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Suitable Use of Capillary Number for Analysis of NAPL Removal from Porous Media

Seung-Woo Jeong

Environmental Impact Assessment Div., Korea Environment Institute (swjeong@ker.re.kr)

Abstract

The capillary number is used to represent the mobilization potential of organic phase trapped within porous media. The capillary number has been defined by three different forms, according to types of flow velocity and viscosity used in the definition of capillary number. This study evaluated the suitability of the capillary number definitions for representing TCE mobilization by constructing capillary number-TCE saturation relationships. The results implied that the capillary number should be correctly employed, according to interest of scale and fluid flow behavior. This study suggests that the pore-scale capillary number may be used only for investigating the organic-phase mobilization at the pore scale because it is defined by the pore-velocity and the dynamic viscosity. The Newtonian-fluid capillary number using Darcy velocity and the dynamic viscosity may be suitable to quantify flood systems representing Newtonian fluid behavior. For viscous-force modified flood systems such as surfactant-foam floods, the apparent capillary number definition employing macroscopic properties (permeability and potential gradient) may be used to appropriately represent the desaturation of organic-phases from porous media.

Key words: Capillary number, Foam, Surfactant, Trichloroethylene, Remediation, DNAPL, Porous media

1. Introduction

Remediation techniques using surfactants have been used to enhance dense nonaqueous phase liquid (DNAPL) solubility and/or to physically displace entrapped DNAPL ganglia by reducing the interfacial tension (IFT) between the organic phase and the aqueous phase [1].

Viscous, capillary, and gravitational forces around a NAPL blob affect the mobilization of NAPL within a porous medium. While the capillary forces act to retain organic phases between the solid grains, the viscous and gravitational forces contribute to mobilize the NAPL blobs. A DNAPL removal pattern by surfactant solution is represented by a relationship between DNAPL saturation and the total trapping number. The total trapping number (N_T) is the sum of the capillary number (N_{Ca})

and the bond number (N_B), as shown in Eq. (1) [2]. Here, α is the angle of dip. The capillary number is a dimensionless magnitude and represents the ratio of viscous force to capillary force. The bond number represents the ratio of gravitational force to capillary force.

$$N_T = \sqrt{N_{Ca}^2 + N_B^2 - 2N_{Ca}N_B \sin\alpha} \tag{1}$$

$$N_B = \frac{kk_{rw}\Delta\rho}{\sigma \cos\theta} \tag{2}$$

$$N_{Ca} = \frac{v\mu}{\sigma \cos\theta} \quad \text{where } v = u/\phi \tag{3}$$

$$N_{Ca}^{*} = \frac{\mathbf{u}\mu}{\boldsymbol{\sigma \cos\theta}} \tag{4}$$

$$N_{Ca}^{+} = \frac{\mathbf{u}\mu_{ap}}{\boldsymbol{\sigma \cos\theta}} \tag{5}$$

$$N_{Ca}^{+} = \frac{\mathbf{u}\mu_{ap}}{\boldsymbol{\sigma \cos\theta}} = \frac{kk_{\mathbf{rw}}\nabla\Phi}{\boldsymbol{\sigma \cos\theta}} \qquad \text{where } = p + gz \tag{6}$$

$$\mu_{ap} = \frac{kk_{\mathbf{rw}}\nabla P}{\mathbf{u}} \tag{7}$$

For a homogeneous isotropic porous medium, the bond and capillary numbers have been described as shown in Eq. (2), (3), (4), and (5). Here, k is the permeability, k_{rw} is the relative permeability of aqueous phase, $\Delta\rho$ is the difference in density between organic and water phases, σ is the interfacial tension, θ is the contact angle between organic and water phases, **v** is the pore velocity, ϕ is the porosity, **u** is the superficial or Darcy velocity, μ is the dynamic viscosity, and μ_{ap} is the apparent viscosity. In Eq. (6) and (7), $\Delta\Phi$ is the potential gradient, ΔP is the pressure gradient, g is the gravitational constant, and z is the elevation.

Although the bond number is consistently defined by Eq. (2), the capillary number has been used with several forms, Eq. (3), (4), and (5), by researchers [3]. However, the difference in using the capillary numbers has not received attention from researchers. The objectives of this study were to evaluate the capillary number definitions for quantifying the removal of DNAPL trapped in porous media and determine an appropriate capillary number definition for surfactant-related remediation system analysis. The relationship between capillary number and DNAPL removal helps to design efficient remediation techniques because the capillary number is dimensionless and gives us important information on flow and interfacial properties.

2. Methods

This study calls the capillary number of Eq. (3) as the pore-scale capillary number (N_{Ca}) because the pore velocity and the dynamic viscosity were used for the definition. The pore velocity is defined as Darcy velocity divided by the porosity. The dynamic viscosity is determined from the shear rate of capillarity or the pore velocity [8]. Therefore, the upper part of the pore-scale capillary number (Eq. (3)) is defined with pore- scale properties.

