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Force analysis and visualization of NAPL removal during surfactant-related floods in a porous medium

Seung-Woo Jeong [a,*], M. Yavuz Corapcioglu [b]

[a] Department of Environmental Engineering, Kunsan National University, Kunsan 573-701, Republic of Korea
[b] Department of Civil Engineering, Texas A&M University, College Station, TX 77843, USA

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Abstract

Governing mechanisms of dense non-aqueous phase liquid (DNAPL) removal during surfactant and surfactant-foam (SF) flooding were studied by porous-patterned glass model experiments. Physical forces, viscous forces and capillary forces, acting on trichloroethylene (TCE) blobs were quantified to understand DNAPL removal mechanisms during the floods, simultaneously visualizing the removal mechanisms. The viscous force of the remedial fluid was intimately related to TCE removal from the porous medium. The remedial fluid with a high viscous force displaced more TCE blobs. Displacement of residual TCE by the remedial fluid began as viscous pressure of flooding was closed to the capillary pressure of the porous medium. In the region of viscous pressure less than the capillary pressure, residual TCE was either retained or solubilized, not displaced, implying that TCE solubilization was the dominant TCE removal process. Glass porous model visualization validated a dominance of the capillary forces during a surfactant flush and a dominance of the viscous forces of the displacing fluid during a SF flood.

Keywords: Surfactant; Surfactant-foam; DNAPL; Viscous force; Capillary force

1. Introduction

Trichloroethylene (TCE) is the most frequently detected groundwater contaminant at hazardous waste sites [1]. As the free product moves downward as a separate phase after an initial non-aqueous phase liquid (NAPL) spill or leak, it leaves behind a residual phase trapped in the aquifer material by capillary forces [2]. The prevalence of NAPLs is a significant impediment to the cleanup of aquifers. Surfactant flushing has been recognized as an efficient technology for the remediation of aquifers contaminated with NAPLs. A surfactant-enhanced remediation technique is used to enhance NAPL solubility and/or mobilize NAPL ganglia by reducing the interfacial tension (IFT) between the organic phase and the aqueous phase [3,4].

The mobilization of dense NAPL (DNAPL) by lowering the IFT has been discouraged since this approach may cause the trapped DNAPL to migrate downward, expanding the area contaminated by DNAPL. Fountain et al. [4] recommended applying an IFT greater than 3–5 dyne/cm to avoid inducing the vertical migration of DNAPLs. Unlike most emulsified mobilization schemes significantly reducing interfacial forces, viscous and buoyancy forces are modified or increased for DNAPL mobilization in recent studies. Miller et al. [5] modified buoyancy forces in a DNAPL-contaminated system by using dense brine solutions. Some researchers used polymers to increase viscous force of remedial fluids to enhance displacement efficiency [6,7]. Jeong et al. [8] used surfactant-foam (SF) for TCE displacement in a moderate IFT system of 4.9 dyne/cm. Although it is expected that surfactant-related remediation systems using increased viscous force would displace more organic phase trapped in pores, the increased viscous force has not been quantified with the organic phase desaturation. It is also known that the

* Corresponding author. Tel.: +82 11 9075 3595; fax: +82 63 469 4964.
E-mail address: superjeong@yahoo.com (S.-W. Jeong).

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organic phases trapped in pores would be displaced under the conditions of viscous force greater than the capillary force of the pore. However, those phenomena have not been clearly visualized together with the acting force analysis.

This study quantified the viscous forces of the surfactant-related remedial fluids (i.e., surfactant and SF) and the TCE desaturation, and also visualized displacement of DNAPL at the region of viscous force greater than the capillary force of the porous medium. Therefore, the objective of this study was to construct a relationship diagram of the viscous force of surfactant-related remedial flood and the TCE desaturation. The results would be utilized to determine the dominant removal process during flooding and design an efficient remediation system. This study used a well-defined porous model for physical force analysis and TCE quantification because the physical properties of porous medium can be easily quantified in the well-defined porous medium and relatively accurate TCE saturation can be directly measured by an image analysis technique.

