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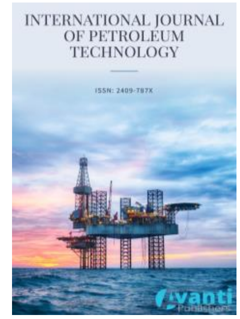

Feasibility of CO_2 Injection for Enhance Oil Recovery: A Case Study in the KMJ Layer of HKY Field

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ABSTRACT

Carbondioxide (CO_2) injection is a very effective and proven technology for enhanced oil recovery (EOR). Minimum miscibility pressure (MMP) and oil swelling are two important factors of the CO_2 gas displacement mechanism that occurs in the reservoir when CO_2 injection is applied to enhance oil recovery. In this study, MMP determination between crude oil samples and CO_2 gas has been conducted using three methods, i.e., empirical equation, correlations method, and laboratory experiment using slimtube. The determination of the swelling factor was conducted using a PVT cell, where recombined fluid is injected at the reservoir temperature. The MMP value from the empirical equation (2810 psig) is relatively close to the MMP value from the laboratory experiment (2807 psig), with a difference of 3 psig. The swelling test results show that the bubble point pressure and the swelling factor increase from 410 psig to 2200 psig and from 1.0 to 1.442, respectively, as the CO_2 gas injection reaches 46.82% mole. Since the fracture pressure of the KMJ Layer in the HKY Field is 2200 psig and the MMP is 2807 psig, only immiscible CO_2 flooding can be applied in the field because the CO_2 MMP is higher than the fracture pressure.

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1. Introduction

The success of carbondioxide (CO_2) injection depends heavily on several parameters, such as the injection pressure, oil swelling, wettability, interface tension, rock permeability, viscosity ratio, °API of oil, fluid saturation, and reservoir heterogeneity [1]. Some research about CO_2 has been conducted by previous researchers in terms of feasibility studies, [2-6], technical studies [7, 8], and laboratory experiments [9]. From those studies, it can be concluded that the main factors causing success in CO_2-EOR include the decrease in oil viscosity [8-11], oil volume expansion [1,12-14], oil extraction and evaporation [9,15,16], injection pressure [1,16-19], and solution gas drive [17, 20].

In order to support the feasibility of applying CO_2 gas injection in the field, it is necessary to determine the minimum miscibility pressure (MMP) and swelling factor between oil samples with CO_2 gas as the injected fluid. Miscibility is described as the ability of two or more substances to form a single homogeneous phase when mixed in all proportions. Miscibility is also defined as a physical condition between two or more liquids that allows them to be mixed in all proportions in the absence of a contact interface. If two liquid phases are formed after the addition of one liquid, then the liquids are considered immiscible [21, 22]. If the miscibility condition is achieved in the injection process above the minimum miscibility pressure, then the pressurization will be efficient, and an optimal increase in oil recovery is obtained, however, pressurization below the minimum miscibility pressure can still increase oil recovery significantly.

Based on reservoir characteristic parameters in the initial screening and CO_2 source availability in the field, the KMJ Layer of the HKY Field [2], then be chosen for CO_2 injection. The study presented in this paper is a fundamental aspect of laboratory study related to the application of CO_2 injection (flooding) in the KMJ Layer of the HKY Field. The screening criteria, determination of minimum miscibility pressure (MMP), swelling test analysis to determine the swelling factor, and observation of oil recovery increase on slimtube at several injection pressures below and above MMP using continuous CO_2 gas injection mechanism were discussed.

2. Fundamental Concept and Methods

CO_2 injection involves injecting CO_2 into a reservoir through an injection well to displace oil in the reservoir towards the production wells. CO_2 is a stable molecule with one carbon atom and two oxygen atoms. It has a molecular weight of 44.01, a critical temperature of 87.8 0F, and a critical pressure of 1071 psig [12]. CO_2 is used as an injection gas for several reasons: it is easy to obtain and relatively cheap compared to other gases; it is miscible with oil and water; it can produce 60 - 90 % of OOIP [1], and it can act as a flooding agent - a miscible substance that can act as a displacing fluid [9, 23].

According to Stalkup [1, 21, 22], the mechanism of CO_2 injection in the reservoir includes oil swelling (due to the high solubility of CO_2 in oil), oil viscosity reduction (more effective than N_2 or CH_4), interfacial tension reduction between oil and CO_2/oil phase at the miscible zone, and miscibility creation when the injection pressure is high enough (greater than the MMP).

The CO_2 source for the injection process is an important parameter to consider regarding the injection volume required for the CO_2 injection program. The CO_2 source should be relatively pure since some gas components such as methane can increase the MMP, and other gas components such as hydrogen sulfide are dangerous, smelly, and cause serious environmental problems. The best CO_2 source can be the CO_2 that is produced from a production well or a gas plant. Other sources are the stock gas from coal-fired plants; acid gas separation from oil fields - as exhaust gas from power plants; limestone calcination facilities; waste products from cement factories; and gas released from an ammonia plant [1, 9].

