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Der Kooij, R. Van; Wang, Y.; Daniilidis, A.; Voskov, D.

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Performance Influences of a Deep High Temperature Fractured Geothermal System

R. Van Der Kooij[1], Y. Wang[1], A. Daniilidis[1], D. Voskov[1]

[1] Delft University of Technology

Summary

To assess the influences of various parameters in ultra deep (>4km), high temperature, fractured geothermal systems, the system's NPV was evaluated as these parameters were varied. The examined fracture network had multiple fractures leading between the wells in a single doublet. The tested input parameters concern rock matrix parameters (permeability, porosity, thermal conductivity and heat capacity), apertures in the fracture network and cold-water injection rates. After simulation of flow, the resulting data has been used for the calculation of NPV, which provided an indication for the performance.

Larger values for matrix parameters and higher fracture apertures amplified each other's positive effect they had on the NPV of the system, as they both prevented bottlenecked flow of injected water from injector to producer wells and kept the system lifetime longer by allowing injected water more time to absorb heat before reaching the production well.

An optimum exists when selecting injection rate with regards to system NPV. Lower injection rates lead to lower energy production, while higher injection rates lead to shorter lifetimes. A balanced injection rate lead to a maximum NPV.

More investigation into optimization of injection rate over system lifetime will prove valuable for maximizing performance.

Introduction

As the global need for additional sources of energy increases and the interest in generating clean energy is becoming more apparent, geothermal power is an attractive method of power production. Ultra-deep (>4km top reservoir depth) geothermal reservoirs are valuable for the large amount of energy they contain. The efficiency of the injection plan will determine to what extent a geothermal project can contribute to energy production.

The performance of the geothermal system can be assessed by determining the net present value (NPV) at the end of the geothermal project lifetime (Daniilidis et al., 2020b; van Dongen, 2019; Zaal, 2020). The NPV of the system is influenced largely by the flow rate and energy production, but is also affected by heat price, OpEx percentage and discount rate (Daniilidis et al, 2017). This implies that NPV is a comprehensive measurement of profitability in regards to both physical and economic aspects (Daniilidis et al, 2020a).
Here, a fracture model by Wang (Wang et al, 2020a) is used for the simulation of geothermal operation. The simulations are carried out using the Delft Advanced Research Terra Simulator (Khait et al., 2020; Wang et al., 2020b), which allows for the construction of a reservoir model and efficient simulation of flow through the reservoir. Different matrix parameters, varying aperture values and a range of cold water injection ranges are applied in the simulations to obtain temperature, pressure and NPV results. The NPV results are obtained through a calculative scheme based on work by Daniilidis (Daniilidis et al., 2020a) and are evaluated to determine the effect of the varied parameters.

