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PHYSICAL MODEL OF A FRACTURED RESERVOIR

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ABSTRACT

The objectives of the physical modeling effort are to: (1) evaluate injection-backflow testing for fractured reservoirs under conditions of known reservoir parameters (porosity, fracture width, etc.); (2) study the mechanisms controlling solute transport in fracture systems; and (3) provide data for validation of numerical models that explicitly simulate solute migration in fracture systems. The fracture network is 0.57-m wide, 1.7-m long, and consists of two sets of fractures at right angles to one another with a fracture spacing of 10.2 cm. A series of injection-backflow tests, similar to those performed at the Raft River Geothermal field, was conducted. These included variable volume injection and injection-backflow tests with varying quiescent periods between injection and backflow. This latter series of tests was conducted with a range of flow fields passing through the model. Tracer recovery is related to the flow field in the physical model and model parameters. Longer quiescent times and greater flow fields result in a lower tracer recovery. A plot of the fractional tracer recovery against quiescent time results in a straight line. This relationship, combined with classical reservoir engineering data, can be used to predict aquifer flow rate and porosity from known injection volumes and tracer recovery.

INTRODUCTION

Injection of spent geothermal fluids for environmental purposes or to maintain reservoir pressures can also have the detrimental effect of lowering the enthalpy of production fluids. In fields, such as Wairakei in New Zealand and Kakkonda and Hatchobaru in Japan, interconnection between injection and production wells appears to be along highly transmissive fractures (Fossum and Horne, 1982; Horne, 1982). Rapid breakthrough of injected fluids at production wells has resulted in significant enthalpy declines and required modifications in field operations. Such situations, where interwell travel times are on the order of days, can readily be studied using tracer tests between wells.

As travel times between wells become longer, the increased residence time permits greater thermal equilibration between injected fluids and reservoir rock. However, enthalpy loss can still occur after several years of plant operation, such as at Onikobe and Otake in Japan (Horne, 1982). It is important to be able to predict such effects in advance. Where residence times in the reservoir are on the order of several months or more, interwell tracer tests may not be feasible. Single-well tracer tests, combined with traditional reservoir assessment methods, can provide information on flow rates and reservoir porosity that can be used to predict future thermal breakthrough.

Methodology for interpretation of interwell tracer tests is well established (Lenda and Zuber, 1970; Grove and Beeten, 1971; Vetter and Zinnow, 1981). Single-well injection-backflow tests have been used to study the dispersion and adsorption characteristics of porous media reservoirs (Sternau et al., 1966; Drever and McKee, 1980; Pickens et al., 1981). Recently, methods have been developed to study interwell tracer tests in fractured reservoirs where well connections are along one or a few major fractures (Fossum and Horne, 1982; Horne and Rodriguez, 1983). Ground-water flow rates can be measured in a borehole using tracer injection techniques; however this flow rate could be very misleading in a fractured reservoir. This paper discusses a method for determining reservoir flow rate and porosity for a finite volume of reservoir and demonstrates its effectiveness using data collected from a laboratory-scale physical model of a fracture network.

METHOD DEVELOPMENT

For injection into a confined geothermal aquifer or into a planar fracture zone, the plume of injected fluid moves out radially from the injection well (Figure 1). If the well is shut in after the plume has been injected, the flow field will begin to carry the plume away from the well. When the well is pumped, after a quiescent time, not all of the initially-injected fluid is recovered after an equal volume has been pumped from

the well. The fraction of the fluid recovered is represented in Figure 1 by the shaded area where the two circles overlap. The fractional recovery is given by:

$$F = \frac{A_o}{A_T} \qquad (1)$$

where

F = fractional tracer recovery

A_o = area of overlap

$$= 2[R^2 \cos^{-1}(d/R) - d(R^2 - d^2)^{1/2}] \qquad (2)$$

A_T = area of injected plume

$$= \pi R^2 \qquad (3)$$

Replacing A_o and A_T in Equation 1 by Equations 2 and 3 and simplifying gives:

$$F = \frac{2}{\pi}\left(\cos^{-1}\xi - \xi(1-\xi^2)^{1/2}\right)$$

where

$$\xi = d/R. \qquad (5)$$

The relation between ξ and F is not linear over the entire range of ξ from 0 to 1. However, for the range $0 < \xi < 0.6$, the relation between ξ and F is well described by the equation:

$$\xi = 0.825(1-F). \qquad (6)$$

Lateral displacement of the plume is 2d and equals:

$$2d = vt_q \qquad (7)$$

where

v = flow-field velocity

t_q = quiescent time.

