Pore-scale study of fluids flow and fluid-fluid interactions during near-miscible CO₂ EOR and storage in oil reservoirs

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SUMMARY

CO₂ injection in oil reservoirs has been widely accepted as an effective EOR and CO₂ storage technique. While oil recovery and CO₂ storage potential of this technique at the core scale has been widely studied, complex fluids flow and fluid-fluid interactions at the pore-scale during near-miscible CO₂ EOR injection require further study. For this aim, a unique high-pressure and high-temperature microfluidic system was used to conduct experiments at 2,500 psi and 40°C using live reservoir crude oil.

According to results, during tertiary CO₂ injection, due to the positive value of spreading coefficient, CO₂ flowed only inside the oil and oil spread over CO₂ and prevented CO₂ contact the water. Due to unfavourable mobility ratios and permeability heterogeneities, displacement during tertiary CO₂ flooding was unstable and viscous fingering occurred which led to an early breakthrough of CO₂ and bypassing of a large amount of oil. However, after CO₂ breakthrough, CO₂ gradually started to flow inside the bypassed oil zones in the transverse/backward directions which is a characteristic of capillary fingering. Due to the gradual diffusion of CO₂ into the bypassed oil, IFT between oil and CO₂ decreased which led to a reduction of threshold capillary pressure, thus CO₂ (non-wetting phase) entered the bypassed oil-filled pores. As a result of this unique mechanism, oil recovery after CO₂ breakthrough significantly increased and almost all the bypassed oil was produced. The extent of this oil recovery mechanism depends on the extent of CO₂-oil IFT reduction which depends on injection pressure.

During CO₂ flow in pores, CO₂ displaced the water through multiple displacement mechanism. CO₂ displaced the oil in the open-end pores thorough bulk flow, and the spreading oil layers were gradually produced by film flow. Uniquely, CO₂ produced the oil in dead-end pores through a mix of bulk flow and film flow.

The outcomes of this study provide an in-depth understanding of fluids flow and fluid-fluid interactions during near-miscible CO₂ EOR-storage.

Key words: near-miscible, miscibility, immiscible, CO₂, EOR, spreading coefficient

INTRODUCTION

With the continuous increase in atmospheric CO₂ concentration, great interest to CO₂ underground storage has been raised. While there is an urge in storing CO₂ in underground formations, there is a need to enhance the oil recovery from majority of mature oil fields. The primary oil recovery in majority of oil reservoirs is low. Even after waterflooding a significant amount of oil will remain in place. The average global oil recovery factor by waterflooding is less than 50% of the original oil in place. One promising scenario to produce some part of the residual oil is CO₂ injection. CO₂ injection is the most well-known Enhanced Oil Recovery (EOR) scenario and has been applied in various fields around the world. By injecting CO₂ into the oil reservoirs some volume of the injected CO₂ will be trapped and consumed in the reservoir due to its solubility in the formation brine and crude oil, geochemical reactions, and residual and structural trapping. Therefore, by injecting CO₂ into oil reservoirs not only we can safely store the CO₂ underground but we can also produce an additional oil that creates a revenue for the storage operation.  

According to previous studies, CO₂ injection into oil reservoirs can enhance the oil recovery through three major oil recovery mechanisms which are oil swelling, oil viscosity reduction and development of miscibility. Miscibility occurs only if the reservoir pressure is above the minimum miscibility pressure (MMP) of the crude oil and CO₂. Under miscible condition the maximum oil recovery by CO₂ injection can be obtained. However, not all the oil reservoirs have a pressure above MMP. Some of them have pressures much smaller than MMP and some have pressures slightly smaller than MMP (near-miscible condition) and therefore their oils are immiscible with CO₂ under reservoir conditions. Several researchers have shown that when the reservoir pressure is below MMP, the CO₂ oil recovery potential decreases as a result of the loss of miscibility. Under this condition, CO₂ injection as an EOR scenario may not be considered for these reservoirs as low sweep efficiency is expected. Therefore, minimum attention has been paid to the near-miscibility condition and its oil recovery mechanisms.