Model setup

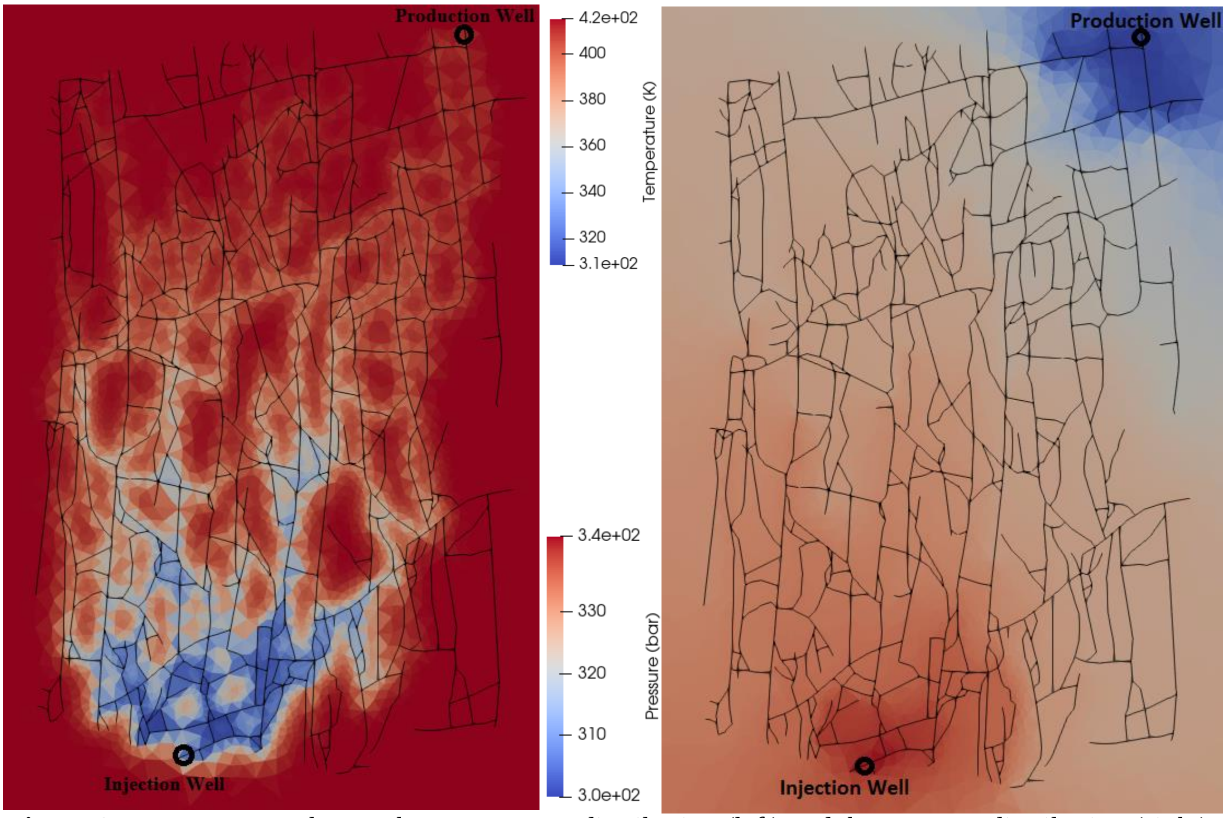

Figure 1 *Fracture network over the temperature distribution (left) and the pressure distribution (right) after 10 years in the carbonate reservoir including relevant legends, including well location indicators.*

The top of the reservoir is taken at 4000m, with reservoir dimensions of 1250m by 1750m by 50m. The pressure and temperature throughout the reservoir are set at 400bar and 150°C respectively. The reservoir is initially under critical condition and exclusively single-phase liquid water is considered as pore fluid.

A single doublet is placed, with both wells positioned in a fracture on opposite ends of the reservoir. The injection well is rate controlled and injects liquid water at a temperature of 25°C. The production well is kept at a constant bottom hole pressure of 300bar. The injection rates range from 500m^3/day to 3500m^3/day.

The fracture paths in the reservoir can be observed in Figure 1. A distribution of values is randomly sampled over this network to obtain 100 different realizations. These realizations are used for the simulation in both the basalt and carbonate reservoirs.

The simulations are run separately for basalt and carbonate rock types, leading to different values in the porosity (ϕ), permeability (k), thermal conductivity (κ) and heat capacity (C) of the matrix.

The NPV in a simulation is taken at the time of thermal breakthrough. Thermal breakthrough is set to occur when the reservoir temperature has dropped by 10% in °C since the onset of geothermal operation.

Results

After running simulations for all fracture network realizations in the carbonate reservoir and using an injection rate of 2000m^3/day, P10, P50 and P90 cases are selected from the resulting temperature profiles. The temperature profiles and the selection are visible in Figure 2. The lifetime condition is indicated at 90% of the initial temperature in °C.

The carbonate reservoir shows less temperature decrease over time in the production well compared to the basalt reservoir, for the same injection rates and fracture network realizations, meaning that the project lifetimes in the carbonate reservoir are longer. Larger cold water injection rates are linked to faster temperature decrease in the production well and shorter project lifetime. P90 shows faster temperature decrease, while P10 has the longest lifetime.

