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Thermo-hydraulic Modeling of an Enhanced Geothermal System in the Upper Rhine Graben using MOOSE/TIGER

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ABSTRACT

The research project GeoFaces aims to analyze the thermo-hydraulic-mechanical properties of possible geothermal reservoirs in the Upper Rhine Graben (URG) in SW-Germany / E-France. The scope is the quantification of the fluid circulation along or through faults and fractures under recent geological conditions. This paper concentrates on the joint analysis of different scientific datasets to predict the physical behavior of the Soultz Enhanced geothermal reservoir in terms of thermal conduction and fluid flow. Different data, including temperature, hydraulic and seismic measurements, were evaluated and used as input and calibration parameters and for the definition of the boundary conditions in a numerical fully coupled FE-13-fracture-modeling of the Soultz reservoir with the TIGER application (Gholami Korzani et al. 2019). On the basis of the models created by Sausse et al. (2010) and Held et al. (2014), new simulations were conducted to evaluate and calibrate the long-term behavior of the reservoir with regard to hydraulic and thermal sustainability. This analysis allows for the prediction modeling of the reservoir temperatures under the new economic power plant design of Soultz-sous-Forêts, as well as the sensitivity to changes in the production- and injection-rates and temperatures.

1. INTRODUCTION

The Upper Rhine Graben (URG) is one of the most promising locations for geothermal energy utilization in central Europe, with elevated thermal gradients up to 100 K.km^{-1} and preferable hydraulic conditions (Pribnow und Schellschmidt 2000). Power plant projects target either the deep crystalline basement as Enhanced Geothermal Systems (EGS) or the hydrothermal mesozoic sedimentary cover (Genter et al. 2016). EGS are designed to use and enhance the natural permeability of faults and fractures by hydraulic or chemical stimulation (Schindler et al. 2010). The most prominent European EGS is located at Soultz-sous-Forêts (Garnish 2002), targeting a 5000 m deep fractured reservoir (Genter et al. 2010). Various kinds of experiments were conducted, creating a huge scientific database and allowing the study of hydraulic and thermal processes in the fractured geothermal reservoirs in general (Genter et al. 2010; Sausse et al. 2010). Experiments, like circulation, tracer and flow-meter tests, allow the quantitative description of the fluid flow through the fractured reservoir rock, but give only punctual data at the wellheads. Spatially distributed and coupled information about the reservoir is quite often missing.

The combination of structural and numerical models can close this existing gap and help to investigate the hydrothermal processes that take place in an EGS (O'Sullivan et al. 2001). In numerical modeling, EGS are very often simplified to a parallel-plate approach, which is not sufficient for the Soultz reservoir. Understanding and quantifying the fault and fracture-network and thus the natural flow paths is crucial for the sustainable utilization of a geothermal power plant. Therefore, an updated numerical model of Held et al. (2014) is presented, considering the quantitative flow along the Soultz fracture network inferred from circulation tests, tracer experiments and the new power plant design for commercial usage of the facility (Mouchot et al. 2018). The findings are used to forecast the thermo-hydraulic long-term behavior of the heat exchanger system in terms of thermal breakthrough and cooling area. Furthermore, the sensitivity of the entire EGS design to different uncertainties, e.g. a further increase of the flow-rates or different reinjection temperatures, is investigated using fully-coupled numerical simulations.

2. NUMERICAL MODELING

The Finite-Element (FE) open-source application TIGER (THC sImulator for GEoscience Research) (Gholami Korzani et al. 2019) was used for the numerical study. The code is based on the MOOSE framework (Gaston et al. 2009) and designed to solve thermo-hydraulic-solute transport problems in geothermal reservoirs in a fully coupled manner. It offers the opportunity to treat features like fractures and well paths in a discrete lower-dimensional way.

2.1 Governing Equations

The hydraulic field is solved by combining the mass and momentum balances (Bundschuh et al. 2010) for the matrix as well as the lower-dimensional elements as:

$$bS_m \frac{\partial P}{\partial t} + \nabla . b\boldsymbol{q} = Q \tag{1}$$

$$\boldsymbol{q} = \frac{\boldsymbol{k}}{\mu}(-\nabla P + \rho^l \boldsymbol{g}) \tag{2}$$

where P is the pore pressure; t is the time; S_m is the mixture specific storage; Q is a source term for mass changes; k is the permeability tensor; μ is the fluid dynamic viscosity; ρ^l is the fluid density; **g** is the gravitational acceleration vector; **q** is the fluid or Darcy velocity vector and b is the scale factor for considering fractures (aperture) and wells (diameter).

