The Role of Film Flow and Wettability in Immiscible Gas Assisted Gravity Drainage

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ABSTRACT

Capillary and gravity forces control the residual saturation of liquid phases before and after gas breakthrough in Gas Assisted Gravity Drainage (GAGD). These forces are determined by the fluid and formation properties. In this research, the effects of capillary and gravity forces on oil film flow have been investigated focusing on the wettability of porous media. Experiments were conducted in oil-wet and water-wet pore network micromodels to investigate the role of wettability on oil recovery during CO_2 GAGD. It has been observed that the GAGD residual oil saturation profile is affected by the state of wettability. In water-wet micromodels, the irreducible water saturation was found in smaller pores (body and throats) and blocked potential pathways for oil film flow. In oil-wet micromodels, the majority of the residual oil was found in smaller pores and around the grains in micro-capillaries in the form of oil rings. In GAGD, the presence of corners and edges enable the liquid phases to maintain a stronger capillary continuity to a limited elevation. We have observed a higher oil recovery in locations with stronger capillary continuity. However, the rupture of liquid films beyond a critical capillary pressure, due to geometric constraints, can arrest liquid film flow.

INTRODUCTION

In the Gas Assisted Gravity Drainage (GAGD) oil recovery, the differential density between the gas phase and oil phase causes the gas-oil capillary pressure to increase behind the gas front [1]. Since GAGD is a drainage process, increasing the gas-oil capillary pressure increases the number of pores invaded by gas (non-wetting phase). Consequently, the ultimate oil recovery factor becomes higher. In order to enhance the capillary pressure behind the gas front, fine capillaries must exist through which downward oil film flow can occur [2].

The role of the oil film flow in GAGD is illustrated by Fig. 1 which is a simple pattern having two pore bodies with different throat sizes. In Fig. 1A, oil (wetting phase) is displaced by gas (non-wetting phase) through the least resistant path. The capillary pressure ahead of the gas front is indicated by P_{cgo}^* (Fig. 1B). Films of oil may occupy the corners of the pattern as gas-oil interfaces with smaller radii (higher capillary pressure) can be formed in the edges. The radius of gas-oil interface at higher elevations is smaller as the capillary pressure is higher. The capillary pressure behind the gas front (P_{cgo}) is calculated by Eq.1

$$P_{cgo} = P^*_{cgo} + \Delta\rho_{go} gH \quad (1)$$

where, $\Delta\rho_{go}$ is the gas-oil differential density, g is the gravity acceleration, H is the elevation of the gas-oil interface behind the gas front. When an oil occupied pore throat, which is not initially invaded by gas, is located at a sufficient vertical distance (H_1 in Fig. 1C) from the gas front, gas can enter the pore through the center of its throat, and oil can drain from the throat corners (Fig. 1D). Gas may enter the smaller throat similarly (Fig. 1E) when the gas front moves downward further (e.g., H_2). However, the roundness of the corners (pore geometry) may not allow the oil and gas to form a highly curved interface with a small radius [3]. Therefore, the oil film elevation can be terminated and the oil in the pore bodies that have a smaller throat cannot be recovered (Fig. 1F). In a three phase GAGD, the presence of water and wettability can affect the geometric constraints and the maximum obtainable capillary pressure [1].

The objective of GAGD is to inject gas to decrease mobile and immobile oil with the aid of gravity. It was found that GAGD performance was more favourable in water-wet media when oil can spread over the water surface [3, 4]. Conversely, higher GAGD oil recovery was measured in oil-wet conditions [5]. Vizika and Lombard [6] studied the effect of wettability on the residual oil saturation conducting tertiary GAGD in a 50 cm long sandpack. A low residual oil saturation was measured in a water-wet medium when the gas-water interfacial tension was high and caused spreading of oil on the surface of water. A very low residual oil saturation was also observed far from the bottom of the oil-wet sandpack (>10 cm) when the gas-water interfacial tension was low. However, the residual oil saturation at bottom the oil-wet sand pack was high due to the capillary end effect which causes the retention of the wetting phase. The gas-oil capillary pressure may drop dramatically due to exit of the gas phase through largest paths in the bottom of a porous medium.

In this research, the influence of wettability on oil recovery of secondary GAGD was studied using oil-wet and water-wet pore network micromodels. The micromodel allows detailed visualization of the gas, oil and water interfaces during GAGD. The mechanisms that affect the recovery of oil in GAGD are presented in this paper.

