NUMERICAL MODELLING OF HDR RESERVOIRS

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ABSTRACT

Mathematical modelling of HDR reservoir behaviour is extremely valuable as a means of understanding available experimental data and extending that understanding to other situations. However, the complexity of the problem means HDR modelling is a highly demanding task. A geometrical spectrum of HDR models has been identified. This highlights the current status of modelling and the restrictions on developing models capable of handling both the strong couplings required for stimulation and the reservoir geometry required for circulation. At the present time the "complete" HDR reservoir model is a long way off. Therefore, the only viable approach to HDR modelling appears to be closely coordinated studies between different modelling groups and classes of model. The European HDR modelling group is an example of this collaborative approach to modelling.

1 INTRODUCTION

Hot Dry Rock geothermal energy extraction relies on the forced circulation of water between injection and recovery boreholes through a naturally fractured rock mass. In such reservoirs, typically developed in granitic or similar crystalline basement, the intact rock usually has very low permeability and porosity. Heat extraction is controlled by conduction through the intact rock blocks towards water conducting fractures whose apertures have been artificially increased and where advection transports thermal energy towards the recovery well(s). Fluid flow rates in fractures are strongly dependent on the fracture aperture. Typically the fluid velocity in response to a given pressure gradient is proportional to the square of the fracture aperture. The hydraulic aperture is, in turn, a non-linear function of effective normal stress, the fracture morphology, material properties and its history. Shear displacement of the fracture wall, caused by engineering interventions such as high pressure injection, or chemical deposition/solution, may alter the hydraulic aperture irreversibly and change the reservoir properties. HDR systems, therefore, respond highly non-linearly, and sometimes irreversibly to changes in operational parameters.

HDR field experiments are expensive to perform and can not be repeated indefinitely from the same borehole due to progressive irreversible changes to the system. Therefore, numerical experimentation is extremely valuable as a means of understanding the available experimental data and extending that understanding to other situations. This ultimately leads to a predictive capability lending support *to* design and operational planning.

However, a number of factors mean that the HDR modelling task is a highly demanding one;

i) The strong and highly non-linear coupling of fluid mechanical, rock mechanical, thermal, chemical and hydraulic processes.

ii) The wide ranging timescales involved in HDR reservoir creation and circulation. From the rapidly evolving fluid-rock mechanical coupling on the scale of seconds to days during stimulation, to thermal-mechanical-chemical coupling during circulation, which is measured in terms of years.

iii) The data-limited nature (Starfield and Cundall 1988) of the problem, due to the inevitable lack of field data sufficient to adequately characterise the rock mass.

2 OBJECTIVES OF HDR MODELLING

It is widely recognised that a number of key parameters dictate the performance of an HDR system. Namely:

i) Pressure drop near the injection and production boreholes, where fluid flux is high
ii) Pressure drop across the body of the reservoir
iii) Thermally active rock volume (ie the reservoir size)
iv) The pattern of fluid flow within this active volume
v) Loss of fluid to the far field

Therefore if modelling is to be of value it must incorporate the physics and geometrical properties required to investigate these features of a reservoir. The key elements that must be modelled are therefore:

i) Development of large fracture apertures in the region of the injection well (through fracture shear dilation, thermoelastic shrinkage and possibly the creation of new fractures)

ii) Development of large fracture apertures in the region of the recovery well (through fracture shear dilation, proppant placement and possibly the creation of new fractures)

iii) Rock mass permeability enhancement through stimulation, and the distribution of the fluid flow through the reservoir volume after stimulation (possible fracture extension and fracture shear dilation through the interaction of the in situ stress field, the fracture length distribution, the fracture orientations and properties).

iv) Heat conduction geometry of the stimulated system following mass stimulation (including thermal interaction between adjacent fractures).

Each of these elements places different requirements on any models treatment of the coupling of fluid mechanical, rock mechanical, thermal, chemical and hydraulic processes within the reservoir and the representation of the system geometry. The way in which these two aspects, coupling and geometry, are approached is the result of compromises between the objectives of the model and the resources available. The degree of the coupling and the complexity of the fracture geometry conveniently defines a spectrum of HDR models, which ranges from abstract geometry models, through reduced, to realistic geometry models (CSMA 1992, Willis Richards and Wallroth 1995) (Figure 1). Typically, strong coupling can be placed in geometrically reduced models, whilst geometrically 'realistic' models require excessive computational resources to support strong coupling. A corollary of this is that realistic geometry models are largely limited to modelling reservoir behaviour during the steady-state or slowly evolving conditions of circulation. In order to model stimulation, proppant placement or thermally induced permeability enhancement, strong coupling, and hence reduced geometry models, are required.

