Pore-Scale Difference between Miscible and Immiscible Viscous Fingering in Porous Media

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Introduction

When one fluid displaces another in a porous medium, the displacement can be stable or unstable. Viscous fingering is an unstable phenomenon that occurs when a less viscous fluid displaces a more viscous one (Saffman and Taylor, 1958; Chouke et al., 1959; Blackwell et al., 1959).

During oil recovery viscous fingering results in a poor recovery due to the bypass of the resident oil by the displacing fluid. In an oil reservoir there is randomness of many different length scales, ranging from pore size to reservoir size. Viscous fingering can have many different length scales due to the randomness. It is important to understand how the randomness on different scales affects the development of fingering. In this note we report experiments on the displacement stability in two-dimensional network models of porous media. The purpose of this work is to better understand the pore-scale phenomena of displacement. Immiscible viscous fingering in a two-dimensional network model, with negligible effects of the interfacial tension, has been studied by Chen and Wilkinson (1985). Although qualitative agreement was found between simulations and experiments for the immiscible case, some fundamental difference was found for the miscible case. The cause of difference and other relevant experimental observations will be discussed.

Experimental

A two-dimensional flow network was made by photoetching a pattern in a 0.10 × 0.10 × 0.0056 m glass plate, and then clamping or fusing a flat glass plate on top. The top plate had a small hole (0.0017 m dia.) drilled in the center for injecting the fluids.

Three different samples were used. Sample 1 had a 120 × 120 square network of interconnected channels of length 5×10^{-4} m, etch depth 3.5×10^{-5} m, and uniform width 2.5×10^{-4} m. Sample 2 had a 90 × 90 square network, with channel length 5×10^{-4} m, etch depth 4.4×10^{-5} m, but with a variable width between 0.8×10^{-4} and 7.3×10^{-4} m. Sample 3 had channels formed by placing approximately circular "grains" at random and etching the region between them. The diameter of the grains was about 2.5×10^{-4} m, the etch depth was 2.6×10^{-5} m, and the average gap between the grains about 2.5×10^{-4} m.

The four different displacement experiments were:

- Dyed water displacing water
- Dyed water displacing glycerine
- Dyed oil displacing water
- Dyed oil displacing glycerine

The first two cases were miscible, while the last two were immiscible and the displaced phases were wetting to the glass plate. The oil used was Soltrol 100, an isoparaffin from Phillips Chemical Co. The dyes (1×10^{-6} kg of dye in 1×10^{-6} m^3 of liquid) used in water and oil were methylene blue and brilliant oil blue, respectively. The interfacial tension was 34.6 mN/m between dyed oil and distilled water (not dyed) and 20.3 mN/m between dyed oil and glycerine. The viscosity of the displacing phase μ_i was 1 mPa · s, and that of displaced phase μ_o was 1 mPa · s for water and 1,200 mPa · s for glycerine. The viscosity ratio, defined as μ_o/μ_i, was 1 in the cases where water was displaced (first and third cases), and 1,200 where glycerine was displaced (second and fourth cases).

The sample was set horizontally, and then the displaced fluid was injected through the central hole in the top plate until it filled most of the flow space in the sample. Since it was a stable displacement, the front was always circular at high volumetric flow rates. The displacing fluid was then injected by a syringe pump at a certain constant flow rate. The experiments were run at high flow rates such that during the experiment the molecular diffusion was negligible in miscible cases with large viscosity ratios. The displacement process was recorded as still photographs or motion pictures. All experiments were run at room temperature, 22 to 25°C.

Results

Miscible displacement

Two different experiments were performed for each sample: dyed water displacing water, and dyed water displacing glycerine. The displacing phase was injected into the micromodel from the center of the pattern at a selected constant flow rate. A stable displacement front was found when dyed water displaced distilled water of the same viscosity, Figure 1, but viscous fingers formed when dyed water displaced glycerine, which is a thousand-times more viscous than water, Figure 2. In sample 1 the fingers grew along the coordinate axes, with some small side branches, mostly at 90 degrees to the main branch, Figure 2a. In sample 2, with some randomness in channel size, more side branches than in sample 1 were observed, most of which emerged from the main branch at 45 degrees, Figure 2b. In sample 3, a more chaotic displacement was observed, Figures 2c, d. The finger patterns were not exactly reproducible.

