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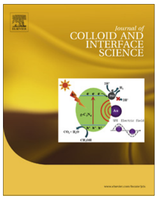

Effects of shear-thinning fluids on residual oil formation in microfluidic pore networks

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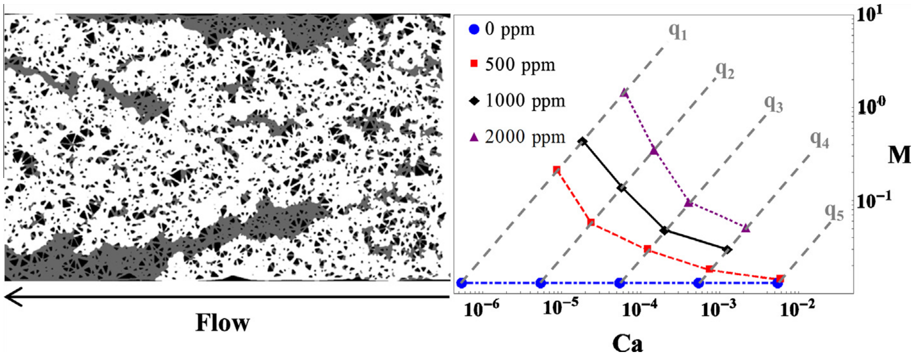
GRAPHICAL ABSTRACT



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ABSTRACT

Two-phase immiscible displacement in porous media is controlled by capillary and viscous forces when gravitational effects are negligible. The relative importance of these forces is quantified through the dimensionless capillary number Ca and the viscosity ratio M between fluid phases. When the displacing fluid is Newtonian, the effects of Ca and M on the displacement patterns can be evaluated independently. However, when the injecting fluids exhibit shear-thinning viscosity behaviour the values of M and Ca are interdependent. Under these conditions, the effects on phase entrapment and the general displacement dynamics cannot be dissociated. In the particular case of shear-thinning aqueous polymer solutions, the degree of interdependence between M and Ca is determined by the polymer concentration. In this work, two-phase immiscible displacement experiments were performed in micromodels, using shear-thinning aqueous polymer solutions as displacing fluids, to investigate the effect of polymer concentration on the relationship between Ca and M, the recovery efficiency, and the size distribution of the trapped non-wetting fluid. Our results show that the differences in terms of magnitude and distribution of the trapped phase are related to the polymer concentration which influences the values of Ca and M.

1. Introduction

On average, two-thirds of the original oil in geological reservoirs remains unrecovered, even after waterflooding [1,2]. The unrecovered oil becomes trapped in the reservoir forming discontinuous or continuous phase in swept or unswept reservoirs zones,

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respectively [1,3]. Reducing the amount of trapped oil is economically very important and is a subject of ongoing research. The amount of trapped oil and the size of the trapped blobs depend on a variety of parameters including (but not limited to) transport properties of porous media and the physical and chemical properties of the displacing and displaced fluid [4–9].

When gravitational forces are negligible, the two-phase immiscible displacement at the pore level is controlled by the competition between capillary and viscous forces whose relative importance is quantified through two dimensionless numbers: the capillary number Ca and the viscosity ratio M. Ca is often defined as:

$$\mathrm{Ca} = \frac{q\mu_1}{\sigma} \tag{1}$$

where q is the Darcy velocity, μ_1 the viscosity of the displacing fluid, and σ the interfacial tension between displacing and resident phases [10,11]. The Darcy velocity q is obtained by dividing the flow rate of the invading fluid (Q) by the cross-sectional area of the porous medium (A). The viscosity ratio M is defined as:

$$\mathrm{M} = \frac{\mu_1}{\mu_2} \tag{2}$$

where μ_2 is the viscosity of the resident fluid. The displacement is considered to be favourable if $M > 1$ and unfavourable if $M < 1$. Depending on the values of Ca and M, capillary fingering, viscous fingering, or stable displacement may be observed, influencing flow patterns and phase entrapment during immiscible two-phase flow in porous media [12–16].

The effect of M and Ca on the residual oil saturation at macroscale has been extensively discussed in literature [12,17]. At small Ca, when viscous forces are negligible and capillary fingering prevails, the patterns described by the invading fluid during imbibition will follow the percolation pathways without any specific direction compared to the flow direction [13]. These patterns are described through the invasion percolation statistical approach [18]. On the other hand, viscous fingering is often modelled through diffusion-limited aggregation [19] and gives rise to tree-like fingers oriented in the direction of flow [13]. Viscous fingers are common features of unstable displacements in which water is more mobile than oil [20]. Since Ca has a significant impact on the amount of trapped fluid, often the residual saturation S_{ro} is experimentally measured as a function of Ca to obtain the so-called Capillary Desaturation Curve (CDC) [14], with S_{ro} (Ca) = (volume of the residual oil at the given Ca)/(total pore volume). The CDC is one of the most important input parameters in the reservoir simulation software for enhanced oil recovery [9,21].

