



# The role of interfacial tension in colloid retention and remobilization during two-phase flow in a polydimethylsiloxane micro-model



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## HIGHLIGHTS

- Lower interfacial tension reduces specific interfacial areas.
- Under transient flow conditions at a lower interfacial tension, fewer colloids were remobilized.
- At a lower interfacial tension, less colloid removal occurred due to a decrease in attachment to fluid-fluid interfaces and contact lines.

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## ABSTRACT

The work presented here consisted of steady-state and transient two-phase flow experiments on the role of interfacial tension in colloid transport. Experiments were performed in a polydimethylsiloxane (PDMS) micro-model containing a network of pores with a mean pore size of 30  $\mu\text{m}$ . The flow network covered an area of 1 mm  $\times$  10 mm. Water and Fluorinert FC43 were used as the two immiscible liquids. Since PDMS is a hydrophobic material, Fluorinert was the wetting phase, and water was the non-wetting phase in this micro-model. The interfacial tension was changed by adding a Fluorinert-soluble surfactant into Fluorinert FC43 to change the interfacial tension from 55 mN/m to 30 mN/m. The colloids were fluorescent carboxylate-modified polystyrene microspheres and 300 nm in diameter. We directly observed colloid movement using confocal microscopy. We also obtained colloid concentration breakthrough curves by measuring the fluorescent intensities in the outlet of the micro-model.

The breakthrough curves showed that during steady-state unsaturated flow, fewer colloids were retained in the system when interfacial tension was lower. During transient flow, more colloids were remobilized by the moving Fluorinert-water interfaces (FWIs) and Fluorinert-water-solid contact lines (FWSCs) under high interfacial tension. Visualization results showed that, at low interfacial tension, the fluid-fluid interfaces were almost flat; thus, less interfacial area was available for colloid attachment.

Generally, confocal images and measured breakthrough curves clearly demonstrate the effect of interfacial tension on colloid retention and remobilization.

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## 1. Introduction

Understanding the processes governing colloid transport and their remobilization in unsaturated porous media can help predict the transport of contaminants, viruses, pathogenic bacteria (Saiers et al., 2003; McCarthy and McKay, 2004), as well as the co-transport of toxic pollutants that can adsorb onto mobile colloids (Seetha et al., 2015). In the vadose zone the flow is primarily transient due to rainfall, irrigation, and evaporation. In column exper-

iments conducted under transient conditions, it is reported that saturation changes result in the enhanced detachment of colloids (Saiers et al., 2003; Zhuang et al., 2007, 2009; Shang et al., 2008; Cheng and Saiers, 2009). Similar results are found in micro-model experiments (Zhang et al., 2013, 2014).

Capillary forces have been reported to play a significant role in colloid attachment to fluid-fluid interfaces and/or fluid-fluid solid contact lines (Shang et al., 2008; Gómez Suárez et al., 1999; Sharma et al., 2008, 2009). Additionally, they are responsible for colloid remobilization by the moving interfaces and contact lines (Zhang et al., 2013, 2014; Aramrak et al., 2011). Capillary forces were reported to be a function of solid surface and colloid surface

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properties, as well as the interfacial tension. However, there are few studies of the effect of interfacial tension on colloid retention and remobilization. These studies suggest that lower interfacial tension could potentially decrease the release of attached colloids from solid–fluid interfaces. The fluids employed in those studies were typically air and water; the surfactants were soluble in water and the colloids were dispersed in water (Gómez Suárez et al., 1999; Zhuang et al., 2010). In these cases, the surfactant may change the colloid solution ionic strength. Thus, it is unclear whether the changes in colloid retention and remobilization were due to variations in interfacial tension or the change of chemical conditions.

Here, we report on micro-model experiments aimed at understanding the effect of interfacial tension under steady-state and transient conditions. Interfacial tension between water and Fluorinert was reduced by adding surfactants to Fluorinert. The surfactant does not change the pH and ionic strength of the colloids solution because the surfactant is Fluorinert soluble and the colloids are dispersed in water. In one set of experiments, the initial water saturation was changed from 100% to 60%. We obtained concentration breakthrough curves in the outlet of the micro-model as well as visualization results in the micro-model flow network using confocal microscopy. Based on the concentration breakthrough measurements and confocal images, we discuss the role of interfacial tension in colloid retention and remobilization.

## 2. Materials and methods

Two-phase flow and colloid transport experiments were conducted in a PDMS micro-model. The distribution of two fluids, the movement of fluid–fluid interfaces, and the behavior of colloids were visualized using confocal microscopy. Details of the experimental setup are given by Zhang et al. (2013). The experimental setup is shown in Fig. 1.

