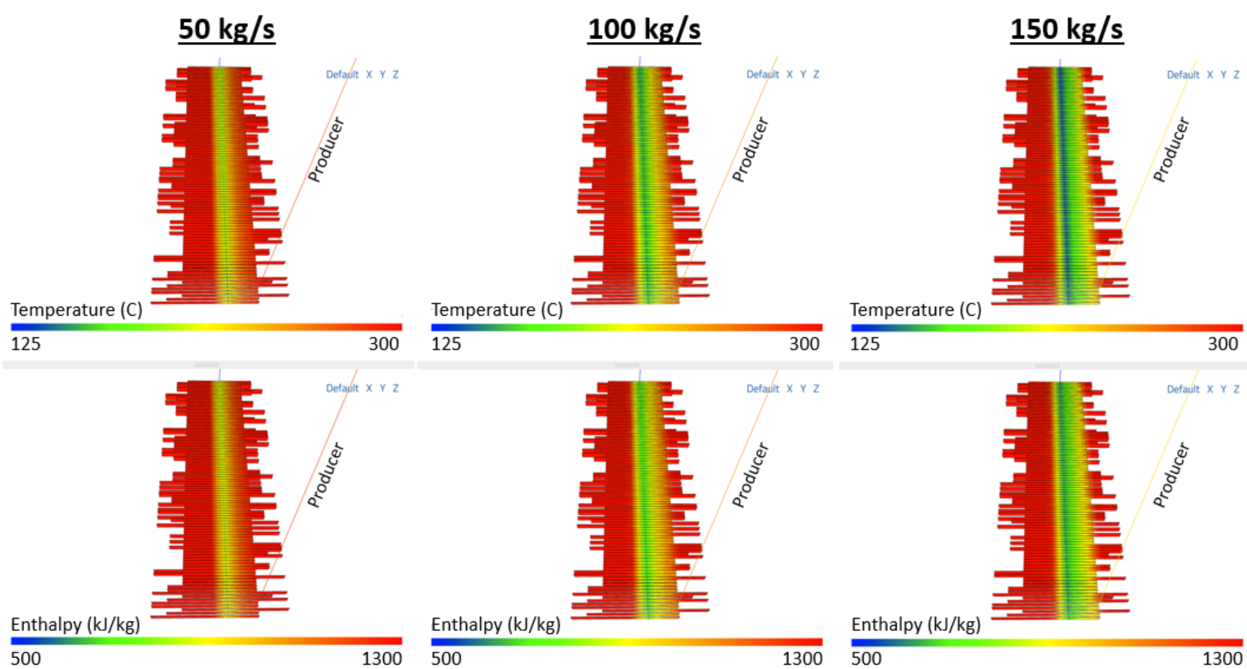

Figure 13. Temperature and enthalpy in the fractures at five years for the three flow rates shown in Figure 11.

At 50 kg/s, the fracture regions around the production well are still near reservoir enthalpy at five years. In contrast, at 150 kg/s, the temperature and enthalpy of the fracture area near the production well have decreased substantially. In Section 4, we discuss how the rate of enthalpy decay observed in Figure 11 can be decreased with well and fracture spacing. In practical application, simulations would be performed to calculate the economically optimal well spacing, lateral length, fracture spacing (controlled by cluster spacing), circulation rate, and other parameters.

If there was an alternating series of injectors and producers, the wells could flow in either direction, doubling the total energy extraction per well (relative to the two well design, which has only flow in one direction).

4. Discussion

The wellhead enthalpy of the three systems for a flow rate of 100 kg/s and a 300' C reservoir are shown in Figure 14.