The radius of the injection plume is proportional to the volume of water injected,

$$R = \left(\frac{V}{\pi h\Theta}\right)^{1/2} \qquad (8)$$

where

V = volume of water injected

h = aquifer or fracture zone thickness

Θ = porosity.

Fractional recovery can be related to reservoir parameters by combining Equations 5, 6, 7, and 8 to give:

$$(1-F) = 0.605\, v\left(\frac{V}{\pi h\Theta}\right)^{-1/2} t_q. \qquad (9)$$

By conducting a series of equal volume injection-backflow tracer tests with various quiescent times, a linear relation should be described between fractional tracer recovery and quiescent time. The slope of the relation is proportional to flow-field velocity and reservoir porosity.

Equation 9, unfortunately, still contains two unknowns, porosity and flow-field velocity. However, combining data collected from injection-backflow tests with traditional reservoir engineering data provides sufficient information for identification of both unknowns.

From geophysical logs, the thickness of the aquifer or fracture zone (h) can be estimated. Pump tests can then provide the hydraulic conductivity of the formation. If the hydraulic gradient of the reservoir in the vicinity of the well can be estimated, then the specific discharge can be calculated from Darcy's Law.

$$q = -KI \qquad (10)$$

where

q = $v\Theta$ = specific discharge

K = hydraulic conductivity

I = hydraulic gradient.

This gives two equations and two unknowns, and a unique solution for reservoir flow-field velocity and porosity can then be determined.

Two factors will complicate the use of the above outlined procedure and limit the conditions under which Equation 9 can be used. In the presence of a flow field, the injected plume will become distorted, with the distance to the upstream edge of the plume being shorter than the distance to the downstream edge. This will decrease the quantity of tracer recovery. This effect can be minimized by injecting and backflowing at a rate that dominates the flow field in the reservoir.

Another factor affecting tracer recovery is dispersion at the boundary between the plume and the native reservoir fluid. Intermixing between the two fluids produces a gradual interface rather than the abrupt interface shown in Figure 1.

Equation 9 may be easily used if its relative simplicity is retained. Including the effects of tracer dispersion and distortion of the plume by the flow field would add

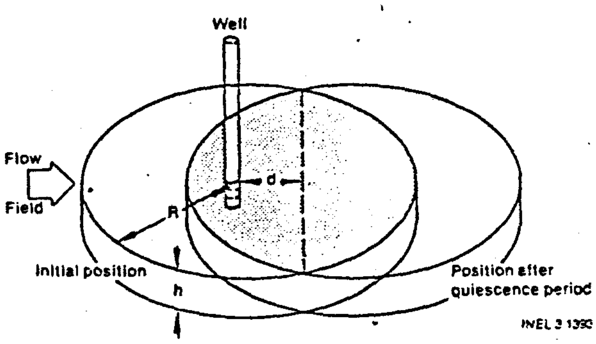

Figure 1. Schematic showing movement of an injected plume due to a flow field in the reservoir.

complexity and decrease reliability by adding additional unknown parameters. The effects of plume movement and tracer dispersion during injection and backflow can be quantified by conducting a test with no quiescent period. Effects of dispersion and movement of the plume during injection and backflow can be accounted for if tracer recovery during this no-quiescence test is used as the basis for calculating fractional recovery rather than the original quantity of tracer injected. All tests, therefore, must be of equal volume and equal injection-backflow rates. Not accounted for, is the dispersion of tracer as it moves under the influence of the flow field during quiescence. This latter factor is of secondary importance unless flow-field velocities are quite high.

PHYSICAL MODEL

To test this reservoir evaluation method, data were collected from a laboratory-scale fracture network. Injection-backflow tests were conducted at constant rate and volume in a simulated fracture network. The series of tests was carried out for a range of quiescent times for each of three different flow fields. This provided data to be compared to theory under circumstances where all reservoir parameters were known.

Description of Physical Model

The fracture network was built by cutting orthogonal fractures 0.32-cm wide and 1.91-cm deep into a 2.54-cm thick sheet of plexiglass (Figure 2). Fracture spacing is 10.16 cm, and fractures intersect the boundaries at 45 degrees. All fractures have uniform aperture and spacing. Plexiglass was selected as the material for model construction to allow for visual observation of tracer movement and because the matrix material is impermeable. Flow is evenly distributed to fractures at the inlet and collected from fractures at the outlet by manifolds. Piezometers and conductance probes are installed at various locations throughout the model to measure hydraulic gradients and tracer concentrations, respectively.

