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Dispersion of Tracers in Fractyres - Experiments at Stanford University

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1: INTRODUCTION

Although reinjection can help to maintain reservoir pressure and fluid volume, in some cases a decrease in reservoir productivity has been observed (Horne, 1982). This is caused by rapid flow of the reinjected water through fractures connecting the injector and producers. As a result, the water is not sufficiently heated by the reservoir rock, and a reduction in enthalpy of the produced fluids is seen.

Tracer tests have proven to be valuable to reservoir engineers for the design of a successful reinjection program. By injecting a slug of tracer and studying the discharge of surrounding producing wells, an understanding of the fracture network within a reservoir can be provided.

In order to quantify the results of a tracer test, a model that accurately describes the mechanisms of tracer transport is necessary. One such mechanism, dispersion, is like a smearing out of a tracer concentration due to the velocity gradients over the cross section of flow. If a dispersion coefficient can be determined from tracer test data, the fracture width can be estimated.

The purpose of this project was to study the dispersion of a chemical tracer in flow through a fracture. To this end, an experimental apparatus was designed and constructed in 1984 (Gilardi, 1984), and early experiments showed that Taylor dispersion could accurately describe the mechanism of tracer transport through fractures. During 1985, the apparatus has been modified to measure tracer concentration at a greater number of points and with greater precision.

2: BACKGROUND

The effects of water reinjection in geothermal systems worldwide is discussed in a paper by Horne(1985), which also includes a summary of tracer testing procedures and results.

In order to derive a model to accurately describe the transport of tracer through a fracture, the physics of dispersion must be understood. Taylor(1953) presented a classic study of dispersion in flow through a capillary tube. He showed that convective dispersion combines with transverse molecular diffusion in what we now know as "Taylor Dispersion". He showed that the tracer concentration is dispersed symmetrically about a plane that moves with the mean flow velocity. Taylor presents the equation governing the effective longitudinal dispersion:

$$\eta \frac{\partial^2 C}{\partial z^2} = \frac{\partial C}{\partial t} \tag{1}$$

where,

C = concentration

z = translated distance = $x-ut$

x = distance

t = time

u = mean velocity of flow

η = net longitudinal dispersivity (derived for pipe flow in Taylor's model)

The solutions to Eq. (1) for different initial and boundary conditions can be found in Carslaw and Jaeger(1959). For a step input,

$$C = C_o + \frac{1}{2}(C_1 - C_o)\left[erfc\left[\frac{x-ut}{2(\eta t)^{1/2}}\right] + \exp^{\frac{ux}{\eta}} erfc\left[\frac{x+ut}{2(\eta t)^{1/2}}\right]\right] \tag{2}$$

where,

C_o = base concentration

C_1 = injected concentration

C = concentration at x

erfc = complimentary error function

Home and Rodriguez(1983) used a method similar to Taylor's to derive an expression for the net longitudinal dispersivity, η, for flow in a fracture:

$$\eta = \frac{2}{105}\frac{b^2u^2}{D} \tag{3}$$

where,

b = fracture half-width

u = mean flow velocity

D = coefficient of molecular diffusion

They also showed that, due to the effects of transverse molecular diffusion, any concentration gradients across the fracture would be equalized after a non-dimensional time, $t_D = 0.5$, where

$$t_D = \frac{D}{b^2}t \tag{4}$$

Fossum and Horne(1982) show how the subroutine VARPRO can be used to determine both linear and non-linear parameters from a set of experimental data. VARPRO uses a non-linear least squares method of curve fitting." Fossum and Horne(1982) matched the calculated response to field data from tracer tests at Wairakei field, and inferred the fracture half-width from the estimate of η using Equation (3).

The present study set out to examine and confirm the applicability of Equation (3), which is only approximate, and to initiate broader investigations into dispersion in fractures. To these ends, an experimental program was undertaken.

The results of several experiments to study dispersion were found in the literature. Bear(1961) performed both one- and two-dimensional studies of dispersion through porous media and produced results which agreed with his theory. Hull and Koslow(1982) present the results of a study of dispersion in a network of channels.

3: DESIGN

The design objectives were aimed at building an apparatus capable of studying dispersion through a fracture in both one- and two-dimensions. The possibility of testing both chemical and fluorescent tracers was another requirement.

