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EXPERIMENTAL STUDY AND CALCULATION OF CO_2-OIL RELATIVE PERMEABILITY

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Abstract

Carbon dioxide-oil relative permeability is measured under reservoir condition using core flood apparatus. Then the results are compared with Nitrogen-oil relative permeability. The results show that oil permeability is higher in Carbon dioxide injection compared to nitrogen injection. The comparison of gas permeabilities shows that at the start of injection, nitrogen and carbon dioxide relative permeability are equal, but as the gas saturation increased, Nitrogen relative permeability becomes higher. Finally, a method is proposed to calculate carbon dioxide-oil relative permeability from nitrogen-oil relative permeability. This method can be generalized to calculate relative permeability for any gas-oil system from a base relative permeability.

Keywords: Relative permeability; CO_2 injection; N_2 injection; two phase flow.

1. Introduction

Gas-injection processes for improved oil recovery are common. At present, carbon dioxide is widely used for many enhanced oil recovery processes. Management of these processes requires accurate simulation before implementing in field or decision making. The relative permeability is a crucial parameter for accurately evaluating reservoir performance. Therefore, it is necessary to find out how CO_2 affect relative permeability in CO_2 based EOR methods.

To find out the effects of CO_2 on relative permeability, N_2-Oil relative permeability is used as base comparison, because N2 has negligible interaction with oil and rock. Many parameters affect relative permeability, but some parameters can be removed if comparison of relative permeabilities done in same temperature and pressure and on same core sample.

Injection of CO_2 in oil reservoir results in reduced interfacial tension and viscosity which improves mobility. Also CO_2 can dissolve in oil leading to oil swelling [8]. The IFT between oil and displacing fluid is an important parameter for most EOR techniques; therefore there has been much interest in the effect of IFT on oil and displacing-fluid relative permeabilities. It has been shown experimentally that residual oil and relative permeability are strongly affected by the variations in IFT [9]. But the effect of oil swelling on relative permeability was ignored, until now. Oil swelling can increase oil saturation and decrease gas saturation; both affect relative permeability, certainly.

In this paper, the effects of CO_2 on relative permeability are studied to propose a method based on Corey model that can calculate CO_2-oil relative permeability from a base relative permeability (e.g. N_2-oil relative permeability). The final purpose is generalizing this method to all Gas-Oil systems. Therefore any Gas-Oil relative permeability can be calculated from a base relative permeability, without expensive and time consuming experiments. It is common for EOR screening that different gases are used in experiments to find best EOR scenario. The proposed method is applicable in such cases to reduce number of experiments and costs.

2. Materials and methods

2.1. Porous medium

Two tight carbonate reservoir rocks and one sandstone outcrop are used in experiments. The core samples are of 3.8 cm diameter and 8-16 cm of length. The permeability of carbonate

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cores is below 1 md and sandstone permeability is 47 md. The core properties are shown in Table 1.

Table 1 Physical properties of used core samples

No.	Type	D (cm)	L (cm)	K (md)	Φ(%)	PV (cc)
S1	Sandstone outcrop	3.81	15.85	47.2	15.3	27.65
C1	Carbonate reservoir	3.81	14.9	0.85	10.76	18.28
C2	rock	3.81	8.5	0.29	15.4	14.92

2.2. Fluid System

The fluids used in the experiments were recombined live oil of Naftshahr oil field as the oil phase and nitrogen and carbon dioxide as gas phases. Oil with 43 degree API and viscosity of 1.05 CP at 46°C and 2000 psi, is used.

2.3. Apparatus

For gas injection experiments, the core flood apparatus is used. Schematic view of apparatus is shown in Figure 1 and various parts are described in Table 2. The core assembly is contained in a constant-temperature air bath with the temperature control at 46°C achieved by an automatic temperature controller. The pumps, having a range of rates from 0.1 to 500 cc/hr delivered the fluids at constant rate to the core under test condition.

