SGP-TR-151-40

PROCEEDINGS

TWENTY-FIRST WORKSHOP GEOTHERMAL RESERVOIR ENGINEERING

January 22-24, 1996

Stanford Geothermal Program
Workshop Report SGP-TR-151

PROCEEDINGS, Twenty-First Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 22-24, 1996
SGP-TR-151

Insight from modelling discrete fractures using GEOCRACK

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Keywords: Hot Dry Rock, Optimization, Simulation, Thermal deformation, Dynamic flow dispersion

Abstract:

This work analyzes the behavior of a numerical geothermal reservoir simulation with flow only in discrete fractures. GEOCRACK is a 2-D finite element model developed at Kansas State University for the Hot Dry Rock (HDR) research at Los Alamos National Laboratory. Its numerical simulations couple the mechanics of discrete fracture behavior with the state of earth stress, fluid flow, and heat transfer. This coupled model could also be of value for modeling reinjection and other reservoir operating strategies for liquid dominated fractured reservoirs. Because fracture surfaces cool quickly by fluid convection, and heat does not conduct quickly from the interior of reservoir rock, modeling the injection of cold fluid into a fractured reservoir is better simulated by a model with discrete fractures. This work contains knowledge gained from HDR reservoir simulation and continues to develop the general concept of heat mining, reservoir optimization, and the sensitivity of simulation to the uncertainties of fracture spacing and dynamic flow dispersion.

Introduction:

GEOCRACK was developed to simulate the physics of a fractured HDR geothermal reservoir. HDR reservoir permeability is initially created by hydraulic stimulation (fracturing of pre-existing joint sets), and subsequently controlled by exerting hydraulic pressure upon sets of discrete interconnected fractures. The HDR reservoir at Fenton Hill, in New Mexico, was created in granitic rock having negligible matrix permeability, so flow is restricted to fracture paths. Reservoir fluid is held under pressure to open joint apertures against in-situ stresses and prevent water from flashing to steam. Thus, GEOCRACK was developed to simulate the structural deformation, single phase fluid flow, and thermal transport of heat mined from a network of discrete joints.

Constrained by in-situ stresses, the productivity of an HDR reservoir depends largely upon joint aperture size, joint surface area, and the connectedness of a jointed system between injection and production wells. At the same time, the thermal lifetime of a fractured reservoir depends upon a number of parameters including: overall reservoir size, well spacing, fluid flow rate, fracture spacing, fracture geometry, and flow distribution.

Brief Description of GEOCRACK:

GEOCRACK is a 2-D finite element simulation of single phase fluid flow through a system of discrete joints. The reservoir rock matrix is assumed to be elastically compressible and thermally deformable. Fracture apertures are modeled as planar features that open nonlinearly with increasing hydraulic pressure. Joint apertures also vary with the thermal and elastic deformation of the rock matrix.

Simultaneously, fluid conductivity in discrete joints is controlled by the cubic law (Witherspoon et. al. 1980), derived from the relation for fluid flow between parallel plates. The rate of flow is proportional to the cube of fracture aperture size and linearly proportional to the pressure gradient along each flow path.

Heat flow in the rock is by conduction, with fluid heat transport by flow in the joints. The important result of coupling conductive heat flow to convective heat transport is that the relatively low conductivity of rock becomes the controlling influence on fluid temperature. In other words, fracture surfaces cool quickly because heat is conducted slowly from the interior of the rock to the flow path surfaces.

Numerical simulations show good agreement with analytic and semianalytic comparisons of elastic deformation, transient joint opening, fluid flow, and heat transfer. (Swenson et. al. 1995) Furthermore, both steady state and transient comparisons of model behavior to Fenton Hill data indicate the model correlates with changes in flow at various pressures and correctly simulates pressure responses for flow transients as well. (Swenson, 1995)

Simulating a Hot Dry Rock Reservoir:

Figure 1 shows a GEOCRACK reservoir flow path configuration where fractures hydraulically open against two horizontal principle stresses, and the inclined flow path apertures open at intermediate pressures. Only alternate rock blocks contain inclined joints to reduce the time for computation. Recognizing that the fractures at Fenton Hill are steeply inclined to the vertical and must have a different spacing and geometry, this model correllates hydraulically with Fenton Hill because reservior data shows increasing fluid conductivity at the four distinct levels of fluid pressure. These levels of fluid pressure correspond to the joint opening pressures in this configuration.

