Journal of Petroleum Exploration and Production Technology (2021) 11:1963–1971
https://doi.org/10.1007/s13202-021-01113-5

ORIGINAL PAPER-PRODUCTION ENGINEERING

Enhanced oil recovery application in low permeability formations by the injections of CO_2, N_2 and CO_2/N_2 mixture gases

E. S. Bougre[1] · T. D. Gamadi[1]

Received: 22 September 2020 / Accepted: 8 February 2021 / Published online: 11 March 2021
© The Author(s) 2021

Abstract

Low oil recovery which is very predominant in shale oil reservoirs has stimulated petroleum engineers to investigate the applications of enhanced oil recovery methods in these formations. One such application is the injection of gases into the formation to stimulate increased oil recovery. In many gas flooding projects performed in the field, the miscibility of the gas injected is usually the most desired displacement mechanism, and carbon dioxide (CO_2) gas has been recognized to be the best performing gas for injection due to its ability to be miscible with oil in the reservoir at low pressures compared to other gases such as nitrogen. This minimum miscibility pressure (MMP) is of very crucial importance because it is the primary limiting factor in the feasibility of a miscible gas flooding project. However, there are other limiting factors such as cost and availability and, in these instances, nitrogen (N_2) and lean gas are the more preferred candidate as opposed to carbon dioxide gas. Mixing carbon dioxide gas with lean gas or with nitrogen in a required ratio can allow us to design an injection gas that will be suitable enough to satisfy both the availability and cost constraints and at the same time allow us to achieve a reachable and reasonable miscibility pressure. The objective of this paper is to investigate the effect of mixing nitrogen gas and carbon dioxide gas in a 50:50 ratio on oil recovery in tight oil formations. The experiment was performed with controlled constraints such as the same core sample, same crude oil and same core cleaning and saturation process which was repeated for each trial. The oil used was live oil from Eagle ford formation, and the gases used were nitrogen (99.9% purity), carbon dioxide and a mixture of nitrogen and carbon dioxide in a 50:50 ratio. The injection pressure ranged from 1000 to 5000 psi with pressure increments of 1000 psi, and the same flooding time was 6 h. The potential of the N_2, CO_2 and N_2–CO_2 mixture for improving oil recovery was assessed along with the breakthrough time. The results showed that CO_2 gas had the highest recovery followed by the N_2–CO_2 mixture and N_2 gas had the lowest recovery. The gas breakthrough time results showed that the N_2–CO_2 mixture had the longest breakthrough time, N_2 had the shortest breakthrough time, and CO_2 had a significantly longer breakthrough time than pure N_2 gas. The RF increased with increasing pressure, but the gas breakthrough time decreased with increasing pressure. However, the incremental RF decreased in all three cases when the injection pressure was above 3000 psi.

Keywords Enhanced oil recovery (EOR) · Minimum miscible pressure mixture of gas · Experimental student of gas injection · Oil recovery by injecting mixtures of gas

Introduction

With the recent advances in technology pertaining to the oil industry, the reduction in hydrocarbon production from unconventional oil and gas resources coupled with the escalation in demand of crude, a lot of focus has been geared toward research and development in unconventional reservoirs (EIA 2015). Unconventional reservoirs usually are unable to produce hydrocarbons at economic flow rates and do require advanced stimulation techniques or treatments of enhanced oil recovery applications and advanced technologies. These stimulation techniques and treatments are the main solutions to being able to recover sufficient amounts of oil and gas from these reservoirs at an economic rate. Gas injection in oil reservoirs usually begins with the injection of gas, usually CO2 gas either typically in a cyclical stream into a production well.

✉ T. D. Gamadi
talal.gamadi@ttu.edu

[1] Texas Tech University, Texas, USA

There have not been many tests conducted in ultra-low permeability shales. Vega et al. (2010) conducted experiments on the performance of CO_2 gas in a fractured shale core with permeability range of 0.02–1.3 mD, and the results showed CO_2 had the potential of improving recovery in shale formations. However, CO_2 is quite expensive to use for injection, tends to corrode oil equipment relatively easy and contributes immensely to the greenhouse effect.

An alternative gas to carbon dioxide injection is using nitrogen gas. Nitrogen gas is much cheaper, more easy to obtain since it is abundant in the air (78%) and also much less corrosive than carbon dioxide. Nitrogen injection has been demonstrated to be an effective EOR method. There have been a lot of experimental studies and successful field cases in many parts of the world. Simulation studies have also shown that N_2 can be effectively used as an injection gas to enhance oil recovery in the fields of Trinidad (Sinanan and Budri 2012) and assets in the South East (Belhaj et al. 2013). However, nitrogen gas has a relatively high miscibility pressure (9300 psi) as compared to most other gases. In most cases, the minimum miscibility pressure (MMP) of nitrogen gas is higher than the fracture pressure of the reservoir in which the gas is to be injected; as a result of this, it is usually better to be used at lower pressures for immiscible displacement.