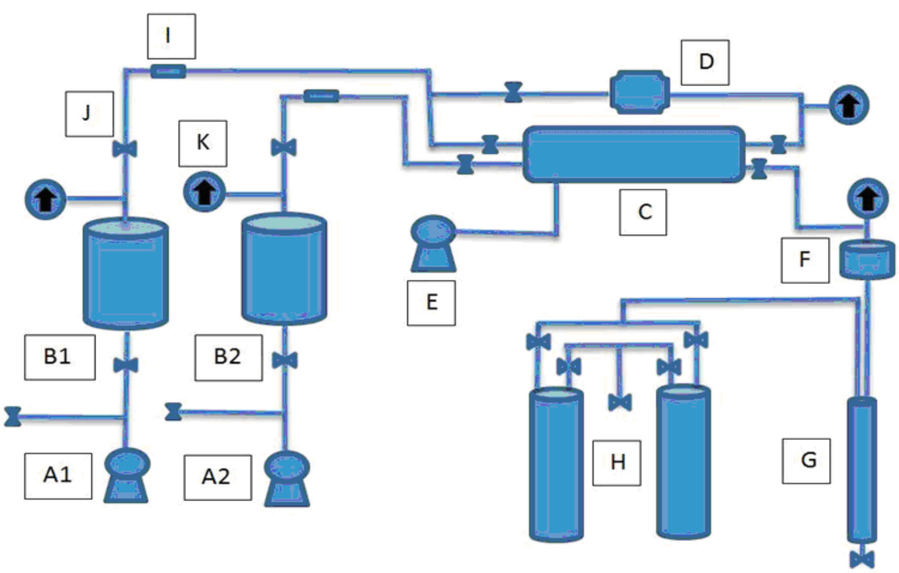

Fig. 1 Schematic diagram of experiment setup

Table 2 Different parts of experiment setup

HPLC pumps	A1, A2	Separator	G
Transfer vessels	B2, B1	Gas production meter	H
Core holder	C	Unilateral valves	I
Differential pressure	D	Valves	J
Overburden pressure pump	E	Gauge pressure	K
Back pressure regulator	F		

2.4. Procedure

The cores were washed in Soxhelt apparatus with toluene and methanol. Toluene dissolves the oil residuals and methanol dissolves salts. Cores were ovened at 120°C for 24 hours to stabilize any clay mineral present in the rock. The different in weight between 100% liquid saturation and total dryness was used to calculate the core porosity. At the start of each experiment the core was evacuated for sufficient time and then saturated with brine. Several pore volumes of brine were cycled through to ensure complete saturation. The absolute permeability to water was determined by measuring the pressure differential across the core, the fluid viscosity and flow rate. The water saturated core was flooded with oil to irreducible water saturation. Gas injection was started with constant injection rate of 0.3 cc/hour and the pressure drop across the core, oil and gas production as a function of the injected fluid, were recorded. The Jones and Roszelle method is used to calculate two phase relative permeability [5]. For measuring relative permeability of gas at residual oil saturation, after 4 pore volume of injection, injection was continued with higher rate until the oil production was ceased.

3. Results and Discussion

For uncovering the effects of CO_2 on relative permeability curves, N_2-oil relative permeability curve is taken as a base. Since nitrogen has negligible solubility in oil and practically has no effect on oil and rock properties.

For comparison of relative permeability curves in full range saturation, the Corey's model is used for normalizing saturation and relative permeability and fitting experimental data. This is especially helpful in unsteady state methods, when relative permeabilities can be calculated only after gas breakthrough. The following equations are used for calculation of relative permeabilities [2]:

$$So^* = \frac{So-Sor}{1-Swi-Sor} \quad (1)$$

$$Kro = Kro^0.(So^*)^{No} \quad (2)$$

$$Krg = Krg^0.(1-So^*)^{Ng} \quad (3)$$

3.1. Oil Relative Permeability Comparison

The results of oil relative permeability comparison for three cores are shown in Figure 2. As can be seen from Figure 2, the oil relative permeability in CO_2 injection is higher than in N2 injection at a given saturation. The interactions between CO_2, oil and rock are the keys for finding these differences. CO_2 affects the Oil and rock in the following way [11]:

