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Residual liquids saturation development during two and three phase flow under gravity in square capillaries at different temperatures

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ABSTRACT

An experimental study on heavy oil with air (two phase flow) and water and air (three phase flow) at different temperatures was carried out in square capillaries under gravity drainage conditions. Fluid retention characteristics (in the corners of capillaries) were determined and evaluated using the trapping number (N_T). In air–heavy oil systems, when $N_T < 2.7\text{E}{-2}$, the residual oil saturation (S_{or}) was constant and equal at 55 and 85 °C. The S_{or} was controlled by capillary forces regardless of viscous and gravity forces, including free fall gravity drainage (FFGD). For higher N_T, the S_{or} was a function of competition between gravity, viscous and capillary forces. The S_{or} was always higher at 85 °C compared to 55 °C for the same gas injection rate and the difference increased as the N_T augmented. FFGD experiments demonstrated that heavy oil retention depended on the Bond number and increased linearly as the Bond number increased.

In the three phase systems (air–heavy oil–water) the oil retention did not diminish with the presence of water, which was also constant for the entire interval of N_T at 55 and 85 °C. High viscous forces originated from heavy oil were responsible for no change in the S_{or}. However, due to the water-wet nature of the capillary tubes, water was not completely swept. More S_{or} and residual water saturation were observed in air–water–heavy oil configuration, especially at 85 °C, due to the unfavorable viscosity ratio oil/water and the negative spreading coefficient of water in oil in the presence of air. Finally, the change of wettability from water wet to oil wet did not modify the S_{or} but the water saturation decreased slightly for air–heavy oil–water systems.

1. Introduction

The application of improved recovery methods has become a recurrent practice these days due to the world reserves depletion and the high prices of crude oil. However, the decision to apply certain recovery techniques depends, to a great extent, on the remaining or residual oil saturation (S_{or}) in the reservoir. Although different approaches have been proposed to estimate the S_{or} and understand the flow mechanisms in gravity drainage type displacement processes in porous media at reservoir, well or core scales, they have not been sufficient to quantify the S_{or} realistically or explain the physics behind the entrapment process. This is due to a lack of understanding of the fluid dynamics originated at the pore scale. Such estimation becomes more complicated if there is three phase flow at non-isothermal reservoir conditions as that encountered in the variations of steam injection (steam assisted gravity drainage (SAGD) Mohammadzadeh and Chatzis, 2009, and steamdrive (Green and Whillhite, 1998), or at isothermal conditions such as gas injection (Hagoort, 1980; Chatzis et al., 1988) or double displacement process (DDP). In addition to these oil recovery processes, residual oil development determination is critically important in oil and heavy-oil remediation processes in which gas or steam are used.

1.1. Statement of the problem

In reference to isothermal and non-isothermal gravity drainage processes for heavy-oil recovery, pore scale studies conducted to clarify the mechanisms responsible for the formation of residual oil saturation are very limited, especially for the latter (Mohammadzadeh and Chatzis, 2009). To mimic the behavior of S_{or} in a single pore of a petroleum reservoir, displacements of oil by other phase can be carried out in lab using circular and non-circular capillary tubes. Argüelles-Vivas and Babadagli (2014) proposed an approach to determine the S_{or} in a circular capillary tube. They analyzed the dynamics of residual oil saturation development (in the form of films) during gas–heavy oil displacement

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by gravity drainage at different high temperature conditions and low capillary numbers (Ca).

However, as also discussed in that research of Argüelles-Vivas and Babadagli (2014) and a few others, circular capillary tubes are highly idealized to represent the realistic pore structure of oil reservoirs due to their low liquid retention power (Blunt et al., 1995; Dong and Chatzis, 2004). The irregular geometry of the pores should be taken into account in any experimental or theoretical modeling work. The residual oil saturation in a circular capillary tube exists only as a thin film while in non-circular capillary tubes the residual or remaining oil saturation is present as layers in their angular zones (Blunt et al., 1995).

Square and triangular capillary tubes are examples of non-circular geometries which have been used to model porous media instead of circular tubes. Although their representation of porous media is restricted to a single pore system rather than capturing the complex nature of pore network, they are preferred as they provide visual data that are useful for understanding multiphase flow characteristics. One of the earliest studies on non-circular capillary tubes was done by Singhal and Somerton (1970). They derived equations for the shapes of fluid–fluid interfaces as a function of the contact angle and fluid saturations and focused mainly on triangular geometry. They pointed out the need for experimental work at the pore scale to validate their theoretical expressions for relative permeabilities.