One of the possible solutions to the issue of using individual gases as an injection gas is to mix these gases in a ratio that may totally eliminate or drastically reduce most of these constraints. A mixture of carbon dioxide and nitrogen gas in the right ratio can serve to reduce the amount of carbon dioxide needed, reduce the high minimum miscibility pressure of pure nitrogen gas to a lesser MMP and also serve as a means of lessening corrosion of the equipments. A gas mixture of carbon dioxide and nitrogen gas can also reduce the amount of CO_2 which would have been required if it were to be injected individually but will be able to maintain a low MMP. A mixture of these injection gases can make a previous project that was deemed to be uneconomical to become much more feasible.

Literature review

The oil and gas industry has been faced with a lot of challenges in keeping up with the increase in global demand for energy. Also, it costs a lot of money for oil and gas corporations to engage in exploration activities to discover new reservoirs. Due to this, one of the best few options to keep up with demand and increase oil production without incurring too much cost is to increase the recovery of the already producing oil reservoirs through the use of enhanced oil recovery (EOR) mechanisms. The implementation of these EOR techniques can maintain reservoir pressures and increase production rates. Two major factors are considered when considering the type of EOR mechanism to employ. These are economic factors and technical practicability. The three most common methods of EOR currently are chemical injection, thermal injection and gas injection (Siregar and Wijaya 2007). Among these three methods, gas injection has been determined to be the most suitable in terms of economics and practicability. In gas injection, different types of gases can be injected, and these include flue gases, hydrocarbons such as methane, air, N_2, CO_2 or a combination of these different gas types.CO_2 gas injection has been the most popular due to its properties such as high miscibility with oil and hence lower viscosity and lower interfacial tension under suitable conditions of pressure and temperature. Several studies have shown that it can achieve an incremental recovery of 5–20% in the Bakken and Eagle ford reservoirs. However, some studies also showed that CO_2 has some major drawbacks including a very rapid decline in oil production and reservoir pressure over the first few years (Siregar and Wijaya 2007).

Also, the cost of storing the required amount of carbon dioxide necessary for a project is so expensive that it makes the project uneconomical to undertake. An alternative gas to carbon dioxide is using nitrogen. Nitrogen gas has not been as widely applicable as CO_2 due to its physicochemical properties. It is much more difficult to dissolve in crude oil and hence does not often the same benefits of reduction in oil viscosity and interfacial tension as carbon dioxide. It also has a relatively high miscibility pressure (9300 psi) as compared to most other gases (Shouya and Zhaomin 2019). In most cases, the minimum miscibility pressure (MMP) of nitrogen gas is higher than the fracture pressure of the reservoir in which the gas is to be injected. It does have some other advantages such as being a cheaper gas to obtain since it is much more abundant in the air (78%), and also much less corrosive than carbon dioxide; this makes it a very suitable candidate for gas injection (Sheng and Soliman 2013).

Siregar et al. studied the recovery of oil and gas with nitrogen via laboratory experiments, and it was determined that nitrogen did not lead to higher oil recovery. Shouya et al. studied various EOR techniques, and the results showed that N_2 is more effective when the permeability of the reservoir was lower than 0.03 mD.

This research seeks to determine the effect of using a mixture of these gases to totally eliminate or drastically reduce the constraints that these gases have when used individually. A mixture of carbon dioxide and nitrogen gas in the right ratio can serve to reduce the amount of carbon dioxide needed and also reduce the high minimum miscibility pressure of pure nitrogen gas to a lesser MMP and also serve as a means of lessening corrosion of the equipments.

Experimental work

Materials

The core plug that was used for this experiment was obtained from the Eagle ford formation. The core plug had a dimension of 1.5 inches in diameter and 2 inches in length. The average porosity measured by the helium porosimeter was 5.36%, and the nitrogen permeability was 0.06 mD. The device used to measure the permeability was the Ultra K 500 + gas permeameter. The oil sample used for saturating the cores was live crude oil with a density of 0.788 g/cc (Fig. 1).

Experimental setup

The experiment consisted of two main stages: saturation of the core sample with crude oil and injection of gas into the core. The core was placed in a vessel to which a vacuum pump was connected. A Quizix pump, vessel and an accumulator were then used for the saturation process. The gas flooding test was performed using the AFS 300 Core Flooding System which had a maximum operating pressure of 10,000 psi and maximum temperature rating of 300°F.. The gases to be injected were supplied from a compressed gas cylinder which was then injected into a vessel and pressurized to the required pressure. The overburden pressure was set at 500 psi higher than the injection pressure for each trial. This was done to ensure that the axial pressure is greater than the internal pressure and also to make sure that the rubber sleeve maintained its integrity. The back pressure is assumed to be the pore pressure of the reservoir, and a value of 1000 psi was used (Fig. 2).

