Geochemical modelling of the Soultz-sous-Forêts Hot Fractured Rock system: comparison of two reservoirs at 3.8 and 5 km depth

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Abstract

This study is carried out in the frame of the European Hot Fractured Rock project in Soultz-sous-Forêts. Due to the very high salinity of the brine contained in the fractured granite and the limited kinetic data for high temperature, a new code called FRACHEM has been built and developed to simulate coupled thermal-hydraulic and chemical processes of the flow in the fractured system. The goal is to forecast the long term behaviour of the reservoir under exploitation. Among the minerals taken into account for this simulation (calcite, dolomite, quartz and pyrite), carbonate reactions predominate. Their reaction rates are higher than the quartz and pyrite reaction rates. The amount of quartz and pyrite precipitated are neglected. As a consequence of calcite dissolution, the porosity increases at the injection point with resulting permeability changes .

Keywords

Hot Fractured Rock, coupled model, Soultz-sous-Forêts, brine, geochemical modelling

Introduction

The European Hot Fractured Rock (HFR) site is located at Soultz-sous-Forêts in Alsace, northeastern France. The final goal of this energy research programme is the building of a geothermal pilot power plant based on the HFR technology. In this technology the natural low permeability of the fractures network is enhanced by hydraulic stimulation. Then a fluid is injected through a well into the hot fractured granite and after circulation at depth, it is recovered by two production wells. Before reinjection in the first well, the fluid is cooled in a surface heat exchanger. During the previous experiments, the well GPK1 drilled at 3590 m was used as an injection well and the well GPK2 initially drilled at 3876 m was the production well. In 1997 a circulation test was carried out which showed that it was possible to circulate at 25 l/s between two deep wells in the depth range of 3500 m - 3800 m separated by 450 m [1]. Following this successful 4-month circulation test, GPK2 was deepened from 3876 m to 5000 m and the bottom hole temperature increased from 165 °C to 200 °C. At the final stage of this project, GPK2 is intended to be the injection well and two new wells GPK3 and GPK4 drilled to 5000 m depth will serve as production wells.

The aim of our study is to forecast the long-term behaviour of the reservoir during exploitation with the help of geochemical modelling. Fluid-rock interactions are complex processes in a HFR reservoir in which the mineral assemblage of the solid phase, chemical content of the fluid, hydraulic behaviour and temperature all affect the behaviour of the system. The fluid-rock interaction in the Soultz reservoir have already been subject of previous studies [2], [3] and [4]. To predict the long term reservoir behaviour, it is essential to combine all processes affecting the reservoir behaviour during its exploitation. Unfortunately, the existing thermo-hydraulic-chemical coupled codes are not well suited to the conditions of the Soultz HFR system (TOUGHREACT2 [5], CHEMTOUGH [6], SHEMAT [7]). Instead of creating a new code, two existing codes FRACTure [8] and CHEMTOUGH were coupled after having adapted the geochemical module in the reactive code CHEMTOUGH to the very high salinity of Soultz fluid. FRACTure is a 3D finite element code for coupled hydraulic, thermal and elastic processes, which was developed to model the long term behaviour of HFR reservoirs.

In this paper, we present the building of the conceptual thermodynamic and kinetic models of the Soultz system, the new thermo-hydraulic-chemical coupled code and its application on the two reservoirs at 3.8 km and 5 km depth.

Building of the conceptual model

Thermodynamic model of the Soultz system

The first stage of thermodynamic modelling consists in defining the fluid-rock system. In the case of Soultz-sous-Forêts, three granitic host rock facies were identified synthetically [4]: healthy granite in which fracturation density is close to zero, veins of alteration entirely cemented by alteration products and hydrothermalized granite. According to [4], the hydrothermalized granite consists of quartz, potassic feldspar and chlorite, partly cemented by alteration products (clay minerals and carbonates). Because of its higher porosity [4] and permeability, the majority of the formation fluid circulation takes place in the hydrothermalized granite and this facies plays the major role in the fluid-rock interaction processes. In this study the fluid-rock system will be represented by the fluid within the fractures, which are partially filled by clays, carbonates and secondary quartz.

