# MODELLING FLOW AND HEAT TRANSFER IN FRACTURED ROCKS: APPLICATION ON HEAT EXTRACTION FROM HOT DRY ROCKS

[1]Olaf Kolditz, [1]Christoph Clauser, [2]Rüdiger Schellschmidt, [2]Rüdiger Schulz

[1]University of Hannover, Institute of Fluid Mechanics, Appelstr. 9A, 30167 Hannover, Germany
[2]Geowissenschaftliche Gemeinschaftsaufgaben, NLfB-GGA, Stilleweg 2, 30655 Hannover, Germany

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## ABSTRACT

The object of this study is to investigate fluid flow and heat transfer within geothermal reservoirs, which are placed within hot dry rocks (HDR). Many lield experiments demonstrate the strong correlation between tectonic stress field. fracture opening, and flow processes in hydraulically stimulated rocks. The proposed model is therefore based on the general idea. that flow and advective transport occur mainly in fracture systems, whose orientation is governed by the tectonic stresses. 3-D deterministic fracture networks are synthesized for the HDR sites at Soultz-sous-Forêts (F) and Rosemanowes (UK), which represent the mean geometrical features of the reservoirs. A preliminary study emphases the necessity taking into account the spatial character of heat a-sion within the rock matrix. Therefore, a truly 3-D model is used to predict the thermal performance of HDR prototypes.

## INTRODUCTION

Since 1970, the development of geothermal hot dry rock systems has been investigated at different sites in the world At the same time several mathematical models have been proposed to analyse the data obtained from field experiments and to predict the performance of an HDR reservoir (Robinson and Kruger 1988, Zyvoloski et al. 1988, Robinson and Brown 1990).

Models can be classified by their conceptualization of the fractured reservoir geometry (discrete fractures or fracture networks, equivalent porous media). Classical analytical methods can be involved for the calculation of heat extracted by steady state flow from single fractures or parallel fracture arrays. To simulate the hydraulic-thermal-mechanical processes occurring during heat extraction from rocks, numerical methods have to be employed (CSM 1991, Kohl 1992, Kolditz and Diersch 1993). These generic models, assuming a simple reservoir geometry, are useful for parameter studies and for understanding the complicated physics of the coupled processes.

Borehole logging, core analysis, and fracture trace mapping in mines or quarries provide geometrical information for a more realistic description of natural fracture systems, e.g. fracture orientations, apparent apertures, dimensions and fracture densities. The available information is statistical in nature, and this kind of data is especially suited for stochastic models. Commonly, Monte Carlo techniques are used, in which a large number of realizations of different but statistical equivalent fracture systems are performed to determine the average and variability of behavior (Bruel and Cacas 1992, Lanyon and Batchelor 1992). Fig.1 shows a part of a synthesized fracture network established on the base of statistic data for the Soultz site. For constructing this spatial fracture network it is assumed that hear data (provided by borehole-logging) may be extrapolated to a volumetric model domain of interest. The extension of the accessible HDR reservoir may be estimated by monitoring microseismic events during hydraulic stimulations.

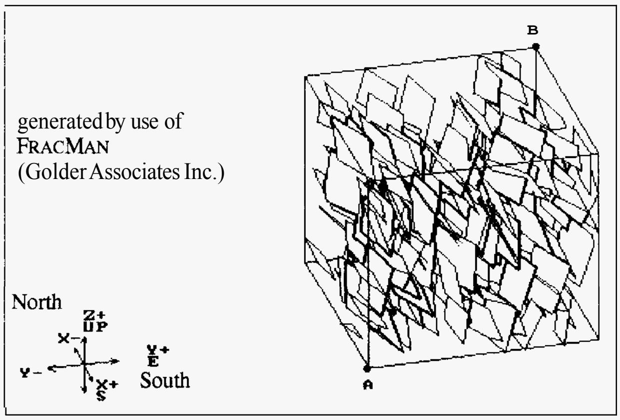


Fig.1: Stochastic fracture network designed the for Soultz HDR site

Typical fracture densities detected from Borehole-Televiewer- or Formation-Microscanner-logging are of the order of 10 $m^{-1}$. Depending on the fracture extensions, model regions of practical interest (about $10^7$ $m^3$) would therefore contain some thousand fractures. Numerical simulations of flow and transport through such fracture networks are quite complicated. For test interpretation or parameter estimating by inverse modelling the computation time would be most expensive. Therefore, Kolditz (1993b) proposed a conceptual model to simplify the flow path geometry for modelling flow and transport in HDR reservoirs.