Experimental procedure

The core sample was first cleaned by using the Dean stark distillation apparatus with toluene for 7 days. This was done to ensure that any residual oil was completely dissolved before the start of the experiment. After cleaning, the core was left in the apparatus for a few hours in order for it to be cooled. The core was then placed in an oven at a temperature of 212 °F in order to completely dry the core. The helium porosity of the core was then measured, and the permeability using nitrogen gas was also measured. For the saturation process, the core was first weighed on an analytical balance to obtain the dry weight measurement. The core was then placed in a vessel and vacuumed for 24 h. The vacuum was stopped, and crude oil was injected into the vessel at a constant pressure of 1200 psi for 24 h using a Quizix pump. The pressure was relieved from the vessel in 30-min intervals by gradually reducing the pressure by 100 psi every 30 min till atmospheric pressure was reached. The weight of the core was taken after removing the core from the vessel. The core was placed into the core holder of the gas flooding equipment for the gas flooding test to begin. The same core sample was used for each gas flooding trial under the same conditions for resaturation of the oil to minimize errors due to difference in sampling and test conditions. Also, each weight measurement was taken three times to ensure a high degree of accuracy and precision.

A test tube was placed at the outlet to collect the oil that was being recovered, but because the porosity and permeability of the sample were low, the recovery of the oil was calculated by taking the weight of the core sample before and after the gas flooding so as to compute the weight of oil collected and hence determine the volume of oil

