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DISPERSION IN FRACTURE NETWORKS

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ABSTRACT

A physical model was built to study the relationship between fracture network characteristics and dispersion of solutes. The study was aimed at evaluating dispersion effects due to differences in the orientation of flow to the fracture network. Radial flow injection tests were conducted at three different flow rates (30, 60, 90 cm^3/min.). Solute breakthrough was measured with specific conductance probes at 14 orientations to the major axis of the fracture network. Dispersivity coefficients were calculated from breakthrough curves. Results indicated calculated dispersivity coefficients increased with increasing flow rates and were affected by flow orientation to the orthogonal fracture network.

INTRODUCTION

Dispersion is the result of two processes, molecular diffusion and mechanical mixing. Molecular diffusion is the independent movement of solute particles from the fluid motion, due to thermal kinetic energy of individual solute particles. In this study, we will deal only with the mechanical mixing process, referring to it simply as dispersion. Mechanical mixing is the spreading-out of solutes due to characteristics of the medium, as measured by the dispersivity coefficient (α) and unequal flow velocities through the medium. In porous media the spreading of a tracer front depends only on the distance traveled by the front (Bear, 1961). Dispersivity coefficients depend on flow direction, due to anisotropy in a porous medium (Nuri, 1974), but will be independent of flow velocity.

In fracture networks, contaminant transport is governed by the same processes as in porous media. However, the actual path length along which dispersion occurs and true local flow velocities within fractures are difficult to determine. Application of traditional data collection and analysis techniques for measuring dispersion in the field is complicated by these factors. For example, the actual path water takes through a fracture network will probably be much longer than the straight distance between injection and measurement points. Flow direction in fractured media often departs from the general hydraulic gradient for much longer distances than is found in porous media. This introduces two unknowns into the advection-dispersion equation, which may preclude developing a unique solution. By developing a better understanding of dispersion in fracture networks under controlled conditions, a better method of interpreting field data may be derived. Hence, a physical model was built to study the relationship between fracture network characteristics and dispersion of solutes.

The experimental studies described here are the first in a series to evaluate characteristics of fracture networks; such as fracture spacing, width, and orientation, believed to affect dispersion of solutes. Actual dispersion parameters calculated from these experiments would not be applicable to field situations because of the disparity in scale. However, general concepts concerning the properties of fracture networks controlling dispersion would be determined, and these concepts would be transferable to field situations.

Few laboratory studies describing dispersion in fracture networks are available. Mandel and Weinberger (1972) analyzed the flow of a tagged liquid through an irregular hexagonal lattice structure. Longitudinal dispersion was found to be a function of the flow velocities within the porous media channels and a function of the pore space geometry.

A laboratory study to measure the mixing effects at fracture junctions was carried out by Krizek et al (1972). Tracer breakthrough curves were measured at outlet fractures leading away from a single fracture junction formed in plexiglass. Complete mixing was found to occur at the intersection, as equivalent breakthrough curves were measured in all outlet fractures. As only one inlet fracture was supplying tracer to the junction, results may not be applicable to situations where more than one fracture is feeding a junction and the head drop along outlet fractures is not equal. They incorporated the complete mixing concept into a predictive numerical model for transport in fracture networks. The model, however, was not verified by laboratory or field experiments.

Experiments carried out by Wilson and Witherspoon (1976) indicated little mixing occured at fracture junctions under laminar flow conditions. Early tests in our fracture network, where tracer solution was observed passing through fracture intersections without mixing, supported this conclusion. The orientation of flow to the major fracture network controls the number of fracture junctions a solute particle will travel through. If the total distance travelled by a solute particle is accounted for, then we should not see any effects of flow orientation to major fracture network on dispersivity coefficients. Therefore, it was hypothesized there would be little difference in dispersion for flow through a fracture network and flow through a single fracture of equivalent length. Hence, orientation of flow direction to fracture network would have little influence on measured dispersivities.

MATERIALS AND METHODS

The physical model was constructed by cutting orthogonal grooves, 0.16 cm wide and 0.95 cm deep, in a sheet of plexiglass (Figure 1). The fracture network consisted of single fractures at right angles to one another, with fracture spacings of 10.2 cm. The network was enclosed in a quarter circle with a radius of 81.28 cm. Therefore, two major fractures compose the boundaries of the model, serving as major axes to flow direction. These two major fractures behave much like single fractures. Actual distance travelled by a solute particle is smallest through these two fractures. Hence, pressure gradient is steepest across these outside fractures and true local velocities within these fractures are greatest.

Radial flow injection tests were selected because data can be collected for a variety of flow orientations to the major fracture axis with a single test. Also, data analysis methodology is well developed for this configuration. Finally, this shape closely simulates configurations often applied in actual field experiments.