Some of the most popular injecting fluids used in Enhanced Oil Recovery (EOR) and in soil remediation practices are non-Newtonian such as polymer solutions, foams or emulsions, and present shear-thinning behaviour, i.e. the viscosity of the fluid decreases as the applied shear stress increases. One of the main purposes of applying these complex fluids is to reduce mobility ratio [22]. This results in viscous fingering reduction and therefore improved sweep efficiency in the reservoir [23]. When a shear-thinning fluid is used as a displacing fluid, both Ca and M are functions of Q (note that μ_1 used in the definition of Ca and M stands for the apparent viscosity of the displacing fluid in the porous medium at a given flow rate). As a consequence, an evaluation of the effects of Ca on S_{ro} and trapped blob sizes assuming a constant M is not acceptable for most shear-thinning fluid displacements.

Several groups investigated the non-Newtonian fluid flow in porous media and its potential application for oil displacement [24–26]. For example, flooding experiments using shear-thinning polymer solutions were previously conducted [20,27] in order to analyse the effect of polymer concentration on front stabilisation and recovery efficiency at a unique flow rate. Other authors [28] carried out computational fluid dynamics simulations using a digitalised pore network to investigate the non-Newtonian fluid displacement at the microscale and compared their results with the flooding experiments [20]. In previous work [2], a micromodel study was performed to investigate the effects of rheological properties of several complex fluids used in EOR on oil recovery.

In subsurface remediation, shear-thinning fluids have been used to create hydraulic stable zones [29] and to force chemical amendments into low permeability zones [30–33]. Although most remediation studies using shear-thinning fluids consist of laboratory experiments, a recent field implementation was reported [34]. Emplacement of amendments into low permeability zones is of particular interest because contaminants in such zones might sustain persistent plumes in adjacent transmissive zones due to diffusion-controlled release processes [35]. Injection of a shear-thinning fluid into a heterogeneous subsurface induces cross-flow between higher- and lower-permeability layers. Mobility reduction behind the polymer solution in a higher-permeability layer then creates a transverse pressure gradient that promotes fluid migration into less permeable layers [32]. In most remediation studies, the shear-thinning fluid contained the biopolymer xanthan [33,34].

Motivated by the widespread use of shear-thinning fluids in porous media and its great potentials in enhanced oil recovery and soil remediation, the specific objectives of the present study are to investigate how Ca and M affect S_{ro} and trapped blob distributions during immiscible two-phase flow in porous media involving shear-thinning fluids. To do so, a comprehensive series of polymer waterflooding displacement experiments were conducted using micromodels with well-defined characteristics to quantitatively investigate the effects of the polymer concentration C_p on oil entrapment patterns, visualised by means of a high resolution microscope at different flow rates. The findings of this paper extend our understanding of the physics governing two-phase flow in porous media using shear-thinning fluids.

2. Materials and methods

2.1. Micromodel

A series of experiments was conducted displacing resident silicone fluid by aqueous polymer solutions in a micromodel. The micromodel was fabricated in a silicon wafer using standard photolithography and inductively coupled plasma–deep reactive ion etching (ICP-DRIE) methods. Details of the fabrication process can be found elsewhere [36]. After the incorporation of nanoports serving as the inlet and outlet of the micromodel, the micromodel was chemically treated to be cleaned and to acquire uniform wettability. After the cleaning procedure, micromodels have a uniform and stable hydrophilic behaviour with contact angles < 16° [37]. The pore-network compartment of the micromodel has a length of 1.4 cm, a width of 0.7 cm, and a thickness of 29 ± 1 μm. The flow network had approximately 3000 pore bodies and 9000 pore throats, resulting in a porosity ε of 0.6. The topology of flow network was based on truncated log-normal for the pore-body distribution and is considered to be a good approximation for pore size distribution in natural porous media [38]. The size of the pore throats was assigned by employing a concept previously proposed in the literature [7], where the size of a pore throat is a function of the dimensions of the connecting pore bodies. The width of the pore bodies varied from 80 to 160 μm, while the width of the pore throats varied from 56 to 159 μm. The pore bodies are cylinders and the pore throats are parallelepipeds. In planar view, pore bodies are circular while pore throats are rectangular, with a minor