Effect of Miscibility Condition for CO₂ Flooding on Gravity Drainage in 2D Vertical System

Jinju Han, Joohyang Kim, Junwoo Seo, Hyemin Park, Hyeok Seomoon and Wonmo Sung*
Department of Natural Resources and Environmental Engineering, Hanyang University, Republic of Korea

Abstract
In CO₂ 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 performed in two dimensional vertical sandstone slab, where unstable gravity drainage phenomena can be formed. CO₂ 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 CO₂ 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 CO₂ flooding is ineffective because of gravity override of CO₂ and generation of CO₂ 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; CO₂ flooding; Unstable gravity drainage; 2D vertical sandstone

Introduction
In CO₂ injection process, the densities and viscosities of oil and CO₂ are the main variables determining the gravity drainage that can cause early CO₂ breakthrough. Once the injected CO₂ moves toward top of the reservoir, CO₂ 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 CO₂ 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 CO₂ 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. Nasrabad 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 CO₂ 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 CO₂ injection experiments have been conducted at immiscible and near-miscible conditions in two dimensional vertical sandstone plates.

Laboratory Study

2D CO₂ 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 CO₂ 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 CO₂ at constant flow rate. The produced fluids are separated at separator, then oil and CO₂ 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 CO₂ and normal decane is about 1062.5 psia at 35°C which were determined using commercial PVT software, i.e. CMG-WINPEP. CO₂ 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 CO₂ flooding process, we conducted the experiments for Immiscible (IMS) and Near-Miscible (NMS) conditions in vertical
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 CO₂ 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 CO₂, oil is more produced than the case of immiscible condition because of higher density of CO₂ in near-miscible condition than in immiscible condition. After the MMP reached (7 hours), the CO₂ of gas phase is changing to

| Sandstone, cm          | 20 X 20 X 2 |
|------------------------|-------------|
| Reservoir Temperature, °C | 35          |
| Fluids MMP @ 35°C, psia | 1,062.5     |
| CO₂ 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.
gravity override of CO₂ leads to displace only oil at upper side. And owing to the generation of CO₂ 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 CO₂ at immiscible and near-miscible conditions during 25 hours. From the results shown in this figure, practical CO₂ 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 CO₂ producing in near-miscible condition is appeared later, CO₂ starts producing significantly comparing to the immiscible case. Eventually, the injected CO₂ in the near-miscible case is produced more.

Conclusion

In this study, we discussed an experimental study of CO₂ 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, CO₂ starts producing much earlier than the one in near-miscible case. This is a reason that as CO₂ immiscibly displaces the oil, CO₂ channel can be generated at upper side because of gravity override of CO₂. Therefore, applying the immiscible CO₂ flooding is ineffective at vertical reservoir. However, in near-miscible case, once practical CO₂ production is appeared, that is, miscibility front is arrived at outlet, CO₂ 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.

Acknowledgement

This research was supported by the Energy Efficiency & Resources of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by Korea Government Ministry of Knowledge Economy. (No. 2012T100201728).

References

1. Asghari K, Torabi F (2008) Effect of Miscible and Immiscible CO₂ Injection on Gravity Drainage: Experimental and Simulation Results. Society of Petroleum Engineers.
2. Torabi F, Asghari K (2010) Effect of Conrate Water Saturation, Oil Viscosity and Matrix Permeability on Rate of Gravity Drainage During Miscible and Miscible Displacement Tests in Matrix-Fracture Experimental Model. J Can Petrol Technol 49: 61-68.
3. Trivedi JJ, Babadagli T (2010) Experimental Investigations on the Flow Dynamics and Abandonment Pressure for CO₂ Sequestration and Oil Recovery in Artificially Fractured Cores. J Can Petrol Technol 49: 22-27.
4. Trivedi JJ, Babadagli T (2008) Experimental Analysis of CO₂-Sequestration Efficiency During Oil Recovery in Naturally Fractured Reservoirs. Society of Petroleum Engineers.
5. Kulkarni MM, Rao DN (2005) Experimental Investigation of Miscible Secondary Gas Injection. SPE Annual Technical Conference and Exhibition, 9-12 October, Dallas, Texas.
6. Nasrabadi H, Firoozabadi A, Ahmed TK (2009) Complex Flow and Composition Path in CO₂ Injection Schemes from Density Effects in 2 and 3D. SPE Annual Technical Conference and Exhibition, 4-7 October, New Orleans, Louisiana.
7. Sung WM, Lee YS, Kim KH, Jang YH, Lee JH, et al. (2011) Investigation of CO₂ behavior and study on design of optimal injection into Gora-

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

Figure 4: Cumulative CO₂ production at immiscible and near-miscible conditions.
8. Al Otaibi MF, Funk JJ, Kokal SL, Al-Mutairi MS, Al-Qahtani J (2012) Best Practices for Conducting CO₂-EOR Lab Study. SPE EOR Conference at Oil and Gas West Asia, 16-18 April, Muscat, Oman.

9. Lee Y, Kim K, Sung W, Yoo I (2010) Analysis of the Leakage Possibility of Injected CO₂ in a Saline Aquifer. Energ Fuel 24: 3292-3298.

10. Moortgat J, Firoozabadi A, Li Z, Esposito R (2013) CO₂ Injection in Vertical and Horizontal Cores: Measurements and Numerical Simulation. Soc Petrol Eng J 18: 331-344.

11. Lee YS, Kim KH, Lee TH, Sung WM, Park YC, et al. (2009) Analysis of CO₂ Endpoint Relative Permeability and Injectivity by Change in Pressure, Temperature, and Phase in Saline Aquifer. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects 32: 83-99.

12. Rashid A, Liu K, Sayem T, Honari A, Clennell MB, et al. (2013) Laboratory Investigation of Factors Affecting CO Enhanced Oil and Gas Recovery. SPE Enhanced Oil Recovery Conference, 2-4 July, Kuala Lumpur, Malaysia.

13. Arshad A, Al-Majed AA, Menouar H, Muhammadian AM, Mtwaa B (2009) Carbon Dioxide (CO₂) Miscible Flooding in Tight Oil Reservoirs: A Case Study. Kuwait International Petroleum Conference and Exhibition, 14-16 December, Kuwait City, Kuwait.

14. Mackay V (1994) Determination of oil and gas reserves. Petroleum Society of the Canadian Institute of Mining, Metallurgy and Petroleum Canada.

15. Ghedan S (2009) Global Laboratory Experience of CO₂-EOR Flooding. SPE/EAGE Reservoir Characterization and Simulation Conference, 19-21 October, Abu Dhabi, UAE.