COUPLED HYDRAULIC, THERMAL AND MECHANICAL CONSIDERATIONS FOR THE SIMULATION OF HOT DRY ROCK RESERVOIRS

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Abstract - The coupled hydro-thermo-mechanical response of a fractured media to forced fluid flow in a simple Hot-Dry-Rock (HDR) system is investigated. The geometry, a single fracture in a 2D matrix, was chosen in order to better understand the relevant processes for the long term behaviour of HDR reservoir. Linear elastic effects of temperature and pore pressure perturbations on stress in the solid matrix are assumed as well as a non-linear joint closure law. Thermal transport by both conduction and advection is included in the fracture and the matrix. The results of these models highlight the importance of the coupled hydraulic thermal and mechanical processes on long term system behaviour.

Key Words: Geothermal reservoirs, modelling, hot dry rock, finite elements

INTRODUCTION

In 1988 a project was launched in Switzerland with the purpose of examining coupled processes within operating Hot Dry Rock (HDR) systems. Central to this project is the development of a versatile finite element code FRACture. The immediate objective was to simulate the long-term behaviour of an elementary HDR system to prolonged circulation. Clearly if any specific aspect of the behaviour of a Hot Dry Rock reservoir is to be adequately simulated, then all the physical processes which have any significant effect upon it should strictly be simulated too. For the purpose in hand the solutions must satisfy equations for the following;

- hydraulic flow in the active fractures and surrounding matrix.
- the transport of heat energy by diffusion and advection.
- elastic deformation of the host rock under thermal and hydraulic perturbation of the natural stress field.

Numerous models have been reported in the literature to date which bear on the problem of predicting the response of HDR reservoirs to high-rate fluid injection and circulation. The feature that distinguishes these models from others developed for hydro-geological and waste isolation studies is that fractures are considered to be deformable. Many models were developed as tools to assist in the interpretation of injection or short-term circulation test data in which thermal drawdown effects are usually not strongly manifest.

Pioneering work in the field of modelling hydro-mechanical coupled processes in HDR reservoirs was made by Cundall (1983) in developing the FRIP code. This was a special purpose simplification of the distinct element technique realised in the UDEC Codes (Cundall, 1980). FRIP has since been developed into a family of related codes to facilitate the detailed study of the behaviour of individual fractures and also of 3-dimensional fracture networks (Nicol et al., 1991, Hicks et al., 1994). The geometry of the FRIP family remains, however, limited to orthogonal, continuous fracture networks. The 2-dimensional
version now includes the coupling of hydraulic fracture flow with thermoelastic deformation in the neighbouring rock matrix.

A new 2-D coupled thermo-hydro-mechanical code GEOCRACK based upon a finite element method is reported by DuTeau et al. (1994) and was applied to modelling the Fenton Hill reservoir behaviour. The thermal or tracer transport calculation is derived from an iterative hydro-mechanical solution, but does not affect the hydro-mechanical field. They succeeded in simulating hydraulic and tracer test data from the reservoir by means of a 2-D model. A noteworthy feature of this model is the inclusion of a non-linear dependence of fracture aperture on effective normal stress.

The representation of fracture networks using stochastic methods has met with considerable favour in modelling passive fluid flow at several intensively studied excavations in crystalline rock and this approach has been extended to HDR reservoir simulation. Hopkirk et al. (1985) adapted a code originally aimed at transport problems in nuclear waste repositories to handle heat transport. Coupling between fracture hydraulic aperture and fluid pressure was determined by assigning compliance coefficients to each fracture flowpath. The model of Bruel et al. (1990) who extended a sophisticated code presented by Cacas et al. (1990) uses a boundary element technique to accomplish the coupling between fracture fluid pressure and the elastic field of the medium. During active flow, the fracture conductivities adjust in accord with the "cubic" law, the hydraulic aperture being governed by both a linear normal compliance law and a linear shear dilation law, shear mobilisation being controlled by a Coulomb friction criterion. The calculation of heat extraction however, is inevitably limited to a simple 1D analytical technique, which limits the accuracy of thermal drawdown predictions, particularly over long periods of reservoir operation.

Recently the effects of thermal shrinkage on reservoir behaviour have come under increased scrutiny (e.g. DuTeau et al., 1994). The importance of temperature influences on the hydraulic system in a HDR reservoir are evidenced by large reductions in system impedance accompanying severe thermal drawdown during the 76 day circulation of the Phase 1 reservoir at Fenton Hill.