EXPERIMENTAL DETAILS

A 256 x 64 mm (LxW) pore network micromodel was fabricated in the Hibernia EOR Laboratory at Memorial University. A heterogeneous pattern containing pore bodies with sizes of 1-1.6 mm and pore throats with widths of 200-800 μm, was etched on an acrylic plate (depth: 185 μm) and the plate was thermally bonded to a blank plate.

A Quizix 20K series pump and three custom floating piston accumulators were used to inject the oil (red dyed Varsol) and water (blue dyed deionized water) into the micromodel at constant pressure. The fluids were produced at constant rates using another 20K pump and accumulator. Secondary GAGD experiments were conducted in the oil-wet and water-wet micromodels. The micromodel wettability was altered from oil-wet to strongly water-wet by flushing the micromodel with Hydrphil™ leaving a hydrophilic silica gel on the acrylic surface. The oil-wet micromodel oil saturation was established in two steps: 1) The fully oil saturated micromodel was aged 24 hrs and then flooded by two pore volumes of water at 10 cc/hr from bottom to top (gravity stable) of the micromodel; and 2) Two pore volumes of red-dyed oil were injected into the micromodel at 3 cc/hr from top to bottom. In the water-wet micromodel, two pore volumes of red-dyed oil were injected (3 cc/hr) into a fully water saturated micromodel from top to bottom. GAGD tests were conducted by injecting 4 pore volumes of CO_2 at 0.1 cc/hr at constant temperature (20°C) and pressure (25 psig / 1.7 bar) conditions.

Saturation profiles and oil recovery were performed visually and results are presented based on 2D image analysis not accounting for the volumetric differences for larger pores being etched more deeply than more narrow pores. A Canon 6D camera and Canon EF 100mm f/2.8 USM macro lens were used to take high quality pictures every 10 minutes in order to calculate the saturation profiles during the GAGD experiments. An in-house image analysis program was used to calibrate the color of each individual pixel as red, blue, or white, depending on their colour. The oil saturation and recovery factor were then calculated knowing the number of total pixels, red pixels, and micromodel porosity.

RESULTS & DISCUSSION

The saturation profiles in the oil-wet and water-wet micromodels are shown in Fig. 2 and 3. It was observed that the injected gas invaded the larger pores before and more quickly than smaller pores, as expected. A few fingers were formed in the gas front as the gas could not enter pores throats smaller than 500 μm. Bypassed and isolated oil occupied zones (groups of pores), especially where the pore throats were smaller than 400 μm, were created behind the gas front which may be subsequently drained in time (Fig 2B, 2C, 3B, 3C). Some of the uninvaded regions that maintained their connection to the gas front, and wetting film continuity started to drain by film flow at later times assisted by gravity. In both wettability states, the oil production, after initial piston-like drainage displacement, was driven by gravity and controlled by capillary forces.

Thick oil films, formed on rough surfaces and in the corners, played an important role in the recovery of the bypassed oil [2]. The additional oil recovery after gas breakthrough occurred only via film flow. The trapped oil occasionally moved with the assistance of film flow. The isolated oil at higher elevations flowed toward neighbouring regions by film flow increasing the local oil saturation of another bypassed zone. When the local oil saturation in the new zone is sufficiently high for the gravity forces to overcome capillary forces, the oil could flow in the direction of gravity. The flow of oil in bypassed zones occurred in a step-wise process. In oil-wet micromodels, the residual oil was observed in the smallest pore sizes and in form of films around the solid grains as shown in Fig. 2D.

In water-wet micromodels, water occupies most of the pores having throats sizes of 200 μm (pores with smallest throats) and around the solid grains. Residual oil is shown trapped in the pore bodies with throats sizes greater than 300 μm. The oil gravity drainage paths are formed through the smaller pores and capillary corners. In water-wet conditions, we observed that the pore bodies with smaller throats and around the solid grains are occupied by water, and the water blocked the formation of an oil film and subsequent drainage. The residual oil was maintained in medium size pores.

