MECHANISM OF OIL RECOVERY BY GAGD IN WATER-WET AND OIL-WET CONDITIONS

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ABSTRACT

Immiscible gas assisted gravity drainage (GAGD) is normally characterized as a slow but efficient process, which leads to a low residual oil saturation. Characterization of multiphase flow in commercial scale gas injection processes and their laboratory duplications forms an important component of the development and application of the GAGD. In this study, the research of the enhanced oil recovery mechanism of GAGD in the high water-cut stage was carried out through the measurements of three-phase saturation by conducting CT scanning on a special core holder. The experimental results indicated that GAGD in the high water-cut stage significantly enhances oil recovery. An oil enrichment zone was observed at the flooding edge of the gas front and the propagation and enhancement of this zone along with the gas injection could be tracked by CT scanning. The impact of wettability on the experiments was also investigated, which showed that there were significant differences between the experimental measurements on cores with different wettability. Both a higher EOR percentage point and a wider ‘oil bank’ were observed for water-wet core than for oil-wet core. These differences can be attributed to the different occurrence states of oil and water in pores prior to the gas injection.

INTRODUCTION

EOR by gas injection currently accounts for about 48% of total enhanced production and for the majority of enhanced production of light oil [1]. However, the unfavorable fluid mobility ratio in a gas injection process leads to unexpected problems such as gravity override and premature gas breakthrough. The gas assisted gravity drainage (GAGD) process, which is normally characterized as a slow but efficient process, utilizes the difference of the densities between injected gas and oil to inhibit viscous fingering to improve oil recovery significantly [2]. The East-Texas Hawkins reservoir has reported an estimated displacement efficiency of 87% by GAGD [3]. The importance of GAGD has motivated many laboratories to investigate the oil recovery process [4~6]. In this study, the EOR mechanism of GAGD in the high water-cut stage for water-wet and oil-wet outcrops has been investigated by conducting CT scanning experiments for in-situ three-phase saturation measurement. The experimental results proved the feasibility of EOR by GAGD in the high water-cut stage. The multi-phase flow mechanism in different wettability conditions has been investigated as well.

EXPERIMENTAL

Core Samples and Fluids

Two core samples (SC1 and SC2) drilled from the same sandstone outcrop were used for the experiment. The petrophysical parameters of these two samples are listed in Table 1. The wettability of SC1 was determined by the Amott method as water-wet and SC2 as weak oil-wet after aging with silicon oil for a week. The refined oil (Caltex White Oil Phamra) used for aging was degassed by vacuum and its viscosity was 4.7 cP at 60 ° C. A 5wt% NaBr solution was used to improve the CT number of the aqueous phase. The purity of the injected nitrogen was 99.93%.

Experimental Set-up and Conditions

The scheme of the experimental set-up is illustrated in Figure 1. A medical CT scanner from GE was used. The core samples and the fluids were scanned under 100kV, 140kV and 150mA, and the scanning results were used for the three-phase saturation calculations [7].The helical mode for CT was adopted to reduce scanning time. CT images were processed by a CT image analysis software (CTIAS 2.0, developed by RIPED).Two sets of QUZIX pumps were employed to control the injection of water and oil. A set of ISCO pumps was used to control the nitrogen injection at constant-rate.

An overburden pressure of 10MPa was maintained in the sleeve and a back pressure of 5MPa was maintained in all the experiments. A special PEEK coreholder was mounted on a single bracket which allows the coreholder to rotate for vertical gas injection and horizontal CT scanning.

Procedure

All the experiments were conducted at ambient temperature. After establishing irreducible water saturation, the core was displaced by 5wt% NaBr from bottom to top with a constant rate of 0.1ml/min until 99.5 % water cut was reached. Subsequently, assisted by gravity, nitrogen was injected from top to bottom with a constant rate of 0.01ml/min until no fluid was produced and the pressure remained constant. The coreholder was placed vertically during the displacement and horizontally in CT scanning.

RESULTS AND DISCUSSION

Water Flooding

According to conventional core analysis and CT scanning, SC1 and SC2 possessed very close petrophysical properties, which indicated similar behaviors of characteristic displacement in these two cores. It also provided a foundation for further one-factor experimental analysis.

Different wettabilities of SC1 and SC2 led to different residual oil distributions after water flooding. The residual oil of the water-wet sample tended to occupy the central area of the pores, while that of the oil-wet sample tended to locate in the corners of the pores. In addition, the residual oil saturation of SC1 was much lower than that of SC2.

