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Assessment of Minimum Miscibility Pressure for CO_2 Injection by an Enhanced Peng-Robinson Equation of State using Different Approaches. A Case Study for an Iraqi Oil Field

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ABSTRACT

One of the advanced techniques in enhanced oil recovery (EOR) is the miscible injection of carbon dioxide (CO_2), which can both boost oil displacement and decrease the greenhouse effect. One of the most important indicators for ensuring full miscibility between two phases and optimal injection process efficiency is the Minimum Miscibility Pressure (MMP). There are many methods, such as experimental methods, that are accurate yet costly and time-consuming for determining the MMP; thus, researchers often turn to mathematical techniques, including equations of state and empirical correlations. This study aims to determine the minimum miscible pressure for CO_2 in one of the Iraqi fields for its importance in determining the pressure at which CO_2 injection is miscible with oil. The equation of state (EOS) was used in different ways and was compared with some correlations such as Glaso, Yelling and Metcalfe, and Lee to determine whether the equation of state is good or not. The PVT model was started, through which a regression was made between the laboratory data and the data that was calculated from EOS. Then, the MMP was evaluated in different ways. Cell to cell, key tie line, and multiple mixing, and when compared with the correlations, it was found that the multiple mixing method gave the highest error rates than the rest of the methods, while key tie line and cell to cell gave the same value of minimum miscible pressure. However, the Yelling and Metcalfe correlation gave a higher error rate than from Cell to Cell, but an acceptable rate.

Keywords: Equation of state (EOS), Pressure-volume-temperature (PVT), Minimum miscible pressure (MMP), Peng Robnsion.

1. INTRODUCTION

One effective enhanced oil recovery technique is miscible flooding. In order to assess and build a miscible flood, the minimum miscibility pressure (MMP) is a crucial metric. The

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minimal miscibility pressure, the lowest pressure at which the injection gas can become miscible with the reservoir oil, is determined by the temperature of the reservoir and the composition of the injection gas and oil. **(Ekundayo and Ghedan, 2013; Adekunle and Hoffman, 2014; Hadi and Hamd-Allah, 2020; Ayoub et al., 2022; Tileuberdi et al., 2024)**. CO_2, hydrocarbon gas, acid gases, flue gas, and N_2 are among the injection gases employed in the enhanced oil recovery process. When a hydrocarbon gas is injected into a reservoir under the right pressure conditions, the process results in miscible displacements. Several techniques, including the slim tube test **(Yellig and Metcalfe, 1980; Stalkup, 1983; Jarrell et al., 2002; Hawthorne et al., 2016; Ahmad et al., 2016)**, rising bubble test **(Elsharkawy et al., 1992; Al-Hinai et al., 2014; Zhang and Gu, 2016)**, vanishing interfacial tension**(Rao and Lee, 2002; Orr and Jessen, 2007; Hawthorne et al., 2016)**, thermodynamic models (equation of state (EOS) which is an equation that links between Pressure-Temperature-volume this is important for describing the state of fluid in reservoir), and empirical correlations **(Zick, 1986; Firoozabadi and Aziz, 1986; Wang and Orr, 1997; Jessen and Orr, 2008; Khorsandi and Johns, 2015; Mohamed Mansour, 2020; Cui et al., 2022)**.

Similar to a reservoir situation, miscibility in a two-phase fluid system can be attained by either first contact or by multiple contacts. Multi-contact arises when it takes some time for the single phase to form, which happens at a lower pressure than first-contact miscibility **(Mihcakan, 1993)**. For the injected fluid to be multi-contact miscible, the reservoir pressure needs to be high enough. The condensing gas drive mechanism, vaporizing mechanism, or combined vaporizing-condensing gas drive mechanism can all cause miscibility in a hydrocarbon gas displacement process **(Srivastava and Huang, 1998; Dindoruk et al., 2021; Johns and Orr, 2021)**.

