Research Article   **Open Access**

Experimental Study of CO$_2$-EOR and N2-EOR with Focus on Relative Permeability Effect

E. Ghoodjani[1]* and S.H. Bolouri[2]

[1]*Sharif University of Technology, Tehran, Iran*
[2]*Shahid Bahonar University, Kerman, Iran*

Abstract

Accurate performance prediction for miscible EOR projects or CO$_2$ sequestration in depleted oil and gas reservoirs relies in precise characterization of reservoir rock and fluid. Simulation of these processes is necessary for implementation, management and decision making. Relative permeability is one of the most important factors in numerical reservoir simulation. In this study, several core flood experiments are done and the relative permeability in CarbonDioxide (CO$_2$) injection is compared with Nitrogen (N2) injection. Oil relative permeability in CO$_2$ injection found to be higher than in N2injection, but Gas relative permeability in CO$_2$ injection found to be lower than in N2injection. Higher oil relative permeability in CO$_2$ injection causes higher recovery factor, lower differential pressure across the core and different trend of differential pressure during CO$_2$ injection. Also results were shown that enhancement of oil relative permeability by CO$_2$ is increasing with decreasing oil saturation.

Introduction

From a technical point of view gasinjection can be a very efficient method for improving the oilproduction. Under normal conditions, oil production is halted and well is abandoned. Except for brief periods, which Enhanced Oil Recovery (EOR) becomes economical, there is no good reason for EOR operations.But appreciable decline in the new reservoirs discovery and increase in the petroleum demands, has forced oil companies to develop EOR methods. Thermal, chemical and gas flooding are three major EOR methods, which have been developed during the last years [1].

Carbon dioxide has been successfully used in more than 80 enhanced oil recovery (EOR) operations in North America, and the number of such operations may increase significantly around the world if CO$_2$ becomes available at reasonable costs. On the other hand, geological storage in deep saline aquifers and hydrocarbon reservoirs of large amounts of CO$_2$, captured from large stationary sources is one method that is under consideration for reducing greenhouse gas emissions into the atmosphere on a worldwide basis. At present, carbon dioxide is widely used for many EOR processes. Management of these processes requires accurate simulation, before implementation 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$_2$ affects relative permeability and how relative permeability affects pressure, gas and oil production and recovery. To find out the effects of relative permeability, CO$_2$ and N2 injection was compared. Effects of rock, pressure and temperature were eliminated while comparisons were done in constant temperature and pressure and on the same core. CO$_2$ reduces interfacial tension and viscosity and causes oil to swell [2].Because the IFT between oil and displacing fluid is an important parameter for most EOR techniques, 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 [3]. But the effect of oil swelling on relative permeability was ignored, until now. It can increase oil saturation and decrease gas saturation; both affect relative permeability, certainly.

Materials and Methods

Two tight carbonate reservoir rocks and one sandstone outcrop are used in experiments. The core samples are of 3.8 inch diameter and 8-15 cm of length. The permeability of carbonate cores is below 1 md and sandstone permeability is 47 md. The core properties are shown in Table 1.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 at 46°C and 2000 psi, is used.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 delivered the gases at constant rateof 0.3 cc/hour to the core under test condition. The core outlet pressure is held constant at 1500 psi with backpressure regulator. The cores were washed in Soxhlet apparatus with toluene and methanol. Toluene dissolves the oil residuals and methanol dissolves salts. Cores were dried at 120°C for 24 hours to stabilize any clay mineral present in the rock. The difference 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

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

Table 1: Physical properties of used core samples.

Figure 1: Schematic diagram of experiment setup

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

Table 2: Different parts of experiment setup.

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 [4].

Results and Discussions

For uncovering the effects of CO_2 on relative permeability curves, N2-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.

Oil Relative permeability

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 [5]:

1. Interfacial tension reduction
2. Oil viscosity reduction
3. Oil swelling
4. Acid effect on rock

Interfacial tension reduction: Carbon dioxide causes the interfacial tension to reduce by dissolving it in oil [2]. Reduction of interfacial tension has significant effect on the relative permeability curves. Interfacial tension reduction lowers energy consumption in fluid interface. 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 [3]. Also reduction in interfacial tension results in lower residual saturation as can be seen in Figure 2.