In Eq. (4), a macroscopic property, Darcy velocity, replaces the pore velocity of Eq. (3), but the dynamic viscosity is still used for the viscosity definition [2]. This study calls Eq. (4) as the Newtonian-fluid capillary number. The upper part of the Newtonian-fluid capillary number consists of two different scale properties, macroscopic scale (for flow velocity) and pore scale (for viscosity) properties.

For Eq. (5), it uses Darcy velocity for the flow velocity definition and the apparent viscosity for the viscosity definition. The apparent viscosity is the viscosity determined for a non-Newtonian fluid without reference to a particular shear rate. The apparent viscosity would be more compatible with Darcy velocity than the dynamic viscosity because the apparent viscosity is determined by Eq. (7) using Darcy's law [10, 11]. This study calls Eq. (5) as the apparent capillary number. Eq. (5) can be rewritten by using the apparent viscosity definition, Eq. (7), to produce Eq. (6). In other words, Eq. (5) and (6) have the same meaning.

Results of surfactant and surfactant foam flood removing TCE from porous media were depicted to construct the relationship between DNAPL saturation and capillary number. Three different capillary number calculated by three different definitions, Eq. (3), (4), and (5), were used to construct the relationships. The relationship results were compared each other to evaluate the suitability of the capillary number definitions for representing surfactant and surfactant foam floods.

3. Results

Fig. 1 shows TCE removal results with the pore-scale capillary number and the Newtonian-fluid capillary numbers. Fig. 2 shows TCE removal results with the apparent capillary numbers (N^{+}_{Ca}) calculated by Eq. (5).

Figures show a distinct difference between N^{+}_{Ca} and other capillary numbers. Although plots of N_{Ca} and N^{+}_{Ca} were relatively scattered over a range of capillary number, plots of N^{+}_{Ca} reflected a definite trend in any floods. The results indicated that the N^{+}_{Ca} definition would be applied to any fluid flooding (surfactant-foam floods at fg = 0.66 and 0.85, and surfactant flood), and would more accurately represent surfactant-foam behaviors in porous media. Therefore, for viscous force-modified systems, such as surfactant foam and polymer-added fluid floods, the definition of N^{+}_{Ca} would be suitable for constructing the relationship between capillary number and organic-phase desaturation. However, if mobilization of a blob trapped in a pore is investigated, N_{Ca} by Eq. (3) may still be used. Exact and accurate relationships between capillary number and organic phase desaturation would help to design efficient remediation schemes.

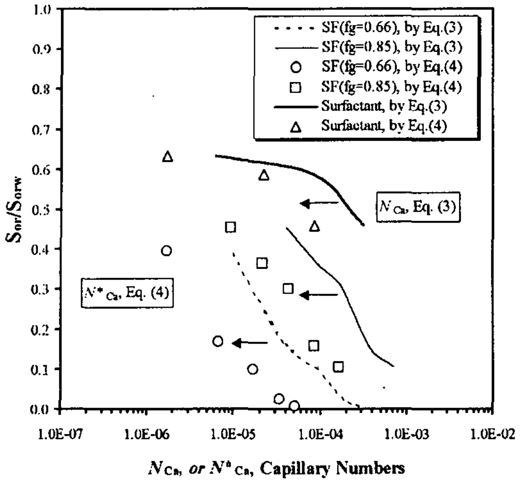

Fig 1.

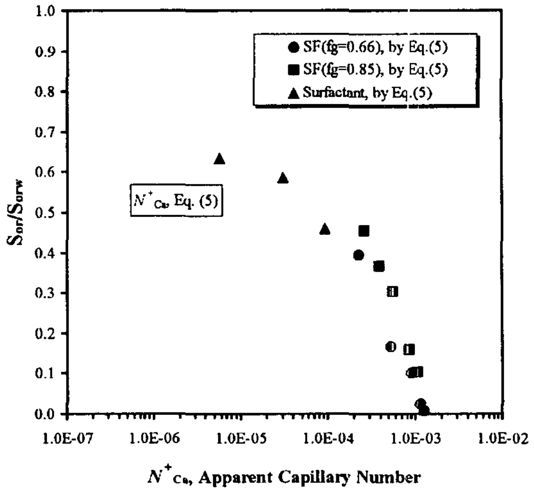

Fig 2.

Fig 1. TCE desaturation results for surfactant and surfactant foam (SF) floods. SF floods were conducted with fg(gas fraction) of 0.66 and 0.85. S_{or}/S_{orw} is the ratio of the final TCE saturation after surfactant-related flood to the initial TCE saturation after water flood.

Fig 2. The TCE saturation ratios are plotted against the apparent capillary number(N^{+}_{Ca}) calculated by Eq. (5 or 6).

References

[1] K. D. Pennell, M. Jin, L. M. Abriola and G. A. Pope, J. Contam. Hydro., 16(1994) 35.
[2] K. D. Pennell, G. A. Pope and L. M. Abriola, Environ. Sci. Tech., 30 (1996) 1328.
[3] R. G. Larson, H. T. Davis and L. E. Scriven, Chemical Eng. Sci., 36 (1981) 75.