2.1. Screening Criteria

The screening criteria for selecting the best EOR method for an oil field is based on the implemented technology case, which is the current implied technology or at least has been proven applicable in an oil reservoir

[24]. The technology includes immiscible flooding, miscible flooding, chemical injection, and thermal methods. There may be several EOR methods that are applicable in one oil reservoir. To determine the optimal method that technically and economically maximizes oil recovery, further research of laboratory study, mathematical model (simulation), and pilot test on the field is required. The screening criteria based on a study by Taber *et al*. [24], are applicable for homogenous reservoirs. However, for a heterogenous reservoir with fractures, faults, lateral discontinuity, or an oil reservoir with a gas cap, the reservoir heterogeneity may affect the performance of the EOR method and require more study [9].

According to Taber *et al*. [24], the parameters that influence the selection of the EOR method can be classified into two groups: oil physical properties (oil gravity, oil viscosity, and oil composition) and reservoir characteristics (oil saturation, reservoir lithology, net sand thickness, porosity, permeability, reservoir depth, and reservoir temperature). Meanwhile, the reservoir brine properties such as salinity and solids content are used as supplementary parameters.

2.2. Minimum Miscibility Pressure (MMP)

Minimum miscibility pressure (MMP) is very important for making the right CO_2 injection design. The highest oil recovery can be achieved if the CO_2 flood happens in a miscible condition. To achieve that condition, the injection pressure must be greater than a certain minimum. MMP is the minimum displacement pressure where gas and oil become completely miscible through a multi-contact mechanism or a dynamic miscibility process. This minimum pressure is hereafter defined as the MMP [1, 21]. Another author defines MMP as the lowest pressure at which the CO_2 injection fluid can develop miscibility with reservoir crude oil at reservoir temperature [19]. In the dynamic miscibility process, the injected gas vaporizes the intermediate component of hydrocarbon in the crude oil according to the vaporizing gas drive mechanism [1].

The MMP can be obtained in three ways, i.e., equation of state, correlations, and laboratory experiment [1]. The empirical MMP is determined by the equation proposed by Stalkup [1] as follows:

$$MMP = -329.558 + (7.727 \times MW \times 1.005^{T}) - (4.377 \times MW) \tag{1}$$

where:

$$T = 0.015\ Depth + 77.45 \tag{2}$$

$$MW = \text{Molecule Weight of } C_{5+}$$

$$MW = \left(\frac{7864.9}{G}\right)^{\frac{1}{1.0386}} \tag{3}$$

$$G = \text{Oil Gravity } (^{0}API)$$

The correlations between oil and gas for MMP determination have been developed by several researchers such as Holm and Josendal [17], Yellig and Metcalfe [18], Mungan [19], Yellig [16] also Stalkup [1]. These correlations relate the MMP to the temperature, light fluid components (C_1, N_2, CO_2), intermediate components (C_2-C_6), C_5-C_{30} contain, impurities (N_2 and H_2S), C_{7+} molecule weight, oil molecule weight, oil density, and the oil type (aromatic, naphthenic, paraffinic). It can be concluded that each correlation has a different variable. Therefore, the correlation used should match the oil composition and the oil type in the correlation.

Alomair *et al*. [25] and Hakim *et al*. [26], explain that the correlation for predicting the MMP should be a function of thermodynamic properties, or physics that affect the fluid miscibility and should be related to multiple contact miscibility processes. However, correlation reliability is usually limited to the range of compositions used when the correlation was developed. None of these correlations provide adequate emphasis on oil composition and properties and all fail to predict the MMP accurately for different types of oil.

MMP can also be determined by performing a laboratory experiment using a slimtube apparatus [1]. The slimtube as shown in Fig. (**1**), simulates a displacement process, where the oil displacement depends on phase behavior. Crude oil is placed in the slimtube and then displaced by gas at a certain pressure. After the displaced volume reaches 1.2 of the gas pore volume, the oil production is calculated as the recovery factor. If a higher pressure does not result in a significant increase in oil recovery, then the pressure is considered as the MMP [1].

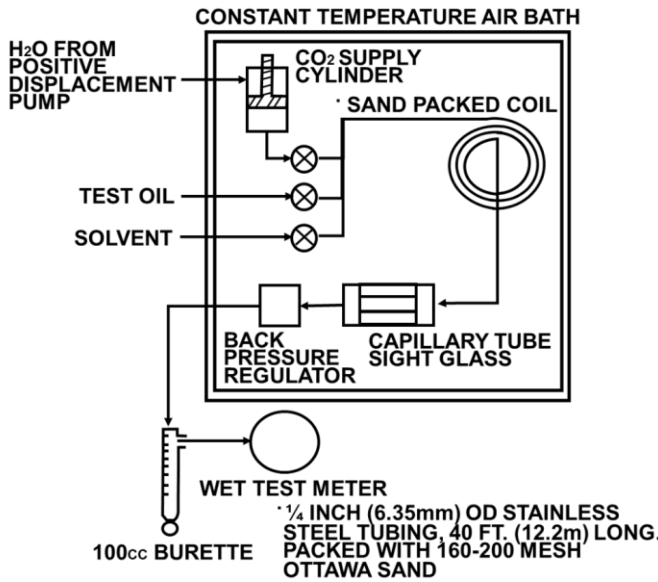

Figure 1: Schematic of slimtube apparatus (After Stalkup1983) [1].

