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Dynamic flow response of crude oil-in-water emulsion during flow through porous media

Mehrnoosh Moradi [a,1], Mahdi Kazempour [a,1], Joshua T. French [b], Vladimir Alvarado [a,*]

[a] Department of Chemical and Petroleum Engineering, University of Wyoming, 1000 E. University Ave., Dept. 3295, Laramie, WY 82071, USA
[b] Petroleum Engineering Department, Colorado School of Mines, Marquez Hall No. 206, 1600 Arapahoe Street, Golden, CO 80401, USA

HIGHLIGHTS

- Experimental results showing fundamental capillary pressure dependence of emulsion flow.
- Experimental demonstration of the blockage-release emulsion flow mechanism.
- Fast Fourier Transform (FFT) of pressure response identifying pore-level contributions to emulsion flow.

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ABSTRACT

Injection of crude oil-in-water emulsion in tertiary mode has been recognized as a potential method to increase oil recovery. Better understanding of emulsion flow through porous media is needed to develop practical improved oil recovery processes based on emulsion flooding mechanisms. In this study, two sets of experiments were carried out to further investigate the flow of emulsion in consolidated sandstone core plugs. First, the efficiency of emulsion injection to improve oil recovery was evaluated in two-phase flow experiments. Second, single-phase flow experiments were designed to understand the flow of emulsion at pore scale. In these experiments, a crude oil-in-water emulsion with known drop-size distribution was injected in water-saturated Berea sandstone cores followed by water injection at increasing flow rate. The overall pressure drop and its Fast Fourier Transform were analyzed to unveil potential connections to pore level flow. The pore throat blockage-release mechanism was inferred to be linked to the acquired pressure drop oscillation. The pore-scale dynamics has been shown to depend on local capillary number and emulsion drop size. The blockage-release mechanism of the trapped drops becomes less effective as the water flow rate or equivalently, the capillary number, increases above a critical value. Also, a larger drop-to-pore size ratio results in higher required capillary number, i.e. larger viscous force to mobilize the drops in the porous media.

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1. Introduction

Injection of oil-in-water (O/W) emulsions has been identified as a potentially effective oil recovery method that has attracted significant interests in the last decades. McAuliffe [1,2] introduced emulsion injection as an approach to increase sweep efficiency in waterfloods in 1973. A variety of modalities of emulsion flooding has been attempted over several decades. In his early study, McAuliffe [1] compared dilute O/W emulsion flooding to water flooding to show how the injection of emulsion in sandstone cores can improve sweep efficiency. Field production results from injection of an O/W emulsion showed an increase in volumetric sweep efficiency and oil production [2]. Emulsified solvent flooding has been shown to be a more efficient heavy oil recovery technique than water or miscible solvent flooding [3]. Qui and Mamora [4] further studied this modality of flooding, but in their case the dispersion was stabilized with nano-particles resulting in an efficient recovery method for heavy oil. Mandal et al. [5] investigated the effectiveness of emulsion flooding as a contributor to improve oil recovery in some enhanced oil recovery processes.

In situ emulsion generation has been studied as a recovery method in post-waterflooding scenarios. Experiments and numerical simulation results show the impact of emulsion formation during alkaline flooding on sweep efficiency improvement in

* Corresponding author. Tel.: +1 (307) 766 6464; fax: +1 (307) 766 6777.
E-mail addresses: mmoradib@uwyo.edu (M. Moradi), Mahdi.Kazempour@tiorco.com (M. Kazempour), jofrench@mymail.mines.edu (J.T. French), valvarad@uwyo.edu (V. Alvarado).
[1] Present address: TIORCO LLC, 2452 S Trenton Way Denver, CO 80231, USA.

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sand packs [6]. Alkali-surfactant injection in heavy oil has been shown to improve oil recovery and emulsion generation in the presence of heavy oil. The emulsion type, i.e. O/W or water-in-oil (W/O), turned out a function of salinity, water–oil ratio and hydrophobicity of the surfactant-soap system [7].

To understand emulsion flooding recovery mechanisms, the concept of ganglia dynamics [8] can be adopted. As illustrated in Fig. 1, emulsion drops can be trapped in pore throats and to mobilize them, a certain local critical capillary number should be attained. At the critical capillary number, viscous forces, i.e. drag forces produced by the continuous phase fluid flow, become large enough to overcome the capillary pressure threshold, resulting in mobilization of oil drops. Below the critical capillary number, trapped oil drops can increase sweep efficiency by diverting water flow toward unswept areas during waterflooding. Soo and Radke [9] developed a filtration model to describe the flow of dilute emulsions in unconsolidated porous media. In this model, drops are trapped in porous media by two mechanisms: straining and interception. Due to these trapping mechanisms, the effective permeability of water decreases in the porous media. In addition, they showed that the extent of the permeability reduction is a function of drop size and pore size distribution. In the second part of their study, Soo et al. [10] evaluated the efficiency of filtration model by comparing simulation results with experimental data.