The flow field in the model is controlled by head loss between two constant head reservoirs and measured with a flow meter. Reservoir fluid is distilled water, dyed yellow, with a specific conductance of 10 μs. Injection is controlled by a syringe pump, and backflow by a third constant-head reservoir and a second flow meter. The injected fluid is a dilute sodium chloride solution, dyed blue, with a conductance of about 60 μs.

Conductance electrodes embedded in the fractures measure the breakthrough curves for the injected sodium chloride solution. A computerized data acquisition system allows point measurements of conductance to be made within a few seconds of each other. Data are recorded on a Hewlett-Packard 1000 computer and stored on magnetic tapes that can be transferred to the Cyber 176 computer for analysis.

Model Testing

Hydrologic testing was performed to determine the hydraulic conductivity of the model. Injection-backflow testing was performed to obtain time variations in tracer concentration data. A series of tests with variable quiescent periods was run to determine if reservoir flow velocity and porosity could be determined by the method outlined previously.

The hydraulic conductivity of the model was determined to be 25.65 ± 2.73 cm/sec. Hydraulic conductivity for a set of parallel fractures is given by (Freeze and Cherry, 1979):

$$K = \frac{\gamma}{\mu} \frac{N(2b)^3}{12} \qquad (11)$$

γ = specific weight

μ = dynamic viscosity

N = fracture density

$2b$ = fracture aperture.

Equation 11 is also valid for two sets of fractures having equal apertures that meet at 90 degrees. The calculated hydraulic conductivity for the physical model is 28.46 cm/sec at 25°C. There is an additional head loss of about 10% in the model over that predicted by theory.

Five tests, each with a different quiescent period, were run with three different flow-field velocities in the physical model (Table 1). Results from the test series conducted at a flow field of 1.57 cm/min are shown in Figure 3. For an injected volume of

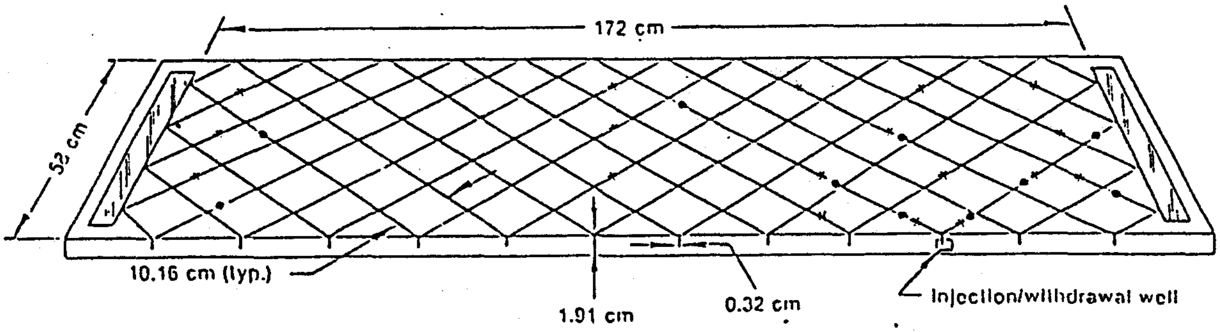

Figure 2. Fracture network used for variable quiescent time injection-backflow tests. Flow field is from right to left.

TABLE 1. QUIESCENCE TESTING SUMMARY

Injected Volume (cm^3)	Flow Field (cm/min)	Quiescent Times (min)	Injection-Backflow Rate (cm^3/min)
120	0.77	0, 1, 7, 15, 19	20
120	1.57	0, 3, 6, 10, 14	20
120	4.35	0, 1, 3, 3.33, 5	20

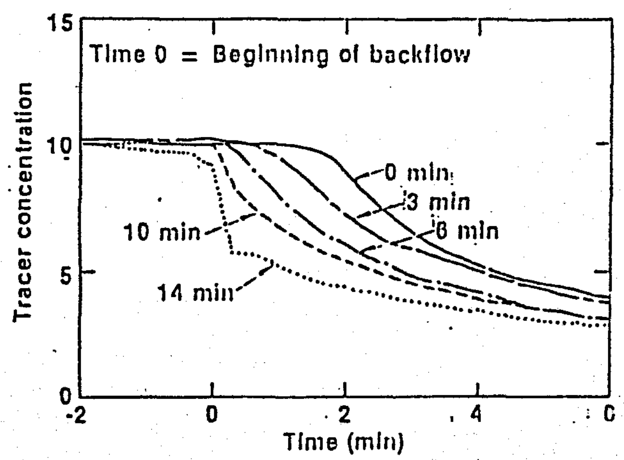

Figure 3. Tracer recovery curves at the injection-backflow port for different quiescent times. Reservoir flow field is 1.57 cm/min. Time = 0 refers to the beginning of backflow.