GAGD Procedure

During the GAGD procedure, the coreholder should be rotated to a vertical position to be consistent with gravity orientation. However, medical CT scanning requires a horizontal position for core sample. Due to the low velocity of gas injection and the smallness of the samples, the gravity differentiation caused by the short time rotation of the coreholder was negligible. Therefore, the change in orientation between the vertical gas injection and the horizontal CT scanning had little impact on the simulation of GAGD.

After waterflooding, nitrogen was injected into the water-wet core SC1 from the top of the coreholder. Water was continuously produced at the beginning. As 0.1PV nitrogen was injected, both oil and water were produced from the outlet with the majority of production being water. With continual injection of nitrogen, the water cut began to decrease. The peak oil production occurred in the range from 0.15PV to 0.18PV of nitrogen injection. Beyond that range, gas was produced rapidly and the liquid production reduced sharply. The gas breakthrough occurred at 0.2PV of nitrogen injection while no more liquid was produced after this stage. The additional oil production due to nitrogen injection was 1.83 ml which is equivalent to an oil recovery improvement of 7.45%.

The GAGD procedure on oil-wet core SC2 was similar to SC1 except for some key points. Oil and water began to produce simultaneously at 0.08PV nitrogen injection. The largest amount oil was produced at 0.13PV to 0.15PV nitrogen injection. The gas breakthrough occurred at 0.18PV nitrogen injection. The additional oil production was 1.08 ml which is equivalent to an improvement of 4.37% on oil recovery.

The oil saturation distribution profiles derived from CT scanning along the core during GAGD procedure for SC1 and SC2 are shown in Figure 2 and Figure 3, respectively. For water-wet core SC1, an enhanced oil saturation section emerged near the inlet of the core (Figure 2). This enhanced section propagated along the core towards the outlet with increasing width and height as the PV injection increases. An oil enrichment zone at the flooding edge of the gas front was indicated from the profile. This zone was enriched with continual residual oil and as it propagated, the oil enrichment zone became wider and the oil content increased gradually (as did the “oil bank” proposed by Kantzas, et al. [8]).When the zone propagated to the outlet, the oil phase started to accumulate. Finally, such phenomena occurred that the closer the oil enrichment zone to the outlet, the higher the oil saturation was. A large gas breakthrough occurred when this zone reached the outlet. After that the oil saturation distribution profile along the core did not change sharply. Small quantities of oil would spurt out at the ending of the experiments, which significantly enhanced the oil saturation at the outlet.

The trend of the oil saturation distribution profile along the oil-wet core SC2 demonstrated the same pattern as along SC1, as illustrated in Figure 3. The differences between the trends of these two cores were mainly reflected in the width and height of the enhanced section. In general, the oil enrichment zone of SC2 at the flooding edge of the gas front was narrower and its height was lower than those of SC1. Further analysis showed that the wider and higher peak value of the oil saturation increase section of SC1 compared to SC2 led to the advance of some key points during the GAGD procedure of SC2, which finally resulted in a lower oil recovery improvement of SC2 than that of SC1.

The difference of experiment results between water-wet and oil-wet cores during GAGD procedure could be attributed to the different occurrence states of oil and water in pores prior to the gas flooding. For water-wet core, the residual oil normally existed as discontinued drops in the center of the pores after water flooding. Injected gas, considered as a non-wetting phase compared with oil, trended to occupy the central spaces of the pores, which forced the residual oil formed in the water flooding to move toward the outlet. During its migration, the residual oil in different positions would gather and form an “enrichment zone”. Meanwhile, due to the difference of gravity forces between gas and liquid, the propagating oil enrichment zone merged with the residual oil in the flooded area and became wider and larger. For oil-wet core, most of the residual oil was located in the corners of the pores after water flooding. Therefore, the merging of residual oil with the propagating oil enrichment zone was weakee in SC2 than in SC1. The gravity difference between gas and liquid would inhibit the gas viscous fingering, so that the injected gas moved down steady and slowly, which enhanced the microscopic sweep efficiency. This is believed to be the main mechanism of enhanced oil recovery.

