The effect of nonlinear groundwater flow on DNAPL migration in a rough walled single fracture

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Abstract

We conducted simple experiments to consider the influence of nonlinear groundwater flow on Trichloroethylene (TCE) as Dense Non-Aqueous Phase Liquid (DNAPL) migration in a rough walled single fracture. A glass replica of a granite sample containing a rough single fracture was made and experiments were conducted over a range of *Re*. Observations are compared to the results of TCE migration tests that were conducted in two parallel glass plates over the same range of *Re*. Results show nonlinear groundwater flow in a single fracture affect TCE migration path and residual saturation of TCE.

key word : single fracture, nonlinear groundwater flow, DNAPL migration

1. Introduction

Considering multiphase flow and transport in fractured rocks, phase structure within fracture networks has been a primary concern because it controls the permeability-saturation-pressure relation, mass transfer between phases, and solute transport in each phase. To identify phase structure within fracture networks we need to evaluate the controlling factors that affect phase structure within individual fractures.

There have been relatively few researches about the effect of viscous force of the defender fluid on the distribution of each phase in fractured rocks. *Longino and Kueper* [1999] analytically induced the relationship between maximum stable DNAPL blob length in a fracture and factors such as capillary effect, gravity effect and viscous effect of water flow as the defender fluid flow, and showed the residual saturation of DNAPL in a rough walled fracture are correlated to a parameter combined capillary and Bond numbers from a Perchloroethylene (PCE) injection tests into a water saturated fracture in limestone. *Ji et al.* [2003] injected TCE as the invader fluid into a fracture network under conditions ambient groundwater flow, and observed groundwater flow controls DNAPL migration path, velocity and channeling patterns in a fracture network. Evidences have been growing that the cubic law and/or the Reynolds equation overestimate fluid flow in rock fractures because nonlinear flow is occurred at high Reynolds numbers (*Re*) from aperture heterogeneity and surface roughness [e.g. *Yeo et al.*, 1998; *Konzuk and Kueper*, 2004], which means groundwater flow regime changes at high *Re* and it can affect characteristics of DNAPL migration in rock fractures.

The influences of nonlinear groundwater flow on DNAPL migration and distribution in rock fractures were experimentally evaluated in this study. A glass replica of a granite sample containing a rough walled single fracture was made, and TCE as DNAPL was injected to the water saturated glass replica over a range of *Re*. Observations were compared to the results of DNAPL migration tests that were conducted in two parallel glass plates over the same range of *Re*. Results show nonlinear groundwater flow change the migration path and the distribution of TCE in a rough walled single fracture.

2. Experimental Approach

To identify the effect of nonlinear groundwater flow on DNAPL migration, two single fracture models were used: one with two parallel glass plates (model A) and the other that was a glass cast of a granite sample (model B). Model A was constructed by clamping two 21.0 × 12.0 cm plates of 1.9 cm thick glass. A fracture of model A was held open by inserting six pieces of 485 μm diameter wire inward ~0.1 cm from the fracture edge at predetermined locations. The rock sample (21.0 × 12.0 × 10.0 cm dimension) with a single fracture for model B was obtained from a massive granite outcrop in Wonju, South Korea, area and was cast in glass using the kiln casting method [*Kervin and Fenton*, 1997].

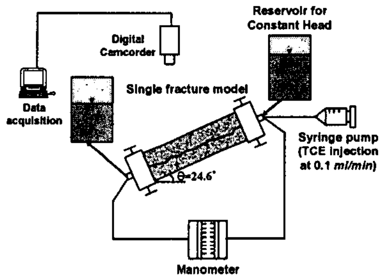
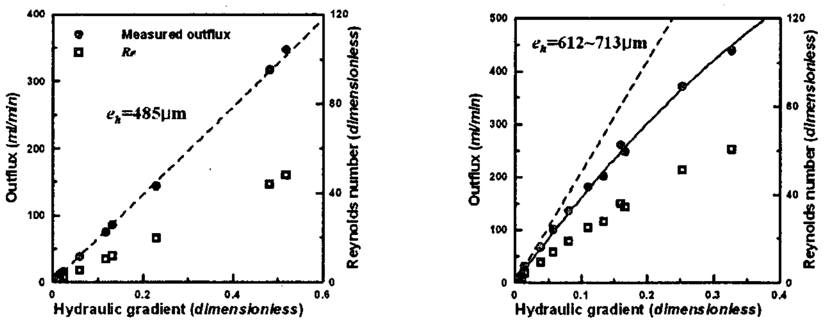


Figure 1. Schematic of experimental setup.