In the study, Stalkup [1] uses a slimtube filled with quartz sand with a length of 1890 cm, a tube diameter of 0.639 cm, a porosity of 25.7%, a permeability of 15.803 darcies, and a pore volume of 155.838 cc at 120 ºC. The slimtube is also filled with crude oil with the composition of H_2S, CO_2, N_2, C_1, C_2, C_3, i-C_4, n-C_5, C_6, and C_{7+}, and the displacement pressures are varied from 1200 to 1500 psig. The oil recovery from CO_2-oil displacement at each pressure is shown in Fig. (**2**).

Fig. (**2**) shows that the oil recovery increases with displacement pressure when the pressure is below MMP, both at breakthrough, 1.2 PV displacement, and blowdown. However, for displacement at or above MMP, the oil recovery does not increase significantly with more pressure. This happens at breakthrough, 1.2 PV displacement, and blowdown. Therefore, the MMP is determined as 1380 psig. Beyond this pressure, the additional pressure only slightly increases the oil recovery.

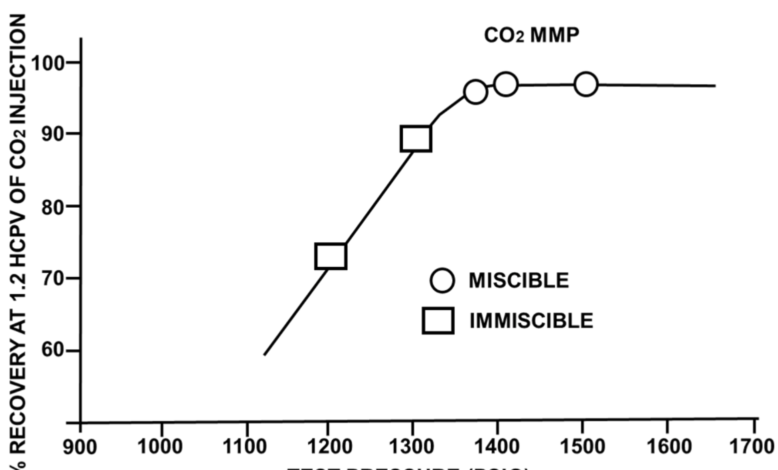

Figure 2: MMP determination on CO_2-Oil displacement (After Stalkup 1983) [1].

2.3. Swelling Factor

The swelling test, originally proposed by Hand and Pinczewski [27], is a method used to determine the amount of additional oil volume when injected with CO_2. Oil volume expands when CO_2 gas dissolves in it. The swelling factor quantifies this expansion as the ratio of the CO_2-saturated oil volume to the initial oil volume before CO_2 dissolution. If the swelling factor exceeds one, it indicates volumetric expansion [12]. Wellker and Dunlop [12] proposed the following equation for the swelling factor:

$$\text{Swelling Factor} = \frac{Volume\ at\ saturation\ pressure\ and\ temperature}{Volume\ at\ 0.1\ mPa\ and\ temperature} \quad (4)$$

Particularly, according to Wellker and Dunlop [12], pressure and temperature also affect the swelling factor. Simon and Graue [13] suggested that the swelling factor depends on the mole fraction of CO_2 in the oil (XCO_2) and the molecular weight density ratio (M/ρ) of the oil. The swelling test method was later developed to determine the MMP by Tsau *et al*. [28] and Abdurrahman *et al*. [29], where MMP is determined at the intersection between the extraction condensation and the extraction stages.

3. Results and Discussion

3.1. Screening Criteria of KMJ Layer

The feasibility of CO_2 injection in the KMJ Layer of the HKY Field is evaluated by mapping the reservoir characteristics, which are summarized in Table **1**. These characteristics include reservoir rock properties, reservoir fluid properties and chemistry, and reservoir conditions. They provide the basis and input for laboratory studies and reservoir simulation of CO_2 injection in the KMJ Layer, both for pilot projects and full-scale applications.

Table 1: Reservoir characteristics in the KMJ Layer of HKY Field.

Reservoir Characteristics	Values
Reservoir Rock Properties	
Type of Lithology	Limestone
Porosity (%)	15 – 24
Oil Saturation (% PV)	56.2
Permeability (mD)	6 – 45
Thickness (ft)	6.8
Well Depth (ft)	3932
Temperature (˚F)	202
Reservoir Fluid Properties	
Oil Gravity (˚API)	34.52
Oil Viscosity (cp)	2.46
Oil Composition	C_1 - C_{7+}

The EOR screening criteria of Taber *et al*. [22] are applied to the KMJ Layer of the HKY Field to select the most suitable EOR methods based on oil and reservoir characteristics. The screening results for KMJ Layer are presented in Table **2**. According to Table **2**, CO_2 injection is a feasible EOR method for the KMJ Layer of the HKY field, with CO_2 miscible flooding scoring 30 and CO_2 immiscible flooding scoring 29.