- Interfacial tension reduction
- Oil viscosity reduction
- Oil swelling
- Acid effect on rock

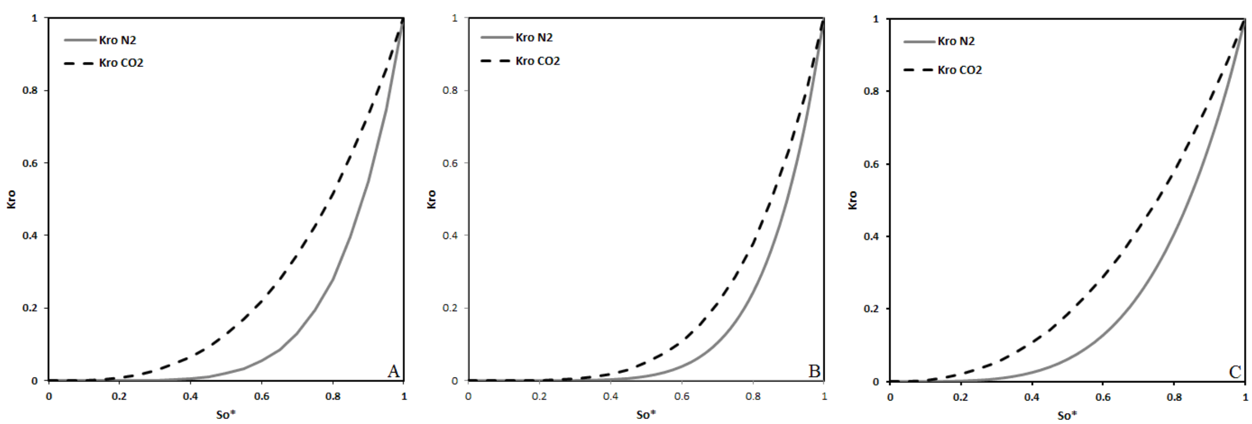

Fig. 2 Normalized oil relative permeabilities comparison of CO_2 with N_2 injections
A) core C3 B) core C1 C) core S1

3.1.1. Interfacial Tension Reduction

Carbon dioxide causes the interfacial tension to reduce by dissolving it in oil [5]. Reduction of interfacial tension has significant effect on the relative permeability curves. Interfacial tension reduction lowers energy consumption in fluid interface [1, 4]. In theory, when interfacial tension tends to zero, relative permeability of each phase tends to the phase saturation. In other words, the relative permeability curves become unit slope straight line. In this situation fluids act as single phase and trapping of fluids in throats is impossible. Therefore, oil relative permeability during injection of carbon dioxide is closer to the straight line and in fact, is higher than oil relative permeability in nitrogen injection [6].

3.1.2. Oil Swelling

When CO_2 comes into contact with crude oil a process of dissolution occurs thereby causing swelling. The degree of swelling depends on pressure, temperature and oil composition [10]. Swelling is important for two reasons: Firstly, the residual oil saturation is inversely proportional to swelling factor. The residual oil saturation is an important point in relative permeability curves and determines ultimate recovery. Secondly, swollen oil droplets will force fluids out of the pores, creating a drainage process. This process causes the trapped droplets that cannot move under present pressure gradient, to move toward production well [8].

3.1.3. Oil Viscosity Reduction

Oil viscosity is reduced dramatically with dissolving CO_2 in oil [6]. The overall reduction of viscosity depends on the initial viscosity, where there is greater reduction for higher viscous crudes. Reducing oil viscosity increases relative permeability of oil and reduces residual oil saturation. Lefebvre du Prey was shown that decreasing oil viscosity increases end point relative permeability of oil, but has no effect on relative permeability ratio [7].