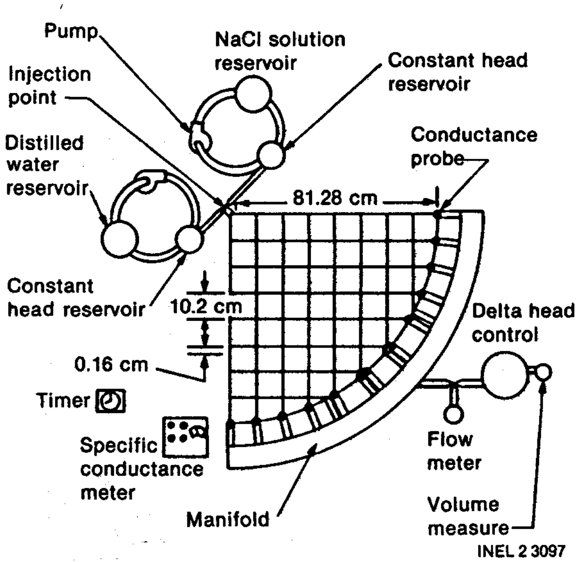

Figure 1. Design of hydrologic model, showing fracture network and support equipment.

Two constant head reservoirs supplied the model with distilled water or a dilute sodium chloride solution (conductance 10 μS). Both solutions were dyed with food coloring, enabling observation of the tracer front. Head drop across the model was controlled by a third constant head reservoir at the outlet. Specific conductance probes were installed at outlets to measure change in solute concentration and determine the resultant breakthrough curves. The laboratory model was designed with the following hydraulic criteria in mind: (1) laminar flow throughout the model (low Reynolds number), (2) advection dominant over diffusion (high Peclet number), (3) discharge on the order of a few liters per hour, and (4) a reasonable headloss (several centimeters) across the model. All tests were run in replicate once with tracer replacing distilled water and once with distilled water replacing tracer solution.

RESULTS

Figure 2 shows representative breakthrough curves for three flow volumes. Under radial flow conditions velocity is not a constant, necessitating the use of volume as the flow parameter. Solute breakthrough was observed to be inversely related to flow volume.

A plot of arrival times, based on the time a concentration of C/Co = 0.5 arrives at the electrode, for electrodes placed at different angles is shown in Figure 3. There is a general increase in arrival times as the angle approaches 45°. The lines in the figure represent the best fit to the data of the equation

$$\Delta t_{0.5} = \frac{81.28\ (\sin\theta + \cos\theta)}{V} \qquad (1)$$

where:

81.28 = radius of model

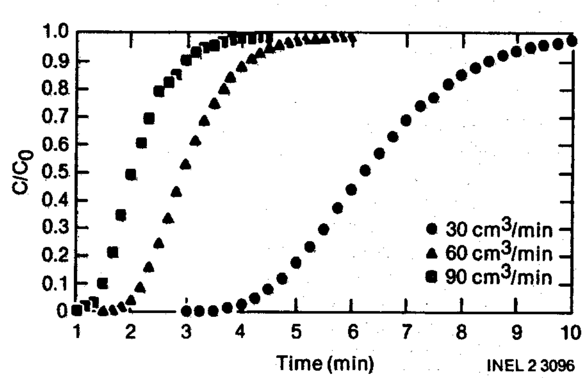

Figure 2. Representative breakthrough curves.

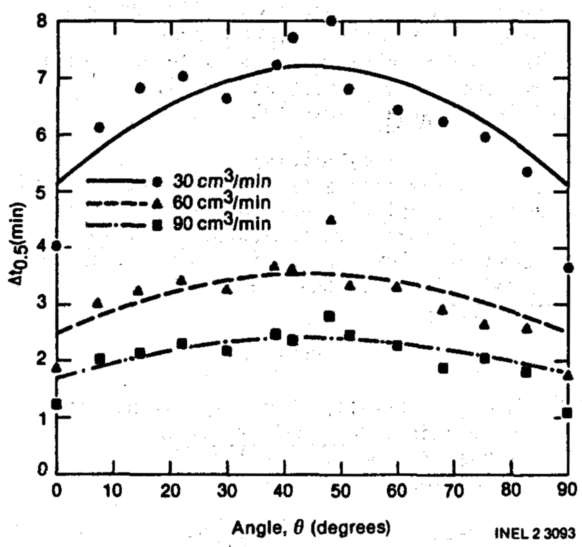

Figure 3. Arrival times versus angle when $C/C_0 = .5$

θ = angle

v = average linear velocity

$\Delta t_{0.5}$ = Arrival time of a tracer concentration equal to 50% of the final value

DATA ANALYSIS

Data were analyzed with the method presented by Hoopes and Harleman (1967). The method is based on the analytical solution to the advection-dispersion equation for radial flow.

$$C/Co = 1/2 \, \mathrm{erfc}\left[\left(1 - \frac{4Qt}{b\pi nr^2}\right)\bigg/\left(\frac{16}{3}\frac{\alpha}{r}\right)^{1/2}\right] \quad (2)$$

C/Co = relative tracer concentration

erfc = complimentary error function

Q = discharge (cm^3/min)

b = full fracture width (cm)

n = porosity

r = distance from injection point (cm)

α = dispersivity coefficient (cm)

A factor of 4 was included to account for the quarter symmetry employed in our model.