Many researchers have put forth different approaches to minimum miscible pressure (MMP) or Minimum miscibility enrichment (MME) calculation; the first one was predicated on the MCM ternary theory **(Hutchinson and Braun, 1961)**. It is considered a straightforward and inexpensive model, which was put forth by Metcalfe et al. in 1973. The procedure involves injecting gas into an oil-filled cell at a specific temperature and pressure, flashing the mixture, moving the extra oil and vapor to the next cell, and repeating the process multiple times. The MMP was defined as the pressure that creates a mixture close to the critical line **(Metcalfe et al., 1973)**. (**Ahmed, 1997)** studied estimating crude oil's MMP using CO_2 injection and hydrocarbon gases. This approach relied on the use of a modified Peng and Robinson EOS with a recently discovered miscibility function. The purpose of the miscibility function was to accurately predict the value of MMP. When the suggested method is used to replicate the experimentally reported MMP data of Metcalfe and Glaso, excellent agreement is seen with an AERR of 3.4%; it could predict MMP for CO_2 and hydrocarbon gases. Numerous mixing-cell methodologies are an easy, useful, and reliable numerical method for determining the MMP. It is based on doing the pressure-temperature (P/T)flash calculations using any well-tuned EOS model **(Ahmadi and Johns, 2011; Saini, 2018)**. Eclipse (v.2010)/PVTi software was used to estimate MMP in the Sadi Formation and East Baghdad field; they compared the results obtained from EOS and the correlations of Glaso 1985 and Firoozaba correlation and found that the error rates were good and acceptable **(Hameed, 2017)**. The minimum miscible pressure in the South Rumila-63 (SULIAY) oil well was estimated based on the modified Peng Robenson (PR-EOR) equation using the PVTi software after splitting, lumping, and regression. A satisfactory match was demonstrated for every experimental PVT, indicating that the equation of state is a useful tool for determining PVT parameters and MMP **(Hamd-allah et al., 2018)**. In this study, the minimum miscible pressure of one of the Iraqi fields will be evaluated in order to create a reservoir model for CO_2 injection and to determine whether mixing occurs or not, and to determine whether the pressure is economic or not. This is done using the equation of state (EOS) by using the modified Peng Robinson 1978 and comparing it with some correlations to determine the best and most suitable method for creating the reservoir model.

2. METHODOLOGY

In order to determine the Minimum Miscible Pressure based on the equation of state using the modified Peng Robinson equation, a PVT model must be created, and then the MMP methods available in the program must be used, which are cell-to-cell, key tie line, and multiple mixing cells.

2.1 PVT Modeling

First, PVT modeling will be done based on the equation of state, and it is done by collecting data from one of the Iraqi fields from the PVT report, which includes bubble pressure of 2280 psi, reservoir temperature of 163.4°F, compositions($C1$-$C7^+$), and laboratory data that includes constant composition expansion and differential liberation. The Winprop was used to create a PVT model based on the modified Peng Robinson equation as in Eq.(1)**(Robinson and Peng, 1978)**. The composition, laboratory data, bubble pressure, and temperature are entered, and regression is helpful when the model parameters derived from the basic characterization procedure do not produce the desired agreement with PVT data. By varying a few model parameters, the regression minimizes the deviation between the measured data experiments and the simulated results of the PVT. Then, matching between the three phases is done, with saturation pressure (bubble point pressure), constant composition expansion (CCE), and differential liberation matching being the first, second, and third phases, respectively. **Table 1** contains some information on the field.

$$P=\frac{RT}{V-b}-\frac{a(T)}{V(V+b)+b(V-b)} \tag{1}$$

T_r=reduced temperature(dimensionless)
ω= acentric factor (dimensionless)
P= pressure (Pisa)
V=volume (ft^3)
a,b= various constants in EOS (dimensionless)
R= constant gas ($\frac{psi\ ft^3}{Ib.mole.R}$)

Table 1. Some Information on the Field

Saturation Pressure	2280 psi
API	26.1
Temperature	163.4 °F
Opening pressure	1200 psi
Number of samples	441

2.2 Minimum Miscible Pressure

After performing a regression, the minimum miscible pressure is determined by three methods that (Cell to Cell, Key tie line, Multiple mixing cell method), then correlation of **(Lee, 1979; Yelling and Metcalfe, 1980; Glaso, 1985)** is used to determine the best method for EOS to determining the minimum miscible pressure.