3.1.4. Acid Effect on Rock

In carbonate rocks, the rate of reactions is faster than sandstones. In the injection front, CO_2 reacts with water and makes carbonic acid. In many EOR projects with high rate of injection, it was observed that permeability around wellbore is increased, due to dissolution of calcite [12]. In carbonate systems, following reaction may occur [3]:

$$H_2O + CO_2 + CaCO_3 \xrightarrow{yields} Ca(HCO_3)_2 \quad (4)$$

Porosity and permeability before and after injection of CO_2 was recorded, for measuring the effect of CO_2 on rock properties. The results were shown negligible change in these parameters, because of low rate. Therefore, this mechanism doesn't account for relative permeability changes in this experimental work.

3.2. Oil Relative Permeability Ratio

For declaring the extent of oil relative permeability changes in CO_2 injection, ratio of oil relative permeability in CO_2 injection to oil relative permeability in N2 injection is used. The results are shown in Figure 3. This Figure shows that at the start of injection when the CO_2 doesn't contact fully with oil, the change in oil relative permeability is low. But in low oil saturations, when the movement of oil is difficult, N2 is an obstacle for oil movement, whereas CO_2 improve the oil flow by lowering interfacial tension and oil viscosity. Also CO_2 can reduce trapped and residual oil saturation by oil swelling mechanism. As results, oil has greater relative permeability in CO_2 injection especially in low oil saturations.

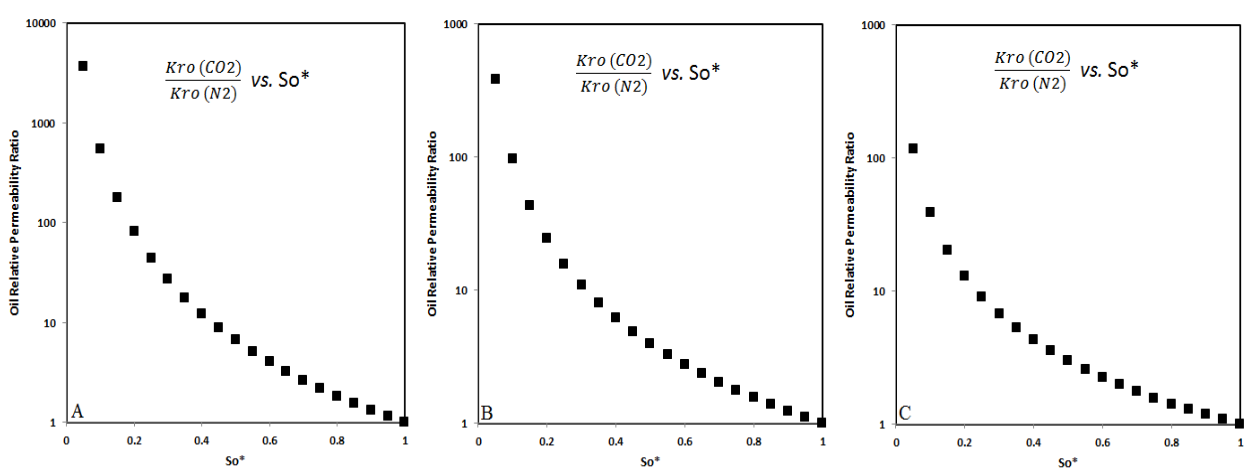

Fig. 3 Oil relative permeability ratio A) core C3 B) core C1 C) core S1

3.3. Gas Relative Permeability Comparison

The relative permeability of CO_2 is compared with N2 as shown in Figure 4. At the start of injection, CO_2 and N_2 relative permeability is equal, but at high gas saturations, the N_2 relative permeability is higher than CO_2 relative permeability. The higher relative permeability of N_2 is as a result of sudden decrease of oil flow therefore gas flows almost single phase. But in this interval of saturation, CO_2 can sweep oil and causes two phase flow. Also oil swelling increases oil saturation and lowers CO_2 relative permeability. As result, CO_2 has lower relative permeability until oil saturation reaches residual oil saturation. At residual oil saturation, relative permeability of CO_2 is slightly higher than N_2, because of lower residual oil saturation and higher void space available for gas flow. But, CO_2 viscosity is lower than N_2 and gas-oil interfacial tension is lower in CO_2 injection that should causes higher CO_2 relative permeability. Figure 5 shows the normalized saturation versus normalized gas relative permeability for CO_2 and N_2 injections. In these curves, the effect of residual oil saturation is normalized by Corey correlations. The normalized gas relative permeabilities in Figure 5 confirm that CO_2 has higher relative permeability provided effect of residual oil saturation had normalized.

