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

A. Ameri* (TU Delft and EOR Lab Services B.V.), R. Farajzadeh (TU Delft), N. Shojai Kaveh (TU Delft), S. Suicmez (Mearsk Oil Denmark), K.H.A.A. Wolf (TU Delft) & H. Bruining (TU Delft)

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 Firoozabadi 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.

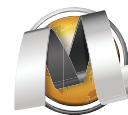
In spite of its importance to enhanced oil recovery from NFRs, there are limited experimental data available in literature detailing the effect of matrix wettability on the performance of gas-oil gravity drainage processes in NFRs at relevant reservoir conditions. In most of the theoretical and experimental 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 ($\sim 20^\circ\text{C}$) 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 of miscible 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 CO₂, water is initially produced by gravity drainage and leaves the trapped oil behind, which is now accessible to CO₂. The oil production by CO₂ injection is limited by the equilibrium between gravity and capillary forces, causing a CO₂ 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, CO₂ 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 CO₂ is the intermediate-wetting phase. When CO₂ 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, CO₂ directly contacts the oil phase. While, in a water-wet case, CO₂ 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 CO₂. Thus, CO₂ 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 CO₂ 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

Experiment	Matrix [*]	Wettability	K_m (Darcy)	S_w	Gas
1	B-1	water-wet	1.5	0	CO ₂
2	B-2	oil-wet	1.4	0	CO ₂
3	B-3	water-wet	1.5	0.42	CO ₂
4	B-4	oil-wet	1.4	0.13	CO ₂
5	B-5	water-wet	1.5	0.41	N ₂
6	B-6	oil-wet	1.4	0.14	N ₂
7	L-1	water-wet	2.4	0.48	CO ₂
8	L-2	oil-wet	2.3	0.21	CO ₂

^{*} B: Bentheimer; L: Limestone

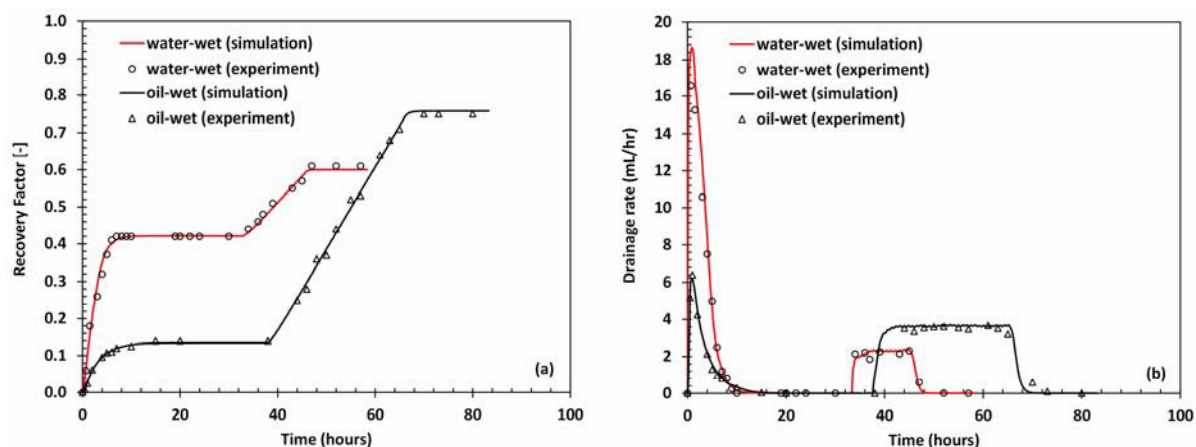
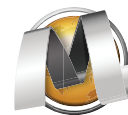


Figure 1 Simulation results and experimental data for a) recovery history and b) drainage rate for Experiments 3 and 4, where water-wet and oil-wet cores were used with CO₂ as the injection gas.

Oil-wet/water-wet sandstone core and N₂ 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 CO₂ and N₂ 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., N₂) contacts with water. Under the conditions



considered in experiment 5, N_2 is purely immiscible with water. Moreover, the solubility of N_2 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 N_2 displaces water and water displaces oil. In other words, water as a continuous 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, CO_2 injection after water injection leads to higher ultimate oil recoveries when compared to N_2 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 N_2 is injected as the gas phase, regardless of the wettability behaviour of the matrix, N_2 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 CO_2 is injected, depending on the wettability conditions of the matrix block, CO_2 can be the intermediate-wetting phase. According to the results, the most favourable condition for higher oil recoveries is characterized by the injection of CO_2 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.