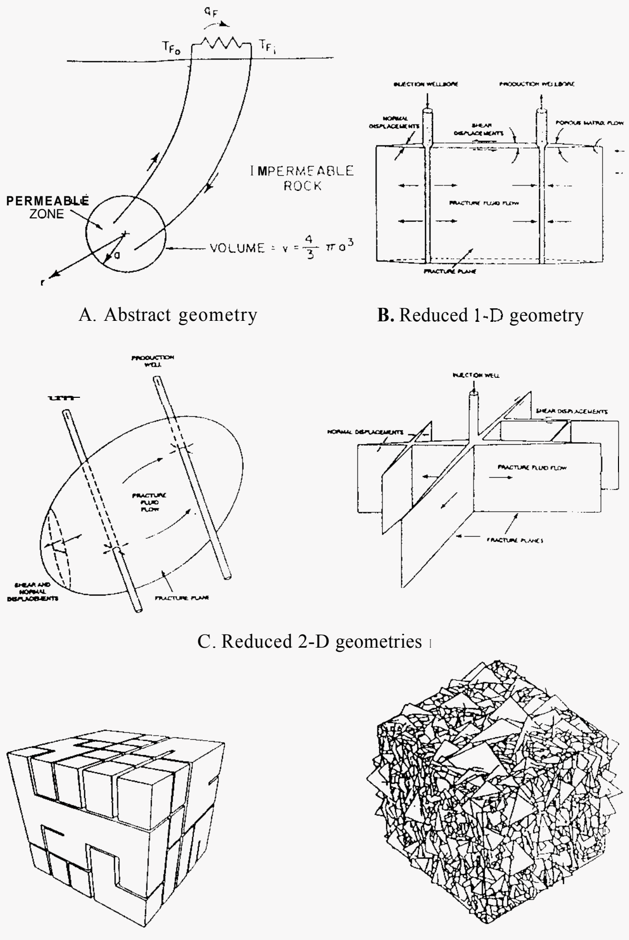

Figure 1 Examples of abstract, reduced and realistic geometry models for HDR reservoirs (A after Elsworth 1990; B, C, D after CSMA 1994a, E after Lanyon et al 1992).

Despite attempts to bring the realistic geometry and coupling aspects of models closer together, at the present time the development of the "complete" HOR reservoir model is a long way off. Therefore the only viable approach open for comprehensive HDR reservoir modelling is through closely coordinated studies where the capabilities of individual reservoir models compliment each other. Clearly the geometrical sophistication of realistic geometry models is required to handle the stochastically driven sensitivity analyses required for circulation modelling. But in order to understand the influence of coupled processes on reservoir behaviour, and to enable the eventual reduction of these processes into forms manageable by realistic geometry models, the continued use of reduced geometry models is also essential.

4 THE EUROPEAN HDR MODELLING GROUP

By necessity this integrated approach to modelling requires the close interaction of individual modelling groups, as well as input from HDR experimentalists. The European HDR modelling group, formed to undertake HDR modelling for the European HDR geothermal project at Soultz-sous-forêts, Alsace France, is an example of this collaborative and interactive approach to HDR modelling. Available to the group are realistic geometry (Bruel et al., 1992) and 3D deterministic, reduced geometry models (Kolditz 1994) for investigating the long term hydraulic and thermal behaviour of circulating HDR systems, but also reduced geometry, models (CSMA 1994a, Evans et al., 1992) for investigating the coupled processes necessary to understand the non-linear behaviour of HDR systems.

The remaining sections of this paper illustrate some of the work carried out by the modelling group into the potential significance of coupled processes in HDR reservoir behaviour.

4.1 Thermally induced permeability enhancement

The process of heat extraction induces thermal stresses within the reservoir rock, leading to rock shrinkage and fracture opening in cooled zones. This study investigated the possible extent of this fracture opening during reservoir circulation, and the potential effects on reservoir impedance, water loss and thermal drawdown.

The study involved the CSMA code HOTGRID, which is 2D reduced geometry model of a horizontal plane through a connected network of orthogonal fractures (CSMA 1993a) (Figure 1c). The most important feature of the model was the coupling of hydro-therm-mechanical processes.

The example simulated was a water circulation of the 2.2 km deep reservoir at the CSM Rosemanowes site in Cornwall (Richards et al., 1994) via two wells 120 m apart. Two orthogonal fracture sets (20 m fracture spacing) were assumed to be orientated at 30° to the directions of the horizontal stresses; the stresses acting normal to the fracture planes were 76.25 MPa and 44.75 MPa respectively, and the shear stress on the fracture surfaces 18.76 MPa. A solution domain of dimensions 1200 m x 600 m was modelled. The rock and fracture properties assumed were typical of the Rosemanowes system.