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(i) **stress** dominated processes

Many field experiments have demonstrated the strong correlation between tectonic stress field, fracture opening, and flow distribution in stimulated crystalline rocks. From hydraulic tests Jung (1991) concludes that former pre-fractured discontinuities may change their orientation during stimulation and become perpendicular to the actual least compressive stresses.

(ii) fracture clustering

Statistic analysis of the fracture data indicates the existence of different directional fracture sets. The individual fractures of such a family scatter around a mean strike direction.

(iii) spacing of hydrothermally relevant fractures

As already mentioned the density of fractures, which may be seen on the borehole wall, is very high. However, the important quantity for flow and transport characteristics of a reservoir is the spacing of those fractures that may actually accept water. These hydrothermally active fractures across the borehole may be recognized eg. by means of the thermal flow meter method. Analysis of tracer breakthrough and thermal drawdown provides an idea about the characteristic fracture spacing within the reservoir, which are about tens of meters (Nicol and Robinson 1990).

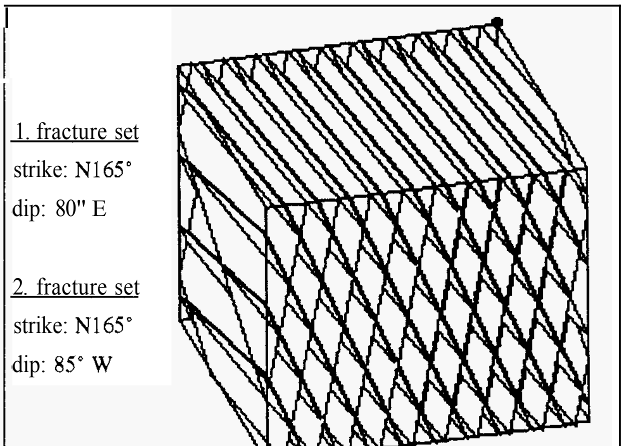



Fig. 2 Synthesized fracture network of the Soultz HDR reservoir

The proposed conceptual model is therefore based on the general idea that flow and advective transport in the hydraulically stimulated rocks occur mainly in fracture systems, whose orientation is governed by the tectonic stress field. Within the deterministic approach the following assumptions and simplifications are invoked for the fracture geometry. As a consequence of item (i) fracture clusters may be represented by large fractures, which are oriented at welldefined average strike and dip directions of each fracture set. There exists two ideas with respect to the fracture spacing. First, fractures are equidistantly separated at the assumed hydrothermally relevant spacings. Second, only those fractures are considered which accept water as detected by flow logs.

A corresponding synthesized fracture network for the Soultz HDR site is presented in Fig. 2. This fracture network model reflects the geometry of the major fracture sets.

The physical model and the corresponding governing equations of this deterministic fracture network model are described in detail by Kolditz (1994b). The system of partial differential qua-tions is solved numerically by use of the Finite-Element (FE) code ROCKFLOW (Wollrath and Zielke 1990, Kröhn and Zielke 1991). This code is particularly suited for the simulation of flow and transport in fractured media. A multidimensional element library allows the convenient approximation of typical geological structures such as 1-D boreholes, 2-D fractures and 3-D rock matrix blocks.