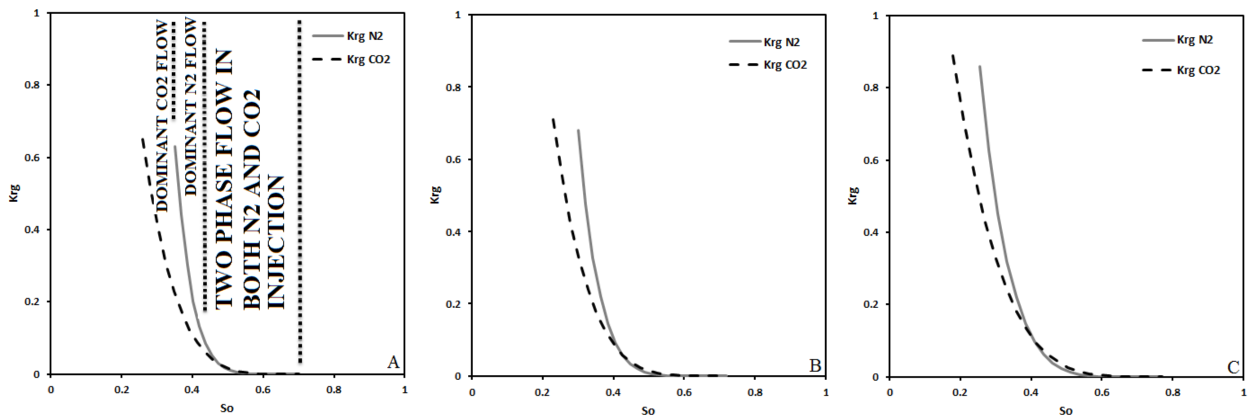

Fig. 4 Gas relative permeabilities comparison of CO_2 with N_2 injections A) core C3 B) core C1 C) core S1

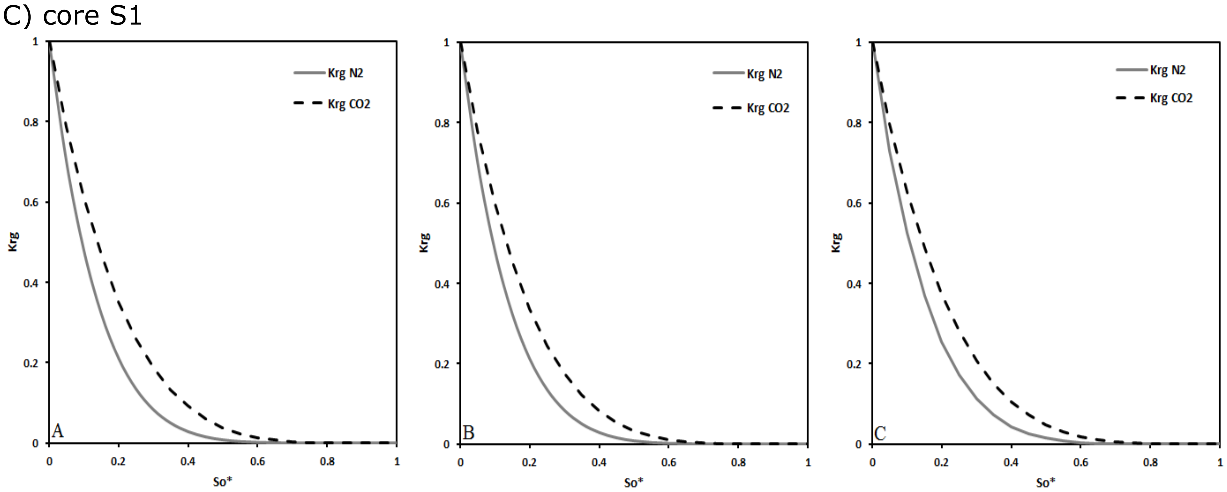

Fig. 5 Normalized gas relative permeabilities comparison of CO_2 with N_2 injections A) core C3 B) core C1 C) core S1

