EVOLUTION OF MODELLING ACTIVITIES REALIZED AT SOULTZ

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INTRODUCTION

Modeling activities cover of a wide range of research fields in EGS research. Modeling efforts lead around Soultz can be classified in three main research fields:

- (thermo-)hydro-mechanical processes,
- hydro-thermal processes,
- (thermo-)hydro-chemical processes (treated by the workgroup "geochemistry").

Various numerical approaches have been developed or used to study the Soultz reservoir. The main goals were the diagnosis of methods to develop permeabilities and the optimization of test efficiencies. A special issue in Geothermics was published mostly from contributions of WG 5 in December 2006.

Models are at different stage of development and resulted in an individual support of the Soultz experiments. The following list provides an overview of the codes applied in the current phase by various scientific groups (Baujard et al., 2007).

- "3DEC" Code for Thermo-Hydro-Mechanical modelling of fractured rock (BRGM - Orléans, F)
- "3FLO" -Code for Flow in fracture networks (BRGM - Orléans, F)
- "Code_Bright" for diffusive-advective transport (EOST - Strasbourg, F)
- "Convection" Code for Darcy flow and convection in a porous media (OMP - Toulouse, F)
- "Fracas" Code for hydraulic, thermal, solute and fracture mechanics (ENSMP, Paris, F)
- "FRACHEM" Code for hydrothermal processes with chemistry (CREGE, Neuchâtel CH)
- "gPROMS" for heat, mass transfer and chemical reactions (NCSR "DEMOKRITOS", GR)
- "HDREC", thermal code for economical modeling (GTC Kappelmeyer, Karlsruhe, DE)
- "HEX-B2" Borehole simulator for hydrothermal and NaCl transport (GEOWATT Zürich, CH)
- "HEX-S" Code for hydrothermal processes and fracture mechanics (GEOWATT Zürich, CH)
- "Rockflow" Code for advection; conduction and viscosity effects (GGA Hannover, D)
- "SHEMAT" Code for coupled flow and heat transport (RWTH Aachen, D)

MILESTONES AND KEY EVENTS

With the beginning of the Soultz project, numerical modeling started to adapt existing codes to the complexity of HDR/EGS reservoirs. At the beginning (first tests at 2000 m) numerical models used synthetic data sets to confirm or infirm proposed processes. Due to the high heterogeneity of the media, people hesitated to compare real data with model results. The massive direct use of real data as input parameters and as modeling objective in the numerical models only appeared in the shallow depth reservoir (3000 m – 3500 m).

GPK1 2000 m (1988-1990)

The first stimulation tests (88DEC13) realized in the Soultz granite lead to the interpretation of the hydraulic measurements using an bilinear flow theory (Jung, 1990). The hydraulic stimulation was then simulated with a numerical model using the equations of bilinear flow and quite a good correlation between the measurements and the results could be obtained (Kohl, 1992).

Reservoir at shallow depth (3000 m - 4500 m)

The first interpretation of observed temperature logs using convection cells appeared in the shallow depth reservoir (LeCarlier et al., 1994). Such interpretations were done using analytical or semi-analytical models.

Stimulation and test GPK1 (1994)

The analysis of results obtained during a 12-day production test in June 1994 (94JUN16) and a 8-day injection test (94JUL04) showed that the obtained results could be well fitted by a single model, assuming non-laminar flow (Kohl et al., 1995). This model clearly shows that turbulent flow is likely to happen in the vicinity of the borehole, even for small Reynolds numbers (Evans et al., 1996; Evans et al., 1998; Kohl et al., 1997).

Stimulation and test GPK2 (1995)

After the stimulation of borehole GPK2, several hydraulic tests were realized in the well. Based on the injection tests of July 1995 (95JUL01) and of September 1996 (96SEP29), the investigations and characterization of non-linear flows continued, using an automatic inversion procedure and the same models as for GPK1 (Bächler et al., 2001). This work confirmed the importance of non-laminar flow into the reservoir and that the procedure of analysis of the results of hydraulic tests could be partially automated through the use of inverse modeling techniques.

