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Drainage type oil and heavy-oil displacement in circular capillary tubes: Two- and three-phase flow characteristics and residual oil saturation development in the form of film at different temperatures

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ABSTRACT

It is still uncertain to what extent pore scale mechanisms, such as the counter and co-current nature of multiphase flow, the trapping mechanisms, the distribution of phases, and heat transfer mechanisms affect the process of isothermal and non-isothermal gravity drainage dominated oil and heavy-oil recovery. This type of processes is encountered during gas injection into oil reservoirs for enhanced oil recovery under isothermal conditions. Steam injection in thick reservoirs where gravity displacement is an effective mechanism and steam assisted gravity drainage (SAGD) are well-known examples of a non-isothermal gravity dominated heavy-oil recovery applications. It is commonly observed that field scale applications of the latter yield less recovery than estimated. One may also encounter this type process in the removal of any crude oil contamination in shallow zones where steam injection is used for cleaning. All these require in-depth analysis of the problem at the pore scale to account for the residual oil saturation (S_{or}) in the swept zone.

In this paper, we used a single capillary tube (radius < 0.03 cm) to mimic an elementary volume in the swept area during gravity dominated displacement applications and studied the flow characteristics of two and three phase flow with emphasis on film development. We carried out two-phase (air–oil) and three phase (air–oil–initial water saturation) flow displacements in a capillary tube under different temperature conditions, varying the air injection rate and the capillary properties. Detailed visualization experiments were carried out to analyze (1) the effects of heavy oil viscosity, wettability and spreading coefficient on displacements at different temperature conditions, (2) the interplay among capillary, gravity and viscous (air injection rates) forces and wettability using different capillary sizes (pore size), and (3) the residual oil saturation in the form of film development and phase distribution in the capillaries (mainly the thicknesses of the wetting and non-wetting phases).

The experimental observations suggest that for heavy oil there is a threshold capillary number around $1.0\text{E}-2$ over which the oil recovery (and therefore the residual oil saturation) is very sensitive to the capillary number, i.e., the injection rate, interfacial tension, wettability and temperature. At lower capillary numbers (typical range for oil reservoirs) temperature and hence viscosity do not have a significant influence in the residual oil saturation of the processed and crude oils; for horizontal displacement the residual oil saturation is a function of the capillary forces and for gravity drainage experiments it depends of the competition between capillary and gravity forces (Bond number).

1. Introduction

Determination of the remaining or residual oil saturation during complex displacement processes such as three phase flow under isothermal and non-isothermal conditions is still a challenge. This is partly due to an incomplete understanding of the displacement mechanisms at the pore scale. Numerous efforts have been made to determine the magnitude and the distribution of the residual oil saturation in some processes such as waterflooding in reservoirs under water wet conditions at ambient conditions (Chatzis et al., 1983, 1988b; Oshita et al., 2000; Kamath et al., 2001; Yang et al., 2013).

More recently, a visual analysis of the steam assisted gravity drainage process (SAGD) was carried out to clarify the physics of the process at the pore scale using micromodels (Mohammadzadeh and Chatzis, 2009). The residual oil development during such processes

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is more crucial as the process efficiency is very critical due to low production caused by the nature of oil and rock and the high cost of steam injection. It was recently shown that the highest ultimate recovery reached during the SAGD process is only 60% (the average in the Albertan applications yielded 35–40% ultimate recovery), which is well below expectations to make the process efficient (Jimenez, 2008; Al-Bahlani and Babadagli, 2009). Hence, one needs to distinguish the reasons for low oil production in such processes and to clarify to what extent it is related to pore scale dynamics. In cases of relatively inexpensive processes, such as gas injection (Hagoort, 1980; Chatzis et al., 1988a) or the double displacement process where gravity drainage is the dominant production mechanism (a double displacement generally occurs when gas is injected in a reservoir after a waterflooding: gas displaces oil and this in turn displaces water), determination of residual oil saturation is also critical as the target oil is not abundant in this type of tertiary recovery application and thereby the efficiency of the process is highly sensitive to the ultimate recovery.

In this regard, one may start with the 'simplest' way of the determination of the residual liquid saturation left behind in a circular capillary tube during a gas–oil displacement. In a pioneering work, Fairbrother and Stubbs (1935) found that in a capillary tube, an air bubble flows faster than liquid being displaced due to the adhesion of a thin film on the walls of the tube. The magnitude of the residual liquid left behind was found to be a function of the balance between the viscous forces and the capillary forces. This was expressed through the capillary number, *Ca*, as follows:

$$Ca = \frac{\mu U_b}{\sigma} \tag{1}$$

where μ is the viscosity of the displaced fluid, U_b is the bubble velocity and σ is the surface tension air–liquid. They introduced an empirical equation to determine the fraction of the liquid supported on the surface of the tube and was related to the capillary number as follows:

$$W = \frac{U_b - U_m}{U_b} = Ca^{1/2} \tag{2}$$

where U_m is the average velocity of the liquid. This correlation is useful for $1.0\mathrm{E}-3 < Ca < 1.0\mathrm{E}-2$. Taylor (1961) found that Eq. (2) can be extended to $Ca = 0.09$ and W approaches an asymptotic value of 0.56.