CO_2 injection involves injecting a certain amount of CO_2 (30% or more of hydrocarbon PV) into the reservoir. CO_2 does not mix with oil immediately but after multiple contacts. CO_2 extracts light-to-medium hydrocarbon components and forms a mixture that displaces oil films from the rocks at high enough pressure. Reservoirs shallower than 1,800 ft are not eligible for miscible CO_2 injection according to the technical screening criteria.

Table 2: Screening criteria result of KMJ layer in HKY field.

Reservoir Characteristics	KMJ Layer of HKY Field	Immiscible Flood		Miscible Flood		Chemical Injection			Thermal Injection	
		Water Flooding	Gas Flooding	CO2	N2 (Inert Gas)	Surfactant	Alkaline	Polymer	Steam Flooding	Insitu Combustion
Reservoir Characteristics										
Type of Lithology	Limestone	Sandstone and Limestone	Sandstone and Limestone	Sandstone or Limestone with minimum	Sandstone or Limestone with minimum	Sandstone (more prefer)	Sandstone (more prefer)	Sandstone (more prefer)	Sandstone	Sandstone
Porosity, %	15 - 24	>10	>10	NC	NC	>15	NC	>15	High Porosity	High Porosity
Oil Saturation (%PV)	56.2	>30	>20	>20	>40	>35	>35	>50	>40	>50
Permeability, mD	6 - 45	>10	NC	NC	NC	>10	>10	>100	>200	>50
Thicknes, ft	6.8	NC	NC	Relatively thin, unless formation dip is low	Relatively thin, unless if formation dip is high	NC	NC	NC	>20	>10
Well Depth, ft	3932	NC	>1800	>2500	>6000	<8000	<9000	<9000	<11500	>4500
Temperature, °F	202	NC	NC	NC	NC	<175	<200	<200	NC	>100
Reservoir Fluids Properties										
Oil Gravity, °API	34.52	>20	>12	>22	>35	>20	>20	>15	8-13.5	>10
Oil Viscosity, cp	2.46	<35	<600	<10	<0.4	<35	<35	<150	<20000	<5000
Oil Composition	C1 - C7+	NC	NC	High percent of C5 to C12	High percent of C1 to C7	Light to Intermediate	Light to Intermediate	NC	NC	Some Asphaltic Component
Total Score		**30**	**29**	**30**	**22**	**24**	**23**	**19**	**16**	**14**

Noted score: Red = 1; Yellow = 2; Green = 3

Furthermore, oil reservoirs with API gravity greater than 22 ˚API, are eligible for immiscible CO_2 injection, where the injection pressure is lower than the minimum miscibility pressure (MMP). Immiscible CO_2 flooding is usually less effective, but it can still improve oil recovery compared to water injection. Moreover, a CO_2 gas source with high quality is essential, which has negligible or no water (H_2O) or dry gas content.

3.2. Minimum Miscibility Pressure (MMP) Determination

Minimum miscibility pressure (MMP) is defined as the minimum pressure at which injected gas and oil become completely miscible. Oil samples are obtained from Well J-151, which operates in the KMJ Layer, where oil samples are taken following the standard practice for the manual sampling of petroleum and petroleum products - ASTM D 4057 [30]. The production zone of Well J-151 has a depth of 3932 ft, reservoir pressure of 1710 psig, temperature of 202 ˚F, formation fracture pressure of 2200 psig, and API gravity of 34.52 ˚API. Therefore, three methods are employed to determine the MMP of Well J-151 oil samples using CO_2 gas, namely empirical equation, correlations, and slimtube laboratory experiments.

The empirical equation (Equation 1) yields an MMP of 2810 psig, while Table **3** shows the MMP values obtained from various correlations, such as Cronquist's correlation [1], Yellig and Metcalfe correlation [18], and Holm and Josendal correlation [17].

Table 3: MMP determination results of oil sample Well J-151 in KMJ Layer based on correlations.

Correlations	Minimum Miscibility Pressure, psig
Cronquist (Stalkup, 1983)	2303
Yellig and Metcalfe (1980)	2494
Holm and Josendal (1974)	2756

The laboratory experiment of MMP determination is conducted using a slimtube with a length of 1890 cm and a diameter of 0.64 cm, filled with quartz sands with a permeability of about 1 Darcy, and placed inside a heater oven. Fig. (**3**) shows the MMP determination using a slimtube in the laboratory, and the procedures are as follows:

- The slimtube is saturated with 160 cc of crude oil at a similar pressure condition as the MMP determination.
- The recombined fluids from the oil sample of Well J-151 are injected into the slimtube at a pressure above the bubble-point pressure.
- CO_2 is injected into the slimtube at a similar pressure and all the crucial parameters that occur during the experiment are recorded or measured.
- The injection process is stopped after 1.2 PV of CO_2 is injected.
- The slimtube is cleaned out.
- The above procedures are repeated with a higher injection pressure than the previous one.
- The experiment is terminated when an additional injection pressure does not result in a significant increase in incremental oil recovery.
- The pressure where the incremental oil recovery does not increase significantly is determined as the MMP. In this experiment, CO_2 gas injection is performed at a reservoir temperature of 94 ˚C for different injection pressures of 2450, 2660, 2950, and 3370 psig.