Circulation test at shallow depth (1996 - 1997)

A circulation test was realized in summer 1997 between GPK1 and GPK2 at shallow depth (97JUL12). This test, associated with tracer injections, was the occasion to reproduce numerically the tracer response of the wells and to derive information about the reservoir. A Discrete Fracture Network approached (Bruel, 1998) as well as a Finite Element model using ROCKFLOW (Pribnow and Clauser, 1998) showed that it was possible to reproduce and even predict with a certain accuracy the tracer response, using particle tracker modules. The Discrete Fracture Network allowed to compute a thermal drawdown approximation, using the results of the tracer test as a calibration for the model. Its estimate predicts a 5% temperature decrease after 20 years of production/injection in the doublet, at a flowrate of 25 $l \cdot s^{-1}$.

The first attempts of integrated modeling, i.e. numerical models capable of reproducing several couplings and physical processes were done between while the borehole GPK2 was extended to 5000 m depth. At that time, the first mechanical couplings with Mohr-Coulomb criterion in order to simulate fracture shear failure and thermal interactions on local stress equilibrium appear and are used in order to calibrate models at reservoir scale (Bruel, 2002).

Deep reservoir (4500 m - 5000 m)

The first interesting data put under the lights thanks to drilling at 5 km depth is the shape of the temperature profile. Revised geochemical analyses and thermal observations lead to the conclusion that the Buntsandstein aquifer fluids are not diluted by meteoric waters coming from the Schwarzwald, and convection in the Buntsandstein alone is not the cause of the thermal anomaly at Soultz (Pribnow and Clauser, 2000). The use of the models calibrated on the shallow reservoir of Soultz could demonstrate the large scale (greater than one kilometer diameter) convection cells in Soultz granite –thus allowing fluid flows in granite could explain the thermal anomaly observed in Soultz (Bächler et al., 2001; LeCarlier et al., 1994).

The stimulation of the deep reservoir of Soultz took place between 2000 (stimulation of GPK2) and 2004/2005 (stimulation of GPK4). The stimulation of GPK3 took place in 2003. It was an extremely interesting and productive phase for the modeling teams working on Soultz, as the models were developed since the early 90's and the data were numerous and of high quality (temperature, pressure measurements as well as seismic events locations and magnitudes).

Stimulation of GPK2 (2000)

The hydraulic stimulation of the reservoir, which was not of primary interest for the modeling teams in the shallow depth reservoir, has been this time intensively investigated. The hydro-mechanical couplings were implemented or improved in several numerical codes at that time. Jeong et al; (2006) re-examine the local normal compliance behaviour and the shear dilation process in FRACAS. After calibration of the hydro-mechanical parameters, the evolution of the seismic events location in time and space could be reproduced in numerical models using the Mohr-Coulomb criterion. This approach, using numerical models on the GPK2 stimulation results (Bruel, 2007), allowed validating the controversial approach to estimate hydraulic diffusivity of a fractured system by analyzing the displacement velocity of the front of shear events (Shapiro et al., 1999). The mechanical couplings introduced in the numerical codes also allowed to quantify the relations between the permeability increase and the shearing of the fractures (Gentier et al., 2005), thus underlining the importance of the geological structural and tectonic context of the site in EGS site assessment.

The stimulation of the wells is realized using heavy brine –when available. This offers the advantage of minimizing pumping efforts of the injection pumps and to maximize the downhole pressure. The influence of this technique on the stimulation of the reservoir was quantified, using biphasic flow in a Discrete Fracture Network approach in order to simulate the density contrast between injected fluid and in-situ fluid was investigated (Baujard and Bruel, 2006).

At the scale of a single fracture, several investigations were lead, with the help of laboratory experiments. The relation between the shear displacement of a fracture during failure and the permeability anisotropy was investigated (Auradou et al., 2005), as well as the heat exchange between the rock matrix and the fluid flowing into a fracture (Neuville et al., 2006).

Stimulation of GPK3 (2003)

For the first time, the pressure and temperature measurements realized during the stimulation of GPK3 were used as a basis for the numerical borehole simulator HEX-B (Mégel, 2005). This software allows computation of borehole data (pressure, temperature), using wellhead measurements (flowrate, temperature, pressure and salinity of injected fluid). The accuracy of such a numerical tool was evaluated and discussed at Soultz (see section "hydraulic test and circulation tests GPK2-GPK3")

The stimulation of GPK3 also offered possibility of multi-well stimulation (injecting high rate fluids in both wells), given that two deep boreholes were available into the reservoir. The benefits of such a stimulation were investigating using numerical models (Kohl et al., 2006), and it was showed that an important pressure increase could be expected in between the boreholes.

