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Effect of Matrix Wettability CO2 Assisted Gas-oil Gravity Drainage in Naturally Fractured Reservoirs

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SUMMARY

The wettability behavior of the matrix block is one of the major factors controlling the effectiveness of the employed EOR methods in NFRs. Water injection in NFRs with mixed-wet or effectively oil-wet matrix blocks usually results in low oil recoveries. In this case, gas injection is considered to be an alternative process, where the process benefits from the gravity forces and the process is called gas-oil gravity drainage.

In this study, the effect of matrix wettability on the efficiency of gravity drainage by CO2 injection is addressed. Laboratory experiments and numerical simulation were performed to analyze the process under different wettability conditions of the matrix. It is concluded that for a system with an effectively oil-wet matrix, water is the most non-wetting phase while CO2 is the intermediate-wetting phase. In the three phase setting, which includes carbon dioxide, this is considered favorable for oil production. However, with a strongly water-wet matrix, CO2 is always the least wetting phase. For this condition, it turns out that when water is displaced by the gravity drainage process part of the oil is also produced. It is observed that higher oil recoveries are achieved by CO2 injection in an oil-wet matrix block.
Introduction

It has been revealed by several studies that oil recovery from naturally fractured reservoirs (NFRs) is mainly governed by the interactions between matrix blocks and fracture networks (Salimi and Bruining 2011). Moreover, the matrix-fracture interactions are highly influenced by the wettability behaviour of the matrix block (Fernø et al. 2011). For example, water injection in NFRs with strongly oil-wet matrix blocks leads usually to low oil recoveries. For such conditions, gas injection is considered as an alternative method, where the process benefits from the gravity forces and oil production occurs through gas-oil gravity drainage. It is usually assumed that the gas phase is the most non-wetting phase when co-exists with oil and water. However, reports from recent studies show that at some conditions CO$_2$ can be the wetting phase (Parsaei and Chatzis 2011, Suicmez et al. 2007, Wu and Firooozabadi 2010). For an immiscible gas-oil gravity drainage process, the ultimate oil recovery is controlled by the capillary pressure curve, which is dictated by the matrix wettability. Therefore, it is essential to understand the effect of matrix wettability on the performance of a gas-oil gravity drainage to be able to estimate the oil production rate and to optimize the production process.

In spite of its importance to enhanced oil recovery from NFRs, there are limited experimental data available in literature detailing the effect of matrix wettability on the performance of gas-oil gravity drainage processes in NFRs at relevant reservoir conditions. In most of the theoretical and experimental efforts, air or N$_2$ has been used as the injection gas. Hence, CO$_2$-facilitated gravity drainage processes have not yet been adequately addressed in literature. The main motivation for the current study originates from our previous study (Ameri et al. 2013) on the interfacial interactions among rock, crude oil, brine, and CO$_2$ system by contact angle measurements. It was proved that, under certain conditions, CO$_2$ can be considered as the wetting or intermediate wetting phase. To extend the results obtained from contact angle measurements to more realistic conditions, core-scale miscible and immiscible gas-oil gravity experiments were performed using effectively oil-wet and water-wet sandstone and limestone matrix blocks. Moreover, the experiments were simulated numerically using Shell’s in-house reservoir simulator, MoRes, to capture the physics behind the process and to validate the experimental data.

Experimental work and simulation model

Table 1 summarizes the experiments conducted to determine the effect of matrix wettability on the production performance of a gravity drainage process involving CO$_2$ and N$_2$. In all experiments, heptane (purity 95%) and doubly distilled water were used as model oil and the aqueous phase, respectively. All experiments were performed at room temperature (~20°C) and 85 bar pressure. Bentheimer sandstone and Maastrichtian chalk cores were used as matrix blocks. All the core samples have a length of 40.5 cm and a diameter of 5 cm. The porosity of the Bentheimer and the Maastrichtian limestone cores is around 21% and 37%, respectively. Both Bentheimer sandstone and Maastrichtian chalk are known to be naturally strongly water-wet. A salinization process was implemented to make the Bentheimer cores oil-wet. The Maastrichtian chalk cores were made oil-wet by treating the samples with a 0.01M solution of stearic acid in n-decane. Moreover, a radially symmetric simulation model with the same geometry, rock, and fluid properties as utilized in the experiments was employed to simulate the experiments. A compositional model was used to perform calculations on a system that consists of a cylindrical matrix block surrounded by the fluid between the core and a cylindrical core-holder, representing the fractures.

