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EFFECTS OF USING A CONTINUUM REPRESENTATION TO SIMULATE DISCRETE FRACTURE NETWORKS

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ABSTRACT

The substitution of matrix or continuum permeability for discrete fracture permeability in the simulation of complex fracture systems requires a radically different treatment of transport in the matrix. The spatial distribution of pressure is reasonably well described by inclusion of only the major fractures. Transport of tracer and heat, however, depends on a detailed knowledge of fluid velocities. Two factors are involved. First, the velocities are dependent on the active porosity of the system. Because fractures channel flow, the active porosity may be much smaller than the total porosity of the system. Secondly, the distribution of velocities is generally not normally distributed precluding the use of a Gaussian dispersion model. Characterization of the active porosity and velocity distribution are necessary to quantify tracer and heat movement.

INTRODUCTION

Simulation of fractured geothermal reservoirs is frequently accomplished by using a continuum approach to represent discrete fracture permeability. This results in a saving of computer resources and permits the simulation of large, complex fracture systems. The substitution of a continuum to represent fracture permeability involves a number of assumptions which must be evaluated. Development of continuum properties for representation of discrete fracture systems is an area of active research [Clemo, 1986; Dershowitz, 1984; Endo et al., 1984; Long and Witherspoon, 1985; and Schwartz and Smith, 1983].

The more intersections between fractures in a fracture network, the more the system is likely to behave as a porous medium [Long and Witherspoon, 1985]. On a large scale (reservoir scale) an equivalent steady-state hydraulic response can be obtained by using an appropriate hydraulic conductivity. Transport depends on a detailed knowledge of fluid velocities, not just fluxes. As a result, the pore volume of the system involved in the movement of water must be well characterized. One method of treating transport is through the development of an active porosity. The active porosity can be much less than the total porosity of the system due to fracture orientation and preferred flow paths [Endo et al., 1984].

A second concern is the distribution of flow velocities in the system. A Gaussian dispersion model, which is the common approach used in equivalent continuum models, is based on the assumption of many paths through the system. So many paths, in fact, that the central limit theorem is valid and residence times are normally distributed. In a fracture network, the number of discrete paths may be small enough that there is a correlation in the velocity of a tracer slug over large distances. This correlation results in a skewed distribution of velocities and consequently residence times [Smith and Schwartz, 1983].

A computer model has been developed at the Idaho National Engineering Laboratory that permits the simulation of hydraulic systems consisting of both discrete fracture permeability and matrix permeability. This dual-permeability model was used to study the effects of replacing fracture permeability with a continuum representation. The dual-permeability approach is uniquely qualified for this type of study because the replacement can be performed gradually so that the cumulative effects of replacing fracture permeability with continuum permeability can be evaluated. This paper illustrates the effects of replacing discrete fracture permeability with matrix permeability on spatial pressure distribution and tracer and heat transport.

CODE DESCRIPTION

The study was conducted using the Fractured Media - Advanced Continuous Simulation Language (FRACSL) code developed at the Idaho National Engineering Laboratory [Miller, 1983; Clemo and Hull, 1986]. The code simulates fluid flow and solute and heat transport in two-dimensional reservoirs consisting of permeable matrix blocks and discrete, parallel sided fractures. Transport processes included are advection, diffusion, dispersion, diffusion between fractures and the surrounding matrix, and advection between fractures and the surrounding matrix. The reservoir is defined within a rectangular, finite difference grid of unit thickness. Fractures connect any two adjacent nodes, vertically, horizontally, or diagonally with a maximum of eight fractures converging at a node. Fractures can have any configuration of length, angle, and termination constrained only by the condition that the fracture connects two adjacent nodes of the finite difference grid. Aperture is constant between nodes, but can change for the continuation of the same fracture between the next set of nodes. Boundary condition options include fixed flow rate, fixed pressure, or fixed conductivity to a constant head boundary.

Heat transport capabilities are currently somewhat simplified. Heat transport by conduction and advection are computed, but there is no coupling to the flow solution. Also, all boundaries are considered to be perfect insulators.

