SUPERCRITICAL CO_2 INJECTION FOR ENHANCED OIL RECOVERY IN FRACTURED CHALK

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ABSTRACT

CO_2 injection for enhanced oil recovery (EOR) has the potential to significantly enhance oil production to meet the world's increasing energy demand, and, at the same time, safely store CO_2 in mature oil fields to curb the release of CO_2 to the atmosphere. We report laboratory supercritical CO_2 injections for enhanced oil recovery by diffusive transport of CO_2 in oil/water systems in fractured, outcrop chalk core plugs. The experiments were performed at reservoir conditions, using different oil phases (n-Decane or a North Sea crude oil) at initial wettability conditions of strongly water-wet and neutral-wet.

Secondary CO_2 injections, recovered 96% original oil in place (OOIP) in both fractured and un-fractured n-Decane saturated systems. During tertiary CO_2 injection after a waterflood, oil recovery varied between 70%OOIP (fractured systems) and 92%OOIP (un-fractured systems). The water shielding effect reduced the efficiency of tertiary CO_2 injection, particularly for strongly water-wet core plugs, by reducing the rate of diffusion and mixing between the injected CO_2 and oil phase. In fractured systems, oil production was controlled by CO_2 diffusion from the CO_2-filled fracture to the oil-saturated matrix. Oil production from crude oil systems was generally lower than from systems with n-Decane.

INTRODUCTION

Injection of CO_2 can increase oil recovery by e.g. viscous fluid drive, oil phase swelling and oil viscosity reduction [1]. Miscible CO_2 floods reduce the interfacial tension between gas and oil, which diminish the capillary differences between matrix and fractures, and may achieve high recovery factors in fractured reservoirs [2]. When CO_2 is injected in a crude oil/rock/brine system, multi-contact miscibility develops through several exchange processes if the injection pressure at a given temperature is above the minimum miscibility pressure (MMP). Hydrocarbon-components from the oil vaporize into the CO_2, which in turn condense into the oil phase until they may be considered one phase [3]. Lighter components vaporize more easily into the gas phase than heavier [4]. A miscible CO_2 flood can in theory displace all oil from a reservoir, however, achieving adequate macroscopic sweep efficiency may be challenging, due to reservoir heterogeneities and naturally occurring fractures coupled with an unfavorable mobility ratio in the displacement process. Also, high water saturations at the onset of CO_2 injection may prevent CO_2 from contacting oil in clusters or dendritic pores: oil shielded by water is not displaced, leaving higher residual oil saturations [5].

Supercritical CO_2 was injected into un-fractured and fractured core plugs at reservoir conditions to miscible displace oil. The main objective was to compare production scenarios when the oil saturating the core plug was either pure mineral oil or complex reservoir crude oil. Secondary and tertiary injection schemes at varying wettability conditions were experimentally investigated and analyzed.

EXPERIMENTAL

Cylindrical core plugs were drilled out from larger rock slabs of Rørdal chalk [6], cleaned and dried at 80°C. The core plugs were thereafter saturated with synthetic brine (4% NaCl, 3.4% $CaCl_2$, 0.5% $MgCl_2$, 0.05% NaN_3) under vacuum, and the porosity was determined from weight measurements. Permeability to brine was calculated using Darcy's law. Four of the core plugs were drained to irreducible water saturation, S_{wi}, with n-Decane, and seven core plugs with crude oil from a North Sea chalk reservoir. A constant differential pressure gradient of 2bar/cm was used during primary drainage. Three core plugs were aged with crude oil to nearly neutral-wet (NNW) conditions using a dynamic aging method [7], where crude oil was continuously flushed through the core plugs at a low rate for six days. Six of the core plugs were fractured longitudinally with a band saw, and assembled with polyoxymethylene (POM) spacers to maintain a constant fracture aperture of 1mm (**Figure 1-top right**). Fluid properties and calculated minimum miscibility pressure from CMG Winprop simulations are listed in **Table 1**, and core plug properties are listed in **Table 2**. Waterfloods and supercritical CO_2 injections were performed at reservoir temperature and pressure conditions, above MMP. **Figure 1** shows a schematic of the experimental setups used for CO_2 displacement of n-Decane and crude oil. For core plugs saturated with n-Decane (2'' diameter), experimental conditions were 40°C/95bar and injection rates were Q_{WF}=2ml/h and Q_{CO2}=2.8ml/h. Experiments with crude oil saturated core plugs (1.5'' diameter) were performed at 75°C/208bar and injection rates were Q_{WF}=1ml/h and Q_{CO2}=1ml/h.

