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A Discussion about Fracture Efficiency as a Function of Well Placement with Application to Geothermal Energy

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ABSTRACT

Enhanced geothermal systems require fractures to allow water circulation in the artificial underground heat exchanger. Various authors as well as the "gebo" project (high performance drilling and geothermal) propose a concept which concentrates on horizontal wells that are connected by multiple fractures. This paper focuses on the optimum positioning of the injector and producer wells as a function of reservoir thickness. For this purpose, we introduce a so called "fracture utilization efficiency", which can be used as a factor to estimate the proper placement of the two wells. The investigation of the well alignment attempts to identify if it is more advantageous to either place the production or the injection well above one another. The development of the production temperature shows no differences for the well alignment. The comparison of the temperature distribution in the fracture shows of course the converse effect but the shape and propagation is still the same. Finally, we found out that the symmetry of the fractures will require two producers in order to use the fracture at its maximum efficiency.

1. INTRODUCTION

Petro-thermal reservoirs require artificial flow paths to allow water circulation for the heat mining process. The reservoir dimensions, especially the thickness, are important parameters that require attention when the optimization of the well placement becomes a design issue.

The Enhanced Geothermal Systems (EGS) can be developed using vertical, deviated or horizontal wells, but the key decision is the well placement and the distance between the well paths for injection and production wells in order to use the reservoir at its maximum efficiency.

The normal flow paths in EGS systems are created by massive water fractures, which connect existing wells to each other. The created water fractures serve as heat exchanger. This approach has some disadvantages like the improbability to achieve sufficient fractures from one well to another, as well as the earthquake risks associated with massive fracturing processes.

Various solutions for unconventional deep geothermal exploitation have been proposed in the literature, some of which have already been implemented in the field. They have been prompted by the need to design methods suitable to situations where the heat is there, but the permeability and/or the porosity of the geothermal resource lacks. These solutions include:

- The original Hot Dry Rock concept (Potter et al., 1974) and its derivatives, based on the creation of hydraulic connectivity between injection and production wells, or injection and production legs of the same borehole (Gedzius and Teodoriu, 2011) (see Figure 1).

- Single-well (open) concepts relying on different sections of the well connected both to a production and an injection layer, isolated from each another –Genesys Concept (Tischner et al., 2010).

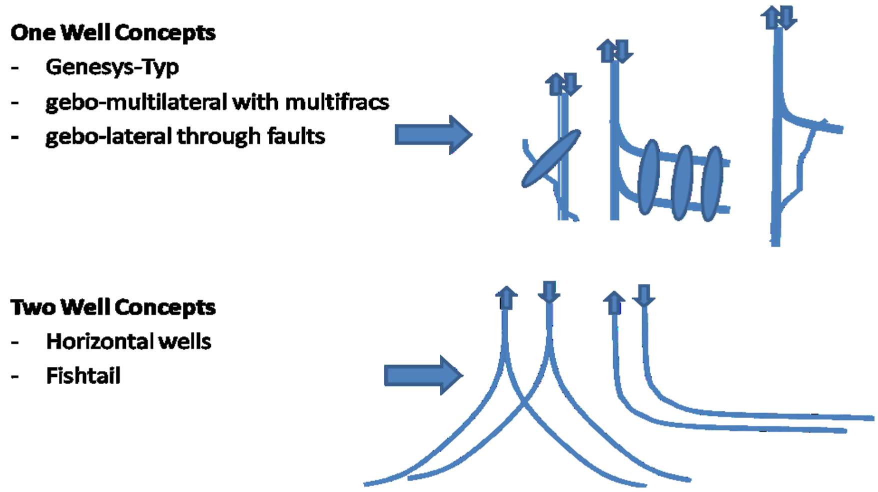


Figure 1. Various methods to connect the geothermal reservoir, after Gedzius and Teodoriu (2011)

Both concepts above rely on fractures to provide the necessary contact area for the pumped fluid to gain heat underground.