The micromodel images after GAGD (Fig. 2D and 3D) indicate that the zones near the vertical edges of the pattern in the oil-wet micromodel contain less residual oil and water phases compared to other regions of the pattern. A stronger capillary continuity existed in the edges of both micromodels where the pattern formed a straight corner vertically. The phase interface with small radii can be formed in the edge of the micromodel which causes drainage of neighbouring pores with a higher capillary pressure. The magnified images of the oil-wet (Fig. 2D) and water-wet (Fig. 3D) micromodel edges show the difference between the oil saturation profiles of the oil-wet and water-wet micromodels. The trapped oil in the margin of the oil-wet micromodel was found in pore bodies with smallest pore throats (200 µm). The trapped oil in the edge of the water-wet micromodel was found in pore bodies connected to larger pore throats (400 µm). This difference implies that capillary continuity of the oil phase in the oil-wet micromodel is stronger.

Fig. 4 shows GAGD oil recovery in micromodels as a function of the pore volume of the injected gas. It is shown that the film flow mechanism after gas breakthrough resulted in a higher additional oil recovery factor in oil-wet rather than water-wet micromodels. Film flow contributes to an additional 6% and 2% recovery for the oil-wet and water-wet micromodels post breakthrough recovery, respectively.

Although the capillary continuity of oil in the margin of the oil-wet micromodel is stronger, the presence of oil in few pore bodies with small throats implies that the capillary pressure elevation behind the gas front is limited as the gas entry capillary pressure to these pores is higher than a critical capillary pressure that can be generated in the edge of the micromodel. The highest achievable capillary pressure depends on the geometry of capillary corners in the edge of the pattern. The enhancement of capillary pressure at higher elevations along the micromodel edge terminates when the equilibrium between capillary pressure at that corner radii can no longer be maintained. Therefore, in oil-wet micromodel, oil occupied pores with very small throats are undrainable. The critical capillary pressure, beyond which a gas-oil interface cannot form, controls the residual oil saturation. Our preliminary observations in micromodel experiments imply that maximum achievable capillary pressure in a water-wet porous medium is lower than in an oil-wet medium, as water in smaller pores interrupts the draining oil film paths.

In a water-wet porous medium, the presence of water in the smallest pores caused the residual oil to locate in small to medium sizes pores. The smallest pores maintain the wetting phase (water in water-wet condition and oil in oil-wet condition) after GAGD. Therefore, the position and saturation of post-GAGD residual oil was not only affected by the porous medium wettability, but also influenced by the pore size distribution.

The pore sizes of the micromodel are more than 10 times larger than the typical pore sizes of a sandstone. According to Eq. 1 gas-oil capillary pressure behind the gas front is determined by the breakthrough capillary pressure and elevation of gas-oil interface. It can be assumed that scaling up the pore sizes scales down both the gas breakthrough capillary pressure and the highest achievable gas-oil capillary pressure due to elevation of their interface behind the gas front. Enlargement of pore sizes, however, reduces the difference between the required gas-oil capillary pressure for drainage of oil from the largest and smallest drainable pores. Although the result of GAGD in micromodel is impacted by the poor capillary continuity condition and large scale pore sizes, it can reflect the mechanism of film flow in GAGD oil recovery effectively.

Future work should include closer examination of GAGD oil recovery mechanisms in a realistic micromodel with surface roughness to determine its effect on capillary continuity and film flow. We are developing a new micromodel with dual pore network containing coarse and fine capillaries. The presence of fine capillaries can improve the capillary continuity of the micromodel, and the quantified residual oil saturation can better represent the GAGD performance. Additionally, the interaction effects of pore size distribution and wettability on GAGD performance will be investigated in the new micromodel.

CONCLUSIONS

The GAGD research in micromodels showed that gravity and capillary forces control the residual oil saturation in an immiscible vertical gas injection process. It has been found that the post-GAGD residual oil saturation profile is affected by the state of wettability and pore geometry. The gas front bypassed the smaller pores due to presence of pore-scale heterogeneities. The irreducible water saturation in the water-wet micromodel reduces the critical capillary pressure beyond which the film flow of oil cannot geometrically exist.

