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TRACER FLOW IN A FRACTURED GEOTHERMAL RESERVOIR MODEL

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ABSTRACT

Tracer injection for identifying reservoir and transport parameters in geothermal sources has become an important procedure for designing an optimum reinjection program. Field tests have been analyzed using convection-diffusion equation to predict fracture size, width and probable thermal breakthrough times. The present study was conducted in a laboratory fractured reservoir model whose physical properties were known. The tracer, KI, breakthrough profiles were analyzed for different injection-production depth schemes. For different patterns different preferential flow paths existed which were then affected by flow through auxiliary paths.

A correlation between heat and mass transport was used to define an apparent heat transfer coefficient for the flow.

INTRODUCTION

In many geothermal development programs, waste geothermal fluids are reinjected for the purposes of disposal and pressure maintenance. The known effects are improved or degraded thermal recovery depending on flow paths and velocities and pressure maintenance. Since these beneficial and harmful results have been observed, reservoir tests to detect and predict the behavior of injected water are desired. In this respect interwell tracer tests have made significant contributions to understand the behavior of reinjected cold water within the reservoir and to develop an optimum injection program to maximize energy production.

Mathematical models for tracer flow through a porous matrix(6), through a double porosity reservoir(4) and through fractures(1,2) have been discussed in literature. The properties of the medium, porosity, permeability and degree of heterogeneity affect the tracer breakthrough profile in a producing well, where tracer is injected from a nearby injection well. The properties of the tracer like its diffusion, dispersion and adsorption also characterize the concentration profile.

In this work a laboratory fractured reservoir model was used for tracer injection tests. In this model matrix blocks do not have any permeability so the flow is through fractures only, which were created between uniform matrix block surfaces.

TEST PROCEDURE

The test procedure and experimental set up were explained in Hosca and Okandan(3). The same procedure was followed with constant injection and production rates of 40 gr/min. Different flow paths were created by changing the injection production depth combinations designated as H_i/H_p with depths measured from the bottom of the model. KI at 4000 ppm concentration was injected as a slug and then displaced by water. The concentration of effluent was measured by an on line conductivitymeter. Cooling of the medium by the injected cold water was measured by 44 thermocouples present at different points in the model.

Tracer breakthrough profile was also obtained from a single fracture where the marble blocks (10x10 cm) were kept at 80°C (Fig.1) while KI solution was injected.

ANALYSIS OF DATA

The breakthrough concentration profile was analyzed using Sauty's hydrodispersive transport model(6). In this study the system of fractures were treated with porous medium concept. The diffusion and adsorption in matrix and in fractures were assumed to be zero. Then one-dimensional tracer mass transport equation given as equation 1 is used

$$\frac{\partial c}{\partial t} + V\frac{\partial c}{\partial x} = \mathcal{D}_L \frac{\partial^2 c}{\partial x^2} \qquad (1)$$

for slug injection at the inner boundary

$$c(x,o) = M/\phi_f \cdot \delta_x \qquad (2)$$

where Dirac Impulse of mass M per unit of model pore volume was applied. With the semiinfinite boundary assumption

$$c(\pm \infty, t) = 0 \quad (3)$$

the solution of equation 1 is[6],

$$C_R = \frac{K}{t_r^{1/2}} \exp\left(-\frac{Pe}{4t_R}(1-t_R)^2\right) \quad (4)$$

where

$$K = (t_{R_{max}})^{1/2} \exp\left(\frac{Pe}{4t_{R_{max}}}(1-t_{R_{max}})^2\right) \quad (5)$$

with

$$t_{R_{max}} = (1+Pe^{-2})^{1/2} - Pe^{-1} \quad (6)$$

and

$$C_R = C/C_{max} \quad (7)$$

For tracer reaching the outflow end apparent Peclet number is

$$Pe = \frac{\nu_B L}{\mathcal{D}_L} \quad (8)$$

and

$$t_R = \frac{\nu_B \cdot t}{L}$$

where ν_B is the darcy velocity, $\mathcal{D}_L$ apparent dispersion coefficient of the medium and L is the distance between injection and production points.

The concentration profiles for different injection production depth combinations were compared with the analytical curves obtained using equations 4-7 for different Peclet numbers and the time when maximum concentration is obtained. The Peclet number and residence time t_R which gave the best fit were then used to calculate, fracture permeability, block size and fracture width and dispersivity in the medium.

The first arrival time of tracer at the producing end indicated the shortest path of flow which will also be the preferential route for cold water. So these first arrival times were used to calculate thermal breakthrough time using

$$t_{BT} = \left[\frac{\phi_f}{3}\right]\left[\frac{\pi h L^2}{b.a.\nu}\right]\left[\frac{(1-\phi_f)\rho_r C_r + \phi_f \rho_w C_w}{\phi_f \rho_w C_w}\right] \quad (10)$$

where h is the thickness of the bed, b fracture opening, a block size (fracture spacing), ν velocity in the preferential path.