Another interesting concept, shown in Figure 2, proposes the construction of geothermal well farms ("Reservoir Farm"), where from one location multiple horizontal wells are drilled. In order to exploit the petro-thermal potential, the author proposes a new technique (Heidinger, 2014): "*The installation of multi-crack systems, which use artificially created flow paths within a certain rock volume, seems to be a promising option. Since the rock volume has a limited extension, the amount of energy (i. e. heat), which can be extracted and the life expectancy of such a petro-thermal plant is limited. In order to overcome this disadvantage a change from the prevalent system, where a drilling rig is rented to exploit one single geothermal multi-crack system, to a system where a drilling rig is purchased in order to exploit continuously one reservoir after the other, is necessary.*"

Geothermal wellbore simulation has become very popular due to the increase in computer power and availability of computer clusters. Xing et al. (2009) shows a comparative review of various EGS simulators, pointing also out that the newly developed tools do strongly focus on fracture modeling and also micro seismicity associated with fracturing jobs.

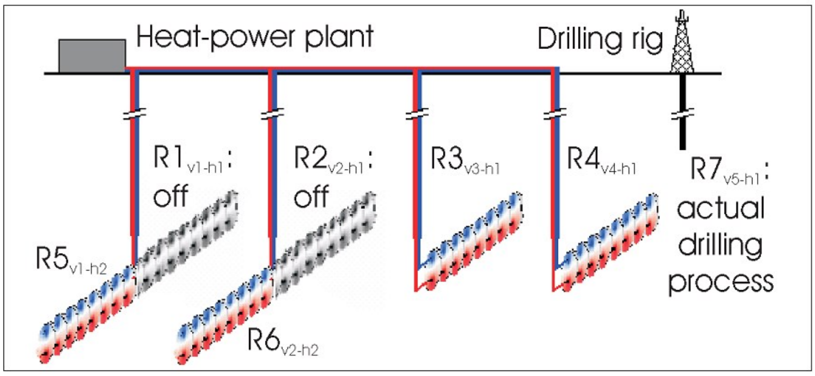


Figure 2. The Geothermal Farm Concept (Heidinger, 2014)

Rühaak, et al. (2008) shows a classic simulation of a doublet geothermal well, pointing out the advantages of using simulation to identify long term behavior of heat exchange in the underground. Figure 3 shows modeled temperature in a doublet after 10 years, indicating that cooling process can affect the well placement.

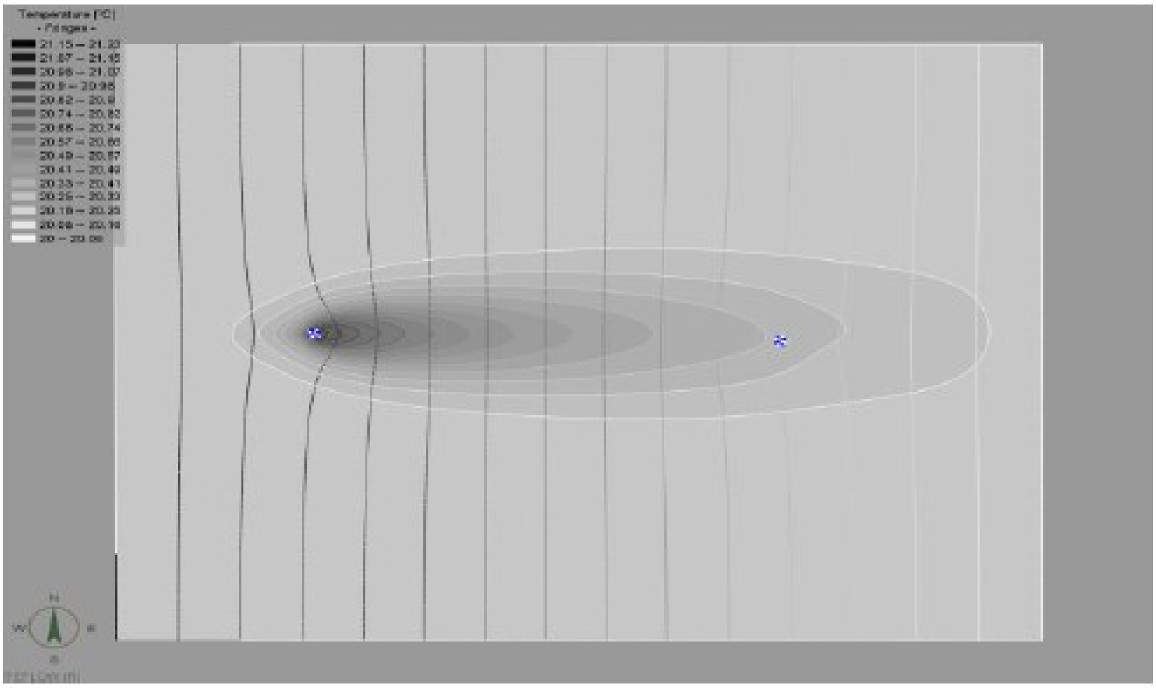


Figure 3. Example of temperature distribution between two vertical wells (Rühaak, et al, 2008)