The simulation involved initial hydraulic stimulations of both wells to reduce near-wellbore impedance and then a steady state circulation was established. Water was injected at a nominal fixed rate of 2.33×10^{-2} kg/s/m. Flow was dominated by a direct connection along a single fracture between the two wells.

Figure 2 shows HOTGRID predicted changes in fracture aperture due to induced thermal stresses after 1, 3, 5 and 10 years of circulation. The width of the lines associated with each fracture indicates the magnitude of the change in fracture aperture since heat extraction began. In the cooled zone between the wells, stress reduction has led to increases in fracture aperture; over the 10 year circulation period the maximum value of the fracture aperture in the network increased from 1.8×10^{-4} m to 3.3×10^{-4} m. Outside the cooled zone, regions of compressive thermal stress were induced, leading to small reductions in fracture aperture. This is the classic reaction to be expected in such differential heating or cooling problems. For example, the cooling of a spherical region in an elastic medium will induce tensile stresses within the sphere, and outside the sphere, will induce compressive stresses tangential to the surface of the sphere and tensile stresses normal to the surface of the sphere.

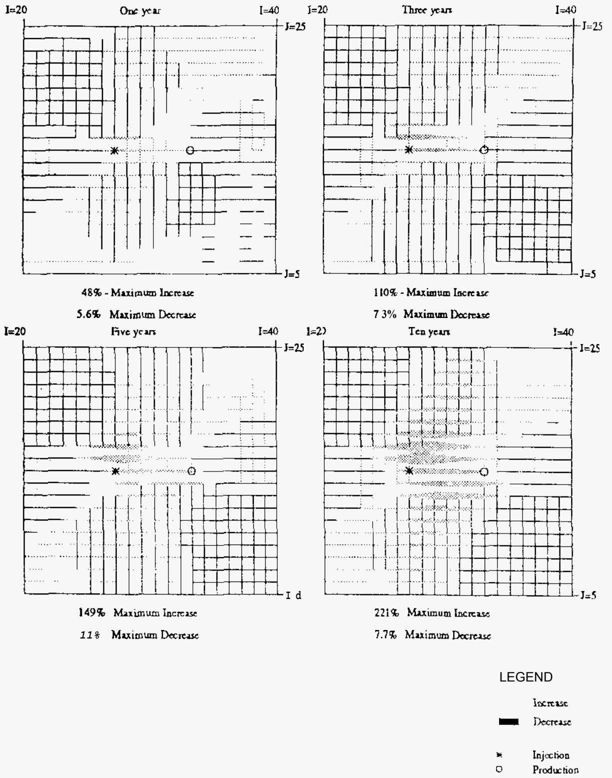

Figure 2 Fracture aperture change due to thermoelastic effects during circulations (after CSMA 1994a).

As would be expected in the case of constant injection flow rate, there was a gradual reduction in the pressure drop across the reservoir over the period of circulation. With a fixed production pressure of 20.65MPa, the increase in local equivalent permeability caused a reduction in injection pressure from 23.07 MPa to 21.20 MPa over the 10 year period (Figure 3a). This was accompanied by a 15% increase in water recovery (Figure 2b), primarily due to the increased hydraulic conductivity between the wells; the direct flow path between the wells carried an increasing percentage of the injected volume with time. In addition the decrease in equivalent permeability outside the cooled region resulted in a small reduction in fluid recovery from the "far-field".

The change in the production temperature during the circulation is shown in Figure 2c. This may be compared with the thermal drawdown curve for the case in which thermal stresses have been ignored. Thermally induced changes in the fluid pattern are responsible for a significant reduction in the production water temperature.

In the example presented here the cooling of the reservoir rock has resulted in significant changes in the hydraulic performance of the reservoir during its lifetime. For a doublet system similar to that considered here thermally induced stress changes could markedly alter the equivalent permeability and the flow distribution in the reservoir leading to impedance reduction. Although the storage volume of a reservoir is likely to increase with time, it is also likely that the coldest flow paths will carry growing proportions of the injected fluid volume. This would certainly have a detrimental effect on production water temperature and reservoir lifetime.

4.2 Stress controlled flow distribution

The second example examines the possible role coupled hydro-mechanical processes might play in determining the distribution of flow exits within an injection borehole. The study follows experimental results obtained during the 1993 high flow rate hydraulic injection tests at the European HDR Geothermal Energy Project, at Soultz-sous-Forêts (CSMA 1994b).