SYSTEM DESCRIPTIONS

To study the effects of using a continuum to represent fractures, a series of simulations was conducted of a fractured geothermal reservoir. The base system consisted of a fracture system connecting an injection well and a production well (Figure 1). Additional simulations were made of modifications of this base system where some of the fractures were removed and the permeability of the matrix increased to compensate for the loss of fracture permeability. Steady-state pressure distributions and tracer breakthrough curves were calculated for each of the systems.

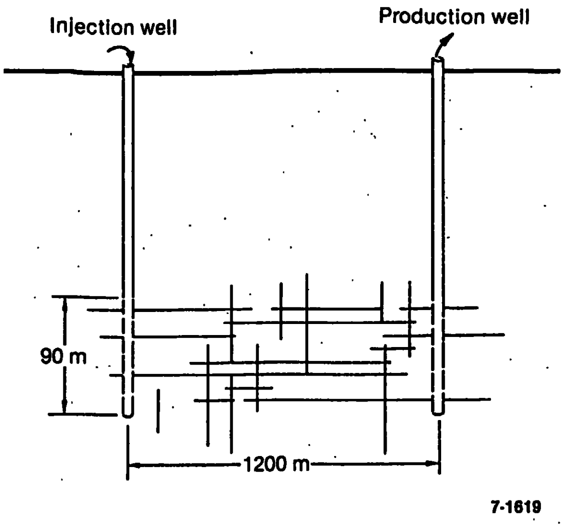
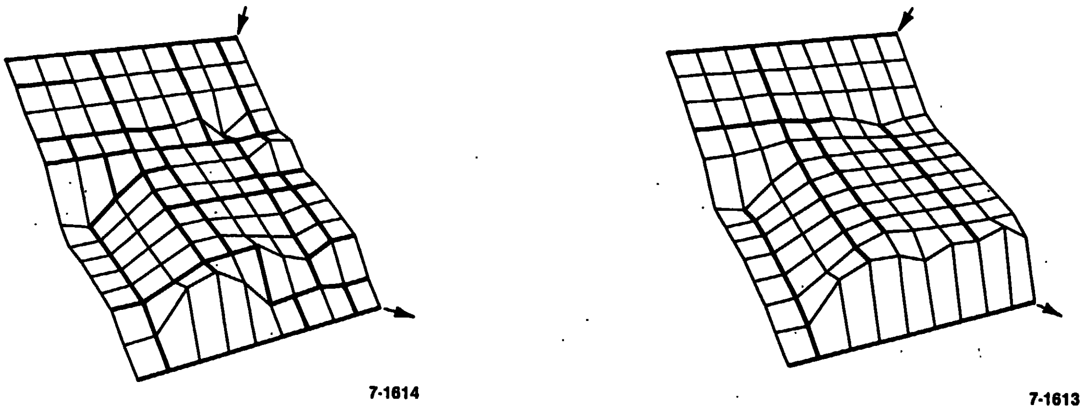


Figure 1. Conceptual model of a geothermal reservoir used in simulations to evaluate the effect of replacing discrete fracture permeability with matrix permeability.

The base system consists of an injection and a production well in a reservoir 1200 m long and 90 m high (Figure 1). The simulation is two-dimensional and a slice of unit thickness through the reservoir assumed. Fluid properties used were those for water at 175°C. Six variations were simulated. The base system is a fracture network consisting of 22 fractures. Three additional fracture networks were derived from the base system by removing fractures from the system, starting with the smallest fractures. This created four fracture systems of differing complexity. A fifth system was created which consists



a. System 5, Full Fracture Network

b. System 2, No Fracture Connections

Figure 2. Steady-state pressure distributions for dual-permeability fracture networks. The networks are shown as dark lines on the grid representing the pressure distribution.

Table 1. Summary of characteristics of the six dual-permeability systems simulated.