In addition to the lack of a comprehensive study for near-miscible CO₂ injection, so far, oil recovery potential of CO₂ injection under different injection scenarios, such as Huff and puff, continues injection, or CO₂-WAG, has been mainly investigated by many coreflooding studies. Although coreflooding is a strong tool for evaluating the oil recovery potential of almost any EOR scenario, due to its black box nature, little information regarding the fluids flow behaviour, displacement mechanisms, and fluid-fluid interactions at pore-scale can be obtained from coreflooding experiments. Some studies performed the coreflooding tests in medical CT rigs to capture more data from the experiment. However, the resolution of the medical CT rigs is not good enough to reveal the fluid-fluid interactions and fluids flow behaviour taking place at the pore scale. Furthermore, some works used micro-CT rigs for
studying fluids-flow in porous media during CO₂ injection. However, these experiments are very time consuming and expensive and usually, for each scan, the flow needs to be stopped to avoid the fluids distribution inside the porous medium. Therefore, real-time behaviour of the flow and interactions cannot be well characterized by this method.

A strong tool for studying the CO₂-oil interactions, and oil recovery and displacement mechanisms at pore-scale under reservoir pressure and temperature is microfluidic rig. By using this tool, we can have direct visualization of phenomena that take place at the pore scale during and after the injection period. This tool has been successfully used by several researchers for various purposes. For example, Sohrabi et al. and Seyyedi et al. investigated the oil recovery mechanisms and fluids flow in porous media during carbonated brine injection under various reservoir conditions. Dahran and Rossen studied the foam flow in a porous medium using the microfluidic rig.

In this study, we are aiming to provide new insights about the fluids flow in porous media, fluids displacement mechanisms, and oil recovery mechanisms during near-miscible CO₂ injection. An in-house designed high-pressure and high-temperature microfluidic rig was used in this study. The experiments were performed under the pressure of 2500 psi and temperature of 40°C using a live reservoir crude oil.

METHOD AND RESULTS

A uniquely designed in-house microfluidic rig, with the ability to work at pressures as high as 10,000 psi and temperatures as high as 100°C, was employed. Figure 1 shows the schematic of the microfluidic rig. All fluids were kept inside the fluid storage oven at test temperature and pressure. The microfluidic chip was housed inside a separate oven under the same experimental condition. The microfluidic chip was a transparent porous medium made of two sapphire glass plates which was placed inside a high-pressure chamber. One of the palates was etched with a pattern to allow fluids to flow in a controlled way and the other one was unetched to seal the system. The pattern was a heterogeneous pattern synthesized in-house to lead to high residual oil saturation after a waterflood. The average pore depth of the microfluidic chip was 50 micrometres and the pore-throat diameters ranged from 300 to 500 micrometres. The microfluidic chip dimensions are shown in Figure 2.

Microfluidic chip was aged with crude oil for 12 hours under the test conditions (2500 psi and 40°C). Next, to mimic the waterflooding scenario, the microfluidic chip was flooded by brine at a constant rate of 0.01 cc/min. The injection was continued until no more oil redistribution in the porous medium and no more oil production were observed. To recover some part of the residual oil after waterflooding, microfluidic chip was flooded by supercritical CO₂ at test conditions. CO₂ was injected from the same head and with the same rate as water was injected. The injection was continued for 24 hours and during this time period the fluids displacement, and redistribution was recorded using a high-resolution microscope kit.

Figure 2. The microfluidic chip when it is fully saturated with blue-dyed water.

A reservoir crude oil with the API of 20.8 was used. To prepare the live reservoir oil, crude oil was fully saturated with methane under experimental condition using a rocking cell. Based on our calculations, the MMP of this crude oil at the temperature of 40°C is expected to be around 2700 psi which is slightly higher than the test pressure (2500 psi).