3.4. Correlating CO2-Oil to N_2-Oil Relative Permeability

Effect of CO_2 and N_2 on parameters that affects relative permeability is shown in Table 3. These values were calculated by Schlumberger PVTi. The results show that N_2 has negligible effect on interfacial facial and oil viscosity and practically cause no oil swelling. But CO_2 decrease interfacial tension and oil viscosity and causes about 10 percent swelling of oil. For correlating CO_2-Oil to N_2-Oil relative permeability, Corey model is used. Ratio of residual oil saturations and Corey exponents for oil and gas are shown in Table 4. Because comparison of relative permeabilities is done on same core and the same pressure and temperature, effects of these parameters are eliminated. Therefore, ratio of residual oil saturations and ratio of Corey exponent for oil and gas reflect only effects of CO_2 on oil and gas properties. As mentioned earlier, interfacial tension, fluid viscosities and oil swelling factor can affect relative permeability curves and residual oil saturation. Based on these parameters two dimensionless numbers are defined as below:

$$RBF_o = \sqrt{\frac{(IFT_{CO_2}).(\mu_{o\,CO_2}).(SF_{N_2})}{(IFT_{N_2}).(\mu_{o\,N_2}).(SF_{CO_2})}} \quad (5)$$

$$RBF_g = \sqrt{\frac{(IFT_{CO_2}).(\mu_{gCO_2}).(SF_{CO_2})}{(IFT_{N_2}).(\mu_{gN_2}).(SF_{N_2})}} \quad (6)$$

RBF_o and RBF_g stand for Relative Permeability Boost Factor for oil and gas, respectively. Note that swelling factor has positive effect on oil relative permeability and has negative effect on gas permeability.

Table 3 Effect of CO2 and N2 on IFT, oil viscosity and swelling factor

	Interfacial Tension (dyne/cm)	Oil Viscosity (CP)	Swelling Factor
Initial	11.868	1.0509	1
N2	11.842	1.0503	1.0001
CO2	8.639	0.735	1.1022

Table 4 Ratio of residual oil saturation and Corey exponents for oil and gas relative permeabilities

	$\frac{Ng_{CO2}}{Ng_{N2}}$	$\frac{Sor_{CO2}}{Sor_{N2}}$	$\frac{No_{CO2}}{No_{N2}}$
Test 1,2	0.671687	0.742857	0.519909
Test 3,4	0.644326	0.766667	0.686395
Test 5,6	0.719673	0.72	0.604524
EQUALS	RBF_g^2=0.69318	$\sqrt{RBF_O}$=0.754288	RBF_O=0.568951
Average Error (%)	4.8	2.6	10.8

The following relations are proposed for calculating Corey's exponents and residual oil saturation in CO_2 injection from N2 relative permeabilities data:

$$N_{o_{CO_2}} = RBF_O \,.N_{o_{N_2}} \quad (7)$$

$$N_{g_{CO_2}} = RBF_g^{\,2} \,.N_{g_{N_2}} \quad (8)$$

$$S_{or_{CO_2}} = \sqrt{RBF_O} \,.S_{or_{N_2}} \quad (9)$$

Normalized Corey relative permeabilities are calculated from Equation 7 and 8 with finding residual oil saturation with equation 9 denormalized curves were obtained. Note that, gas relative permeability in residual oil saturation is practically unchanged. Also it is obvious that oil relative permeability at the start of injection is equal.