Microvisualization of the pore scale displacement process showed the following:

1. When dyed water displaced water, it displaced the resident water from the pore space rather uniformly except in the region behind each grain in the radial flow direction. This region (which appears white in Figure 3) was gradually occupied by the dyed water (which appears black in Figure 3) through local mixing and diffusion. The diffusion time of dye in each pore was estimated to be about the same as the experimental time (about 300 s at a flow rate $q = 1.3 \times 10^{-10}$ m^3/s), assuming that the molecular diffusion coefficient of the dye in water was 10^{-9} m^2/s.

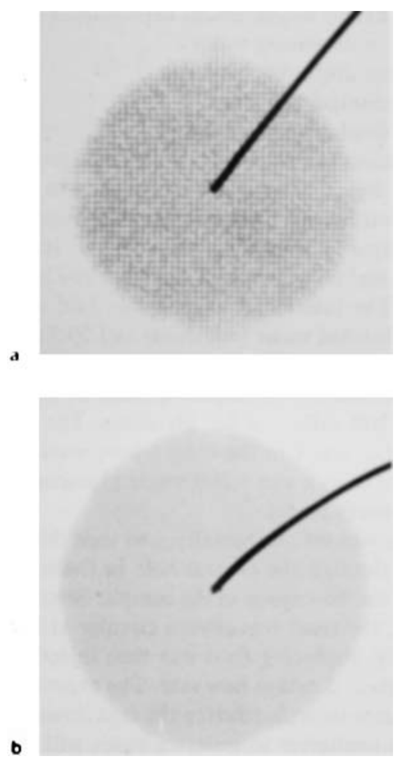

Figure 1. Stable, circular displacement front when dyed water displaced water of the same viscosity.

(a) 80 s after start of experiment; $q = 2.7 \times 10^{-10}$ m^3/s in sample 2 (fused).
(b) 220 s after start of experiment; $q = 1.3 \times 10^{-10}$ m^3/s in sample 3 (fused).
White spots inside circular front are "grains" of etched plate fused onto another plane plate. Four bumps on the circular front in (a) are due to the anisotropic effect of the square network. A close-up of a bump is shown in Figure 3c.

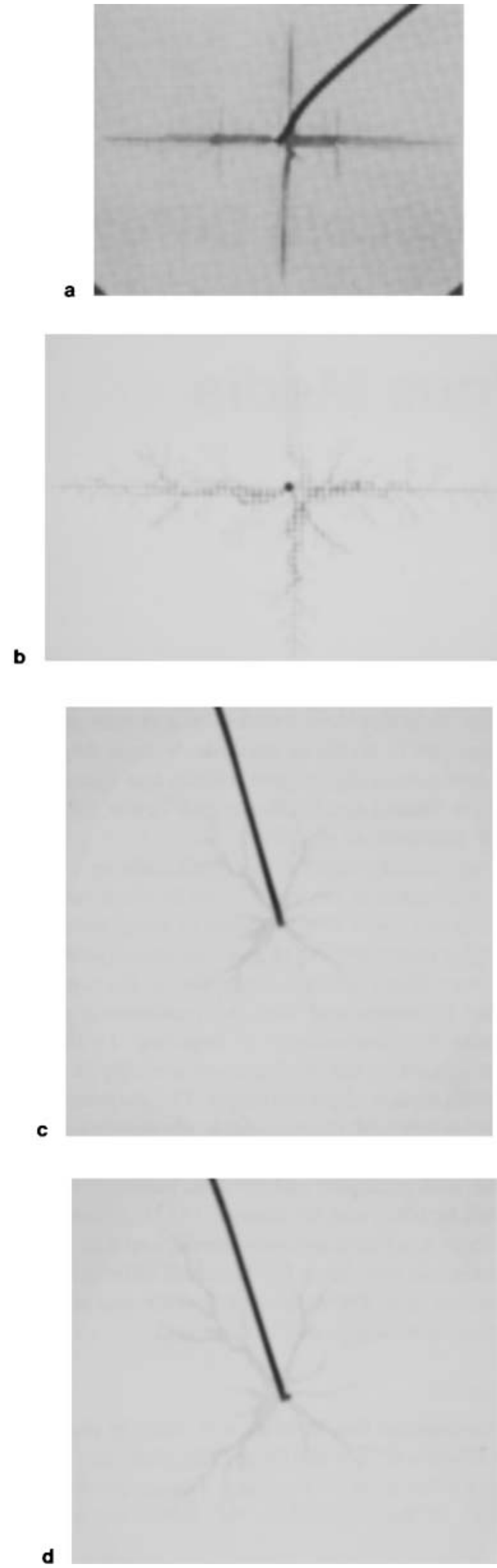

Figure 2. Miscible viscous fingering when dyed water displaced glycerine, $q = 1.3 \times 10^{-10}$ m^3/s.

