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Pore-scale flow characterization of low-interfacial tension flow through mixed-wet porous media with different pore geometries

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ABSTRACT

The low-interfacial tension flow through porous media occurs in surfactant-based enhanced oil recovery (EOR), soil clean-up, underground removal of the non-aqueous phase liquid and dense non-aqueous phase liquid, etc. In surfactant-based EOR processes, numerous works have been carried out to characterize – either qualitatively or quantitatively – the micro- and macro-scale flow behavior. What has been lacking is to link the statistics of oil blobs population (e.g., distribution of blob length and diameter) to the pore-scale phenomena and macro-scale quantities. In particular, no work has been reported to elucidate the effect of the ratio of pore body to throat diameter (i.e., aspect ratio) on the pore-scale characterization based on the blobs population statistics. The significance of the aspect ratio lies in that it describes the geometry of a porous medium and is one of the foremost morphological features. The aspect ratio is also one of the fundamental factors governing the pore-level events. This study presents the effect of aspect ratio on the statistical distribution of the blob length and equivalent diameter and links the blobs population statistics to the observed pore-level events. The pore-scale variation of the ratio of viscous-to-capillary forces acted on the oil blobs at the threshold of displacement is utilized to characterize the effect of blob length distribution at different aspect ratios. It also provides some insight into correlating the change in oil recovery efficiency and capillary number, by change in aspect ratio, with the change in blobs population statistics.

1. Introduction

The fluid flow through porous media at low-interfacial tension (IFT) flow condition occurs in several applications, such as surfactant-based processes for the removal of the non-aqueous phase liquid (NAPL) and dense non-aqueous phase liquid (DNAPL) from underground water resources, surfactant-based chemical enhanced oil recovery, clean-up of contaminated soils using surfactants, etc. Some works have been carried out in the past to characterize, either qualitatively or quantitatively, the behavior of low-IFT flow through porous media on the micro- and macro-scale basis.

The characterization of the low-IFT flow in surfactant-based chemical enhanced oil recovery (EOR) has progressed considerably [1]. This has helped to develop some mathematical models for this type of flow [2,3] or optimize the process [4–6]. Conducted studies in this area are either macroscopic or microscopic. The results from both types of studies has shown that the mobilization of oil blobs is significantly affected by the adsorption of surfactant, level of IFT, phase behavior of the different surfactant systems, and different microscopic as well as macroscopic phenomena.

The adsorption of surfactant influences the oil mobilization [7,8] by decreasing permeability [9] and sweep efficiency [10]; and is affected by oil/brine ratio, alkaline additives [11], phase behavior and temperature [12,13], surfactant precipitation and redissolution [14], rock type and brine composition [15], presence of polymer [16], use of biosurfactant [17], etc. Delivering the surfactant in vesicle form [18] or use of some preflushing methods [19] can significantly reduce the adsorption, which is a source of huge surfactant loss during oil mobilization [20,21].

Another dictating factor influencing the oil mobilization is the level of IFT [22,23] and the phase behavior of different surfactant systems [24–26], which lead to different dynamic interfacial behavior of the crude oil/sulfonate systems [27], and therefore, suggests that the formulation of surfactant/water/oil systems should be optimized so as to achieve a favorable mobilization of the oil ganglia at either low- or ultralow-IFT regimes [28] at different pressures, temperatures, and oil compositions [29,30].

In order to address the effect of different phenomena in mobilization of oil blobs, some studies have been conducted to understand the emulsification and film-forming phenomena, physical

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Nomenclature

Letters

Ca	macroscopic capillary number
CA_{imb}	imbibition capillary number
CA_{mob}	pore-scale mobilization capillary number
D	median bulge diameter (m)
d	blob diameter (m)
F_c	cumulative frequency
IFT	interfacial tension ($\mathrm{N\,m^{-1}}$)
k	absolute permeability ($\mathrm{m^2}$)
L	length of the core (m)
MSDI	modified structural difficulty index ($\mathrm{m^{-1}}$)
M_X	number of data Y
N	total number of data
NAPL	non-aqueous phase liquid
DNAPL	dense non-aqueous phase liquid
r_{dr}	equilibrium radius of curvature of the meniscus of the blob at the threshold of mobilization (m)
r_{imb}	equilibrium radius of curvature of the meniscus of the blob at the threshold of mobilization (m)
R_{eq}	equivalent pore radius (m)
R_b	pore body diameter (m)
R_t	pore throat diameter (m)
S_{di}	initial displaced phase saturation
u	Darcy velocity ($\mathrm{m\,s^{-1}}$)
v_p	interstitial velocity of the displacing phase ($\mathrm{m\,s^{-1}}$)
X	a reference value
Y	a given variable