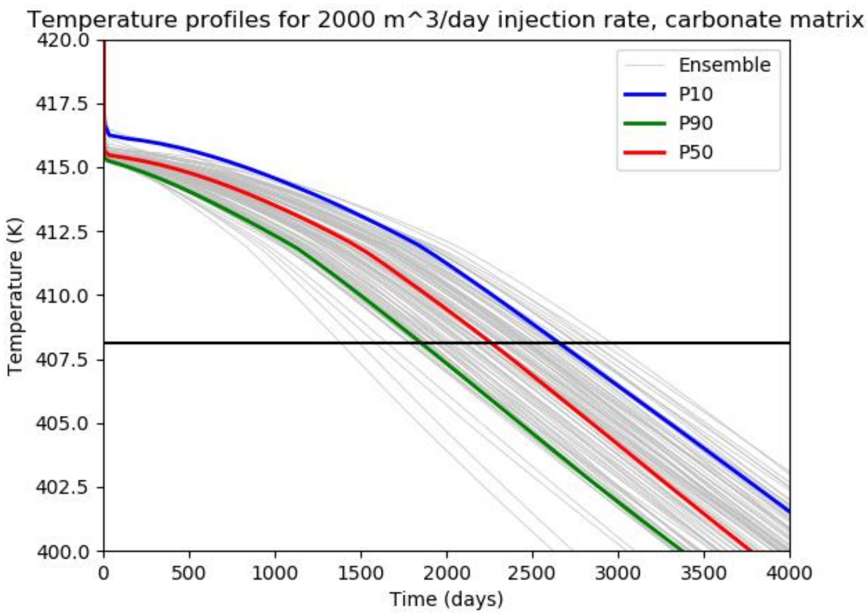

***Figure 2** Temperature profiles for all fracture network realizations in the carbonate reservoir, including temperature threshold for lifetime condition in black.*

The temperature decrease in the carbonate reservoir is observed over a more widespread area around the fractures in the matrix than for the basalt reservoir, where flow is almost entirely limited to the fractures due to poor matrix flow conditions. In the fracture network of the carbonate reservoir the temperature decrease is less significant than for the basalt reservoir. For the P90 case, the injected cold water flows through less fractures near the production well, leading to large flow velocities going from production to injection well. In the P10 case, more fracture paths support flow of water, leading to less bottle-necking. This holds true for both basalt and carbonate reservoirs, although the matrix properties of basalt further amplify the flow bottlenecks.

The pressures in the basalt reservoir are larger overall than for the carbonate reservoir. As the flow in basalt is limited by the matrix properties, pressure build-up is more significant in the basalt reservoir. Larger injection rates cause larger pressure build-up. Of the three selected case, the reservoir pressures in the P10 case are the highest. The pressures in the P90 case are the lowest, although the difference between P50 and P90 is minimal compared to the difference between P10 and P50.