System	Description	Number of Fractures	Connecting Paths	Hydraulic Conductivity (m/day)	Intrinsic Permeability (darcy)	Active Pore Volume (%)
1	Matrix only	0	0	7.9	1.62	108
2	No fracture connection between wells	5	0	0.78	0.16	78
3	One cross connection between wells	10	4	0.42	0.086	36
4	Several connections between wells	14	12	0.18	0.037	44
5	Full network	22	21	0.009	0.002	40
6	Single fracture	1	1	0.009	0.002	16

entirely of porous matrix. The sixth and final system is a single fracture connecting the injection and production wells.

System 5 was defined as the base case and the other systems were derived from System 5. Table 1. shows the characteristics of the six systems. All the systems have the same effective hydraulic conductivity. For the same steady-state injection and production rates, the pressure difference between injection and production wells is identical. This is accomplished by increasing matrix permeability as fractures are removed from the system. For System 6, the matrix permeability was set equal to that for System 5 and the aperture of the single fracture adjusted until the pressure difference matched that of System 5.

The porosity of the fracture system, calculated by dividing the volume of fractures in System 5 by the total volume of the reservoir, is 10^{-4}. Therefore, the matrix porosity of the six systems was set to 10^{-4} to mimic that of the fracture system. This small matrix porosity was used so that the matrix flow rates would be similar to flow rates in the fracture system. One consequence of this very small matrix porosity is that diffusion of tracer into the matrix is essentially prevented for time scales of interest in this study. Tracers can, however, be carried into the matrix by advection for the systems with significant matrix permeability.

The active pore volume shown in Table 1 is the ratio of pore volume calculated from tracer breakthrough to total system pore volume. Tracer breakthrough pore volume is calculated from the volume of fluid which had been pumped at the time 50% of an injected tracer pulse had been recovered. For the single fracture representation of the reservoir, only a very small volume of the system is actively involved in solute transport. For the porous matrix representation, the active pore volume is somewhat greater than 100% due to residence time in the injection and production wellbores. The various fracture systems have an intermediate value for active porosity.

SIMULATION RESULTS

Simulations for each of the six systems provided steady-state pressure distribution, tracer breakthrough, and spatial distribution of the tracer front.

Pressure Distribution

The steady-state pressure distribution for Systems 1 and 6 showed a uniform, featureless pressure decline from the injection well to the production well. The fracture networks, however, showed spatial variations in pressure due to the distribution of fractures (Figure 2). The spatial variations in pressure are very similar for all of the fracture networks. This indicates that only the largest, most significant fractures need be included in a simulation to obtain a reasonable estimate of spatial pressure distribution. As a result, the general distribution of flow in the systems should be fairly similar. This similarity requires replacing the smallest fractures with matrix and explicitly simulating the larger fractures. The more dominant effects of the major fractures must be retained.

Tracer Transport

The method of representing permeability has a substantial effect on tracer transport. Figure 3 shows tracer breakthrough for Systems 1, 5, and 6. For the single fracture, all fluid moves along a single path which encompasses a very small volume of the reservoir. As a result, tracer breakthrough occurs rapidly and is distributed over a very short time interval. On the other hand, the entire volume of the reservoir is swept by the tracer when a porous matrix representation is used. Thus the active porosity is a maximum, and the arrival of the tracer takes the longest time. Because flow is uniformly distributed over the reservoir, the distribution of arrival times is very clustered, and the breakthrough curve is fairly steep.

For the fracture network, an intermediate breakthrough curve is obtained. Some tracer arrives fairly rapidly, moving along the most direct discrete fracture pathway. Other tracer moves along less direct pathways and takes a longer time to arrive at the production well. Because of the wide distribution of flow rates in the many fracture flow paths, the distribution of tracer arrival times is very broad. Thus, simply using a matrix with a small porosity to represent fractures can distort the shape of the breakthrough curve.

