Modeling Studies of Single-Well EGS Configurations

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ABSTRACT

Single wellbore configurations show promise for Enhanced Geothermal Systems because they would reduce the number of wells that need to be drilled. We performed numerical modeling to investigate a variety of single wellbore configurations and compared them to a two-well injector/producer doublet. Wellbore and reservoir models were constructed separately and then coupled together using an iterative process. Some of the configurations included a downhole heat exchanger, which circulates a secondary working fluid through the wellbore. A separate loop brings heat to the well by circulating water through the reservoir and through a second annulus outside of the casing. The energy output of such a downhole heat exchanger system was found to be limited by the amount of fluid that could be induced to flow in the reservoir, although careful specification of the downhole tubulars resulted in worthwhile improvement. Appropriate choice of the circulating secondary fluid was also found to be important. In other configurations, fluid would be injected directly into the formation and produced back into the wellbore from a different interval in the same well. Fluid flow through the reservoir was assumed to occur either through an idealized single planar fracture, or through simple fracture networks.

Introduction

Coaxial single wellbore configurations may be promising for Enhanced Geothermal Systems (EGS) because they could cut in half the number of wells that need to be drilled. We investigated variations on two general coaxial designs: a coaxial downhole heat exchanger and a coaxial production and injection arrangement. We compared these designs to a more traditional two-well producer/injector EGS doublet.

Coaxial heat exchangers circulate fluid down and back up within the wellbore in a closed loop that may be isolated from the reservoir. Several authors, including Horne (1980) and Nalla (2004) have shown that coaxial downhole heat exchangers are hampered by low thermal recovery due to the slow rate of heat conduction through rock. To enhance the thermal recovery capacity, we investigated the effect of placing a heat exchanger so that geothermal fluid could circulate through reservoir fractures by way of a secondary annulus. Heat transport to the wellbore is enhanced by free convection that would occur in the reservoir. Different variations of this design were tested including changing the working fluid and including a crossover device in the wellbore. The downhole heat exchanger could offer some advantages: (1) preventing scaling; (2) removing the necessity of a heat exchanger on the surface; (3) spontaneous flow is achievable because of the density variation caused by temperature difference. In this work, two secondary working fluids —isopentane and CO2, were compared by calculating the power generation in each case. We

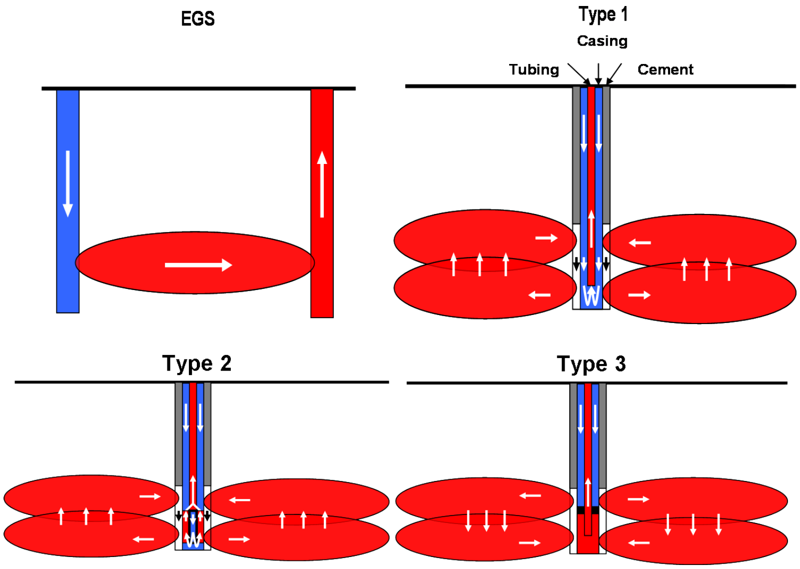


Figure 1. Sketches of different well types.

investigated how fast free convection can bring heat to the wellbore from the reservoir.

