An Experimental Investigation of Performance Evaluation for Seawater and CO_2 Injection Using Dual Cores Methodology at Reservoir Conditions

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ABSTRACT

In this study, a novel methodology of dual core flooding was first developed and described in detail, and applied to evaluate displacement efficiency and performance of seawater and supercritical CO_2 (sc-CO_2) injection for two carbonate core plugs with different permeabilities at reservoir conditions. The dual core flooding apparatus consists of seven components and can be used to inject individually or simultaneously for one or two phases fluids into core plugs with variety of length in a single or dual core flooding configuration. The orientation of single or dual core holder with test core plugs can change horizontally or vertically for the different experiments. The experimental conditions of this new apparatus are up to 150^{o}C for temperature, up to 6000 psi for pore pressure and 10,000 psi for confining pressure.

As an example of application of dual core flooding experiments, the different oil recovery schemes of seawater flooding, as a secondary EOR process followed by a sc-CO_2 injection, as a tertiary EOR process was conducted at reservoir conditions. The results from the dual core flooding experiments are discussed for high and low permeability carbonate rocks, and show the potential of CO_2-EOR projects. Experimental procedures are provided for conducting these dual core experiments, and show the potential to become a gold standard for such studies.

INTRODUCTION

Development of core flooding apparatus started in the 1940s. There is various equipment in laboratories experiments for reservoir engineering processes. Some examples of the classical steady-state method are the Penn State method [1], the Hassler method [2], the single-core dynamic method [3], the stationary fluid method [4] and the Hafford's method [3]. With development of laboratory testing techniques, the apparatus included in-situ saturation imaging techniques by X-ray to measure saturations when two or three fluids are injected into core. Based on research objectives, the components of core flooding apparatus have to be changed to meet the requirements of the investigation. The utilization of core flooding apparatus covers many research areas such as oil recovery by seawater and Low-Salinity waterflooding [5], Chemical Flooding [6] and CO_2 injection [7]. A review of the core flooding apparatus described in areas above found that one core holder was used, no matter which research objectives were investigated.

In this paper, dual core flooding apparatus (DCFA) is proposed and designed to apply to oil recovery and performance studies by different oil recovery schemes of seawater flooding and initial and post sc-CO_2 injection at reservoir conditions as an evaluation of the practicability of a dual core flooding system.

Dual Core Flooding Apparatus

A dual core flooding apparatus (DCFA) is custom designed to perform tests on stacked or composite core plug samples to study oil recovery by IOR and EOR processes and evaluate the impact of reservoir heterogeneities such as permeability contrast and gravity override on performance of oil/water production at reservoir conditions. The schematic of the core flooding apparatus are presented in Figure 1. The core holders are placed horizontally with high permeable core plug (HPCP) on top of low permeable core plug (LPCP) core-holder. A detailed description of dual core flooding system has been presented [8].

Application of Dual Core Flooding Apparatus

As an example of application of the dual core flooding experiments the different oil recovery schemes of seawater flooding, as secondary EOR and sc-CO_2 injection, as tertiary EOR were conducted for carbonate core plugs with different permeabilities at reservoir conditions.

Properties of fluids

Brines: Two types of brines were used in this study, field connate water and seawater. The field connate water was used to saturate the core plugs for brine permeability measurement and acquiring the initial water saturation (S_{wi}). Seawater was used to displace live oil for evaluating displacement efficiency by injecting seawater simultaneously into both HPCP and LPCP. The compositions, density and viscosity of both brines were described [8].

Dead and live crude oils: A dead crude oil from a carbonate reservoir was used in this study to set up initial water saturation (S_{wi}) and age core plugs at reservoir conditions. Separator crude oil and gas were collected from the same reservoir to recombine the live crude oil sample. The live oil was then used to age the core plugs and to represent the oil phase for the seawater flood and sc-CO_2 miscible flooding experiments. The viscosity and density of dead and live crude oils at reservoir temperature were described [8].

Supercritical CO_2 (sc-CO_2): sc-CO_2 was also used as a displacing agent for tertiary oil recovery at a pressure of 3200 psi and temperature of 102^{o}C. This created the miscible flooding condition with the live crude oil in reservoir. The minimum miscible pressure (MMP) between live oil and sc-CO_2 was 2600 psi. The viscosity and density of sc-CO_2 were described [8].