A model was suggested for predicting minimal miscibility pressure (MMP) that only uses reservoir temperature as input data and accounts for carbon dioxide (CO_2) vapor pressure, as shown in Eq. (2) **(Lee, 1979)**. The bubble point pressure (Pb) of any reservoir oil is regarded as the minimum miscibility pressure when the MMP is smaller than the Pb **(Mansour et al., 2018)**.

$$MMP = 7.3924 * 10^{b}, \text{ where } b = 2772 - \frac{1519}{(492+18TR)}, \; T_R = \text{Temperature } ^{o}F \tag{2}$$

An empirical correlation was suggested for determining the minimal miscibility pressure (MMP) for different reservoir temperatures using equation Eq. (3) **(Yelling and Metcafe, 1980)**. This relationship is independent of the composition of the oil and is based only on reservoir circumstances. The minimal miscibility pressure (MMP) of this empirical correlation ranges roughly from 15 to 19 MPa and temperature between $35.8^{o}C \leq T < 88.9^{o}C$ **(Yelling and Metcafe 1980).**

$$MMP = 12.6472 + 0.015531 * (1.8TR+32) + 1.24192 * 10^{-4} (1.8TR+32)^{2} - \frac{716.9427}{(1.8TR+32)} \tag{3}$$

T_R=*Temperature* ^{o}F

A correlation was suggested to calculate MMP for CO_2 and N_2 and enter the molecular weight of C7+ in the equation. The intermediate (C2-C6)<18mol% is required to use Eq.(4) **(Glaso, 1985)**.

$$MMP = 5.58657 - 0.02347739 * MW_{C7+} + [1.1725 * 10^{-11} * MW_{C7+}^{3.73} e^{786.8} e^{786.8 * M_{C7+}^{-1.058}}] * (1.8TR+32) \tag{4}$$

3. RESULTS AND DISCUSSION

After making the regression process for the entered laboratory data, we notice that the AAERR (Average Absolute Relative Error) rate for bubble point pressure is 0.0105%, which is a very small percentage. Also, oil formation volume factor Bo, gas oil ratio GOR, and gas formation volume factor Bg gave small and acceptable AAERR error rates, which are 1.072%, 4.81%, and 3.4%, respectively. The specific gravity of oil, the specific gravity of gas, and the gas composability factor gave small AAERR error rates, which are 0.82%, 1.43%, and 1.43% respectively. Also, the viscosity of oil and relative volume gave small and acceptable AAERR error rates, which are 2.16% and 0.95. This means a good equation because it gave lower and better error rates for making a PVT model for CO_2 injection, as shown in **Table 2** and **Figs. 1 to 5**. The AAERR (Average Absolute Relative Error) is calculated from Eqs. (5 and 6):

$$AERR = \frac{yexp - yest}{yexp} * 100 \tag{5}$$

$$AAERR = \left(\frac{1}{n_d}\right) \sum_{i=1}^{n_d} |AAERR| \quad (6)$$

Where: yest=estimated value *and* yexp=experimental value

Table 2. Error Percentage in fluid properties by modified PR.

	ROV	GOR	SG Gas	Gas FVF	Oil Viscosity	Bo	SG Oil	Gas Z factor	P_b
PR (avg)	3.97%	4.81%	1.962%	3.4%	2.16%	1.072%	0.82%	1.43%	0.0105%
PR. (highest)	8%	7.1%	6.13%	6.83%	9.03%	3.18%	2.11%	4.38%	-

