CORNER OIL FILM ELEVATION ABOVE THE GAS-OIL INTERFACE IN WATER-WET CAPILLARIES

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This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in St. John's Newfoundland and Labrador, Canada, 16-21 August, 2015

ABSTRACT

In gas assisted gravity drainage, very high oil recovery factors can be obtained when a thin oil film is formed over the water surface in water wet porous media. The formation of an oil film, as an intermediate wetting phase, over the water (wetting phase) surface in the presence of gas (non-wetting phase) is typically linked to the spreading coefficient which is the gas-water interfacial tension subtracted by the sum of the oil-water and oil-gas interfacial tensions. However, the oil film characteristics not only depends on the interfacial tension, but also depend on the geometry of the phase contacts on solid surface which is affected by the geometry and wettability of the solid surface. The oil film, which may exist between the water and gas in the corner of capillaries, can play an important role in oil recovery by gravity drainage during immiscible gas injection. The thin oil film can be the path to transfer the trapped oil in smaller pore-throats, which is left after gas injection, toward the oil bank beneath the gas front. Additional oil recovery can be obtained by gravity drainage if the gas-oil capillary pressure is high enough for the entry of non-wetting phase into the smaller pore-throats. In this article, the oil film characteristics in the corner of a simple square capillary tube are modelled, based on the size of the capillary tube, phase interfacial tension, phase differential density and the distance between the gas front and oil front, through balancing the gravity and capillary pressure under equilibrium condition. The results show that having a higher gas-oil interfacial tension, lower gas-oil differential density and larger oil bank size provides an intermediate phase (oil) with better hydraulic communication over a greater elevation. The proper hydraulic communication above the gas front assists the gravity drainage mechanism to recover more oil from smaller pore-throats in particular scenarios. These scenarios are identified and discussed in this article.

INTRODUCTION

Oil displacement by gas-assisted gravity drainage in a water wet porous media often results in a high recovery factor. In gas-assisted gravity drainage, both gravity and capillary phenomena affect the oil recovery. The conditions that provide an efficient oil recovery factor can be identified by characterizing mechanisms of fluid displacement in gas-assisted gravity drainage. Oren and Pinczewski [1] investigated three phase fluid flow in porous media and drew a relationship between the phase interfacial tensions and the state of the fluids' contacts configuration. In many investigations, it has been stated that high oil recovery by vertical gas injection in water-wet porous media can be obtained if the oil phase spreads over the water surface in the presence of gas, and the spreading condition of oil over the water surface is only controlled by the interfacial tension between each pair of fluids [2, 3, 4]. Further investigations showed that the oil displacement mechanism is also affected by capillary pressure rather than by interfacial tension alone [5]. The capillary pressure in addition to the fluids' interfacial tensions is a function of the curvature of the interfaces between fluids, which is affected by the capillary geometry and phase contact angle. A stable oil layer over the water surface has also been observed in a system with a negative oil spreading coefficient [5, 6]. Dullien et al. [7] showed that the rate of oil recovery in porous media, when an oil film forms on the smooth glass bead surfaces having positive spreading coefficient, is very low and unmeasurable. Conversely, an oil film that is formed in corners of wedges and crevices on the surface of scratched glass beads is thicker. The thick oil films yielded higher rate of oil recovery that could be measured. Blunt et al. [8] calculated the height of the oil film in porous media for the three phase system. They compared the oil-water and oil-gas contact radii in capillary corners evaluating capillary pressures based on the fluids interfacial tensions and densities. Depending on the fluid interfacial tensions and differential densities, two different types of the oil film are formed in the corner of capillaries. In the first type, the oil film can be present over the water surface at any elevation, and in the second type, the presence of the oil film is limited to a critical elevation. Blunt et al. [8] predicted that for conditions in which the oil height is limited, the oil saturation after vertical gas injection is very low. However, a reverse result was observed for a system in which oil has a negative spreading coefficient.