EXPERIMENTAL RESULTS

Secondary injection of CO_2 in un-fractured and fractured core plugs with different oils

Figure 2 shows the development in oil saturation (frac PV) and oil recovery (frac OOIP) during secondary supercritical CO_2 injections in initially strongly water-wet (SWW), un-fractured core plugs (PS10 and AR5) and fractured core plugs (PS12 and AR8). Core plugs AR5 and AR8 were saturated with crude oil, and core plugs PS10 and PS12 were saturated with n-Decane. The impact from oil composition was clearly observed as oil recovery was 96%OOIP for core plugs with n-Decane, compared to 56-71%OOIP for core plugs containing crude oil. The presence of fractures reduced the initial production rate and hence the rate of recovery for both n-Decane and crude oil saturated core plugs. Oil recovery from the crude oil saturated fractured core plug AR8 was 15%OOIP lower compared to un-fractured core plug AR5. In general, oil recovery from fractured systems was identified by: 1) a rapid breakthrough of CO_2, where most of the oil was produced after breakthrough, 2) a low production rate from the onset of CO_2 injection and 3) a long tail production, which indicated a diffusion dominated recovery process. For both crude oil core plugs, residual oil saturations were not reached when the CO_2 injection tests were terminated.

Secondary injection of CO_2 in core plugs at varying wetting conditions

Figure 3 shows the effect of wettability on oil recovery during CO_2 injection in crude oil saturated un-fractured core plugs (AR1 and AR5) and fractured core plugs (AR6 and AR8). Core plugs AR5 and AR8 were not aged and assumed SWW, whereas core plug AR1 and AR6 were aged dynamically and assumed NNW prior to CO_2 injection. The Amott-Harvey indices were not explicitly measured but based on previous work using the same oil/rock/brine system [8]. Increased oil production was observed in un-fractured core plugs during CO_2 injection at NNW compared to SWW wettability conditions. A plausible explanation for this observation is the higher oil mobility at NNW compared with SWW conditions: oil remains mobile at lower saturation values due to the distribution of the residual oil phase in the pore space, and less snap-off [9]. The wettability impact was not observed in fractured systems, where diffusion was the dominating production mechanism, and oil recovery Rf=55%OOIP was observed at both wetting conditions.

Tertiary injection of CO_2 in un-fractured and fractured core plugs with different oils

Figure 4 shows the development in oil production during waterflooding and subsequent tertiary CO_2 injection for initially SWW fractured core plugs (AR4 and A5) and un-fractured core plugs (AR3 and A7). Core plugs A5 and A7 were saturated with n-Decane, whereas core plugs AR3 and AR4 were saturated with crude oil. Waterflooding was efficient for all core plugs, and oil recovery ranged from 49 to 63%OOIP. During tertiary CO_2 injection, un-fractured core plugs exhibited higher total recovery (92%OOIP) compared to fractured core plugs (60–70%OOIP), where water shielding caused by high water saturations after the waterflood was more prominent. When CO_2 channeled through the fracture, contact between CO_2 and the oil phase was crucial to obtain recovery by diffusion, which was the main recovery mechanism during CO_2 injections in fractured media. In un-fractured core plugs, forced extrusion of CO_2 through the porous system supplied a viscous component. The oil phase composition did not significantly affect oil recovery during tertiary CO_2 injections.

Tertiary injection of CO_2 in core plugs at varying wettability conditions

Prior to waterflooding and subsequent tertiary CO_2 injection the fractured core plug AR4 was at SWW conditions, and core plug P11 was aged to NNW conditions before fracturing. Both core plugs were saturated with crude oil and the initial wetting conditions may have changed during the injections. At NNW conditions, waterflood oil recovery was 6%OOIP, compared to 38%OOIP for the SWW core plug, as a result of reduced capillary spontaneous imbibition of water from the fracture into the matrix. Tertiary CO_2 injection increased the oil recovery by 59%OOIP (NNW) compared to only 10%OOIP (SSW) during injection of 5.2PV and 3.1PV CO_2, respectively, which indicated water shielding. **Figure 5** shows the wettability effect during tertiary CO_2 injection in two fractured core plugs saturated with crude oil.