(a) Sample 1, clamped; black spots are chrome on "grains" of etched plate.
(b) Sample 2.
(c), (d) sample 3; time interval between (c) and (d) is 27 s.

Figure 3. Microphotographs showing mixing of clear water in previously unaffected region with dyed water, when displaced by dyed water at q = 1.3×10^{-10} m^3/s.

Sample 2; time intervals between successive photographs are 6 and 7 s.

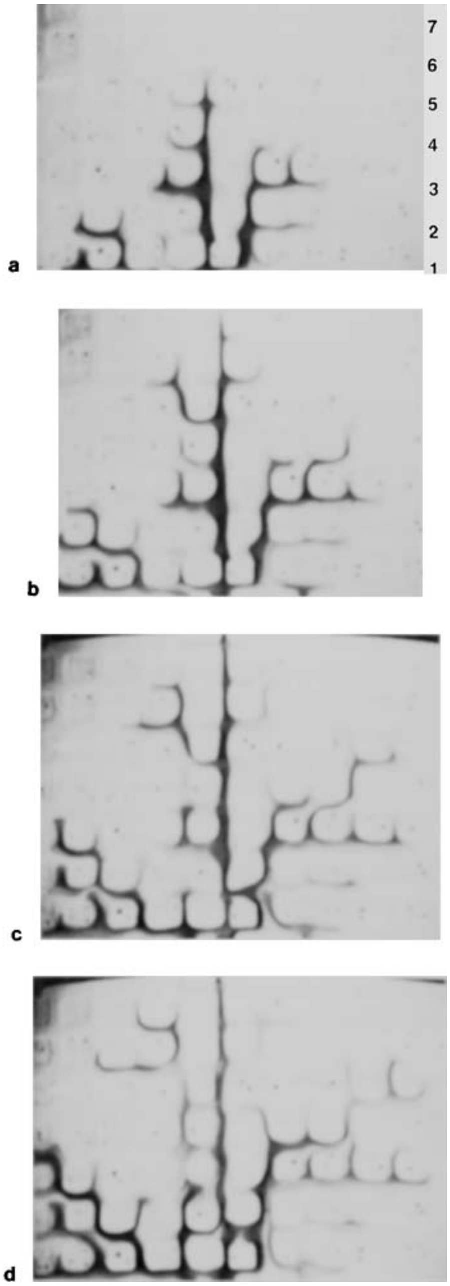

Figure 4. Microphotographs showing water fingers avoiding each other, and convective mixing in sample 2 at q = 1.3×10^{-10} m^3/s.

Longest vertical straight finger in (a) grew along one of the axes of the square network. Time interval between successive photographs is 4 s.

(a) 0 s; (b) 4 s; (c) 8 s; (d) 12 s

2. When dyed water displaced glycerine, it displaced only part of the glycerine initially in the pore, the rest could be washed out by the continuous flow of water. Some photographs of the fingering process are shown in Figure 4, where the rectangles are "grains." The color was weaker (whiter) on the tips and the boundaries of fingers, indicating a thinner water layer there. Also, thinner fingers were observed when they ceased to develop due to the obstruction of other fingers. As shown in Figure 4a, the vertical finger at the center of the photograph grew along one of the axes of the square network, and the growth of three small short fingers at levels 2, 3, and 4 on the right side was obstructed by the presence of the big side finger to their right. The growth of the small side finger at level 2 on the left of the vertical straight finger was similarly inhibited, Figures 4a,b. Two water fingers entering a pore junction did not join immediately, but rather tended to avoid each other. These effects could explain the 45-degree and other tilted side branches shown in Figure 2b and the disagreement with the simulation of Chen and Wilkinson (1985), which assumed a pistonlike displacement in each pore. Two separate fingers in the same pore were also observed (not shown). The previously unaffected region could be displaced by water through convective mixing. One finger could penetrate into the region originally occupied by another, and mixing took place. These can be seen in Figure 4, where the white streaks between dark bands of water fingers are glycerine being convectively displaced by water. This explains the widening of branches during the displacement. An example is shown in Figures 2c and 2d.