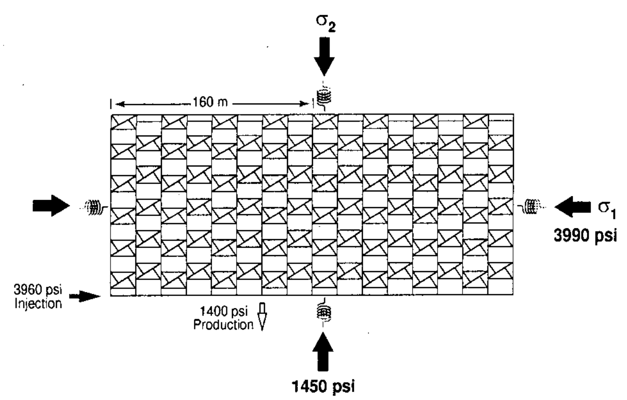

Figure 1. Simulated reservoir configuration

Table 1 shows that such a model reproduces the observed changes in reservoir productivity as a function of wellhead pressures fairly well.

Injection (psi)	Production (psi)	Fenton Hill (Kg/s)	GEOCRACK (Kg/s)
	1400	5.62	5.62
3960	1800	5.68	5.56
	2200	5.18	5.18
3248	1400	3.81	3.06
2475	1200	1.5	1.5

Table 1. Comparison of flow rates at various pressures.

Simulated 2-D flows can be scaled to the 3-D volume of an actual reservoir by stacking a number 2-D models to the vertical height of a reservoir, as illustrated in figure 2. Since the production well at Fenton Hill has about fifteen major outlet fractures, spaced at roughly ten meters vertically along the well, the proceeding reservoir simulations represent the sum of fifteen flows, each conducted through a 2-D model with a 10 meter unit depth. In these simulations the temperature gradient with depth was neglected and each simulation used an initial rock temperature of 250 °C.

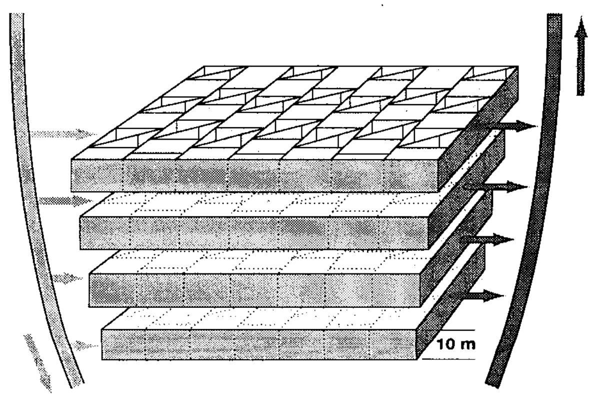

Figure 2. Stacking flow contributions of 2-D models to simulate a 3-D reservoir.

Optimal Heat Mining:

Without regard to economics, one definition for optimal heat mining is to maximize the integrated thermal energy contained in fluid produced above an arbitrarily "useful" temperature over a specified time interval. That is, given a number of fixed parameters such as reservoir size, well spacing, fracture spacing, flow distribution, and an operating time interval, an optimal flow rate maximizes the quantity of energy from "useful", (i.e. high temperature) fluid. Since the operating time span has a predominant influence on economics, this concept for optimization should be complimentary to economic models. Optimization is illustrated in figures 3 and 4. Figure 3 shows the thermal drawdown plots for a Fenton Hill reservoir simulation (with 3.16E6 m^3 of rock) at various flow rates over a selected time interval of ten years. For the calculations in figures 3 and 4 the coefficient of thermal expansion of the rock is set equal to zero to prevent thermal deformation from causing changes in flow distribution. These results compare with published predictions of thermal longevity for Fenton Hill (Robinson and Kruger, 1992), but utilize the fracture spacing and geometry shown in figure 1.

