



# Influencing Factors of Impure CO<sub>2</sub> Near Miscible Flooding and Its Feasibility Evaluation

Xian-song Zhang<sup>(✉)</sup> and Bao-zhen Li

State Key Laboratory of Offshore Oil Exploitation, CNOOC Research Institute Co. Ltd.,  
Beijing, China  
zhangxs@cnooc.com.cn

**Abstract.** Compared with CO<sub>2</sub> miscible flooding, near miscible flooding reduces the requirements of crude oil quality and reservoir pressure, CO<sub>2</sub> source purity, and reduces the operation cost, which attracts more and more attention. High content CO<sub>2</sub> (24%–90%) gas reservoir was found in an offshore x oilfield. It is difficult to realize miscible flooding by reinjection gas of high CO<sub>2</sub> content, so it is necessary to evaluate the feasibility of near miscible flooding. This paper summarizes the main displacement mechanism of CO<sub>2</sub> flooding, analyzes the main controlling factors of miscibility degree, and establishes an empirical formula suitable for impure CO<sub>2</sub> near miscible displacement pressure, which can quickly evaluate the feasibility of pure/impure CO<sub>2</sub> near miscible displacement for low permeability reservoirs. The results show that the purity of CO<sub>2</sub> near miscible flooding is more than 64%, and the feasibility is very high by near miscible flooding. The research results provide technical basis for the feasibility and rapid evaluation of low permeability reservoir.

**Keywords:** Impure CO<sub>2</sub> · Near miscible flooding · Displacement mechanism · Influencing factors · New empirical formula

## 1 Introduction

The natural gas with high CO<sub>2</sub> content and industrial waste gas in offshore oilfield provide sufficient gas source for CO<sub>2</sub> flooding. However, the existence of impurity gas aggravates the difficulty to realize miscible flooding. It is urgent to study the feasibility of CO<sub>2</sub> near miscible flooding technology to provide theoretical and technical basis for its application. Shyeh Yung (1995) [1], Crigg (1997) [2], Schechter (1998) [3] and Dong (2000) [4] have confirmed that the near miscible region is the transition region between the miscible and immiscible zone, which is described as a region close to but lower than minimum miscible pressure (MMP). With the decrease of injection pressure, the oil recovery of this area does not decrease as obviously as that of slim-tube experiment. Li Yang [5] put forward the theory of incomplete miscible flooding based on miscibility degree, which reflects the actual process of CO<sub>2</sub> flooding in low permeability reservoir. The degree of oil-gas miscibility is mainly related to oil-gas system, and depends on reservoir temperature, the composition of crude oil and injected gas [6]. For a specific

reservoir, the temperature changes little, so the miscibility is mainly affected by the composition of crude oil and injected gas. Foreign scholars mainly use empirical formula method and numerical simulation to calculate the MMP, Rathmell [7] thought that MMP is related to volatile components and intermediate components in crude oil. Alston and others [8] found that it has a greater impact on the MMP when the content difference between volatile components and intermediate components is large. Yelling and Metcalfe [9] found that the change of gas oil ratio in saturated reservoir would lead to the change of MMP. Dong [10] and others systematically summarized the mixing mechanism of CO<sub>2</sub> crude oil system, and considered that the content of dissolved gas and the ratio of light hydrocarbon to intermediate hydrocarbon are two important parameters affecting the value of MMP.

According to the characteristics of oil and fluid components in X oilfield, based on a large number of experiments and application data at home and abroad, this paper summarizes the CO<sub>2</sub> miscible/near miscible displacement mechanism, and analyzes the main control factors affecting the miscibility degree. A new empirical formula for predicting miscible/near miscible pressure of impure CO<sub>2</sub> is established by multivariate nonlinear fitting with the molar content of each component of impure CO<sub>2</sub>, C<sub>1</sub> content of oil component and formation temperature as parameters.

## **2 Mechanism of Enhanced Oil Recovery by CO<sub>2</sub> Flooding**

### **2.1 Reduction the Viscosity of Crude Oil**

When CO<sub>2</sub> is dissolved in crude oil, the viscosity of crude oil decreases significantly, and the decreasing range depends on the pressure, temperature and the viscosity of no carbonic acid crude oil. Generally speaking, the higher the viscosity of crude oil, the higher the percentage of viscosity reduction under the action of carbonic acid.

### **2.2 Extraction and Vaporization of Light Hydrocarbons in Crude Oil**

When the pressure exceeds a certain value, CO<sub>2</sub> mixture can extract and vaporize light hydrocarbons of different components in crude oil. CO<sub>2</sub> first extracts and vaporizes light hydrocarbons in crude oil, then vaporizes heavier hydrocarbons, and finally reaches stability. Extraction and vaporization are important mechanisms of CO<sub>2</sub> flooding.