**NON-LINEAR JOINT LAW**

Of all the couplings included in the FRACture code (Kohl & Hopkirk 1995), the one between forced fluid flow in fractures and elastic deformation of the host rock matrix demands the greatest numerical complexity in its treatment. Currently only normal stress effects on fracture opening are considered. However, the implementation procedure remains practically identical for the additional treatment of shear effects if the irreversibility of shear dilatation is taken into account. The constitutive law we use to describe the normal stress dependence of hydraulic aperture, $a_n$, is given by,

$$a_n = a_{n0} + (\frac{\partial K_n}{\partial \sigma_n})^{-1} \cdot \ln\left(\frac{\sigma_{n0}}{\sigma_n}\right)$$

Here, $\sigma_n$ is effective normal stress (given by the difference between normal total stress acting on the fracture and the fluid pressure in the fracture), and $\sigma_{n0}$ and $a_{n0}$ are the values of $\sigma_n$ and $a_n$ prevailing under ambient (pre-disturbance) conditions. Throughout this paper, tension is taken positive as is fluid compression. The equation is based on a logarithmic closure law relating changes in mechanical aperture to changes in effective normal stress, as suggested by laboratory experiments on multiply-cycled fractures (Bandis et al., 1983, Raven & Gale, 1985) and simple theoretical models of surface interaction using Hertzian contact theory (Walsh & Grosenbaugh, 1979). For this law, the stress-dependent compliance of a fracture is uniquely determined by a constant $(\frac{\partial K_n}{\partial \sigma_n})^{-1}$, which we refer to as the "stiffness characteristic". Also implicit is the assumption that changes in mechanical aperture result in an equal change in hydraulic aperture; that is, that the cubic law is valid for incremental quantities, although not necessarily for absolute quantities (Schrauf & Evans, 1986).
It should be noted that this equation applies only for fractures supporting a compression of 1 MPa or more. Since flow is proportional to the cube of hydraulic aperture the hydraulic-elastic coupling of the fracture is strongly non-linear, and it is this that accounts for the numerical complexity.

SIMULATION

Background

The study serves two primary purposes. Firstly, to clarify the effects on long-term system performance that can arise from fracture deformability, even when the system is driven at pressures less than those required for "jacking" conditions. Secondly, to introduce the program FRAC'Ture with particular regard to demonstrating its applicability to coupled thermo-hydro-elastic problems.

The present work seeks only to simulate changes in system behaviour during long term circulation. The assumption is that the stimulation phase of reservoir development has been completed, leaving a network of conductive flow paths between the wells. The work should be considered as a study of the behaviour of one such flow path acting entirely independently of the others.

Similar thermo-hydro-elastic considerations for the simulation of Hot Dry Rock reservoirs have been published by Kohl et al. (1992a) and Kohl (1992b).

Fracture and Medium Geometry

This study represents the flow path as a rectangular, vertical, deformable fracture embedded in a permeable, deformable 2D-medium. Poro-elastic and thermo-elastic effects are included. The horizontal breadth of the fracture is arbitrary (taken as 1 m for convenience) as is the net volume throughput between the wells. The latter are represented by a horizontal line source and sink in the plane of the fracture (Figure 1). For the elastic calculations plane strain conditions are assumed. This leads to a slight (< 20%) enhancement of poro- and thermo-elastic stresses on the fracture, but nonetheless provides a useful quantitative insight into the effects of these mechanisms.

The geometry of the fracture and the surrounding matrix is shown in Figure 1. The fracture is located at the centre of a 10 km by 10 km rock matrix, whose properties are listed in Table 1. The origin of the local (x, z) co-ordinate system is located in the centre of the fracture cross section. The fracture has a height of 200 m and thus the location of its upper and lower boundaries are (0,100) and (0,-100) respectively. The wells intersect the fracture in its plane, and are symmetrically placed about its centre a distance of 100 m apart with injection at (0,-50) and extraction at (0,50). The symmetry of the problem allows the calculation to be conducted for only one side of the fracture plane.

