Jurnal
Teknologi

Full Paper

Effect of Low Temperature CO_2 Injection in High Temperature Oil Reservoirs Using Slimtube Experiment

Article history
Received
1 June 2015
Received in revised form
3 September 2015
Accepted
12 December 2015

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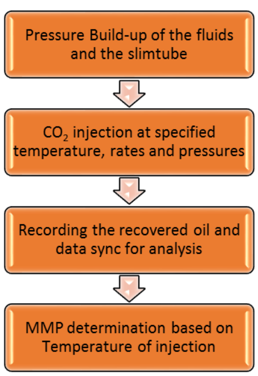
Graphical abstract



Abstract

A set of slimtube experiments is designed and presented to study the effect of cold temperature CO_2 on recovery factor in reservoirs with high temperature. The comparison of the results indicates the positive effect of temperature on recovery trend in early stage as well as ultimate recovery in different injection pressures. The approach is based on a long slimtube to show the effect of temperature on the recovery. The study considers different temperatures and pressures of injection and reservoir allowing both miscible and immiscible flooding of CO_2. Using non-isothermal conditions, the results show that, lowering temperature of injection can yield in higher recovery in early stage significantly. Also, considering ultimate recovery, it is observed that low temperature CO_2 injection into high temperature reservoir can result in slightly higher recovery factor than isothermal injection. The reason for recovery increase is mainly due to elimination of the interfacial tension between CO_2 and reservoir fluids especially near the injection point. Another finding is that the minimum miscibility pressures is lowered by means of lowering the temperature of injection which is again caused by elimination of interfacial tension between CO_2 and oil. This is important because forming a single phase can increase the ability of CO_2 to extract different components of the crude oil as well as lowering viscosity of the mixture, resulting in a better sweep efficiency. It appears that using liquid CO_2 in high temperature reservoirs can be a promising method for better oil recovery in high temperature reservoirs.

Keywords: CO_2 injection, Slimtube Displacement, Enhanced Oil Recovery

1.0 INTRODUCTION

For the past decades, CO_2 flooding has proven to be an acceptable tertiary recovery method in enhanced oil recovery (EOR) [1-3]. CO_2 causes a massive viscosity reduction due to component exchange between oil and CO_2 [4-10].

During tertiary recovery by CO_2 injection, the miscibility between the gas and oil has become a major point of interest in gas flooding mechanisms. Reaching miscibility has been considered as an optimized scheme for injection purpose. In thermodynamics, when two or more than two fluids form a single phase at any proportion mixed, they are said to be miscible at the pressure and temperature of the fluids.

As a result, the interface between the fluids vanishes, or on the other words, the interfacial tension (IFT) reaches zero.

If the fluids form a single phase at any proportion in their first contact, it is categorized as first contact miscibility (FCM). In the meantime, reaching miscibility after several contacts between the fluids is considered as multi-contact miscibility (MCM). Formation of single phase mixture is based on vaporizing/condensing gas drive mechanisms which are not of the main interest of this study. In a CO_2 flooding, first the CO_2 dissolves in the oil phase and some of the oil vaporizes into the gas phase. The dissolution mechanism of the CO_2 causes swelling of the oil, resulting in reduction of its viscosity. Multiple contacts between these two fluids in desired thermodynamic condition may form a single phase resulting in miscible displacement mechanism. If the displacement becomes fully miscible, a high recovery of the oil may occur up to 95% depending of the oil properties.

The miscibility is based on composition of the fluids, pressure and temperature. Considering CO_2 as the gas flooding agent with constant crude oil composition, the miscibility can be achieved by altering pressure and temperature. Traditional approach was only to increase the pressure when using CO_2 flooding. But effect of temperature was not considered to be effective in large scale.

The minimum miscibility pressure (MMP) is the pressure in which above that, the fluids will form a single phase. Since FCM usually needs much higher pressure than MCM, the MMP will be the minimum pressure to achieve MCM. Lately, the MMP is considered as of high importance in related industry. Several methods of MMP determination were introduced including numerical, analytical and experimental procedures. Numerical methods include slimtube simulations and different cell models [11, 12]. Characteristics of the fluids were the base of calculations for analytical methods [13]. Some empirical methods are available in the literature that are predictions based on different correlations [14-16]. Finally, several experimental methods were introduced in early 80s, which were considered as standard MMP prediction method, including slimtube experiments [17], rising bubble technique [18] and vanishing IFT experiment [19].