The composition of the fluid was defined from the chemical analyses resulting from the 1997 circulation test for the fluid at 3.8 km depth and from the 1999 production test for the fluid at 5 km depth. These analyses show that the reservoir fluids are brines (TDS ≥ 100 g/kg) with an ionic strengh of 1.65 [9]. For such highly saline fluids, the calculation of activity coefficients based on the Debye-Hückel concept which is limited to ionic strengths of 0.8 is not accurate. For the Soultz reservoir fluid, a significant difference was found between the Debye-Hückel concept and the Pitzer concept [10]. The application of the Pitzer concept for the high salinity of Soultz fluids is not simple: on one hand the complexity of the code increases whereas the performances of the model decrease and on the other hand the parameters for some species are unknown or not available at high temperatures (165°C and above). To overcome these problems, some assumptions are adopted in the case of Soultz-sous-Forêts [10]: (i) the fluid used is the natural fluid, in equilibrium with the minerals of the host fractured rock , (ii) no boiling, degassing or condensation takes place in the system, (iii) there is no mixing with a different type of fluid and the fluid-rock interactions do not modify the concentrations in major species such as chloride and sodium. It results from these assumptions that for the fluid of the Soultz system only the temperature has a significant effect on the activity coefficients. The activity of each aqueous species is then a simple function of the temperature and the molality .

$$\gamma_i(T) = B_0 + B_1T + B_2T^2 + B_3T^3 + B_4T^4$$

$$a_i = \gamma_i(T) * m_i$$

where T is the fluid temperature, a_i is the chemical activity of species, γ_i is the activity coefficient, m_i is the molality. The coefficients B_i are determined by calculating the activity coefficients using the softwares TEQUIL[11] and EQ3nr[12] and by referring to the reservoir conditions.

Kinetic model of the Soultz system

Re-injection of the cooled brine strongly affects temperature and pressure conditions in the reservoir and leads to a chemical disequilibria between different minerals in the fractured host rock and the formation fluid. A kinetic model was determined in order to predict the evolution of the chemical reactions and their corresponding rates. Due the lack of many parameters especially for hot brines, [13] proposed a simplified model based on one kinetic law to describe each dissolution and precipitation reaction for each mineral considered (calcite, dolomite, pyrite and quartz).

The reaction rate is reduced to the following form :

$$v = k_{co} s f(a_i^*) g(T) h(\frac{Q}{K})$$

v: is the reaction rate in mol s^{-1}

k_{co} : is a constant independent of the conditions in mol m^{-2} s^{-1}

s : is the reaction surface area in m^2

$f(a_i*)$: is a term accounting on the catalysing or inhibiting effect of the aqueous species (including H^+)

g(T): is a term accounting on the temperature effect

$h(\frac{Q}{K})$: is a term accounting on the distance from equilibrium

The laws are taken from published experiments conducted in NaCl brines: for the quartz from [14] and [15], those for the carbonates from [16] and [17] and for pyrite are from [18] and [19].

Coupled modelling applied to the Soultz reservoir

The thermodynamic model of the Soultz reservoir taking into account the new method to calculate the activity coefficients and the kinetic laws of the Soultz system are implemented in CHEMTOUGH. Then, the new geochemical module in CHEMTOUGH was extracted and coupled with the code FRACTure using a sequential non iterative approach (SNIA) for the coupling of transport and chemical reaction. Each hydraulic and thermal step is followed by a chemical step. The new coupled code is called FRACHEM [13]. An application of

FRACHEM is the modelling of a realistic 2D model of the Soultz reservoir with a simple geometry. The injection and production wells are linked by fractured zones and surrounded by granitic matrix. These zones have an aperture of 0.1 m, 10 m deep and a porosity of 10%. Each zone consists of several fractures and one of these fractured zones is modelled. The model is composed of 198 2D-elements, near the injection (at x = 50 m) and the production point (x = 500 m), the discretization is finer (figure 1). Due to the symmetry of the model, only the upper part of the fractured zone (figure 1) is taken into account for the simulation, in order to save calculation time. This geometry model is applied for the two reservoirs at 3.8 and 5 km depth. Initially, the temperature was set to the reservoir temperature (165 and 200°C for 3.8 and 5 km depth, respectively) and was fixed to this temperature at the upper, left and right boundary during simulation.

Due to the sensitivity of the SNIA method on the time discretization, FRACHEM is limited to a time step size of 10^2s for the chosen parameters of this model [20]. It means that long term simulations take several days of computer time and that numerical oscillations occur for long time step size.