Fig. 1 Core sample picture

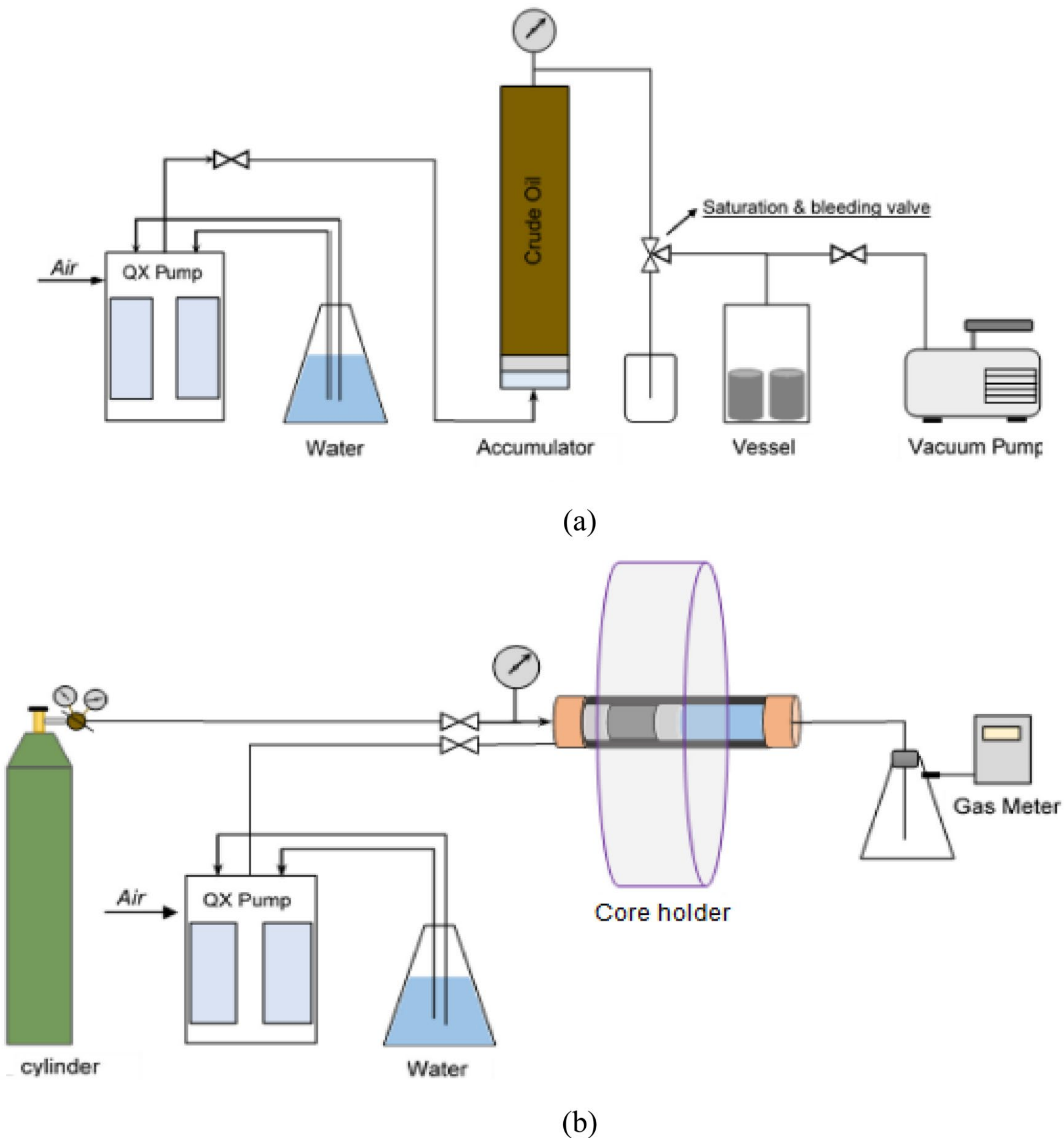

Fig. 2 Schematic diagram of experimental setup used for **a** oil saturation and **b** gas flooding

Table 1 Experimental design for gas flooding

Nitrogen			Carbon dioxide			Nitrogen + carbon dioxide 5050		
Inj pressure	Back pressure (psi)	Over burder	Inj pressure	Back pressure (psi)	Over burder	Inj pressure	Back pressure (psi)	Over burder
2000	1000	2500	2500	1000	3000	2000	1000	2500
3000	1000	3500	3000	1000	3500	3000	1000	3500
4000	1000	4500	4000	1000	4500	4000	1000	4500
5000	1000	5500	5000	1000	5000	5000	1000	5500

recovered. Table 1 shows the injection pressure, overburden and back pressures that were used in each trial.

Results and discussion

In this test the performance of N_2, CO_2 and a 50:50 ratio of N_2 and CO_2 gas on oil recovery in tight sandstone formations as well as their breakthrough times were analyzed. In total, 12 different tests were performed with varying gases with the same injection pressures, an overburden pressure of 500 psi above the injection pressure for each test and the back pressure set to 500 psi. The recovery of oil for the N_2 gas is presented in Fig. 3. The gas injection was done with an injection pressure at 3000 psi and above since the MMP of N_2 gas is usually above 4000 psi from the literature review. The recovery of oil increased as the injection pressure increased. The incremental RF was significant at 3000 and 4000 psi but decreased from 4000 to 5000 psi because of reaching the miscibility condition at pressures

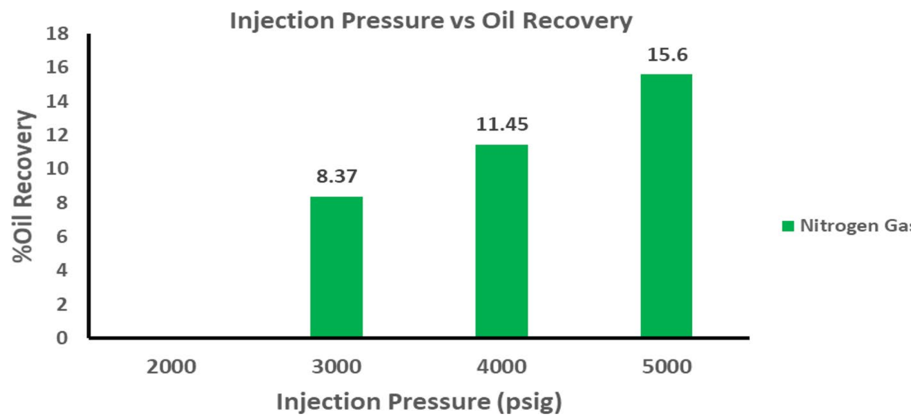

Fig. 3 Oil recovery factor at different injection pressures for N_2 gas

Table 2 RF and gas breakthrough time at different pressures for the core sample

Nitrogen gas (N_2)				Carbon dioxide gas (co_2)				N_2/CO_2 50:50			
Inj pressure	RF	Error (%)	Breakthrough (S)	Inj pressure	RF	Error (%)	Breakthrough (S)	Inj pressure	RF	Error (%)	Breakthrough (S)
2000				2000	7.73	(±) 0.5	2167	2000	6.12	(±) 0.5	3678
3000	8.37	(±) 0.4	924	3000	14.78	(±) 0.3	1876	3000	10.47	(±) 0.4	2564
4000	11.45	(±) 0.4	678	4000	17.35	(±) 0.4	1438	4000	14.36	(±) 0.5	1678
5000	15.6	(±) 0.5	454	5000	19.34	(±) 0.3	1146	5000	17.96	(±) 0.5	1456