Khanbharatana [11] studied the rheology of emulsions in porous media as well as oil drops trapping mechanism for a system of comparable pore and drop sizes. They investigated the filtration process of the drops and the rheological properties of the emulsion for both caustic- and surfactant-stabilized emulsions flowing through Ottawa sand packs and Berea sandstone. Results revealed that when the drop size is comparable to the typical pore size, the overall rheological behavior of the emulsion remains the same, though not quite due to the emulsion quality alteration attributed to the filtration process. Mendoza et al. [12] referred to emulsion flooding as one of the promising non-thermal methods for heavy oil reservoirs, concluding that flow rate determined the efficiency of mobility control. They also observed that optimum flow rate depends on the drop size, type and rheology of the emulsion. Injection of a mixture of crude oil and emulsifier, denominated activated crude oil, was introduced [13] as a new technique for using in situ emulsion formation to block water channels by significantly reducing water permeability, and consequently acting as a conformance or "plugging" agent. When the blend enters the water producing zone in porous media, the blends leads to the formation of a viscous water-in-crude oil emulsion that can serve as the conformance agent. Cobos et al. [14] studied flow of O/W emulsions through quartz micro-capillary tubes to demonstrate the change in the local fluid mobility caused by pore-throat blockage. Results revealed that a blockage mechanism is dominated by drops larger than pore-throat at low capillary number.

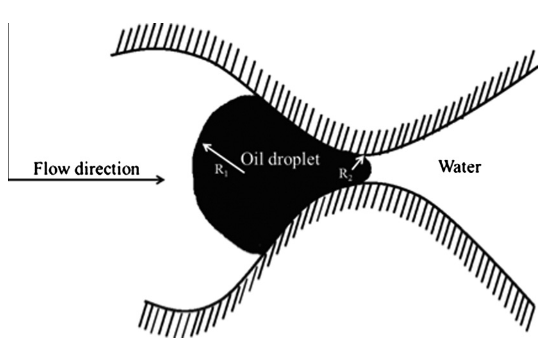

Fig. 1. Capillary trapped drop: Jamin Effect.

Romero [15] studied flow of emulsion in sandstone cores and investigated the effect of drop size to pore-throat size ratio and flow rate on injection pressure as well as the effectiveness of the emulsion to block the pores. A network model developed to simulate emulsion flow in porous media qualitatively matched experimental observations of emulsion flow. Guillen et al. [16] proposed a selective mobility control mechanism driven by capillary forces based on the idea that drops' mobility is controlled by the local capillary number. In view of the changes in capillary number that occur in radial flow around wells, resulting from changes in fluid flow velocity, Guillen et al. proposed that emulsion systems could be designed to more effectively control fluid mobility in specific regions away from wells. The experiments were carried out at several values of the capillary number and oil recovery efficiency was monitored. Results revealed that higher efficiency can be obtained at low capillary number. In a separate study, Guillen et al. [17] investigated the flow of emulsion through transparent sand packs to visualize pore-level displacement, showing flow diversion at the pore level. This was attributed to the obstruction of pore-throats by the emulsion drops. Emerging sweep efficiency of emulsion flooding was shown with flooding experiments in two parallel sandstone cores with different permeability values. Plugging of high permeable zones in fractured formations was demonstrated by placement of a flow-diverting emulsions [18].

Injection of W/O emulsion has also been shown to be effective in secondary and tertiary modes. This was shown in a case where emulsion flooding was followed by polymer injection in Berea sandstone [19]. Emulsions may also contribute to enhanced-oil recovery, when formed during chemical floods. Abdul and Farouq-Ali [20] demonstrated the efficiency of mobility control and blocking potential of emulsion flooding followed by polymer flood. Arhuoma et al. [21] showed that the increase of pressure drop and oil recovery during alkaline flooding can be attributed to in situ formation of W/O emulsion and blockage of the high permeable zones. Numerical results that included these mechanisms were consistent with experimental observations. Shen et al. [22] highlighted that emulsion formation contributes to enhanced oil recovery during ASP flooding. They showed that deviation in flow direction from high permeable zone to low permeable layers was the main mechanism.

Connections between pore-level mechanisms and Darcy-level behavior represent the key to designing processes that exploit emerging responses of emulsion flow in rock. Olbricht and Leal [23] researched flow of a drop in a horizontal tube with a sinusoidally varying diameter. They studied the contribution of the drop to the local pressure gradient and the time evolution of the drop shape as a function of viscosity ratio, volumetric flow rate and drop size. Results showed that the dynamic of the drop motion is strongly affected by the capillary number and tube geometry impacts the local pressure gradient such that the maximum pressure drop was always associated with the passage of the drop through the tube constrictions. In addition, results revealed that the peak of the pressure drop decreases at the high capillary number. Tsai and Miksis [24] showed that while a drop passes through the constriction, it can either break into smaller drops or pass through the constriction depending on the capillary number, viscosity ratio and the size of the drop. Drop passage increases pressure drop followed by a decrease in pressure drop when drop passed through.

In this research, the capillary trapping of the drops in porous media as a function of drop to pore size ratio and capillary number is investigated experimentally. To further demonstrate the dynamics of the emulsion drops in porous media, the influence of emulsion flow on pressure drop oscillation is studied in this paper. Pressure drop oscillation are used to show the occurrence of blockage-release mechanism of emulsion drops while moving in porous

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