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Surfactant effects on the efficiency of oil sweeping from the dead ends: Numerical simulation and experimental investigation

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ABSTRACT

The objective of this work is to investigate the effects of the surfactants on the oil extraction from the dead ends through the numerical simulations and experimental evidences. The volume of fluid approach in the frame of the finite volume method has been used for numerical simulations in 2-D domain and experimental flooding tests have been done using a glassy micro-model. The effects of the water–oil, water–wall and oil–wall interfacial tensions have been investigated numerically and some results are compared to experimental flooding results. Simulations have been done in the cases of water-wet, neutralized-wet and oil-wet micro-models also. The numerical results show that in the case of water-wet walls, the sweep efficiency is more than that of oil-wet walls. Also the results show that with increasing the interfacial tension between the oil and water, sweep efficiency increases dramatically. Comparisons between the experimental observations and numerical results confirm these conclusions.

Keywords: Surfactant; Oil; Dead end; Finite volume method; Capillary number; Flooding

1. Introduction

The petroleum industry recognized the problem of inefficient oil recovery by the conventional (primary and secondary) recovery methods in the early 1900. After that, extensive researches have been conducted to improve the displacement and sweep efficiency of oil recovery processes. Many different processes have been designed to enhance the displacement efficiency by reducing the residual oil saturation in the reservoir.

The water flooding is one of the enhanced oil recovery processes. However, this process has some drawbacks. One of them is the fingering problem, in which water goes through the oil instead of sweeping it. Although the residual oil trapped in the dead ends within the porous media is one of the most part of residual oil in a reservoir, the water flooding cannot displace or recover the trapped oil in them. However, it seems that adding surfactant to the flooding water, enhances oil sweeping from the open capillaries and dead ends.

Surfactants are important chemical compounds widely used in industries. These materials mostly have synthetic amphipathic molecules which place themselves in the interface of two immiscible phases and reduce the interfacial tension through the partial dissolution of one phase in the other phase. Surfactants at the concentrations less than CMC (critical micelle concentration) congregate at the interface of fluids or free surface of fluids or adsorbed by the container surface. Surfactants could increase sweep efficiency in flooding process by the same mechanisms.

Maldal et al. (1998) evaluate polymer–surfactant flooding on the Gulfex field, Norway. Kon et al. (2002) used ASP (alkaline surfactant polymer) to assess EOR (enhanced oil recovery)

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Table 1 – Power of length in different forces of fluid mechanics.

Origin of the force	Definition	Power of length
Body force	$F = \rho g D^3$	3
Inertia force	$F = \rho \mathbf{V} . \nabla \mathbf{V} D^3$	2
Viscose force	$F = \mu \nabla \mathbf{V} . D^2$	1
Interfacial force	$F = \sigma D$	1

in Illinois reservoirs which were water injected for a period of times. They found that decreasing capillary forces could improve oil recovery. Al-Attar (2011) investigated the effects of the surfactant on the oil foam as a displacing phase to improve oil recovery. Li et al. (2011) investigated adsorption of betaine type surfactant on quartz sand. The adsorption affects the wettability of the medium.

Despite the fact that experimental results show that the surfactants enhance the displacement efficiency considerably, there are few theoretical studies on this subject, especially to determine the effects of the oil–water, oil–wall and water–wall interfacial tensions on the oil recovery from the dead ends.

Dakhlia (1995) simulated polymer and surfactant flooding using horizontal wells. Mollaei et al. (2011) studied application and variance based sensitivity analysis of surfactant-polymer flooding using modified chemical flood predictive model.

