WAG-CO$_2$ process: pore- and core-scale experiments

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Abstract
The present work was performed within a project concerning the study of immiscible Water Alternating Gas (WAG) process through three-phase hysteretic displacement modeling. WAG processes promise satisfying results in applications such as CO$_2$ storage in reservoir rocks, enhanced oil recovery or soil remediation. The optimization of such a process requires a petrophysical description of the reservoir and representative three-phase transport properties. Hysteretic phenomena (due to imbibition/drainage processes, to varying wettability prevailing on the displacement mechanisms, and consequently on the three-phase relative permeabilities) need to be quantified. CO$_2$ injection experiments have been performed in transparent micromodels, for visualization purposes, and N$_2$ injections were conducted in a composite core. Visualization experiments in micromodels were conducted under reservoir conditions, using dead oil and reconstituted brine. The effect of saturation history on the sweep efficiency and on the phase distribution in the pore space are investigated by performing displacements at irreducible water ($S_{wi}$) and at residual oil ($S_{orw}$) saturations. For a better understanding of the role of wettability, the solid surface has been treated from water-wet to intermediate-wet (aging with dead oil) and strongly oil-wet (chemical treatment). CO$_2$ has been injected either as gas, liquid or supercritical phase. Such differences in thermodynamic conditions lead to different final states. Different displacement processes take place resulting in different configurations of the interfaces at the pore space.

Flow experiments in a composite core have been conducted and two-phase relative permeabilities were extracted through numerical simulations, using an in-house software (reservoir simulator PumaFlow adapted to lab experiments). The two-phase relative permeabilities were used to build three phase relative permeability curves. Besides, imbibition and drainage capillary pressure curves were measured, both for cleaned and restored (aged) plugs and used in the simulations. Displacements and simulations were performed in the case of restored plugs.

Introduction

In some cases, the two-phase flow is less efficient than the three-phase flow, which is difficult to be interpreted, due to the coexistence of complex interfaces within the pore space. The spreading coefficient of oil on water plays an important role in the flow mechanisms and the final oil recovery, in the case of water-wet and fractional-wet porous media. On the contrary, in the case of oil-wet porous media, the important parameter is the spreading coefficient of water on oil (Vizika and Lombard, 1996).

The evolution of WAG experiments is strongly affected by wettability. In strongly water-wet models, the main displacement mechanism during a waterflood is flow through filaments, whereas during a gas injection the interfacial tensions are responsible for the oil mobility - and therefore the increased oil production (Tehrani et al, 2000, Sohrabi et al, 2001). The wettability effect on the oil recovery during WAG injections is very strong (Sohrabi et al, 2001) due to the different prevailing flow mechanisms. The relative permeabilities in the case of Simultaneous WAG (SWAG) have been predicted by Van Dijke and Sorbie, 2002. Pore network simulators were developed to approach the WAG processes in water-wet pore networks (Van Dijke et al, 2004), but it is well known that hysteresis, which is present in both steady-state and unsteady state relative permeabilities (Eliei et al, 1995), is difficult to be simulated (Suicmez et al, 2007). The efficiency of various models (Stone, 1970 and 1973, Baker 1988, Killough 1976, Carlson 1981) on the three-phase relative permeabilities for WAG experiments was investigated by Spiteri and Juanes (2006). The model proposed by Larsen and Skauge (1998) is representative for the hysteresis but it fails to reproduce WAG experimental data.