120 cm^3, the radius of the plume is 25 cm. With a flow field of 1.57 cm/min, it takes 16 min for the plume to move away from the injection well. From Figure 3, it can be seen that as quiescent time increases, the concentration curve drops off more rapidly. At a quiescent time of 14 min, the dropoff is immediate, indicating that the plume has already moved past the injection-withdrawal port. This difference is due to distortion of the injected plume by the flow field.

Because the curves drop off more rapidly with increasing quiescent times, fractional tracer recovery decreases. Tracer recovery was determined by integrating the area under the normalized tracer breakthrough curves. The zero quiescent-time curve was defined equal to 100%, and fractional recoveries calculated relative to that value.

Data collected from the physical model are plotted in Figure 4, along with predicted relations based on Equation 9 using known model parameters. To determine how well the data fit the model, linear regression was used to determine the best fit slope for the three sets of data points. A velocity was calculated from the best fit slopes and compared to the known flow-field velocities. The discrepancy between calculated velocities and known flow-field velocities is +30% for 4.35 cm/min and +20% for 1.57 cm/min. There is no significant difference between known and calculated velocities for 0.77 cm/min.

One of the assumptions upon which the derivation of Equation 9 is based is that the injection plume will be roughly circular. That is, the distortion caused by the presence of the flow field will be minor. This was not the case for the physical model tests with flow fields of 1.57 and 4.35 cm/min. The head change at the injection port is on the order of 2×10^{-2} cm. The head loss across the model for flow fields of 4.35, 1.56, and 0.77 cm/min is 3.1×10^{-2}, 2.0×10^{-2}, and 0.5×10^{-2} cm. Therefore, at the two higher flow rates, the injection plume is significantly distorted during injection. The successful application of the method, therefore, depends on dominating the reservoir hydraulic gradient with the cone of impression (depression) during injection (backflow).

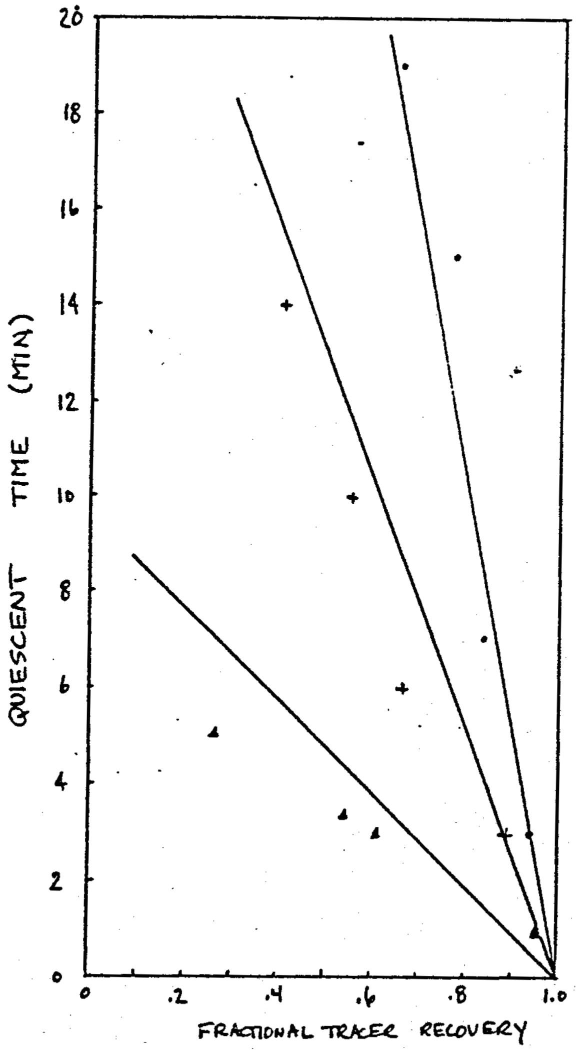

Figure 4. Predicted and measured relations between fractional tracer recovery and quiescent time for three flow-field velocities.

CONCLUSIONS

Single well injection-backflow tests using tracer solutions can provide valuable reservoir information when interwell tracer tests are not feasible. A method for determining reservoir flow-field velocity and porosity has been developed and tested against data collected from a laboratory-scale physical model. Agreement between measured and predicted values is excellent when the injection-backflow rate is much larger than the reservoir flow field. When reservoir flow rate equals or exceeds the injection-backflow rate, reservoir flow velocities are overestimated and porosities underestimated.

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