Role of temperature change in micro seismic activity during fluid injections in faulted and fractured zones. Part 1 : Updating the thermal modelling in a DFN model using a double media approach

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Keywords: induced seismic, heat transfer; fracture system; geothermal system; hot dry rock,

Introduction

According to the general agreement that carbon emissions use should be strongly controlled, governments are now committed to diversify the primary fossil energy resource and particularly use more renewable resources. This is even more vital for countries that depend on imported oil products. Developing electricity production obtained from geothermal fields is therefore a priority at many places in the world. A step forward in this domain has been achieved with the Enhanced Geothermal System (EGS) concept, which was demonstrated at a pilot plant scale at the Soultz sous Forêts site (Genter et al., 2009). In such reservoirs, developed in deep hard rocks, the overall flow pattern is controlled by the pre-existing network of geological discontinuities. Access to the reservoir can be improved thanks to hydraulic stimulation techniques resulting in better connections between boreholes and these natural pathways. Controlling the efficiency of stimulation techniques upon the natural structures forming the bulk part of the reservoir is still a matter of research, as results obtained at various sites are highly variable. In all cases, raising the pore pressure, thereby reducing the shear strength of fractures zones and promoting shear failure and some increase in fracture permeability, is accompanied by micro seismic activity and acoustic emissions (AE). These signals are recorded and analysed. The spatial localization of rupture sources often delineates planar structures where pressure perturbations were propagated. It is therefore confirmed that flow occurs in a 3D network of 2D structures and that specific quantitative models are required to capture the coupled hydraulic-mechanical processes at issue. During the past decade, attention was first given to the engineering of the reservoir using various combinations of hydraulic tests, and to the evaluation of the hydraulic improvement of the pathways developed the fractured system, using tracer tests (Sanjuan et al., 2006). Recent works are re-focussing at physical processes, such as the determination of fracture/matrix transfer area, (K. Pruess and C. Doughty, 2010) or at comparisons of tracer and thermal transport in fractured reservoirs (Juliusson et Horne, 2010) to investigate the extent to which tracer return can be used to predict thermal breakthrough. Very few new programmes were dedicated to long term thermal behaviour, assuming that a reservoir with sufficient size would last long enough for industrial purposes. The phenomenon of large induced seismic events (LISE) then received considerable interest after the generation in 2003 of a Magnitude 2.9 earthquake at Soultz sous Forêts (France). In 2006, a M 3.4 earthquake was generated during the hydraulic development of a new EGS reservoir, near the Swiss city of Basel, that stopped the project.

This issue of large seismic event is also raised at other places where natural steam reservoirs exist and are exploited for decades. At the Geysers site (California) it is clearly observed that earthquakes with magnitudes larger than 4 become more frequent, in correspondence with continuous re-injection of fluid performed to maintain the reservoir pressure. In this case, it was argued and demonstrated (Rudqvist et al., 2002) ° that the thermal poro-elastic cooling below re-injection zone is responsible for mechanical changes, sufficient to activate dislocation mechanisms along pre-existing fractures. However the working hypothesis of equivalent porous media did not offer the possibility to the authors of going further ahead with fracture failure analysis in a realistic fractured reservoir. Other pioneer 3D modelling works can be mentioned. Conceptual models based on deterministic regular fracture patterns or simplified geometries (Swensson 1990, Hicks *et al.*, 1996, Kolditz and Diersch, 1993, Kolditz and Clauser, 1998) were first developed. Since fractures are unevenly distributed in space, forming clusters, with widely variable size (see Genter *et al.*, 2000 at Soultz sous Forêts site), and since the heat to mine out is stored in the matrix surrounding the fractures, continuum models based on equivalent porous materials are not adequate. Randomly distributed networks (Robinson, 1990; Bruel, 1995, 2002; Willis-Richard *et al.*, 1996) embedded in the rock mass have been developed. Most of the recent efforts are attempts to mix both representations, a discrete randomly distributed network embedded in a porous system. A recent example is given by (E. Juliusson and R.N. Horne, 2010) using Finite Element type numerical methods, and working on sophisticated unstructured computational grids. One of their conclusions is however that numeric for a realistic (2D) network was at the margin of being feasible, and the authors claim for the need of new appropriate upscaling algorithms and new non meshing techniques.