Many authors focus on temperature variation in well (Kutun et al., 2014, Rosca, 2000), as well as on complex simulation of the fracture network (Sandve, 2013, Juliusson, 2010), however, few papers consider the proper placement of the well into the reservoir as a function of reservoir thickness and "farming" process. Nevertheless, there are papers focusing on well placement to enhance the heat output of a given reservoir, especially hydrothermal resources (Ansari, 2014, Akin, 2008).

Güyagüler and Horne (2004) use the uncertainty assessment theory for well placement and they point out that because the data used to establish numerical models have uncertainty, so the model forecasts do. They generate a utility framework used to assess the uncertainty in numerical-simulation forecasts when evaluating different well configurations.

Opposite to their concept, this paper considers an ideal fracture system with little errors, whereas the focus lies on the temperature distribution between fractures and the re-charging behavior of the reservoir. First, this paper proposes the investigation of the proper placement of one single well pair which will be called "geothermal cell based on efficiency". Second. it focuses on the use of a "reservoir farm" based on the recharging principle: one cell produces heat, whereas all other cells recharge.

2. FRACTURE EFFICIENCY CONCEPTS

The investigation of well alignment attempts to find out if it is more advantageous to either place the production or the injection well above. The development of the production temperature shows no differences for the well alignment. The comparison of the temperature distribution in the fracture shows of course the converse effect but the shape and propagation is still the same.

We investigated two types of fracture efficiency:

- ***volumetric efficiency,*** defined as the total fracture volume divided by the volume of liquid pumped. This efficiency can be used as factor to estimate the proper stimulation design.
- ***fracture utilization efficiency***, defined as the area which reaches a given temperature value (195 °C) after 20 years divided by the total fracture area, which can be used as factor to estimate the proper placement of the two wells.

The basic concept comprises a pair of horizontal injection and parallel production well in the vulcanite layer. A multi-water-fracture stimulation provides a direct connection between both wells. The simulation study distinguishes between two scenarios. In scenario 1 the wells are placed with a horizontal spacing (Figure 4a), which is also feasible for a lower vulcanite thickness. In scenario 2 the wells are located vertical above each other (Figure 4b), which requires a high thickness of the vulcanite layer and is not possible at all locations. In total, seven cases have been examined for these investigations. We considered two types of reservoirs: thin and thick, and correspondingly we placed the wells in order to enhance the heat extraction. An example of temperature changes for two parallel wells in vertical plane with time measurement is shown in Figure 5.

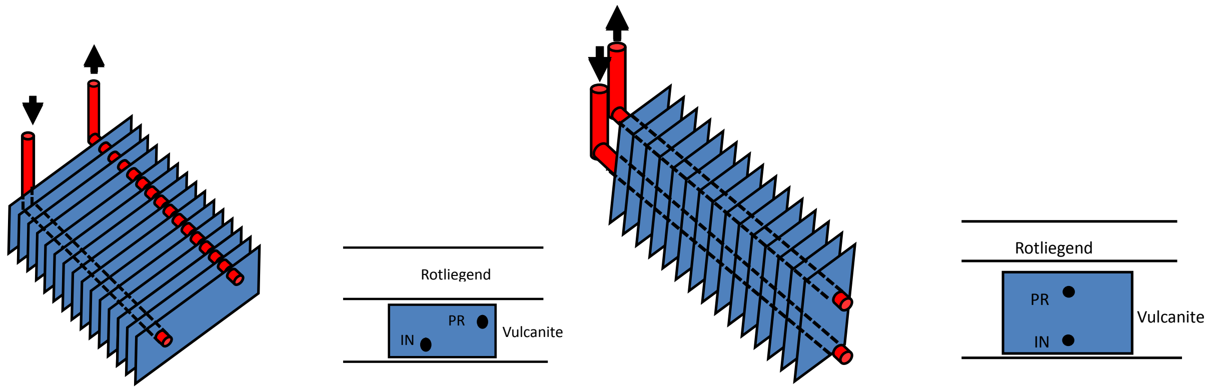


Figure 4. Injector and producer well locations: thin reservoir left and thick reservoir right