Results and Discussions

**Oil-wet/water-wet sandstone core and CO$_2$ system.** The recovery history and the drainage rate of experiments 3 and 4 are shown in Figure 1a and 1b, respectively. As can be observed, the existence of mobile water saturation considerably decreases the efficiency ofmiscible CO$_2$ injection. For this configuration, the pores at the boundary between fracture and matrix are mainly filled with the water phase and CO$_2$ cannot directly contact the oil phase. Therefore, oil production by CO$_2$ injection is mainly governed by the equilibrium between gravity and capillarity forces between CO$_2$ and water.
Note that it is assumed that after water injection, the oil phase is no longer continuous and forms isolated blobs at low oil saturations. By injecting CO\textsubscript{2}, water is initially produced by gravity drainage and leaves the trapped oil behind, which is now accessible to CO\textsubscript{2}. The oil production by CO\textsubscript{2} injection is limited by the equilibrium between gravity and capillary forces, causing a CO\textsubscript{2} bank above the oil, which becomes stationary after capillary-gravity equilibrium is reached. Hence, only a small part of the matrix is exposed to gravity drainage potential when water is drained from the matrix. However, the remaining oil in the core remains in the capillary hold-up range. Further penetration of carbon dioxide into the matrix is limited by molecular diffusion and hence very slow. It can be concluded that for a water-wet substrate, CO\textsubscript{2} is always the non-wetting phase compared to water. In an oil-wet matrix, the oil phase is the most-wetting phase, water is the most non-wetting phase, and CO\textsubscript{2} is the intermediate-wetting phase. When CO\textsubscript{2} is injected into the fracture, as it is the intermediate phase, it is imbibed into the matrix and displaces the oil phase. For this wettability configuration, CO\textsubscript{2} directly contacts the oil phase. While, in a water-wet case, CO\textsubscript{2} contacts the water-phase. For the conditions considered in experiment 4, the matrix is considered to be mixed-wet. This means that those pores that exhibit water-wet behaviour are not accessible to CO\textsubscript{2}. Thus, CO\textsubscript{2} is the non-wetting phase and cannot contact the oil phase directly. This explains the incomplete oil recovery from the matrix. Another characteristic of oil production from an oil-wet matrix compared to a water-wet matrix using CO\textsubscript{2} is that higher drainage rates can be achieved in case of an oil-wet matrix (Figure 1b), indicating faster mass transfer between matrix and fracture.

### Table 1
Experimental conditions considered in this study

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Matrix*</th>
<th>Wettability</th>
<th>$K_m$ (Darcy)</th>
<th>$S_w$</th>
<th>Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>B-1</td>
<td>water-wet</td>
<td>1.5</td>
<td>0</td>
<td>CO\textsubscript{2}</td>
</tr>
<tr>
<td>2</td>
<td>B-2</td>
<td>oil-wet</td>
<td>1.4</td>
<td>0</td>
<td>CO\textsubscript{2}</td>
</tr>
<tr>
<td>3</td>
<td>B-3</td>
<td>water-wet</td>
<td>1.5</td>
<td>0.42</td>
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</tr>
<tr>
<td>4</td>
<td>B-4</td>
<td>oil-wet</td>
<td>1.4</td>
<td>0.13</td>
<td>CO\textsubscript{2}</td>
</tr>
<tr>
<td>5</td>
<td>B-5</td>
<td>water-wet</td>
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<td>0.41</td>
<td>N\textsubscript{2}</td>
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<tr>
<td>6</td>
<td>B-6</td>
<td>oil-wet</td>
<td>1.4</td>
<td>0.14</td>
<td>N\textsubscript{2}</td>
</tr>
<tr>
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<td>L-1</td>
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<td>0.48</td>
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</tr>
<tr>
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<td>L-2</td>
<td>oil-wet</td>
<td>2.3</td>
<td>0.21</td>
<td>CO\textsubscript{2}</td>
</tr>
</tbody>
</table>

* B: Bentheimer; L: Limestone

**Figure 1** Simulation results and experimental data for a) recovery history and b) drainage rate for Experiments 3 and 4, where water-wet and oil-wet cores were used with CO\textsubscript{2} as the injection gas.