In a second configuration, without the heat exchanger, the coaxial producer/injector operates in an open loop through the formation. The configuration was originally proposed by Outman (1980). The advantage is that drilling cost is saved by providing the functions of a producer and an injector out of a single wellbore. A potential disadvantage is that frictional pressure loss in the wellbore will increase due to the reduced cross-sectional area for flow.

We compared the performance of the two different wellbore configurations connected to the same reservoir model. The model parameters were chosen to be reasonable for an EGS project. It is possible that different configurations could be better for different reservoirs, but our reservoir was chosen to be representative for a baseline comparison between the two.

Description of Different Types of Single Wellbore Configurations

All the configurations studied in this work are sketched in Figure 1.

1. Two-well EGS: we set the thermal extraction capacity in conventional EGS as a benchmark in the comparison. Though not shown in the sketch, this system requires a downhole pump and surface heat exchanger.

2. Type 1—Single wellbore downhole heat exchanger: as shown in Figure 1, the wellbore is cemented to the fracture interval (not to the very bottom), cased and then has a tubing installed. Water, or secondary working fluid, is injected downward through the annulus between the tubing and casing. To enhance heat transfer, the formation is stimulated to form a fractured reservoir. Formation fluid flows downward in the outer annulus below the cement (named second annulus hereafter in this paper) and this fluid would be heated up in passing upward in the fracture because of buoyancy. This phenomenon is known as a thermosiphon, which has spontaneous flow caused by the density variation at different temperature. There is also a thermosiphon inside wellbore. For low flow rate friction is small, thus the wellbore flow is also spontaneous due to the thermosiphon effect. For high flowrate, an on-surface pump might be needed to overcome the friction. A pump operating on the surface is much more reliable than one working downhole. Removing the downhole pump is a benefit of the single wellbore system.

3. Type 2—Crossover: a limitation of Type 1 is that there is cocurrent flow between the flows in the second annulus and in the wellbore; both of the flows are downward. A better heat transfer can be reached in counter-current flow. A counter-current flow can be achieved by using a crossover device, depicted in Figure 2.

4. Type 3—single well EGS: to circulate the fluid through fractures directly would increase the heat extraction, an idea proposed by Outman (1980). In this configuration, a packer is installed to divert the fluid flow into the fracture high in the wellbore and recover it lower down. As this configuration circulates fluid through the fractures, it is referred to as single-well EGS hereafter in this paper.

We compared the thermal extraction capacity of these four configuration based on a realistic thermal environment and well geometry, as listed in Table 1.

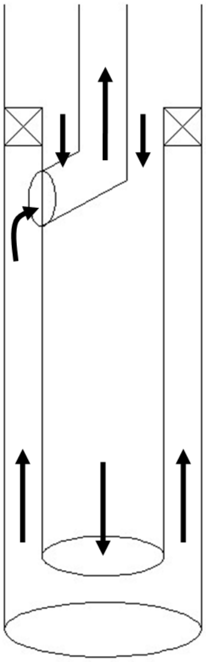


Figure 2. Sketch of crossover device.

Methodology

Wellbore and fracture were modeled separately. The wellbore model calculated the heat transfer within wellbore and between wellbore and formation, the phase change and the pressure loss by solving mass, momentum and energy balances equations in a finite-difference numerical model.

Reservoirs in an Enhanced Geothermal System are a complex network of stimulated fractures. To simplify, we modeled the reservoir as a vertical planar fracture with the wellbore in the middle. The fracture is 1000m long and 1000m wide. By symmetry, only one half of the fracture needs to be modeled. The fracture permeability and aperture were chosen to be similar to the reservoir characteristics of the European EGS site at Soultz-sous-Forêts in France. Soultz is a good site to use an example because it has been the subject of extensive research and characterization. The details of the model can found in Wang et al. (2009).

The flowchart of coupling wellbore and fracture models is shown in Figure 3. The pressure at the inlet point to the fracture can be calculated from the wellbore model. The flow rate in the fracture should be consistent with the wellbore, so we iterated on the value of the fracture outlet pressure until obtaining a match of the two flowrate values (in the fracture and in wellbore).