## DIMENSIONAL EFFECT OF MATRIX-HEAT-DIFFUSION

Kolditz (1993a) investigate the dimensional effect of heat diffusion within the rock matrix and its impact on the thermal performance of single and multiple fractured HDR reservoirs. This dimensional effect is estimated by comparing the predictions of 2%-D analytical models with numerical results of a fully 3-D model. Analytical models based on Laplace-transform technique are restricted to onedimensional heat flow within the rock matrix orthogonal to the fracture plane. The fully 3-D numerical model reflects the natural situation of spatial heat propagation in geological formations much better.

The numerical study **starts** with verifying investigations concerning the stability and accuracy of the numerical model. The usage of global characteristic numbers, such as Courant-, Neumann- and Peclet-numbers to guarantee correct discretizations is complicated, because these numbers are theoretically derived for onedimensional problems in homogeneous domains. Kolditz & Lege (1992) determine a range of possible discretizations for numerical solutions with satisfying accuracy (5% range) by systematically matching the exact solutions of the analytical 2½-D models by Gringarten & Sauty (1975) and Rodemann (1979).

The Fig. 3 shows the comparison of the drawdown with time of the average temperature at the production well due to the 2%-D model and the 3-D model, respectively. An interesting transient effect is observed. At the beginning the temperature decline predicted by the 3-D model is a little bit more as this by the 2%-D model. With proceeding time the thermal performance of the 3-D models improves significantly. After **20** years production time the calculated extraction temperature exceeds the forecasting of the reduced 2%-D model by 11%.

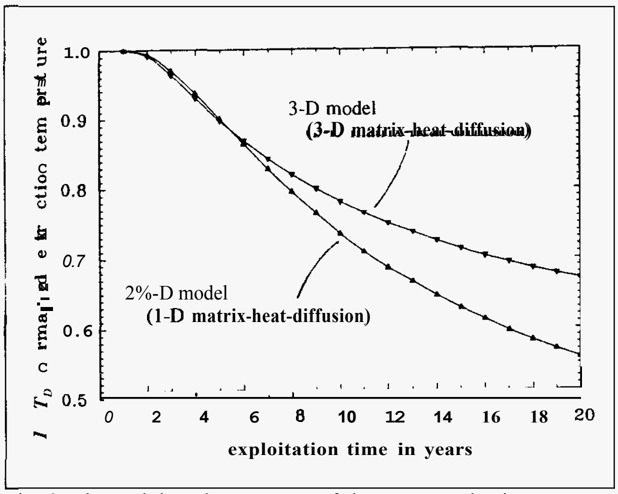



Fig. 3. Thermal drawdown curves of the mean production temperature

To explain this transient effect the following grafic should provide more insight into the thermophysical differences of both models. Fig. 4 shows temperature-isoaurfaces within the rock matrix for the 2½-D and the 3-D model, respectively. At the beginning of the heat extraction the reduced 2%-D model overestimates the heat flux from the rock into the fracture due to the 1-D heat diffusion within the matrix orthogonal to the fracture plane. Heat flux vectors

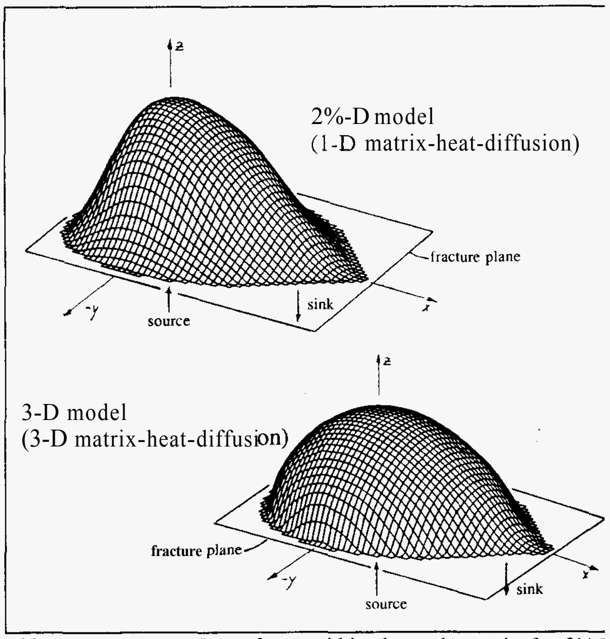



Abb. 4 Temperature-Isosurfaces within the rock matrix for 2½-D and 3-D models, respectively