Preparation of Core plugs

Core plugs: The core plugs were selected from a carbonate reservoir and scanned to ensure consistency, i.e. no fractures or permeability barriers in single core plug. The length (L) and diameter (D) of core plugs show in Table 1.

Set up initial water saturation (S_{wi}) and original oil in core (OOIC):

Before running dead crude oil flooding for setting up initial conditions, S_{wi} and S_{oi}, several tests were done to saturate the core plugs with field connate water and measure brine permeabilities. Core plugs were assembled using Teflon Tape, aluminum foil and 1 layer of Teflon shrink tube as a stack. The aluminum foil functioned as a diffusion barrier between the core plug and the overburden sleeve. The procedure of setting up initial conditions was described in detail [8]. Table 1 shows these data.

Table 1 Initial Date of live oil flooding at reservoir conditions

Composite ID	L (cm)	D (cm)	PV (cc)	K_b (mD)	S_{wi} (%)	S_{oi} (%)	K_{eo} at S_{wi} (mD)
Composite 1 (HPCP)	6.394	3.8	20.6	967	24.6	75.4	104
Composite 2 (LPCP)	6.018	3.8	14.1	22.3	17.6	82.4	3

Aged composite core plugs with live crude oil: After initial water and original oil saturation was set up, live oil flooding was conducted at reservoir condition of pore pressure 3200 psi, confining pressure of 4500 psi and temperature of 102^{o}C for both HPCP and LPCP. One pore volume of live oil was injected into each composite core at a flow rate of 1.0 cc/min in order to check stabilization of injection pressure and effective oil permeability of core plugs every day for three weeks. The initial water saturation (S_{wi}) and original oil in core (OOIC) were 24.6% and 75.4% for HPCP and 17.6% and 82.4% for LPCP, respectively.

Oil Recovery by Seawater and sc-CO_2 Injection

Oil recovery by seawater flooding: Once both composites were aged with live oil at reservoir conditions, seawater was injected simultaneously into both HPCP and LPCP at injection rates of 0.5, 1.0 and 2.0 cc/min until the water cut reached 99%. The recovered oil was collected separately from the two composites as a function of pore volumes of seawater injected. The differential pressures across both composites and injection pressure were also recorded as a function of time.

Oil recovery by initial sc-CO_2 miscible flooding: After the initial seawater flooding and the remaining oil saturation was established, the inlet and outlet valves of both composites were closed. All the lines which were filled with seawater were first displaced with sc-CO_2. Thereafter the two composites were opened again and sc-CO_2 was injected simultaneously into both at a rate of 0.2 cc/min. The recovered oil was collected from the two composites separately. Differential pressures and injection pressure for each composites was also recorded as a function of time.

Injection of a diverting system: To investigate the effect of permeability contract and to mitigate its impact on oil recovery, a diverting system was injected into the HPCP composite. The main idea was to block the HPCP composite so that the subsequent sc-CO_2 would travel through the LPCP composite and recover the bypassed oil. The diverting system used for this experiment was described [8].

2^{nd} sc-CO_2 miscible flooding: After accomplishing the diverting system injection, both HPCP and LPCP composites were opened for the 2^{nd} sc-CO_2 miscible flooding at injection rate of 0.2 cc/min. Oil production and differential pressure across composites and injection pressure were recorded individually for HPCP and LPCP.

Results and Discussion

Profile of differential pressure during seawater and sc-CO_2 injection

The differential pressure across the high and low permeable core plugs vs total pore volume of seawater injection is presented in Figure 2 (left). At breakthrough of injection fluid, the differential pressure across the HPCP core reached a maximum value of 0.8 psi and then dropped to a value of about 0.2 psi at an injection rate of 0.5cc/min. For the LPCP, the differential pressure across the core reached a maximum value of 11 psi and then dropped down to same value as the HPCP. This phenomenon is due to the seawater bypassing through HPCP and the effect of rock heterogeneity. Figure 2 (right) presents the differential pressure drop across both cores during initial sc-CO_2 injection. The performance of initial sc-CO_2 injection was quite different to that of the seawater injection for LPCP composite. After sc-CO_2 breakthrough, the differential pressure drop across the two cores was different (unlike the case during in the seawater flood). A second peak value of differential pressure was observed for LPCP, and the value was greater than 5psi. This was due to two-phase and three-phase flow in the LPCP. Slow continuous oil production was observed beyond 0.2 PV sc-CO_2 injected.