Heat transport is considered with an advection-diffusion equation considering Fourier's law:

$$b\rho c_p \frac{\partial T}{\partial t} + b(-\boldsymbol{\lambda}\nabla . \nabla T + \rho^l c_p^l \boldsymbol{q}\nabla . \boldsymbol{T}) = Q \tag{3}$$

where ρc_p and $\boldsymbol{\lambda}$ is the heat capacity and thermal conductivity of mixture, respectively. $\rho^l c_p^l$ is the heat capacity of the fluid.

2.2 Numerical Model

The numerical model is based on a 3D-discrete fracture matrix model (DFM) incorporating the hydraulically active faults and fractures as a discrete fracture network (DFN), as well as the granitic basement as matrix rock. The open-hole-sections of the Soultz wells (GPK1 to GPK4) are included as line elements. The available information of the local reservoir setting is merged into a structural model of the Soultz EGS. The FE-model is based on the structural model of Sausse et al. (2010) and the numerical model of Held et al. (2014). For a better hydraulic adjustment, the numerical model is updated with two additional fractures, intersecting GPK1 (GPK1-FZ2856) and between GPK3 and GPK4 wells. The latter fracture is called “Separation” and not drilled but suspected from seismic measurements (Kohl et al. 2006).

The mesh for the numerical study is shown in Figure 1 and extends 13 (E-W) x 11 (N-S) x 5 km (vertical depth) and is located between 1000 m and 6000 m below surface. The model contains 141’271 nodes, which are connected by 714’453 elements. It contains 13 hydraulically active faults and fractures as lower-dimensional elements, neglecting out-of-plane flow. A homogenous equivalent aperture is used to describe pressure and temperature changes along the fractures. Mesh refinement is applied around and along the four well paths as well as on the main fractures and fracture-well-intersections. The element size differs between 1.5 m and 500 m. The lateral distance between the main wells GPK2, GPK3 and GPK4 is 650 m, while the direct connection along GPK3-FZ4770 results in a true distance of 840 m between GPK2 and GPK3.

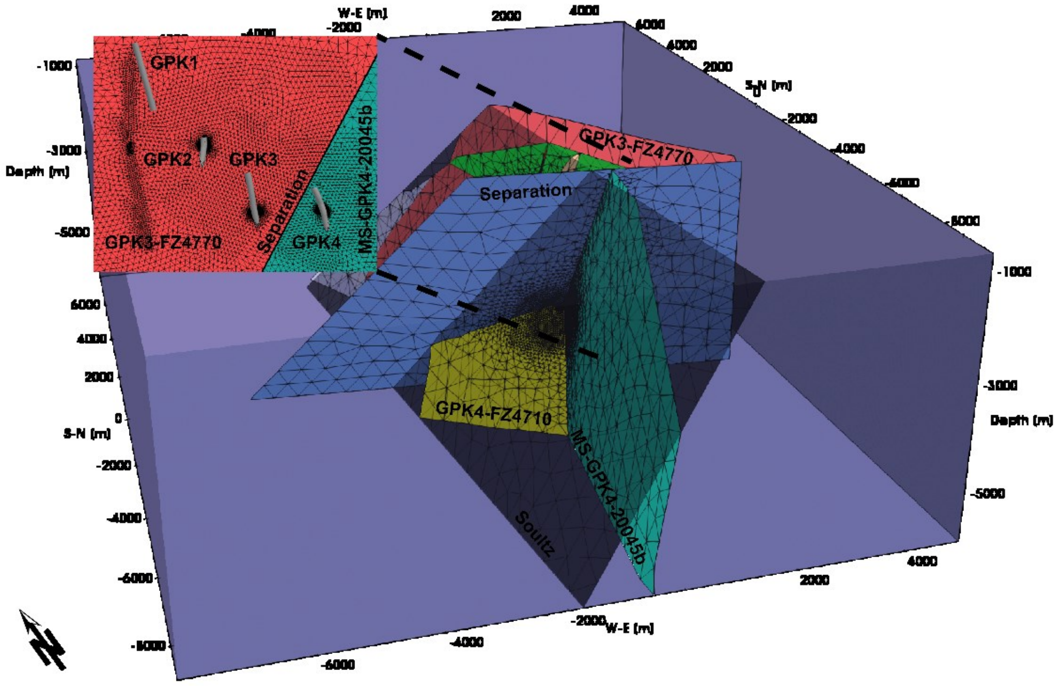

Figure 1: Subset of the mesh for the FE-modeling with the main faults and fractures in the Soultz reservoir (modified after [Held et al. 2014]). The central area around along around the deep wells is shown in detail.

