

Experimental Determination of Tracer Dispersivity in Fractures

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1: INTRODUCTION

Reinjection of waste hot water is commonly practiced in most geothermal fields, primarily as a means of disposal. Surface discharge of these waste waters is usually unacceptable due to the resulting thermal and chemical pollution.

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 design and construct an apparatus to study the dispersion of a chemical tracer in flow through a fracture.

2 LITERATURE SURVEY

The effects of water reinjection in geothermal systems worldwide is discussed in a paper by Horne (1983), 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 velo-

city. Taylor presents the equation governing the effective longitudinal dispersion:

$$\eta \frac{\partial^2 C}{\partial z^2} = \frac{\partial C}{\partial t} \quad (1)$$

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

$$C = C_0 + \frac{1}{2}(C_1 - C_0) \left[\operatorname{erfc} \left(\frac{x - ut}{2(\eta t)^{1/2}} \right) + \exp \frac{uz}{\eta} \operatorname{erfc} \left(\frac{x + ut}{2(\eta t)^{1/2}} \right) \right] \quad (2)$$

where,

C_0 = base concentration

C_1 = injected concentration

C = concentration at x

erfc = complimentary error function

Horne 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:

$$\eta = \frac{2}{105} \frac{b^2 u^2}{D} \quad (3)$$

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, $t_D = 0.5$ (Fig. 2), where

$$t_D = \frac{D}{b^2} t \quad (4)$$

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.¹² 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(1981) 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

$$t = \frac{0.5 b^2}{D} \quad (5)$$

Using a diffusion coefficient for potassium iodide (KI) $\approx 2 \times 10^{-9} m^2$ /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.

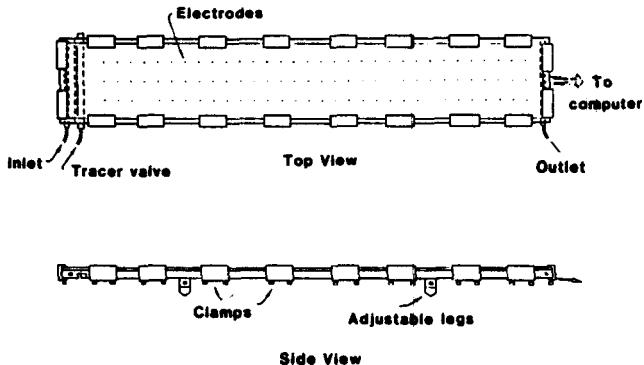


Figure 1. Hele - Shaw cell

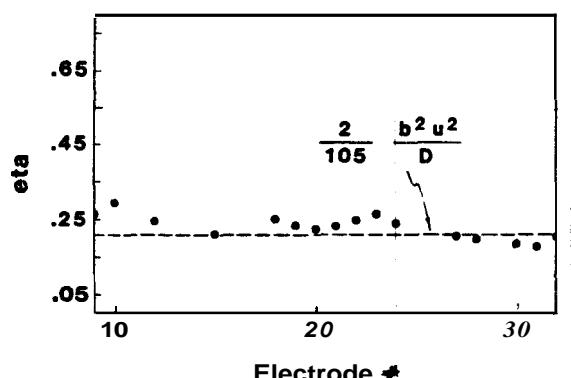


Figure 2. Comparison of estimated and calculated dispersivity. Run 3

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 aquisition system, and the outer electrode is grounded to the plate.

An instantaneous current is flowed across the electrode while the resulting voltage is measured (requiring less than 0.1 sec.). Voltages can be measured once each second and are stored in a Compaq personal computer. The data is displayed on the screen so it is possible to "watch" the tracer as it flows through the cell. The circuitry and electronics are described in Appendix A of Gilardi (1984), and the computer scanning algorithms are described in Appendix B of Gilardi (1984).