### **2.3 Expansion of Crude Oil Volume**

A certain volume of CO<sub>2</sub> dissolved in crude oil can increase the volume of crude oil by 10%–100% with difference of pressure, temperature and composition of crude oil. The dissolves CO<sub>2</sub> in crude oil expands the volume of crude oil and increases the kinetic energy in the fluid, so as to improve the oil displacement efficiency.

## 2.4 Improvement Mobility Ratio

A large amount of CO<sub>2</sub> dissolved in crude oil and water will acidify the crude oil and water. The viscosity of crude oil decreases after carbonation. Since the mobility of oil and water tends to be close after carbonation, it can improve the mobility ratio of oil and water and expand the swept volume.

## 2.5 Reduction the Interfacial Tension

The oil-water interfacial tension (IFT) of most reservoirs is 10–20 mN/m. In order to make the residual oil saturation close to zero, the oil-water interfacial tension must be reduced to 0.001 mn/m or lower, and the oil recovery will be significantly improved if the interfacial tension is reduced to below 0.04 mN/m. The main function of CO<sub>2</sub> flooding is to extract and vaporize light hydrocarbons in crude oil. A large number of light hydrocarbons mixed with CO<sub>2</sub> can greatly reduce the oil-water interfacial tension, reduce the residual oil saturation, and improve the crude oil recovery.

## 2.6 Function of Dissolved Gas Flooding

When a large amount of CO<sub>2</sub> is dissolved in crude oil, it has the effect of dissolved gas drive. With the decrease of pressure, CO<sub>2</sub> escapes from the liquid, and gas driving force is generated in the liquid, which improves the displacement effect. In addition, some CO<sub>2</sub> displaces crude oil and occupies a certain pore space to become bound gas, which can also increase crude oil production.

## 3 Influence Factors of Near Miscibility of Impure CO<sub>2</sub>

Previous studies have shown that MMP mainly depends on the purity of CO<sub>2</sub>, crude oil composition and reservoir temperature [11, 12]. MMP increases with the rise of reservoir temperature and the relative molecular weight of components of C5+. If the critical temperature of impurities is lower than that of CO<sub>2</sub>, MMP decreases; otherwise, MMP increases. Through statistical analysis of a large number of slim-tube experimental data, the main controlling factors of MMP are analyzed with the help of the empirical formula established by yuan [6]. Reservoir temperature, volatile component content and C7+ molar mass are positive correlation variables with the value of MMP, MMP increases with the increase of these three parameters, in turn, the influence degree decreases. C2–C4 and C5–C6 are negative correlation variables, and the miscibility degree increases with the increase of above parameters. It is obvious that reservoir temperature is the primary influencing factor of miscibility and near miscibility, followed by volatile component content and C7+ molar mass, which are positive correlation variables of MMP and MNMP; while C2–C4 and C5–C6 content in crude oil are negative correlation variables, and miscibility increases with the increase of content (Fig. 1).