Slimtube is a stainless steel cylindrical tube with about ¼ inch width and 16-60 ft length. Small uniform sand or glass beads are packed inside the slimtube, giving a reasonable porosity to the tube. The slimtube is being heated by oven. At first, the slimtube is filled with single phase crude oil with desired pressure and then the fluid is displaced by gas flooding method having a small and constant injection rate (equivalent to 1-3 ft/day for a total of 1.2 PV). The pressure is fixed usually by a back pressure regulator at the end of the slimtube. The slimtube is designed to create an environment where viscous fingering is almost eliminated by transverse dispersion [20]. This is due to very high ratio of length over diameter of the slimtube.

The miscibility is determined by performing the procedure at different injection scheme (generally different pressures are considered) and ultimate recoveries are recorded. The recovery is then plotted against the pressure and the MMP is determined by the curve obtained.

Previous studies have mainly focused on the pressure and composition of the oil to achieve miscibility, while another important factor is the temperature. Reduction of temperature can highly lower the MMP. A few studies have tried to consider this matter [17]. Generally, the studies considered isothermal conditions for the slimtube experiments, while a few recent studies showed that using cold CO_2 injection (less than critical point of CO_2 i.e. 88 °F) in high temperature reservoir (above 100 °F) may lead to a better efficiency and the MMP is expected to be dropped significantly [21, 22].

Low temperature CO_2 can be of great importance since liquid CO_2 has a selectivity criteria which can have component exchange with crude oil up to C30. The critical temperature of CO_2 is at 31.1 °C and below that temperature CO_2 will be in liquid form while the pressure is kept above 1100 psi. A few simulation studies were done to prove the possible benefits of low temperature CO_2 injection, but no solid experimental work is found using non-isothermal conditions [23].

For this study, a set of slimtube experiments is designed and presented to predict the effect of cold temperature CO_2 on recovery factor in high temperature reservoirs.

2.0 EXPERIMENTAL

2.1 Materials

The crude oil used in the experiments is taken from a Malaysian oil field. The API gravity for this oil is recorded as 35° and the molecular weight (MW) is 296.1 g. The gas injected in the slimtube is purified 99.99% CO_2 supplied by MOX. Toluene is also used as cleaning agent for the process.

Table 1 Slimtube physical properties

Entry	Parameter	Amount
1	Total length	12.19 m (40 ft)
2	Porosity (Φ)	35%
3	Outside Diameter	6.35 mm
4	Inner Diameter	3 mm
5	Pore Volume (PV)	37.2 ml
6	Dry weight	3070 g

2.2 Apparatus

The setup provides the operator with a computer controlled system for MMP determination. The device model used is MMP-100. It includes an oven containing accumulators filled with CO_2, Toluene (as scrubbing fluid) and the crude oil sample stored at specified user temperature, representing the reservoir. An extra accumulator is located outside of the oven and filled by liquid CO_2 for related experiments. The device also contains a sand packed coil of stainless steel tubing to be charged with reservoir fluid. A computer controlled injection pump is placed to control the fluid injection process based on flow rate or constant pressure injection. A back pressure regulation system is also used to provide a pressure controlled system at the end of the slimtube (sand packed coil). The whole system is controlled through a PC based workstation.

The modification that has been applied to this device in this study is the recording of the recovered oil amount in real-time by means of a weight balance and a recording camera. By the end of each experiment, the data recorded is entered manually in addition to the PC recorded data.

The sand pack column (slimtube) length is 40 ft packed with 80-120 mesh Ottawa sand contained by 325 mesh stainless steel screens at both ends. The details are as shown in Table 1.

2.3 Experimental Procedure

The experimental procedure for the slimtube consists of four parts. At first, the slimtube must be cleaned up and make sure no fluids are inside. The weight must be checked and compared with the dry weight to ensure no fluids are kept inside. Then, the accumulators must be filled with crude oil, toluene and CO_2. The third part is the main experimental run, which is the slimtube filled with the oil. The pressure is then risen to the desired pressure. Then CO_2 is injected and the produced crude oil is recorded. The last part is the clean-up after each run to ensure no residue oil or asphaltene is present. This step includes several toluene flushing as cleaning agent followed by CO_2 flooding as drying agent. After 2-3 cyclic runs, the slimtube is to be put in the oven for drying.

The flow rate of the CO_2 injection is 0.0125 ml/min for the first 30 minutes. The rate increased to 0.025 ml/min for an hour. The rate is increased to 0.05 ml/min for at least 10 hours to ensure the injection of a minimum 1.2 PV of CO_2.