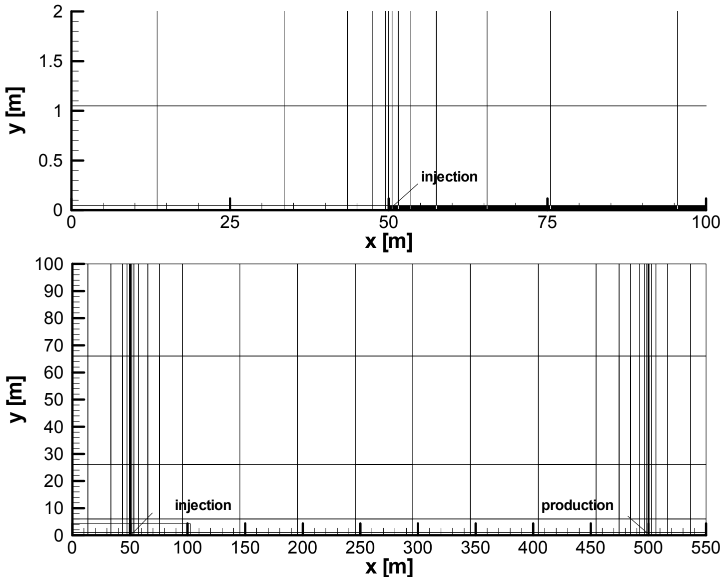

Figure 1 : Spatial discretization of the model

According to the 1997 circulation test, the production rate is $25*10^{-3}$ m^3s^{-1}. The produced fluid flows through a buffer which represents the fluid volume contained in wells and surface installations before being re-injected at a temperature of 65°C. Assuming 1250 fractured zones, mass conservation leads to a reinjection rate of $2*10^{-5}$ $m^3.s^{-1}$ for each fractured zone. A relative pressure of 6 MPa is fixed at the injection well at 3.8 km depth and 12 MPa for the reservoir at 5 km depth. Hydrostatic pressure conditions are applied to the production well. The thermo-hydraulic parameters are listed in table 1. No heat production is integrated in the model. Due to the low hydraulic conductivity and zero matrix porosity, the fluid flow mainly takes place in the fracture and all chemical reactions occur in the fracture.

Table 1:Thermo-hydraulic model parameters for matrix, fracture and fluid.

Parameter	**Fracture**		**Matrix**	**Fluid**
Hydraulic conductivity K $[m^2/Pa]$	$4.2*10^{-8}$ (T=165°C)	$3.0*10^{-8}$ (T=200°C)	10^{-15}	-
Thermal conductivity λ $[W/m.K]$	2.9		3	0.6
Density ρ $[kg/m^3]$	-		2650	1000
Heat capacity C_p $[J/kg.K]$	-		1000	4200
Porosity Φ [%]	10		0	-

Results and Discussion

Table 2 shows the mean fluid compositions at 3.8 and 5 km depth. These compositions are recalculated from the chemical analyses assuming that the fluids are in equilibrium with the mineral assemblage of the fracture. The results are obtained using codes based on the Pitzer concept such as TEQUIL and EQ3nr.

Table 2: Mean fluid composition recalculated from chemical analyses.

Composition ($mmol.kg^{-1}$)	**Na^+**	**K^+**	**Ca^{2+}**	**Mg^{2+}**	**Fe^{2+}**	**SiO_2**	**Cl^-**	**S**	**C**
T = 165°C pH ~4.78 (Fluid at 3.8 km depth)	993	80.8	160	5.42	0.501	2.17	1460	2.19	40.1
T = 200°C pH ~4.9 (Fluid at 5 km depth)	1079	68.5	157	3	2.4	5.7	1452	1.6	19

The fluid composition at the two depths is similar. Nevertheless, some discrepancies are observed. The higher contents of silica and iron could be explained by the variable solubility of the minerals with a temperature difference of 35°C. The decrease of total dissolved sulphur is linked to the decrease of dissolved sulphate with increasing well depth. [8] explained this evolution by the dissolution of marine evaporites during the raise and the cooling of the geothermal brine. The total dissolved carbon decreases linked to the alkalinity decrease with increasing depth and may be due to the dissolution of carbonate minerals (e.g calcite) and/or dissolution of organic compounds during the raise and cooling of the geothermal brine.

After 300 days of circulation, the reaction rates along the fractured zone are illustrated hereafter. Negative values indicate mineral precipitation and positive reaction rates represent dissolution. The trends of the reaction rates of both reservoir are similar. At the vicinity of the injection point, dissolution of carbonate occurs with a predominance of the calcite dissolution at a rate of $2.8*10^{-4}$ mol.m^{-3}.s^{-1} (figure 2). Towards the production point, calcite precipitates but dolomite dissolves all along the fracture.