The size of the model fracture, particularly its aperture, was constrained by the results of Horne and Rodriguez (1983). Any concentration gradient across the width of the fracture will be equalized after a non-dimensional time, $t_D = 0.5$. The real time it takes to become equalized is proportional to the square of the fracture half-width:

$$t = \frac{0.5\, b^2}{D} \tag{5}$$

Using a diffusion coefficient for potassium iodide $(KI) \simeq 2x10^{-9} m^2$ /sec and a fracture half-width of 0.25 mm, the time required is about 16 sec. By using an aperture of 0.54 mm and flowrates of approximately 50 cc/min we could keep the apparatus small enough to fit on a lab bench! The cell is 6 ft long by 1 ft wide. Fig. 1 shows an overall view of the design.

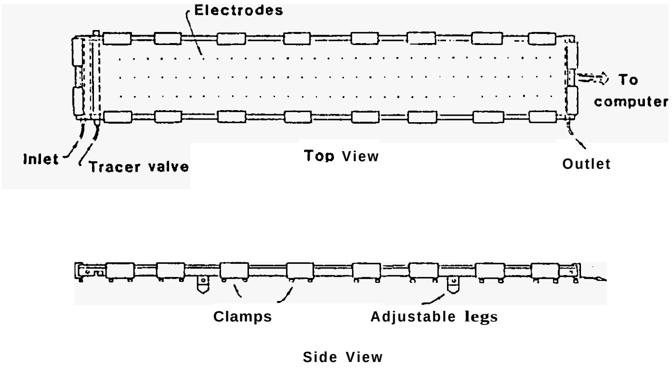

Figure 1: Experimental flow cell.

The lower plate is 1 in. thick cast aluminum alloy. It is hard anodized to prevent corrosion and provide a tough, non-conductive finish. The upper plate is 1/4 in. float glass and is separated from the aluminum by a gasket made up of three layers of plastic electrical tape. A series of aluminum clamps holds the cell together while four adjustable legs support it horizontally on the lab bench.

The inlet and outlet ports were implemented by drilling holes 11 in. through the width of the plate. A 0.25 in. slit was then sawed through the surface. Since the pressure drop across the length of the drilled hole is negligible compared with that across the slit, water will flow into the cell at uniform velocity over its width.

An on-off valve was designed to allow instantaneous initiation of tracer flow. The valve is activated by hand and can be locked in either on or off position.

In order to continuously monitor the tracer concentration as it flows through the cell, an array of 96 electrodes was employed. For a KI tracer the conductivity of solution will increase linearly with the log of concentration. Thus we are able to measure the tracer concentration at any electrode location and any chosen time.

The coaxial electrodes were constructed using brass conductive elements and a teflon insulator. The brass surfaces were electroplated with gold to prevent corrosion and polarization. Each electrode is press fit in to the aluminum plate and mounted flat to within .0015 in. The central electrode is connected to the data acquisition system, and the outer electrode is grounded to the plate.

In the original apparatus (Gilardi, 1984), an instantaneous current was flowed across each of the 32 electrodes lying along the centerline of the plate. The resulting voltage was measured in a bridge circuit, and the resistance of the electrode (which is a function of tracer concentration in the cell) determined by comparison with a fixed 100 kohm resistor. One of the purposes of redesigning the measurement side of the equipment was to be able to pass an alternating current through the electrodes (which was previously impossible due to the use of analog IC switches in the bank select multiplexer) and to measure a greater number of electrodes. The use of a direct current, even though it lasted less than 0.1 sec, was found to cause polarization of the electrodes and a resulting signal drift. Thus, the original analog-digital converter (Tecmar Labmaster board combined with a custom 32-channel multiplexer made at Stanford by Jawahar Barua) has been replaced by a Keithley/DAS Series 500 data acquisition system which contains its own 96-channel multiplexer on board. The data are received and processed by a Compaq personal computer (an IBM-PC compatible), and stored for later analysis and interpretation on the same computer. The data may also be transferred by network to the Department of Petroleum Engineering VAX 11/750 minicomputer for analysis, plotting etc. The data is displayed on the screen so it is possible to "watch" the tracer as it flows through the cell.

Two constant pressure reservoirs, one for the base concentration and one for the tracer, were constructed. The flowrate can be adjusted by changing the height of the center tube.

4: PROCEDURE

The following sections describe the experimental procedure followed:

I. Solution Preparation

(a) Prepare solutions of desired concentrations using distilled water and iodide standard. In the original apparatus, a base concentration of 175-200 ppm was used. Voltage readings from lower concentrations tended to be too unstable for accurate analysis. By injecting ~300 ppm the electrode response remains in the linear portion of the voltage vs. log concentration curve, thus simplifying analysis. Using the 1000 ml volumetric flask. the concentration is:

$$C(ppm) = \frac{(x)\ liter\ of\ iodide\ standard\ ^{*}\ 12690\ mg/l}{1\ liter}$$

(b) Clean reservoirs and fill with solution.