oriented orthogonally on the fracture surface. Due to this intensive heat removal, the production temperature is exaggerated in the short-time scale. As can be seen the thermal front propagates more quickly through the rock matrix, especially in the region directly about the injection (cooling) source. In the following the remaining heat stored in the rock matrix must be moved over larger distances to the fractures. The intensive heat mining due to the 1-D heat diffusion within the rock matrix normal to the fracture plane implies a more rapid depletion of the thermal reservoir. In contrast the 3-D model reflects the lateral heat fluxes within the matrix. Heat is also supplied from the outer parts of the matrix to the region of most intensive heat removal (the region between source and sink wells corresponding to fracture parts conducting most of the fluid flow). The temperature-isosurface is smoothly spreaded over the whole fracture area.

***application for optimizing borehole separations***

From economic considerations Kappelmeyer et al. (1993) assess the the required performance of a HDR prototype. In the following parameter study the borehole separations ***(2a)*** for multiple fractured HDR systems are determined as function of fracture spacing ($l$) and flow rate per fracture ($q$) for fixed time ($t_0$ = $10a$) and thermal drawdown ($\Delta T=10\%$). To this end inverse modelling is necessary. Forward modelling provides the temperature function depending on borehole separation, flow rate, fracture spacing, time and several material parameters: $T = f\ (a,q,l,t,...)$. To investigate the parameter of interest: $a = f^{-1}(T, q, l, t_0)$, a large number of forward calculations have to be carried out to quantify the inverse functional dependence.

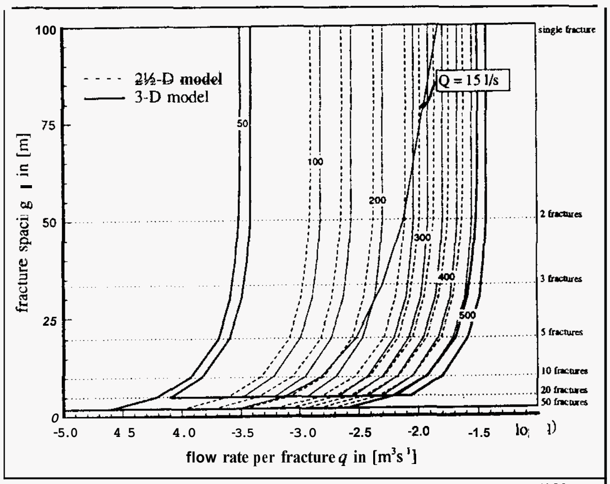



Fig. 5. Minimum half borehole separations (a in meter) for different multiple parallel fracture systems

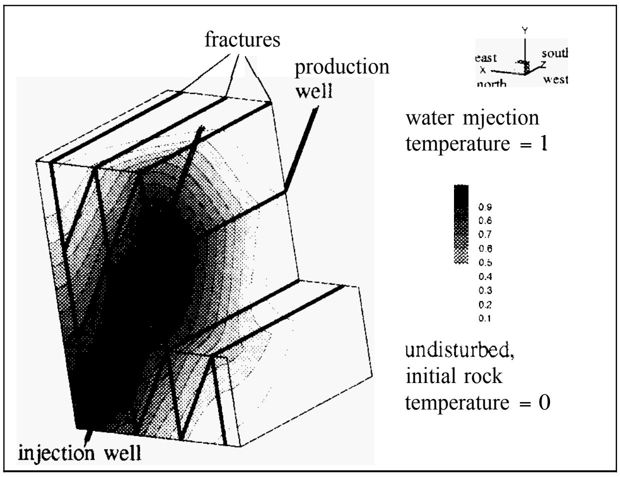
Fig. 5 shows the minimum borehole distances for different multiple fracture systems and varying flow rates corresponding to the analytical 2%-D model by Heuer et al. (1991) and to the 3-D numerical model, which accounts for the threedimensional heat diffusion within the rock matrix. Fracture flow is directed by a borehole doublet. The solid line in Fig. 5 corresponds to the averall production flow rate of Q = 15 $ls^{-1}$. The flow rate per fracture $q$ is Q divided by the number of fractures $n$, respectively. Furthermore, Fig. 5 illustrates the dimensional effect of linear against spatial heat diffusion within the matrix due to the minimum borehole separation.

