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Multiphase flow analysis in rock fractures with dynamic MMIP model

지성훈 · 여인욱 · 이강근
서울대학교 지구환경과학부
ji0511@snu.ac.kr

Abstract

In order to characterize the migration of DNAPL in rock fractures, the dynamic macromodified invasion percolation (DMMIP) model, that is able to reflect the viscous force of groundwater in a fracture network, is suggested. DMMIP simulations are verified against the laboratory experiments, which shows a good qualitative and quantitative agreement.

key word : DNAPL, rock fractures, DMMIP model, laboratory experiment

1. Introduction

Groundwater contamination by dense nonaqueous phase liquids (DNAPLs), such as trichloroethylene, has received considerable attention in recent years, and characterizing and quantifying the migration of DNAPL in geological formations has been the subject of intense investigation. Especially the attention was given to the migration of DNAPL in porous media for several reasons. But aquifers in Korea are mostly fractured rocks, and the spilled DNAPL that is heavier than water migrates downward to fractured bedrocks under the influence of gravity and is a long term contaminant source. To design the remediation system of DNAPL contaminated rocks, it is needed to analyze the multiphase flow in fractured rocks. The macromodified invasion percolation (MMIP) model was developed by Glass et al. [2001] and applied to the gravity-destabilized, DNAPL migration problem. In this study, we modified MMIP model by considering the dynamic behavier during the DNAPL invasion. DMMIP simulations are verified against the laboratory experiments.

2. DMMIP Model Conceptualization

The basic concept of DMMIP model comes from the invasion percolation (IP) model [Wilkinson and Willemsisen, 1983]. Figure 1 shows the algorithm of the classical IP model. In the IP model, random numbers ("invadability") are assigned to each site on a lattice representing a random medium. Initially, all but one of the sites are occupied by the wetting fluid ("defender fluid"), and one site is occupied by the non-wetting fluid ("invader fluid"). The algorithm works by repeating the following two steps:

1. Identify the defender fluid site adjacent to the invaded region.
2. Invade the identified site that has the highest invadability by filling it with invader fluid.

The IP model was very successful in describing the displacement of wetting fluid by nonwetting fluid in porous media [Admunsen et al., 1999; Glass et al., 2001]. The success of the IP algorithm depends on the definition of invadability assigned to the sites.

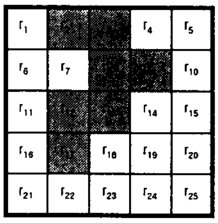


Figure 1. The Algorithm of IP model. The yellow sites are occupied with invader fluid, and the white sites are occupied with defender fluid.

To apply IP algorithm in rock fractures, the invadability of each sites is defined in DMMIP model as follow. First, The nonwetting fluid must overcome the capillary pressure P_c to invade a fracture. For a fracture aperture e, P_c is given by

$$P_c = \frac{2\sigma\cos\theta}{e}$$

where σ is the interfacial tension, and θ is the contact angle with respect to the fracture plain. Buoyancy pressure is represented by the density difference between wetting fluid and nonwetting fluid [Ewing and Berkowitz, 1998]:

$$P_b = (\rho_{nw} - \rho_w)gh$$

where ρ_{nw} is the density of nonwetting fluid, ρ_w is the density of wetting fluid, g is the component of the acceleration due to gravity, and h is the distance in the network. Viscous pressure due to hydraulic gradient is given by

$$P_v = \frac{Q_w \mu_w L}{KA}$$

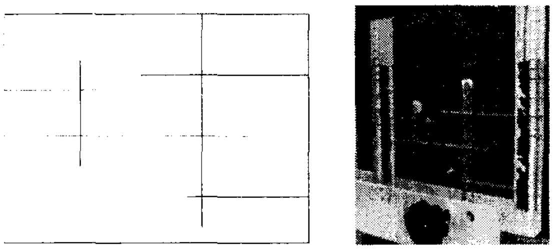
where Q_w is the flow rate of wetting fluid, μ_w is the water viscosity, K is the hydraulic conductivity of a fracture, L is the distance along the flow path from the invasion front to the area of interest, and A is the cross-sectional area of the conducting pathway normal to the local flux. From these, the invadability is given by

$$I = -\frac{2\sigma\cos\theta}{e} + (\rho_{nw} - \rho_w)gh\sin\alpha + \frac{Q_w \mu_w L}{KA}$$

where α is the dipping angle of a fracture. In addition to the classical IP model, the DMMIP model considers the gravity-destabilization effect, the effect of water viscous force, and variable flow conditions.