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

I. Solution Preparation

- (a) Prepare solutions of desired concentrations using distilled water and iodide standard. A base concentration of 175-200 ppm should be used. Voltage readings from lower concentrations tend 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:

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

- (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.
- (b) 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. Prepare computer for run

- (a) Switch on the multiplexor, then turn on the printer, then the computer.
- (b) When "clock" appears (~ 60 sec) hit <F10>.
- (c) Type b:
- (d) Remove system diskette from the A drive: replace with a blank diskette,

IV. Ready to run

- (a) To begin recording, enter SCAN. Note time. SCAN 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). SCAN will stop automatically after 7 min., or sooner if you hit <F1>.
- (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, enter FIXUP. FIXUP processes the data (~15 min) and stores it in a new file named labfix.dat on the A diskette.
- (d) Enter PLOTFIX. This plots the voltage vs. time for each electrode, individually.
- (e) Take diskette out and label it; these are your results.
- (f) To start a new run, insert a blank disc in the A drive, shut off the tracer, and flow the base concentration (~500 cc). Repeat steps 7-11.
- (g) After runs are finished, disassemble and wash down thoroughly. Unplug the multiplexor board, shut off computer and printer.

5: DATA PREPARATION

The processed data (labfix.dat) 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. The program is run as follows:

- (a) Copy labfix.dat from drive A to drive C (C must be erased first).
- (b) Create a file PARAMS on C as follows:
 1. $N =$ number of unknowns (12), [$=2$ (u and η), can be 3 if t_0 is unknown a\$ well].
 2. Initial estimates of u , η ; one per line (F10.4).
 3. Base concentration (C_0) and injected concentration (C_1); one per line (F10.4).
 4. Number of electrodes to be analyzed and electrode numbers (4012): e.g. 080104052122232932 will analyze 8 electrodes - 1,4,5,21,22,23,29 and 32.

- (c) Load a blank diskette in drive A
- (d) Type a:
- (e) Type b:curvefit
- (f) Type c: pararns <CR>, con <CR>, c:labfix.dat <CR>, prn <CR>.
- (g) The program will output a summary of estimated parameters on the printer, and will create output files (1.dat through 32.dat) on A. These may be used for plotting. The program takes several hours to run.
- (h) On completion, type b:plot, this will plot the results on the screen for a specified range of electrodes.

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_0 , 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.

7: CONCLUSIONS

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

Table 1. RUN 3 Results

Electrode	C_0 (ppm)	C_1 (ppm)	u (cm/sec)	η (cm 2 /sec)	apparent t_0 (sec)
1	193.6091	305.1784	0.6992	1.0367	72.9236
2	201.2811	304.9338	0.6131	0.6220	72.6622
3	202.9373	305.0957	0.5908	0.4181	72.1461
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	0.3113	72.3291
7	200.8080	449.3800	0.3034	2.8423	73.1011
8	199.9427	800.0960	0.5661	0.3005	73.4000
9	203.0065	305.0846	0.5711	0.2633	72.6024
10	203.0301	305.0726	0.5663	0.2930	72.8913
11	203.0107	305.1142	0.5647	0.3158	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	72.6916
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	0.6409	0.2078	72.5939
28	203.0491	305.1325	0.5416	0.1099	72.5580
29	203.0428	305.1451	0.5429	0.1009	72.8735
30	203.0459	305.1377	0.5435	0.1885	72.8586
31	203.0372	305.1767	0.5450	0.1787	72.3092
32	203.0167	305.2894	0.5471	0.2055	72.1761

