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Effect of Miscibility Condition for CO_2 Flooding on Gravity Drainage in 2D Vertical System

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Abstract

In CO_2 flooding process, gravity drainage and miscibility condition are the main factors on the efficiency of oil recovery. In this study, we observed oil recovery for different miscibility conditions in vertical oil reservoir. This was investigated in two dimensional vertical sandstone slab, where unstable gravity drainage phenomena can be formed. CO_2 is injected at bottom into 100% saturated with oil and production port is open at top of the system. We have performed a series of experiments using continuous CO_2 flooding for immiscible and near-miscible conditions. From the experimental results, oil recovery at near-miscible condition is 3.77 times greater than at immiscible condition, particularly in vertical system. It indicated that applying the immiscible CO_2 flooding is ineffective because of gravity override of CO_2 and generation of CO_2 channel at upper side in vertical reservoir. Meanwhile, the results revealed that oil recovery increases considerably once miscibility is reached at outlet. That is, miscibility condition is found to be a sensitive factor on oil recovery particularly in vertical oil reservoir.

Keywords: Miscibility condition; Oil recovery; CO_2 flooding; Unstable gravity drainage; 2D vertical sandstone

Introduction

In CO_2 injection process, the densities and viscosities of oil and CO_2 are the main variables determining the gravity drainage that can cause early CO_2 breakthrough. Once the injected CO_2 moves toward top of the reservoir, CO_2 front contacting with oil is gravitationally unstable, which leads to the decrease in oil recovery. Several researchers showed the importance of miscibility condition and gravity drainage effect on the oil recovery during CO_2 injection. Asghari et al. [1] and Torabi et al. [2] conducted experiments and simulation study considered miscibility condition in fractured system. They showed the oil recovery may decrease far above the miscibility. Trivedi et al. [3,4] also conducted experimental work about effect of CO_2 injection rate at various miscibility conditions in fractured reservoir. Kulkarni et al. [5] reported gravity drainage effect for Gas Assisted Gravity Drainage (GAGD) process under immiscible and miscible conditions. Nasrabadi et al. [6] conducted the simulation study to investigate the effect of density in the 2D vertical reservoir and shown significant effect of gravity and heterogeneity. Although a number of researchers [1-10] have investigated about CO_2 flooding under the various miscibility conditions and the gravity drainage mechanism, none of researches have been done in vertical oil reservoir.

In this work, we discussed an experimental study to examine the influence of gravity drainage on the oil recovery for the vertical oil reservoir. A series of CO_2 injection experiments have been conducted at immiscible and near-miscible conditions in two dimensional vertical sandstone plates.

Laboratory Study

2D CO_2 flooding apparatus

A special high-pressure aluminum sandstone plate holder with internal diameter of 26 cm and length of 47 cm was manufactured for 2D CO_2 flooding experiments (Figure 1). The sandstone sample is placed between two half-cylindrical acryl within the holder. The confining pressure was always kept 400 psi greater than internal pressure to avoid effect of non-flowing direction [11]. Moreover, the sample plate holder is covered by thermal jacket which is connected at bath circulator to keep the reservoir temperature during experiments. A backpressure regulator was installed at the outlet to maintain the pressure at 600 to 1,000 psi. The syringe pump was used to inject fluids of oil and CO_2 at constant flow rate. The produced fluids are separated at separator, then oil and CO_2 are measured by electronic balance and mass flow meter, respectively, automatically in real time. The CIMON-SCADA data acquisition system was connected to acquire the data automatically per second in real time for pump, pressure transmitters, electronic balance, gas mass flow meter, and temperature sensor [12,13].

Sandstone sample and fluid

The sister berea sandstone plate (dimension: 20×20×2 cm) was used, and its average permeability and porosity were measured as 31 md and 20.04%, respectively. Normal decane was a saturated fluid as oil phase throughout these experiments. The density and viscosity of normal decane are at 35°C is 0.72 g/cc and 0.74 cp. The miscibility pressure of CO_2 and normal decane is about 1062.5 psia at 35°C which were determined using commercial PVT software, i.e. CMG-WINPTOP™ [1,2]. The CO_2 (purity 99.999%) was injected constantly at 20 ml/hr as a solvent at immiscible and near-miscible reservoir conditions of 600 psig and 1,000 psig at 35°C.