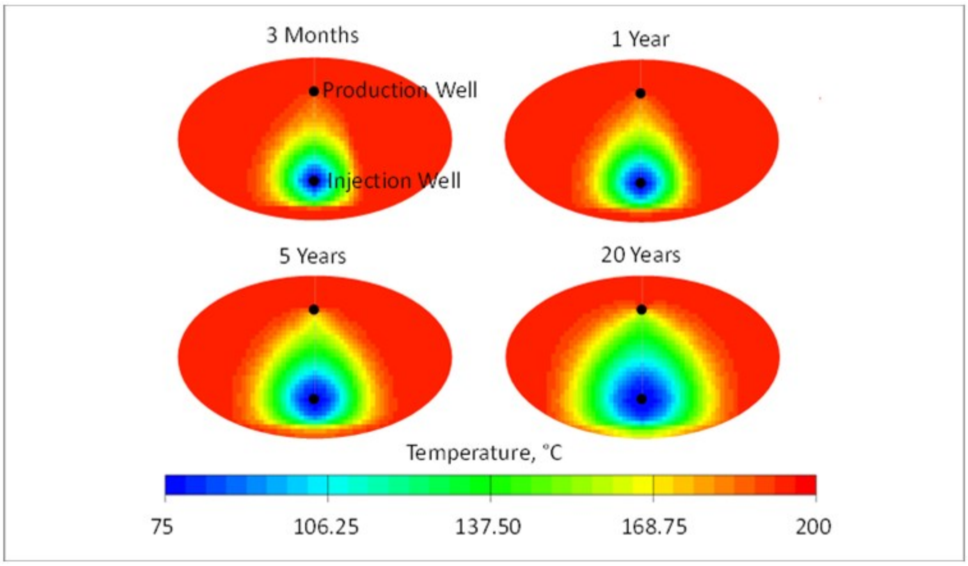


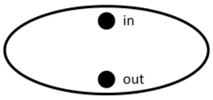
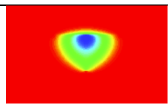
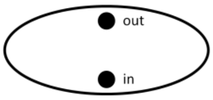
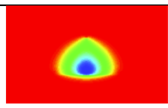
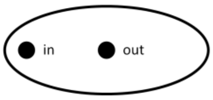
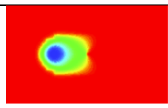
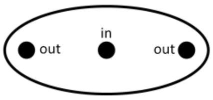
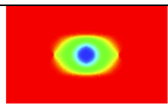
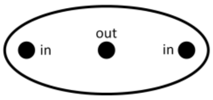
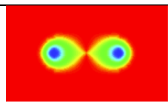
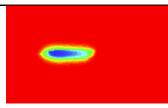
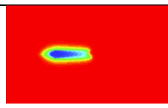
Figure 5. Temperature distribution in a vertical plane through one fracture at different time periods

The following well positioning cases have been considered.

- Scenario 1: two horizontal parallel wells in vertical plane, injector on top
- Scenario 2: two horizontal parallel wells in vertical plane, injector on bottom
- Scenario 3: two horizontal parallel wells in horizontal plane, injector on one side of the fracture
- Scenario 4: three horizontal parallel wells in horizontal plane, injector in center
- Scenario 5: three horizontal parallel wells in horizontal plane, two injectors left and right
- Scenario 6: two horizontal parallel wells on diagonal plane, injector on one side of the fracture
- Scenario 7: two horizontal parallel wells in horizontal plane, injector on one side of the fracture

Scenarios 1 to 5 are based on the assumption of thick geothermal reservoir, whereas the scenarios 6 and 7 consider a thin reservoir. Table 1 shows the calculated efficiencies based on the cases shown above, as well as the well placement for each one of the cases.

Table 1. Fracture utilization efficiency

Well alignment	Fracture utilization efficiency	Temperature profile after 20 years
	71.1 %	
	73.3 %	
	68.1%	
	81.8 %	
	93.6 %	
	66.8 %	
	64.6 %	

The volumetric efficiency was calculated using the following input parameters:

- Depth: 5000 m
- Fracture Half Length: 600 m
- Inj. Temp.: 75°C
- Plane Strain Modulus: 50 GPa
- Nolte Factor: 1.5
- Leak Off Coefficient: 0.0002 (ft/min^0.5)
- Ratio Net to Fracture Height: 0.85

Based on these input parameters the volumetric efficiency of the fractures is shown in Table 2.