The purpose of this paper is to go back to the understanding of the long term potential impacts of coupled Thermo-Hydro-Mechanical processes (THM) in EGS geological settlements, using a discrete fracture network (DFN) specific approach. This discrete approach is able to handle the specific geometrical characteristics of fracture networks and faulted zone. Such an approach was already introduced for EGS modelling by Bruel (1995, 2002) for the study of a 3 year long circulation test at the Rosemanoves site (UK) and for the simulation of a four months long circulation tests at 3.5 km depth performed in 1997 in the upper reservoir of the Soultz sous Forets site (France). For the latter case, no long term fluid circulation was planned for this EGS sites, so that only local thermo-elastic couplings were considered, with no interactions in between temperature changes and fluid properties.

The work presented here after is an update of the FRACAS DFN code (Baujard et Bruel, 2006) where a double media is introduced to solve for thermal conductive heat transfer at the reservoir scale coupled with local heat exchange along the fractures embedded in the rockmass and heat convection along the flowing pathways. These efforts are clearly required to tackle new research aspects concerning long term seismic risk analysis. This should be also particularly useful for new sites as those planned in faulted rift zones of eastern Africa, where the prevailing tectonic regime makes fractures very close to instability. As an example, C. Doubre et G. Peltzer (2007) analyse natural micro-seismic activity and show that present day fracture propagation at Asal rift (Djibouti) is probably linked with natural flow along fractures. The Asal hydrothermal region has been identified as a favorable area to develop the geothermal resources and projects are already underway. But the first evaluation of the production potential considers that re-injection of (cold) fluids will be necessary to compensate for reservoir drawdown (Houssein and Axelsson, 2010).

Theoritical background of the FRACAS Discrete Fracture Network flow code

The FRACAS modelling approach is based on the assumption that fluid moves through a rock mass within a system of interconnected fractures and that flow in the rock matrix is negligible by comparison. The three-dimensional hydraulically conductive network of planar, discshaped fractures generation is inherited from Cacas et al.(1990) modelling work. Series of individual fractures are generated within a rectangular block of rock, based on stochastic descriptions of fracture density, fracture orientation, and fracture size. Improvements were achieved to capture more realistic geological systems. Specific fracture sets can be defined as models of faults zones. Relay structures or simple planar fault segments can be generated as well as combinations of adjacent blocks with different fracture network properties.

Flow rules

Hydraulic conductivities

The overall flow model is based on the premise that flow in granitic basements primarily occurs on channels within fractures. The 3D structure resulting of the superimposition of the connected portions of planes is thus treated as a 3D network of 1D pipes. Equivalence of this channel flow approach with others solving true 2D flow in planes has been discussed (Dershowitz and Fidelibus, 1999).

Time-dependant analysis requires assumptions to be made concerning the form of fluid flow within the fracture network. The general form of fluid flow assumed in each fracture is based on an analytical solution, known as the « cubic law », for fluid flow between approximately parallel surfaces. Modified forms of the cubic law are used to account for the effects of changes in the morphology of contact between fracture surfaces. As the effective stress across a fracture increases flow through the fracture becomes confined to a limited number of channels. Thus, in FRACAS, the single phase volumetric flux (m^3s^{-1}) in the *x*-direction through a length *l* (m) of a fracture has the form :