In this paper we try to investigate the Water Alternating CO₂ step by step starting from micromodel and core experiments aiming to a future modeling of the hysteretic relative permeability curves. Thus, gas injection experiments have been performed both in transparent micromodels and in a composite core. The visualization experiments in micromodels have been conducted under reservoir conditions using dead oil and reconstituted brine. The effect of saturation history on the sweep efficiency of a CO₂ injection and the phase distribution in the pore space is studied. The solid surface has been treated from water-wet to intermediate-wet (aging with dead oil) and strongly oil-wet (chemical treatment). The injected CO₂ is either gas or liquid or supercritical phase, leading to different flow mechanisms and final states. A slight effect of aging was observed from both the micromodel experiments and the centrifuge capillary pressure curves. The quantification of rock wettability is given by the Amott, Amott-Harvey and United States Bureau of Mines macroscopic indices (Anderson, 1986, Sharma and Wunderlich, 1987). These indices are complex functions of the pore size distribution, pore and throat connectivity, and wettability; they do not provide information on the wettability distribution of a porous medium (Dixit at al, 2000, Dominguez et al, 2001). A new method was proposed in order to correlate the capillary pressure signals with the fractional wettability of porous media (Sygouni et al, 2006, 2007) but the application on real rocks needs the extension of this method and more research. In our case, the wettability was estimated by using the USBM index.

Flow experiments have been conducted in a composite core consisting of four aged plugs and twophase relative permeabilities were extracted through numerical simulations using an in-house software (reservoir simulator PumaFlow adapted to laboratory conditions). The plugs were cored by samples taken by REPSOL wells at different depth and the most homogeneous plugs were selected in order to perform the flow experiments. The two-phase relative permeabilities were used to build three-phase relative permeability curves.

Experiments in micromodels

Experimental set-up

The visualization experiments have been performed using the equipment "Micromodel HP/HT" (Figure 1a) which is rather simple and includes several distinct parts:

- a positive-displacement pump to inject the fluids,
- an oven containing cells, valves and fittings,
- a confining cell containing the micromodel itself,
- a stereo microscope allowing the visualization of the fluids contained in the micromodel,
- a frame grabbing and display device (camera, photography, video recording...).
Inside the oven, two piston cells store the fluids to be injected. A third cell is devoted to CO\(_2\), which is simply prepared by filling of the cell with solid CO\(_2\) under laboratory conditions. The fluids are injected into the micro model, and recovered through a backflow pressure regulator. The injection line is thermostatic using a heating resistance, in order to maintain the thermodynamic conditions at the porous medium inlet. Since the micromodel is made of glass and consequently fragile to a high pore pressure, it is placed in a confining cell which maintains an external pressure of nitrogen. Overpressure is approximately 2 bars. The confining cell (Figure 1b) containing the micromodel is designed to work up to 200 bars; it is equipped with an integrated heating device (with heating candles) allowing experiments up to 60 °C. Two sapphire windows, one located at the top and the other at the bottom of the confining cell, allow lighting and visualization.

**Glass micromodels**

The micromodel (Figure 2) consists of two glass plates: one supports the etching representing the “pore” network and the other the two openings for the inlet and the outlet of the fluids. The two plates are stuck together in a furnace, at high temperature, to ensure the sealing around the etched network, where the fluids circulate. The pore network is initially transferred onto the glass plate by a serigraphic method. The porous zone (Figure 2) is 65.5 mm of length, 12.5 mm of width and the two ends consist of 2.5 mm width veins. The drawn circles diameter is 0.3 mm and the distance between their centers is 0.45 mm; two consecutive circles are shifted of a distance from 0.45/2 = 0.225 mm.

**Experimental conditions and procedure**

Visualization experiments have been conducted in the previously described transparent micromodels (Figure 2) under reservoir conditions (60 bars, 55 °C). The used fluid system consisted of: reconstituted brine, stock tank oil (dead oil) and CO\(_2\). Under these thermodynamic conditions the CO\(_2\) is a gaseous phase.
Two different initial saturations were investigated prior to gas injection:
- irreducible water saturation ($S_{wi}$),
- residual oil saturation ($S_{orw}$).

Three wettability conditions were reproduced:
- clean state, which corresponds to water wet conditions,
- restored state (where the porous medium is aged in the crude oil at ambient conditions for two months),
- silanated state (the micromodel became oil-wet by grafting silane molecules onto the glass surface).