Table 2: Fracture volumetric efficiency

Fracture Height (m)	Injection Rate (bpm)				
	40	***60***	***80***	***100***	***120***
100	58 %	66 %	70 %	74 %	76 %
500	31 %	40 %	46 %	51 %	54 %

2. "RESERVOIR FARM" BASED ON THE RECHARGING PRINCIPLE

In case of multiple wells drilled from the same location it is necessary to understand the waiting time for the wells to recharge. For this case a detailed numerical work was carried out.

2.1. Geometry and grid of the Geothermal Farm

The numerical model was implemented by using Eclipse 100. The conceptual geometry is a cuboid with the dimensions 2000x2000x1500m. It is discretized by a Cartesian grid with 100x100x75 grid blocks. The top of the model is located in a depth of 4250m. Dependent on the case, two or three horizontal wells are located in a depth of about 5000m. The distance between the wells is in all cases 400m. The wells are directly connected by 20 uniform transversal fractures which have a length of 600m and a height of 100m (for the thin reservoir) or 500m (for the thick reservoir). The distance between the parallel fractures is 100m. For a more applicative realization of the fractures the grid was refined in its vicinity by using a logarithmic distribution. In this way the grid blocks which represent the fractures have a dimension of 0.7x10x10m. Figure 6 shows a horizontal slice through the reservoir model in a depth of 5000m. .

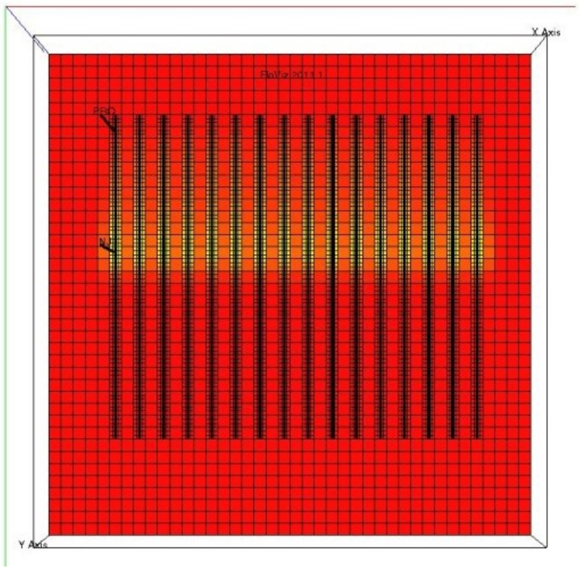


Figure 6: The model of the simulated geothermal reservoir

2.2. Rock and fluid properties

For the conceptual model a homogeneous reservoir is assumed. The parameters of the rock are related to the vulcanite which is present in the North German basis. The initial and the injected fluid is moderate saline water. All relevant hydro- and thermodynamic properties are summarized in Table 3. The viscosity of water was correlated in dependence on the temperature.

2.3. Initial and boundary conditions

Initially, the reservoir is saturated by water and the pressure is defined with 467.5 bar at the reference depth of 4250m. The initial temperature is 200°C without any gradient. All outer boundaries are defined with no flow of fluid or heat. The total injection rate is 130 l/s, which is equally distributed to all fractures. The water production is controlled by a bottom-hole pressure of 450 bar.

Table 3. Input data for reservoir simulation

Parameter	Value
Permeability (mD)	0.1
Fracture permeability (upscaled) (mD)	2500
Porosity (%)	0.5
Thermal conductivity of rock and fluids (kJ/m/day/K)	194.4
Rock specific heat data (kJ/m3/K)	2800
Reference Pressure (bar)	467.5
Water FVF at Pref. (rm^3/m^3)	1.1
Water Compressibility (/bar)	4 E-5
Water Density (kg/m^3)	1100
Water specific heat, (kJ/kg/K)	4.0

2.4. Results of the "reservoir farm" simulation

Figure 7 shows the simulation of geothermal well production using all cells simultaneously. The numerical results show a depletion of the reservoir (heat) after approximately 20 years.

Figures 8 to 11 show the temperature of the reservoir when using one cell after another (the concept considers that one cell is producing while the other cells are recharging). We consider the same production time of 20 years per cell. Figure 10 shows that after 80 years the temperature around the producer of the first cell is not fully recharged.