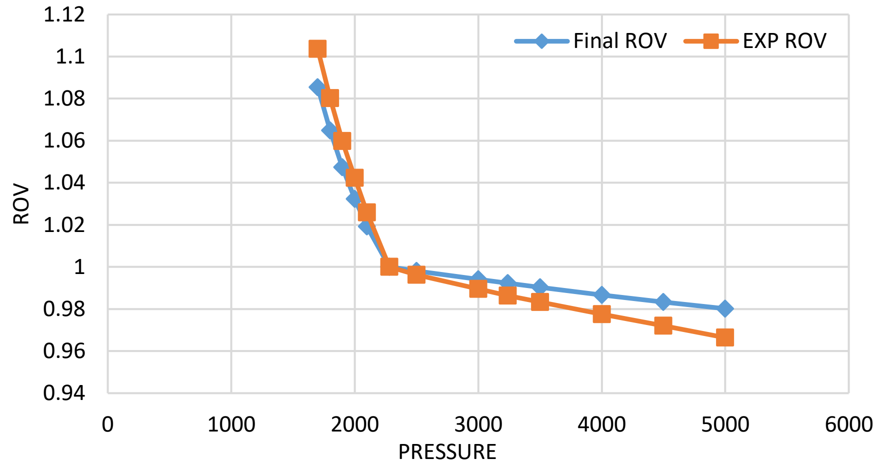

Figure 1. Relative volume Regression by PR.

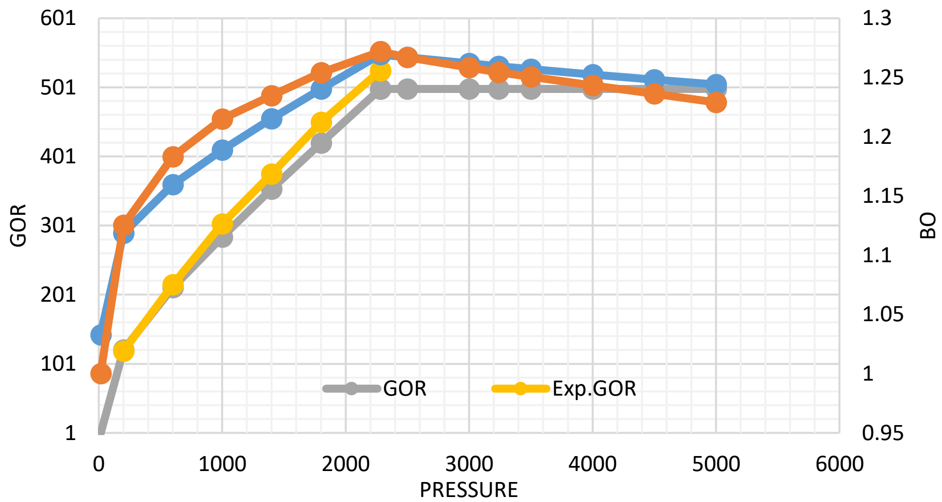

Figure 2. Bo and GOR Regression by PR.

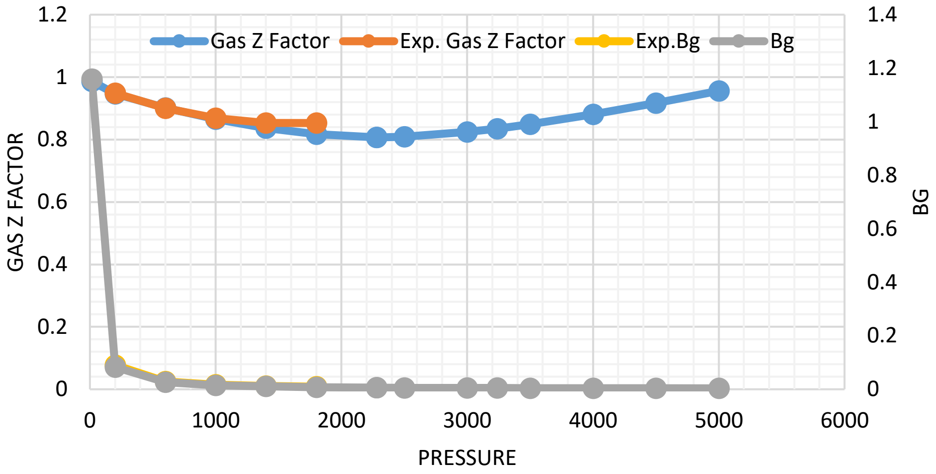

Figure 3. Gas Z factor and Gas volume factor Regression by PR.