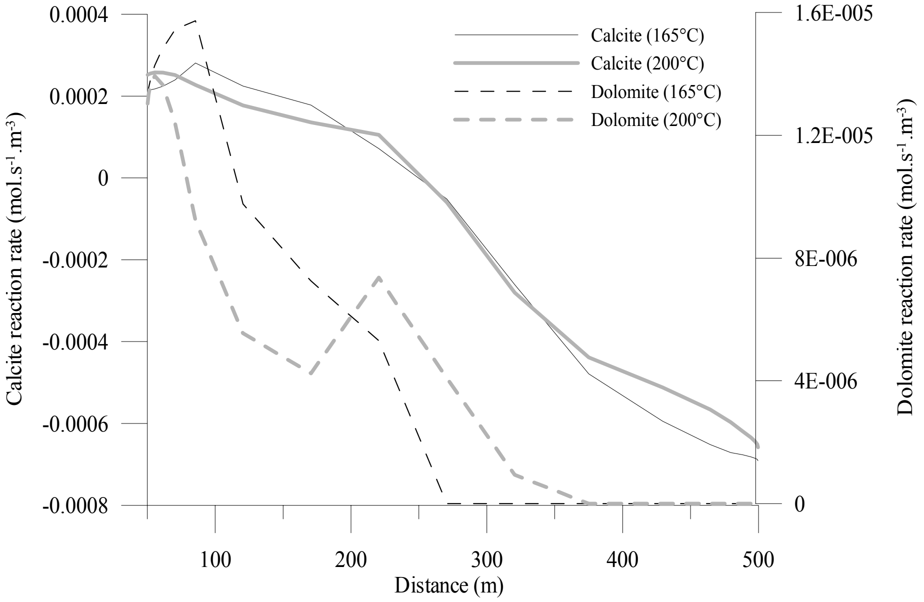

Figure 2: Evolution of carbonate reaction rates along the fractured zone after 300 days of circulation.

As is shown in figure 3, no quartz and no pyrite dissolution are observed after 300 days of circulation. The augmentation of temperature field affects the precipitation rates due the dependence of the kinetic law to temperature. The maximum rate of quartz precipitation is $1.6*10^{-8}$ mol.s^{-1}.m^{-3} at 3.8 km depth and $1.8*10^{-7}$mol.s^{-1}.m^{-3} at 5 km depth. The maximum pyrite reaction rate is $3.8*10^{-12}$ mol.s^{-1}.m^{-3} at 3.8 km depth and a maximum rate of $7*10^{-11}$ mol.s^{-1}.m^{-3} is observed at 5 km depth.

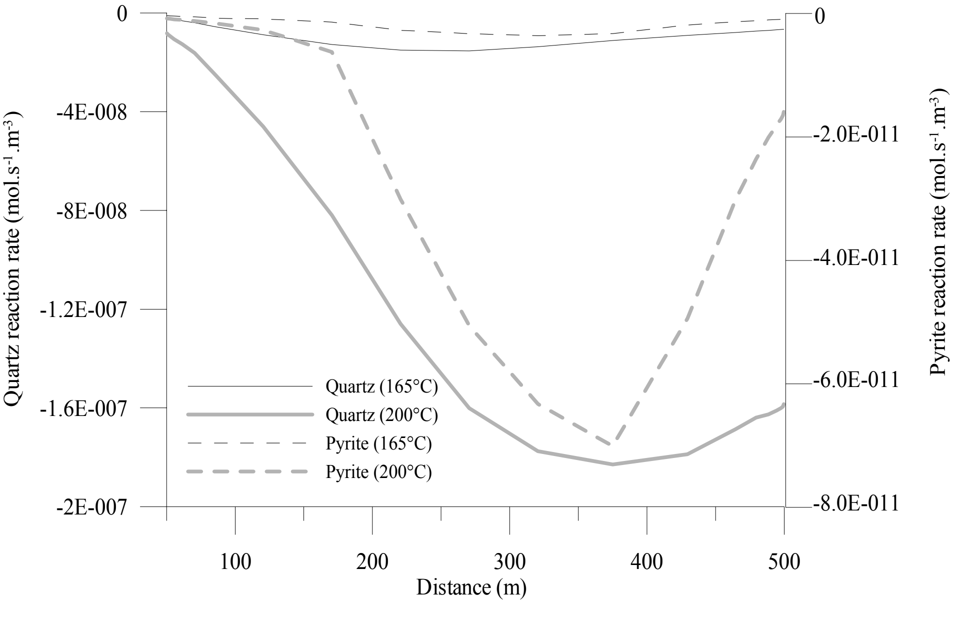

Figure 3: Evolution of quartz and pyrite reaction rates along the fractured zone after 300 days of circulation.