A plot of relative concentration versus relative flow volume on arithmetic probability paper is shown in Figure 4. Theoretically, dispersion in an idealized system, will yield a straight line for this type of plot. The standard deviation is obtained from the average of the 16th and 84th percentile, and is related to α by the equation:

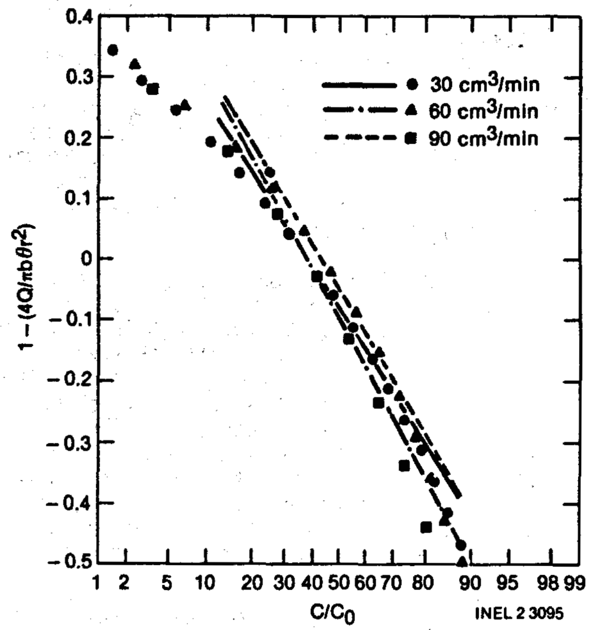

Figure 4. Relative concentration versus relative flow volume.

$$\alpha = 3/8 \, r \, \sigma^2 \quad (3)$$

A straight line was fit to the central data points by eye. Curvature of the plot may be the result of mixing in the conductance electrodes. A new electrode layout, with electrodes imbedded in the fracture walls, is being designed in an attempt to resolve this problem.

Dispersivity coefficients were calculated from breakthrough curves measured at 14 orientations to the fracture network. Because of bilateral symetry about 45°, there are actually two replicate locations at seven orientations. Figure 5 is a plot of α versus orientation.

CONCLUSIONS

The original hypothesis, indicating little difference of dispersion between flow through

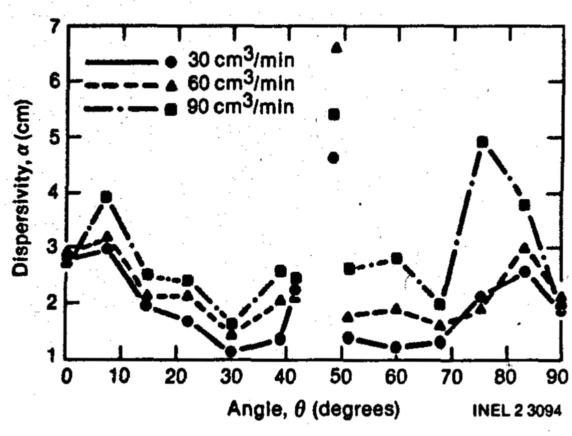

Figure 5. Dispersivity coefficient versus angle.

a fracture network and flow through a single fracture of equal length, was invalid. A relation between dispersivity and orientation of flow direction to the major fracture was observed, with highest dispersivity coefficients occuring at angles near the boundary fracture. The extremely high value measured at 48.59° was not substantiated by the equivalent electrode at 41.41°, and is probably an effect of the individual electrode.

Movement of the tracer front, illustrating rapid solute arrival near boundary fractures is shown in Figure 6. Breakthrough is greatest near boundary fractures and smallest when orientation of flow direction to boundary fractures nears 45°. This delayed passage of the front is due to a lower pressure gradient across fractures orthogonal to the boundary fracture. As orientation of flow direction to the boundary fracture deviates, the number of junctions a solute passes through increases. Hence, solute travel time across the model

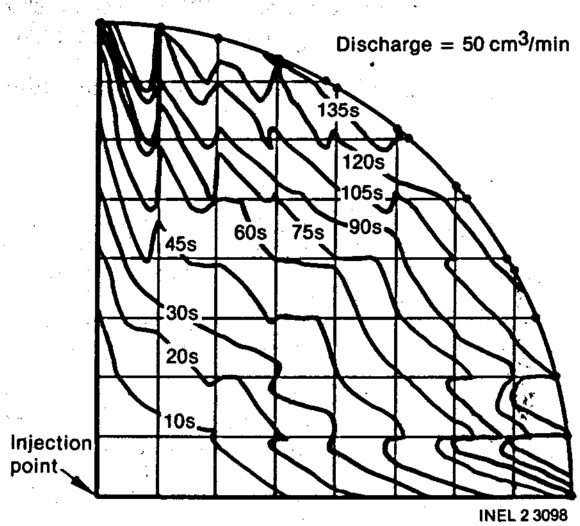

Figure 6. Movement of tracer front over time(s).

increases, as the solute particle encounters more and more orthogonal fractures. Dispersivity coefficients increased with increasing flow rates. The effect was small, but consistent at all orientations.

True local velocities within individual fractures may also affect dispersivity coefficients. Velocity is not constant in radial flow, therefore, evaluation of local velocities is complex. Further testing is required to determine local velocity effects on dispersivity.

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