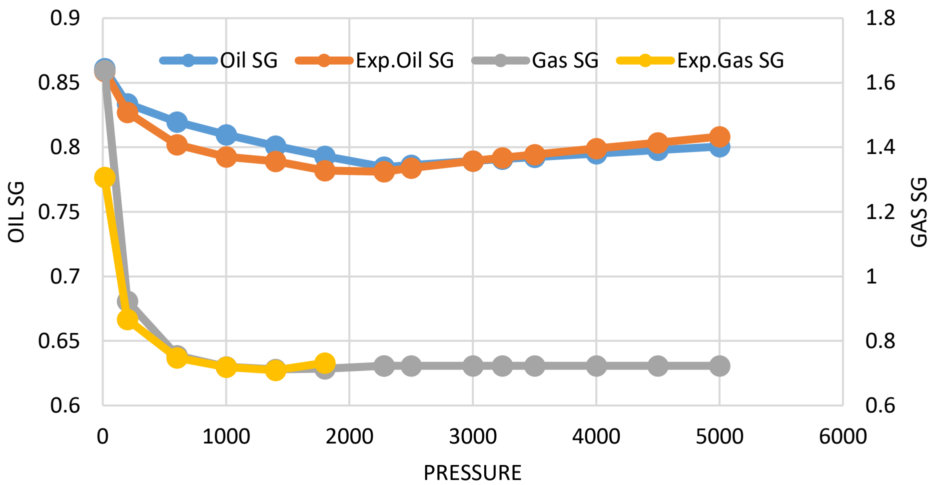

Figure 4. Oil specific gravity and Gas specific gravity Regression by PR.

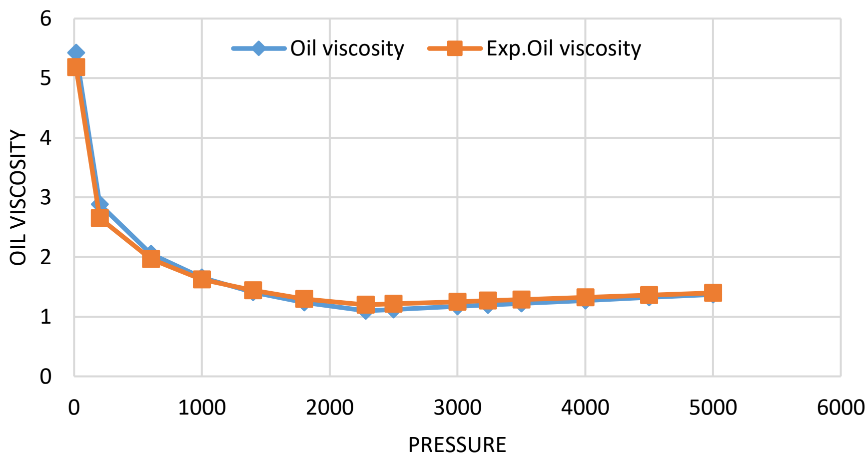

Figure 5. Oil Viscosity Regression by PR.

Winprop software can calculate MMP at reservoir temperature 163.4 °F using the modified Peng Robinson equation of state when a suitable match between the calculated and observed PVT characteristics is reached. **Tables 2** display MMP readings by three methods with a comparison of correlations **(Lee, 1979; Yelling, 1980; Glaso, 1985)** and minimum miscible pressure calculated by the equation of state (Peng Robinson) in the cell-to-cell (**Fig. 6**) key tie line and multiple mixing cell methods. These correlations were close to this field in terms of temperature and molecular weight; thus, the required terms are met for these equations; therefore, they were chosen for this study.