Modeling Results and Discussion

1. Fracture Effect

As we mentioned, heat extracted only by heat conduction is modest, and to overcome this limitation, circulation through the fracture system is required. As shown in Figure 4, the effects of

Table 1. Parameters for wellbore and formation configurations.

Thermal Environment	
Surface temperature	20 °C
Geothermal gradient	40 °C/km
Formation volume heat capacity	1800 kJ/m^3 °C
Formation thermal conductivity	1.5 W/m °C
Formation density	2500 kg/m^3
Formation thermal diffusivity	10^{-6} m^2/s
Well Geometry	
Casing diameter	306 mm
Tubing diameter	75 mm
Insulation material conductivity	0.05 W/m °C
Insulation thickness	5 mm

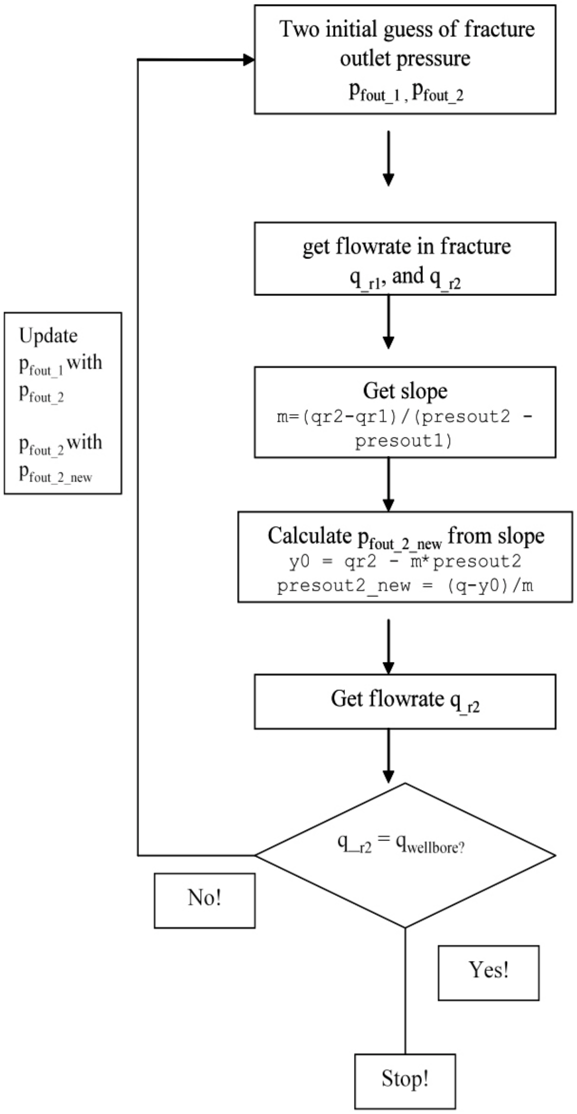


Figure 3. Flow chart of iterative method.

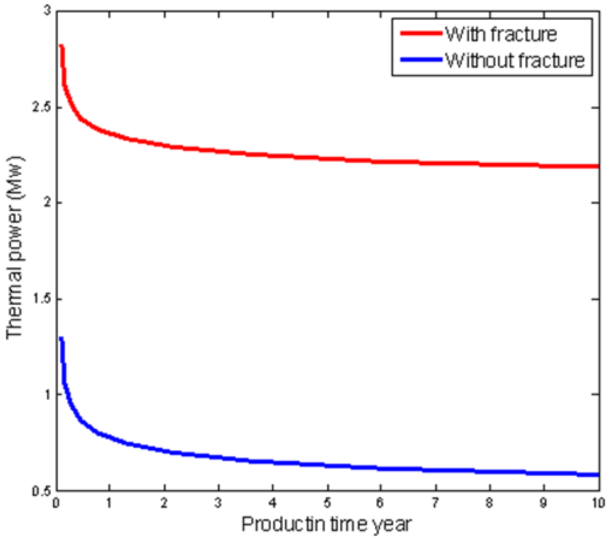


Figure 4. Effect of fracture connection.

fracture circulation on the overall heat extraction are twofold: (1) it would increase the amount of thermal recovery; (2) it would make the system sustainable over a longer production period, as the thermal recovery decreases more slowly when connected to the fracture.