Oil recovery during seawater and sc-CO_2 injection

Figure 3 shows the overall oil recovery with seawater, sc-CO_2 before and after the diverting system slug injection. The results show exceptional recovery (98%) in the HPCP composite after the seawater and first CO_2 injection cycles. Due to seawater and sc-CO_2 bypassing through the HPCP, the performance of the LPCP composite was relatively poor. By plugging the HPCP with the diverting system slug, the subsequent CO_2 was able to extract some of the remaining oil from the LPCP composite.

Conclusions

Based on results and observations of seawater and sc-CO_2 flooding using dual core flooding apparatus at reservoir conditions, the following conclusions can be drawn:

1. A novel apparatus and experimental procedure for dual core flooding experiments were first developed and then applied successfully to study oil recovery by seawater and sc-CO_2 as well as conformance control using a diverting system at reservoir conditions.

2. Novel methodologies of dual core flooding are an effective technique, and dual core flooding apparatus is a very useful tool to study oil recovery and performance by IOR and EOR processes, and to evaluate the effect of permeability contrast, reservoir heterogeneities and injection flow rate on oil recovery at reservoir conditions.

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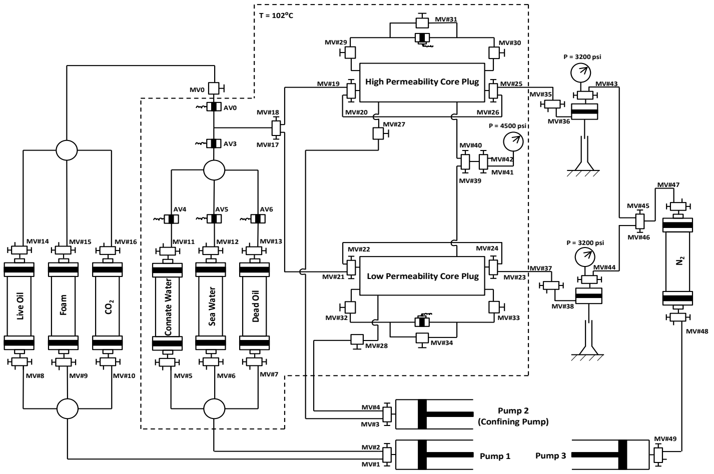

Fig.1 flow chart for dual core flooding apparatus at reservoir conditions

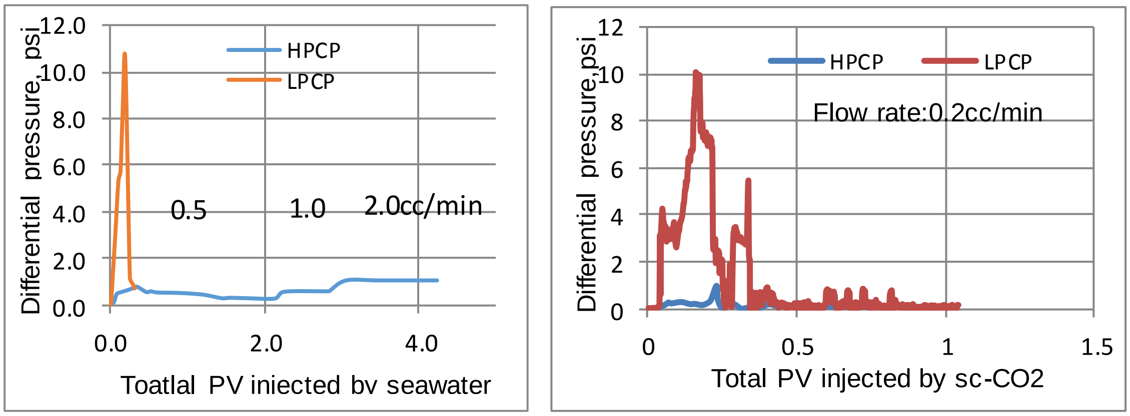

Fig.2 Comparison of differential pressure vs. the sum of PV injected during simultaneous seawater injection for LPCP and HPCP composites, Left: Seawater flooding; right: sc-CO2 injection