Results and Discussion

In order to investigate the oil recovery performance by the continuous CO_2 flooding process, we conducted the experiments for Immiscible (IMS) and Near-Miscible (NMS) conditions in vertical

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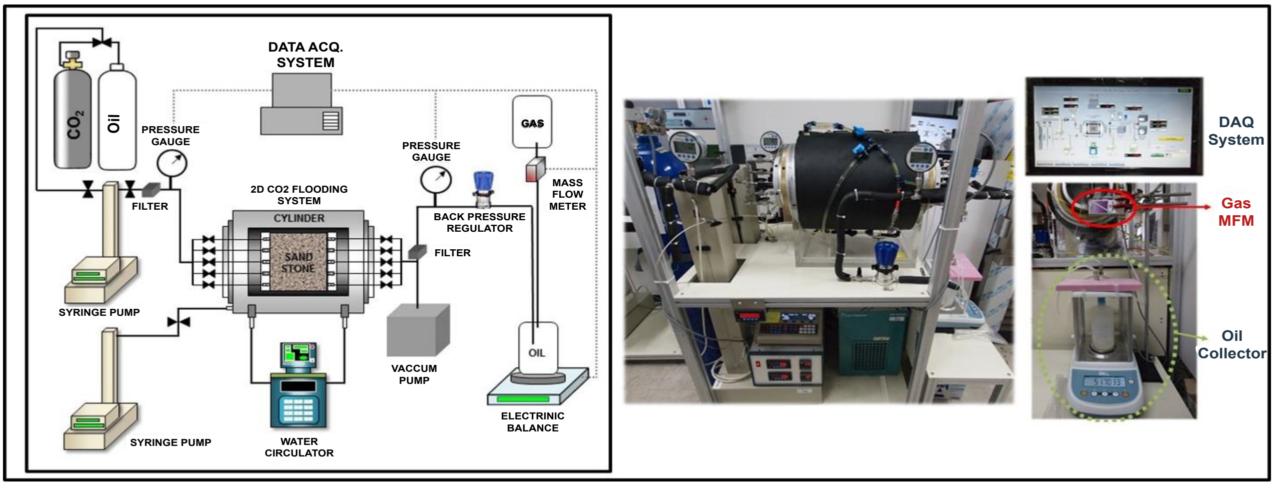

Figure 1: 2D CO_2 flooding experimental system.

Sandstone, cm	20×20×2	
Reservoir Temperature, ℃	35	
Fluids MMP @ 35℃, psia	1,062.5	
CO_2 Injection Rate, ml/hr	20	
Well Position in Vertical System	Injection at Bottom	
	Production at Top	
Reservoir Condition	Pressure, psig	Oil Recovery, %
Immiscible	600	20.09
Near-miscible	1,000	75.71

Table 1: Experimental data and results.

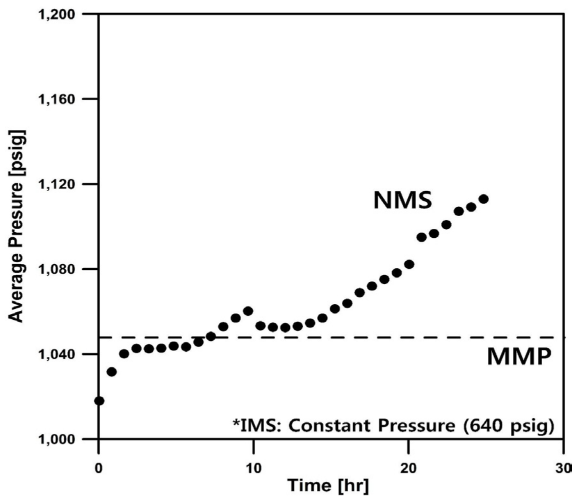

Figure 2: Average pressure at immiscible and near-miscible conditions.

oil reservoir. The experimental conditions are listed in Table 1. The experimental results were illustrated in Figures 2-4.

Figure 2 represents the behavior of the average pressure between inlet and outlet of the reservoir system and Figure 3 presents oil recovery during 25 hours. As shown in Figure 2, in the case of immiscible condition, the average pressure was almost maintained at 640 psig, that is, pressure difference between inlet and outlet is close to zero. However, unlikely the immiscible condition, the average pressure in near-miscible condition is increased and it became above the Minimum Miscible Pressure (MMP). At the early stage of CO_2 injection before 7 hours (0.88 PV injections) in the case of near-miscible condition, even though the oil is immiscibly displaced by the injected CO_2, oil is more produced than the case of immiscible condition because of higher density of CO_2 in near-miscible condition than in immiscible condition. After the MMP reached (7 hours), the CO_2 of gas phase is changing to