In fully coupled simulations the flow distribution is dynamic due to thermal deformation, which changes pressure gradients, the state of stress, and other factors. All simulations were conducted with a fluid injection temperature of 100 °C and fluid pressures at least 1400 psi above hydrostatic.

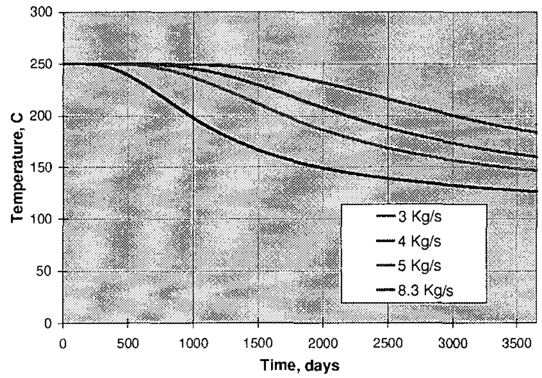

Figure 3. Outlet thermal drawdown curves for various production rates.

Figure 4 shows that the higher flow rates produce more thermal energy, however, the integrated energy of fluid produced at high temperature declines beyond the optimal rate due to a premature decline of the outlet fluid temperature. The premature temperature decline at high flow rates is due to the fast cooling of fracture surfaces and relative slow conduction of heat from the interior of the rock matrix.

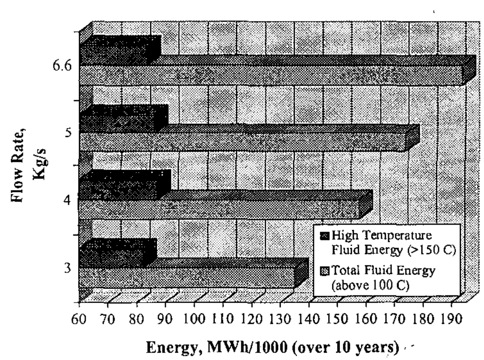

Figure 4. High temperature fluid energy and total energy production.

Not surprisingly, the optimal flow rate provides useful fluid temperatures for the operating life span specified as a constraint.

While reservoir size, well spacing, and operating time span are designed and controlled in the creation of an HDR reservoir, fracture spacing and flow distribution have very significant impacts on thermal life and heat mining efficiency. For larger fracture spacing and higher flow rates cooling extends quickly from the injection well along fracture surfaces to the production well. Conversely, for closely spaced fractures and for relatively low flow rates heat is extracted more volumetrically from the reservoir. As figure 5 shows, even at high flow rates per unit reservoir volume, heat energy is extracted much more volumetrically for joint spacing of 5 meters than if fractures are spaced an order of magnitude farther apart, where cooldown at the outlet occurs quickly after in onset of flow. For this case the flow was distributed over 750,000 m^3. With a 50 meter spacing all of the flow is directed through a single joint, and for the case of 5 meter spacing the flow is evenly distributed over 10 evenly spaced parallel joints.

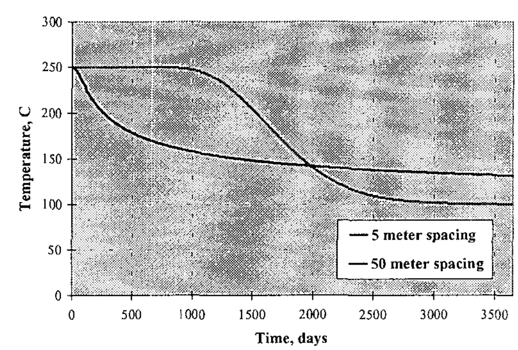

Figure 5. Thermal drawdown plots for 5 vs. 50 meter joint spacing at a 5 Kg/s flow rate.

At large joint spacings and high flow rates isothermal temperature contours in the rock develop nearly parallel to fracture surfaces. In contrast, when flow is distributed over the volume by a smaller fracture spacing, the temperature gradient in the rock develops in the direction of fluid flow and energy is extracted volumetrically from the injection to the production well.

In developing this concept of optimal heat mining three major questions stand out. First, is the optimal flow rate determined by simulation achievable in an actual HDR reservoir given the relative high flow impedance demonstrated at Fenton Hill? Second, are joint spacings sufficiently small for volumetric heat removal at commercial energy production rates? And importantly, Fenton Hill tracer data shows a temporally dynamic flow dispersion through the reservoir. Can dynamic changes in flow distribution be predicted and considered?