The effect of spatial heat extraction from the matrix allows generally closer borehole separations then conventional 2½-D models predict, which assume onedimensional heat flow within the rock matrix.

The fracture spacing limits the amount of heat stored in the adjacent rock layer accessible for each fracture. Small spacings require larger borehole distances to keep the drawdown in acceptable bounds. On the other hand the individual flow rate per module decreases with growing number of fractures, which allows closer borehole positions.

## PARAMETER STUDIES AT THE SOULTZ HDR SITE

Near Soultz-sous-Forêts (F) in the northern Alsace a European HDR project has in progress since 1987 (Kappelmeyer et al. 1992). Many experimental work has been conducted in the field, which is summarized in a report by Heinemann (1994). Due to the situation at Soultz (valley structure) it is assumed that only those fractures are fluid conducting which are aligned along the direction of maximum horizontal stresses (N169°±12°) (Rummel and Baumgartner 1991). Because of the different dip directions of the major frachire sets a spatial fracture network is present (cf. Fig. 2).




ig. 6 3-D temperature distribution within the deterministic fracture network at the Soultz site

Fig. 6 presents the computed 3-D distribution of normalized temperature within the fracture network after 10 years production time. In this first case the boreholes for fluid injection and production are placed in the same fracture. Normalized temperature $T_D$ is used for convenience. The real temperature $T$ can be evaluated easily from: $T = T_0 - T_D \cdot (T_i - T_I)$ . where the temperature of injected fluid is $T_i$ and the initial, undisturbed rock temperature is $T_0$. In Fig. 6 a part of the rock block was removed to permit a look inside the reservoir. The position of the injection borehole is easily identified by the area of high thermal drawdown (dark region in Fig. 6). As can be seen the heat is mined preferentially through the fractures by advection. The heat **flux** from the rock into the fractures is insufficient to equilibrate the removed heat. Consequently, thermal drawdown is developing. Due to the adiabatic (no heat flow,) boundary conditions the thermal reservoir is not replenished from outside. Furthermore, the borehole positions at the boundaries of the reservoir induce short flow paths. Hence, the results correspond to a lower limit for the extractable heat content from this reservoir.

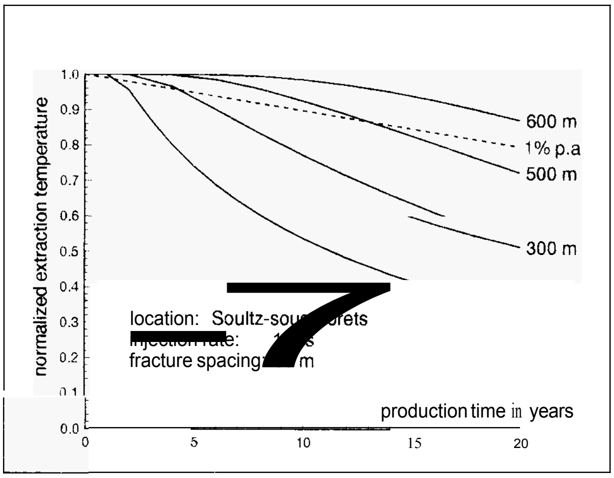



Fig. 7 Thermal draudoun depending on the borehole separation

Following these initial tests the model is ready to investigate the dependence of the thermal long-term performance on important technical parameters such as borehole separation, fracture spacing and borehole position within the fracture network (Kolditz 1993b).. Fig. 7 shows for example the thermal drawdown as a function of the borehole separation. According to the desired performance of an HDR prototype, the thermal drawdown should be less then 1% per year for ten years. Due to these calculations the borehole separation should therefore be at least about 500m for the fracture network considered. Thermal efficiency proves to be very sensitive to the borehole distance. A doubling of the well separation (eg. from 300m to 600m) reduces the thermal drawdown by a factor of seven after 20 years of production.

