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Influence of a simple fracture intersection on density-driven multiphase flow

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Abstract

The influence of a single fracture intersection on density-driven immiscible flow is compared between wetting (water into air) and nonwetting (Trichloroethylene into water) flows. At low supply rates, the intersection acted as a hysteretic gate to pulsed flow of the wetting phase, but had minimal influence on nonwetting phase flow. For both cases, increasing the supply rate led to the formation of continuous fluid tendrils that crossed the intersection without interruption. The wetting experiment returned to pulsed flow as the supply rate was decreased, while the nonwetting experiment maintained a continuous flow structure. Results suggest a fundamental difference between wetting and nonwetting phase flows in fracture network.

key word : fracture intersection, wetting invasion, nonwetting invasion

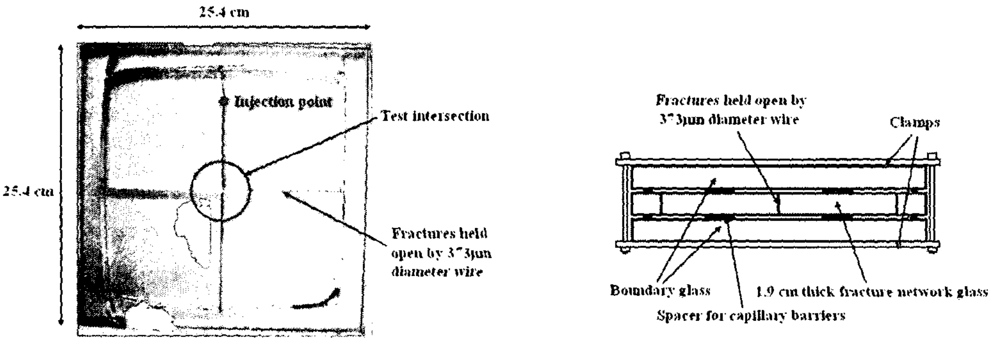
1. Introduction

Recent experiments considering unsaturated flow in hydrophilic fracture networks have shown that capillary barriers formed at simple intersections between vertical and horizontal fractures can act to divert flow [*LaViolette et al.*, 2003], impose a temporal signal [*Glass et al.*, 2002], and/or block lateral spreading [*Glass et al.*, 2003]. While not fully understood, this complex behavior clearly results from a sudden change in the relative importance of capillary forces that rises from the difference in void geometry between an intersection and the contributing fractures. Experiments to date have focused on the density-driven flow of a wetting phase (i.e., water into an otherwise air-filled hydrophilic system). The influence of fracture intersections has yet to be considered for the density-driven flow of a nonwetting phase, such as would occur during the invasion of a water-saturated fracture network by a Dense Nonaqueous Phase Liquid (DNAPL). Here, we present a first experiment designed to explore the differences between wetting and nonwetting flows at a simple intersection between vertical and horizontal fractures of equal aperture (~371 mm). Density-driven flow of a wetting phase was considered by supplying water to an air-filled (dry) system; for nonwetting phase flow, we submerged the same intersection in water, then introduced Trichloroethylene (TCE) as a DNAPL. From the results of these experiments we observed that the wetting and nonwetting invasion show differences in behavior at a single fracture and inferred that network scale flows may also be very different between wetting and nonwetting phase flows.

2. Experimental design

A two-dimensional analog intersection was fabricated by inducing controlled breaks in a 25.4 × 25.4 × 1.9 cm glass plate (Figure 1). The fractures composing our test intersection (center of Figure 1a) were held open by inserting three short (0.1 cm) pieces of 371 mm diameter wire into each fracture segment. Vertical fractures to the left and right of the test intersection were designed to act as capillary barriers to the flowing phase; 650 mm wire was inserted to block wetting phase flow and 295 mm wire for nonwetting phase flow. To facilitate entry by the flowing phase, the horizontal fracture below the test intersection was held open with 650 mm wire for nonwetting phase flow and 295 mm wire for wetting phase flow.

The fractured plate was supported by clamping it between two unbroken glass plates of the same size (Figure 1b). The fractured plate was separated from the supporting plates by spacers. The intervening gap was designed to form a capillary barrier, and keep the flowing phase within the fractured plate. The gap was set at ~1100 mm for wetting phase flow, and ~80 mm for nonwetting phase flow.



(a) (b)

Figure 1. Schematic of a fracture intersection model used for experiments

The flowing phase (water or TCE) was injected into the vertical fracture at a location 7.6 cm above the intersection (Figure 1a). The non-flowing phase (air or water) was allowed to escape freely through all fracture edges. In both cases, the flowing phase was dyed to improve visibility; for water, we added 1.0 g/l of FD&C Blue #1, while 0.9 g/l of Oil-Red-O was added to the TCE.

3. Results

In each experiment, we began the experiment by filling the fracture network with a single fluid phase (air or water). Then we applied the flowing phase (water or TCE) in a series of contiguous steps; first increasing the supply rate (0.012, 0.10, 0.50, 1.00, 5.00, and 10.00 ml/min) and then decreasing it along the same sequence. At each step, the supply rate was held constant for the longer of 5 minutes or 2 ml injection volume. Capillary and gravity forces were defined by the system geometry, surface chemistry, and fluid properties.