DISCUSSION

Diffusion as a recovery mechanism in fractured reservoirs

During secondary CO_2 injection in fractured core plugs, oil recovery was mainly produced by diffusion from the CO_2-filled fracture to the oil-saturated matrix, observed by low production rates and long tail production after CO_2 breakthrough. Oil recovery was more efficient in systems saturated with n-Decane compared to crude oil, most likely because CO_2 and n-Decane were first-contact miscible above MMP and the crude oil hydrocarbon composition (97% C_{7+}, 28% C_{30+}) resulted in multiple-contact miscibility with CO_2. After breakthrough of CO_2 in crude oil saturated systems, visual observations indicated that the lighter components in the crude oil, which developed miscibility first, were also produced first. Other experiments confirm that crude oil composition changes at different production stages during CO_2 injections: oil with composition similar to the original crude oil in place is viscously produced first, followed by the light end components and finally the heavy end components [10].

Water shielding during tertiary CO_2 injection

Compared to secondary CO_2 injection, the oil recovery during tertiary injection was observed to depend on water saturation after the waterflood. A significant reduction in oil recovery by CO_2 was observed in fractured systems after efficient waterfloods at SWW compared to NNW conditions. Total recovery after tertiary CO_2 flooding in fractured core plugs was similar for SSW and NNW systems. In SWW systems, the majority of oil was, however, produced during waterflooding and CO_2 was less efficient in recovering oil. In NNW systems, the opposite was observed, and the waterflood was inefficient with the majority of oil produced during CO_2 injection. This behavior is explained by the water shielding effect that effectively reduce mixing between oil and CO_2 and the rate of by diffusion. Water shielding was less pronounced in un-fractured core plugs where oil was recovered by viscous forces in addition to diffusion.

CONCLUSIONS

The key observations from this experimental study on oil recovery by CO_2 injection in fractured chalk were:

- During secondary CO_2 injections, oil recovery was 96%OOIP in both fractured and un-fractured systems saturated with n-Decane.
- Oil production from crude oil systems was generally lower than from systems with n-Decane, likely due to the development of multi-contact miscibility and a less favorable mobility ratio.
- In fractured systems, oil production was controlled by CO_2 diffusion from the CO_2-filled fracture to the oil-saturated matrix.
- Water shielding reduced the efficiency of tertiary CO_2 injections, particularly in strongly water-wet systems.

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Table 1. Fluid and CO_2 properties.

Fluid	Density [kg/dm^3]	Viscosity [cP]	MMP [bar]
n-Decane, 1bar/20°C (90bar/40°C)	0.74 (0.72)	0.92 (0.77)	80.9 @40°C
North Sea crude oil, 1bar/20°C (1bar/80°C)	0.85 (0.85)	14.3 (2.7)	125 @75°C
CO_2, ^{1}(95bar/40°C) ^{2}(90bar/90°C) ^{3}(208bar/75°C)	^{1}0.580 ^{2}0.175 ^{3}0.643	^{1}0.043 ^{2}0.021 ^{3}0.051	

Table 2. Core plug characteristics and results. Superscript ^{a} = aged.

							Waterflood		CO_2					
Name	L [cm]	Por [frac]	K [mD]	Oil	System	S_{oi} [frac.]	Rate [ml/h]	$S_{o,WF}$ [frac]	Inj. mode	Rate [ml/h]	Vol. inj. [PV]	$S_{o,1PV}$ [frac]	S_{or} [frac]	Rf %OOIP
PS10	5.97	0.45	4.26	n-Dec	u-Frac.	0.731	-	-	Sec.	2.8	4.1	0.340	0.028	96.1
PS12	6.00	0.44	2.79	n-Dec	Frac.	0.685	-	-	Sec.	2.8	8.6	0.373	0.028	95.9
A7	5.92	0.44	4.45	n-Dec	u-Frac.	0.764	2.0	0.364	Ter.	2.8	5.3	0.210	0.060	92.2
A5	5.96	0.45	3.06	n-Dec	Frac.	0.735	2.0	0.273	Ter.	2.8	4.1	0.241	0.216	70.6
AR5	7.09	0.46	4.56	Crude	u-Frac	0.778	-	-	Sec.	1.0	3.9	0.385	0.225	71.0
AR1^a	5.89	0.46	4.50	Crude	u-Frac	0.705	-	-	Sec.	1.0	4.3	0.262	0.115	83.7
AR8	6.01	0.40	2.42	Crude	Frac.	0.665	-	-	Sec.	1.0	4.5	0.440	0.300	55.5
A6^a	6.02	0.44	3.81	Crude	Frac.	0.756	-	-	Sec.	1.0	4.6	0.511	0.350	53.7
AR3	5.63	0.47	3.19	Crude	u-Frac.	0.655	1.0	0.278	Ter.	1.0	4.9	0.113	0.042	93.6
AR4	7.08	0.46	4.97	Crude	Frac.	0.760	1.0	0.378	Ter.	1.0	3.1	0.302	0.282	47.8
P11^a	5.96	0.43	2.60	Crude	Frac.	0.781	1.0	0.736	Ter.	1.0	5.2	0.481	0.274	65.0