3. Results and Conclusions

Figure 2a shows a simulated domain. Three assumptions are applied to groundwater flow simulation: (i) the flow of defender fluid is in steady state; (ii) the matrix is impermeable; and (iii) Darcy's law is valid for the groundwater flow. A piston flow of DNAPL is assumed for simulation of DNAPL migration.



(a) (b)

Figure 2. Used fracture network: (a) simulated domain;
(b) fracture network used in laboratory experiments

Figure 3 shows the results of DMMIP simulations with no hydraulic gradient. Injected DNAPL migrates through vertical fracture initially, then invades horizontal fractures after filling the vertical fracture. This invasion pattern is repeated until DNAPL percolates through the network.

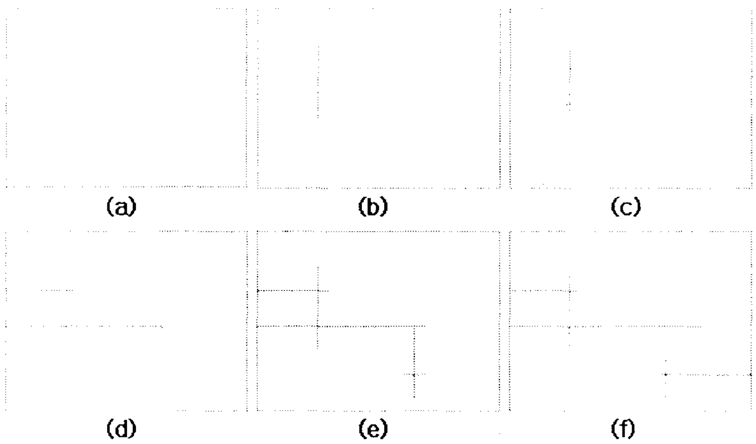


Figure 3. Results of DMMIP simulations

For the verification of DMMIP model, laboratory experiments are carried out. Figure 2b shows the fracture network used in experiments. Experiments are conducted under no hydraulic gradient condition, and DNAPL is injected at the same point with DMMIP simulation. As shown in the simulation results, injected DNAPL fills the vertical fracture initially, then invades horizontal fractures with similar migration rate (Figure 4).

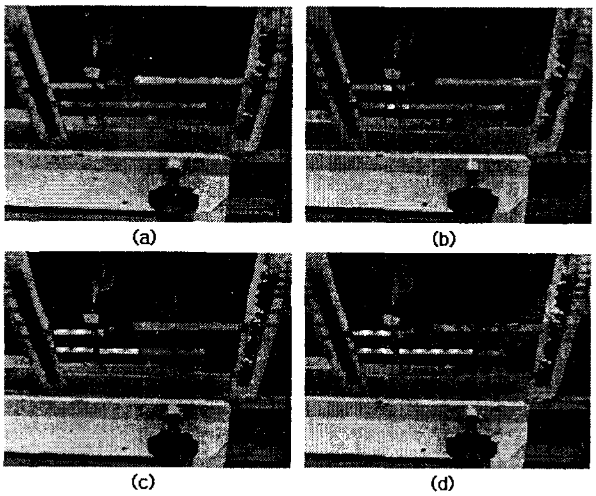


Figure 4. Results of laboratory experiments

In conclusion, the slow displacement of water by DANPL in a fractured rock is studied experimentally, and DMMIP model, which considers the capillary effect, the buoyancy effect and the viscous effect in DNAPL invasion, shows the same transport characteristics as found experimentally.

4. References

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