3.1. Wetting invasion

Initial injection of water into the air-filled system at 0.012 ml/min produced a slow sequence of small water blobs (~0.7 x 0.2 cm) in the upper vertical fracture. As a larger void space than the fracture, the intersection acted as a capillary barrier, causing water to pool above. The growing pool was constrained laterally by capillary barriers at the fracture edges, while the top of the pool exhibited a curvilinear surface within the fracture plane. Upon reaching a height of 2.18 cm above the intersection the pool invaded the right-hand horizontal fracture. Pool height rose after the right-hand fracture was full, then fell as water entered into the left-hand fracture. At the same time (59 minutes after starting flow), a single water blob was released into the lower vertical fracture.

Storage in the left-hand fracture filled ~134 minutes after starting flow. The intersection then developed a regular fill and drain cycle. In each cycle, pool height rose to 1.42 cm, breaching the capillary barrier and releasing fluid into the lower vertical fracture as a discrete blob. Before the blob separates, it applies sufficient tension to lower pool height to 0.87 cm. Note also that the maximum pool height during each cycle (1.42 cm) is less than that required for initial invasion of the intersection (2.18 cm).

Flow above the intersection transitioned from pulsed blobs to a continuous tendril when the supply rate was increased to 0.1 ml/min. The intersection continued to act as a dynamic barrier, releasing large fluid blobs at regular intervals. Pool height fell from a maximum of 1.33 cm to a minimum of 0.87 cm when a blob was released. At supply rates of 0.5 ml/min and higher, tendrils also formed below the intersection, eliminating pulsation. The tendrils widened as the supply rate was stepped up to 10 ml/min (Figure 2a), however the maximum pool height remained intermediate to that observed during pulsing regimes (~1.03 cm). The fluid tendrils narrowed as the supply rate was stepped down, with pulsed flow returning below the intersection at 0.1 ml/min, and above at 0.012 ml/min (Figure 2c).

3.2. Nonwetting invasion

Initial injection of TCE into the water-filled system at 0.012 ml/min produced a sequence of small (~1.1 x 0.6 cm) TCE blobs in the upper vertical fracture. Blobs formed with a bulbous head and narrow tail, but quickly became rounded during advancement. The first blob entered the intersection and stopped because the fractures exiting the intersection formed capillary barriers. Additional blobs reaching the intersection led to upwards growth and then the TCE pool began to invade the lower vertical fracture when it reached a maximum height of 0.62 cm above the intersection. Continued addition of fluid led to growth of a hanging fluid column beneath the intersection and the release of a fluid blob.

The first release of pooled TCE from the intersection occurred 1.5 minutes after starting the experiment. Afterwards, flow rapidly settled into a steady regime; a pool of TCE remained pinned across the intersection, acting as a capillary bridge between the upper and lower vertical fractures.

The persistence of this bridge precluded TCE entry into either of the horizontal fractures.

Blob flow above and below the intersection continued as the supply rate was increased to 0.1 ml/min. At 0.50 ml/min, flow above the intersection transitioned to a pulsing tendril and TCE was released below the intersection in large blobs. The tendril above the intersection stabilized at a supply rate of 1.0 ml/min, and a stable tendril formed below the intersection at 5.0 ml/min. Tendril width increased to a maximum at 10.0 ml/min (Figure 2b). As the supply rate was stepped down from 10.0 ml/min to 0.012 ml/min the tendril of flowing TCE narrowed, but did not snap (Figure 2d). Throughout the sequence of increasing supply rates the pool trapped across the intersection decreased in size, but remained in place. This smaller size pool was retained as flow was stepped down.

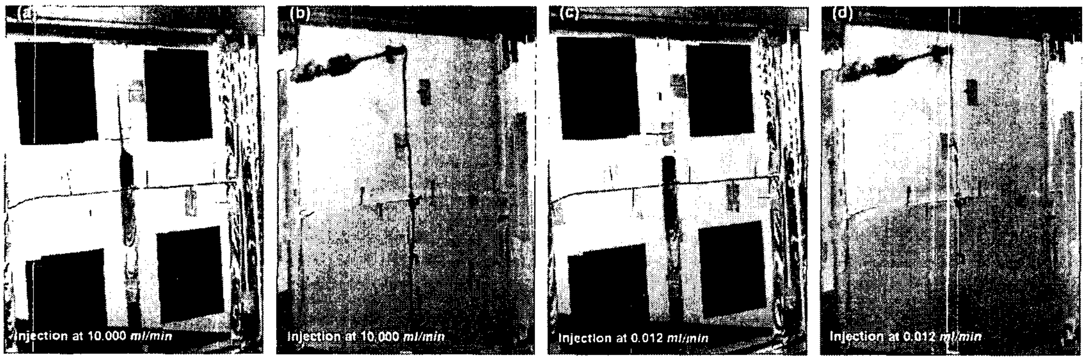


Figure 2. Phase structure at the fracture intersection

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