The boundary conditions (BCs) for the different models are kept constant. Hydrostatic pore pressure is applied on the upper and lower boundary as Dirichlet BC and as an initial condition (IC). The lateral boundaries are constrained as no flow Neumann BC. Injection and extraction are considered as mass-flux-function on the top of the open-hole sections. An orthotropic matrix permeability, with higher values in N-S-direction, considers the effects of small-scale fractures and the recent stress field on the hydraulic conductivity (Cornet et al. 2007). A natural graben-parallel background flux of 1 m^3 (Bächler et al. 2003) is applied to the main hydraulic features. The transmissivity of the different fractures was calibrated in Held et al. (2014) with two circulation experiments. Since two fractures were added, the hydraulic properties of the DFN had to be recalibrated, by the usage of the same circulation experiment data and an additional inter-well tracer experiment conducted in 2005 (Sanjuan et al. 2006). Table 1 shows the transmissivity of the fractures which differ from Held et al. (2014).

A linear temperature gradient is defined by fixing the top and bottom boundary. The temperature gradient is in accordance to Held et al. (2014), assuming a gradient of 0.026 $K.m^{-1}$ and an upper boundary temperature of 101 °C. The Streamline Upwind method is used to increase the stability of the simulations (Brooks und Hughes 1982). According to Kestin et al. (1981), a brine with a constant density of 1065 $kg.m^{-3}$ and dynamic viscosity of $2.32x10^{-4}$ Pa.s, representing a fluid at a temperature of 150 °C, pore pressure of 35 MPa and salinity of 1.5 $mol.kg^{-1}$, is assumed. The different thermal and hydraulic material properties of the matrix, fractures, and fluid are shown in Table 2. Mixture properties are calculated internally with the porosity of the element, leading to effective fluid properties in the fractures.

Table 1: Transmissivity of the different faults and fractures. Only structures with changes compared to Held et al. (2014) are shown.

Structure	Transmissivity [m²．s^{-1}]
GPK1-FZ2856	5.0e-5
GPK4-FZ4710	3.8e-5
MS-GPK2-2000a	5.1e-5
MS-GPK4-20045b	3.2e-5
PS3-Int	6.4e-4
Separation	6.8e-5
GPK3-FZ4770 around GPK2	5.65e-5

Table 2: Material properties of the matrix and fractures

	Matrix	Fractures	Reservoir brine
Porosity [-]	1e-2	1	-
Compressibility [Pa^{-1}]	5e-13	1e-9	5e-10
Specific heat capacity [J.kg^{-1}.K^{-1}]	950	950	3950
Density [kg.m^{-3}]	2316	2316	1065
Thermal conductivity [W.m^{-1}.K$^{-1]}$	3	0.6	0.6

3. RESULTS AND DISCUSSION

3.1 Old Power Plant Design

Held et al. (2014) carried out long-term forecast modeling and economic evaluation of the Soultz EGS. The assigned flow rates for the analysis were 13 kg.s^{-1} (GPK1), -26 kg.s^{-1} (GPK2) and 10 kg.s^{-1} (GPK3). Note that negative mass rates mean fluid extraction, while positive values represent an injection of mass. The reinjection temperature was fixed with 70 °C. For comparison reasons, the new simulation was done with the same flow rates. Figure 2 shows the temperature at the top of the open-hole section in the GPK2 well for 60 years as a result of ongoing and constant production/injection for the new simulation and the comparison to Held et al. (2014).

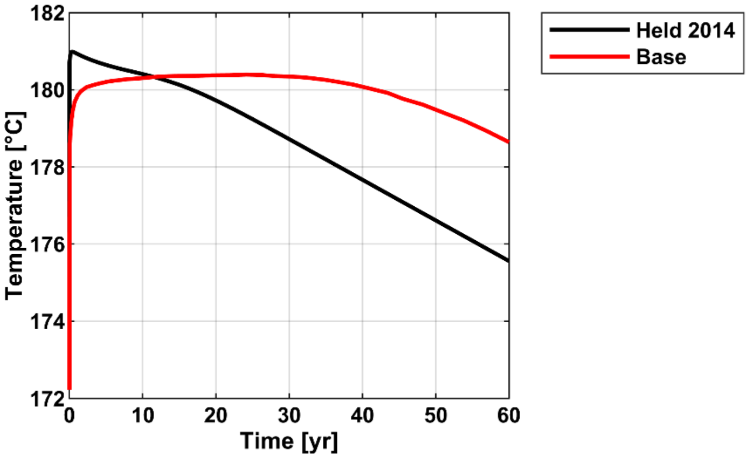

Figure 2: Comparison of the temperature in the well GPK2 of Held et al. (2014) and the recalibrated model.