Figure 12 shows the temperature distribution in the underground after 100 years, when the first cell is being reused. The figure shows clearly that the recharging of the additional cells is not fully completed. Based on this simulation we found out that a "reservoir farm" will require at least 10 or more cells (20 or more wells) when doublets are considered, in order to allow the cell to fully recharge. This recharging process is already visible when comparing Figure 9 with figure 11, whereas the temperature around the first cell is still not 100% of the initial reservoir temperature (~150°C instead of 200°C).

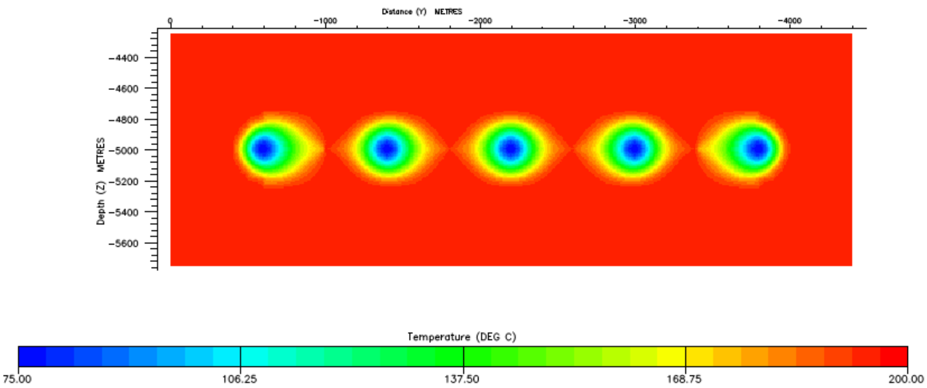


Figure 7: Temperature distribution in a reservoir farm after 20 years of using all wells to produce simultaneously

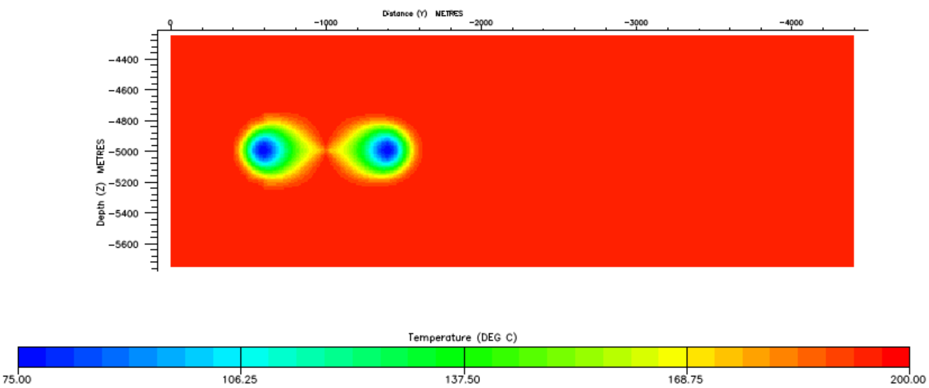


Figure 8: Temperature distribution in a reservoir farm after 20 years of using one producing cell: first cell (three wells scenario 5)

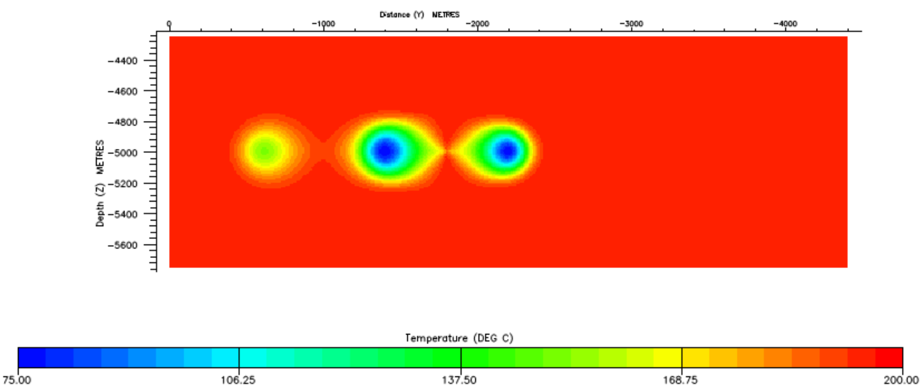


Figure 9: Temperature distribution in a reservoir farm after 40 years of using one producing cell: second cell (three wells scenario 5)