2. Crossover Device

The crossover device was found to increase thermal recovery. As shown in Figure 5, the increase amount depends on flowrate. As mentioned previously, the advantage of the crossover is achieved by converting the cocurrent flow between wellbore annulus and second annulus to countercurrent flow. Heat transfer is reduced by co-current flow when the flowrate is low, thus the effect of crossover device is more prominent. Nonetheless, we should note that this downhole heat exchanger form of the single well geothermal system, even with the help of crossover, has limited thermal production capacity.

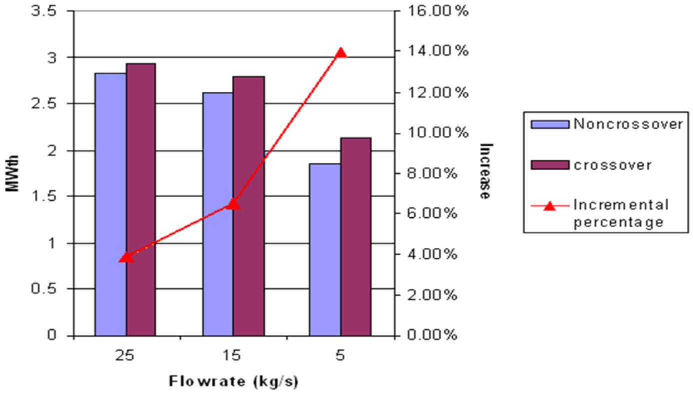


Figure 5. Crossover effect at different flow rates.

3. Single-Well EGS and Two-Well EGS

Both in single-well EGS and two-well EGS configurations, fluid is circulated through the fractures, which will greatly enhance thermal energy recovery. Thermal outputs of these two configurations were compared. The comparison was made under two production scenarios: with the same flow rate or with the same wellhead pressure.

In a single-wellbore design, the fluid can flow through the planar fracture on both sides of the wellbore. In a two-well design, fluid can only flow through the fracture on one side of the wellbore. This would seem to favor a single-wellbore design because fluid would flow through twice as much reservoir. However at scale, alternating producers and injectors would allow flow to occur in both directions away from the wellbore. Because of this, we allowed both the singlet and doublet to flow through both sides of the reservoir symmetrically. Rather than a doublet, we modeled a single pair in a chain of alternating producers and injectors. In this way we avoided prejudicing the results in favor of the single-wellbore design.

First, in both models, flowrates were set to be 25 kg/s. The thermal outputs from the two configurations are shown in Figure 6. Roughly speaking, thermal output equals the product of flowrate, heat capacity and temperature increase. Both models have almost identical thermal outputs under the same flowrate;