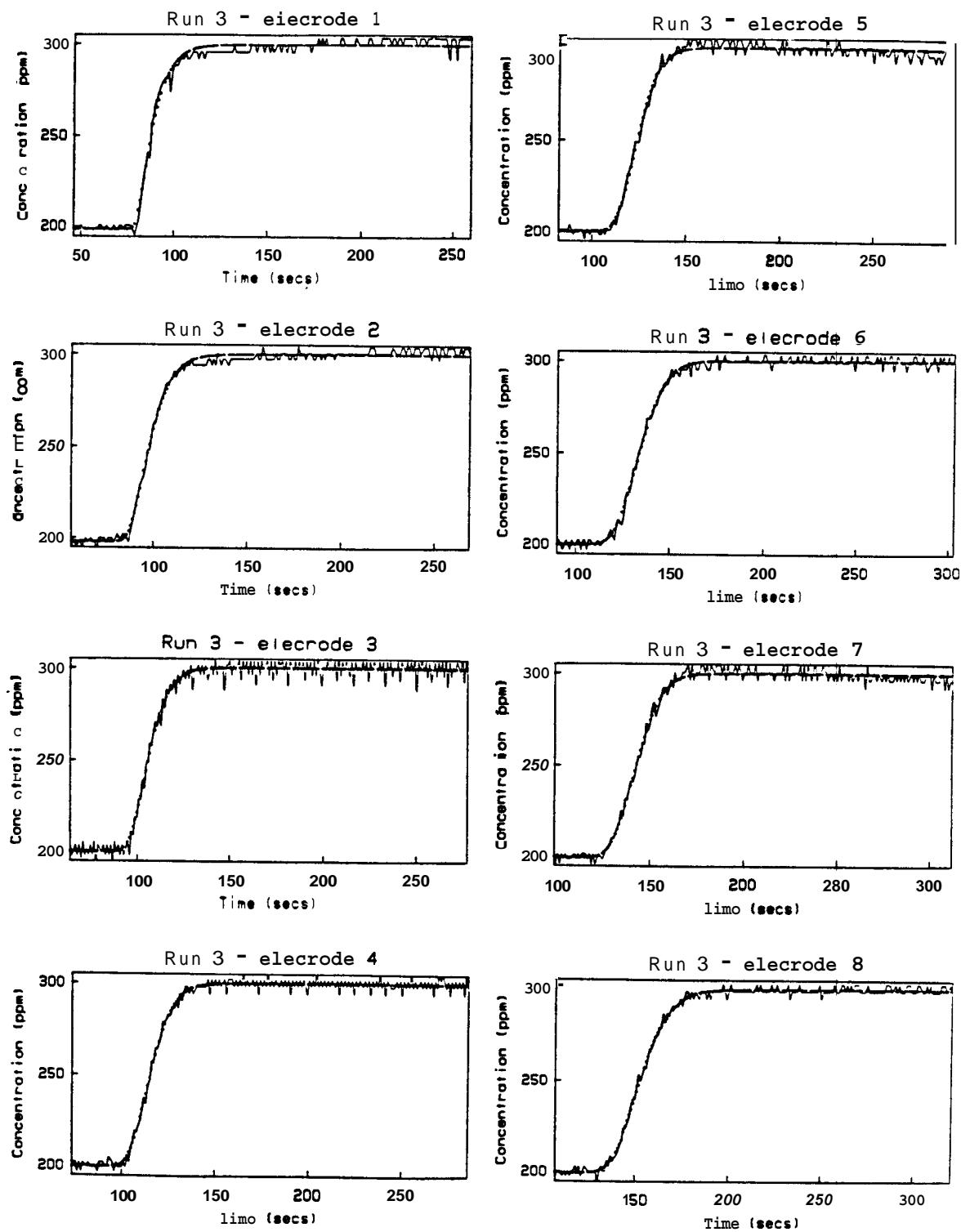


Figure 3. Run 3

8: 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. Fossurn. M.P. *"Tracer Analysis in a Fractured Geothermal Reservoir"* , Masters Report. Stanford University, June 1982.
7. Fossum, M.P. and Horne, RN. "Interpretation of Tracer Return Profiles at Wairakei Geothermal Field Using Fracture Analysis", Geoth. Res. Counc., *"Transaction 6"* , 1982.
8. Horne. R.N. "Reservoir Engineering Aspects of Reinjection". *"Japan Geoth." "Energy Assoc. Jour."* , "19" 23-30. (1982). (in Japanese).
9. Horne, RN and Rodriguez, F. "Dispersion in Tracer Flow in Fractured Geothermal Systems", *"Geoph. Res. Let."* , Vol. 10, no. 4, 289-292, 1983.
10. Hull. LC. and Koslow, KN. "Dispersion in Fracture Networks", *"Roc."* , Eighth Wkshp Geoth. Res. Engr., Stanford University. Dec. 1982.
11. Gilardi, J. "Experimental Determination of Tracer Dispersion in Fractures", *MS Report, Dept. of Petroleum Engineering, Stanford University, June 1984*. SGP-TR-72
12. Taylor, Sir Geoffrey, F.R.S. "Dispersion of Soluble Matter Flowing Slowly Through a Tube", *"Roc. Roy. Soc."* , A 219, pp 186-203, 1953.
13. VARPRO. Computer Science Dept.. Stanford University.