Optimal flow rates:

Because Fenton Hill was designed to be an experimental facility, the injection and production wells were spaced approximately 120 meters apart so that thermal drawdown could be observed in a relatively short time. Thus, modeling Fenton Hill and arbitrarily selecting 3650 days (10 years) for a time interval for heat extraction, figure 4 shows that an optimal flow rate for Fenton Hill would be in the neighborhood of 4 or 5 kg/s. This shows that the flow rates demonstrated at Fenton Hill, (about 5.5 kg/s) are appropriate for the reservoir volume between wells spaced at 120 meters over a period of 10 years. If economic energy production rates require an order of magnitude larger flow rates, then a tenfold increase in swept reservoir volume would be necessary for operating life spans of a decade or more. Thus, multiple production wells spaced 500 meters or more from the injection location are implied by modelling flow rates of 50 kg/s or greater.

These calculations indicate that the rates of flow per unit reservoir volume demonstrated at Fenton Hill are quite appropriate for productive thermal time scales of decades. Much larger flows per unit volume would lead to swift outlet fluid temperature decline, smaller flows would only be beneficial for very large joint spacings.

Flow distribution:

Widely dispersed flow through a reservoir volume increases the surface area for heat transfer and is therefore desirable in heat mining. Tracer tests at Fenton Hill show that fluid residence times and flow dispersion have changed with time and thermal energy extraction. The flourocene tracers in figure 5 show an initial long term trend of increasing fluid residence time, as indicated by later initial tracer arrival, and increasing dispersion, as indicated by a broadening of the peak of tracer return concentration. Then, in May 1993, an increase in flow by 50% at constant wellhead pressures occurred and was accompanied by a reversion toward less fluid dispersion and a shorter fluid residence time. Therefore, the Fenton Hill reservoir has displayed two kinds of dynamic flow, increasing dispersion into more flow paths, and increasing productivity coincident with channeling into a less dispersed flow distribution. Other researchers have suggested heat extraction may lead to fracture extension and reservoir growth (Tester et. al. 1989 and Nielson, 1996). However, ignoring the potential for reservoir growth, a closer examination of reservoir constraints and thermal deformation may offer insight into changes in flow and its dispersion into fewer or more flow paths.

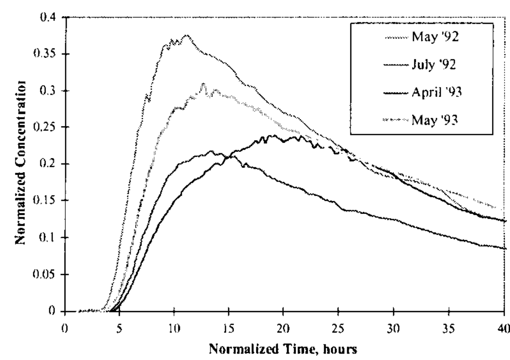

Figure 5. Tracer return concentrations at different times during energy extraction.

Single joint analysis:

The examination of a single joint with thermal deformation and its coupling to confining stresses can help to illustrate the reasons for dynamic flow behavior.