Oil viscosity reduction: Oil viscosity is reduced dramatically with dissolving CO_2 in oil. 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 [6].

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 [7]. Swelling is important for two reasons: Firstly, the residual oil saturation is inversely proportional to swelling factor. The residual oil saturation
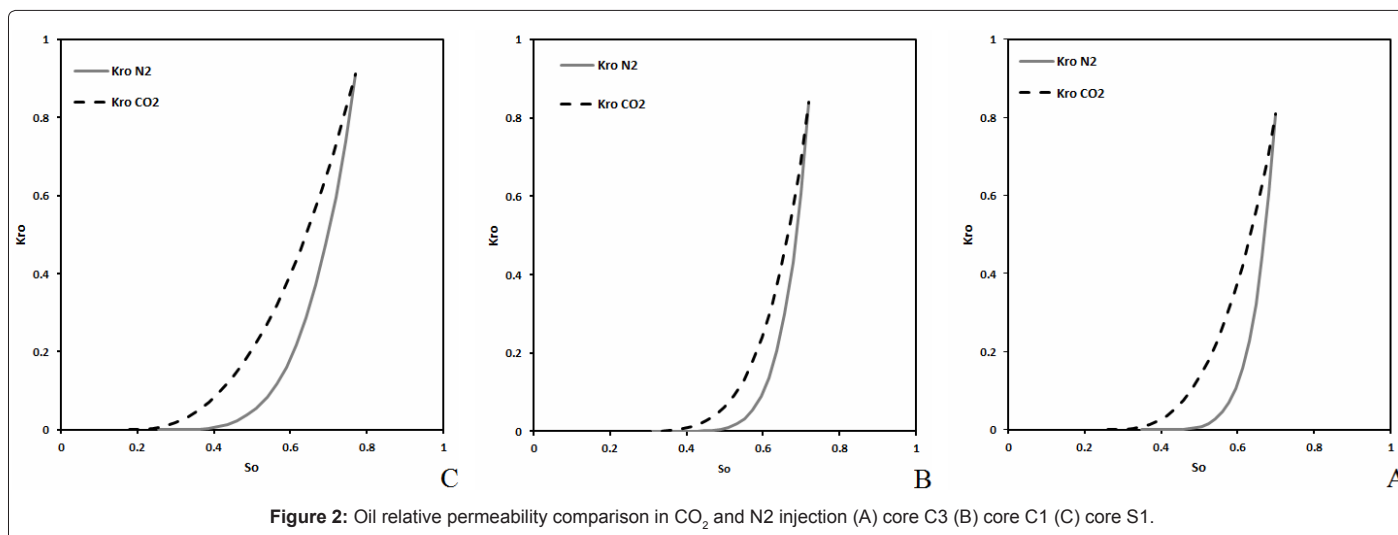

Figure 2: Oil relative permeability comparison in CO_2 and N2 injection (A) core C3 (B) core C1 (C) core S1.

	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 3: Effect of CO_2 and N2 on IFT, oil viscosity and swelling factor.

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 [5]. Also effect of oil swelling on oil saturation is undeniable. The oil swelling increases oil saturation, therefore increases oil relative permeability, too. Overall effects of CO_2 and N2 on IFT, oil viscosity and swelling factor are summarized in Table 3.