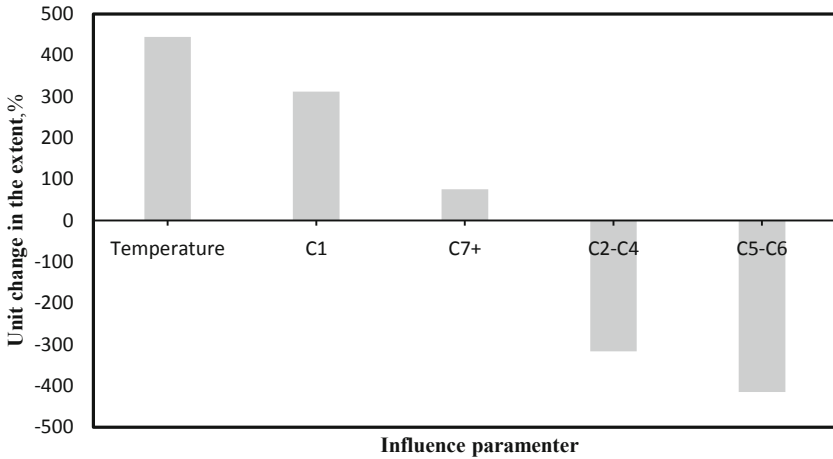


Fig. 1. The influence degree of unit change of each influencing factor on MMP

## 4 Prediction of Near Miscible Pressure of Impure CO<sub>2</sub>

### 4.1 Existing Empirical Formula

The empirical formula is not as accurate as the slim-tube experiment and the slim-tube simulation, but it is simple and convenient, so it is widely studied to calculate the MMP by foreign scholars. Based on the existing empirical formula [6, 11–13], the pure CO<sub>2</sub> and impure CO<sub>2</sub> flooding pressures of the target reservoir were calculated and compared with the results of thin tube experiment. The results were shown in Table 1 and 2. It can be seen from Table 1 that the empirical formula error of Lee (1979), Orr (1986) and Yuan (2004) methods is less than 10% compared with the slim-tube experiment. Considering the wide range of impurity gas content, Glaso (1985) is not suitable, and Yuan (2004) is used to calculate MMP of impure CO<sub>2</sub> flooding, but the error is more than 15%.

Table 1. Comparison of MMP on the existing empirical formula (100% CO<sub>2</sub>)

Empirical formula	Formula calculation, MPa	Experiment, MPa	Results relative error, %
Orr(1986)	28.19	30.33	7.06
Cronquist (1978)	24.27		17.71
Lee (1979)	28.27		4.17
Yelig.M.F (1980)	19.99		32.24
Alston (1985)	34.23		16.04
Glaso (1985)	36.59		24.05
Yuan (2004)	27.24		7.67

**Table 2.** MMP comparison of yuan (2004) formula with slim-tube test/simulation (impure CO<sub>2</sub>)

CO <sub>2</sub> content, mol%	Empirical formula, MPa	Slim-tube test/simulation, MPa	Relative error, %
100	27.24	30.33	7.67
85	27.88	32.96	15.40
70	29.56	35.01	15.57
55	31.34	37.96	17.44
40	33.12	39.78	16.75

## 4.2 New Empirical Formula of MMP

Based on a large number of slim-tube experimental data in domestic and foreign literatures, the empirical formula of MMP for pure/impure CO<sub>2</sub> flooding is established.

### (1) Empirical formula of pure CO<sub>2</sub>.

When the injected gas is pure CO<sub>2</sub>, the formation temperature, the molar content of (C<sub>2</sub>–C<sub>4</sub>), the molar content of (C<sub>5</sub>–C<sub>6</sub>) and the average molar mass of C<sub>7+</sub> are taken as independent variables, MMP is taken as dependent variable, and the linear regression is carried out by the regress function:

$$MMP_{PURE} = -2.455 + 0.169 * T_R + 0.039 * MW_{C_{7+}} + 0.127 * X_{C_1} - 0.145 * X_{C_2-C_4} - 0.233 * X_{C_5-C_6} \quad (1)$$

where,  $T_R$ , reservoir temperature, °C;  $Mw_{C_{7+}}$ , molar mass of C<sub>7+</sub> in crude oil, g/mol;  $X_{C_1}$ , molar content of C<sub>1</sub> + N<sub>2</sub> in crude oil, mol%;  $X_{C_2-C_4}$ , mole content of C<sub>2</sub>–C<sub>4</sub> in crude oil;  $X_{C_5-C_6}$ , mole content of C<sub>5</sub>–C<sub>6</sub> in crude oil, mol%.

All the data points of the slim-tube experiment under pure CO<sub>2</sub> condition are within 10% of the error of the fitting formula, and the fitting effect is good.

### (2) Empirical formula of impure CO<sub>2</sub>.

Since the impurity gases contained in the injection gas are generally N<sub>2</sub>, H<sub>2</sub>S, C<sub>1</sub>, C<sub>2</sub>–C<sub>6</sub>, the impurity gases should be considered in the empirical formula fitting process of impure CO<sub>2</sub>. In addition, the influence of C<sub>1</sub> content in injected gas on MMP is closely related to the existing C<sub>1</sub> content in crude oil. Taking the MMP difference of under the condition of impure CO<sub>2</sub> and under the condition of pure CO<sub>2</sub> as the dependent variable, taking the molar content of each component of impurity gas, C<sub>1</sub> content of oil component and reservoir temperature as the parameter variables, the multivariate nonlinear fitting is carried out, and the empirical formula of MMP for impure CO<sub>2</sub> flooding is established.

$$MMP_{IMP} = \{(3.44 * X_{injC_1} + 4.89 * X_{injN_2}) * vol^{0.11945} - 1.08 * X_{injH_2S} - 4.01 * X_{inj(C_2-C_6)}\} / 6.91 * T_R^{0.22524} + MMP_{PURE} \quad (2)$$

where,  $MMP_{IMP}$ , minimum miscible pressure with impure CO<sub>2</sub>, MPa;  $X_{injC_1}$ , molar content of C<sub>1</sub> in the injection gas, mol%;  $X_{injN_2}$ , molar content of N<sub>2</sub> in injection gas, mol%;;  $X_{injH_2S}$ , mole content of H<sub>2</sub>S in injection gas, mol%;  $X_{injC_2-C_6}$ , mole content of C<sub>2</sub>–C<sub>6</sub> in injection gas, mol%; Vol, mole content of C<sub>1</sub> and N<sub>2</sub> in formation oil, mol%.

