ANALYSIS OF VISCOUS FINGERING IN TWO-DIMENSIONAL FLOW CELL BY FRACTAL DIMENSION

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KEYWORDS: Fractal dimension, Viscous fingering, CO_2 sequestration

INTRODUCTION

The potential global warming effects of increased carbon dioxide (CO_2) in the atmosphere have recently gained national and international attention. Consequently, the search for different ways to reduce CO_2 emissions has increased, and among the options available is sequestration of CO_2 by injection into deep brine formations. However, when a less viscous fluid, such as CO_2 is used to displace a more viscous fluid, such as brine, a flow instability phenomenon known as viscous fingering occurs. During this type of flow, the less viscous fluid forms fingers extending into the more viscous fluid. This phenomenon is significant to CO_2 sequestration in brine-saturated formations, because it will govern how much volume is available for CO_2 storage. Researchers desire to maximize the saturation of sequestered CO_2. A greater understanding of the flow patterns might yield insight that could ultimately lead to the increase of CO_2 sequestered. One way of observing the complex flow patterns that occur during immiscible displacements is to use an artificial porous medium made by etching channels of random width into glass plates. Since this medium is transparent, images of the flow can be recorded and used to characterize the geometry of the flow. Fractal dimension is one method that has been used to describe random geometries, including porosity (Hildgen et al, 1997), aggregates formed in different fluid mechanical environments (Logan and Kilps, 1995), and characterization of waste water treatment systems (Bellouti et al, 1997). The fractal dimension is used in this study to characterize relative saturations of air under different fluid flow conditions.

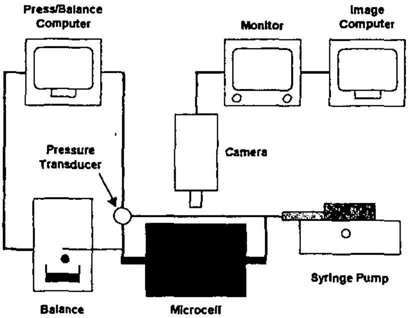

Figure 1: Experimental flow system

EXPERIMENTAL

The experimental flow system (see Figure 1) consists of a micro flow cell, which simulates the porous medium; a syringe pump, which provides a constant-volume-rate injection of fluid into the flow cell; a pressure transducer for measuring the pressure drop across the flow cell; and a balance for measuring the mass of the displaced fluid. The flow cell is made by etching channels of random width into a glass plate and fusing a second, flat plate to it, thereby creating a network of enclosed channels connected to inlet and outlet manifolds. A picture of one of the micro flow cells having random distribution of different channel widths used in this study is shown in Figure 2.

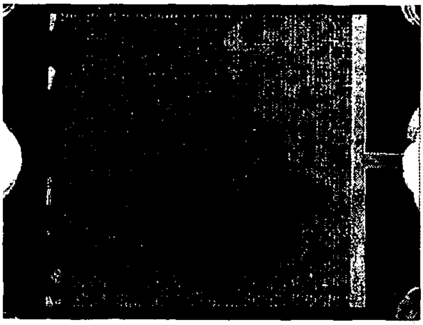

Figure 2: Flow cell showing pattern formed by injection of air into a water-saturated cell. The cell inlet is on left and the outlet on right.

Channel widths for cell #1 are in the range of 175-575 μm and for cell #2 are in the range of 260-1305 μm. In the experiment, the cell was first flooded with water to residual gas saturation. Then air was injected while the pressure drop across the cell and the mass of water displaced were recorded. Digital images of the cell were taken at regular intervals, usually 5 seconds, with a CCD camera. A computer program was developed to analyze the images for saturation and relative permeability calculations. Experiments were performed at different capillary numbers by use of different flow rates.

ANALYSIS

We use the box counting method (Aker, 1997) to analyze the pattern formed by the viscous fingers. In this method the image is covered with an array of square boxes, each box of size L, and the number of those boxes N that cover the injected-air pattern is counted. The relationship between N and the size of the box can be represented by

$$N(L) \sim L^{-d} \qquad (1)$$

where d is the box-counting dimension and is a function of the geometry of the pattern. For example, if all the channels of the cell were filled with air, N would be proportional to L^{-2}. Or, if the air were to flow straight across the cell from entrance to exit filling only one channel, N would be proportional to L^{-1}. Since the actual pattern of the air flow is somewhere between these two extremes, N will be proportional to L^{-d}, where $1 < d < 2$. A log-log plot of the box counts can be used to determine d, as shown in Figure 3.

RESULTS AND DISCUSSION

Results from three experiments are discussed in this paper. These were conducted using two flow cells, and fixed injection rate Q and slightly different mobility ratios M. The mobility ratio is defined as ratio of the viscosity of the displaced fluid to that of the displacing fluid. The experimental conditions are shown in Table 1.

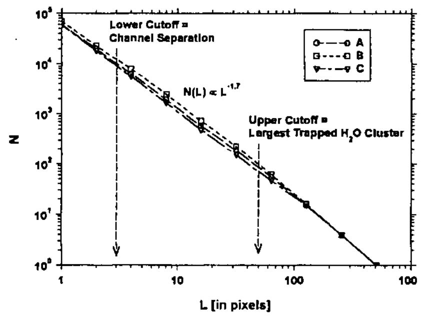

Table 1. Experimental Conditions

Experiment	Flow Cell	Fluids	Channel Width [μm]	Q [ml/min]	M
A	#1	Water and gas	175-575	0.87	53.76
B	#2	Water and gas	260-1305	0.90	53.76
C	#1	Nacl soln. and CO_2	175-575	0.91	72.53

The fractal dimensions of the flow patterns for these experiments are presented in Figure 3. The data plotted are for the ultimate flow patterns observed at the end of each experiment. The plots of data from the dynamic phase of the experiment, when the flow patterns are changing, are parallel to the plots of the ultimate values. Fractal dimensions of 1.7 were obtained with water and air as the immiscible fluids. When a sodium chloride solution and CO_2 were used (experiment C), no change in d was observed. We also noted that the injection rate does not change the value of d over the range of injection rates used.

Thus, in our work we found that *d* does not depend on the physical properties of the flow cell; the mobility ratios, although the two mobility ratios are relatively close; and on the level of air saturation of the cell. This implies that *d* is more of a characteristic of the flow patterns than any other parameter. The values of *d* obtained in our studies characterize viscous fingers for diffusion-limited aggregation (DLA) (Meakin, 1983). Figure 4 shows the correlation between fractal dimension and saturation.

CONCLUSIONS

These experiments demonstrate that fractal dimension is a function of fluid saturation but is independent of physical properties of the porous media. This analysis will be useful for

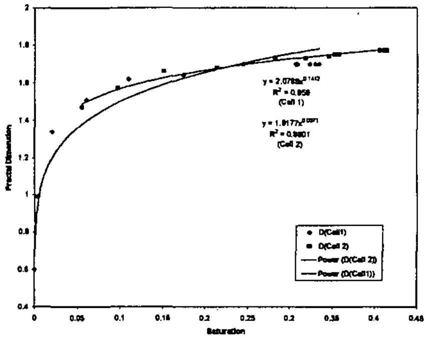

Figure 4: Fractal Dimension as a Function of Saturation

determining the fraction of the porous media that the displacing fluid will occupy. This is critical in the case of CO_2 sequestration into brine-saturated formations, because the more volume of space occupied by CO_2 during sequestration the more effective the process is.

Acknowledgments: Olubunmi Ogunsola was a National Research Council Sr. Associate. Her associateship and this work were funded by the Office of Fossil Energy, U.S. Department of Energy.

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