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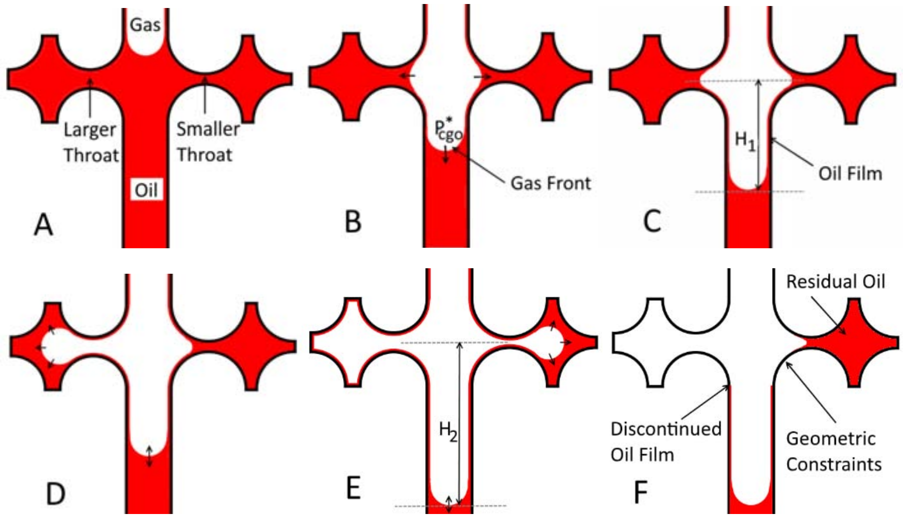
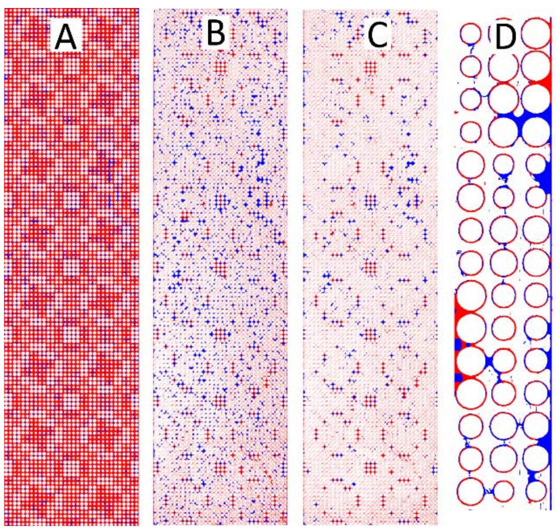


Fig. 1: Oil draiange behind the gas front through film flowm in capillary corners



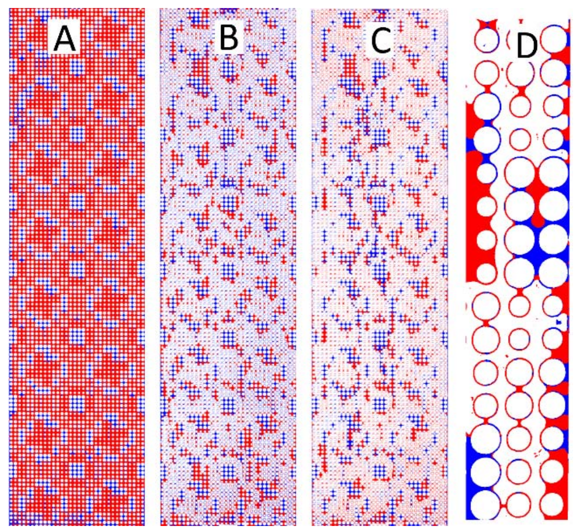


Fig. 2: GAGD in oil-wet micromodel **Fig. 3: GAGD in water-wet micromodel**
(blue: water, red: oil, A: Before GAGD, B: Post breakthrough at 0.6 P.V. injected gas, C: After 4.1 P.V. injected gas, D: Magnified micromodel margin)

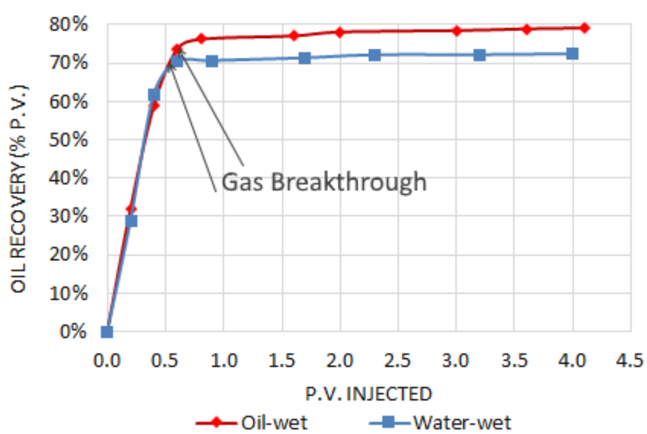


Fig. 4: Oil recovery curve in both states of wettability vs. pore volume of injected gas