A mass transport-heat transport correlation proposed by Sieder and Tate[7] as

$$Nu_m = 1.86\left(Re.Pr.\frac{b}{L}\right)^{0.33} \quad (11)$$

was used with the assumption that there is no variaton in physical properties of water within the fracture. An average effective heat transfer coefficient, h_m for the flow medium was obtained using equation 11 and Pe=Re Pr

$$h_m = 1.86\left(Pe \cdot \frac{D}{L}\right)^{0.33} \frac{K_f}{L} \quad (12)$$

where K_f is the thermal conductivity of fluid and D hydraulic diameter of the rectangular conduit.

ANALYSIS OF DATA AND DISCUSSION

Tracer breakthrough profiles obtained for different injection-production depth combinations indicated flow paths differed in each case. (Fig.2-5) Experimental data from conductivity measurements were also checked by colorimetric analysis .

The fluctuations indicated secondary fracture flow paths which fed the main flow route. The match between the analytical model and the experimental data was acceptable. The model was not sufficient to model the tailing end of the breakthrough profile because of heterogeneities in flow.

Table 1 gives the parameters calculated using the Peclet numbers and residence times obtained from the analytical model and laboratory model.

Although the residence time of tracer slug for injection from bottom and production from top (H_i/H_p = 0.25/0.75) was similar to that of injection from top and production from bottom configuration, the difference in Peclet number and first arrival times indicated the flow pattern to be different.

Table 1. Peclet Numbers and Residence Time for Different Injection-Production Depths

H_i/H_p	Pe	Dispersion Coeff. $\mathcal{D}_L$ (cm^2/min)	Dispersivity $\mathcal{D}_L/V_B$ (cm)	First Arr. Time (min)	Res. Time (min)	Darcy Velocity in preferen.path, ν (cm/min)	Darcy velocity of the bulk; ν_B (cm/min)
0.75/0.25	10.5	11.5	8.1	10	60	8.5	1.42
0.25/0.75	19.5	6.0	4.4	20	62	4.3	1.37
0.75/0.75	3.75	22.2	22.7	6	87	14.2	0.98
0.25/0.25	15.0	6.2	5.7	9	77.5	9.4	1.10

The permeabilities of these flow paths were calculated using darcy equation. A simple two dimensional flow model around cubical blocks, [4] was used to estimate effective fracture size and fracture spacing in the preferential path (Table 2).

Table 2. Calculated Values of Fracture Size and Fracture Spacing in the preferential path

H_i/H_p	kf (darcy)	Frac.Size,b, (mm)	Frac.Spacing,a (cm)
0.75/0.25	30.5	1.16	8.7
0.25/0.75	15.3	0.82	6.2
0.75/0.75	50.8	1.50	11.3
0.25/0.25	33.9	1.22	9.2

The values calculated for fracture spacing were comparable with 10x10 cm of the marble block dimensions.

The thermal breakthrough times were estimated from calculated values of fracture size b, fracture spacing a and darcian velocity along the preferential path. Early breakthrough will be observed in H_i/H_p of 0.75/0.75 which indicated the shortest path for cold water (Table 3).

Effective heat transfer coefficients for each flow pattern was calculated from the correlation given in equation 12. Injection of cold water at deeper points was more preferable in terms of heat efficiency of reinjection.

Table 3. Effective Heat Transfer Coefficient During Cold Water Injection

H_i/H_p	b,cm	h_m ($W/m^2\ {}^oC$)	Thermal BT time (min)
0.75/0.75	0.116	0.43	$13.5x10^4$
0.25/0.75	0.082	0.47	$27.8x10^4$
0.75/0.75	0.150	0.33	$12.3x10^4$
0.25/0.25	0.122	0.49	$15.7x10^4$

CONCLUSION

A laboratory model study was conducted for interpretation of tracer breakthrough profile in a fractured geothermal system whose properties were known.

The analytical model used to fit the experimental data had made it possible to predict apparent Peclet numbers and residence times of flow.

Changes in the depths of injection and production points resulted in different flow paths, which was also reflected in the dispersivities calculated from apparent Peclet numbers.

The fracture size and spacing calculated from experimental results were similar to the block dimensions in the model.