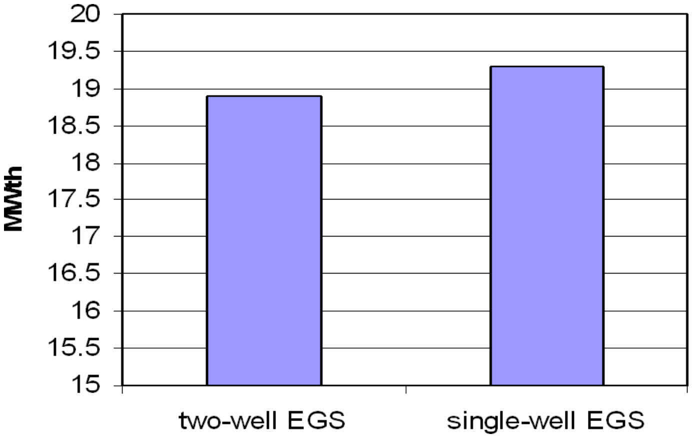
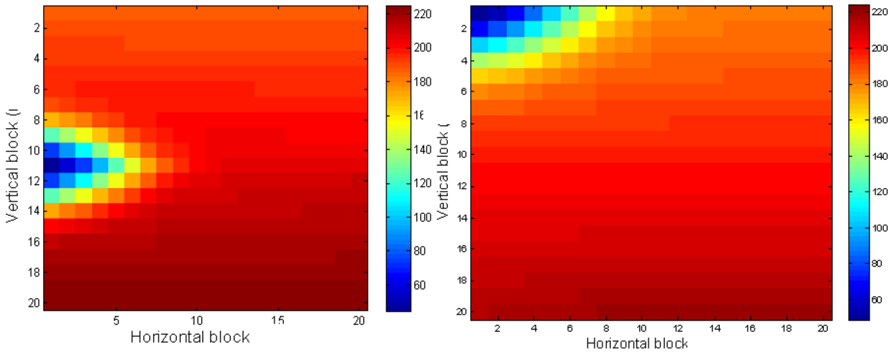


Figure 6. Comparison of two-well EGS and single-well EGS at the same flowrate.

therefore, the flowrate has a dominant effect on the thermal extraction capacity.

The fracture temperature distribution maps, shown in Figure 7, show that the temperature increase depends on the outlet location, i.e. at bottom for single-well EGS, at middle point for two-well EGS. Although single-well EGS has higher thermal output than two-well EGS in this case, this slight advantage is only because of the choice of outlet location. The comparison result would be different if the outlet location changes.



EGS **Type 3**

Figure 7. Temperature distributions in the fracture.

Second, we noted that single-well EGS might have high friction in the inner tubing due to its smaller dimension, which means it has lower flowrate under the same wellhead pressure. Figure 8 shows the thermal outputs of the two models with the same wellhead pressure. The wellhead pressure was set to be 50 bar as inlet, 5 bar as outlet. The result shows that single-well EGS has lower thermal output than two-well EGS in this case. The flowrates under the constant wellhead pressure are 24.9 kg/s for single-well EGS and 28 kg/s for two-well EGS. The result is consistent with our previous discussion: single-well EGS has larger flow resistivity and flowrate plays an important role in thermal recovery.

4. Circulation Secondary Working Fluid Downhole

The idea of circulating secondary working fluid downhole has been suggested in a number of papers, including Matthew (1980) and Gurgenci et al. (2008). The flowing path can be chosen to flow through the fractures or not. In this work, we chose not to circulate through the fracture, because when circulating through the fracture the secondary fluid, which is usually hydrocarbon, the fluid itself would be lost and would contaminate the formation. Therefore, based on our Type 2 configuration, we compared the difference of CO2 and isopentane as a working fluid. Both thermal extraction and electricity power generation were calculated, and results are shown in Figure 9. CO2 has advantages over isopentane from the aspects of both heat extraction and thermal efficiency in a turbine. Furthermore, unlike hydrocarbons, CO2 can be circulated through the fractures, since it would be a benefit of sequestrating greenhouse gas if it is lost or trapped in the formation. We did not simulate this case due to the limitation of our model; however, it is worthwhile to explore the potential application of CO2 sequestration in geothermal systems.