Initially, the micromodel is saturated with reconstituted brine under ambient conditions. Pressure and temperature are raised up to reservoir conditions under a slow brine flow. Then, the porous medium is flooded with oil until irreducible water saturation is reached. If the initial conditions correspond to $S_{orw}$, the porous medium is then flooded by brine until steady state occurs. Once the micromodel and the CO$_2$ (equilibrated with brine) are stabilized at the desired pressure and temperature, the CO$_2$ is injected at a low flow rate (about 1 cm$^3$/h). The evolution of the phase distribution is recorded until steady state is reached and no flow event is observed. The results reported in this study correspond to the steady state. Once the steady state has been observed, the porous medium is cleaned, dried and then re-saturated to the desired initial conditions for the next experiment.

**Experimental results**

The aim of the study is the observation of the fluid distribution in the porous medium. Considering a water-wet system, the wetting phase (water) covers the pore walls (Figure 3).

The fluid distribution in the pore network depends on the value of the spreading coefficient $S$, which is a function of the interfacial tensions:

$$S = \gamma - \gamma_{wo} - \gamma_{og}$$

(where $\gamma$ represents the interfacial tension, and w, o and g respectively the water, oil and gas phase).

1. If the spreading coefficient $S$ is positive (Figure 3a), the oil spreads on the water film and forms a continuous phase which can easily flow within the porous medium.
2. If the spreading coefficient is negative (Figure 3b), the oil is distributed on the water film under the form of separated droplets. The oil can be trapped easily within the pore space.
Water wet micromodel (clean state)

a. CO₂ injection at Swi

Two different magnifications of the cleaned porous medium at Swi are shown in Figure 4. Brine is present either under the form of a film surrounding the grains either under the form of pendular rings. It is obvious that the porous medium is water-wet.

![Figure 4: Clean porous medium at Swi](image)

After CO₂ injection at Swi (Figure 5), and at steady state, we can distinguish the oil from its brown color, the brine which is white and the CO₂ which is white surrounded by a dark line (the dark line corresponds to the edge of the gas bubble). By comparing Figure 4 and Figure 5, we can see that the oil phase remains continuous and it spreads on the brine (case Figure 3b where the oil is not distributed under the form of separated droplets). Therefore, the spreading coefficient is positive.

![Figure 5: Two different areas of the porous medium after CO₂ injection at Swi](image)

b. CO₂ injection at Sorw

The porous medium has been cleaned, saturated with brine and then flooded by oil till Swi is reached. Then a brine injection was performed until steady state is reached : Sorw (Figure 6). Both contact angles and fluids distribution show that this porous medium is water-wet (Figure 6). Brine films exist at the surface of the grain even though the resolution of the picture is not enough to detect their presence.

![Figure 6: Clean porous medium at Sorw](image)
After CO$_2$ injection at $S_{orw}$ (Figure 7), the porous medium is still water-wet. We can observe three-phase coexistence around some grains (Figure 7). A brine film can be observed, lying on the surface, oil spreads on this film and is found in between the brine and the gas phase (Figure 7a). Some gas blobs are observed in the middle of the pore bodies, surrounded by oil (red circles on Figure 7b).

**Figure 7: Clean porous medium after CO$_2$ injection at $S_{orw}$.**

Intermediate-wet micromodel (Restored state)

- **a. CO$_2$ injection at $S_{wi}$**
  
  In order to reproduce the wettability conditions prevailing in the reservoir, the porous medium has been aged in dead oil for two months. As the mineralogy of the reservoir mainly corresponds to quartz sandstone, the mineralogy of the micromodel is quite representative of the reservoir (except the carbonate cement). The micromodel at $S_{wi}$ (Figure 8) seems to remain water-wet as the brine is either present under the form of films surrounding the grains either under the form of pendular rings.

**Figure 8: Restored porous medium at $S_{wi}$.**

After CO$_2$ injection at $S_{wi}$ (Figure 9) the oil phase spreads on the brine and consequently the spreading coefficient is still positive.