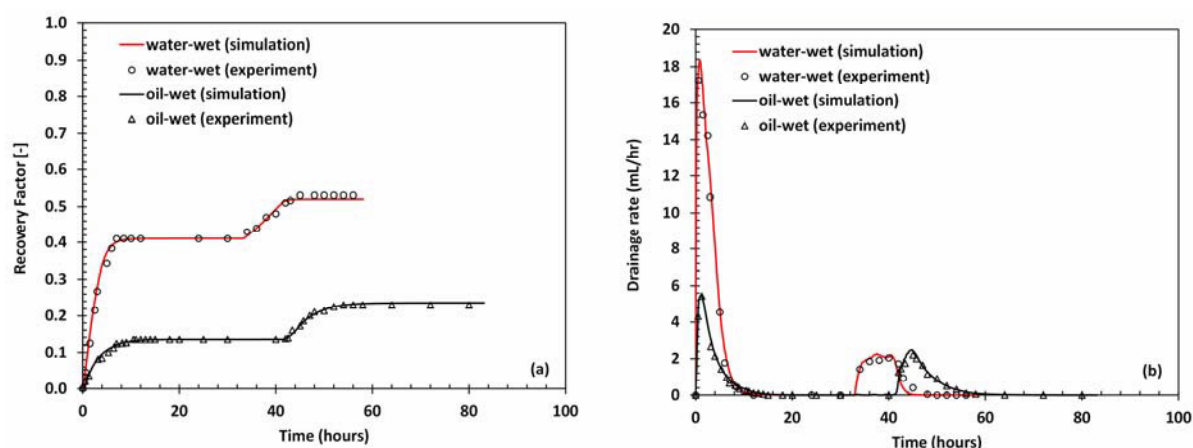


Figure 2 Simulation and experimental data for a) recovery history and b) drainage rate for Experiments 5 and 6, where water-wet and oil-wet cores, where N_2 was injected as the injection gas.

Oil-wet/water-wet limestone core and CO_2 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 CO_2 injection was about 69%. This low incremental recovery by CO_2 injection indicates that the existence of some mobile water saturation in a strongly water-wet matrix hinders the performance of the CO_2 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, CO_2 injection into a system with effectively oil-wet matrix is considerably more efficient than the case when CO_2 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 CO_2 is the intermediate-wetting phase and can enter the matrix easier.

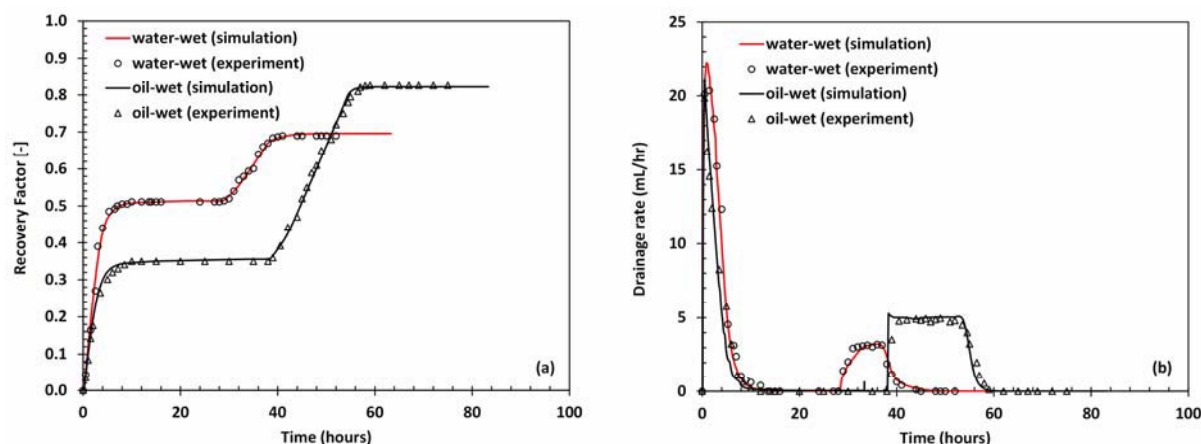


Figure 3 Simulation and experimental data for a) recovery history and b) drainage rate for Experiments 7 and 8, where water-wet and oil-wet limestone cores were used with CO₂.

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 CO₂ injection, indicating that injecting water prior to the miscible CO₂ 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 CO₂. While, CO₂ injection in a water-wet matrix leads to lower incremental oil recovery after water injection.
- Higher oil production rates was achieved when CO₂ was injected into an oil-wet matrix, indicating faster mass exchange rate between fracture and the matrix.
- Experimental results obtained from N₂ injection in an oil-wet matrix and a water-wet matrix show that N₂ 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 CO₂ 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, CO₂ can be considered as the intermediate-wetting phase regardless of lithology of the matrix.

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