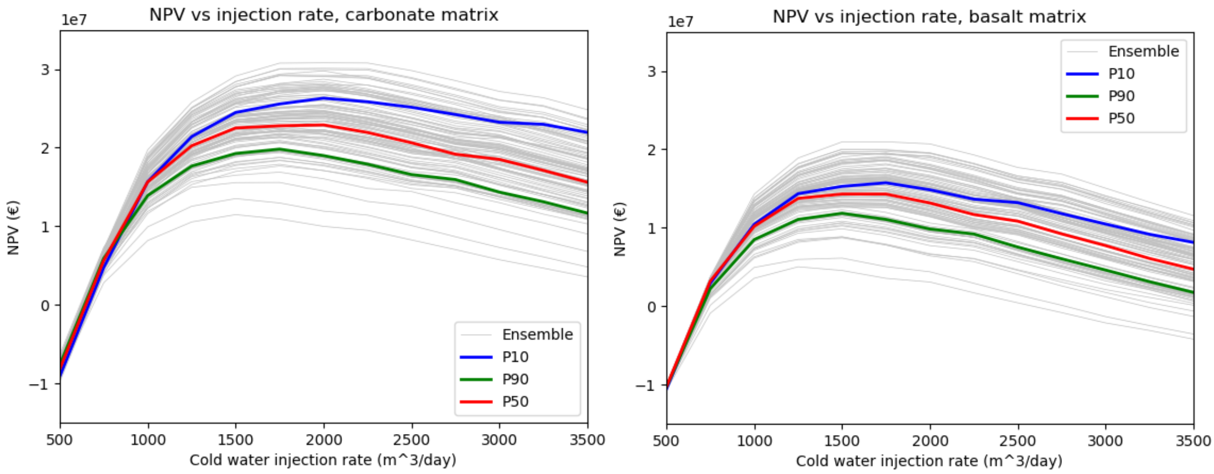

Figure 3 *NPV over cold water injection rate for carbonate and basalt matrix types respectively*

The carbonate reservoir NPV over cold water injection rate is visible in Figure 3. The behaviour of the NPV over injection rate plots are similar for both reservoirs and all 100 realizations, the largest difference being that the carbonate plots have larger NPV results overall. For all 100 realizations, an optimal injection rate can be found in order to maximize the NPV. This injection rate is larger when a larger maximum NPV is obtainable. This is supported by the fact that P10, which has the largest NPV values out of the three selected cases, and P50 reach a maximum NPV value for larger injection rates than for P90, which has the smallest NPV values. The NPV for injection rates on the lower end of the injection rate range shows insignificant difference between the realizations. As the increase in NPV over increasing injection rate diminishes, the difference becomes larger. After the maximum values have been achieved, the NPV decreases at a steady rate, and the difference between the realizations remains relatively constant as a result.

The NPV over time per injection rate for the three selected cases and the two matrix types show larger injection rates cause larger NPV over time, while lower injection rates are linked to longer lifetimes. The lifetime of the largest injection rate is too short to obtain larger NPV values. For the lowest injection rate, the periodic costs weigh too heavily to obtain significant NPV over time, leading to the project to be unable to offset the initial project expenses. Therefore, an optimum exists at a balanced injection rate, which is different per realization and matrix type.

The matrix flow and thermal parameters likely complement each other in transferring more energy to the injected water. A higher permeability leads to more flow throughout the matrix and larger porosity allows for more contact of the injected water with the matrix. A higher thermal conductivity leads to faster transfer of energy when this contact is made and a larger heat capacity leads to more total energy in the reservoir to provide the water with.

The fracture network is the deciding factor for the flow direction. When multiple fractures lead from the injection well to the production well, the contact surface of the water with the matrix further increases. When the apertures in a fracture path are too narrow, however, the flow there will be limited, causing concentrated flow in the wider fracture paths. In that case, less energy will be transferred from the matrix to the water, causing less produced energy over time and the project lifetime is reduced, as the temperature in the production well will decrease more rapidly. Increased matrix flow and thermal parameters amplifies the effect of a favourable fracture network, because with both more fracture flow and matrix flow, even more contact can be made between the injected water and the matrix, leading to more energy and longer lifetime.

Conclusions

The results obtained for the temperature progression and the NPV at the end of project lifetime indicate that the combined effect of varying injection rates, fracture network parameters and matrix rock parameters is quite significant. Increased matrix flow parameters and a fracture network with a multitude of favourable fractures leading from injection to production well amplify each other's effect on the resulting NPV of a project. The cold water injection rate can be selected to achieve an optimum in NPV, as it controls both the power production rate as well as the lifetime of the project.

Since the injection rate is assumed to be constant over project lifetime, more investigation on periodically optimizing the injection rate could provide more insight on maximizing the NPV of a geothermal project.

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