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# Oil recovery modeling of macro-emulsion flooding at low capillary number

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ABSTRACT

Emulsion flooding has been shown to offer a significant potential as an enhanced-oil recovery (EOR) strategy. Moreover, recovery mechanisms of several chemical EOR methods, including alkaline and alkaline-surfactant flooding applied to heavy oil, are linked to *in situ* formation of emulsions. To enable emulsion flooding designs, EOR mechanisms must be adequately represented in reservoir simulators to upscale pore-level effects to the continuum in porous media. In this work, we have incorporated two known effects of emulsion flooding, namely an increased pore-level displacement efficiency and a macroscopic mobility control through changes in relative permeability curves. To this end, we used three types of emulsion and oil relative permeability curves: (1) through history matching of unsteady-state emulsion flooding data; (2) from direct use of Darcy law on steady state two-phase flow experiments; and (3) synthetic curves at which pore level displacement efficiency is characterized by the curve end-point saturation and the macroscopic sweep efficiency by the water curve end-point. A parametric analysis of a 1/4 of a 5-spot geometry shows that the displacement efficiency effect is predominantly responsible for the incremental oil recovery observed experimentally. The results also indicate that the amount of oil recovered depends on the complete relative permeability curves, and not only the end-point values. These findings imply that properly designed emulsions should produce significant recovery benefits.

## 1. Introduction

Traditional enhanced-oil recovery designs seek to address optimal mobility control and increase in capillary number through reduction in interfacial tension. However, these designs rely on the use of complex viscosifying and tensoactive agents that give rise to dispersions with complex fluid flow behavior in porous media. These responses leave a number of questions opened that require scrutiny in order to develop new EOR strategies and designs. Complex fluids exhibit emerging non-linear responses as they flow through porous media. These observations cannot be fully explained on the basis of their bulk rheological properties. As an example, polymeric solutions frequently behave as shear-thinning fluids under shear flow outside porous media, but can give rise to apparent shear-thickening responses when they are forced to undergo flow events in porous media geometries (Sorbie, 1991; Kazempour et al., 2012). In the case of emulsions, the drop size to the pore throat radii ratio impacts the macroscopic response of emulsion flow through porous media (Cobos et al., 2009). This implies that viscosity alone is insufficient to describe flow responses. For purposes of enhanced-oil recovery (EOR), the concept of mobility and the related mobility ratio are used to understand fluid–fluid displacement in oil reservoirs (Babadagli, 2007). When the displacing fluid viscosity is lower than that of the displaced fluid, viscous fingers can form (Homsy, 1987), leading to low sweep efficiency. This motivates the addition of polymers and other additives into a lower viscosity displacing liquid to increase its viscosity and consequently the sweep efficiency (Lake, 1989; Babadagli, 2007).

Macro-emulsions, i.e. micron-scale suspended drops in a continuous phase, offer a mobility control mechanism based on capillary resistance (Jamin effect), in contrast with viscosity enhancement of the displacing phase (Tallakstad et al., 2009). This capillary-driven mobility control is characterized by two effects in multiphase flow displacement. The first effect relates to mobilization of residual oil left after waterflooding (Guillen et al., 2012a). This effect is responsible for improvement of displacement (pore level) efficiency in emulsion flooding over water injection efficiency. Payatakes (1982) proposed the concept of ganglia dynamics to describe the flow of a dispersed non-wetting phase in porous media. Mobilization of residual oil can be attained by flow diversion caused by trapped emulsion drops and subsequent

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**Nomenclature**

| | |
|---|---|
| IFT | interfacial tension (N/m) |
| $k_{rw}$ | aqueous-phase relative permeability |
| $k_{ro}$ | oil-phase relative permeability |
| $\mu_o$ | oil viscosity (Pa s) |
| $\mu_w$ | water viscosity (Pa s) |
| $\rho_o$ | oil density (kg/m$^3$) |
| $\rho_w$ | water density (kg/m$^3$) |
| PV | pore volume |
| RF | recovery factor |
| $S_w$ | water saturation |
| $S_{wi}$ | irreducible water saturation |
| $S_{orw}$ | residual oil saturation to water |
| $V$ | Dykstra–Parsons coefficient |
| WAE | water-alternating-emulsion |

increase in the viscous pressure gradients around oil ganglia that overcome capillary pressure differences along the length of ganglia. Emulsion drops can be thought of as dispersed-phase ganglia that compete for mobility in the pore space, and hence a proper choice of drop-size distribution and interfacial properties should create water flow path diversion to mobilize oil ganglia originally trapped after waterflooding. The second emerging effect is an increased macroscopic sweep efficiency, which is commonly denominated volumetric sweep efficiency (Lake, 1989). Since oil droplets are transported by water, when fingers develop, appropriately designed drop size distributions will cause pore blockage, which will effectively decrease water mobility. This should lead to reduced water flow along water channels and diversion of flow, as to produce a better sweep of oil.