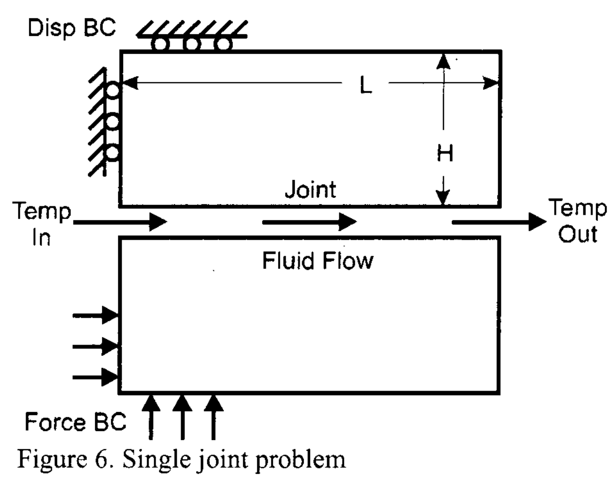

Figure 6. Single joint problem

How thermal contraction and deformation change the flow depends not only on the temperature distribution in the rock but also the boundary constraints. For example, if the periphery of the rock is maintained in a fixed position (Displacement BC), thermal contraction will open the joint, and, if the inlet pressure is held constant, flow in the joint will increase. This will increase the heat removal rate. However, if force boundary constraints (Force BC) are applied to the periphery of the rock, thermal distortion of the rock can locally decrease the joint opening and can result in a reduced rate of flow. Such behavior is illustrated in figure 6.

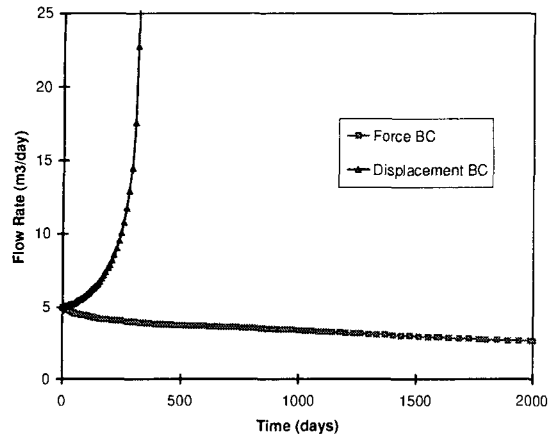

Figure 6. Flow in joint with constant pressure difference

The pinching of the joint when force boundary conditions are applied is shown in figure 7 (symmetry conditions were applied at the left edge). To maintain equilibrium with the peripheral forces, as thermal shrinkage reduces the joint contact stress near the inlet, the contact stress increases away from the inlet.

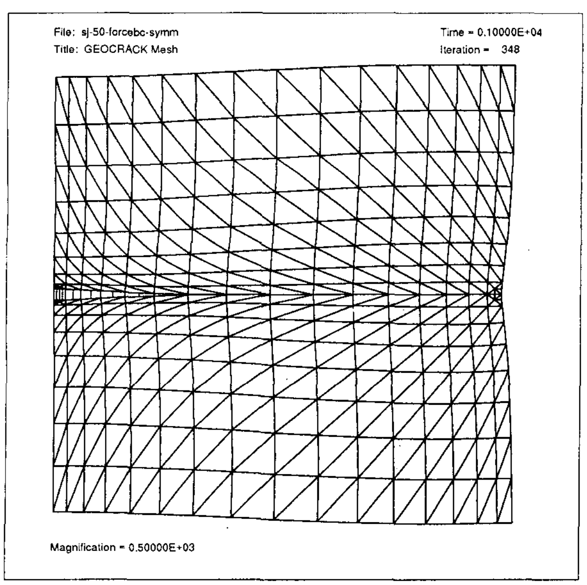

Figure 7. Displacement plot for force BC on periphery of rock blocks

Thus, the stress normal to the plane of a joint and the hydraulic pressure within the flow path can influence either an increase or a decrease in the conductivity of flow during heat extraction. When the hydraulic pressure is high enough to maintain equilibrium with the stress perpendicular to the joint, the fracture opens with the thermal contraction of the rock. Also, if in-situ stresses are bridged around a flow path, so that no force BC exerts pressure to close a joint, this would also lead to an increase in fluid conductivity. If, however, the in-situ stress imposes a compression force acting to reduce a joint aperture, thermally opening one portion of the joint aperture causes other portions of the flow path to bear more stress and locally reduce fluid conductivity. Because a variety of fracture orientations and boundary constraints must exist within a reservoir, both of these fluid conductivity influences may occur simultaneously during heat mining. These specific results correlate with the general conclusions of European coupled HDR simulations. (Jupe, et. al. 1995)

Double flow path model:

Calculations with a two flow path simulation have also been useful. Figure 8 shows the rock temperature contours of a dual flow path geometry. The lower path in this model has been given a larger initial aperture. Initially, a slightly larger fraction of flow through the lower path results, and as heat is extracted, the lower path tends to conduct an increasing fraction of the total flow. (DuTeau, et. al. 1994)