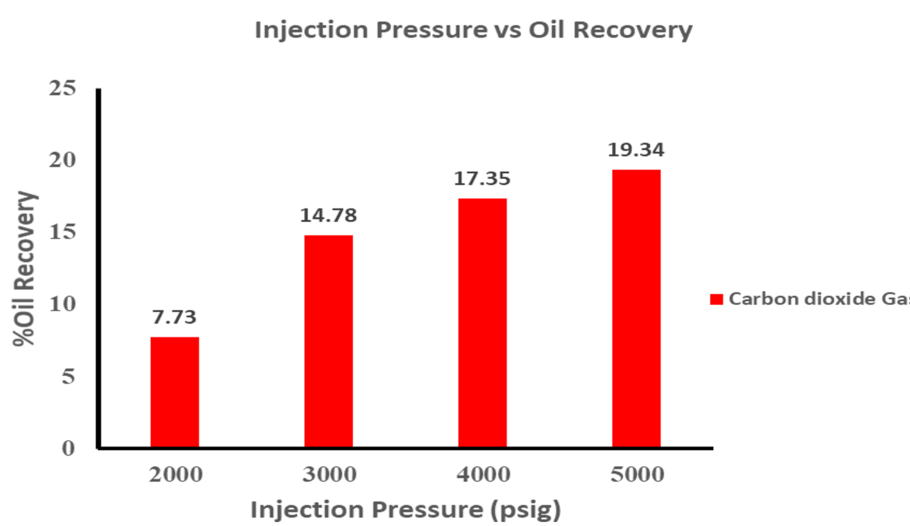

Fig. 4 Oil recovery factor at different injection pressures for CO_2 gas

above 4000 psi. Table 2 shows the RF and breakthrough times of the 11 different trials at different pressures with the 3 different gases.

CO_2 gas was injected at the same pressures as N_2 gas but also at a pressure of 2000 psi. This is because the MMP of CO_2 is known to be within the range of 1500–2000 psi. A similar trend was seen with increasing RF as injection pressure increased. Figure 4 shows the results of the RF of CO_2 with the injection pressures. The RF of the CO_2 injection however was greater than that of N_2 at all pressures, but the incremental RF decreased between 4000 and 5000 psi.

The N_2/CO_2 gas mixture was performed within the same pressure range of 2000–5000 psi. The RF of the N_2/CO_2 gas mixture case was higher than that of pure N_2 but lower than that of CO_2. A similar trend of increasing RF with increasing injection pressure was also noticed. This is due to having 50% of the CO_2 injected with gas mixture that helped in reaching the miscibility conditions. Figure 5 shows the RF of the N_2/CO_2 gas mixture, and Fig. 6 shows the comparison of the RF of all three gases against the injection pressure.

Figure 7 shows the breakthrough times of N_2 when the gas is injected through the core plug at different pressures. It is observed that the time it takes for the gas to breakthrough the outlet of the core decreases as the pressure increases. The breakthrough time of N_2 was the lowest compared to CO_2 and the N_2/CO_2 mixture at the same pressures. This is because N2 is not forming a displacing font (immiscible conditions). Furthermore, because the adsorption capacity of N_2 is much lower than that of CO_2, as a result of this N_2 flows through the core plug fastest.

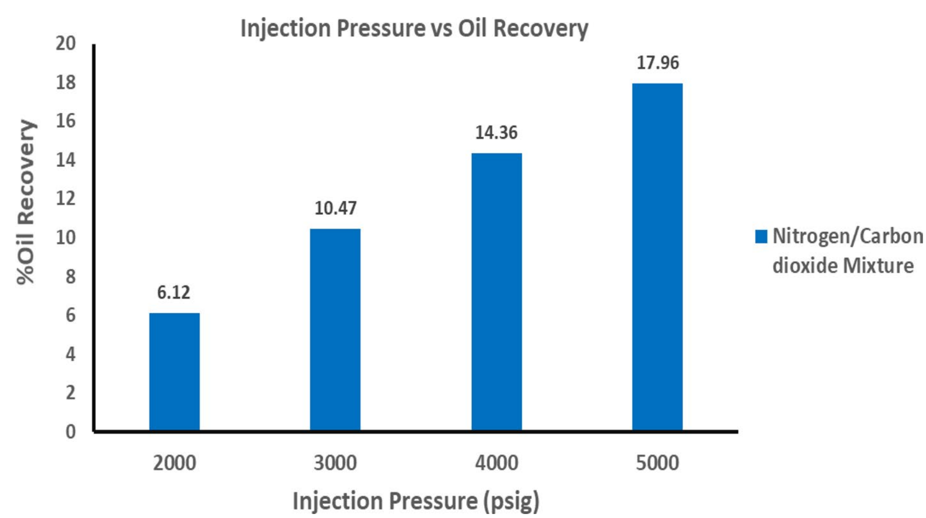

Fig. 5 Oil recovery factor at different injection pressures for 50:50/N_2: CO_2 gas mixture