Figure 3: MMP determination apparatus in the laboratory using slimtube.

The slimtube laboratory experiment for the oil sample from Well J-151 of the KMJ Layer gives a CO_2 gas MMP value of 2807 psig. Table **4** and Fig. (**4**) summarize the oil recovery measurements using a slimtube for different CO_2 injection pressures.

Table **4** and Fig. (**4**) show that oil recovery increases with injection pressure when the pressure is below MMP, both at breakthrough and at 1.2 PV injection. However, when the injection pressure is equal to or above the MMP, the oil recovery does not increase significantly with more injection pressure. Therefore, the MMP of the laboratory experiment is determined as 2807 psig.

Table 4: Oil recovery results using slimtube.

Injection Pressure, psig	Oil Recovery Prior to Breakthrough, %	Total Oil Recovery, %
2450	78.53	85.68
2660	80.35	93.35
2950	96.71	98.49
3370	97.28	99.47

Moreover, the MMP value from the slimtube laboratory experiment (2807 psig) is relatively close to the MMP value from the empirical equation (2810 psig), with a difference of only 3 psig. Thus, it is concluded that the empirical method and the laboratory experiment are consistent in determining MMP because they use the same oil sample composition. The difference value of the MMP result between the slimtube laboratory experiment and the empirical equation is due to slimtube properties and is affected by experiment parameters such as injection rate.

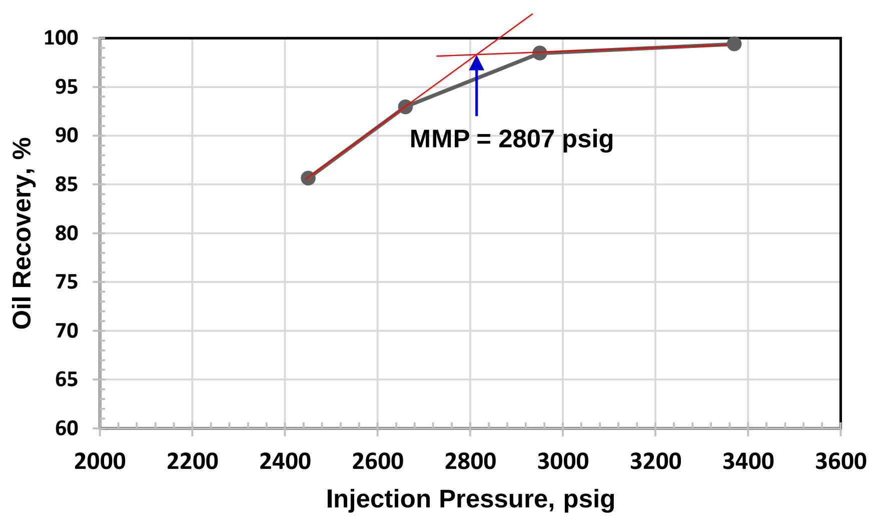

Figure 4: Plot of MMP determination results using slimtube at the laboratory.

Based on the MMP determination results, hence the MMP of the laboratory experiment result is chosen for the application in the KMJ Layer of the HKY Field. Ekundayo and Ghedan [31], Flock and Nouar [32] state that the laboratory experiment using slimtube has been used to determine the MMP because its models could represent the interaction of flow in porous media and phase behavior of crude oil, and also often considered as the standard way to measure the MMP.

3.3. Swelling Test

The swelling test is carried out using a PVT cell, where recombined fluids are injected and conditioned at a reservoir temperature of 202 ˚F. Then, the pressure-volume relationship is analyzed to determine the bubble-point pressure at different pressures until it reaches a bubble-point pressure of 410 psig. After that, a certain amount of CO_2 is injected into the PVT cell, the CO_2 volume is recorded, and the same pressure-volume analysis is repeated to the newly determine bubble-point pressure. This process is done four more times, by adding the amount of injected CO_2. The more CO_2 is injected, the more oil swelling and bubble-point pressure increase. This injection process continues until the bubble-point pressure is close to the minimum miscible pressure. The results of this swelling test are shown in Table **5** for swelling factor and CO_2 solubility. The changes in reservoir fluid composition during CO_2 injection are shown in Table **6**. A correlation between the swelling factor and saturation pressure is shown graphically in Fig. (**5**), and a correlation between saturation pressure and injected CO_2 mole percentage is shown in Fig. (**6**).

Table 5: Experiment results of oil swelling test.