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. In carbonate systems, following reaction may occur [8]:
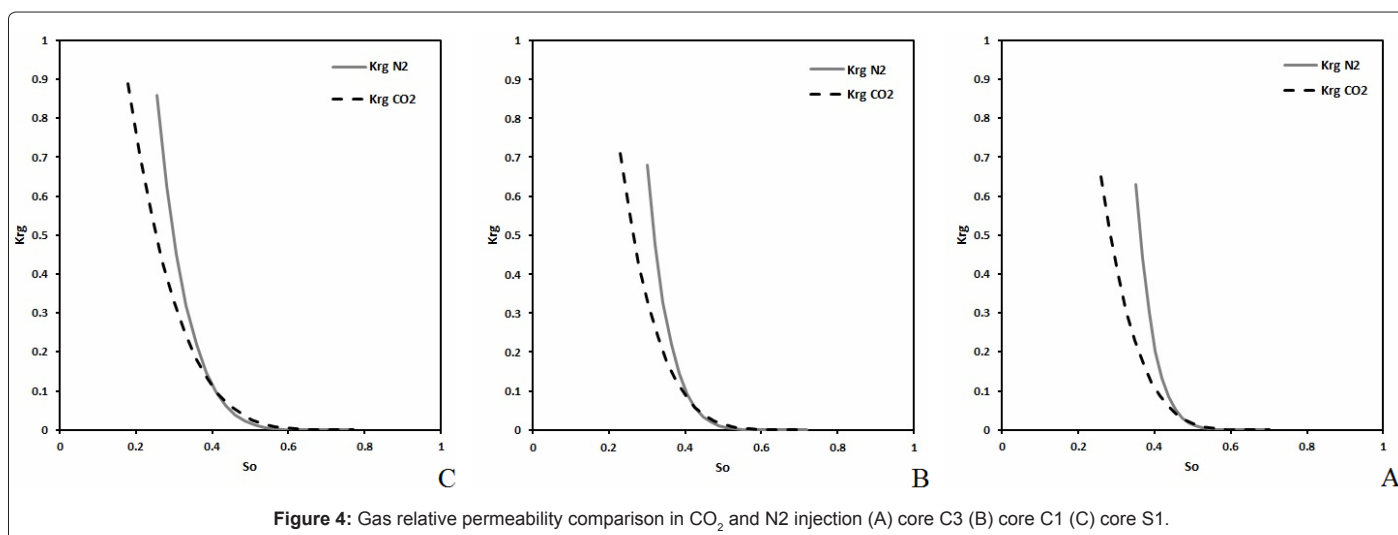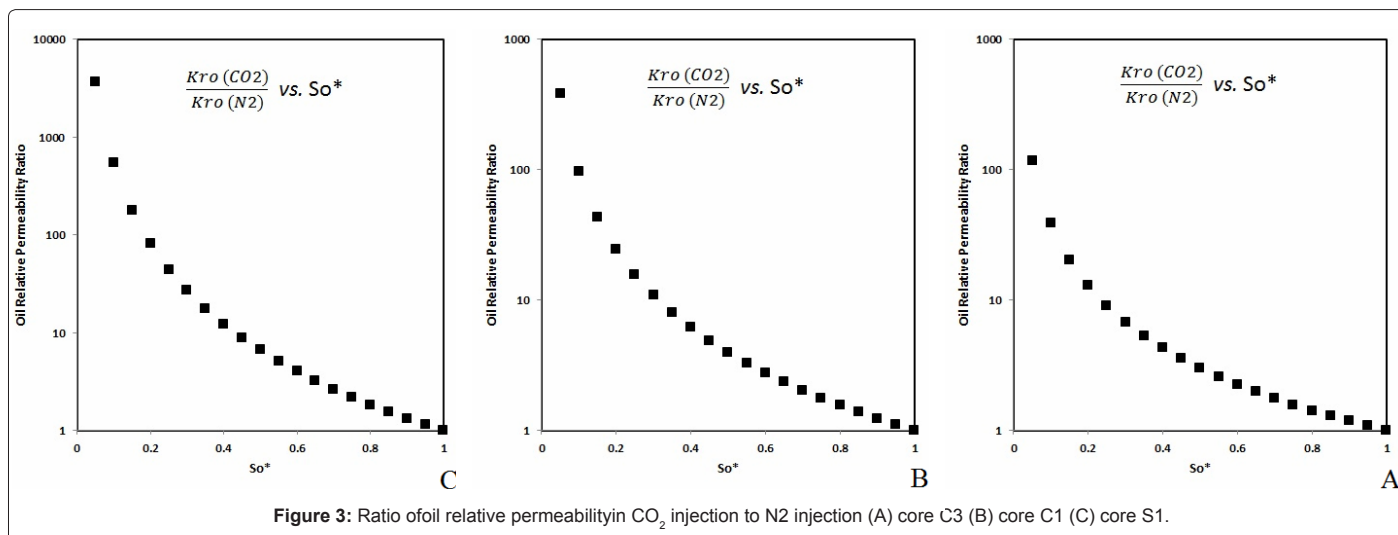
$$H_2O + CO_2 + CaCO_2 \xrightarrow{\text{yields}} Ca(HCO_3)_2 \qquad (1)$$
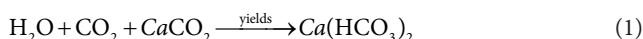
Porosity and permeability before and after injection of CO2 was recorded, for measuring the effect of CO_2 on rock properties. The results were shown negligible change in these parameters, because of low rate. Therefore, this mechanism doesn't account for relative permeability changes in this experimental work.