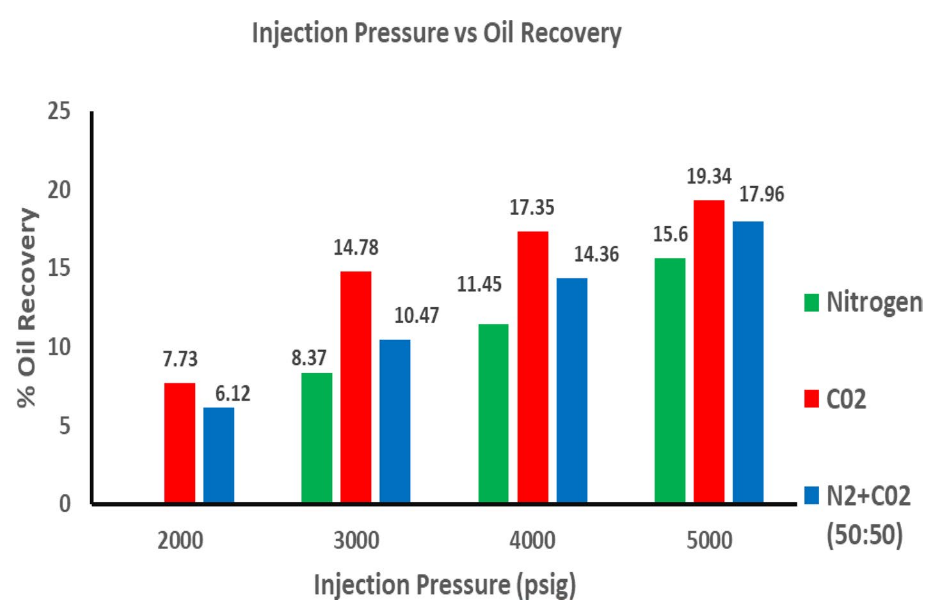

Fig. 6 Oil recovery factors at different injection pressures for the N_2, CO_2 and N_2/CO_2 gas mixture cases

The CO_2 gas had higher breakthrough times at the same injection pressure used for N_2 injection. This is because the adsorption capacity of CO_2 gas is higher than that of N_2, and this makes CO_2 gas to be more easily adsorbed into the pore system and therefore takes a considerably longer time for the gas to exit through the outlet of the core. The gas breakthrough time also decreased as the injection pressure was increased between the range of 2000 and 5000 psi. The results of the CO_2 case are shown in Fig. 8.