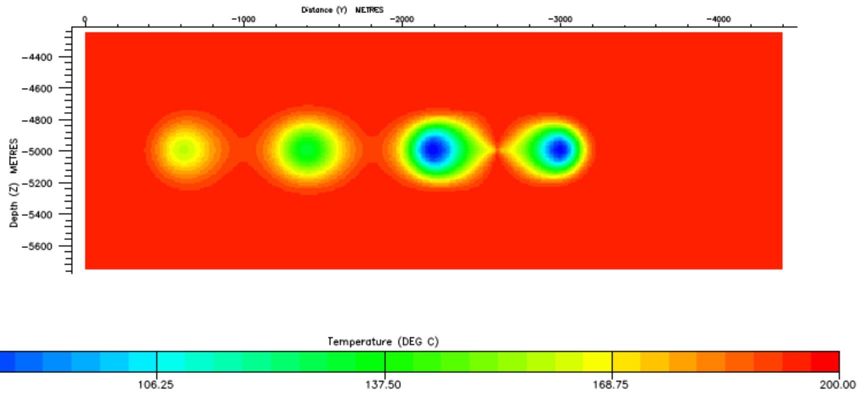


Figure 10: Temperature distribution in a reservoir farm after 60 years of using one producing cell: third cell (three wells scenario 5)

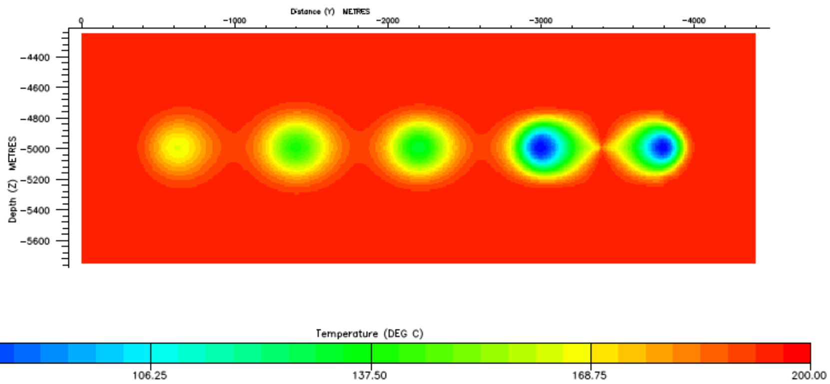


Figure 11: Temperature distribution in a reservoir farm after 80 years of using one producing cell: fourth cell (three wells scenario 5)

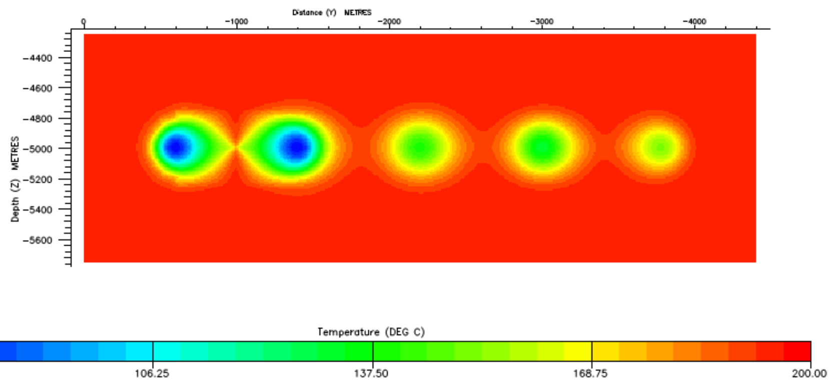


Figure 12: Temperature distribution in a reservoir farm after 100 years of using one producing cell: cell number one after recharging (three wells scenario 5)

CONCLUSIONS

This paper defines a thermal and volumetric efficiency of fractures with respect to heat mining. The volumetric efficiency is high when the fracture length is small. The thermal efficiency is maximum when 2 injectors and one producer in the center of the fracture are used.

Finally, we found out that the symmetry of the fractures will require two producers in order to use the fracture at its maximum efficiency.

When the "reservoir farm" concept is used, alternating heat mining is recommended, whereas the number of wells depends on the recharging time of the reservoir. The simple reservoir simulation showed that a minimum of 10 cells (20 wells) are necessary if fully recharging of the reservoir is needed.

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