Reservoir System	CO_2 Injection, SCF/STB	Saturation Pressure, psig	CO_2 Solubility, SCF/BBL Reservoir*)	Swelling Factor, fraction**)
Original Reservoir Oil	0.00	410	0.00	1.00
CO_2 / Oil System I	105	700	130.38	1.12
CO_2 / Oil System II	220	1200	253.26	1.18
CO_2 / Oil System III	560	1700	615.26	1.34
CO_2 / Oil System IV	765	2200	836.85	1.44

*) at current reservoir condition; **) ratio of volume at saturation pressure

Table **5** shows that the bubble-point pressure and the swelling factor increase from 410 psig to 2200 psig and from 1.0 to 1.442, respectively, as the CO_2 injection reaches 46.82% mole. As more CO_2 is injected and the saturation pressure increases, more CO_2 dissolves in oil and reduces its density, leading to more oil volume expansion, as indicated by the higher swelling factor in Fig. (**5**). This also means that the higher CO_2 concentration (% mole) and the changes in fluid composition, especially the lower C_{7+}, are related to the higher CO_2 solubility in hydrocarbon, as shown in Table **6** and Fig. (**6**). This result was similar with the laboratory experiment result conducted by Holm [33], Sugiharjo and Purnomo [34], and Tsau *et al*. [28], where the swelling factor will increase when the % mole increases and fluid composition changes.

Table 6: Experiment results of changes in reservoir fluids composition.

Components	Original Reservoir Oil, % Mole	CO_2 / Oil System I % Mole	CO_2 / Oil System II % Mole	CO_2 / Oil System III % Mole	CO_2 / Oil System IV % Mole
Hydrogen Sulfide (H_2S)	0.00	0.00	0.00	0.00	0.00
Carbon Dioxide (CO_2)	2.59	7.92	18.46	38.73	46.82
Nitrogen (N_2)	0.25	0.38	0.34	0.25	0.22
Methane (C_1)	4.88	4.35	3.86	2.90	2.51
Ethane (C_2)	0.53	0.49	0.43	0.32	0.28
Propane (C_3)	0.90	1.55	1.38	1.03	0.90
Iso-Butane (i-C_4)	0.37	0.69	0.61	0.46	0.40
n-Butane (n-C_4)	0.66	1.64	1.45	1.09	0.94
Iso-Pentane (i-C_5)	0.66	1.37	1.21	0.91	0.79
n-Pentane (n-C_5)	0.67	1.78	1.58	1.19	1.03
Hexane (C_6)	2.30	3.41	3.02	2.27	1.97
Heptane plus (C_{7+})	86.20	76.42	67.67	50.85	44.14
Total	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**

4. Conclusions

The following conclusions are drawn from the comprehensive analysis and discussion:

1. The empirical equation gives an MMP of 2810 psig between Well J-151 oil sample of KMJ Layer and CO_2 gas; Cronquist correlation gives 2303 psig; Yellig and Metcalfe give 2494 psig; Holm and Josendal give 2756 psig, while the slimtube experiment in the laboratory gives 2807 psig.
2. The laboratory experiment result is chosen as the MMP for the application in the KMJ Layer of the HKY Field.

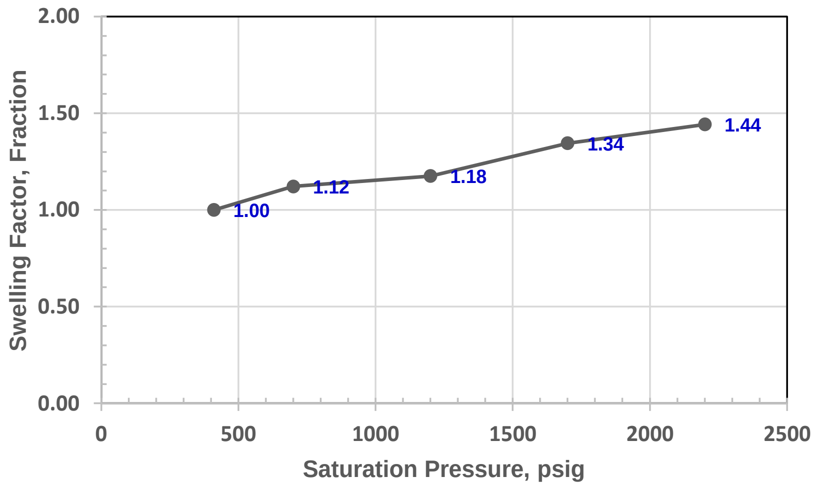

Figure 5: Correlation results of swelling factor to saturation pressure.