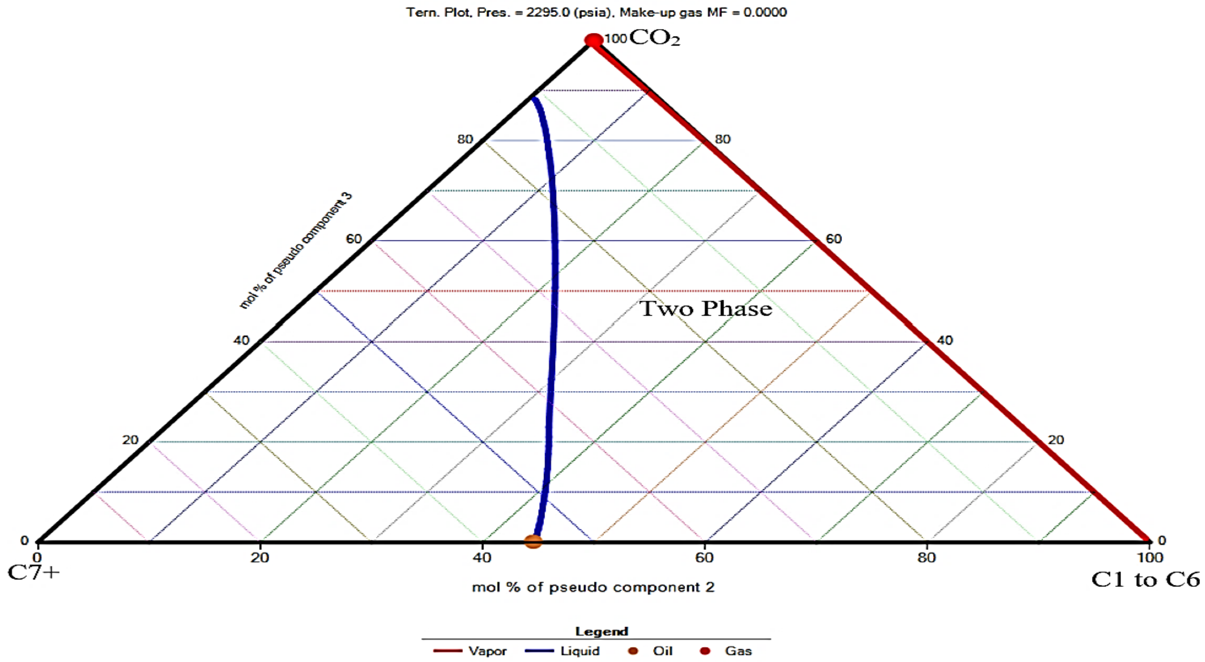

Figure 6. Minimum Miscible pressure calculated by cell to cell.

Where **Fig. 6** illustrates a ternary diagram that shows how miscibility occurs. The ternary diagram for the Iraqi oil field was produced using MCM (vaporizing gas displacement). Three points on this diagram indicate the CO_2; the light and intermediate components are indicated by the lower-right apex [C1, N2, C2, C3, C4, C5, C6], and the heavy component is indicated by the lower-left apex [C7+]. Also, it is expected that MMP will occur at 2295 psi in this Iraqi oil field. The reason for the lack of laboratory data for this field and not knowing whether EOS is suitable for this field or not, therefore, it was compared with correlations in order to evaluate the MMP. These correlations were used depending on their terms (temperature and molecular weight). Where cell to cell, key tie line gave the same value of minimum miscible pressure and also gave low error rates for the two correlations **(Lee, 1979; Glaso, 1985),** while **(Yelling and Metcalfe, 1980)** gave higher error rates due to the fact that Yelling and Metcalfe 1980 relies on reservoir temperature only, while Glaso 1985 relies on reservoir temperature and molecular weight of C7+, and since the two correlations gave low error rates, we expect that a miscibility will occur at 2295 psi. The multiple mixing cell method gave high and unacceptable error rates for the mentioned correlations, consequently the cell to cell and key tie line method is considered a suitable method for this oil field, and also the pressure was not very high and suitable from an economic point of view, i.e. the higher the pressure, the higher the cost, so this is considered an economic pressure. Through this, a reservoir model can be created to inject CO_2 as a miscible in this field using the equation of state.

Table 2. MMP Estimation from Correlation and EOS Methods.

Correlation from literature	MMP Psi	MMP by Cell to Cell (EOS)	Error (AAE)%
(Lee, 1979)	2320.751	2295	1.10959771
(Yelling and Metcalfe, 1980)	2046.944	2295	12.1183579
(Glaso, 1985)	2331.276	2295	1.55605771
Correlation from literature	**MMP Psi**	**MMP by Key tie line (EOS)**	**Error (AAE)%**
(Lee, 1979)	2320.751	2295	1.10959771
(Yelling and Metcalfe, 1980)	2046.944	2295	12.1183579
(Glaso, 1985)	2331.276	2295	1.55605771
Correlation from literature	**MMP Psi**	**MMP by Multiple mixing cell (EOS)**	**Error(AAE)%**
(Lee, 1979)	2320.751	2465.3	6.22854412
(Yelling and Metcalfe, 1980)	2046.944	2465.3	20.4380775
(Glaso, 1985)	2331.276	2465.3	5.74895465