Breakthrough curves are more similar for the three systems where a fracture connection between the injection and production wells was retained (Figure 4). Small differences exist due to the number of connecting paths and the replacement of discrete fracture pathways with permeable matrix. The general shape of the breakthrough curves is similar because most of the tracer still travels through the fracture system. The tail on the breakthrough curves for Systems 3 and 4, however, is much longer than the tail for System 5. This is because significant matrix permeability in Systems 3 and 4 results in tracer entering the matrix. Even though the matrix porosity is 10^{-4}, there is a significant increase in the residence time of tracer in the reservoir.

The increase in active porosity is shown by comparison of Figures 5a and 5b. These figures show the spatial distribution of tracer 10 days into the injection test. For System 5 (Figure 5a), the tracer has remained in the fractures and the matrix does not participate in the movement of tracer. Figure 5b shows the distribution of tracer for System 3, which has significant matrix permeability relative to System 5. In this case, tracer moves from the fractures through the matrix. This matrix increases the residence time of the tracer that travels by these paths.

The effect of fractures on channeling flow through the system can be seen in Figure 5b. Tracer is not uniformly distributed throughout the matrix, but is confined to matrix in a few areas between fractures. The rate of tracer movement is not dependent on the pore volume of the entire reservoir, but on the porosity of a fraction of the reservoir. This fraction of the reservoir which is actively involved in the transport of tracer is the active porosity.

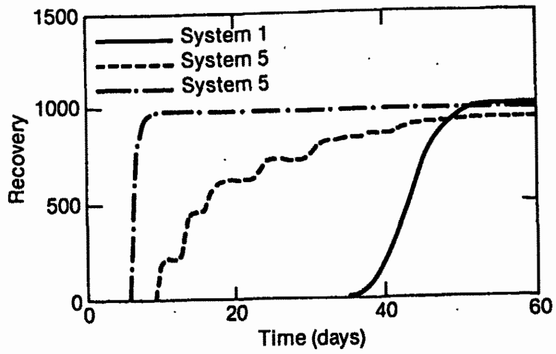


Figure 3. Tracer breakthrough curves for the single fracture, full fracture network, and the porous matrix representation of the geothermal reservoir. Recovery of 1000 particles injected as a pulse.

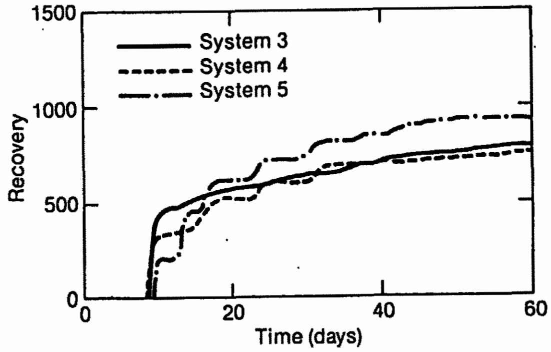


Figure 4. Tracer breakthrough curves for three fracture networks which retain a discrete fracture connection between the injection and production wells but which have different numbers of fractures and matrix conductivity.

The active porosity for this reservoir is on the order of 40% for tracer transport (Table 1).

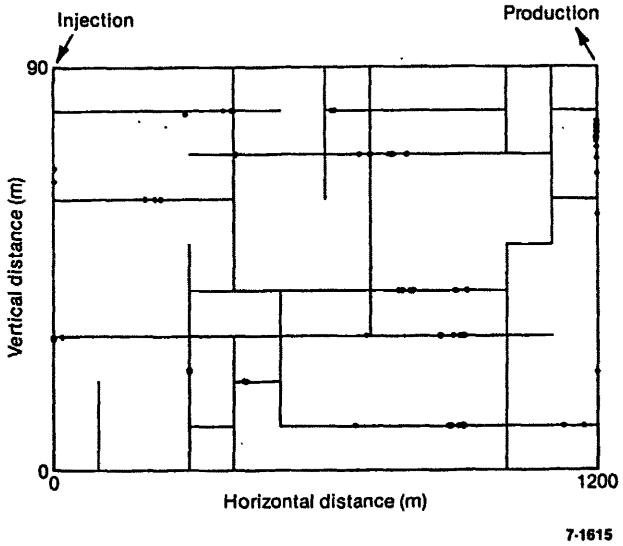
When fracture permeability was replaced with matrix permeability, the active porosity of that part of the system was increased. Based on the results from System 6, a single fracture has an active porosity 0.16 times the total porosity. As most matrix blocks represent replacement of a single fracture, using a matrix porosity of $1.0\text{X}10^{-4}$ may overestimate the active porosity by a factor of 6.25. System 2 was resimulated using a value of $0.16\text{X}10^{-4}$ for the matrix porosity to determine if the active porosity did a better job of emulating the full network. The active porosity for the entire reservoir, based on Systems 3, 4, and 5, is on the order of 40%. System 1 was resimulated using a porosity of