GPK3 stimulation was numerically reproduced and the jacking and tensile failure processes were investigated (Kohl and Mégel, 2005) and quantified.

The idea of variations of the stress field in the reservoir or in changes in the Coulomb-Criterion raised up in Soultz with the stimulation of GPK3. This idea was for the first time tested and the interest demonstrated using an appropriate numerical model in 2008 (Dorbath et al., 2008), using the data sets of the stimulations of GPK2 and GPK3.

Hydraulic tests and circulation tests GPK2-GPK3

Evaluations of the downhole parameters from single borehole (GPK3; GPK4) tests and from circulation tests in summer 2005 (production GPK2 and GPK4; injection GPK3) have been performed. It was shown that results from single borehole tests significantly differ from multi borehole tests. Internal discussion on the borehole simulator HEX-B applied to derive downhole pressure and temperature data from surface measurements were conducted in Soultz. It was concluded that a numerical simulation could hardly reproduce the critical relaxation periods of the well ("shut-in phases") that may be of interest for scientists. But the reliable corrections obtained for injection or production phases (thus allowing the injectivity/productivity index evolution), demonstrated that the use of such a tool is complementary to downhole pressure and temperature measurements, and could participate to costs reduction.

Stimulation of GPK4 (2004)

The stimulation of GPK4 offered the opportunity to predict the seismic events distribution in time as well as the borehole pressure response to the injection, using the numerical models calibrated on the previous stimulation phases, acoustic logs showing main fractures orientation in the borehole and a flowlog. This technique gave interesting results, with a good correlation between the predicted location of the seismic events and what was observed (Kohl and Mégel, 2007).

The analysis of the data of the stimulation of GPK4 showed that the use of a Discrete Fracture Network allowed reproducing a realistic seismic moment-frequency diagram (Bruel, 2007). As an example, it was possible to discuss the fracture size distribution used in the stochastic models to recreate during the numerical simulation of injection tests the so-called Gutenberg-Richter law, which links the seismic moments of the events with their frequency.

The exact interpretation of the stress field in Soultz was subject to several interpretations and varied over the years. The strong hydro-mechanical couplings from numerical codes made possible to analyze the exact influence of the various estimations on the shear mechanisms (Rachez et al., 2007)

Hydraulic tests and circulation tests GPK2-GPK3-GPK4

In July 2005, a circulation test was performed in Soultz (injection in GPK3 and production in GPK2 and GPK4), using tracers. The tracer recovery peak was observed after 9 – 16 days in GPK2 and no peak was observed in GPK4 during 150 days of observation. Right orders of magnitude for this heterogeneous behavior were quantitatively obtained in term of spatial distribution, mass recovery and timings by Baujard et al.(2006). The use of these data after Blumenthal et al. (2007). in order to calibrate a model to predict the thermal breakthrough lead to very pessimistic prognostic Differences observed between experimental and computed tracer data done in 2005 suggest the existence of an additional quasi-infinite fluid flow loop, which may connect both GPK2 and GPK4 to GPK3 (Sanjuan et al., 2006).

CONCLUSION; UNRESOLVED CHALLENGES AND PERSPECTIVES

As explained in the previous lines, the direct use of measured data in the models, replacing the use of synthetic datasets progressively appeared during the early experiments in Soultz. Much effort was done in the first reservoir (3000 m – 3500 m) in order to use the observed tracer responses, reproduce them numerically with particle tracker algorithms to predict the thermal breakthrough between the wells. This effort was not continued in the deep reservoir - except for a little number of teams-, where the works were more focused on the stimulation of the reservoir. It is indisputable that interesting results have been obtained in this domain in Soultz during the last years.

In spite of the efforts of the different modeling teams, no satisfactory explanation could be found to the problem of the bad hydraulic connection between GPK4 from the well-connected boreholes GPK2-GPK3, as both assumptions (drain or not-fractured zone) could partially fit the data.

For the future, modeling activities should go back to the thermal issues in the deep reservoir, using the latest tracer tests, the recent advances realized in process understanding at the fracture scale, and new geometrical models proposed, integrating the results of various scientific investigations (Sausse et al., 2008).

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