The diffusion time of dye in glycerine was estimated to be two orders of magnitude longer than the experimental time (about 60 s at $q = 1.3 \times 10^{-10}$ m^3/s), so that molecular diffusion was not an important feature of these experiments. Here we assume that the molecular diffusion coefficient of dye in glycerine is three orders of magnitude smaller than that in water.

Immiscible displacement

Two different experiments were performed for each sample: dyed oil displacing water, and dyed oil displacing glycerine. The displacement front for oil displacing water of the same viscosity in samples 1–3 at two different flow rates, 1.3×10^{-10} and 2.1×10^{-9} m^3/s, was stable, but due to the effect of interfacial tension it was not as circular as in the miscible cases. One example is shown in Figure 5. The capillary number *Ca*, defined as $\mu_o v/\gamma$, is about 10^{-6} and 10^{-5} for these two flow rates. (That we were able to obtain a roughly circular displacement front at such low *Ca* was due to the shallow and rather uniform etch depth on the glass plates.) When oil displaced glycerine at 1.3×10^{-10} m^3/s ($Ca \approx 10^{-2}$), it fingered into the networks, Figure 6. Here v is the speed of the displacement front or the finger and is not a constant in the experiment. The value of *Ca* is only an estimate based on an average speed for each experiment. In sample 1 the main fingers grew along the coordinate axes and some side branches emerged from the main branch at 90 degrees. In sample 2 a similar finger pattern was formed but with more side branches due to the random distribution of the flow channel size. No 45-degree side branches were observed, presumably due to the presence of interface in this case; compare Figures 2b and 6b. Pistonlike displacement was observed when the oil displaced water or glycerine in the pore. In sample 3 the fingers are more chaotic. Since the displacing fluid was bounded by the menisci in the smaller pores, no widening of the main fingers was observed during the displacement. This is different from the case shown in Figures 2c and 2d.

Conclusions and Discussion

In this note we have shown that for some particular flow rates and two viscosity ratios, the flow pattern is strongly influenced by viscosity ratio, miscibility, and network geometry.

1. Both miscible and immiscible displacement experiments show that for matched viscosity cases, the displacement front is stable at high flow rates in all samples. But for cases of high viscosity contrast, the finger pattern is strongly dependent upon the sample, Figures 2 and 6. We have shown that viscous fingering can occur even in a regular network of channels of uniform size and that the finger pattern is determined by the anisotropic effect of the network structure, Figures 2a and 6a. With some randomness in channel size, more side branches of fingers develop, Figures 2b and 6b. When there is randomness in channel size and orientation, as is characteristic of porous rocks, chaotic fingers develop, Figures 2c, d, and 6c.

2. Miscible displacement experiments for the matched viscosity case show that the displacement in each pore is rather uniform, Figure 3, whereas for the unfavorable viscosity ratio case

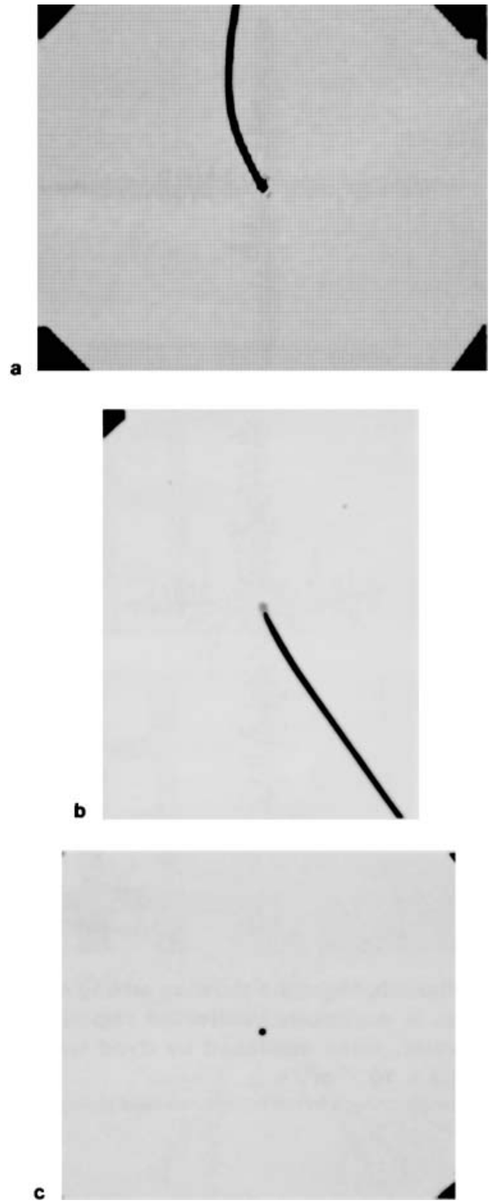

Figure 6. Immiscible viscous fingering when dyed oil displaced glycerine at $q = 1.3 \times 10^{-10}$ m^3/s.