For validation of proposed relations, CO_2-oil relative permeability was calculated from N_2-oil relative permeability for each core samples. The results of comparison between experimental and calculated normalized CO_2-oil relative permeabilities are shown in Figure 6 and 7. In addition comparisons of experimental and calculated denormalized relative permeabilities are shown in Figure 8 and 9.

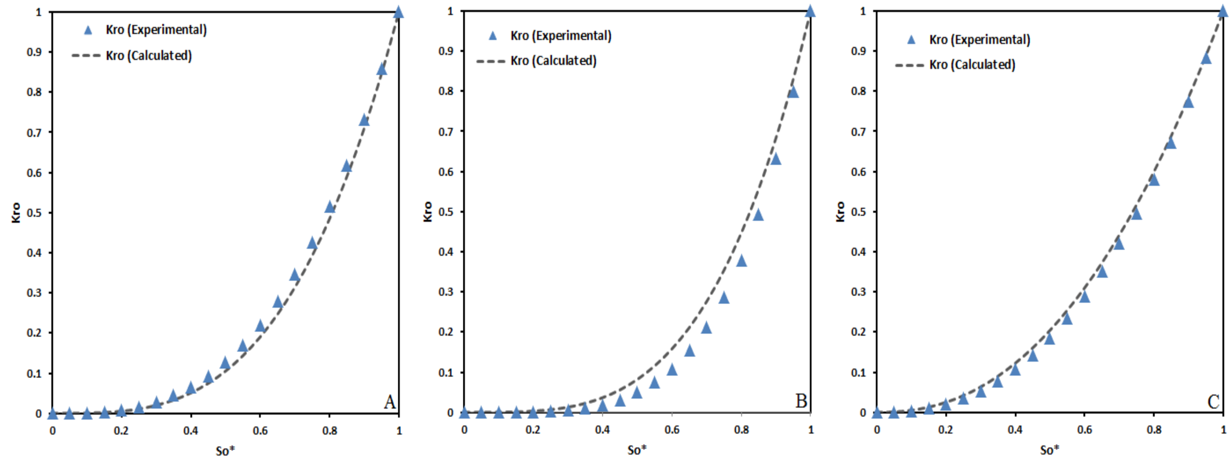

Figure 6: Comparison of experimental and calculated normalized oil relative permeabilities A) core C3 B) core C1 C) core S1

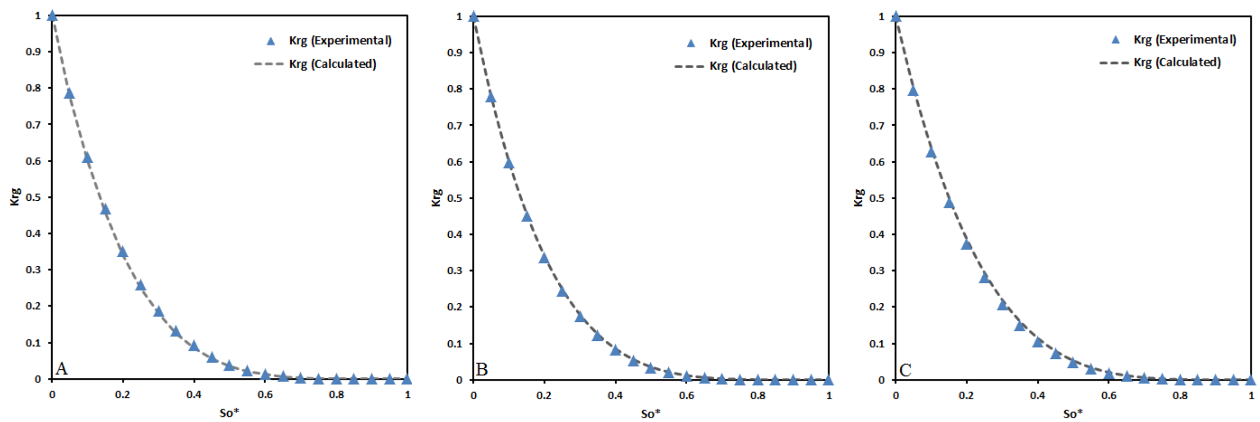

Figure 7: Comparison of experimental and calculated denormalized oil relative permeabilities A) core C3 B) core C1 C) core S1