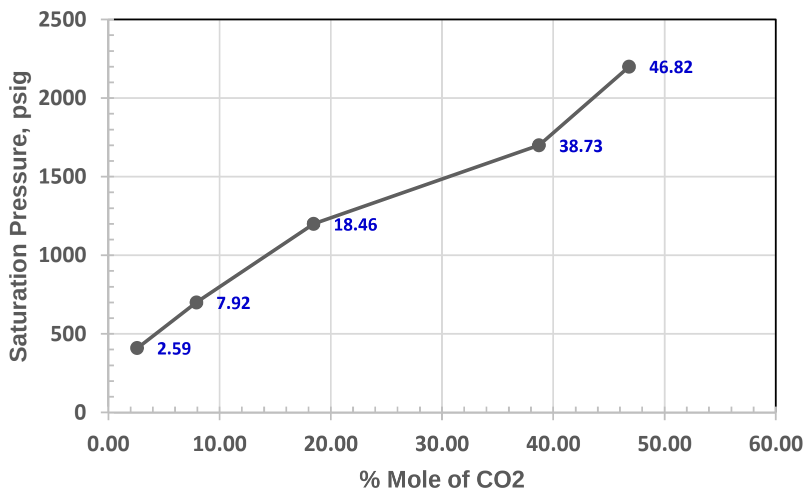

Figure 6: Correlation results of saturation pressure vs injected % mole of CO_2.

3. CO_2 purity, oil composition, temperature, and depth are the most important factors that influence the miscibility of CO_2 gas with oil.
4. The swelling test shows that the swelling factor increases from 1.0 to 1.442 as the CO_2 gas injection reaches 46.82% mole and the bubble pressure rises from 410 psig to 2200 psig.
5. Since the MMP is 2807 psig and the formation fracture pressure in the KMJ Layer is 2200 psig, only immiscible flooding can be applied in the KMJ Layer of the HKY Field, because the CO_2 MMP is higher than the fracture pressure.
6. CO_2 gas injection is a feasible and recommended method for enhancing oil recovery in the KMJ Layer of the HKY field.
7. For future research, it is recommended to conduct the slimtube simulation for comparison with the laboratory experiment to obtain a reliable determination of the MMP.

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Conflict of Interest

The authors declare no conflict of interest.

References

[1] Stalkup FI. Miscible displacement. Vol. 8. Texas: Henry L. Doherty Memorial Fund of AIME, Society of Petroleum Engineers; 1983.

[2] Universitas Pembangunan Nasional Veteran "UPN". Feasibility study of CO_2 flooding, lapangan Jatibarang, Pertamina EP Region Java. Yogyakarta. 2011.

[3] Abdurrahman M, Bae W, Permadi AK, Am S, Gunadi B, Saputra DDSM, *et al*. Opportunities and challenges of CO_2 flooding implementation in Indonesia. SPE Asia Pacific Oil and Gas Conference and Exhibition, SPE; Jakarta, Indonesia: 22-24th October 2013. https://doi.org/10.2118/165847-MS

[4] Chae KS, Lee JW. Risk analysis and simulation for geologic storage of CO_2. Proceedings of the World Congress on Advances in Civil, Environmental, and Materials Research, Incheon, Korea: 25-29th August 2015.

[5] Lee JY, Permadi AK, Kim H-T, Huh D-G, Park JM, Lee W, *et al*. Overview of CO_2-EOR operation plan of meruap field. Proceedings of the World Congress on Advances in Civil, Environmental, and Materials Research, Incheon, Korea: 25-29th August 2015.

[6] Abdurrahman M, Permadi AK, Bae WS, Masduki A. EOR in Indonesia: past, present, and future. Int J Oil Gas Coal Technol. 2017; 16: 250-70. https://doi.org/10.1504/IJOGCT.2017.087024

[7] Suarsana IP. Producing high CO_2 gas content reservoirs in Pertamina Indonesia using multi stage cryogenic process. SPE Asia Pacific Oil and Gas Conference and Exhibition, Brisbane, Queensland, Australia: SPE; 18-20th October 2010. https://doi.org/10.2118/134278-MS

[8] Rostami A, Arabloo M, Kamari A, Mohammadi AH. Modeling of CO_2 solubility in crude oil during carbon dioxide enhanced oil recovery using gene expression programming. Fuel 2017; 210: 768-82. https://doi.org/10.1016/j.fuel.2017.08.110

[9] Abdassah D, Siregar S, Kristanto D. The potential of carbondioxide gas injection application in improving oil recovery. Society of Petroleum Engineers International Oil and Gas Conference and Exhibition in China, Beijing, Chin:, SPE; 7-10th November 2000. https://doi.org/10.2118/64730-MS

[10] Miller JS, Jones RA. A laboratory study to determine physical characteristics of heavy oil after CO_2 saturation. SPE/DOE Enhanced Oil Recovery Symposium, Tulsa, Oklahoma: SPE; April 1981. https://doi.org/10.2118/9789-MS

[11] Barclay TH, Mishra S. New correlations for CO_2-Oil solubility and viscosity reduction for light oils. J Pet Explor Prod Technol. 2016; 6: 815-23. https://doi.org/10.1007/s13202-016-0233-y

[12] Welker JR, Dunlop DD. Physical properties of carbonated oils. J Pet Technol. 1963; 15(8): 873-6. https://doi.org/ 10.2118/567-PA