The fracture is assumed to have an initial (i.e. post-stimulation) uniform hydraulic aperture of 50 μm under ambient conditions. This aperture increases with reduced effective closure stress in accord with a logarithmic closure law, and the resulting change in hydraulic conductivity is calculated assuming the incremental form of the cubic law to be valid. The key parameter describing the compliance of the fracture, the stiffness characteristic, has been assigned a value of 59 mm⁻¹. This is approximately consistent with values predicted for a fracture of nominal aperture 50 μm from Hertzian contact theory considerations (Evans et al., 1992) and corresponds to a moderately stiff fracture. Thus these simulations in no way present results for extremely compliant fractures which would exaggerate the effects of deformability on system behaviour.
Fig 1. Situation and size of fracture and matrix in a perspective view. The origin of the coordinate system is in the middle of the fracture.

Table 1: Material properties for matrix, fluid, and fracture

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Matrix parameters</strong></td>
<td></td>
</tr>
<tr>
<td>permeability</td>
<td>$6.10^{18}$ [m$^2$]</td>
</tr>
<tr>
<td>storage coefficient</td>
<td>$3.10^{-11}$ [Pa$^{-1}$]</td>
</tr>
<tr>
<td>porosity</td>
<td>1 %</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
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</tr>
<tr>
<td>Young’s modulus</td>
<td>$3.10^{10}$ [Pa]</td>
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<tr>
<td>Biot’s constant</td>
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</tr>
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<td>coefficient of linear expansion</td>
<td>$10^5$ [K$^{-1}$]</td>
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<tr>
<td>density</td>
<td>2650 [kg/m$^3$]</td>
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<tr>
<td>specific heat capacity</td>
<td>850 [J/K kg]</td>
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<tr>
<td>thermal conductivity</td>
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<tr>
<td><strong>Fluid parameters</strong></td>
<td></td>
</tr>
<tr>
<td>dynamic viscosity</td>
<td>$3.10^4$ [Pa s]</td>
</tr>
<tr>
<td>fluid compressibility</td>
<td>$5.10^{-10}$ [Pa$^{-1}$]</td>
</tr>
<tr>
<td>density</td>
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<tr>
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<tr>
<td>thermal conductivity</td>
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<tr>
<td><strong>fracture parameters</strong></td>
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<tr>
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<td>stiffness characteristic</td>
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<td>ambient hydraulic aperture</td>
<td>50 [$\mu$m]</td>
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<tr>
<td>ambient mean aperture</td>
<td>500 [$\mu$m]</td>
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</table>
GENERAL DESCRIPTION OF PHYSICAL PROCESSES

Simulation Steps

The current study comprised a series of coupled 2D simulations, of circulation through a single vertical fracture over 30 years. Injection pressure and temperature are held constant and the extraction well allowed to produce at zero back-pressure. This work is reported in detail in Evans et al. (1992) *(The authors would like to express their thanks to T. W. Hicks of CSM Associates in bringing an erroneous description at the previous computations to their attention).* Here, the results of the two most significant simulations in this series will discussed. Essentially three mechanisms can affect the system behaviour during the tests. These are deformability of the fracture and changes in poro-elastic and thermo-elastic stresses on the fracture. Throughout all experiments, the thermal and hydraulic fields are always coupled. A summary of mechanisms and couplings active in the three simulations we discuss denoted by DV-A2, DV-D and DV-E is given in Table 2.

Hydraulic processes

The principal input variable held constant in this study is the hydraulic injection pressure (rather than the flow rate). Thus since system impedance is defined as the difference in pressure between reservoir inlet and outlet points divided by the production rate, changes in system impedance will be manifest as changes in production rate. In reality as well as in this simulation the inlet pressure will be strongly influenced by the regional stress situation of the reservoir. Under ambient (undisturbed) conditions the far field total stress normal to the plane of the fracture exceeds the pore pressure in the fracture and elsewhere by 10 MPa. Thus, prior to local stress disturbance (i.e. thermo- or poro-elastic stress perturbations) "jacking" conditions will be reached near the injection well if the injection pressure exceeds 10 MPa.