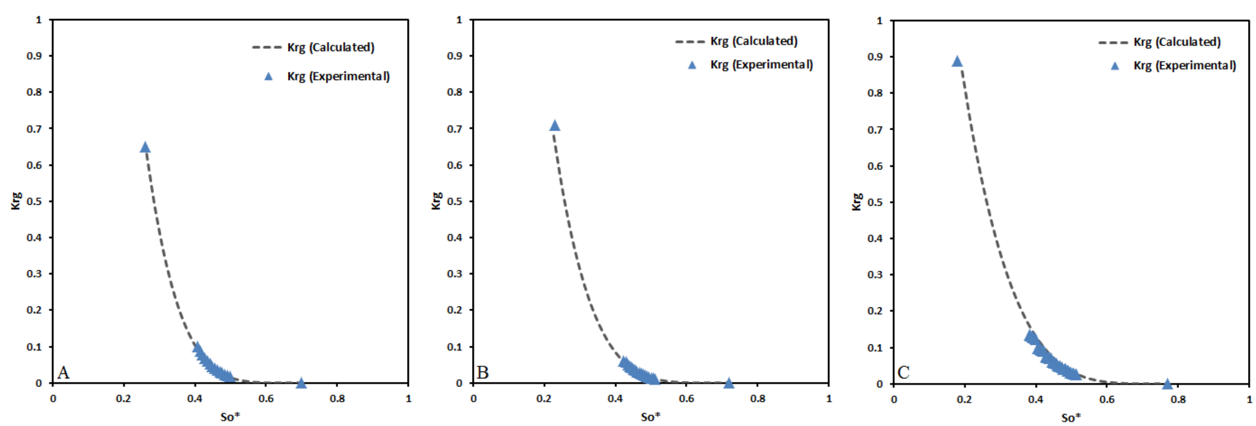

Figure 8: Comparison of experimental and calculated denormalized gas relative permeabilities A) core C3 B) core C1 C) core S1

4. Conclusions

1. A method was proposed for calculating CO_2-Oil relative permeability from N_2-Oil relative permeability based on interfacial tension, viscosity and swelling factor. More experiments are needed for validating or modifying this method. This method can be generalized to all Gas-Oil systems.

2. Oil permeability is higher in CO_2 injection as compared with N_2 injection. Interfacial tension, viscosity reduction and oil swelling are mechanisms which account for oil relative permeability improvement.
3. The comparison of gas permeabilities shows that at the start of injection, N_2 and CO_2 relative permeability are equal. But as the gas saturation increased, N_2 relative permeability becomes higher than CO_2 relative permeability since single phase flow occurs sooner in N_2 injection due to higher residual oil saturation.
4. If normalized saturation and normalized relative permeability are used for comparison of gas relative permeability, CO_2 gas relative permeability will be higher than N_2 due to lower interfacial tension and viscosity effects.

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Nomenclature

IFT_{N2}	:	Interfacial Tension in N_2 injection
IFT_{co2}	:	Interfacial Tension in CO_2 injection
K_{rg}	:	Gas relative permeability
K_{ro}	:	Oil relative permeability
N_g	:	Corey exponent for gas relative permeability
N_o	:	Corey exponent for oil relative permeability
RBF_g	:	Gas Relative permeability Boost Factor
RBF_o	:	Oil Relative permeability Boost Factor
SF_{co2}	:	Swelling Factor in CO_2 injection
SF_{N2}	:	Swelling Factor in N_2 injection
S_o	:	Oil saturation
S_o*	:	Normalized oil saturation
$\mu_{o\,CO2}$	:	Oil viscosity in CO_2 injection
$\mu_{o\,N2}$	:	Oil viscosity in N_2 injection
μ_{gCO2}	:	Gas viscosity in CO_2 injection
μ_{gN2}	:	Gas viscosity in N_2 injection

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