$0.4X10^{-4}$ to match the active porosity of the fracture networks.

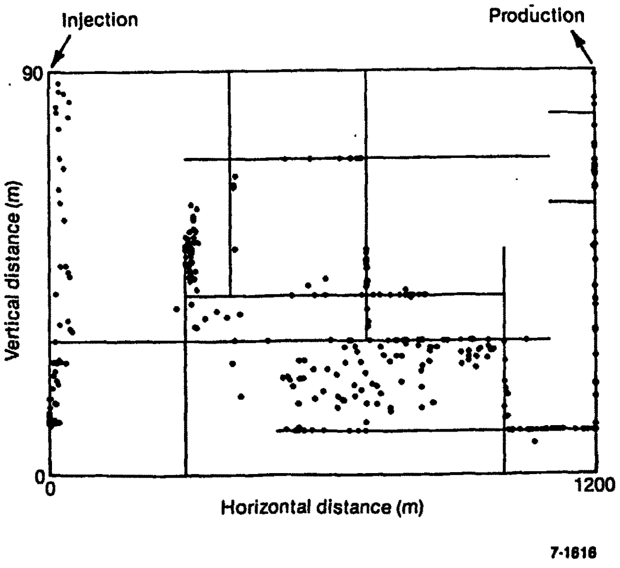
Figure 6 shows the effects of using the active porosity to simulate transport in the matrix rather than the total porosity. Using an active porosity of $0.16X10^{-4}$ in System 2 resulted in a significant improvement in matching the response of the full fracture network. Using an active porosity for the full matrix representation improved the match to the mean arrival time, but the breakthrough curve has the wrong shape. Critical information on the distribution of flow velocities is lost when all the fracture permeablitity is replaced with matrix permeability. When the major fractures are explicitly considered, sufficient information on the flow system remains to achieve a good match between the full fracture system ana a system where most of the fracture permeability has been replaced with matrix permeability.

Thermal Response

As used for these simulations, the code does not take into account the effects of density differences between fluids. Simple calculations indicate that density differences can induce presure differences as large or



a. System 5



b. System 3

Figure 5. Spatial distribution of tracer remaining in the reservoir after 10 days.

larger than those developed for flow alone. Therefore, the results presented here are more applicable to the phenomenon of heat conduction from fractures to matrix than for reservoir scale transport.

The time required for the system to respond thermally is much greater than the time required for the system to respond to tracer injection (Figure 7). This difference is attributable to two differences between tracer and heat. Diffusion of tracer into the matrix is dependent on the open porosity of the the matrix and the diffusion coefficient of the tracer. Both these numbers are relatively small. The diffusion of heat into the matrix (conduction) is dependent on the heat capacity of the matrix and the thermal diffusivity of the rock. These numbers combine to give a difference between tracer diffusion and thermal conduction on the order of three orders of magnitude.

Figure 8 shows the position of the thermal front in the reservoir 2000 days after injection began. The large difference between the advance of the thermal and tracer fronts can be seen by comparing Figures 5a and 8. On one hand, there is much more interaction between the fractures and matrix with the matrix around the fractures cooling off. Thus the matrix immediately surrounding the fractures is more involved in advance of the thermal front than of the tracer front. On the other hand, the thermal front generally follows the active fractures, rather that sweeping the heat from the entire reservoir. Thus, the information on active porosity will provide at least qualitative information on the active porosity of the system for prediction of thermal breakthrough.