In this article, the equilibrium height of the oil film in the corner of a water-wet and square shaped capillary tube is calculated varying the fluid characteristics. The relationship between the residual oil saturation after gas breakthrough and the state of the thin oil film is discussed. The results of this study provide insight for the phenomena affecting the gas-assisted gravity drainage oil recovery method.

THEORY

The oil film in a water-wet and square shaped capillary tube with sharp corners can be characterized if the capillary pressure between each pair of phases is known. Fig. 1 schematically shows a square capillary tube containing gas (non-wetting phase), oil (intermediate wetting phase) and water (wetting phase). The equilibrium capillary pressure between oil and water at point 1 in Fig. 1a, (P^*_{cow}), is shown in Eq. 1 [8]

$$P^*_{cow} = \frac{4\sigma_{ow}\cos\theta_{ow}}{D} \tag{1}$$

where, 'σ_{ow}' is the oil-water interfacial tension, 'θ_{ow}' is the oil-water contact angle, and 'D' is the size of the square tube side. The capillary pressure (P_c) at any point inside the tube is the local differential pressure between the non-wet phase (P_{nw}) and wetting phase (P_w) as indicated by Eq.2 [8].

$$P_c = P_{nw} - P_w \tag{2}$$

Oil and water hydrostatic pressure along the corners of the vertical tube vary differently depending on their densities. The water and oil pressure above point 1 (oil-water contact front) in Fig. 1a are calculated by Eq. 3 and 4;

$$P_w = P_w^* - \rho_w g(H+L) \tag{3}$$

$$P_o = P_o^* - \rho_o g(H+L) \tag{4}$$

where, ‘P_w’ and ‘P_o’ are water and oil pressures along the tube, ‘$P^*{}_w$’ and ‘$P^*{}_o$’ are the water and oil hydrostatic pressure at point 1 in Fig. 1a, ‘ρ_w’ and ‘ρ_o’ are oil and water densities, H is the height of the oil film above the gas-oil contact front (point 2 in Fig. 1a), L is the oil bank length (distance between point 2 and point 1 in Fig. 1a), and g is gravitational constant, which is assumed to be 9.8 m/s^2 in the calculations.

The oil-water capillary pressure at any location above point 1 can be calculated by substituting Eq. 3 and 4 in Eq. 2. Knowing the gas-oil interfacial tension (σ_{go}) and gas-oil contact angle (θ_{go}), the gas-oil capillary pressure above their contact at point 2 in Fig. 1a can be calculated in the same manner. The oil-water and gas-oil capillary pressures, ‘P_{cow}’ and ‘P_{cgo}’, are given in Eqs. 5 and 6, respectively;

$$P_{cow} = P_{cow}^* + \Delta\rho_{ow} g(H+L) \tag{5}$$

$$P_{cgo} = P_{cgo}^* + \Delta\rho_{go} gH \tag{6}$$

where, ‘$\Delta\rho_{ow}$’ and ‘$\Delta\rho_{go}$’, are the oil-water and gas-oil differential densities respectively, $P^*{}_{cow}$, is the local oil-water capillary pressure at point 1, and ‘$P^*{}_{cgo}$’ is the local gas-oil capillary pressure at point 2. Neglecting the fluid contact curvature along the capillary corner, the oil-water and gas-oil contact radii can be calculated using Eqs. 7 and 8.

$$r_{ow} = \frac{\sigma_{ow}\cos\theta_{ow}}{P_{cow}^* + \Delta\rho_{ow} g(H+L)} \tag{7}$$

$$r_{og} = \frac{\sigma_{go}\cos\theta_{go}}{P_{cgo}^* + \Delta\rho_{go} gH} \tag{8}$$