<table>
<thead>
<tr>
<th>Model</th>
<th>Injection Pressure</th>
<th>Activated coupling</th>
</tr>
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<tbody>
<tr>
<td>DV-A2</td>
<td>8 MPa</td>
<td>hydro-thermal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>hydro-thermal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>compliant fracture</td>
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<tr>
<td></td>
<td></td>
<td>elastic back-stress</td>
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<tr>
<td></td>
<td></td>
<td>poro-elasticity</td>
</tr>
<tr>
<td>DV-D</td>
<td>4 MPa</td>
<td>hydro-thermal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>compliant fracture</td>
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<tr>
<td></td>
<td></td>
<td>elastic back-stress</td>
</tr>
<tr>
<td></td>
<td></td>
<td>poro-elasticity</td>
</tr>
<tr>
<td>DV-E</td>
<td>4 MPa</td>
<td>thermo-elasticity</td>
</tr>
</tbody>
</table>

Field experiments suggest that the optimum injection pressure for a system lies several MPa below that required for "jacking". However, it will be seen that the predicted reductions in reservoir stress during circulation are sufficiently large that the adoption of such a constant injection pressure would soon result in positive (tensile) effective stresses developing near the injection point. To avoid this and maintain effective stress levels within the range of validity of the logarithmic closure law, an injection pressure is used that assures that effective stress remains no greater than -1 MPa everywhere on the
fracture throughout the duration of the simulation. The production well is assumed to be open and hence pore pressures there must always be hydrostatic (no hydraulic overpressure).

For the far field hydraulic boundary a circumscribing constant potential (i.e. zero pore overpressure) boundary is specified at a minimum distance of 1 km from the fracture (the so-called Dirichlet boundary condition). Physically such boundaries might be realised as high permeability faults. The pressure field near the fracture is not affected by the type of far field boundary. The use of the symmetry at x=0 requires that flow across that plane be set to zero (Neumann boundary condition) except at the injection and extraction points. Our simulations show that steady-state flow conditions are attained in the matrix after about 2-3 years; In contrast flow in the fracture attains steady-state after only 3 hrs by which time an approximately linear pressure gradient is established along the fracture. Deviations from linearity are due to permeation losses into the matrix, and are promoted by lower fracture transmissivities or higher matrix permeability. The fluid velocity in the fracture between injection and extraction wells is of the order of $10^{-2} \text{ m/s}$ whereas the maximum flow velocity in the matrix near the wells is of the order of $10^{-11} \text{ m/s}$.

**Thermal Processes**

Heat transport in the fracture is found to take place almost entirely by advection, and that in the matrix by conduction, even for flows driven by injection pressures as low as 1 MPa. Injection temperature is maintained constant at 50°C below undisturbed rock temperature in all simulations. This value was chosen for reasons discussed previously; so that effective normal stress on the fracture would remain less than -1 MPa everywhere at the fracture surface throughout the duration of the experiment. The chosen value of 50°C below undisturbed rock temperature is not unrealistic for commercial systems.

The boundary conditions of the thermal and hydraulic systems are identical. The specific choice of thermal boundary condition is unimportant since the cooling perturbation does not extend 1 km from the fracture by the end of 30 years.

**Elastic Processes**

The elasticity, unlike thermal and hydraulic calculations, is not explicitly driven; rather it reacts to different mechanisms which are activated in different simulation steps. For example, the movement of the fracture walls can come about by changes in either fracture fluid pressure or the normal total stress component acting across the fracture (imposed by the matrix). The difference between the two (i.e. changes in effective closure stress) determines the aperture change in accord with the adopted logarithmic closure law. Changes in the total stress normal to the fracture arise both from aperture changes and more importantly from processes occurring within the matrix itself; specifically, stresses arising from evolving pore pressure and temperature distributions within the matrix.

The calculations show that provided "jacking" conditions are not reached, the change in the total stress acting on the fracture due to changes in aperture is rather small. For the problem considered the maximum aperture change is of the order of 20 μm and this generates a back-stress of the order of $3\times10^{-3} \text{ MPa}$.

The primary mechanisms affecting elastic behaviour are the poro- and thermo-elastic volume forces. The poro-elastic stress produced by increased reservoir pore pressure tends to produce an outward displacement of the rock matrix reservoir towards the far field boundary. This is an equilibrating response to the local increase in total stress. The thermo-elasticity acts in the opposite sense, tending to produce displacements towards the fracture to equilibrate the tensile change in total stress in the reservoir due to cooling. The displacements generated by a temperature difference of -50°C can be as large as centimetres and may generate stresses of more than 10 MPa, whereas a pore pressure increase of 4 MPa will create a maximum total stress change of -0.5 MPa.