1.2. Background and solution methodology

In the present research, square capillary tubes were chosen as the pore model to study the gravity drainage dominated flow in a heavy-oil reservoir at different temperature conditions. Reviewing the specialized literature, one finds that the investigations of multiphase flow in square channels or square capillaries such as the displacement of a liquid by a gas phase are really few compared to those on circular capillaries (Argüelles-Vivas and Babadagli, 2014). Works on air bubbles-liquid displacements in square capillary tubes were presented by Dong and Chatzis (2004), Thulasidas et al. (1995), Ratulowski and Chang (1989), Kolb and Cerro (1991, 1993) and Kamişli (2003). However, except the study done by Dong and Chatzis (2004), these studies focused on applications different from the fluid flow in an oil reservoir. It is generally assumed that capillary number is less than 1.0E−4 at reservoir conditions (Schwartz et al., 1986; Dullien, 1992). Note that all these studies were conducted for light oil systems whereas the focus in the present study is the development of S_{or} in heavy oil reservoirs.

Dong and Chatzis (2004) carried out experimental research to analyze the behavior of the retention of liquids in the corners of a square capillary tube of 0.03 cm in width in the range of the capillary numbers existing in a reservoir from 1.0E−3 to 1.0E−6 in two and three phase horizontal displacements using air as the displacing phase. In two phase displacements (gas-wetting liquid), they observed that for Ca > 5.0E−4, the retention of the wetting liquid diminished with decreasing capillary number. For Ca < 1.0E−4, the retention of the wetting liquid was observed to be dependent on the capillary forces and the rate effect was negligible.

In the case of three phase displacements (as a double displacement process: air displaces oil which in turn displaces water), Dong and Chatzis (2004) stated that the total retention of water and oil vs. the capillary number curve had the same trend as the retention of the wetting phase for the case of two phase displacements. However, with a decreasing capillary number (up to very low values) or increasing viscous forces, the water retention decreased and the oil retention increased.

To date, the investigation of Dong and Chatzis (2004) has been the only one focused on the analysis of the developed S_{or} in square capillaries and it was restricted to light mineral oils and room conditions. In this paper, the liquid retention characteristics in square capillary tubes during two and three phase gravity drainage experiments were investigated at different temperature using heavy crude oil, water and air. The findings and observations will help understanding the development of residual oil and water saturations during isothermal and non-isothermal oil recovery processes (such as SAGD and steamdrive) and oil remediation from soils. Also, the results will shed light on further modeling studies attempting to clarify the physics of three phase flow of heavy oil, water and gas in more complex pore networks.

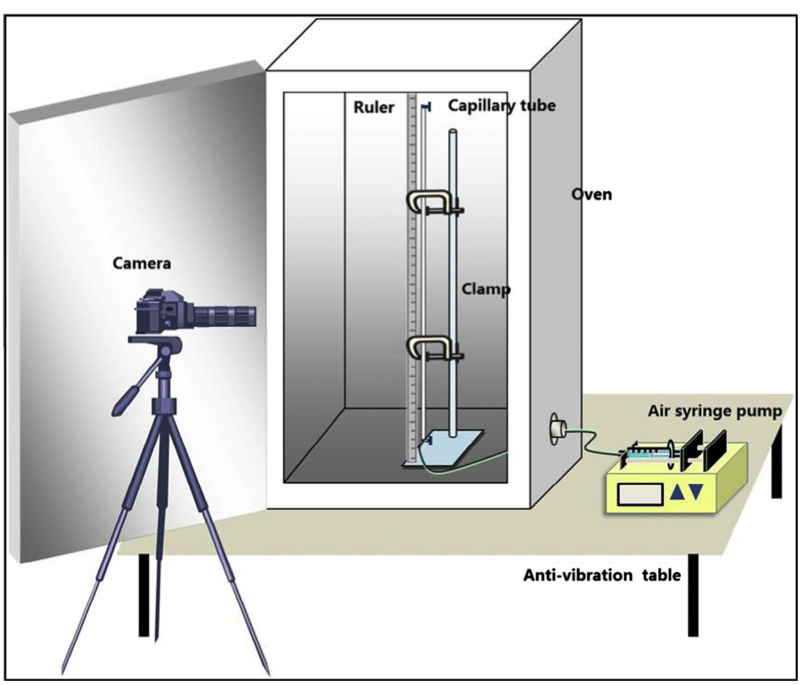

Fig. 1. Experimental setup (Argüelles-Vivas and Babadagli, 2014).