Typically, there are four forms of the residual oil in the reservoir, the oil droplet, the oil film, the oil in throats and the oil trapped in the dead ends (see Zhang et al., 2008). However, the residual oil available within the reservoir pores can be in more complicated forms. In the theoretical studies, geometry of the micro-pores are often simplified, for example, an abrupt axisymmetric expansion, an abrupt axisymmetric contraction, rarely micro-pore with dead ends, etc. (see Hongjun et al., 2006). Kamyabi and Ahmad Ramazani (2011) investigated ability of generalized Newtonian fluids to extract oil from dead ends. They also studied effects of the viscoelastic fluids on the oil sweeping from dead ends (see Kamyabi et al., 2013). One of conclusions of these two recent studies is that Reynolds number has minor effects on the sweeping of oil from dead ends.

The FVM (finite volume method) based on the pressure-correction strategy has been extensively and successfully employed for the fluids flow and the heat transfer problems, for more than three decades. Using benefits of FVM, VOF (volume of fluid) approach (see Hirt and Nichols, 1981) and SIMPLE (semi implicit method for pressure linked equations) and PISO (pressure implicit with splitting of operators) (see Patankar, 1980; Versteeg and Malalasekera, 2007) algorithms together, on the structured grids, the effects of the oil–water, water–wall and oil–wall interfacial tensions on the oil sweeping from the dead ends have been investigated in the presented work and some results are compared with an experimental study. OpenFOAM which is an open source FVM software was used for simulation purposes and any needed scripts has been added to its core.

2. Importance of forces in the capillary flows

In order to make a conceptual study on the oil sweeping, the importance of involved forces must be understood. Table 1 shows the participating forces and their relation to the dimensions of the considered environment. It is clear that with decreasing the length scale, the magnitude of body forces and inertia force becomes less than that of viscose and interfacial forces. In the micro-fluids studies this called square–cube rule (see Nguyen and Wereley, 2002). Therefore, in the micro-pore simulations this two recent forces are very important. As a result in the EOR processes, polymer flooding changes the viscose force and the surfactant changes the interfacial force. So in the presented study the more important dimensionless number is the *Ca* number (Capillary number) which is the ratio of viscose force to the interfacial force.

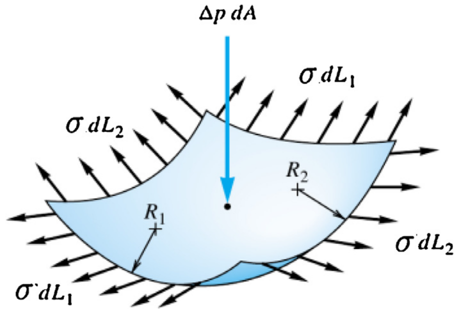

Fig. 1 – Surface curvature and related forces.

3. Governing equations

The conservation of mass and momentum are the main governing equations in this subject. These equations for incompressible fluids and with neglecting the gravitational forces (see Edussuriya et al., 2003) have been written as Eqs. (1) and (2) respectively.

$$\nabla \cdot \mathbf{V} = 0 \quad (1)$$

$$\frac{\rho D\mathbf{V}}{Dt} = -\nabla p + \nabla \cdot \tau + \mathbf{F}_s \quad (2)$$

In this equation τ is stress tensor which is defined as below for Newtonian fluids with viscosity μ:

$$\tau = \mu \dot{\gamma} \quad (3)$$

where the rate of deformation tensor $\dot{\gamma}$ is given by

$$\dot{\gamma} = \nabla \mathbf{V} + \nabla \mathbf{V}^T \quad (4)$$

As the result of discussions in previous section, $\mathbf{F}_s$ which is interfacial force and defined as Eq. (5) exists in the conservation momentum equation.

$$F_s = \sigma L \mathbf{n} \quad (5)$$

In this equation σ is interfacial tension coefficient, L is the length of considered surface and $\mathbf{n}$ is normal vector of the surface according to Fig. 1.

Interfacial force induces pressure difference P_c between both sides of interface which is calculated by equation

$$P_c = \sigma \kappa \quad (6)$$

In this equation κ is surface curvature and its concept comes from this equation (see Fig. 1):

$$\kappa = \left(\frac{1}{R_1} + \frac{1}{R_2}\right) \quad (7)$$