It can be seen in Fig. 1a and Fig. 1b, the fluids’ contact radii become smaller by moving up along the tube corners. In a water-wet capillary tube with sharp corners, depending on fluids’ interfacial tensions and differential densities, two different configurations of oil film can be formed. In the first configuration, the oil-water contact radius shrinks toward corner of the tube with a smaller rate rather than the gas-oil contact radius. Since at gas-oil contact front (*H=0*) the gas-oil contact radius is larger than oil-water contact radius, there is an elevation above the gas-oil contact front at which the contact radii of both gas-oil and oil-water pairs are equal (point 3 in Fig. 1a). The second configuration of the oil film is formed when the gas-oil contact radius along the tube corner remains larger than the oil-water contact radius, as depicted schematically in Fig. 1b. Such a condition is likely to occur when the differential density of the gas-oil pair is lower than the oil-water pair. The elevation of the oil film in this configuration is no longer limited by the oil-water contact radius, and the oil film exists at all heights above the water surface in the tube corners.

The maximum equilibrium oil film height above the gas-oil contact front (H_{max}) for the first configuration is shown by Eq. 9, which is derived by equating the oil-water and gas-oil contact radii.

$$H_{\max} = \frac{(\sigma_{og} \cos\theta_{go} \Delta\rho_{ow} .L)}{(\sigma_{ow} \cos\theta_{ow} \Delta\rho_{go}) - (\sigma_{go} \cos\theta_{go} \Delta\rho_{ow})} \tag{9}$$

DISCUSSION

We can see from Eq. 9 that the size of tube has no effect on the maximum oil film elevation. Fig. 2 shows the variation of 'H_{max}' vs. gas-oil interfacial tension and the gas density when the oil-water interfacial tension (σ_{ow}) is 0.03 N.m^{-1}, oil density (ρ_o), is 700 kg.m^{-3}, water density (ρ_w) is 1000 kg.m^{-3}, length of oil bank (L) of 0.05 m, and all contact angles are zero degrees. It can be seen that the

Fig. 3 shows the maximum oil film elevation (H_{max}) vs. the oil bank length when the gas-oil interfacial tension is fixed at 30 mN.m^{-1}, gas density at 300 kg.m^{-3} and other parameters at their previous fixed levels. A greater oil film elevation can be expected for the first configuration when the length of the oil bank is longer. Fig. 4 shows the gas-oil capillary pressure at the top of the oil film in a square tube with the size of 100×100 µm, versus the gas density (ρ_g) and gas-oil interfacial tension (σ_{go}), and keeping all other parameters fixed at their levels, previous indicated in Fig. 3. It is shown that the gas-oil capillary pressure is higher when the gas-oil interfacial tension and gas density are increased. Fig. 3 and 4 also illustrate that the effect of gas density on the oil film elevation and gas-oil capillary pressure is more significant when the gas-oil interfacial tension is higher.

In porous media, a thin oil film can be formed in the crevices and corners between the rock grain and on their surface roughness. During a vertical gas injection, thick oil films are the major paths for both hydraulic communication and recovery of trapped immobile oil. Increasing the gas-oil capillary pressure provides a potential for the gas to enter the small size pore-throats and deplete any residual oil through these paths. Consequently, the overall oil recovery can be higher. Since the fluids' contacts are not under equilibrium conditions during vertical gas injection, the oil recovery from small pores should be studied in a dynamic state of capillary pressure. The dynamic state of the oil film during vertical gas injection is different from the equilibrium state. The non-equilibrium state of oil film in gravity drainage is currently under experimental investigation at Memorial University of Newfoundland.

CONCLUSIONS

The oil film elevation above the gas-oil contact front in a water-wet, non-circular capillary tube is a function of the oil-water and gas-oil interfacial tensions and their differential densities. Additionally, the oil film elevation can be limited due to the presence of wetting phase in the sharp corners of the capillary tube. It is expected that a longer oil film elevation results in higher oil recovery, since, it yields a higher gas-oil capillary pressure, which allows the gas to enter the small pore-throats that are not swept by primary gas injection. The analysis of the static oil film characteristics implies that the injection of a gas with a higher density and having a greater gas-oil capillary pressure can potentially improve the oil recovery factor in gas-assisted gravity drainage EOR methods.