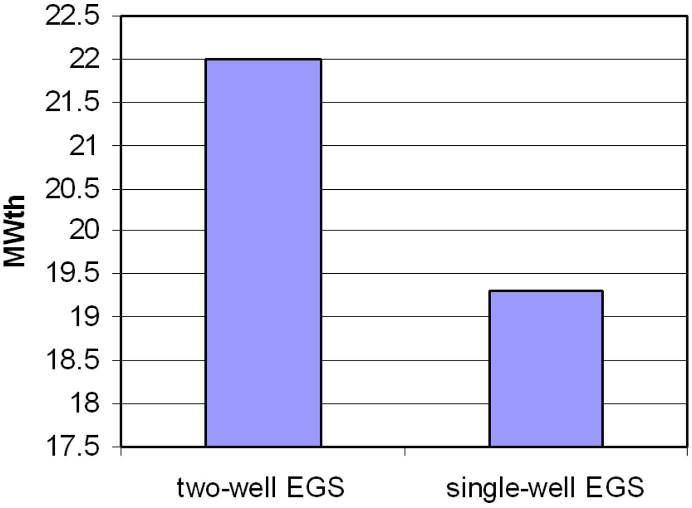


Figure 8. Comparison of two-well EGS and single-well EGS at the same wellhead pressure.

Discussion

The coaxial heat exchanger configurations produce significantly less energy than the others because free convection drives fluid at a low flow

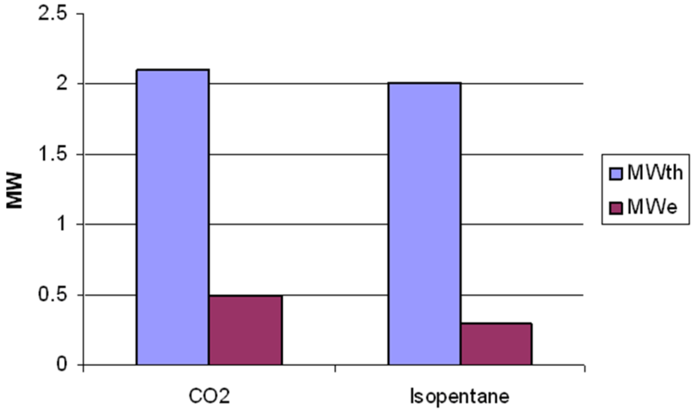


Figure 9. Comparisons between CO2 and isopentane circulation in Type 2 configuration.

rate through the reservoir compared to the rate that can be achieved with a direct connection to the surface. The choice of working fluid has a small effect on the thermal output of the system, but it can be an advantage in improving the efficiency of the turbine.

The constant wellhead pressure trials indicate that the achievable flow rate and energy output are only somewhat lower in the single wellbore than in the doublet configuration. The additional pressure drop caused by the reduction in cross-sectional area in the single wellbore configuration is relatively small. Geothermal wells are traditionally drilled with large diameter, but this is because they need to support high rates of vapor flow. Frictional pressure drop is much lower in single-phase liquid flow because the fluid velocity is much lower than in vapor flow. EGS reservoirs are deep and will most likely exhibit single-phase flow, making the frictional pressure drop in the wellbore less significant. This suggests that a higher thermal output per well could be achieved using coaxial single-wellbore designs.

An important caveat to our single-wellbore design is that it requires vertical flow in the fractures. We can only speculate about the vertical permeability of EGS reservoirs because vertical flow through EGS reservoirs has never been attempted. It is possible to imagine a single-wellbore design that allows horizontal flow by using a deviated wellbore.

Conclusion and Future Work

In this paper, the power generation capacity of coaxial single-wellbore EGS designs has been explored based on numerical modeling. A key factor to enhance the power generation of this system is to connect the wellbore to the fracture. Several other findings in this study are:

1. The configurations with fluid flowing through the fracture have satisfactory thermal recovery capacity;
2. Flowrate through the system has a dominant effect on the overall thermal recovery;
3. Single-well EGS has higher flowing resistivity than a two-well system, but overall produces significantly more per well.

The use of CO2 as working fluid in a coaxial heat exchanger was also studied in this paper. As CO2 is working in the super-critical region in the turbine, it shows higher thermal efficiency than other common secondary working fluids, like isopentane studied in this paper. However, in this paper, we did not model the case where CO2 circulated through the fracture. This direction is worthwhile for future research.

As mentioned, flowrate in the fracture greatly affects the thermal output of the system, thus, a direction for future study would be to explore the connection within the fracture, which is a key factor in determining the flowrate in the fracture. Both theoretical and experiment methods may be needed for this purpose.

Acknowledgement

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