Generally the boundaries of the discretised elastic area must be placed at a distance that is sufficiently far from the sources of stress (temperature, pore-pressure or fracture aperture changes) that the
disturbance at the boundary is negligible. Hence the elastic field in the vicinity of the sources will not be sensitive to boundary conditions. Experiments showed, that this was satisfied by taking the elastic medium boundary 4 km beyond the hydraulic and thermal boundaries. The boundary conditions adopted hold that normal displacements are zero everywhere except on the fracture plane but that tangential displacements are permitted. In other words the four corner nodes are fixed in space and the joining boundaries are allowed to slide in their plane. This condition also defines the boundary conditions at the symmetry plane with the exception that nodes situated on the fracture walls are permitted to undergo displacement, as defined by the total change in joint aperture.

COMPARISON TO ANALYTICAL SOLUTION AND DISCRETISATION

Bodvarsson (1969) derives some analytical results for fluids flowing in 1D fractures surrounded by impermeable rock and exchanging heat with the surrounding medium. One of the problems he describes has a geometry similar to ours. The domain however is limited at the top and bottom of the vertical crack by two horizontal planes that contain the injection and extraction line sources (at z=-50 m and by z=50 m respectively). In between these planes an infinite rock mass is assumed. Uniquely 1-D diffusive heat flow from the crack is admitted in this matrix (characterised by the thermal conductivity \( \lambda \)). Bodvarsson (1969) gives an expression for temperature drawdown at the injection point at time \( t \) after the commencement of a constant flow of fluid within the fracture at a mean velocity \( q \) as,

\[
T_{ex} = \Delta T_0 \cdot \text{erfc} \left( \frac{2\lambda/\rho C_p q}{2\sqrt{\alpha t}} \right)
\]

where \( \Delta l \) is the distance between the injection and the extraction points, \( a_l \) is the fracture aperture, \( \rho C_p \) is the specific heat of the fluid, \( \lambda \) is the thermal conductivity of rock, \( \alpha \) is the thermal diffusivity of rock and \( \Delta T_0 \) is the initial temperature difference between the injected and the extracted water. This equation has been used to verify that the discretisation used in our models gave sufficient accuracy.

These models were discretised with 10 m long Lagrange type elements (i.e. with quadratic shape function) along the fracture. Radially from the fracture the mesh rapidly became coarser, the elements nearest the fracture having a lateral length of 2 m whereas those 100 m distant have a lateral length of 50 m. The time discretisation was also graduated, with very small time steps of 0.1 s at the beginning of the injection increasing to \( \Delta t=10 \) days. In order not to conflict with Courant number restrictions, a fully implicit scheme was used.

Model DV-A2 was specifically set-up to compare against the Bodvarsson solution. An injection pressure of 8 MPa was used in the simulation. This ensured a sufficient flow through the assumed rigid fracture that pronounced thermal drawdown at the extraction point occurred. Other parameter values used in the simulation are as listed in Table 1. In accord with the Bodvarsson solution, Neumann boundary conditions were placed on the two horizontal boundaries at the injection and extraction points. The temperature field predicted by model DV-A2 after 10 years and after 30 years is shown in Figure 2. Very clearly it can be recognised how the cold fluid injected at (-50/0) cools down the matrix. The linear cooling front is implied by the vertical borders of the discretised domains boundary conditions at \( z=50 \) m and \( z=-50 \) m.

A comparison of the thermal drawdown histories predicted by DV-A2 numerical solution and Bodvarsson's analytic solution is shown in Figure 3. After 30 years, the difference in the predictions is about 1°C or 6% of the drawdown. This discrepancy can be ascribed to the 1-D approximation of heat conduction within the matrix used by the Bodvarsson model, whereas model DV-A2 considers 2-D heat conduction. This result shows that the discretisation in time and space was sufficient for a hydro-thermal simulation of 1-D fracture flow in a 2-D matrix.
Fig. 2 Simulation DV-A2: snapshots of the thermal perturbation. The model assumes a rigid planar fracture, advective/diffusive heat transport along the fracture and heat conduction in the matrix. Water which is 50°C colder than the initial matrix temperature is injected at 8 MPa into the fracture at -50,0 and extracted at +50,0.

Fig. 3 Thermal drawdown at the extraction point for the DV-A2 model (straight line) and for the analytical equation of Bodvarsson (square symbols). After 30 years the difference between the two predictions is about 1°C or 6% of prevailing drawdown. The discrepancy arises from the 1-D heat conduction approximation inherent in Bodvarsson’s solution, whereas DV-A2 considers 2-D heat conduction.
SIMULATION RESULTS

Format of Graphical Presentation of Simulation Results

A necessarily condensed selection of the more important results of the two simulations DV-D and DV-E is presented as a series of illustrations and graphs, constituting one figure. The format of each figure is as follows.