Several experiments are done based on different pressure and temperature and the recovery is recorded simultaneously which are presented and analyzed in the next section.

3.0 RESULTS AND DISCUSSION

Several runs of CO2 injection in the slimtube is done, aiming at the recovery trend in different pressure and temperature.

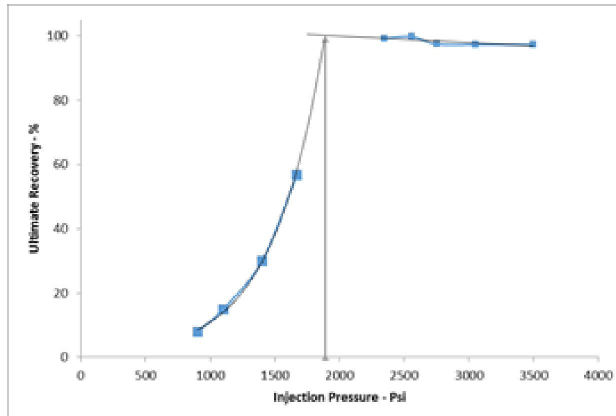


Figure 1 Determination of MMP in Isothermal Displacements (60 °C)

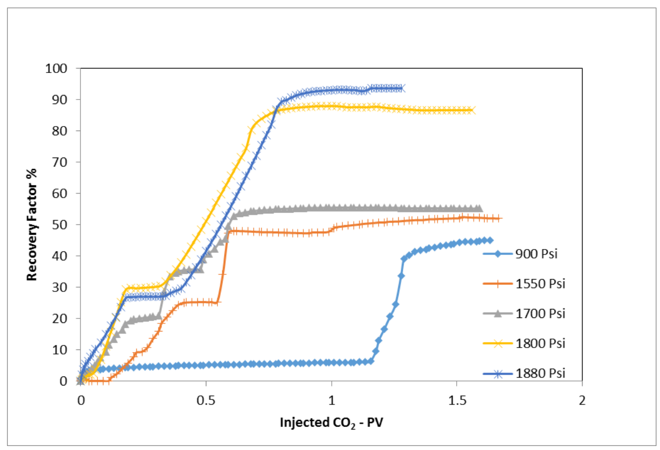


Figure 2 Recovery of Crude Oil vs. Pore Volume of Injected CO2 in Isothermal Injection Displacements

For the first set of runs, the built-in accumulators inside the oven are used. The temperature was kept constant at 60 °C. The pressure range was from 900 to 3500 psi, to make sure that it covered both immiscible and miscible regions.

Figure 1 shows the ultimate recovery in each run according to the injection pressure. According to the figure, two trend lines were identified. The intersection of these two lines is interpreted as the MMP of this crude oil that recorded as 1890 psi.

Each of these experiments were closely monitored by the weight balance and a recorder. The recovery trend in each of this set of experiments is shown as Figure 2. Only one of the pressures below the MMP is presented as the rest of them are showing the same trend. Several fluctuations were observed that is mainly due to presence of heavy hydrocarbons in the crude oil (up to C68) and non-uniformity of the packed sand inside the slimtube.

For immiscible region where the pressure was 1670 psi, it is observed that the major production was after injection of ¼ of pore volume and the production was recorded less than 60%. This is normal since no miscibility was formed between the two phases.

The next point was 2350 psi, which can be categorized as near-miscible to miscible region. No major production was observed until after 1 PV of injection. The recorded recovery factor shows that in near-miscible region, longer time for MCM is needed, but the ultimate recovery is as miscible flooding.

In the miscible region, four pressures were tested that are 2555, 2750, 3050 and 3500 psi. The first three show the same high recovery factor in the beginning of the injection that proves the miscibility between crude oil and CO_2. At very high pressure, the recovery rate was almost constant along with CO_2 injection. This can be interpreted as semi-FCM between the phases which results in highest recovery, but along with injection rate.

For the second part of experiments, the outside accumulator was used containing 24 °C Liquid CO_2. The oven temperature was kept at 60 °C. The pressures tested in this set of displacements were less than the MMP obtained from the first part. The reason was that lowering the temperature may decrease the MMP but surely not increasing it. The recovery trend is shown in Figure 3.