II. Assembly

(a) Wipe clean the aluminum and glass plates with wet sponge and assemble; clamps should be finger tight. In the original apparatus it was found that small distortions of the glass plate, caused by even moderate tightening of the clamps, resulted in non-uniform flow across the plate. In the modified apparatus, the glass plate has been stiffened with a metal framework bonded to the top surface.

(b) There is considerable difficulty preventing small bubbles of air from sticking to the plates and blocking the flow. As a first means of reducing this occurrence, flush the Hele-Shaw cell with CO_2 (at p <2 psi or glass may shatter).

(c) Begin flowing water slowly, making sure to clear both the inlet and tracer valve of air, otherwise bubbles will become trapped in the cell. (distilled water was flowed until the cell was void of all air bubbles to save the prepared solutions for test experimental runs.) Pounding on the glass with the butt of your hand, or tapping the glass with the rubber mallet while flowing at high rate can prevent the water front from fingering and forming air pockets.

(d) Now start flowing the solution of base concentration; allow 2 pore volumes (~ 500 cc) to flow before starting to SCAN (see next step).

III. Operation

(a) The computer software will measure and store the voltage at each electrode, once per second, and will fill the C (internal) diskette after about 7 min. The voltages will be plotted against the location of each electrode on the screen (they will vary for each electrode since each has different sensitivity). The scanning program will stop automatically after 7 min., or sooner if selected.

(b) Allow base concentration to flow for ~ 1 min. before injecting tracer. To inject, open gate valve, slide tracer valve into position and shut off inlet valve. Record time of injection.

(c) When run is over, the computer can plot the voltage vs. time for each electrode, individually. This is useful to examine whether all electrodes are functioning properly.

5: DATA PREPARATION

The processed data can be matched to the model given by Equation (2) to provide estimates of the mean speed of flow (u), and the effective dispersivity (η). A FORTRAN program, CURVEFIT, performs this operation, and simultaneously calibrates the measured voltages to concentrations.

6: RESULTS

Some typical results from CURVEFIT are displayed in Table 1, and are compared with the dispersivity predicted by Equation (3) in Figure 2. Graphs of the data collected from each electrode and the curve that fits it are presented in Figure 3. Since it was a one-dimensional study, only the central row of 32 electrodes was used.

The dimensions of the fracture were 179.1cm (length) by 24.46cm (width) by 0.0515cm (thickness). Since the glass plate used for these runs was slightly curved, the aperture was measured at the centerline.

The flowrate was measured by recording the time required to fill a 50 ml flask at the outlet. The time of injection, t_o, was only recorded for runs 8,9, and 10.

The velocities from CURVEFIT that best match the data are used in Equation (3) to provide an estimate of the dispersivity (η).

The dispersivities predicted by Equation (3) are compared with those estimated by CURVEFIT in Figure 1. Only selected electrodes are plotted, as some are inconsistent due to faulty data collection or transmission. Electrodes 1 and 2 were usually inconsistent, probably because the tracer front had not yet become equalized.

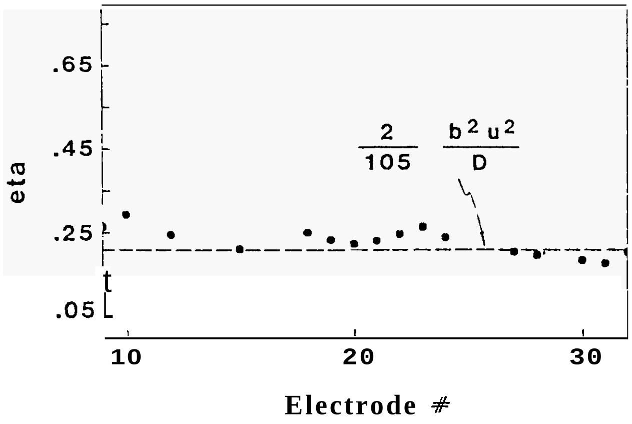

Figure 2: Comparison of estimated and calculated dispersivity.