In the first couple of days, a strong temperature increase is shown in both simulations with a maximum temperature of 181 °C (current simulation) and 180 °C (Held et al. 2014). The maximum temperature of GPK2 was simulated after less than a year, while the older model expected a long-lasting, but slow temperature increase up to the year 25. Afterward the temperature decreases until the end of the simulation (60 years) to 175 °C and 178 °C, respectively. The temperature breakthrough in the new simulation was achieved by the good hydraulic connection of the GPK2 and GPK1 wells when cold fluids sink along the fractures in the deeper areas of the geothermal reservoir. The described connection of GPK3 and GPK2 contributed only slightly to the cooling of GPK2 even with increasing time runtime. The GPK4 well was not used for this production concept, as its hydraulic connection to the reservoir is significantly less favorable than that of the other wells.

3.2 Current Power Plant Operation

After 30 years of research activities, the power plant was put into commercial operation in 2015. As the old power plant design expected a hydraulic short circuit and thermal breakthrough between the GPK1 and GPK2 wells, the production and injection design were changed to avoid cooling in the production well with increasing uptime (Mouchot et al. 2018). GPK2 is still used as a production well, while the fluid is reinjected in GPK3 and GPK4 well with a temperature of 70 °C (BINE Information Service 2017). The new flow rates are -30 kg.s^{-1} (GPK2), 20 kg.s^{-1} (GPK3) and 10 kg.s^{-1} (GPK4). The conducted thermo-hydraulic simulations allow the forecast of the cooling in the Soultz reservoir. Additionally, the influence of de-/increased flow rates and changed injection temperatures to the long-term behavior of the current power plant design was investigated. It was assumed that the current power plant design is the standard case, percentage changes of the flow rates always refer to this setup.

Figure 3 shows the temperature at the top of the open-hole section of the GPK2 well with increasing simulation time when the flow rates of the wells GPK2 to GPK4 are uniformly changed between -50 % and +100 % of the standard rates. All models show an instant temperature increase after the start of operation up to 181 °C, a long period of constant production temperature and a decline until the end of the simulations. The expected minimum production temperature for the standard case after 60 years was 178 °C (-3 K) and a first reduction of the temperature was simulated after 25 years of continuous operation. The models show that even a 50% reduction in flow rates would completely prevent a thermal breakthrough at the GPK2 well within the forecast period. In contrast, an increase in the overall flow rates could lead to a faster thermal breakthrough and reduced temperatures after 60 years. The simulations show that a doubling of the flow rates leads to a reduction of the fluid temperature of 13 K to 168 °C and first indicators for a thermal breakthrough after 11 years of production.

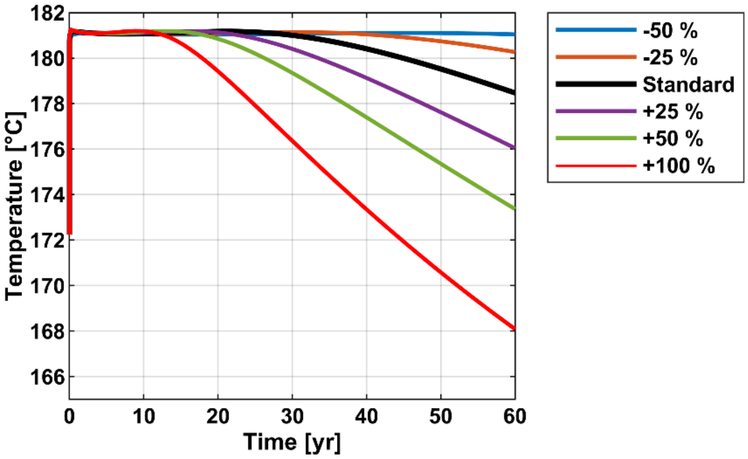

Figure 3: Temperature at the top of GPK2 open-hole section after 60 years of forecast modeling. The flow rates of the three wells GPK2 to GPK4 were changed as a ratio of the current standard power plant design (Mouchot et al. 2018). The injection temperature was kept constant with 70 °C.