ACKNOWLEDGEMENTS

The authors would like to thank Petroleum Research Newfoundland and Labrador (PRNL), the Research Development Corporation of Newfoundland (RDC), Hibernia Management and Development Company (HMDC), and the Natural Sciences and Engineering Research Council of Canada (NSERC) for their technical and financial support in this research.

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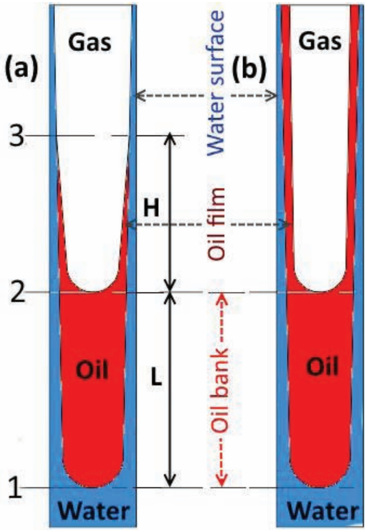

Fig. 1: Water, oil and gas in a non-circular tube a) oil film elevation limited by water film, and b) oil film elevated along the tube corner

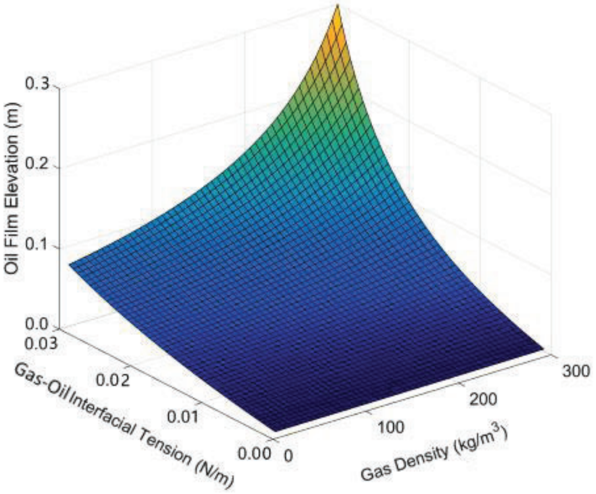

Fig. 2: Oil film elevation above the gas-oil contact front vs. gas density and oil-gas interfacial tension

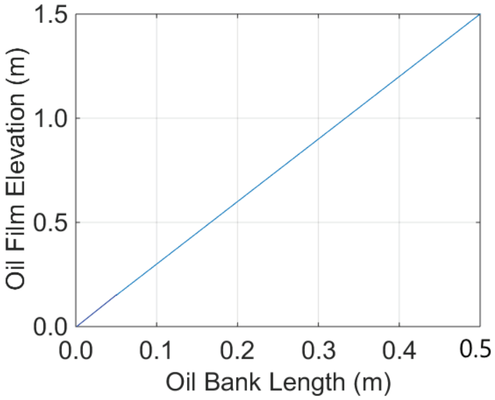

Fig. 3: Oil film elevation vs. oil bank length

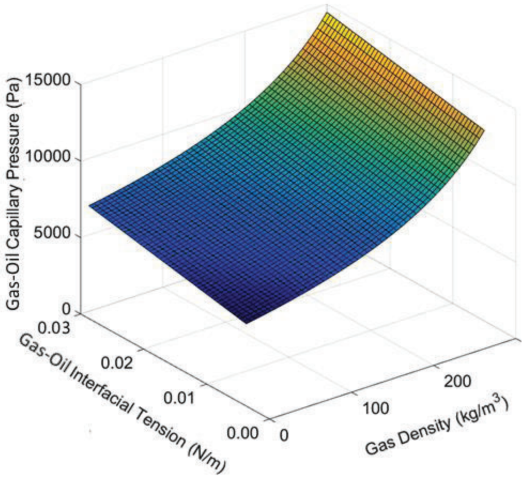

Fig. 4: Gas-oil capillary pressure at the top of the oil film vs. gas density and oil-gas interfacial tension