Table 1. RUN 3 Results

lectrode	C_0 (ppm)	C_1 (ppm)	u (cm/sec)	η (cm^2/sec)	apparent I, (sec)
1	193.6091	305.1784	0.6992	1.0367	72.9238
2	201.2811	304.9338	0.6131	0.6220	72.6622
3	202.9373	305.0957	0.5908	0.4181	72.1451
4	200.0074	300.0581	0.5835	0.3585	72.6364
5	200.0959	300.0331	0.5846	0.2719	72.4763
6	202.9865	305.0680	0.5715	03113	72.3291
7	200.8080	449.3800	0.3034	2.8423	73.1011
8	199.9427	300.0960	0.5661	0 3005	73.4000
9	203.0065	305.0846	0.5711	0.2633	72.6024
10	203.0301	305.0725	0.5663	0.2030	72.8913
11	203.0107	305.1142	0.5647	0.3156	72.6204
12	200.0911	300.0483	0.5638	0.2449	73.4000
13	203.0176	305.1285	0.5593	0.2173	72.4066
14	203.0000	305.1503	0.5545	0.2358	73.1522
15	203.0166	305.1168	0.5543	0.2118	72.9312
16	203.0227	305.1229	0.5513	0.2623	72.9191
18	203.0147	305.1194	0.5498	0.2511	72.0139
19	203.0314	305.1045	0.5463	0.2341	72.6125
20	203.0683	305.1092	0.5455	0.2260	72.0204
21	203.0394	305.1175	0.5428	0.2326	72.6915
22	202.9910	305.1639	0.5442	0.2481	72.8799
23	202.9789	305.1957	0.5401	0.2652	72.8374
24	203.0310	305.1272	0.5410	0.2411	72.8148
25	202.9533	305.2214	0.5405	0.2708	72.2095
26	203.0517	305.1082	0.5406	0.1829	72.8609
27	203.0475	305.1186	0.5409	0.2078	72.5939
28	203.0491	305.1325	0.5416	0.1999	72.5580
29	203.0428	305.1451	0.5429	0.1909	72.8735
30	203.0459	305.1377	0.5435	0.1865	72.8586
31	203.0372	305.1767	0.5450	0.1787	72.3092
32	203.0167	305.2894	0.5471	0.2055	72.1761