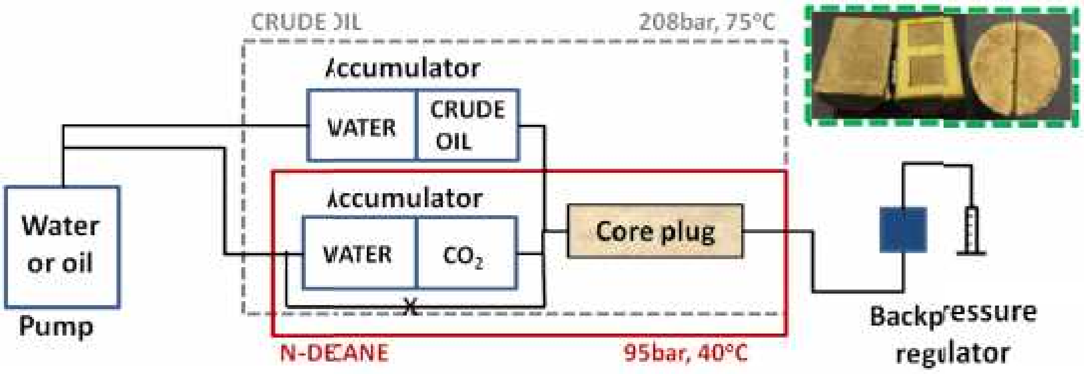

Figure 1. The experimental set-ups used for n-Decane and crude oil saturated core plugs. Top right: Images of a fractured core plug with a POM spacer.

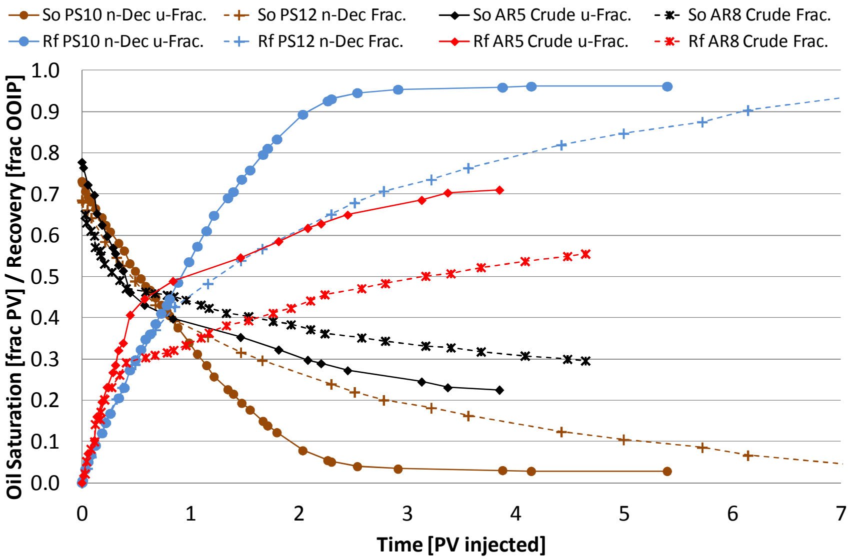

Figure 2. Secondary inj. of CO_2 in un-fractured and fractured core plugs with different oils.