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.

Figure 3 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. On the other hand, in low oil saturations, N2 cannot push oil droplets toward production well, but CO_2 decrease interfacial tension and increase oil saturation by swelling mechanism, therefore decrease residual oil saturation. As results, oil has greater relative permeability in CO_2 injection especially in low oil saturations.

Gas relative permeability: The relative permeability of CO_2 is compared with N2 as shown in Figure 4. At the start of injection, CO_2

Figure 3: Ratio of oil relative permeability in CO_2 injection to N2 injection (A) core C3 (B) core C1 (C) core S1.

Figure 4: Gas relative permeability comparison in CO_2 and N2 injection (A) core C3 (B) core C1 (C) core S1.

and N2 relative permeability is equal, but at high gas saturations, the N2 relative permeability is higher than CO_2 relative permeability. The higher relative permeability of N2 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 N2, because of lower residual oil saturation and higher void space available for gas flow.

Recovery factor: The results in Figure 5 show that at the start of injection (high oil saturation), when the CO_2 doesn't contact fully with oil, the recoveries are almost equal. 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, thus higher recovery factor occurs in CO_2 injection.

The comparison of gas productions are shown in Figure 6. The gas production in first pore volume injected is equal. After that, N2 production is higher than CO_2 production due to higher gas relative permeability of N2.

Differential pressure: The results of differential pressure comparison are shown in Figure 7. In carbonate cores, differential pressure in N2 injection is increasing before breakthrough and decreasing after breakthrough. Increase of differential pressure before breakthrough is due to high compressibility of gas. After breakthrough gas has an open path to flow and with increasing gas saturation, gas relative permeability increased and differential pressure decreased. But differential pressure in sandstone is decreasing before and after breakthrough due to high permeability and early breakthrough of gas.

In CO_2 injection, differential pressure is always decreasing due to increase in relative permeability that causes oil to move easier by viscosity and interfacial reduction. Also oil swelling causes trapped oil to move and lower residual oil saturation.

Conclusions

- Oil permeability is higher in CO_2 injection compared to N2 injection. Interfacial tension and viscosity reduction, and oil swelling are mechanism that accounts for oil relative permeability improvement. These causes the recovery factor of CO_2 injection becomes higher than N2 injection.

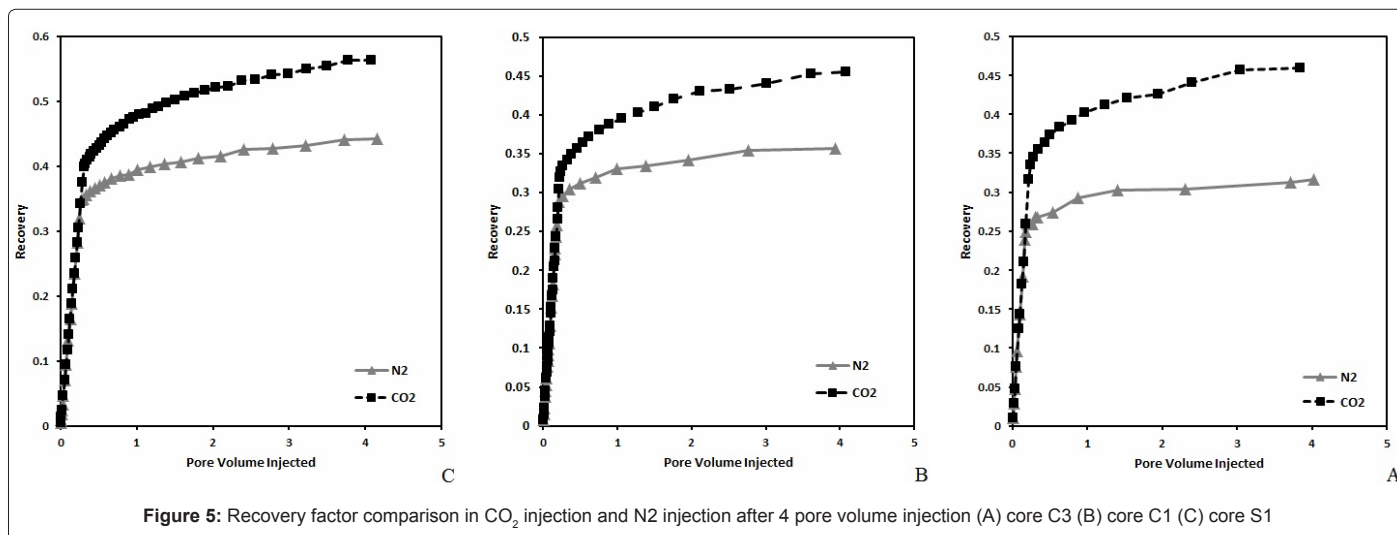- The comparison of gas permeabilities shows that at the start of