The plots are subdivided into three parts. The two leftmost constitute "snapshots" of the key parameter fields (temperature, fluid overpressure, displacement) in the vicinity of the fracture taken after 10 and 30 years respectively. The temperature changes are drawn as grey-toned isothermal areas and hydraulic overpressure as white labelled isolines. The displacement field in the matrix is also shown with black vector arrows.

The rightmost column of each figure presents a number of plots that chart either the history or the spatial variation of several variables that are particularly useful for interpreting the results. The upper plot shows the variation in time of output temperature (left y-axis) and production rate (right y-axis) during the 30 years of circulation. The middle graph shows profiles of aperture (left y-axis) and particle velocity (right y-axis) along the fracture after 10 years (both DV-D and DV-E) and 30 years (DV-E only since steady-state in DV-D is reached after 3 years). The lower plot shows the 10 year (both DV-D and DV-E) and 30 year profiles (only DV-E) of the perturbations to the initial normal and tangential total stresses across the fracture resulting from the activated mechanisms. Note that the profile of net total stress normal to the fracture is obtained by adding to the perturbation profile the far field (compressive) stress of -10 MPa. The effective stress profile governing fracture aperture is obtained by subtracting the profile of fracture fluid pressure from the net normal total stress profile.

Discussion of Models DV-D and DV-E

In both simulations, fracture aperture is allowed to vary locally as a unique function of effective closure stress whilst observing elastic equilibrium in the matrix. As is evident in the aperture profile of Figure 4 and 5, the aperture is widest at the injection point at -50 m, where the effective stress is least compressive, and narrowest at the extraction point at 50 m.

The model DV-E differs from DV-D in that thermal stresses are also considered. In model DV-D the poro-elastic effects in the matrix create a compressive stress perturbation on the fracture that is of the order of 0.5 MPa near the injection point. The displacement field in the matrix generated by the pore pressure features displacements of up to half a centimetre, several orders of magnitude larger than the displacements that arise from the fracture opening alone (about 20 μm). Because the net perturbation to the ambient stress is everywhere compressive, the effect of "switching-on" poro-elasticity is to slightly reduce fracture aperture. The displacements tend to align with the maximum pressure gradients. Thus the greatest compressive perturbation tends to be focused on the injection point.

The particle velocity in the fracture varies along the joint profile with the fastest flow occurring at the point with the smallest width. In model DV-D the production rate nevertheless quickly becomes constant because the fluid field in the fracture rapidly attains steady-state. After 3 years the fluid flow in the matrix attains steady-state and thus the poro-elastic stress becomes constant.

The results of model DV-E which also includes thermoelastic stresses are shown in Figure 5. The effects of thermo-elasticity are the greatest of all three mechanisms, and give rise to large tensile stresses particularly near the injection well. Since simulation of hydrofrac conditions are avoided in the current modelling and the stresses on the fracture restricted to the range of validity of the logarithmic closure law (i.e. effective stress < -1 MPa), it was necessary to limit injection pressures to 4 MPa to avoid violating this condition during the simulation. The same consideration also dictated that we limit the injection temperature to be no more than 50°C cooler than the undisturbed reservoir temperature (the limits of injection pressure and temperature are of course dependent upon other parameters such as far field stress level). This explains the choice of the final operation parameters, although we believe they are realistic for shallow (2-3 km) systems in areas of average heat flow. We have, however, chosen
Fig. 4 Simulation DV-D with activated non-linear fracture compliance and poroelastic stresses in the matrix.
Fig. 5 Simulation DV-E with activated non-linear fracture compliance and thermo- and poro-elastic stresses in the matrix.
values that led to limiting effective stress levels in the long term so as to give visibility to the effects of deformable fractures on production.

The substantial long-term reduction in effective normal stress arising from thermo-elastic effects gives rise to an increase in fracture aperture and hence production rate. Figure 5 shows that over a 30 year period production increases by approximately 25% implying a similar decrease in system impedance. Since net throughput is dependent upon the geometric mean of hydraulic aperture along the flow path, it is largely limited by the smallest aperture, which occurs in the vicinity of the production well. This underlines the result that although the changes in effective normal stress after 10 years of operation are comparatively small, they are greatest in the critical region of smallest aperture. Hence production rate continues to steadily increase after 10 years.