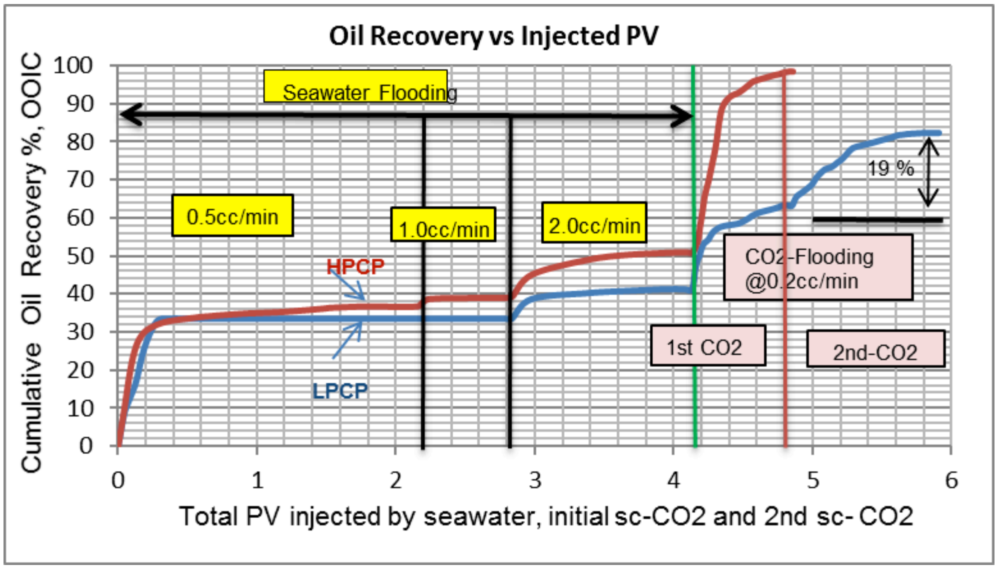

Fig.3 Overall oil recovery by seawater, initial sc-CO_2 and 2^{nd}-sc-CO_2 flooding after diverting system slug injection at reservoir conditions

References

1. Morse, R. A., Terwilliger, P. L. and Yuster, S. T.: "Relative permeability measurements on small Sample," Oil and Gas Journal, (Aug. 23) 109, 1947.
2. Hassler, G.L.: "Method and Apparatus for Permeability Measurements." U. S. patent No. 2,345,935, April, 1944.
3. Richardson, J. G., Kerver, J. K., Hafford, J. A., and Osoba,J . S.: "Laboratory determination of relative permeability," Trans. AIME, 195, 187, 1952.
4. Leas, W. J., Jenks, L. H. and Russell, C. D.: Trans AIME, 189, 65, 1950.
5. Yousef, A. A., Al-Saleh, S. H., Al-Kaabi, A. and Al-Jawfi, M. S.: "Laboratory Investigation of the Impact of Injection-Water Salinity and Ionic Content on Oil Recovery From Carbonate Reservoirs", Society of Petroleum Engineers. doi:10.2118/137634-PA, 2011.
6. Shedid, S. A.: "Experimental Investigation of Alkaline/Surfactant/Polymer (ASP) Flooding in Low Permeability Heterogeneous Carbonate Reservoirs", Society of Petroleum Engineers. doi:10.2118/175726-MS, 2015.
7. Zhou, X, Al-Otaibi, F. and Kokal, S. L.: "Laboratory Evaluation of Performance of WAG Process for Carbonate Rocks at Reservoir Conditions", Society of Petroleum Engineers. doi:10.2118/167646-MS, 2013.
8. Zhou, X., Al-Otaibi, F., Kokal, L. S., Alhashboul, A., Balasubramanian, S. and Alghamdi, F.: **"**Novel Insights into IOR/EOR by Seawater and Supercritical CO2 Miscible Flooding Using Dual Carbonate Cores at Reservoir Conditions," Presented at 18th European Symposium on Improved Oil Recovery, Dresden, Germany, April 14-16, 2015