2. Materials and methods

2.1. Measurements and procedures

This study used a well-defined porous medium for physical force analysis of remediation floods. A porous pattern-regularly-etched glass model was allowed us to quantify physical forces and visualize removal phenomena during flooding. The glass model and experimental set-up used in this study were already described in Jeong et al. [8]. Details of the experimental procedure were also given in ref. [8]. Fluid properties used in this study were shown in Table 1. The micromodel was initially saturated with water and then injected with dyed PCE. This resulted in the micromodel being almost saturated with dyed TCE. The micromodel was then flushed by water until only residual NAPL remained. After water flooding was completed, residual TCE saturation (S_{TCE}) was measured as 0.32 ± 0.01. The residual S_{TCE} was quantified by taking pore-scale images and then measuring the TCE blob area.

After 25 pore-volume (PV) flooding, a final S_{TCE} was determined by the ratio of TCE blob area to pore area and was quantified through a direct image analysis [8]. A pressure transmitter monitored the pressure at the injected port and the results were stored in a computer containing data logging software. The results of the pressure variations during 20–25 PV fluid flow were used to determine the average pressure gradient since the pressure variations in this range were small and assumed to represent the steady state conditions.

Table 1
Fluid properties

Fluid	Interfacial tension with red-dyed TCE[b,c]	Viscosity (cP)[d]	Contact angle of TCE[e] (°, TCE phase)
Water	27.3	0.949	147
Surfactant[a]	4.9	1.029	130

[a] Two percent (weight basis) sodium $C_{14–16}$ olefin sulfonate.
[b] Measured by pendant drop method.
[c] Five gram of Oil-Red-O was added to 1 l of TCE.
[d] Measured by a glass tube viscometer.
[e] Contact angle of a TCE blob on the glass was measured by image analyser.

2.2. Viscous and capillary force determination

Three forces, viscous, capillary and gravitational forces, around a NAPL blob is related to the mobilization of NAPL trapped in a porous medium. It is known that the capillary force acts to retain organic phases between the solid grains, while the viscous and gravitational forces contribute to mobilize NAPL blobs. An analysis of these forces acting on NAPL blobs would aid in understanding of the NAPL mobilization. Note that in this study all viscous and capillary forces are expressed as pressures.

2.2.1. Apparent viscosity

Fluid flow in porous media is expressed by Darcy's law, which correlates the flow rate to the potential gradient only if the pore space of the medium occupied with a single Newtonian fluid. Darcy's law has been extended to express the multi-phase flow in porous media by using the relative permeability concept. For a homogeneous isotropic porous medium, Darcy's law is expressed as followed:

$$\boldsymbol{q}_i = -\frac{k_{\mathrm{o}}\, k_{\mathrm{ri}}}{\mu_i} \nabla \Phi_i \tag{1}$$

where $\boldsymbol{q}_i$ is the volumetric flux of phase i (i.e., volumetric flow rate per unit area); k_{o} the intrinsic permeability of the medium; μ_i the viscosity of phase i; k_{ri} the relative permeability of phase i and Φ_i is the potential of phase i, $\Phi_i = P_i + \rho_i g z$, where P_i is the pressure of phase i, ρ_i the density of phase i, g the gravitational acceleration constant and z is the vertical distance. Foam flow in porous media has been described in two different ways. Previous studies described foam as a mixture of two phases (gas and liquid) [9,10] or as a single phase fluid [11,12]. This study treats SF as a single phase fluid and employed the apparent viscosity concept of SF. The apparent viscosity is usually determined by a method strictly applicable to Newtonian fluids [12,13]. Then, for a horizontal micromodel, the apparent viscosity, μ_{a} can be expressed as:

$$\mu_{\mathrm{a}} = \frac{k_{\mathrm{o}} k_{\mathrm{r}} \nabla P}{\boldsymbol{q}} \tag{2}$$

where ∇P is the pressure gradient. This study used a horizontal micromodel and thus treated the pressure gradient as the potential gradient. The relative permeability, k_{r} was calculated by Corey's equation [14]. The relative permeability of the foam flow was approximated using the sum of the liquid and gas phase saturations after foam flooding.