$$Q = \frac{-a_0^3}{12\nu} g l F \frac{dh}{dx} \quad (1)$$

where a_0 is the hydraulic aperture (m) of the fracture at zero effective stress, *g* is acceleration due to gravity (ms^{-2}), ν is the kinematic viscosity (m^2s^{-1}), *dh/dx* is the hydraulic head gradient driving flow through the fracture, and *F* is a dimensionless function dependent on effective stress. The effective stress is defined as $\sigma' = \sigma_\pi - p$, where σ_π (Pa) is the rock stress normal to the fracture surface and *p* (Pa) is the fluid pressure in the fracture. Empirical expressions for the closure law *F*, in which *F* decreases as the effective stress increases (*F*=1 at zero effective stress) are presented by Jeong (2006). This coupled approach was tested against various *in situ* experiments performed in hard rocks in the frame work of a nuclear waste storage research program, and predictive results were compared with those of other numerical approaches (Rejeb and Bruel, 2001). The approach was extended (Bruel, 2007) to account for shear loading and Coulomb frictional failure, in an attempt to simulate reservoir hydraulic stimulation processes and micro-seismic predictions.

However, in this paper the objective is to incorporate the potential effects of a short term thermal perturbation to evaluate how significantly it may alter the reservoir performances. Therefore F will be re-derived later, according a new procedure described in the section devoted to the thermo-hydro-mechanical interactions, after the basics for heat exchange modeling in the FRACAS discrete fracture network model have been introduced.

Specific storage of the fractures

The specific storage *S* (m^{-1}) of a fracture with *R* as radius (m) is given by:

$$S = \rho g \frac{1}{a_0} \frac{da}{d\sigma'} + S_0 \quad (2)$$

where ρ is the fluid density (kgm^{-3}) and g the acceleration due to gravity (ms^{-2}). S_0 denotes the potential specific storage of the adjacent weathered rock that can be identified on cores and in situ, using sonic logs. These zones exist on both fracture sides and can extend up to a metric scale (Genter *et al.*, 2000). In deriving the specific storage term, the rock stress has been assumed constant, such that changes in effective stress are caused only by fluid pressure changes. Also, fluid compressibility is generally much smaller than fracture compressibility and, thus, has been neglected. The form the of the term $da_i/d\sigma$' calculated at the center of the fracture disc, depends on the assumed form of the relationship between the hydraulic fracture aperture and the effective stress, as discussed above.

Thermal modelling

Convective and conductive heat transfer along individual fractures

Heat exchange along the circulated fractures can be evaluated assuming that heat conduction develops perpendicular to each fracture plane. No energy is retained by the volume of fluid within the fractures. The conservation of energy is written at each fracture centre as a balance between energy transferred by convection from or to neighbouring fractures and energy dissipated by conduction in the current cell. At any time, continuity of the temperature at the fracture wall is assumed, that is :

$$\theta_f = \theta_m(y=0) \qquad \textbf{(3)}$$

Subscript *f* and *m* respectively stand for fluid and matrix. If q_{ij} and q_{ik} [m^{3}s^{-1}] denotes fluxes entering and leaving a given disc *i* at time *t*, with respective temperatures $\theta_{fi}(t)$ and $\theta_{fi}(t+dt)$, the energy exchanged during dt is dQ_i [J], given by :

$$dQ_i = \Sigma_j \rho_f C_f q_{ij} \theta_{fj} dt - \Sigma_k \rho_f C_f q_{ik} \theta_{fi} dt \qquad \textbf{(4)}$$

This energy is related to the heat flux at the fracture wall, Φ_i , across the exchange area S_i [m^2], that has to dissipate in an adjacent rock volume according to a diffusive equation. The shape of this adjacent block is cylindrical, with a radius equal to that of the fracture-disc and a length l_i chosen so that the total volume cumulating all the cylinders is equal to the reservoir volume in order to fulfil the global heat capacity conservation.
The temperature at the face opposite to the circulated fracture is a new variable. $\theta_{ml} = \theta_m(y=l)$. This initial value of this local variable is set to the temperature estimated at depth for the corresponding fracture, given the natural measured temperature profile..
The developments insuring block to block thermal interactions for predicting long term thermal depletions are proposed in the next section. We will assume that interactions are controlled by the thermal diffusivity coefficient, which is in the order of 1. m^2 s^{-1} for rocks. Temperature changes may propagate at significant distances greater than 10 m within time periods no longer than a year. The equations presented here below are solved sequentially.