Figure 5: Recovery factor comparison in CO_2 injection and N2 injection after 4 pore volume injection (A) core C3 (B) core C1 (C) core S1
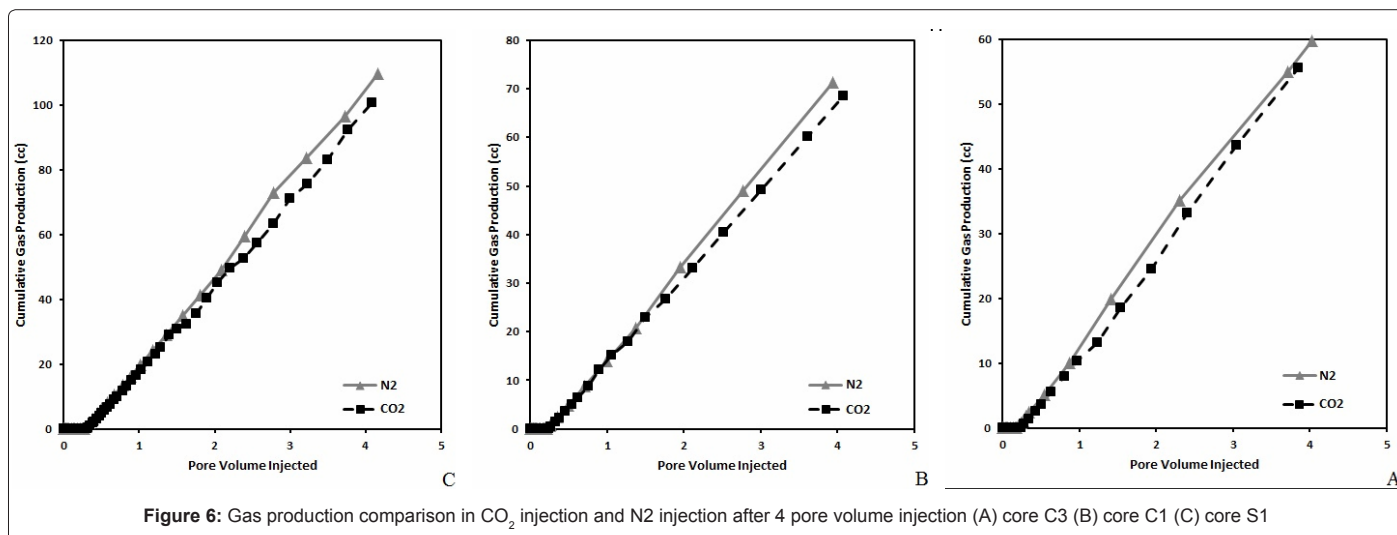