**Figure 9: Two different magnifications of the restored porous medium after CO$_2$ injection at $S_{wi}$.**
b. \( \text{CO}_2 \) injection at \( S_{\text{orw}} \)

The restored porous medium was cleaned, saturated with brine and then flooded by oil until \( S_{\text{orw}} \) is reached. Then it was flooded with brine until steady state is obtained: \( S_{\text{orw}} \) (Figure 10). Both the contact angles and the phase distribution (oil in the center of the pores) show that the porous medium is water-wet. Brine films exist at the surface of the grains although the picture resolution is not enough to detect them.

![Figure 10: Restored porous medium at \( S_{\text{orw}} \).](image)

The images in Figure 11 correspond to the phase distribution at steady state after \( \text{CO}_2 \) injection at \( S_{\text{orw}} \). A film of brine can be observed, lying on the surface whereas some brine pendular rings exist in the porous medium. The oil spreads on the brine film and it is found in between the brine and the gas phase. Sometimes, oil bubbles are found at the pore centers. Gas blobs are present in the middle of the pore throats, surrounded by oil (red circles on Figure 11c). The porous medium remains water-wet.

![Figure 11: Restored porous after \( \text{CO}_2 \) injection at \( S_{\text{orw}} \) at various magnifications.](image)

From the previous experiments, it was shown that the wettability was not much altered by aging in the crude oil. The system remained preferentially water-wet. These observations have been confirmed by wettability measurements obtained by centrifuge.

c. Capillary pressure curves of real cores

In order to compare the micromodel wettability results with the wettability of a real core, the capillary pressure curves were measured by centrifuge for both cleaned and restored plugs. The capillary pressure curves obtained for two cleaned plugs are shown in Figure 12. For both plugs, an important spontaneous imbibition was observed indicating a water-wet behavior and the entry pressure ranged between (-83, -131 mbars) whereas no spontaneous drainage could be detected (Table 1). The entry pressure for the forced drainage ranged between (138, 240 mbars) for both plugs. The calculated USBM wettability indices were found equal to 0.03 for the sample 92-2 and 0.06 for the sample 114-1. It can be concluded that the cleaned plugs exhibit a water-wet tendency.
Table 1 Initial and final fluid saturations in clean plugs

<table>
<thead>
<tr>
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<th>Before forced Imbibition</th>
<th>After forced Imbibition</th>
<th>After forced Drainage</th>
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<tbody>
<tr>
<td><strong>Sw 92-2</strong></td>
<td>0.24</td>
<td>0.41</td>
<td>0.31</td>
</tr>
<tr>
<td><strong>Sw 114-1</strong></td>
<td>0.29</td>
<td>0.45</td>
<td>0.32</td>
</tr>
<tr>
<td><strong>Soil 92-2</strong></td>
<td>0.76</td>
<td>0.07</td>
<td>0.69</td>
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<tr>
<td><strong>Soil 114-1</strong></td>
<td>0.71</td>
<td>0.06</td>
<td>0.68</td>
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Figure 12: Water-oil capillary pressure curves of forced imbibition and secondary drainage for the cleaned plugs 92-2 and 114-1.

The capillary pressure curves obtained for the restored plugs 110-3 and 114-2 are shown in Figure 13. For both samples, the critical pressure values for pore entrance are of the same order of magnitude with those calculated for cleaned samples. The critical pressure for pore penetration for the drainage process in restored plugs is smaller than in the case of cleaned plugs (60, 96 mbars) and a spontaneous drainage is observed (Table 2). The USBM wettability indices for the restored plugs were found equal to -0.15 and -0.13 for plugs 110-3 and 114-2 respectively, meaning that they present a weaker waterwet behaviour but we cannot conclude that the restored plugs are oil-wet.