(a) Sample 1, clamped; black spots are chrome on "grains" of etched plate.
(b) Sample 2, fused.
(c) Sample 3, fused.

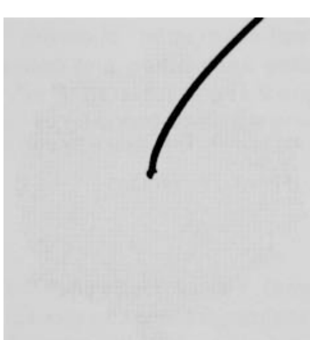

Figure 5. Roughly circular displacement front when dyed oil displaced water of the same viscosity 40 s after start of experiment.

$q = 2.1 \times 10^{-9}$ m^3/s in sample 2. White rectangles inside circular front are "grains."

the water fingers even in each pore, Figure 4. The microvisualization suggests that the high viscosity of the displaced phase influences the miscible displacement in two respects: first, it promotes the fingering of the displacing phase; second, it inhibits the mixing and molecular diffusion.

3. Since there is no meniscus present, the water finger can penetrate part of the pore originally occupied by glycerine and can also penetrate and mix with neighboring fingers. This explains the discrepancy between the miscible finger patterns and the simulation results of Chen and Wilkinson (1985). This is in contrast to the immiscible case, where the two fluids are separated by a meniscus in each pore and the oil finger displaces glycerine much more completely than the water finger does. When a nonwetting fluid displaces a wetting fluid in a pore, the displacement is like a piston. For more details on pore-scale immiscible displacement, see Chen and Koplik (1985) and Chen (1986).

The immiscible finger patterns are similar to those produced from simulation of viscous fingering in a square lattice of tubes with randomly chosen radii. When the randomness of tube radii is small, the fingers grow mostly along the coordinate axes with side branches emerging at right angles. As the degree of randomness is increased, more side branches occur and the fingering becomes more chaotic (Chen and Wilkinson, 1985).

The immiscible viscous fingering discussed here is in the drainage mode. The capillary force is expected to enhance the fingering in the drainage mode and to inhibit the fingering in the imbibition mode. Since in drainage both the viscous and the capillary resistances are less in the larger pores, the displacing fluid will penetrate the large pores more easily than the smaller pores. In imbibition the viscous resistance is less in the larger pores but the capillary suction is stronger in the smaller pores. From this we expect that in imbibition mode viscous fingering should occur at a higher flow rate than in drainage mode, with other conditions being the same.

In the work for this note the observations were made under special experimental conditions. The experiments were run at high flow rates such that the molecular diffusion time in a pore was negligible compared to the experimental time for the miscible case with high viscosity ratio, and it was comparable to the experimental time for the miscible case with matched viscosity. For immiscible cases, the displaced fluid was wetting to the samples. There are many variables that need to be considered, such as the network size, the viscosity ratio, the flow rate, the dispersion, the wettability, and the initial partial saturation.

Acknowledgment

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Literature cited

Blackwell, R. J., J. R. Rayne, and W. M. Terry, "Factors Influencing the Efficiency of Miscible Displacement," *Petrol. Trans. AIME*, **216**, 1 (1959).

Chen, J. D., "Some Mechanisms of Immiscible Fluid Displacement in Small Networks," *J. Colloid Interface Sci.*, **110**, 448 (1986).

Chen, J. D., and J. Koplik, "Immiscible Fluid Displacement in Small Networks," *J. Colloid Interface Sci.*, **108**, 304 (1985).

Chen, J. D., and D. Wilkinson, "Pore-Scale Viscous Fingering in Porous Media," *Phys. Rev. Letters*, **55**, 1892 (1985).

Chouke, R. L., P. van Meurs, and C. van der Poel, "The Instability of Slow, Immiscible, Viscous Liquid-Liquid Displacements in Permeable Media," *Petrol. Trans. AIME*, **216**, 188 (1959).

Saffman, P. G., and G. I. Taylor, "The Penetration of a Fluid into a Porous Medium or Hele-Shaw Cell Containing a More Viscous Liquid," *Proc. Roy. Soc. London, Ser. A.*, **245**, 312 (1958).

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