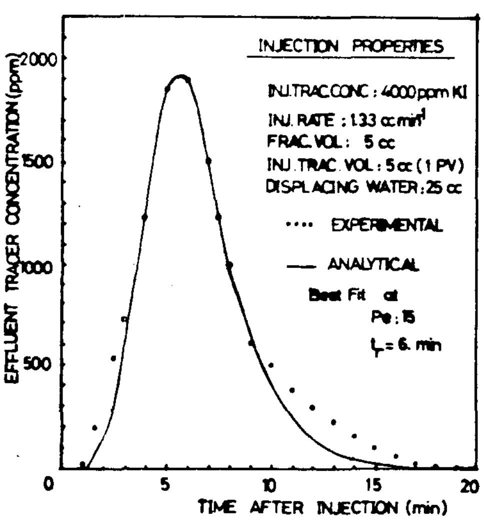

Figure 1. Tracer Breakthrough Profile in a Single Horizantal Fracture

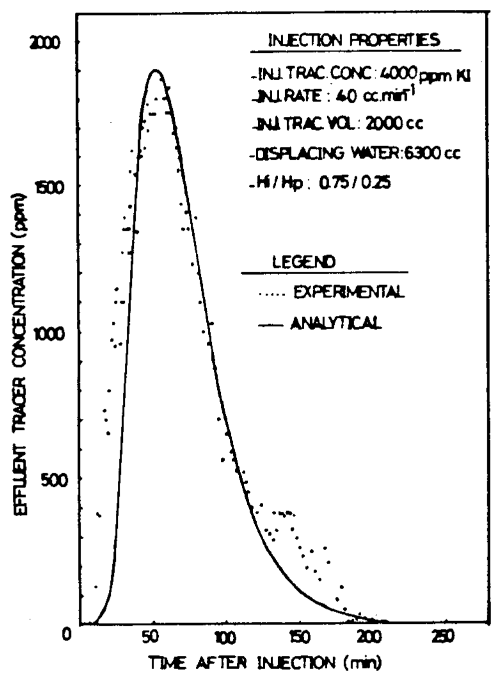

Figure 2. Tracer Concentration Profile at the Producing end for H_i/H_p of 0.75/0.25

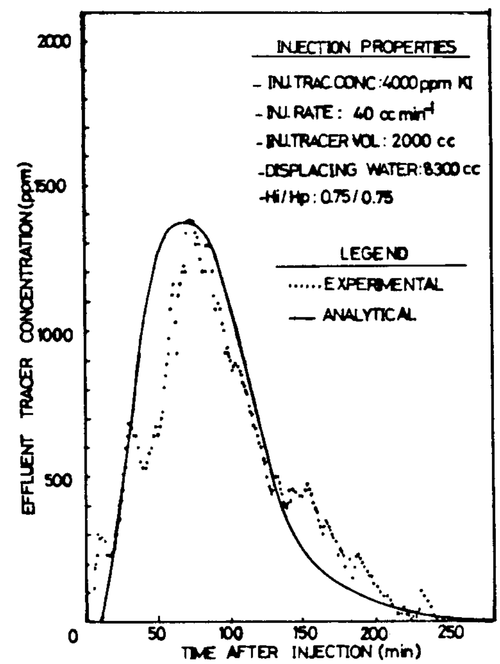

Figure 4. Tracer Concertration Profile at the Producing end for H_i/H_p of 0.75/0.75

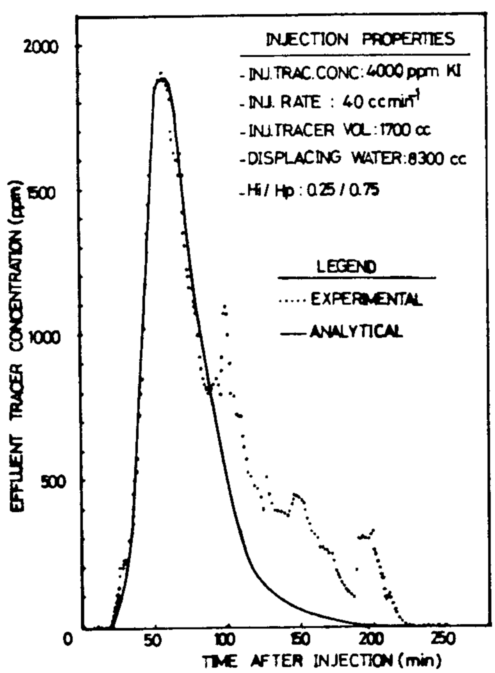

Figure 3. Tracer Concentration Profile at the Producing end for H_i/H_p of 0.25/0.75

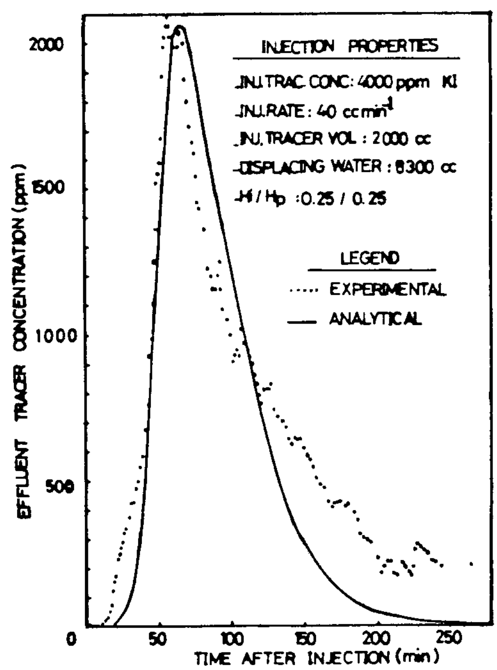

Figure 5. Tracer Concentration Profile at the Producing end for H_i/H_p of 0.25/0.25

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