Waterflooding of the microfluidic chip led to very low oil recovery and, as shown in Figure 3, a significant amount of oil was bypassed by water and remained in the porous medium.

Figure 3. Significant amounts of oil remained in the porous medium after waterflooding.

During tertiary CO₂ injection, CO₂ flowed only inside the oil and oil spread over CO₂ and prevented CO₂ contacts the water. This behaviour shown in Figure 4 can be attributed to the positive value of the spreading coefficient (SC). For immiscible gas injection scenario, depends on the spreading coefficient value and wettability of the system gas can spread differently between water and oil which can directly affect the surface contact area of the gas with the oil and therefore the oil recovery. The maximum oil recovery occurs when the oil has the maximum contact with CO₂ or in other words when CO₂ is flowing inside the oil and oil is spread on CO₂. Spreading coefficient can be measured as:

$$SC = γ_{CO₂-water} - γ_{CO₂-oil} - γ_{oil-water}$$
Since the oil viscosity under the test condition was around 14 cP and CO₂ viscosity was around 0.07 cP, the CO₂ front was un-stable and viscous fingering happened which led to the early breakthrough of the CO₂ and bypassing of a large volume of the residual oil. In addition to the high viscosity ratio, the presence of permeability heterogeneities in the microfluidic chip helped to early breakthrough of CO₂. Figure 5 is taken from a section of microfluidic chip just after CO₂ breakthrough.

Although the CO₂ breakthrough occurred at very early times of injection, after CO₂ breakthrough, CO₂ gradually started to flow inside the bypassed oil zones in the transverse/backward directions which is a characteristic of capillary fingering (Figure 6). Due to the gradual diffusion of CO₂ into the bypassed oil, IFT between the oil and CO₂ decreased which led to a reduction of threshold capillary pressure, therefore CO₂ (non-wetting phase) entered the bypassed oil-filled pores. As a result of this unique mechanism, oil recovery after CO₂ breakthrough significantly increased and almost all the bypassed oil was produced. The extent of this oil recovery mechanism depends on the extent of CO₂-oil IFT reduction which depends on injection pressure. As it has been shown by several researchers, CO₂ has very low IFT values with oil near the miscible condition⁴. Figure 7 shows the changes in IFT of a crude oil-CO₂ system versus pressure⁴.

During CO₂ flow in the porous medium, CO₂ displaced the brine through multiple displacement mechanism. Multiple displacements refer to several piston events, where a fluid phase (CO₂) displaces a fluid (oil) which in turn displaces another fluid (brine). CO₂ displaced the oil in the open-end pores thorough bulk flow, and the spreading oil layers were gradually produced by film flow. Uniquely, CO₂ produced the oil in dead-end pores through a mix of bulk flow and film flow (This phenomenon is shown in Figure 6). As discussed above, CO₂ gradually diffuses into the oil trapped in dead-end pores which causes a reduction in IFT and capillary threshold pressure and consequently, CO₂ (non-wetting phase) enters the dead-end pores. As CO₂ flows into the dead-end pores, it displaces the oil
by bulk flow however since the pore is dead-end, oil flows out of the pore through the film flow.

Furthermore, during CO₂ flow in the porous medium, due to capillary pressure hysteresis, CO₂ snap off occurred (Figure 8). Due to the presence of capillary pressure hysteresis, CO₂ residual trapping during CO₂ underground injection takes place which leads to the safe storage of CO₂ in the porous medium. At the same time, coalesces of CO₂ bubbles when they get close to each other was observed.

Figure 7. CO₂-Oil IFT versus pressure.

Figure 8. CO₂ snap off that leads to CO₂ residual trapping.

During near-miscible CO₂ injection, a strong extraction of light to intermediate oil components into the CO₂ stream was detected which caused CO₂ became enriched in hydrocarbon components and oil became heavier (as seen by the change in the colour of the oil shown in Figure 9). This extraction was not strong enough to lead to miscibility. Interestingly, this extraction did not cause any unfavourable asphaltene precipitation or wettability change which reveals that these effects are a function of oil type. Figure 9 shows the extraction during near-miscible CO₂ injection.