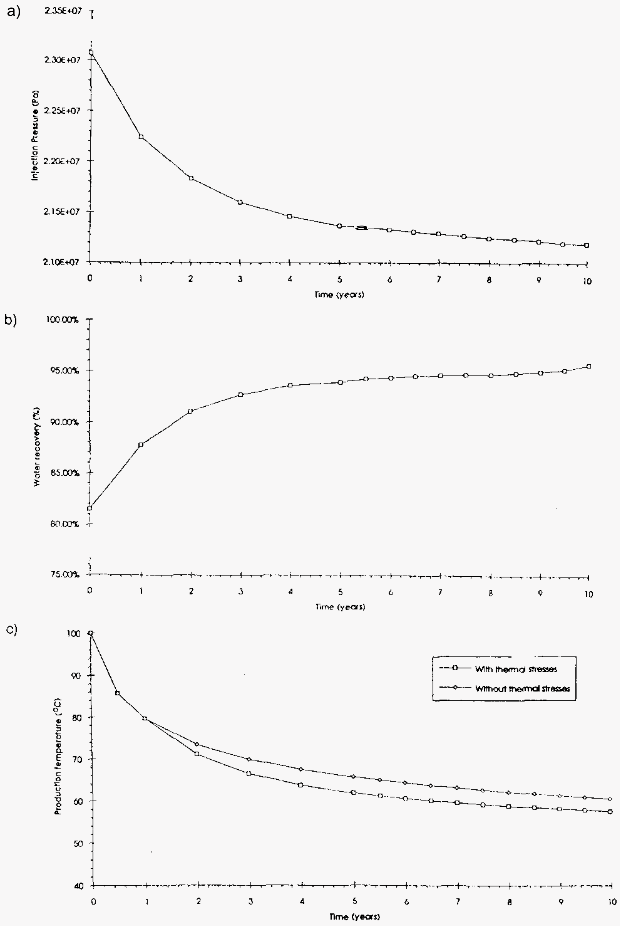

Figure 3 Evolution of a) Injection pressure b) Water recovery c) Production temperature with time (After CSMA 1994a).

Throughout the openhole (**750** m) injection tests into borehole GPK1 it was found that approximately 60% of the fluid exited the borehole in the first 100m below the casing shoe (2840m). This was despite the fact that permeable fracture zones were observed throughout the openhole section. Furthermore, the monitoring of microseismic activity associated with the injections (CSMA 1994b) indicated a preferential upwards growth of the reservoir at higher flow rates (30-50 l/s). It was suspected that this might be a jacking controlled phenomenon due to overpressures being close to the minimum effective normal stress level (10 MPa), rather than a systematic difference in the fracture distribution.

The CSMA model HOTGRIO was used to simulate the injectivity at different depths within the GPK1 borehole. Runs were carried out with the in situ conditions set to values appropriate to 3 km and 3.4 km depth at the Soultz site, and the borehole was held at a constant overpressure of 10 MPa. After reaching a steady-state pressure response the injection flow rates were compared in order to assess the flow fraction that might be expected to leave at each of these specified depths. Results **of** the simulations are summarised in Table **1**, where it can be seen that flow accepted in Case 1 (shallow) was roughly 18 times that accepted by Case 2 (deep). This result was entirely due to the variation in the in situ stress with depth, which resulted in lower fracture apertures, and therefore fracture conductivity, with increasing depth. This suggests that the flow distribution observed in GPK1 could largely be a consequence of the variation of in situ stress and fracture apertures with depth, without the need to invoke strong geological heterogeneity.

Table 1: Summary of HOTGRID inputs and results

Overpressure	= 10.00 MPa
σH	= 73.95 MPa
σh	= 38.56 MPa
σv	= 76.55 MPa
Resulting injection flow	= 1.51×10^{-5} m^3/s
Case 2: Depth	= 3.40 km
In situ fluid pressure	= 34.59 MPa
Overpressure	= 10.00 MPa
σH	= 85.55 MPa
σh	= 44.64 MPa
σv	= 86.95 MPa
Resulting injection flow	= 8.34×10^{-7} m^3/s
Ratio of injection flow (Case1:Case2)	= 18:1

5 DISCUSSION

The cost of HDR field experimentation and the progressive irreversible changes to the rock mass that occur as a result, mean that mathematical modelling is an attractive means of understanding available data and moving towards predictive capabilities which can support reservoir design and operational planning.

However, the wide range of coupled hydraulic-thermal-mechanical processes taking place in HDR reservoirs and the time-scales over which they operate, mean that the development of a "complete" HDR reservoir modelling, which encompasses realistic geometries and is capable of modelling both short term stimulations and long term circulation, is rather ahead of current computational resources.

Nonetheless, the range of abstract, reduced and realistic geometry models that are currently available, taken as a whole, are capable of handling many of the problems faced by HDR investigators. However, the most likely route to progress in HOR modelling seems to lie in a synergistic approach, achieved through close collaboration between modelling groups and HDR experimentalists.

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