Compared to the carbonate reaction rates, the quartz and pyrite rates are much lower. Carbonate reactions are quantitatively more important. The amount of dissolved and precipitated mineral within the fracture zones are listed in the table 3 .

Table 3 : Amount of precipitated and dissolved mineral within the fractures zones .

	Dissolved amount (kg)		**Precipitated amount (kg)**	
Temperature	**165°C**	**200°C**	**165°C**	**200°C**
Calcite	758’000	762’000	747’000	738’000
Dolomite	59’200	52’500	-	-
Quartz	-	-	40.7	70.9
Pyrite	-		10.9	0.16

The large amount of dissolved and precipitated calcite alters the porosity and the permeability of the reservoir. A net increase of permeability occurs in a 150 m wide zone near the injection well (figure 4). The permeability increases from its initial value of $6.8{*}10^{-12}$ to $17.8{*}10^{-12}$ m^2 at 3.8 km depth and from $4{*}10^{-12}$ to $9.6{*}10^{-12}$ m^2 at 5 km depth. The permeability decreases gradually along the pathway towards the production well. The evolution of the porosity is similar, an increase of 40% of the porosity observed.

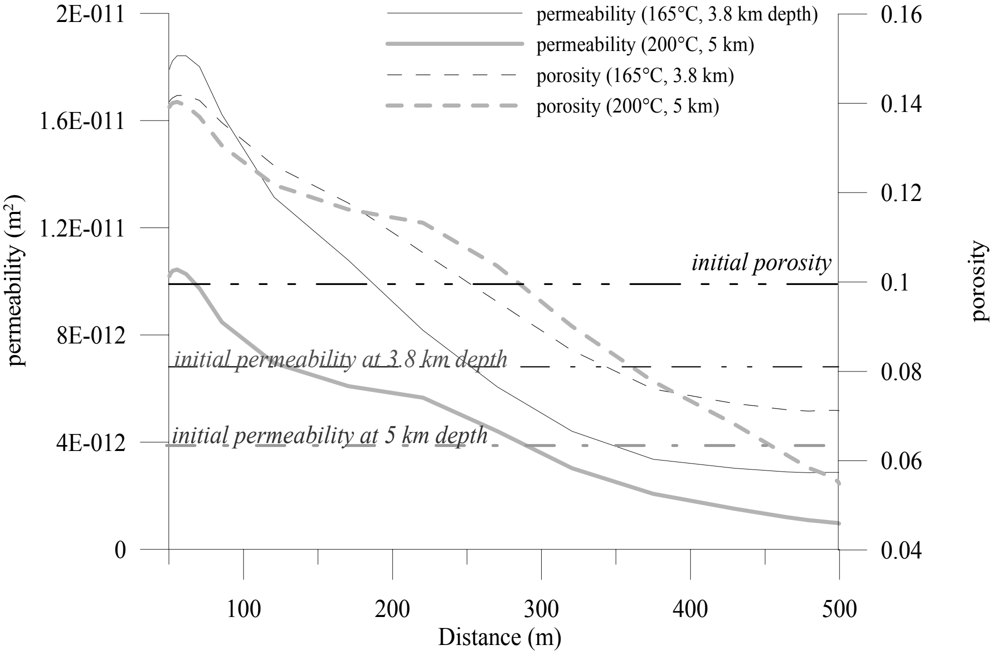

Figure 4 : Evolution of permeability and porosity along the fractured zone after 300 days of circulation.

Conclusions

A new code FRACHEM was built for geochemical modelling of Soultz-sous-Forêts fluid coupled to thermo-hydraulic processes. The use of the Pitzer concept is limited due to the lack of data for high temperature and the absence of parameters for some species. Assumptions on the specificities of the Soultz system allowed to simplify the calculation of the activity coefficients of the aqueous species. New kinetic laws are defined from published works performed in conditions as close as possible to the Soultz fractured reservoir. The mean fluid compositions at 3.8 and 5 km depth are not significantly different expected for a few species. The evolution of the reaction rates is similar for the two fluids. It appears that calcite reactions predominate compared to those of quartz and pyrite. At the injection point, the porosity increases with resulting permeability changes. Quartz and pyrite reactions do not influence the characteristic of the reservoir. The behaviour of clays present in the fracture is not taken into account for this simulation due the lack of Pitzer parameters for aluminium. In the future, it is planned to model a more complex geometry, closer to the real Soultz system and for a longer simulation period.

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