Table 2 Initial and final fluid saturations for restored plugs

<table>
<thead>
<tr>
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<th>Before forced Imbibition</th>
<th>After forced Imbibition</th>
<th>After forced Drainage</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sw 110-3</strong></td>
<td>0.32</td>
<td>0.37</td>
<td>0.34</td>
</tr>
<tr>
<td><strong>Sw 114-2</strong></td>
<td>0.33</td>
<td>0.38</td>
<td>0.34</td>
</tr>
<tr>
<td><strong>Soil 110-3</strong></td>
<td>0.68</td>
<td>0.05</td>
<td>0.66</td>
</tr>
<tr>
<td><strong>Soil 114-2</strong></td>
<td>0.67</td>
<td>0.06</td>
<td>0.66</td>
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</table>
These results are fairly similar to the ones obtained for the micromodel experiments (cleaned and aged micromodel). Aging has not significantly altered the wettability neither of the micromodel, nor of the plugs. The wettability after aging could be characterized as intermediate.

**Oil-wet micromodel (Silanated state)**

Displacement experiments have been performed in silanated micromodels under different pressure conditions:

1. Experimental conditions 1: 60 bars and 55°C - CO$_2$ is a gas.
2. Experimental conditions 2: 90 bars and 55°C - CO$_2$ is supercritical.

**a. Experimental conditions 1 - CO$_2$ gaseous**

*CO$_2$ injection at $S_{wi}$*

The snap-shots taken at $S_{wi}$ from the silanated micromodel (*Figure 14*) show that the silanated medium is strongly oil-wet. The oil phase is present almost every where in the porous medium and covers all the pore walls. Brine is distributed in the middle of the pores, separated from them by an oil film. There is no contact between brine and glass surface.

*Figure 14: Silanated porous medium at $S_{wi}$*

After CO$_2$ injection at $S_{wi}$ under reservoir conditions (60 bars and 55°C), oil is the only phase which is in contact with the pore walls (*Figure 15*). It is not easy from these pictures to detect whether
there is any contact between gas and brine but they seem to be always separated by an oil film (red circles on Figure 15b).

**Figure 15: Silanated porous medium after CO\textsubscript{2} injection at S\textsubscript{wi}**

**CO\textsubscript{2} injection at Sorw**

The silanated porous medium has been cleaned, saturated with brine, then flooded by oil till S\textsubscript{wi} is reached and finally it was flooded with brine until steady state is reached (S\textsubscript{orw}). Oil either is covering the pore walls either it is under the form of pendular rings whereas all the pore walls are covered by an oil film (Figure 16). The micromodel is oil-wet.

**Figure 16: Porous medium at S\textsubscript{orw}**

After CO\textsubscript{2} injection at S\textsubscript{orw} under reservoir conditions (60 bar and 55°C) the silanated porous medium is oil-wet (Figure 17). Dark films of oil cover the grains and it is also under the form of pendular rings. Brine is present within the oil phase (red circles on Figure 17). There is no contact between the brine phase and the CO\textsubscript{2}, they are always separated by an oil film.

**Figure 17: Silanated porous medium after CO\textsubscript{2} injection at S\textsubscript{orw}**

**b. Experimental conditions 2 - CO\textsubscript{2} supercritical**

Some experiments were also conducted in silanated micromodels under 90 bars and 55°C. Under these conditions, CO\textsubscript{2} is a supercritical phase. The experiments were quite difficult, and some
problems occurred (mainly due to dead volumes) to get initial reliable $S_{sw}$ or $S_{orw}$ saturations. Thus two different situations were investigated; porous medium saturated by only CO$_2$ and brine, and a three phase situation.

**Brine and CO$_2$**

On *Figure 18*, it is possible to observe the silanated micromodel saturated with brine, after CO$_2$ injection at 90 bars and 55°C. There is no visible wetting film (either brine or CO$_2$) on the pore walls. Hence, these pore walls do not seem to be preferentially water-wet. Due to the fact that numerous triple lines may be observed (*Figure 18*), it seems to be intermediate; The observed contact angles tend to show that the system is even slightly preferentially CO$_2$-wet (red circles, *Figure 18b*).