4. CONCLUSIONS

To summarize the findings of building PVT model and estimating the minimum miscible pressure study, it is concluded that:

- PVT modeling and regression were performed between the laboratory data and the data calculated from the equation of state, and good agreement and low error rates were obtained.
- The minimum miscible pressure was evaluated by EOS in three methods and compared with correlations. It was found that the key tie line method and the cell-to-cell method gave the same MMP and when compared with correlations, it gave low error rates for Glaso, Lee, but gave higher error rates when compared with Yelling and Metcalfe.
- The key tie line and cell-to-cell were relied upon to determine the MMP for this field, and the miscibility will occur between CO_2 and oil at a pressure of 2295 psi to perform reservoir modeling for CO_2 injection in the future. Therefore, the equation of state is considered a faster and more economical calculation method.

NOMENCLATURE

Symbol	Description	Symbol	Description
B_o	Formation-volume factor, STB/bbl.	SG	Specific gravity
B_g	Gas formation-volume factor, ft3/Scf	MW	Molecular weight, Ib/Ib mol
TR	Reservoir temperature, ^oF	ω	acentric factor, dimensionless
Pc	Critical pressure, psi	Ω	parameter in EOS, dimensionless

Credit Authorship Contribution Statement

Rusul H. Rabeeah - writing paper. Mohammed S. Al-Jawad – review and editing

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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تقييم الحد الأدنى لضغط الامتزاج لحقن ثاني أكسيد الكربون باستخدام معادلة بنج–روبنسون المحسنة للحالة باستخدام طرق مختلفة. دراسة حالة لحقل نفط عراقي

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قسم هندسة النفط، كلية الهندسة، جامعة بغداد، بغداد، العراق

الخلاصة

إن إحدى التقنيات المتقدمة في تحسين استخلاص النفط هي الحقن القابل للامتزاج بثاني أكسيد الكربون(CO_2) ، والذي يمتلك القدرة على تعزيز إزاحة النفط وتقليل تأثير الاحتباس الحراري. ومن أهم المؤشرات لضمان الامتزاج الكامل بين مرحلتين نفط و محقون وكفاءة عملية الحقن المثلى هو ضغط الامتزاج الأدنى (MMP) وهناك العديد من الطرق، مثل الطرق التجريبية التي تتسم بالدقة – ولكنها مكلفة وتستغرق وقتاً طويلاً – لتحديد ضغط الامتزاج الأدنى؛ وبالتالي، يلجأ الباحثون إلى التقنيات الرياضية بدلاً من ذلك، مثل معادلات الحالة والارتباطات التجريبية. تهدف هذه الدراسة إلى تحديد الضغط القابل للامتزاج الأدنى لثاني أكسيد الكربون في أحد الحقول العراقية لأهميته في تحديد الضغط الذي يمتزج عنده حقن ثاني أكسيد الكربون بالنفط. وقد استخدمت معادلة الحالة (EOS)بطرق مختلفة وتمت مقارنتها ببعض الارتباطات مثل Glaso و Yelling and Metcalfe و Lee لتحديد ما إذا كانت معادلة الحالة جيدة أم لا. تم البدء بنموذج PVT والذي تم من خلاله عمل انحدار بين بيانات المختبر والبيانات التي تم حسابها من EOS ثم تم تقييم MMP بطرق مختلفة وهي cell to cell و key tie line وmuiltiple cell mixingوعند المقارنة بالارتباطات وجد أن طريقة muiltiple mixing cell أعطت أعلى معدلات خطأ من باقي الطرق بينما أعطت cell to cell key tie line نفس قيمة الضغط القابل للامتزاج أما ارتباط Yelling and Metcalfe 1980 فقد أعطى أعلى معدل خطأ ولكن بمعدل مقبول.

الكلمات المفتاحية :معادلة الحالة، ضغط–حجم–حرارة، ضغط الامتزاج الأدنى، معادلة بنج روبنسون.