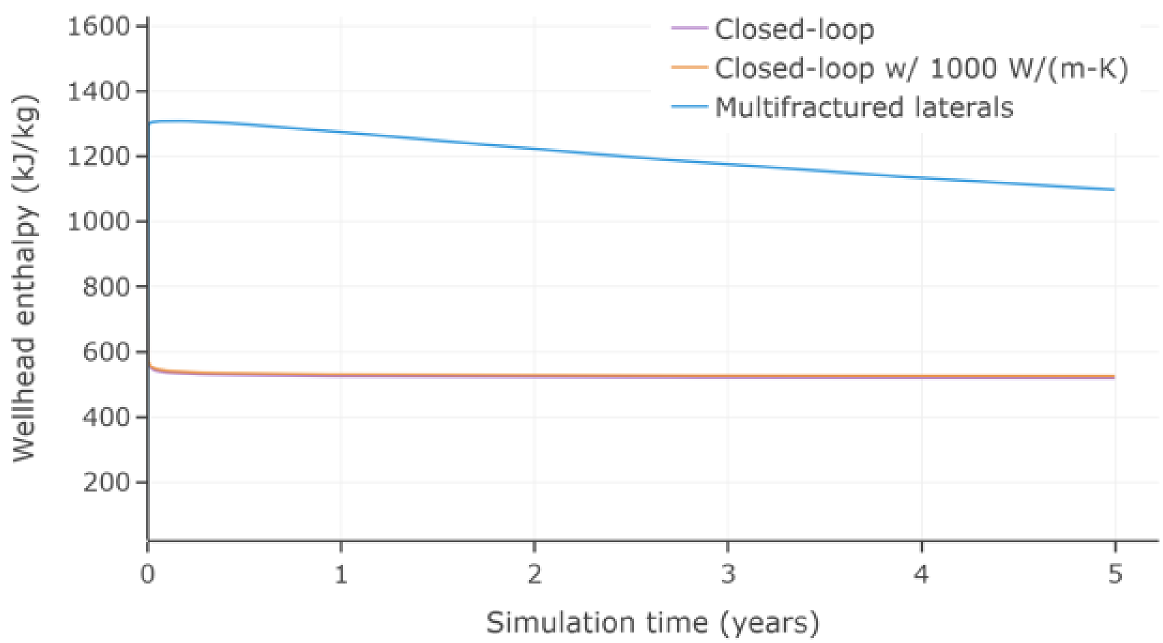

Figure 14. Energy output of the three geothermal systems investigated at 100 kg/s and 300' C reservoir temperature.

In all cases, the injection temperature and pressures are the same, for an injection enthalpy of 485 kJ/kg. Thermal power output is calculated as ([$Enthalpy_{Production}$] – [$Enthalpy_{Injection}$]) x [Mass Flow Rate] and plotted in Figure 15.