Figure 6: Gas production comparison in CO_2 injection and N2 injection after 4 pore volume injection (A) core C3 (B) core C1 (C) core S1
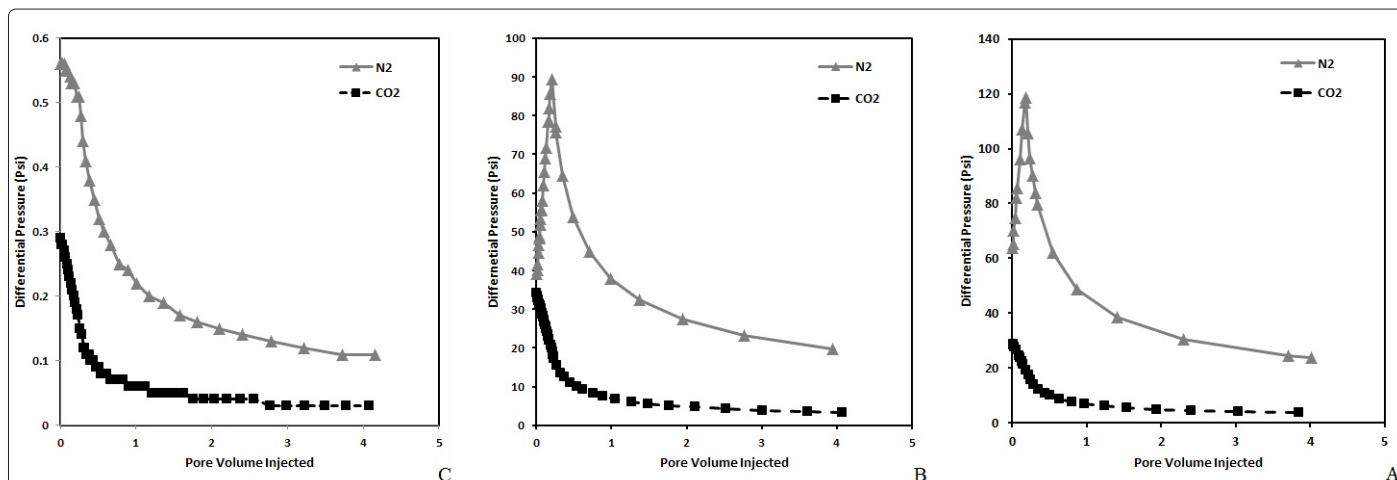
Figure 7: Differential pressurecomparison in CO_2 injection and N2 injection after 4 pore volume injection (A) core C3 (B) core C1 (C) core S1.

injection, N2 and CO_2 relative permeability are equal, but as the gas saturation increased, N2 relative permeability becomes higher than CO_2 relative permeability, because single phase flow occurs sooner in N2 injection due to higher residual oil saturation. This causes the gas production to become higher in N2 injection.

- Differential pressure across core in CO_2 injection is lower than N2 injection due to higher relative permeability, lower oil viscosity and lower interfacial tension in CO_2 injection. Also differential pressure in CO_2 injection is decreasing due to solubility of CO_2 in oil, but in N2 injection it has a maximum because of gas compressibility.

- Recovery factor in CO_2 injection is higher due to swelling effect of CO_2 and lower interfacial tension result in lower residual oil saturation. Also sooner breakthrough was seen in N2 injection due to higher gas relative permeability. Thus Gas production and gas-oil ratio is higher in N2 injection compared to CO_2 injection.

Acknowledgement

References

1. Donaldson EC, Chilingarian GV, Yen TF (1989) Enhanced Oil Recovery: Processes and Operations. Elsevier Science Publishing Company, p154.

2. Mangalsingh D, Jagai T (1996) A laboratory investigation of the carbon dioxide immiscible process. SPE 36134, Fourth Latin Am erican and Caribbean Petroleum Engineering Conference. Trinidad and Tobago 23-26.

3. McDougall SR, Salina PA, Sorbie KS (1997) The Effect of Interfacial Tension upon Gas-Oil Relative Permeability Measurements: Interpretation Using Pore-Scale Models. SPE 38920, SPE Annual Technical Conference and Exhibition, San Antonio, Texas.

4. Jones SC, Roszelle WO (1978) Graphical techniques for determining relative permeability from displacement experiments. JPT 5: 807-817.

5. Srivastava RK, Huang S (1997) Comparative Effectiveness of CO2, Produced Gas, and Flue Gas for Enhanced Heavy Oil Recovery. SPE 37558, International Thermal Operations and Heavy Oil Symposium, California.

6. Lefebvre du Prey EJ (1973) Factors Affecting Liquid-Liquid Relative Permeabilities of a Consolidated Porous Media. JPT 39-47.

7. Simon R, Graue DJ (1965) Generalized Correlations for Predicting Solubility, Swelling and Viscosity Behavior of CO_2-Crude Oil System. JPT 23: 102-106.

8. Crawford HR, Neill GH, Bocy BJ, Crawford PB (1963) Carbon Dioxide, a Multipurpose Additive for Effective Well Stimulation. JPT 237-242.