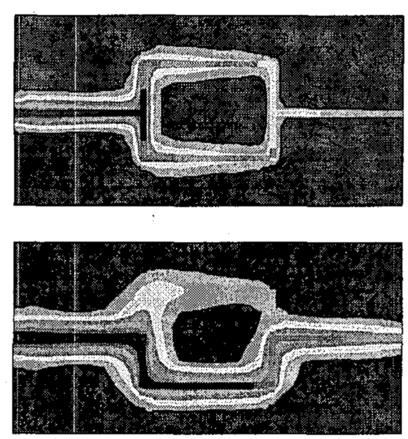

Figure 8. Temperature contours resulting from channeling of flow into the lower path due to its initially larger aperture.

This redirection of flow into flow paths with initially larger fracture apertures has previously been termed short-circuiting. Further examination reveals that the in-situ stresses, flow path geometry, joint opening pressures, boundary constraints, changing pressure gradients, and flow rates all affect the tendency toward short circuiting behavior. For example, figure 9 shows how the geometry of the flow paths change with thermal deformation and how this geometry influences the pinching off or opening up of flow path apertures.

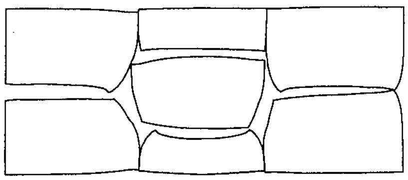

Figure 9. Thermal deformation result of a two flow path simulation.

At higher flow rates these geometric effects become more influential. Under the constraint where displacement of the outside boundaries is limited, thermal contraction of the rock eventually allows flow to disperse back into the smaller aperture path. So, even a simple dual flow path model demonstrates the same behaviors that Fenton Hill has displayed, both channeling of flow and dispersion of flow.

This dynamic flow distribution leads to decreased predictability of production temperatures because the swept reservoir volume is changing during heat extraction. Figure 10 shows the resulting outlet temperature for a two path model that initially channeled flow into the larger aperture flow path, but later redistributed flow into the initially smaller path.

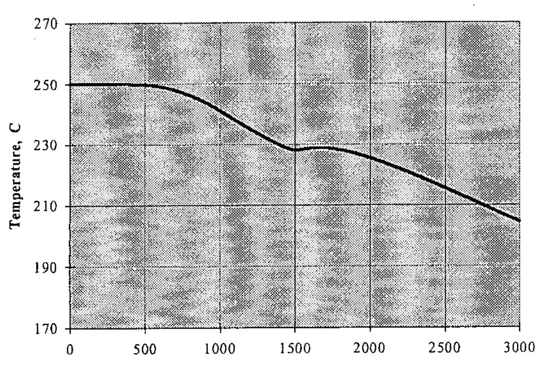

Figure 10. Fluid outlet temperature of a two flow path simulation.

This unanticipated fluid outlet temperature variation with time would occur in an actual reservoir if flow distribution is as dynamic as simulations indicate. Inspection of Fenton Hill data seems to show a long term tendency toward increased flow dispersion (Callahan, 1996), however, GEOCRACK simulations show a stronger tendency toward channeling than increased dispersion. Continuing research will attempt to understand and reconcile these and other discrepancies between real data and simulated reservoir behavior.

Conclusions:

1. Given sufficient information on fracture spacing and flow distribution, the simulation of flow in a fractured reservoir leads to an optimal flow rate per unit reservoir volume constrained by an operating time interval.

2. The flows per unit reservoir volume demonstrated at Fenton Hill are the correct order of magnitude for sustaining heat mining for a time scale of decades; larger swept reservoir volumes will be necessary for commercially scaled heat mining.

3. Thermal deformation of reservoir rock causes local changes reservoir stresses, fracture geometry, pressure gradients, and flow dispersion.

4. In simulations, the injection of cold fluid into a hot fractured reservoir causes dynamic changes in flow distribution that can lead to unanticipated production fluid temperatures.

5. The uncertainties of mining heat in fractured reservoirs develop from a lack of knowledge of fracture geometry and joint spacing, and a lack of understanding of dynamic flow dispersion.

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