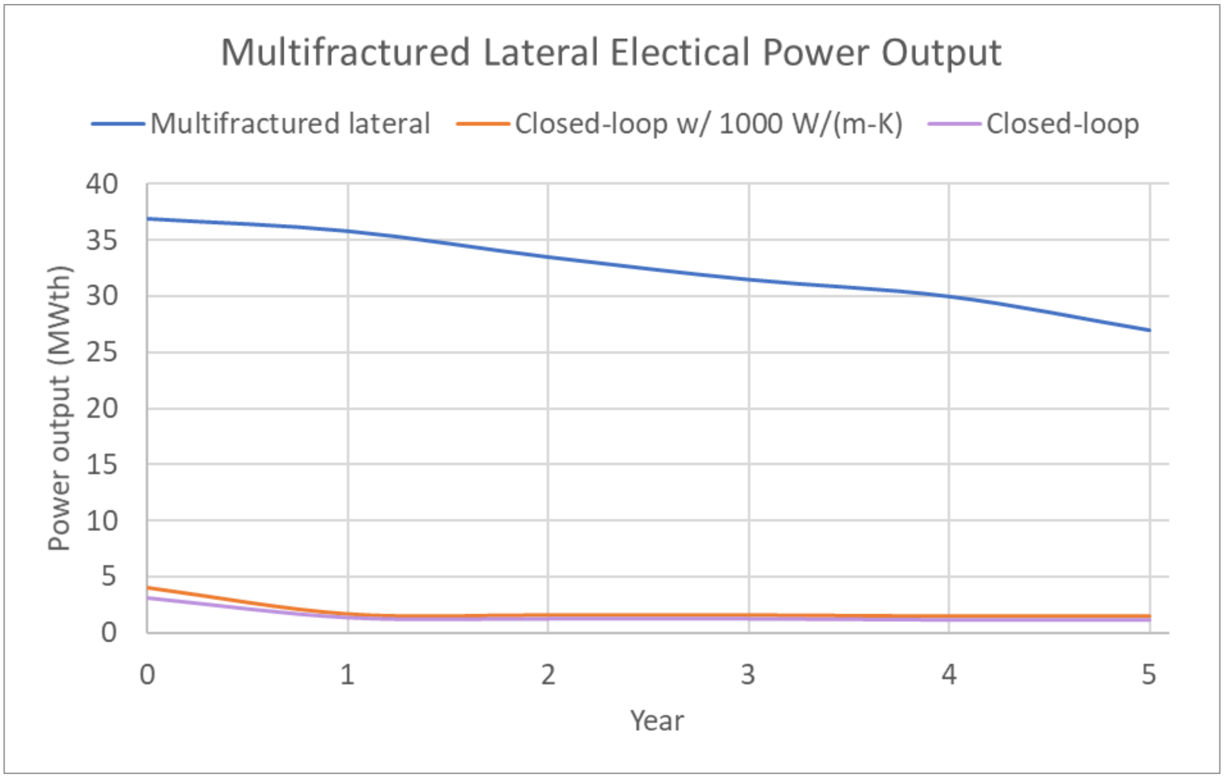

Figure 15. Thermal power output of the three geothermal systems circulating 100 kg/s at 200’ C over time.

Figure 15 shows that the multifractured open-loop design generates far more power than the closed loop designs.

Conversion from thermal power to electrical power necessarily results in lower power output. Zarrouk et al. (2014) document, power generation efficiencies increase with higher energy output (enthalpy). The temperature from the closed-loop systems is too low to produce meaningful electrical power. Using Equation 18 from Zarrouk et al., we calculate the electrical power output of the multifractured open-loop lateral systems at 200’ C and 300’ C in Figure 16.

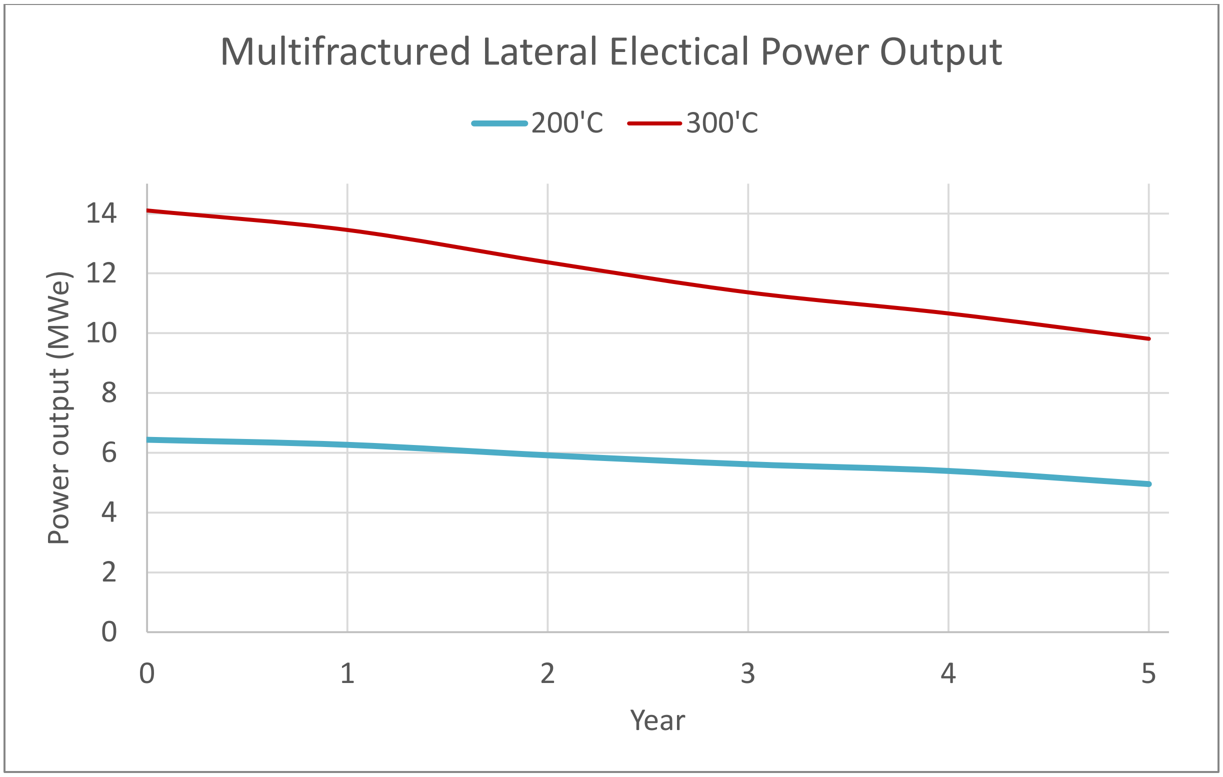

Figure 16. Electrical power output for the multifractured lateral geothermal system at 200’ C and 300’ C. Electrical output is calculated using Equation 18 from Zarrouk et al. (2014).