## DATA EVALUATION AT THE ROSEMANOWES HDR SITE

The Rosemanowes HDR site is located at Comwall (UK) within the Carmenellis granite. Three wells (RH11, RH12, RH15) have been drilled to depths between 2.0 and 2.6 km. Stimulation and circulation experiments have been conducted from them over a period of more than ten years (CSM, 1992). Two reservoirs were developed and tested: the RH11/RH12 and the RH12/RH15 system. The long-term circulation test was canied out within the improved RH12/-

RH15 reservoir, which is the object of the modelling investigation here. Nicol and Robinson (1990) analyzed the thermal drawdown using a parallel fracture model, which was calibrated on tracer data.

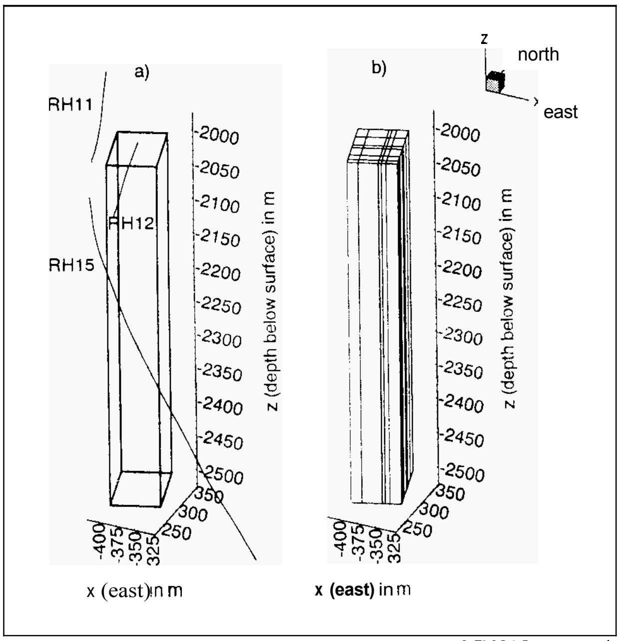



Fig. 8: Perspective view of the stimulated RH12/RH15 reservoi and the synthesized fracture network

The size and the shape of the accessible reservoir (cf. Fig. 8) can be estimated by monitoring the microseismicity during the stimulation of the wells (Green and Parker 1992). Different methods have been employed for the determination of the fracture system. eg. surface mapping, borehole logging. From statistical analysis of the data it was concluded, that two subvertical fracture sets exist, which are scattering around the mean strike directions of N165° and N250°. Within the deterministic concept a fracture network is established according to these average orientations. Furthermore, the number of fractures is restricted to these, which accept water as detected by the well flow logs (Fig. 8).

Fig. 9 shows projections of the network and the corresponding flow fractions, which are accepted by the fractures. Four main fluid entry zones exist, each of them produces more than 10% of the fluid. The RH12/RH15 system has been continuously circulated for about three years beginning August 1985. Optimum performance of the system was achieved at an injection pressure of 10 MPa above hydrostatic, producing a hydraulic impedance of 0.6 MPa $l^{-1}$ s and an average production rate of 14 kg/s. The overall impedance is the key parameter for the calibration of the hydraulic model.