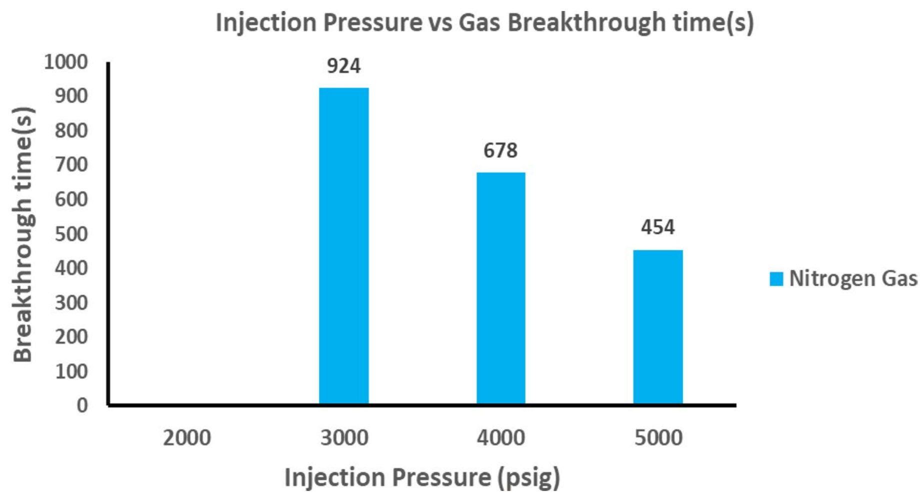

Fig. 7 Breakthrough times of N_2 at different injection pressures

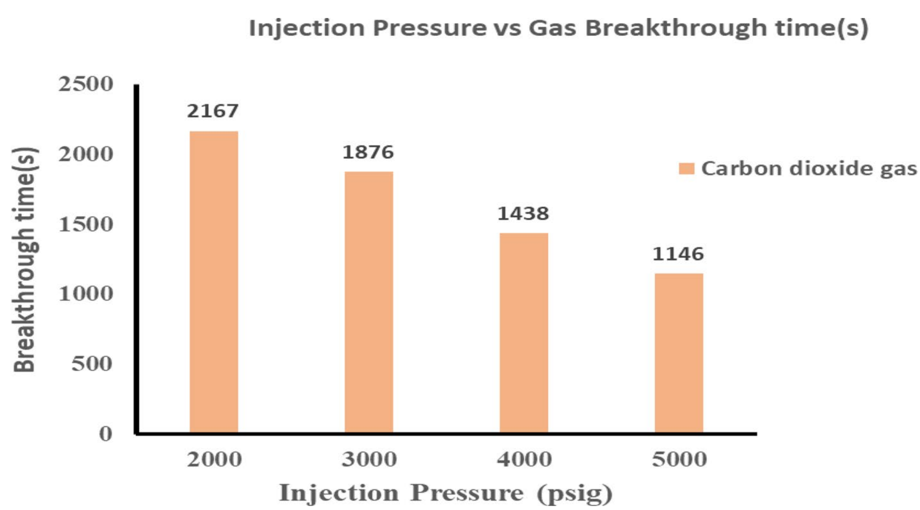

Fig. 8 Breakthrough times of CO_2 at different injection pressures

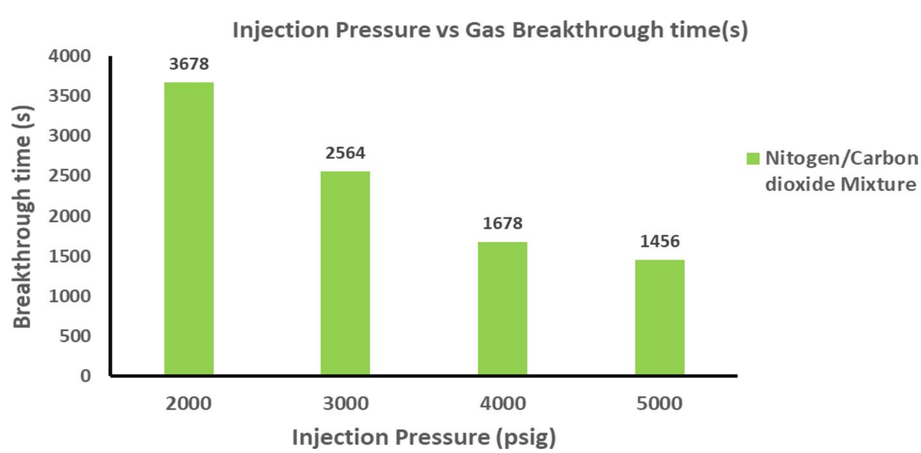

Fig. 9 Breakthrough times of 50:50/N_2: CO_2 gas mixture at different injection pressures

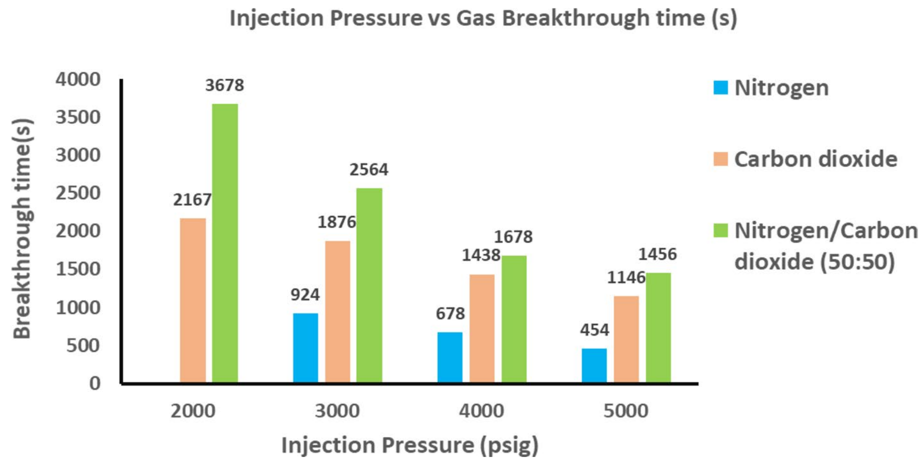

Fig. 10 Breakthrough times of the N_2, CO_2 and N_2/CO_2 gas mixture cases

The N_2/CO_2 gas mixture case had the longest breakthrough times within the same injection pressure range and the same trend of decreasing breakthrough time as injection pressure was increased was also observed. The results of the 50:50 N_2/CO_2 gas mixture case are shown in Fig. 9, and a comparison of the breakthrough time of all three cases is shown in Fig. 10. Yang et al. conducted a similar experiment with core samples from Eagle ford reservoir with N_2 gas injection under injection pressure range from 1000 to 5000 psi. It was discovered that an increase in the injection pressure resulted in an increase in the oil recovery and gas breakthrough from the plug was earlier when flow rate was stabilized. At gas injection pressure of 5000 psi, gas flowed through the plug in less than two hours and the RF achieved was 33.6% (Yang and Sheng 2016).