Direct injection of stable oil-in-water emulsions for EOR purposes was completed in the 1970s (McAuliffe, 1973a) with demonstrable oil recovery benefits. The injected oil-in-water emulsion can be either stabilized by surfactants or solid particles (Pickering emulsions). A connection with emulsion flow has been established with chemical flooding of heavy crude oil reservoirs. Jennings et al. (1974) proposed that emulsification in alkaline flooding, in addition to wettability reversal, offered the potential of reducing water mobility and hence increases oil recovery. Complex EOR mechanisms are involved with the injection of alkaline solutions (Samanta et al., 2011), including the formation of water-in-oil emulsions (Pei et al., 2011), but the response is system-specific (Samanta et al., 2011). Zhang et al. (2010) completed a total of 33 floods in sandpacks to investigate the dominant EOR mechanisms during chemical flooding in heavy-oil reservoirs. Results from straight injection of either an alkaline agent (A) or polymer (P), or a combination of A or P with surfactant (S) were carried out. The goal of their work was to investigate recovery efficient benefits of interfacial tension (IFT) reduction versus mobility control sandpack experiments. One of the conclusions relevant to the work presented in this paper relates to plugging of water channels. Zhang et al. concluded that the recovery enhancement correlated well with the pressure drop during flooding, rather than IFT alteration and this in turn denoted that the EOR benefit was mainly due to plugging of water flow paths and not reduction in IFT. Dong et al. (2009) carried out 21 floods in sandpacks to study tertiary recovery in connection with alkaline flooding of heavy oils. In their experiments, a low concentration of surfactant was used to guarantee the *in situ* formation of oil-in-water emulsions, as demonstrated in phase behavior studies. Pressure responses and tertiary recovery correlated well with surfactant and alkali concentrations. One interesting result in their study was a decrease in recovery at higher flow rate. This, in our opinion, might have been connected to a dependence emulsion flow response on capillary number. It turns out that direct emulsion injection recovery should decrease at high capillary number, as observed in the experiments reported by Dong et al. (2009) and Guillen et al. (2012b). *in situ* emulsion formation can also be associated to changes in the ionic content of the injection water and may explain some of the behavior observed in the injection of low salinity water (Moradi et al., 2011; Wang and Alvarado, 2012).

Romero et al. (2011) studied experimentally the flow of emulsions through porous media and described the flow using a capillary network model that uses experimental pore-level constitutive relationships of the flow through constricted quartz microcapillaries to obtain a representative mesoscopic flow behavior. Numerical results showed a qualitative match with experimental flow response obtained in sandstones and the expected mobility-capillary number dependence, evidencing the main physical mechanisms involved in oil-in-water emulsion processes.

Macroscopic description of such complex flow in porous media is crucial to develop feasibility analyses of emulsion injection as an EOR method and also to determine the optimum emulsion design that will maximize the amount of oil recovered. This is a challenging task that requires, not only a deep understanding of the fundamental physics at pore scale, but also the appropriate modeling of the governing parameters to describe the improved pore-level displacement efficiency and macroscopic mobility control performance at the Darcy scale.

In this paper, we present a reservoir modeling strategy of emulsion flooding that includes both the microscopic and macroscopic phenomena associated with emulsion injection by incorporating relative permeability curves that depend on the emulsion dispersed phase concentration. We have used relative permeability curves of emulsion and oil obtained by history matching emulsion flooding data, steady state two-phase flow experiments and synthetic curves that capture the main flow features associated with emulsion flow. In the parametric analysis performed both in a 2D and 1D model at lab scale using a pseudo-compositional commercial reservoir simulator (CMG-STARS™), emulsion was injected in tertiary mode. The goal of the analysis was to determine which of the mechanisms is dominant for oil recovery and the impact of emulsion design parameters as well as operational conditions in the amount of oil recovered with emulsion flooding.

## 2. Emulsions simulation model

Experimental results (McAuliffe 1973a,b; Cobos et al., 2009; Romero et al., 2011) strongly suggest that the Jamin effect can lead to reduction in fluid mobility in pores smaller than emulsion drops. This mechanism, in the case of oil-in-water (o/w) emulsions, is associated with a decrease in water phase mobility. This change in water mobility can be represented in Darcy-level models or continuum through a reduction in water relative permeability. Arhuoma et al. (2009b) developed a model for alkaline flooding in heavy oil based on the *in situ* formation of water-in-oil (w/o) emulsions. In the model, two aqueous phases, i.e. water and alkaline solution, and two oil components, crude oil and w/o emulsion, were considered. A pseudo-reaction in the model generates w/o *in situ* emulsification. They determined relative permeability curves from coreflooding production data using the JBN method (Johnson et al., 1959), which is a semi-analytical unsteady-state determination that neglects capillary pressure.