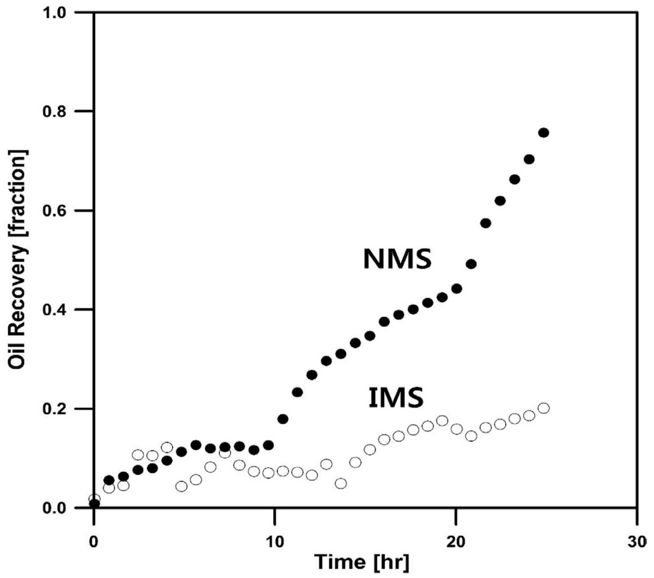

Figure 3: Cumulative oil recovery at immiscible and near-miscible conditions.

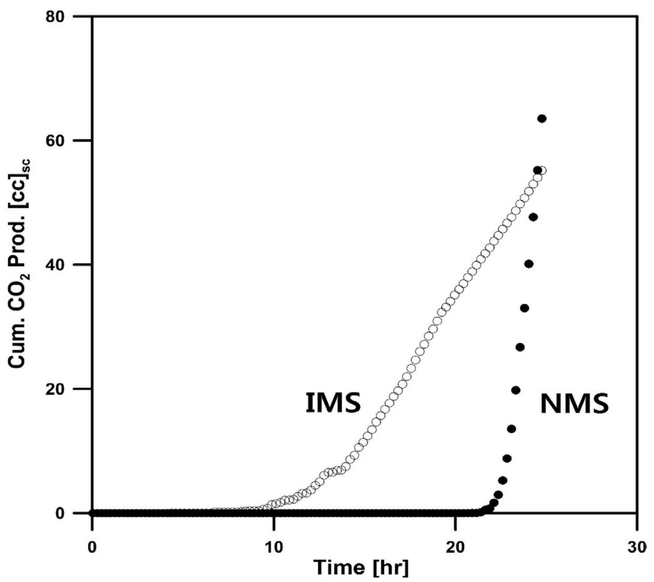

Figure 4: Cumulative CO_2 production at immiscible and near-miscible conditions.

the supercritical state because of increasing in pressure. Therefore, the pressure is slightly decreased due to the decrease in CO_2 volume and oil is more produced due to miscibility. After that time, miscible front is reached at outlet, oil is more rapidly produced together with CO_2 from 22 hours (Figures 3 and 4).

As shown Figure 3, the oil recovery of immiscible condition is 20.09% at 25 hours of CO_2 injection (3 PV). Generally, miscibility may not occur, but there will be significant benefits for oil recovery due to a reduction in interfacial tension and viscosity, and swelling and solution gas effects [14,15]. However, according to these results, oil recovery is very low for the vertical oil reservoir at immiscible condition. These reason is, although some of injected CO_2 dissolved into oil, due to the movement of CO_2 of low density into upper side of vertical reservoir, gravity override of CO_2 leads to displace only oil at upper side. And owing to the generation of CO_2 channel at upper side, oil recovery is found to be very low. Meanwhile, in the near-miscible condition, due to the miscibility effect, oil recovery is 75.71% which is 3.77 times larger than the oil recovery of immiscible condition. This is because, in the case of near-miscible condition, oil production is greatly increased once miscibility reached.

Figure 4 presents cumulative production of CO_2 at immiscible and near-miscible conditions during 25 hours. From the results shown in this figure, practical CO_2 breakthrough times of immiscible condition is 10 hours of injection. The miscible front in near-miscible case is arrived at outlet on 22 hours of injection. Although practical CO_2 producing in near-miscible condition is appeared later, CO_2 starts producing significantly comparing to the immiscible case. Eventually, the injected CO_2 in the near-miscible case is produced more.

Conclusion

In this study, we discussed an experimental study of CO_2 injection process to examine the influence of gravity drainage on the oil recovery for the vertical oil reservoir. From the experimental results at different miscibility conditions, we have drawn the followings: In the case of immiscible condition, CO_2 starts producing much earlier than the one in near-miscible case. This is a reason that as CO_2 immiscibly displaces the oil, CO_2 channel can be generated at upper side because of gravity override of CO_2. Therefore, applying the immiscible CO_2 flooding is ineffective at vertical reservoir. However, in near-miscible case, once practical CO_2 production is appeared, that is, miscibility front is arrived at outlet, CO_2 starts producing much more great than the case of immiscible. Eventually, as results afore-mentioned, oil is recovered in near-miscible condition is significantly larger than the amount of oil in immiscible condition. As a result, we found out that oil recovery at immiscible condition (600 psig) is 20.09% which is significantly less than the one at near-miscible condition (1,000 psig) of 75.71%, in vertical oil system.

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