Since the CO₂ was injected in a tertiary scenario and the microfluidic chip was previously flooded by water, some oils were shielded by water layers and were initially inaccessible to the CO₂ stream. This phenomenon is well-known and is called water-shielding effect which can negatively impact the oil recovery during gas injection as the oil is directly inaccessible to the main gas stream. For example, in our case, CO₂ first diffuses into the thin oil layer surrounding the CO₂ stream and then from the thin oil layer, CO₂ diffuses into the water layer shielded the oil ganglia and finally from the water layer, CO₂ diffuses into the isolated oil. As the gas reaches the oil, the oil starts to swell and if the oil swelling would be strong enough to rupture the water layer and meet the CO₂ stream, the oil can be produced otherwise the oil will remain trapped. Therefore, the oil recovery of water shielded oil ganglia is governed by the diffusion rate of CO₂ into the thin oil layer, from the thin oil layer into the brine and from brine into the oil and extent of oil swelling. As a result, since the diffusion is a slow process, it would be expected that the water shielded oil ganglia will not be produced or they will be produced only at the very late times of injection. Unexpectedly, in our experiment, we noticed different behaviour. The water shielded oil ganglia were produced only in less than 5 hours of CO₂ injection. This could be attributed to the in-situ formation of a new gaseous phase inside the water shielded oil ganglia during CO₂ injection (Figure 10). The new gaseous phase led to a very strong swelling of water shielded oil ganglia and consequently rupturing of the water layer which made the oil accessible to CO₂ stream and thus producible. This behaviour (shown in Figure 10) can only be explained by the in-situ formation of carbonated brine during CO₂ injection. CO₂ diffuses into the water layer around the oil.
ganglia and forms the carbonated brine. As shown by Seyyedi et al. when carbonated brine comes in contact with a live oil a new gaseous phase forms inside the oil that leads to a very strong hydrocarbon swelling and therefore additional oil recovery. The amount of this swelling was shown to be higher than normal swelling that happens for dead oils.

**CONCLUSIONS**

The outcomes of this study provide an in-depth understanding of fluids flow and fluid-fluid interactions during near-miscible CO₂ EOR/storage. Near-miscible CO₂ injection has a strong oil recovery potential. Although the miscibility is not taking place during this scenario and we may have a high mobility ratio that leads to poor sweep efficiency of CO₂, the diffusion of CO₂ into the oil leads to a strong reduction in the IFT of CO₂-oil which leads to a strong reduction in the capillary threshold pressure. Thus, CO₂ capillary fingering will be developed during the near-miscible CO₂ injection that can lead to additional oil recovery and production of bypassed oils or oils in dead-end pores. This unique phenomenon only occurs at the near-miscible condition.

At near-miscible condition, the spreading coefficient value will determine the gas-oil surface contact area and therefore will directly impact the oil recovery. When the spreading coefficient is positive, CO₂ only flows inside the oil and a layer of oil spreads on the CO₂ stream which avoids CO₂ contact the brine. Under this condition, CO₂ displaces the oil in the open-end pores thorough bulk flow, and the spreading oil layers gradually are produced by film flow. CO₂ will displace the brine through multiple displacement mechanism. Interestingly, at near-miscible condition CO₂ displace the oil in dead-end pores by a unique mix of bulk and film flow.

During near-miscible CO₂ injection strong extraction of oil components into the CO₂ takes place that leads to enrichment of the CO₂. However, this extraction is not strong enough to lead to miscibility. Finally, as the majority of oil reservoirs have live crude oils, the formation of a new gaseous phase inside the water-shielded oil ganglia is expected during near-miscible CO₂ injection. This phenomenon leads to strong oil swelling and rupturing of the water layer around the isolated oil ganglia. As a result, these trapped oil ganglia become accessible to the CO₂ and will be produced.

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