CONCLUSIONS

In this study, the EOR mechanism of GAGD in the high water-cut stage of water-wet and oil-wet cores was investigated by CT scanning. The experimental results showed that GAGD in the high water-cut stage could enhance oil recovery significantly. Some conclusions can be drawn from the experiments. First, the difference of buoyancy between gas and liquid could inhibit gas viscous fingering which enlarged the microscopic sweep efficiency. Second, due to the different wettability of fluid, the residual oil formed in the water flooding was forced to start moving downward with gas injection. The residual oil then merged to form an enrichment zone which propagated towards the outlet with gas injection and became wider and larger.

In this experiment the activity of the refined oil was weak, and its interfacial tension at ambient temperature was much larger than that in the real reservoir condition. Also, the back pressure applied in the experiment was lower than the underground pressure. These discrepancies limited the possibilities to perform the measurements at underground conditions. In the future, it will be necessary to carry out experiments under reservoir conditions to acquire further and comprehensive understanding of the GAGD procedure.

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Table 1.Petrophysical Parameters of Core Samples

Sample No.	Porosity,%	K_{air},10^{-3}μm^2	Length, cm	Area, cm^2	Wettability
SC1	23.4	851	12.25	11.51	Water-wet
SC2	23.1	846	12.31	11.67	Weak oil-wet

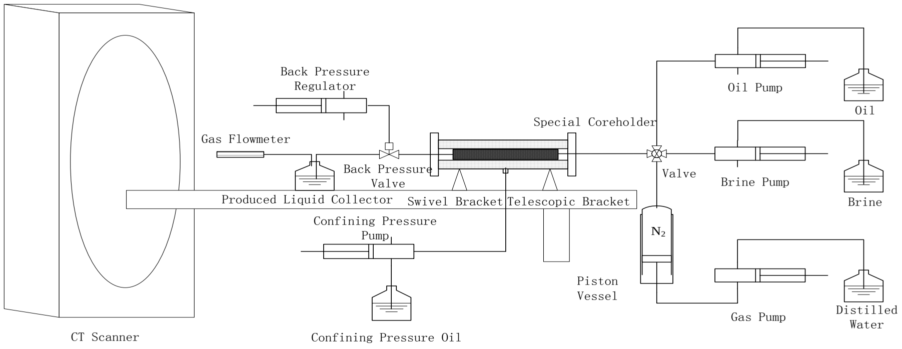

Figure 1. Experimental Schematic

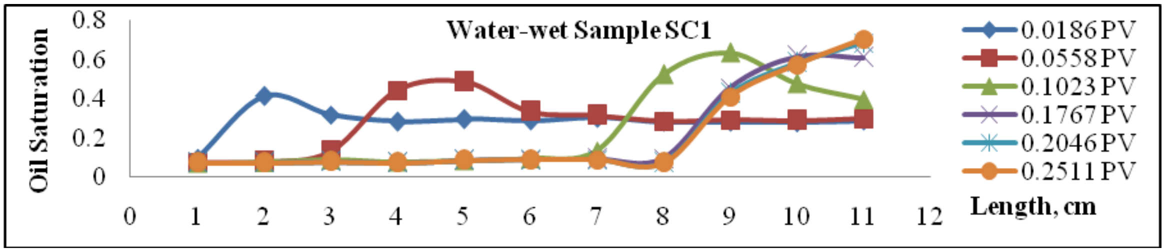

Figure 2. Oil Saturation DistributionAlong CoreDuring Gas Flooding

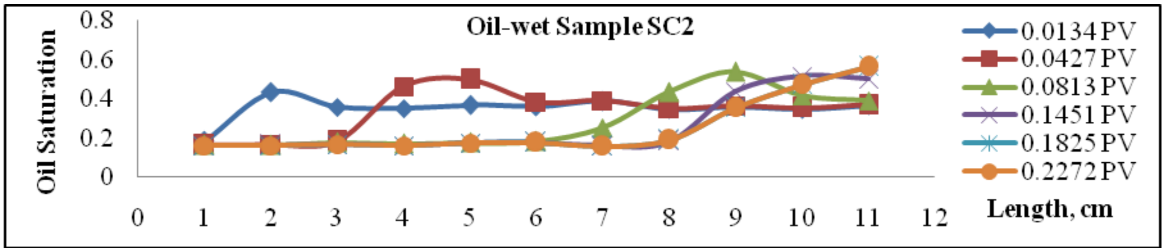

Figure 3. Oil Saturation Distribution Along Core During Gas Flooding