Figure 1 shows the schematic of experimental setup. Hydaulic gradient was controlled with reservoirs connected to either end of a single fracture model and measured with a manometer. TCE dyed with Sudan IV at concentration of 1.0 g/l was injected using a syringe pump at a rate of 0.1 ml/min.



(a) outflux through model A (b) outflux through model B

Figure 2. The measured outflux and their considering the Reynolds numbers

For preliminary tests, we measured water flow rates through models A and B, and characterized flow regimes in models A and B. Models A and B show the linear and nonlinear relations between outflux and hydraulic gradient, respectively. From the results, we classified the flow regimes in model B into three types corresponding the values of *Re*: Darcy-type regime for *Re* in the range of 0-5, weak inertia regime for *Re* in the range of 5-30, and strong inertia regime for *Re* in the range of 30-100.

3. Results

Figure 3 shows observed TCE migration patterns following established *Re*. As *Re* was increased, TCE blobs shrank and migrated faster.

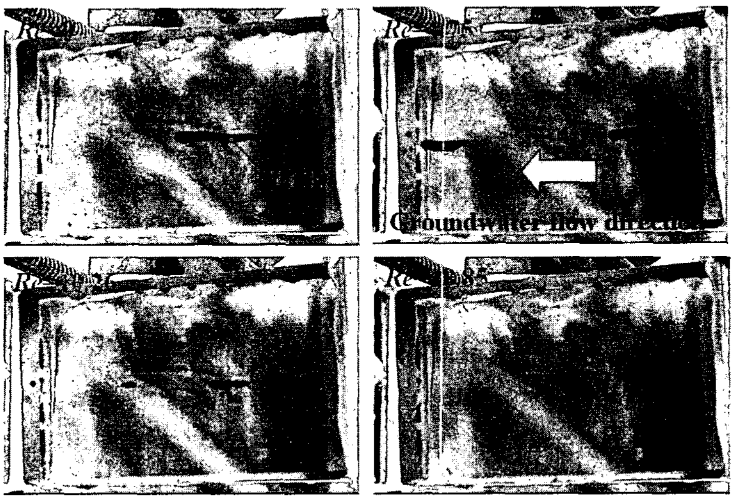


Figure 3. Observed TCE migraions through model A over a range of *Re*.

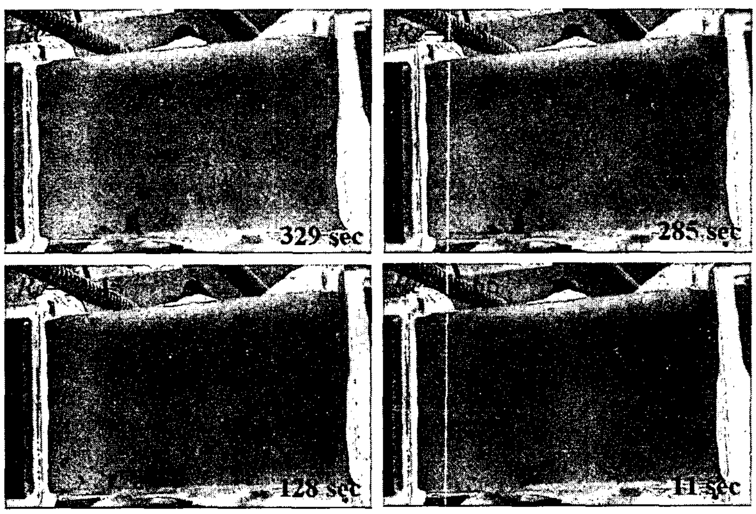


Figure 4. Observed TCE migraion through model B over a range of *Re*.

When TCE injected to model B the migration path of TCE was complicated (Figure 4). At low *Re*, when it met a region with small apertures injected TCE was accumulated and then moved downward after getting sufficient pressure. This process was repeated until TCE met the end of the model. As *Re* was increased, the TCE migration path was changed intermittently in weak inertia regime and the changed migration path was fixed in strong inertia regime. From the water flow analyses using the Reynolds equation and the LBM model of water flow, it is suggested that the inertia of TCE blobs due to sudden changes of groundwater flow velocity make these changes.

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