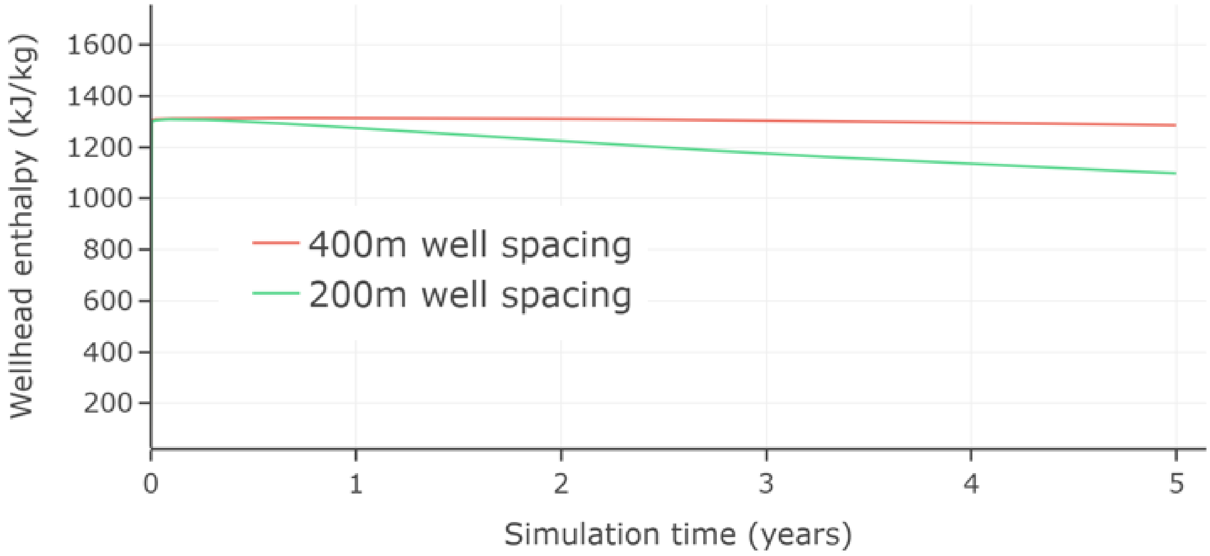

Figure 17. Produced enthalpy of the multifractured lateral geothermal system at 200 m and 400 m well spacings.

We should again emphasize - the multifractured design presented in this paper has not been optimized. The simulations are performed to assess overall feasibility. A fully optimized design could likely achieve greater and more robust results.

In a full-scale design, it would be necessary to consider:

- The multifractured lateral geothermal system will show fall-off in energy production over time. This decrease in enthalpy for a given reservoir temperature is controlled by surface area exposed to the working fluid and flow rate. Increasing the spacing between injector/producer, increasing the number of fractures, and/or decreasing flow rate will slow the energy depletion. The optimal well spacing, fracture spacing, and flow rate should be determined from an economic optimization (Li et al., 2016). For instance, Figure 17 shows that spacing the wells at 400 m versus 200 m (base case) substantially curtails the enthalpy decline.
- The hydraulic conductivity of the fractures was assumed equal in Section 3.2.3. There is likely to be variation in conductivity between fractures in reality, which would result in uneven distribution of flow between fractures and create the potential for short-circuiting.
- In addition to short-circuiting, there is also potential for fluid losses from reservoir heterogeneities. Such losses would require additional make-up water and negatively impact economics.
- We assumed only a single planar fracture per cluster. In reality, the fractures may form a more complex path, increasing surface area. Thus, fracture surface area in the model may be pessimistic. Core across studies in hydrocarbon bearing reservoirs in recent years have document swarms of parallel fractures for each hydraulic fracture initiation point (Gale et al., 2018; Raterman et al., 2019). Fracture swarms would greatly increase the total fracture surface area and improve heat sweep efficiency.
- The conductivity of natural fractures is likely to be more variable than the conductivity of newly forming hydraulic fractures. Thus, natural fractures may actually be disadvantageous for the development of a multifractured geothermal system.
- Capital efficiency of the system would increase if many injectors and producers are alternated in sequence. In such an arrangement, flow from the injector is distributed between both wings of the fracture, taking advantage of the entire surface area.
- This paper did not consider environmental risks like induced seismicity. Such risks would need to be evaluated prior to any field implementation.

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