DISCUSSION AND CONCLUSIONS

If advection in the matrix is switched off, the predicted thermal field remains unchanged. Thus, thermal transport in the matrix is governed entirely by conduction, at least for matrix permeabilities of the order of \(10^{-17} \text{ m}^2\). It is noteworthy that the 20% thermal drawdown contour (10°C) in the matrix extends out to 50 m after 30 yrs. This compares with a 20% penetration distance of 112 m obtained using a simple 1D model with the same material constants. The difference between the two is due to lateral spreading of the diffusing cooling front, and further reductions in predicted penetration distance can be anticipated for 3D simulations. This highlights the unsuitability of 1D thermal transport assumptions for simulations of long-term reservoir behaviour.

The significant long-term reduction in system impedance predicted by model DV-E highlights the importance of the thermo-elastic mechanisms in modifying system behaviour over time. A large reduction in system impedance was seen to accompany severe thermal drawdown during the 75 day circulation of the Phase 1 reservoir at the Fenton Hill site (Dash et al., 1983). As far as we are aware, our coupled analysis, originally reported by Kohl (1992a), was the first quantitative study of the phenomenon that simultaneously satisfies elasticity relations in the medium and across a realistically deformable fracture. Previous studies have approximated the effects of thermal shrinkage by assuming that the medium outside the thermally perturbed source volume undergoes no displacement. However, examination of Figure 5 shows that displacements of more than one centimetre occur outside the thermally depleted volume. The effect of these displacements is to substantially reduce the stress change on the fracture that would occur were the source volume to be embedded in a rigid medium. This also means that conditions favouring thermal cracking are not as ubiquitous as might seem to be the case from calculations based on this assumption. For our extreme model, where effective stress normal to the fracture just remains compressive, in-plane stresses on the fracture wall remain sufficiently compressive after 30 years to inhibit fluid-driven fracture propagation provided that the far field stress in the plane of the fracture is at least 30% more compressive than the far field normal stress.

The large inwardly-directed, near-radial displacements in model DV-E that develop towards and beyond the extremity of the thermally perturbed zone give rise to a compressive circumferential stress in the outlying region. This arises in much the same way as the well known circumferential stress concentration that develops around well bores. Figure 6 shows the variation of the stress perturbation in the matrix near the fracture after 30 years. The distribution of the plotted \(\sigma_{XX}\) and \(\sigma_{ZZ}\) stress perturbations indicate the presence of a compressive circumferential stress cage. The stress perturbation turns from tension to compression just beyond the thermal front and reaches a peak compression of about 1 MPa at 80 m radial distance from the reservoir, as can be seen on \(\sigma_{ZZ}\)-profile perpendicular to the plane of the fracture. The effect is potentially beneficial for HDR reservoir operation since it represents a 'stress-cage' around the active reservoir which serves to increase the effective stress across fractures aligned with the radial from the reservoir. Thus it may be helpful for reducing fluid losses to the far-field.
Fig. 6 Stress perturbation within the HDR reservoir. The compressive $\sigma_{xx}$-components potentially reduce fluid losses through vertical fractures and the compressive $\sigma_{zz}$-components reduce fluid losses through horizontal fractures.
All perturbation stresses calculated in this study are slightly exaggerated by the plane strain assumption and will reduce when full 3D calculations are performed as planned for the future. The reduction in stresses and strains, however, is not large (probably between 10-20% for most reasonable fracture height-to-length ratios) and so the results presented here convey a good sense of the magnitude of the effects to be anticipated.

As shown in Kohl et al. (1992b) such models also give rise to short time tensile stresses at the extraction point, immediately after the injection begin. These tensile stresses produce a transient reduction in the level of wells sampling fluid pressure in rock volumes remote from the injection point. It has been observed during fluid injection at the HDR investigation sites of the Fjällbacka (Wallroth, 1992) and Rosemanowes Quarry (CSM, 1984).

In the future, parameter studies on the coupled hydro-thermo-elastic behaviour of HDR reservoirs with 3-D geometry and a more complex fracture geometry will be conducted. Apart of analysis of coupled 3D behaviour, this next step of our work is directed towards optimising the operation parameters of a HDR pilot plant.

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