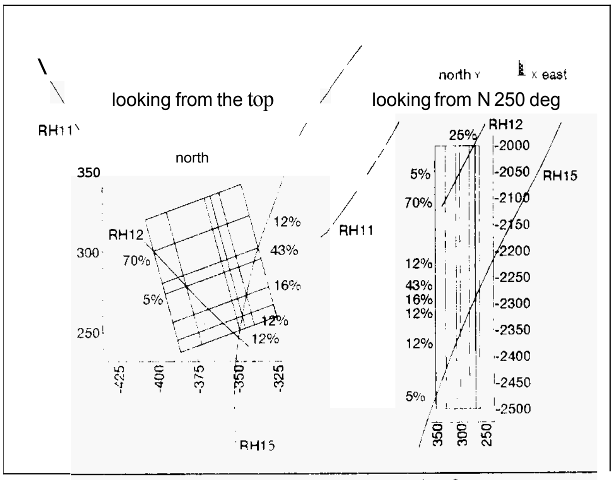
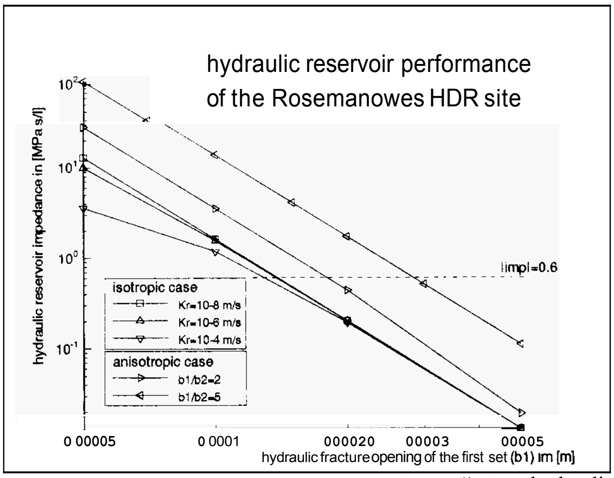



Fig. 9 Flow fractions absorbed by the fractures

Using the fracture network model we can study the dependence of the reservoir impedance on the fracture permeabilities. Because of normal and shear forces acting on any fracture. the hydraulic characteristics of the fracture network are strongly affected by the tectonic stress field. The anisotropic tectonic stress field implies hydraulic anisotropy of the fracture system. The maximum horizontal principle stress direction at the Rosemanowes HDR site is about N 330" (Pine et al. 1990). The first fracture set is nearly aligned with the maximum principle stress direction. therefore. we expect a better permeability of the first set then of the second set, which strikes at N250° nearly uith the minimum principle stress direction. While changing the relation of apertures of both fracture sets, Fig. 10 shows the effect of hydraulic anisotropy on the overall impedance. For each case one can find the corresponding fractures apertures, which match the measured impedance of 0.6 MPa$l^{-1}$s.




. ig. 10: Impedance of the fracture network depending on hydraulic fracture apertures

Fracture aperture and hydraulic transmissibility of a fracture are related by the well known 'cubic law'.

Another aspect, which is discussed in Fig. 10, concerns the conductivity contrast between fractures and rock matrix. $K_r = 10^{-4} ms^{-1}$ is used for an upper limit of the hydraulic conductivity of crystalline rocks (Clauser, 1992). Especially if considering the hydraulic long-term behavior, thermal cracking within the rock matrix can reduce the conductivity differences, and therefore, change the hydraulic reservoir performance.

## CONCLUSIONS

A 3-D fracture network model is established for simulation of forced flow and advective-conductive heat transfer within fractured crystalline rocks. The deterministic approach reflects the main geometrical features of a stimulated HDR reservoir based on mechanical considerations of the tectonic stress situation. The actual flow distribution within the boreholes due to the hydrothermal relevant fractures may be considered. The model permits an effective calculation of the long-term performance with respect to the important parameters of an HDR system. The required computation time is within acceptable bounds. Consequently, even inverse modelling can be tackled for the identification of reservoir parameters. Therefore, the proposed model is suited for field test interpretation, particularly of long-term circulation tests such as that carried out at Rosemanowes (UK) and Fenton Hill (US).

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