As shown in Figure 4, at the end of the standard simulation, the cooling area is mainly oriented along the affected faults and fractures GPK3-FZ4770 and MS-GPK4-20045b. Fluids that were cooled and reinjected into the GPK3 well affect the producer GPK2 and decreased the production temperature. The GPK4 well has a low hydraulic connection to GPK3, which means that its influence on production temperatures is negligible. In addition, the spread of the cooling front is significantly smaller, as the injection rates are just half of GPK3.

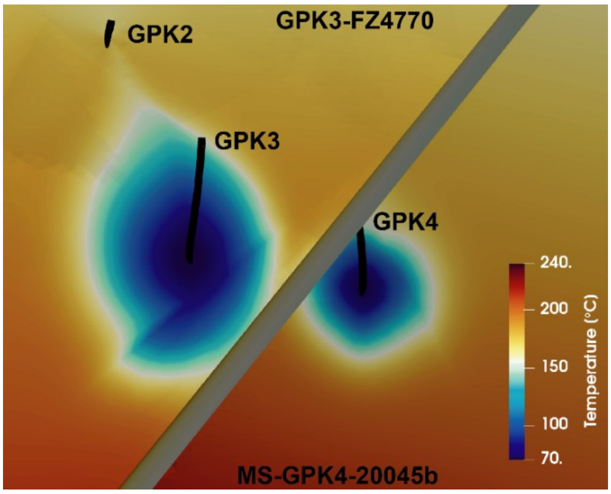

Figure 4: Temperature distribution on the fractures GPK3-FZ4770 and MS-GPK4-20045b after 60 years of production and injection in the standard case.

Figure 5 shows the change in the fluid temperature at the top of the open-hole section of the GPK2 well with increasing simulation time when the injection temperature of GPK3 and GPK4 was changed as opposed to the standard case. In comparison to the change in flow rates, the effect of a changed injection temperature is very small. A change in the final fluid temperature of less than one degree (178 – 179 °C) can be expected after 60 years of continuous operation. All investigated variants are consistent with the standard case, the temperature increased at the beginning of the operation to 181 °C and a first reduction the fluid temperature was simulated after 25 years.

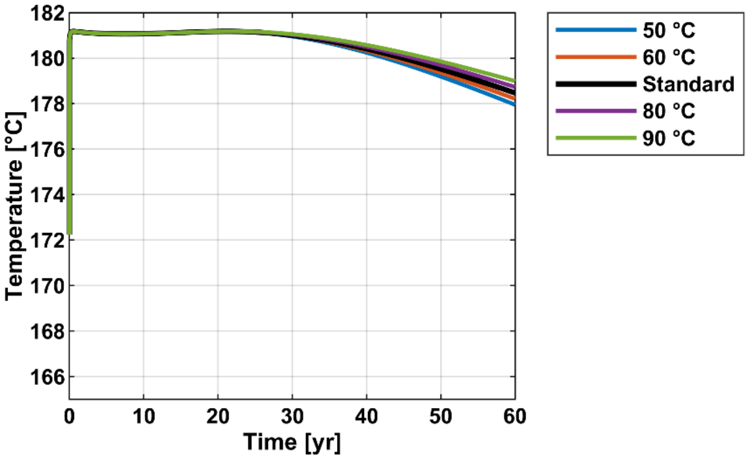

Figure 5: Temperature at the top of GPK2 open-hole section after 60 years of forecast modeling. The injection temperature of the wells GPK3 and GPK4 was changed, while the flow rates were kept constant. The standard injection temperature was 70 °C.

4. SUMMARY

The recently developed numerical models of the Soultz-sous-Forêts geothermal reservoir were solved with the TIGER thermo-hydraulic application. Different kinds of experiments, like circulation and tracer experiments, were used to update the calibration of the fault and fracture-network with respect to the hydraulic connections, the natural and artificial fluid flow along the network, and the wells GPK1 to GPK4.

Based on the recent production design of the Soultz EGS, forecast-modeling was performed that focused on the long-term development of the production temperature. After 60 years of continuous production, a temperature drop of 3 K was simulated. It could be shown that the production and injection flow-rates have significant influence on the temperature decline and thermal sustainability of the reservoir. While a 50 % reduction of the flow-rates would prevent any thermal breakthrough, a doubling of flow-rates would result in a 13 K temperature decrease. On the other hand, changes in the injection temperature (± 20 K) has a negligible influence on the long-term temperatures.

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