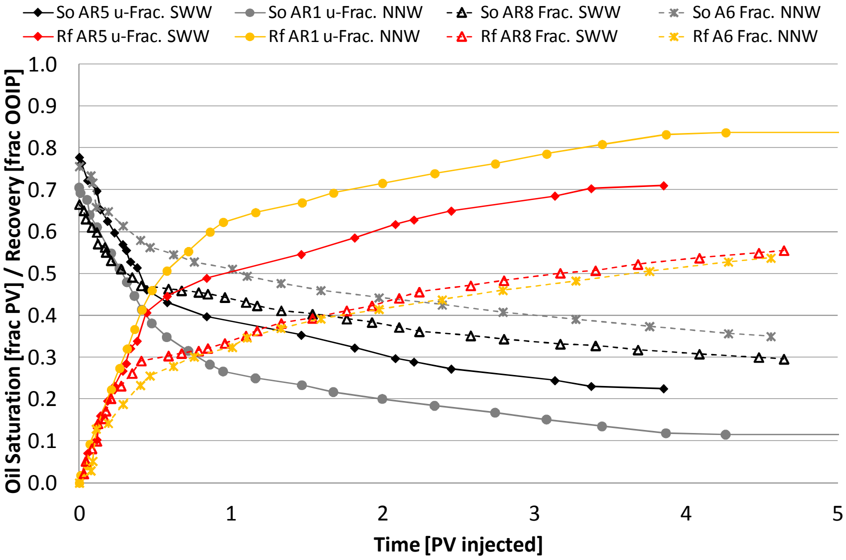

Figure 3. Secondary injection of CO_2 in core plugs at varying wetting conditions.

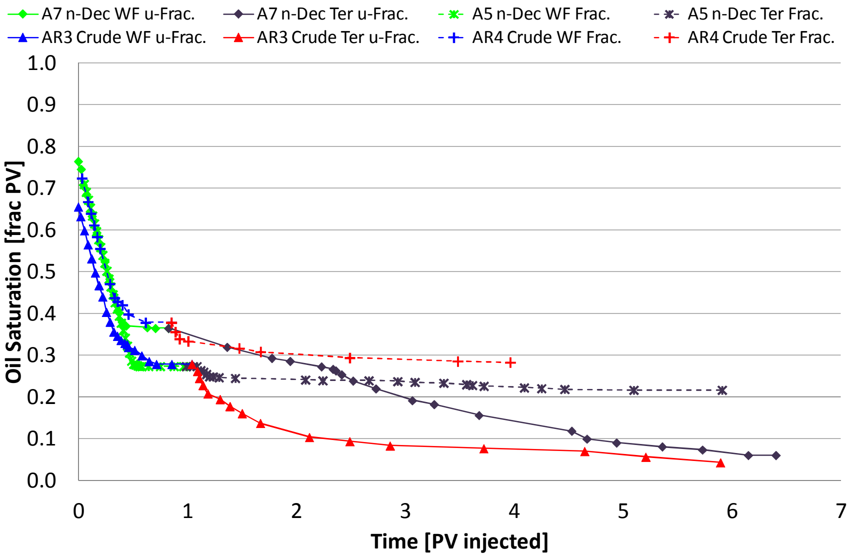

Figure 4. Tertiary injection of CO_2 in un-fractured and fractured core plugs with different oil.

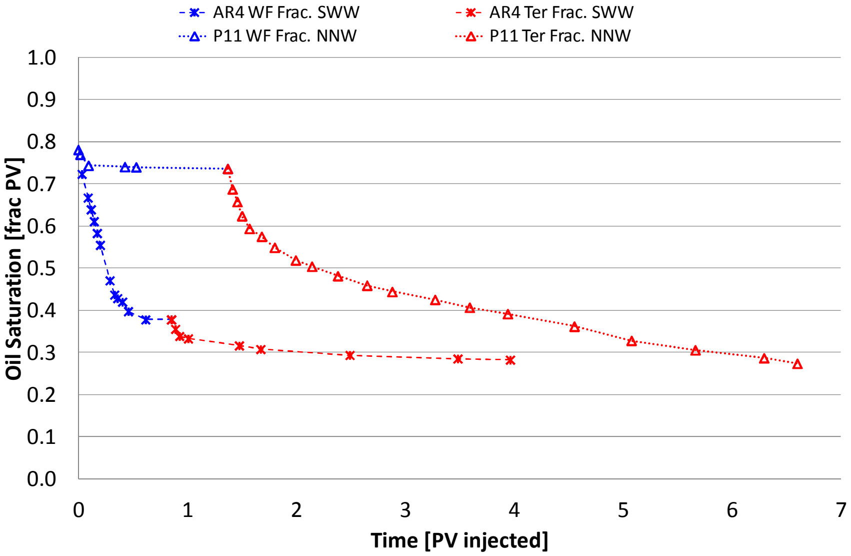

Figure 5. Tertiary injection of CO_2 in fractured core plugs at varying wetting conditions.