Greek symbols

μ	dynamic viscosity of the displacing phase (Pa s)
θ_A	Advancing contact angle
σ	interfacial tension between the displacing and displaced phase ($\mathrm{N\,m^{-1}}$)
ℓ	blob length (m)
Ø	porosity of the porous medium
ξ	blob size distribution function

displacement mechanisms [31–38], dispersion and chromatographic separation [39], salinity gradient concept [40], viscous fingering [35–37,41,42], gravity underride and segregation [43], mechanism of adsorption [44], and wettability alteration [45]. In microscopic studies, pore-level events have been investigated to understand the effect of pore geometry [36], pore wettability [36], connate water saturation [37], and pore connectivity and topology [38] on two-phase filtration and topology of the trapped oil.

The results of the above-mentioned studies help to understand how oil–chemical solution menisci move, why the oil phase breaks into ganglia or blobs and sometimes remain trapped, and what mechanisms help to mobilize them. Moreover, the results have guided the design of macroscopic studies. What has been lacking is a means of linking important statistical information to some of the mechanisms observed at the microscopic level and to macroscale quantities, such as recovery efficiency and capillary number. The statistical information of flow help in network modeling studies, developing more realistic pictures of pore-level physics, and finally better correlating the macroscopic quantities needed to interpret corefloods and to design EOR processes [46]. If oil blobs are mobilized by lowering IFT, then the statistical information on length distribution of the blobs becomes a key factor in determining the recovery efficiency [47,48]. It also helps to determine the distribution of viscous forces exerted on blobs that provides insights into modeling of the blob mobilization [49]. Moreover, linking the statistical information on blobs diameter and shape to pore-scale phenomena paves the way for designing efficient displacement techniques [50]. On the other hand, in displacements controlled by capillarity, which are typical of oil reservoir floods, the pore-level events are governed by the local pore geometry, pore topology, and fluid properties. Therefore, to gain a better knowledge of the pore-level statistics, it is desirable to determine the effect of morphological features of the pore space. The most important morphological feature of a porous medium can be described by the ratio of pore body to throat diameter, i.e., aspect ratio [46]. This study presents the effect of pore throat size (or aspect ratio) on blob size distribution and links the observed statistics to some of the observed pore-scale phenomena. The distribution of the viscous forces exerted on blobs is determined at different aspect ratios through the use of pore-scale mobilization capillary number. It also provides some insight into correlating the observed blob size distribution with the trend of change in pore throat size, recovery efficiency, and the capillary number. The findings of this study lead to a better understanding of some of the displacement mechanisms that are important for modeling blob mobilization under low-IFT condition. In addition, these findings can be used in network modeling studies where realistic description of the pore-level physics should be available to better incorporate them into the model.

2. Experimental set-up, materials, and procedures

2.1. Set-up description

The micromodel set-up consists of a cleaning system, a fluid injection section, an optical system, a photography system, a micromodel holder, and the monitoring computer system. Fig. 1 shows the schematic diagram of the experimental set-up. A high-precision Quizix model micro flow piston pump (positive displacement, stepper motor-driven pump, QL-700 Pump) drives the displacing fluid at the desired rates (between 10^{-5} and $10\ \mathrm{cm^3/min}$). The camera system can be moved horizontally and is capable of working at a magnification up to 200 times. The digital microscope was used to capture the microshots given in Fig. 2. It should be noted that the magnification number of the given microscopic pictures in this study is 35. Additional parts of the micromodel set-up are the pump supply, transfer vessels, pump pressure supply, Eldex pump, and filter.

2.2. Materials

West Paydar crude oil (West Paydar is an oil field located in western Iran) has been used as the crude oil in this study. The crude oil properties are given in Table 1. The density and viscosity of the crude oil at different conditions were measured using a digital densitometer (512P, Anton Paar®) and a rolling-ball viscometer (P/N, Chandler Engineering), respectively. A petroleum sulfonate was used as the surfactant material. Surfactant properties are given in Table 2. A dilute surfactant solution was prepared and used in all tests. To make the surfactant solution, pure surfactant was dis-