![Figure 18: Silanated porous medium after CO$_2$ injection in a brine saturated model.](image)

**Three phase saturation**

*Figure 19* represents a silanated (OW) porous medium, saturated with brine, oil, and supercritical CO$_2$, after CO$_2$ injection 90 bars and 55°C. The *Figure 19a* corresponds to "high initial oil saturation", and the *Figure 19b* corresponds to a "low initial oil saturation"; it means almost primary and secondary CO$_2$ injection. Dark films of oil covers the grains which can also be found under the form of pendular rings. Brine is included within the oil phase (red circles *Figure 19b*). There is no contact between the brine phase and the CO$_2$ and they always are separated by an oil film. Therefore the porous medium is oil-wet but is not wetted by the CO$_2$.

![Figure 19: Silanated porous medium after CO$_2$ injection.](image)

**Flow experiments in real cores**

The aged plugs selected for the flow experiments (*Table 3*), were placed in a flooding cell (*Figure 20a*). Then, miscible solvents were injected successively through the samples in order to clean them according to an IFP’s cleaning procedure. The samples have been saturated in brine; afterwards, dodecane was injected (*Table 4*) in order to reach the $S_{sw}$ state (*Table 3*). The two-phase flow experiments under ambient conditions in the composite core consisted of: i) a gas injection at $S_{sw}$ until $S_{org}$, ii) a brine injection at $S_{sw}$ until $S_{orw}$ and iii) a gas injection at $S_{orw}$. The injections were continued until no more oil was produced. For the gas phase, we used N$_2$ to simplify the experiments. CT-scan measurements have been recorded during the experiments,
whereas the pressure drop along the composite and the oil and gas production at the outlet have also been measured.

| Table 3 Characteristics of the plugs used for the displacement experiments |
|-----------------------------|----------------|----------------|----------------|----------------|
|                            | Length (cm)    | Diameter (cm) | Porosity (%)  | Permeability (mD) | Swi  |
| 1                          | 5.98           | 4.9           | 16.2          | 2.7             | 0.26 |
| 2                          | 5.98           | 4.9           | 15.9          | 1.6             | 0.28 |
| 3                          | 5.98           | 4.9           | 16.4          | 2.6             | 0.28 |
| 4                          | 5.98           | 4.9           | 15.7          | 1.8             | 0.29 |

Table 4 Fluid system properties

<table>
<thead>
<tr>
<th></th>
<th>Dodecane</th>
<th>REPSOL brine</th>
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<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>0.749</td>
<td>1.1</td>
</tr>
<tr>
<td>Viscosity (cp)</td>
<td>1.37</td>
<td>1.08</td>
</tr>
<tr>
<td>Interfacial tension (mN/m)</td>
<td>35.5</td>
<td></td>
</tr>
</tbody>
</table>

a. Gas injection at Swi
The gas injection at the desired Swi was performed under constant pressure drop (0.5, 1.8 and 3.8 bars) and a backpressure of 5 bars was implied. The gas BT (breakthrough time) is estimated at 149 min. 63% of the initial oil volume was recovered at the end of the experiment. The initial and final fluid saturations in the composite are summarized in Table 5. The oil and gas relative permeabilities (Kro and Krg, Figure 21a) were calculated by history matching using the IFP’s reservoir code "PumaFlow" (adapted to laboratory conditions). The oil production measured at the outlet of the composite, calculated from CT-Scan measurements and simulated by using the estimated relative permeabilities is shown in Figure 21b. Experimental and simulated results are in good agreement (the CT-Scan measurement error is +/-3% in terms of saturation and +/-2.145 ml in terms of volume). The simulated relative permeabilities reproduce well the experimental results (Figure 21b,c,d).

| Table 5 Average saturations in the composite before and after the gas injection |
|-----------------------------|-----------------|----------------|
|                            | Start of the experiment | End of the experiment |
| Oil saturation             | 0.73             | 0.27           |
| Brine saturation           | 0.27             | 0.27           |
| Gas saturation             | 0.00             | 0.46           |
b. Brine Injection at \( S_{wi} \)