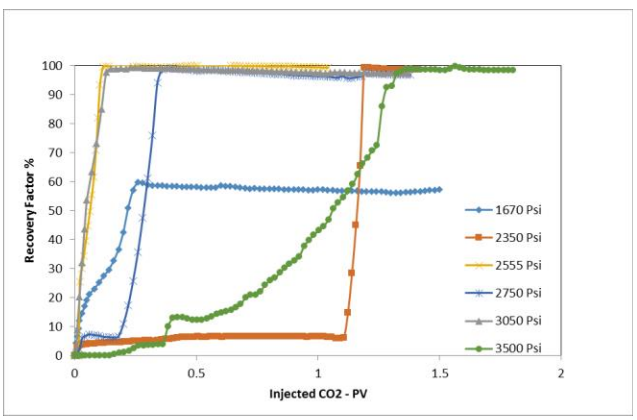


Figure 3 Recovery of Crude Oil vs. Pore Volume of Injected Liquid CO_2 in Thermal Displacements

At 900 psi injection, the recovery was negligible till almost 1.2 pore volume (reference injection amount for MMP determination) was injected, after that a slight increase was observed. In 1550 and 1700 psi, the recovery was recorded about 50%, showing immiscible conditions.

Miscible displacement was observed at 1800 and 1880 psi. The recovery rate was constant, along with the liquid injection of CO_2. This shows that although the slimtube temperature was the same, the injection temperature can make a difference in the miscibility in early time.

The miscibility is calculated using the results and plotting as Figure 4. As shown the behavior of thermal displacement is different than isothermal mode. The lower trendline for MMP determination is happening close to the miscible region, making it difficult to plot. Since the intersection of the trendlines of immiscible and miscible region must take place at ultimate recovery above 85%, the miscible trendline can be extended up to that point. In this set of experiments, the MMP is calculated as 1770 Psi, which is 120 Psi lower than Isothermal injection. This result is in tally with previous findings although they were at rough simulation stage [21].

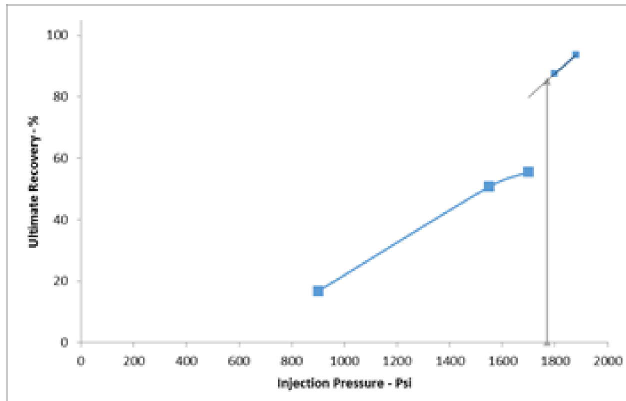


Figure 4 Determination of MMP in Thermal Displacements (24 °C Injection in 60 °C Slimtube

The reason for MMP reduction can be mainly due to viscosity ratio of the two phases which it lowers the mobility ratio. This will result in elimination of interfacial tension and better sweep. Also, the expansion of the CO_2 inside the porous media will cause the oil trapped inside to get connected and lower residual oil is observed. Because of this matter, the recovery rate was almost constant as the sweep was taking place smoothly, unlike the immiscible injection that was in sudden form.

The novelty of slimtube usage in this condition resulted in the ability to represent the reservoir in much higher length than regular core flooding systems considering the limitations. This method can be further investigated by other displacement experiments such as core flood. The behavior of liquid CO_2 can be monitored by micromodel displacements. Verifying this method of displacement can yield to implementation in field scale.

4.0 CONCLUSION

A set of slimtube experiments is designed and presented to study the effect of cold temperature CO_2 on recovery factor in reservoirs with high temperature. The comparison of the results represents the effect of temperature on recovery trend in early stage as well as ultimate recovery in different injection pressures.

The results confirm that lowering the temperature of injection will have impact on MMP even considering high temperature reservoirs. The MMP is lowered significantly by using low temperature CO_2 although the slimtube was kept at high temperature. Also, this temperature difference can cause uniform recovery rate especially at early stage. Based on these findings, it seems that using liquid CO_2 in high temperature reservoirs can be a promising method for elimination of interfacial tension, which results in a better sweep efficiency.

Acknowledgement

Authors would like to thank Center of Research in Enhanced Oil Recovery, Universiti Teknologi PETRONAS for the experimental and assistantship support. Also, they would extend their thanks to Yayasan Universiti Teknologi PETRONAS for funding the project.

Nomenclature

MW: Molecular Weight, g

P: Pressure, Psi

PV: Pore Volume

T: Temperature, °F

Φ: Porosity, %

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