The micro-model we employed was made of two-dimensional polydimethylsiloxane (PDMS). The flow network of the micro-model covered an area of 1 mm × 10 mm. It contained approximately 90 pore bodies and 200 pore throats, with a mean pore size of 30 μm, and porosity of 40%. The micro-model started with three inlet reservoirs and inlet channels, and ended in an outlet channel leading to an outlet reservoir. A schematic image of the micro-model can be found in Fig. 2. Instead of water and air, de-ionized (DI) water and 3M Fluorinert TM FC-43 were selected as the two immiscible liquids. As mentioned in the previous work, our PDMS micro-model was hydrophobic (Zhang et al., 2013), thus, water was the non-wetting phase and Fluorinert was the wetting phase in our experiments. During the two-phase flow experiments, three interfaces were formed: water–Fluorinert interfaces (FWIs), water–solid interfaces (SWIs) and Fluorinert–solid interfaces (SFIs). Additionally, contact lines between the three phases were formed and designated by FWSCs. As colloids, hydrophilic carboxylate-modified polystyrene microspheres (Polysciences Inc. GmbH) with a density of 1055 kg/m<sup>3</sup> and a mean diameter of 300 nm were employed. The colloid suspensions were prepared by dispersing the microspheres in deionized (DI) water.

The interfacial tension of Fluorinert and DI water was measured to be 55 mN/m by Karadimitriou et al. (2013). This was reduced using a non-ionic fluorosoluble surfactant, namely perfluorotetradecanoic acid (PFTDA) (Sigma-Aldrich, the Netherlands). In preparation, following the procedure described by Batra et al. (2001), 30 mg of 0.096 mmol PFTDA was added to 1 mL of Fluorinert FC-43. The resulting suspension was shaken vigorously and then filtered through a 0.2-μm filter. The PFTDA filtrate was diluted 1:500 (v/v) with Fluorinert FC-43 reaching a final PFTDA concentration of 14 μg mL<sup>-1</sup>. The solution was used within 24 h. The interfacial tension of this modified Fluorinert with water was measured to be 30 mN/m. The surfactant does not change the pH

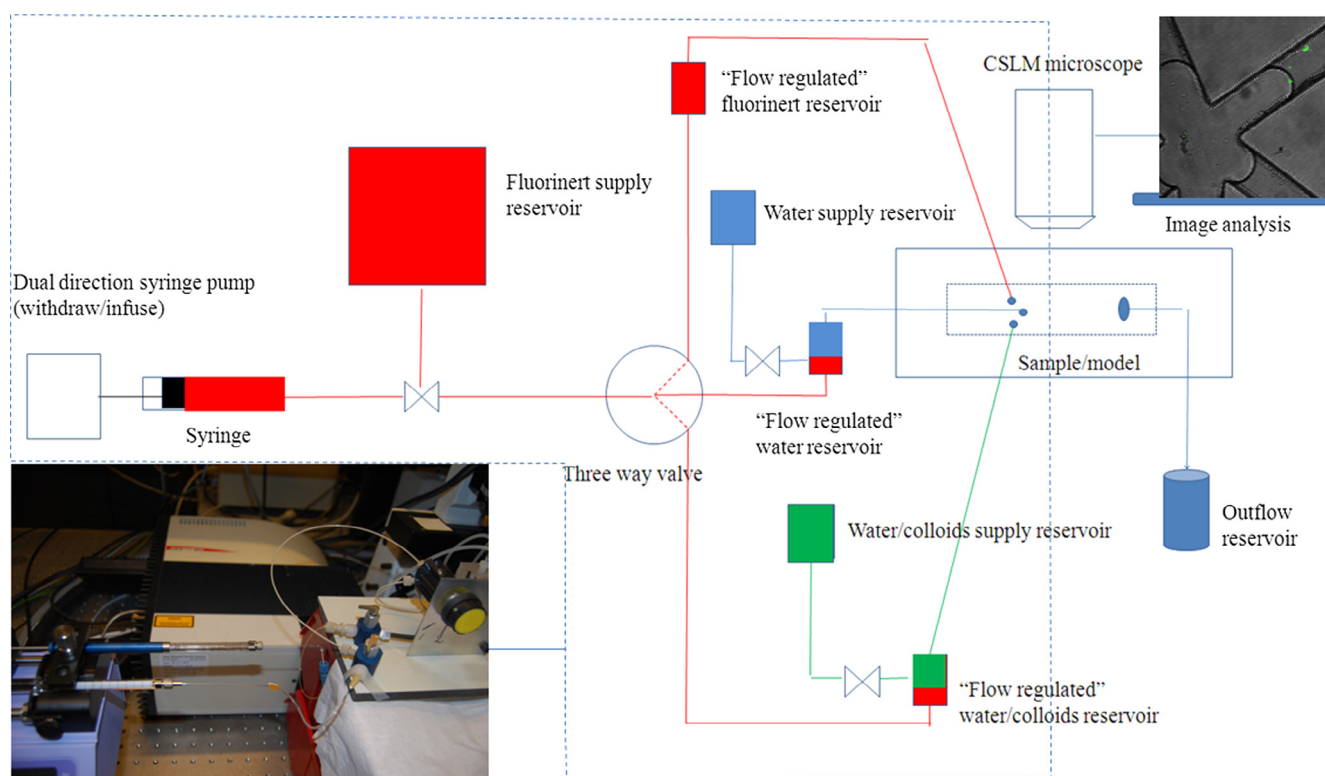


Fig. 1. Schematic image of the experimental setup.

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