For the porous matrix representation of the reservoir, the thermal front moves very slowly across the reservoir extracting heat from the entire volume of the reservior. The porous media approach to prediction of of thermal breakthrough would greatly overestimate the breakthrough time.

CONCLUSIONS

Simulations were conducted of six representations of a geothermal reservoir. The systems differed with respect to the number of fractures, the connectivity of the fracture system, and the permeability of the matrix material. Steady-state pressure response and tracer breakthrough were calculated for each of the systems. Very good agreement was obtained between dual-permeability representations of the fracture network and the network itself when active porosity was used in the matrix elements and the most significant discrete fractures were explicitly simulated.

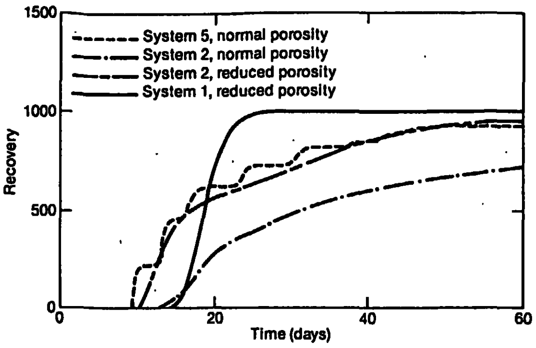


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Figure 6. Effect on tracer breakthrough of adjusting matrix porosity to match active porosity estimates.

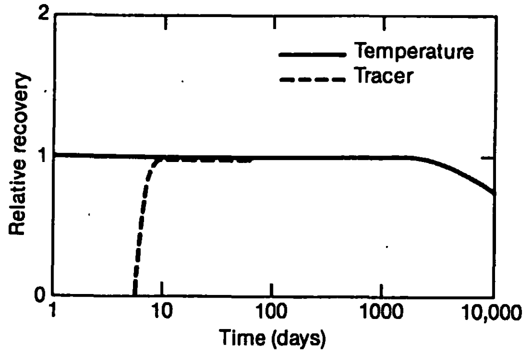

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Figure 7. Comparison of tracer and thermal breakthrough for System 6, a single fracture connecting the injection and production wells.

Thermal response of the single fracture, the complete fracture system, and the porous medium systems showed that the active porosity concept is also important for heat transport. Conduction of heat away from the fractures results in a greater volume of the reservoir participating in heat transfer than in tracer transport. However, the effects of channeling along the major fracture pathways was still evident.

ACKNOWLEDGEMENTS

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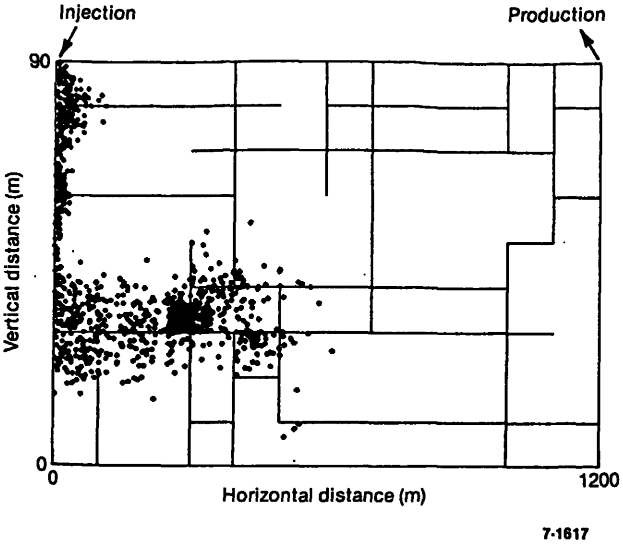

Figure 8. Spatial distribution of the cooling front in the geothermal reservoir 2000 days after the beginning of injection.

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