Conclusion

Core-flooding experiments using N_2, CO_2 and a 50:50 ratio of N_2 and CO_2 were conducted on a core plug under controlled conditions from the Eagle ford formation. This was done to analyze the recovery factor and gas breakthrough time using the same core plug under varied injection pressures. The main conclusions that were drawn from this experiment are as follows:

- CO_2 gas had the greatest oil recovery factor, and N_2 gas had the lowest oil recovery factor within the same injection pressure range of 1000–5000 psi
- The incremental RF increased significantly with all three gases between 2000 and 4000 psi, but the incremental RF between 4000 and 5000 psi decreased
- The gas breakthrough time decreased as injection pressure increased
- N_2 had the shortest breakthrough time, and the 50:50 mixture of N_2 and CO_2 had the longest breakthrough time. This is because the N_2 has a very low adsorptive capacity and hence moves through the core quickly, while CO_2 has a higher absorptive capacity and therefore takes longer to sweep through the core
- Therefore, injecting a mixture of CO_2 and N_2 serves to grant some major benefits such as further delaying the breakthrough of CO_2 gas and also using lower volumes of CO_2 gas for injection. This will help in reducing greenhouse gas emissions and saving cost associated with obtaining CO_2 gas. The gas injection can also be performed at a much lower pressure as compared to injecting pure N_2 gas which is usually done at much higher pressures if miscibility is desired

Acknowledgement The authors would like to recognize Keane Group for the supply of the live crude used in the experiment.

Funding This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

Reference

Atan S, Ajayi A, Honarpour M, Turek E, Dillenbeck E, Mock C, Ahmadi M, Pereira C (2018) The viability of gas injection EOR in Eagle Ford shale reservoirs. Presented at the SPE annual technical conference and exhibition, Dallas, Texas, USA, 24–26 September. SPE-191673-MS. https://doi.org/10.2118/191673-MS

Belhaj H, Khalifeh HA, Javid K (2013) Potential of nitrogen gas miscible injection in south east assets, Abu Dhabi. Presented at the North Africa technical conference and exhibition, Cairo, Egypt, 15–17 April. SPE-164774-MS. https://doi.org/10.2118/164774-MS

Clancy JP, Gilchrist RE, Kroll DE (1981) Nitrogen for the enhanced recovery of oil and gas. Presented at the SPE California Regional Meeting, Bakersfield, California, 25–27 March. SPE-9912-MS. https://doi.org/10.2118/9912-MS

EIA (2015) US crude oil production to 2025: updated projection of crude types. https://www.eia.gov/analysis/petroleum/crudetypes/pdf/crudetypes.pdf

Jia B, Tsau J-S, Barati R (2019) A review of the current progress of CO_2 Injection EOR and carbon storage in shale oil reservoirs. Fuel 236:404–427. https://doi.org/10.1016/j.fuel.2018.08.103

Sheng JJ, Soliman MY (2013) An experimental study of cyclic gas injection to improve shale oil recovery. Presented at the SPE annual technical conference and exhibition, New Orleans, Louisiana, USA, 30 September-2 October. SPE-166334-MS. https://doi.org/10.2118/166334-MS

Sheng JJ (2015) Enhanced oil recovery in shale reservoirs by gas injection. J Nat Gas SciEng. https://doi.org/10.1016/j.jngse.2014.12002

Shouya W, Zhaomin L (2019) Investigation of CO_2/N_2 injection in tight oil reservoirs with confinement effect. Energy SciEng. https://doi.org/10.1002/ese3.578

Siregar S, Wijaya B (2007) Laboratory experiments on enhanced oil recovery with nitrogen injection. ITB J EngSc. https://doi.org/10.5614/itbj.eng.sci.2007.39.1.2

Sinanan BS, Budri M (2012) Nitrogen injection application for oil recovery in Trinidad. Presented at the SPETT 2012 energy conference and exhibition, Port of Spain, Trinidad, 11–13 June. SPE-156924-MS. https://doi.org/10.2118/156924-MS

Vega B, O'Brien WJ, Kovscek AR (2010) Experimental investigation oil recovery from siliceous shale by miscible CO_2 injection. Presented at the SPE annual technical conference and exhibition, Florence, Italy, 19–22 September. SPE-135627-MS. https://www.onepetro.org/conference-paper/SPE-135627-MS

Wan T, Sheng JJ, Soliman MY (2013) Evaluation of the EOR potential in shale oil reservoirs by cyclic gas injection, paper SPWLA-D-12–00119 presented at the SPWLA 54th annual logging symposium held in New Orleans, Louisiana, 22–26 June

Wijaya N Effect of initial water saturation on post-fracturing soaking performance with different tight reservoir realization model. SPE-200875-MS

Yang Y, Sheng JJ (2016) Experimental evaluation of shale oil recovery from eagle ford samples by nitrogen gas flooding. Presented at the SPE improved oil recovery conference, Tulsa, Oklahoma, 11–13 April. SPE-179547-MS. https://doi.org/10.2118/179547-MS

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.