Later, Bretherton (1961) proposed an equation to predict the film thickness surrounding the bubble as follows using the lubrication theory and assuming that the bubble profile is of constant curvature except very near the wall, where the meniscus is deformed by viscous forces:

$$\frac{h}{r} = 0.643(3Ca)^{2/3} \tag{3}$$

Through his own experiments, Bretherton found that Eq. (3) applies for $Ca > 1.0\mathrm{E}-4$. At lower gas velocities, the experimental film thickness surpassed the theoretical value and at the very lowest capillary numbers ($Ca < 1.0\mathrm{E}-6$) the difference between experimental results and the two-third power law involve a factor of 8. Following the work of Bretherton, Cox (1962) solved the Stokes equation using a stream function for $2 < Ca < 10$ and presented experimental results indicating that the ultimate value of W was about 0.6. Park and Homsy (1984) formalized the Bretherton model through perturbation techniques and Ratulowski and Chang (1989) extended it to higher capillary numbers using a composite lubrication equation. Chen (1986) measured the film thickness through a conductimetric technique and found that it decreased as the capillary number diminished until it approaches a constant value at low *Ca*. He found a deviation from Bretherton theory and argued that such deviation was due to the roughness of the tube wall. Ratulowski and Chang (1990) investigated the Marangoni effect due to impurities in the liquid during the movement of long air bubbles in capillaries. They stated that the Marangoni effect could explain the underestimation of the film thickness of the Bretherton model at low air bubble velocity. Berg (2010) analyzed the implications of the Marangoni effects in different situations and the emergence of such effects due to variations of surface or interfacial tension as well as of temperature gradients.

Schwartz et al. (1986), through experimental research for very small capillaries numbers, $Ca < 1.0\mathrm{E}-5$, explained some of the discrepancies of the literature with respect to the dependence of the deposited film thickness on bubble length. They found that for the bubbles of length many times greater than the tube radius, the ratio of film thickness to tube radius is a function of the capillary number. For bubble length less than 20 times that of the tube radius, there is a good agreement with the Bretherton theory over two orders of magnitude of the bubble velocity.

More recently, the research in this topic has focused on solving the equations of motion (generally reduced to the Stokes equation for slow motion) through different numerical techniques covering different capillary number ranges (Reinelt and Saffman, 1985; Shen and Udell, 1985; Martinez and Udell, 1989). The work of Giavedoni and Saita (1997) covered the widest capillary number range, $5.0\mathrm{E}-5 < Ca < 10$, and observed an excellent agreement with the Bretherton's theory for $Ca \leq 1.0\mathrm{E}-3$. However, it is still a challenge to model the low velocity region due to the complexity of solving the thin-film region (Dong and Chatzis, 2004). Low capillary numbers ($Ca < 1.0\mathrm{E}-4$) are characteristic of oil reservoirs (Schwartz et al., 1986; Dullien, 1992).

While the previous works focused on solving the problem of the residual liquid saturation for high capillary numbers and ambient conditions, we focused on the analysis of the effects of different high temperature conditions on the residual oil saturation (film thickness) in gas–oil displacements at low capillary numbers. In practice, this is a way to approximate non-isothermal heavy-oil recovery processes such as SAGD or steam injection in thick reservoirs.

We are conscious that, in steam based heavy-oil recovery methods, the process is a complex multiphase flow problem where it is possible to find steam, condensed water, oil, water in oil emulsions and organic depositions in a single pore at the same time, depending on the temperature gradient, the stage of the process and the thermodynamic behavior. For the sake of minimization of this complexity, we started from the simplest way to determine the residual oil saturation as a thin film having a liquid phase (heavy-oil) and a gas phase (air) in a circular capillary tube. Also, although it was recognized that circular capillary tubes are not the best option to mimic the network of pores in a real reservoir (Blunt et al., 1995; Dong and Chatzis, 2004) due to its low retention power, we used this approach on the basis of their availability for relatively small diameters and ease of use in visualization, especially with heavy crude oil. We believe that, as a starting attempt, this research contributes to a better understanding of the behavior of residual oil in gas/steam–oil displacements where there is a significant temperature gradient. To the best of our knowledge, there are no experimental and quantitative pore scale studies (capillary tubes) of this kind in the literature focus on high temperature heavy oil recovery applications.

2. Experimental work

2.1. Setup

An experimental set up was designed for horizontal displacements as shown in Fig. 1a. A Pyrex circular capillary tube ($r = 0.0254$ cm) was placed in a leveler which had a millimeter