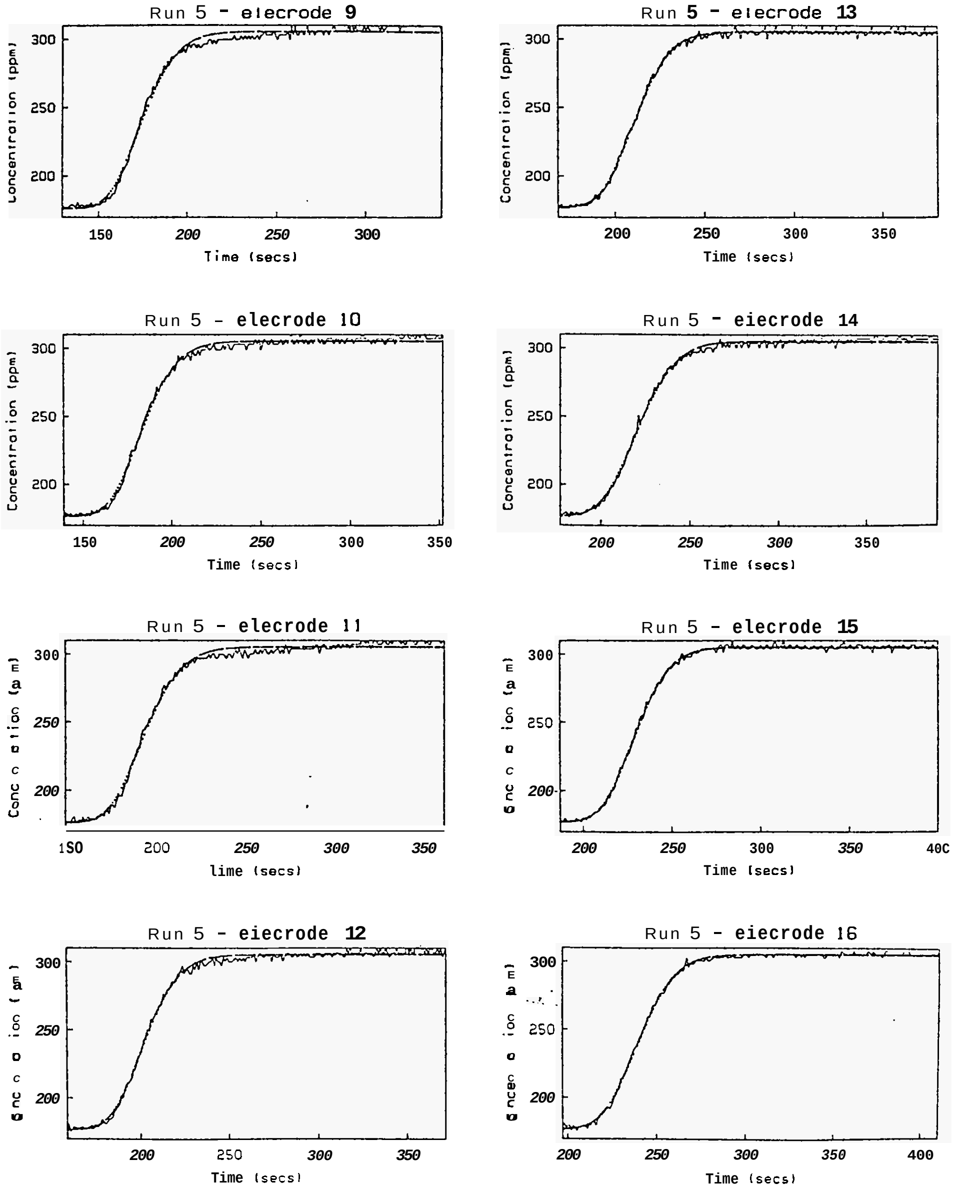

Figure 3: Typical electrode data cycles.

7: COKCLUSIONS

The flow of tracer through the fracture model was found to exactly duplicate the theory of Horne and Rodriguez (1983), at least in regard to the effective Taylor dispersivity for a fracture. Thus the applicability of both the theory and the apparatus have been confirmed.

Using the original setup, several difficulties were experienced during the experiments. These were distortion of the glass plate, and various inaccuracies in the measured tracer concentration. The apparatus has been modified to stiffen the glass plate, and the data acquisition system has been completely replaced. The new system allows for monitoring of all 96 electrodes on the plate, and permits an alternating current to be used in order to prevent polarization of the electrodes.

The next stage of study using this equipment will examine the effects of turbulence **and** transverse mixing.

8: ACKNOWLEDGEMENT

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9: REFERENCES

1. Bear, Jacob. *"**Dynamics of Fluids in Porous Media**"* , American Elsevier, New York, NY. 1972.
2. Bear, Jacob. "Some Experiments in Dispersion", *J.* **Geoph. *Res.*** ,Volume 66, no. 8. pp. 2455-2467.
3. Carslaw, **H.S.**& Jaeger, **J.C.** "*Conduction of **Heat in Solids"*** ,Oxford University Press, 2nd Ed., 1959.
4. Coats, K.H. "Dead End Pore Volume and Dispersion in Porous Media", ***Soc. Pet. Eng. Jour.*** , March 1964.
5. Davies, Cecil W. *"**The Conductivity** of Solutions"* , John Wiley & Sons, Inc., New **York.** 2nd Ed. 1933.
6. Fossum, M.P. ***"Tracer Analysis in a Fractured Geothermal Reservoir"*** , Masters Report, Stanford University, June 1982.
7. Fossum, M.P. and Horne, R.N. "Interpretation of Tracer Return Profiles at Wairakei Geothermal Field Using Fracture Analysis", Geoth. Res. Counc., ***Transaction 6*** , 1982.
8. Gilardi, J. "Experimental Determination of Tracer Dispersivity in Fractures", ***MS Report, Dept. of Petroleum Engineering, Stanford University, June 1984***. SGP-TR-72
9. Horne, R.N. "Geothermal Reinjection Experience in Japan" *J.* ***Pet. Technology* ,*34*** , 495-503, (1982).
10. Home, R.N. "Reservoir Engineering Aspects of Reinjection", *Geothermics* , July 1985.
11. Home, R.N. and Rodriguez, F. "Dispersion in Tracer Flow in Fractured Geothermal Systems", ***Geoph. Res. Let.*** , Vol. 10, no. 4, 289-292, 1983.
12. Hull, L.C. and Koslow, K.N. "Dispersion in Fracture Networks", ***Proc.*** , Eighth Wkshp Geoth. Res. Engr., Stanford University, Dec. 1982.
13. Taylor, Sir Geoffrey, F.R.S. "Dispersion of Soluble Matter Flowing Slowly Through a Tube", ***Proc.** Roy. Soc.* , A 219, pp 186-203, 1953.
14. VARPRO, Computer Science Dept., Stanford University.