The brine injection at irreducible water saturation (\( S_{wi} \)) was performed at ambient conditions, under constant flow rate (4 ml/hr and 14 ml/hr). The brine breakthrough occurs at t=486 min. The initial and final fluid saturations are summarized in Table 6. 77.4% of the initial oil volume was recovered at the end of the experiment. Same as before, the brine and oil relative permeabilities (\( K_{rw}, K_{ro} \)) were calculated by history matching (Figure 22). We can notice a good agreement between the experimental and simulated results (Figure 23). We can observe that the brine relative permeability is very low for high brine saturations and it rapidly increases after the breakthrough. The displacement seems to be frontal due to the late breakthrough after which the brine becomes connected along the composite and the oil production is almost stabilized.

Table 6 Average saturations in the composite before and after the brine injection at \( S_{wi} \)

<table>
<thead>
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<th>Start of the experiment</th>
<th>End of the experiment</th>
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<tbody>
<tr>
<td>Oil saturation</td>
<td>0.73</td>
<td>0.16</td>
</tr>
<tr>
<td>Brine saturation</td>
<td>0.27</td>
<td>0.84</td>
</tr>
</tbody>
</table>
c. Gas injection at $S_{orw}$

The gas injection at $S_{orw}$ was performed at ambient conditions and under constant pressure drop (0.5, 1, 4 and 8 bars). In this experiment except the brine, a small quantity of oil was also recovered. The gas breakthrough occurs at $t=262$ min. The fluids saturations in the composite are given in the Table 7. The oil produced during the experiment is around 4.23% of the initial oil volume. In order to model this three-phase flow experiment the models "Stone1" and "Stone2" were employed. As we can see (Figure 24) the oil production obtained by modelling with "Stone1" is quite higher (0.79 ml) than the experimental (0.5 ml). The oil production modelled with Stone 2 (0.22 ml) (Figure 24) is lower than the experimental (0.5 ml). Both of the models predict well the brine production.
Table 7 Saturations in the composite before and after the gas injection at $S_{orw}$

<table>
<thead>
<tr>
<th></th>
<th>Start of the experiment</th>
<th>End of the experiment</th>
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<tbody>
<tr>
<td>Oil saturation</td>
<td>0.165</td>
<td>0.158</td>
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<tr>
<td>Brine saturation</td>
<td>0.835</td>
<td>0.555</td>
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<tr>
<td>Gas saturation</td>
<td>0.00</td>
<td>0.287</td>
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</tbody>
</table>

Figure 24: a) Experimental and simulated with Stone 1 fluid productions (gas injection at $S_{orw}$), b) Experimental and simulated with Stone 2 fluid productions (gas injection at $S_{orw}$).

Conclusions

The ulterior aim of this study is to investigate the flow mechanisms during CO$_2$ injections in porous media for varying thermodynamic conditions and wettability and the relative permeability curves hysteresis that occurs during WAG experiments. Visualization experiments have been conducted in micromodels of different wettabilities. The aging process with dead oil did not strongly alter the wettability in both micromodels and cores. From the micromodel experiments it is shown that the fluid distribution varies with the surface wettability and the experimental conditions. The conditions under which an experiment is performed determine the CO$_2$ behavior which does not always play the role of a non-wetting phase. Flow experiments have been also performed in a composite core, consisting of four plugs, in order to estimate the two-phase relative permeabilities which will be used in the future to model a WAG experiment. The experiments showed that the gas injection at $S_w$, where fingering and early breakthrough occurred, is less efficient than the brine injection at $S_{wi}$, where the displacement was frontal, and where, after the breakthrough, the oil recovery was almost stabilized. The fingering which occurred in the first case could be due the presence of some oil-wet or intermediate-wet pathways in the plugs. The weak three-phase flow (small volume of oil was produced) which occurred during the gas injection at $S_{or}$ is generally well simulated by Stone 1 and Stone 2.

Acknowledgements

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