**Oil-wet/water-wet sandstone core and N\textsubscript{2} system.** The results from experiments 5 and 6 allow to further examine the combined effect of matrix wettability and gas phase properties. Comparison between Figures 1 and 2 reveals that, with a strongly water-wet matrix, both CO\textsubscript{2} and N\textsubscript{2} are the non-wetting phase and process is mainly governed by capillary forces. As can be observed, the incremental oil recovery by gas injection for both cases is roughly the same. This means, for a strongly water-wet system, the gas phase is always the most-non-wetting phase. Similar to experiment 3, at the fracture-matrix interface, the gas phase (i.e., N\textsubscript{2}) contacts with water. Under the conditions...
considered in experiment 5, N₂ is purely immiscible with water. Moreover, the solubility of N₂ in water is negligible. Consequently, the interaction between matrix and fracture is controlled by capillary and gravity forces. The additional oil production after water imbibition is explained by a double drainage process where N₂ displaces water and water displaces oil. In other words, water as a continues phase is displacing the trapped phase, i.e., the oil phase. When gas is injected into the system, the oil phase no longer occupies the biggest pores. Instead gas, which is the most non-wetting phase in a water-wet system pushes the oil patches into the smaller pores. Most of this oil is trapped. It is likely that during gas injection some part of the trapped oil is again reconnected, which can now be produced through gravity drainage process. Comparison between Figures 1 and 2 reveals that, for an oil-wet matrix, CO₂ injection after water injection leads to higher ultimate oil recoveries when compared to N₂ injection. These results show the strong influence of the combined effect of matrix wettability and gas phase properties on the effectiveness of a gravity drainage process. The results obtained from experiments 3-6 suggest that if N₂ is injected as the gas phase, regardless of the wettability behaviour of the matrix, N₂ is always the most non-wetting phase. Therefore, the process is governed by an immiscible gravity drainage process, which is determined by the equilibrium between capillary and gravity forces. However, if CO₂ is injected, depending on the wettability conditions of the matrix block, CO₂ can be the intermediate-wetting phase. According to the results, the most favourable condition for higher oil recoveries is characterized by the injection of CO₂ in an oil-wet matrix. In this case, the process benefits from a faster mass exchange between matrix and fracture, which leads to higher oil production rates.

Oil-wet/water-wet limestone core and CO₂ system. Gas-oil gravity drainage process is mainly applied in carbonate reservoirs as most carbonate reservoirs are naturally fractured. Experiments 7 and 8 were performed using water-wet and oil-wet limestone cores. The simulated recovery and drainage rate curves as well the experimental data are shown in Figures 3a and 3b, respectively. The oil recovery after water imbibition was about 46% of the original oil in the core, while the ultimate oil recovery after CO₂ injection was about 69%. This low incremental recovery by CO₂ injection indicates that the existence of some mobile water saturation in a strongly water-wet matrix hinders the performance of the CO₂ gravity drainage process. Similar to experiment 3, it is assumed that after water injection the oil phase is completely trapped in the form of isolated oil blobs, which leads to very low oil relative permeability. The results obtained for experiment 8 are comparable with the results obtained from experiment 4, where an oil-wet sandstone core plug was used as matrix block. This consistency of the results suggest that for both oil-wet limestone and sandstone matrix blocks, CO₂ injection into a system with effectively oil-wet matrix is considerably more efficient than the case when CO₂ is injected into a water-wet matrix. This attributed to 1) higher remaining oil saturations after water injection in case of an oil-wet matrix, and 2) facilitated mass-exchange between matrix and fracture as CO₂ is the intermediate-wetting phase and can enter the matrix easier.
Conclusions

- Experiments and simulations were conducted to examine the effect of matrix wettability and gas properties on the performance of gas-oil gravity drainage process in NFRs.
- For a water-wet matrix, a significant amount of oil was remained in the matrix even after miscible CO$_2$ injection, indicating that injecting water prior to the miscible CO$_2$ injection step reduces the efficiency of the miscible gravity drainage process.
- Experimental results reveal that higher oil recoveries can be obtained in case of an effectively oil-wet matrix with CO$_2$. While, CO$_2$ injection in a water-wet matrix leads to lower incremental oil recovery after water injection.
- Higher oil production rates was achieved when CO$_2$ was injected into an oil-wet matrix, indicating faster mass exchange rate between fracture and the matrix.
- Experimental results obtained from N$_2$ injection in an oil-wet matrix and a water-wet matrix show that N$_2$ remains always as the non-wetting phase. The incremental oil recovery above the water imbibition for both water-wet and oil-wet cases were almost the same.
- Experimental and simulated oil recovery data obtained by miscible CO$_2$ injection in effectively oil-wet sandstone and limestone matrix blocks were almost comparable. These result suggest that, as long as the matrix block is effectively oil-wet, CO$_2$ can be considered as the intermediate-wetting phase regardless of lithology of the matrix.

References