[13] Simon R, Graue DJ. Generalized correlation for predicting solubility swelling and behaviour CO_2-Crude oil system. J Pet Technol. 1965; 17(01): 102-6. https://doi.org/10.2118/917-PA

[14] Emera MK, Sarma HK. A genetic algorithm-based model to predict CO_2-oil physical properties for dead-live oil. Canadian International Petroleum Conference, Calgary, Alberta: Petroleum Society of Canada; 13-15th June 2006. https://doi.org/10.2118/2006-197

[15] Leach MP, Yellig WF. Compositional model studies CO_2 oil displacement mechanisms. Soc Pet Eng J. 1981; 21: 89-97. https://doi.org/10.2118/8368-PA

[16] Yellig WF. Carbon dioxide displacement of West Texas reservoir oil. Soc Pet Eng J. 1982; 22: 805-15. https://doi.org/10.2118/9785-PA

[17] Holm LW, Josendal VA. Mechanisms of oil displacement by carbondioxide. J Pet Technol. 1974; 26: 419-27. https://doi.org/10.2118/4736-PA

[18] Yellig WF, Metcalfe RS. Determination and Prediction of CO_2 Minimum Miscibility Pressures (includes associated paper 8876). J Pet Technol. 1980; 32: 160-8. https://doi.org/10.2118/7477-PA

[19] Mungan N. Carbon dioxide displacement fundamentals. J Can Pet Technol. 1981; 20: 87-92. https://doi.org/10.2118/81-01-03

[20] Sohrabi M, Emadi A. Novel insights into the pore-scale mechanisms of enhanced oil recovery by CO_2 injection. SPE Europec/EAGE Annual Conference, Copenhagen, Denmark: SPE; 4-7th June 2012. https://doi.org/10.2118/154529-MS

[21] Stalkup FI. Carbon dioxide miscible flooding: past, present, and outlook for the future. J Pet Technol. 1978; 30: 1102-12. https://doi.org/10.2118/7042-PA

[22] Stalkup FI. Displacement behavior of the condensing/vaporizing gas drive process. SPE Annual Technical Conference and Exhibition, Dallas, Texas, USA: SPE; 27-30th of September 1987. https://doi.org/10.2118/16715-MS

[23] Klins MA. Carbondioxide flooding: Basic mechanisms and project design. Boston: Springer; 1984.

[24] Taber JJ, Martin FD, Seright RS. EOR screening criteria revisited-Part 1: Introduction to screening criteria and enhanced oil recovery field projects. SPE Res Eng. 1997; 12: 189-98. https://doi.org/10.2118/35385-PA

[25] Alomair O, Malallah A, Elsharkawy A, Iqbal M. Prédiction de la pression miscibilité minimum (MMP) du CO_2 en utilisant un algorithme basé sur l'ACE (Alternating Conditional Expectation). Oil Gas Sci Technol. – Rev. IFP Energies Nouvelles. 2015; 70: 967–82. https://doi.org/10.2516/ogst/2012097

[26] Hakim ALL, Permadi AK, Bae W, Ryoo WS. A new integrated HPHT experimental apparatus to measure interfacial tension, swelling factor, and viscosity simultaneously. J Pet Explor Prod Technol. 2022; 12: 2405-17. https://doi.org/10.1007/s13202-022-01469-2

[27] Hand JL, Pinczewski WV. Interpretation of swelling/extraction tests. SPE Res Eng. 1990; 5: 595-600. https://doi.org/10.2118/19471-PA

[28] Tsau JS, Bui LH, Willhite GP. Swelling/extraction test of a small sample size for phase behavior study. SPE Improved Oil Recovery Symposium, Tulsa, Oklahoma, USA: SPE; 24-28th April 2010. https://doi.org/10.2118/129728-MS

[29] Abdurrahman M, Permadi AK, Bae WS. An improved method for estimating minimum miscibility pressure through condensation–extraction process under swelling tests. J Pet Sci Eng. 2015; 131: 165-71. https://doi.org/10.1016/j.petrol.2015.04.033

[30] ASTM-API standard. Standard practice for manual sampling of petroleum and petroleum products. West Conshohocken, PA, USA: Reference number: FDUS 1732: 2017.

[31] Ekundayo JM, Ghedan SG. Minimum miscibility pressure measurement with slimtube apparatus. SPE Reservoir Characterization and Simulation Conference and Exhibition, Abu Dhabi: SPE; 16-18th September 2013. https://doi.org/10.2118/165966-MS

[32] Flock DL, Nouar A. Parametric analysis on the determination of the minimum miscibility pressure in slim tube displacements. J Can Pet Technol. 1984; 23: 80-8. https://doi.org/10.2118/84-05-12

[33] Holm WL. Evolution of the carbon dioxide flooding processes. J Pet Technol. 1987; 39: 1337–42. https://doi.org/10.2118/17134-PA

[34] Sugihardjo S, Purnomo H. The changes of reservoir fluid properties in CO_2 injection. LPMGB. 2009; 43(1): 11-16. https://doi.org/10.29017/SCOG.44.1.492