$$dQ_i = \Phi_i S_i dt, \qquad \textbf{(5)}$$

$$\Phi_i = K_m (d\theta_m/dy)_{y=0} \qquad \textbf{(6)}$$

$$\frac{K_m}{\rho_m C_m} \Delta\theta_m = \frac{\partial \theta_m}{\partial t} \qquad \textbf{(7)}$$

At each disc *i* in the network, the diffusivity equation is written in a discrete form following a standard finite difference scheme, and the set of equations is solved for θ_{fi} and θ_{mi} at time $t+dt$ knowing similar quantities and boundary θ_{mli} values at time *t*. The temperature of the injected fluid is continuously prescribed. Parameters are matrix heat conductivity K_m [W m^{-1} K^{-1}], heat capacity C_f , C_m [J kg^{-1} K^{-1}] for both fluid and matrix, density ρ_f , ρ_m [kg m^{-3}] for both fluid and matrix.

Conductive heat transfer at the global scale and derivation of internal boundary values θ_{ml}

The basic idea suggested in this section is that the heat extracted during a given time step from a sub volume containing a number of connected fractures by a fluid forced to circulate along these fractures can be approximated by an equivalent density term, source or sink, depending on the sign of the calculated heat balance. Therefore, the method consists at any time step, when fluxes, fluid temperature and local matrix temperature profiles are known at each fracture disk i,, in solving a succession of tasks as follows:

- Define a regular 3D grid, with cells cubic in shape, overlapping the fractured reservoir, each cell being large enough to contain a sub-network of fractures
- Identify the discs belonging to each cell
- Calculate the net heat balance per cell, from the differences in temperature profiles at t and t+dt at each disc within the cell
- Derive a source term from the temperature change for each cell, accounting for cell volume and time step duration.
- Solve for a heat conduction problem over the 3D grid, using prescribed temperature at the top of the reservoir, regional geothermal heat flux at the base of the reservoir, heat conduction and capacity coefficients for the rock mass, and the discrete volumic heat source at each cell.
- Use the temperature obtained at each cell at date *t* as the new θ_{ml} value for all the discs belonging to that cell.

The two step algorithm is sequential, but the time stepping for the conductive behaviour at large scale can be larger than the time stepping for solving the local convective-conductive heat exchange at the local scale. This new algorithm has been iùplemented in our FRACAS code. Numemerical verifications are now focussing on the hydro-thermal global behaviour of the double media, using benchmarking against other numerical codes that can handle some fracture patterns (GEOFRACK, TOUGH2). An outcome of the FRACAS code development is that experimental testing programmes running over years but combining successions of injection/production phases separated by month long rest periods can be modelled in a single run.

Preliminary conclusion

Apart from standard numerical checking, a series of verification examples against true data sets is under construction. The first one will be based on results obtained on one of the first Hot Dry Rock research programme run at the Rosemanoves quarry site (Cornwall, UK), extensively documented by RH Parker (1988).
A main aspect in this data base is that it contains a long term circulating test that lasted about 3 years and that shows a thermal breakthrough partly due to thermo mechanical interactions. Fracture network is well described, as a dense regular network made of 3 directional sets (blocky pattern). A large number of hydraulic tests in between the different wells have been performed as well as tracer tests to discuss heterogeneity and role of main flow paths. A main interest in running a model in such a system is to revisit the potential impact of fracture

stimulation at the network scale and rediscuss some of the remarks concerning single well injection-withdrawal tracer tests done by Pruess and Doughty (2010), stating that temperature return is insensitive to fracture aperture changes. As thermal processes may combine with mechanical processes, we also intend to derive rock thermal shrinkage at the reservoir scale, and obtain the dramatic short-circuit effect observed at Rosemanoves site. Given shear rupture modelled along thermo-mechanical perturbed pathways, we will suggest, as done in Bruel(2007), a catalogue for the thermally induced micro-seismicity.

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