Based on the data points of thin tube experiment, the error of the new empirical formula of MMP for impure CO<sub>2</sub> flooding is less than 10%, as shown in Fig. 2. Taking the target reservoir E-5 (3303–3330 m) as an example, the newly established pure/impure CO<sub>2</sub> flooding empirical formula is used to calculate the MMP. Compared with the results of thin tube experiment/numerical simulation, the relative error is less than 7%, and the calculation accuracy is higher, as shown in Table 3.

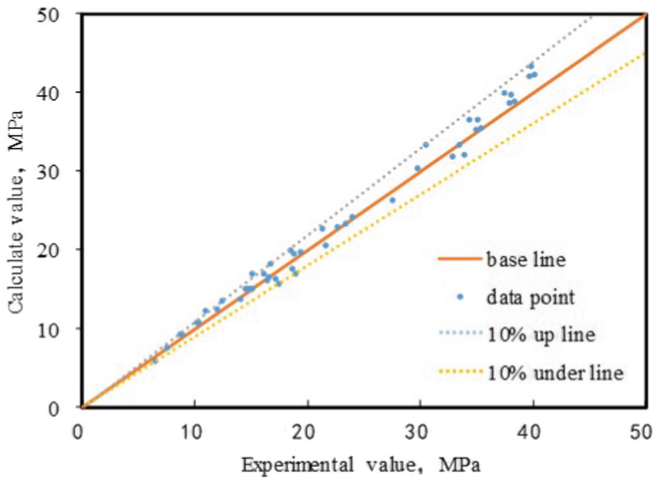


Fig. 2. Comparison of calculated values and slim-tube test

Table 3. Comparison of MMP by new empirical formula and slim-tube test

CO <sub>2</sub> content, mol%	new empirical formula, MPa	slim -tube test /simulation, MPa	Relative error, %
100	28.46	30.33	6.18
85	31.85	32.96	3.36
70	35.25	35.01	0.67
55	38.64	37.96	1.79
40	42.03	39.78	5.66

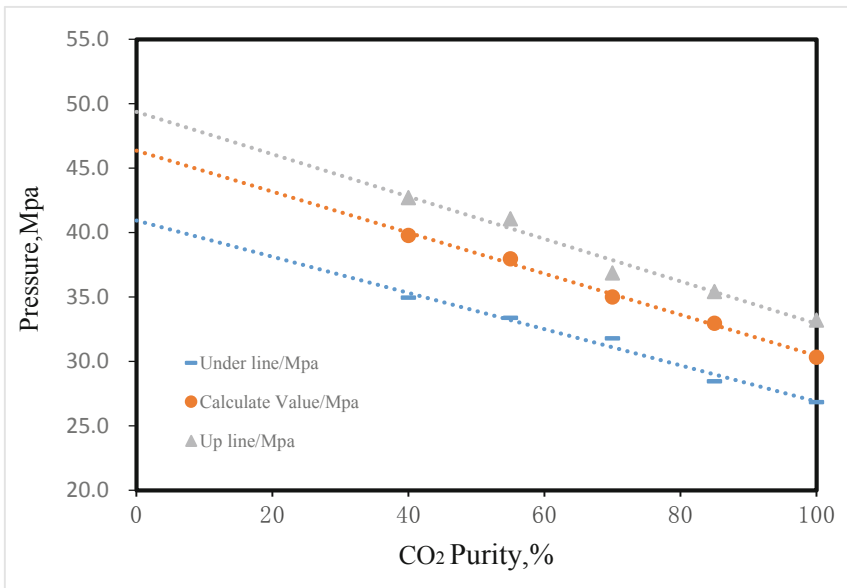
### 4.3 Near Miscible Pressure of Impure CO<sub>2</sub>

Using reference [14] to determine the upper and lower limits of near miscible pressure region, and comparing with the method of slim-tube to determine MMP, the relationship

between the low and up limit of near miscible pressure (MNMP) is obtained under different CO<sub>2</sub> purity, as shown in Table 4 and Fig. 3. Compared with the experimental results, the relative error of the new formula is less than 7%. With the decrease of CO<sub>2</sub> purity, both MMP and MNMP increase linearly. By comparing with formation pressure, it can be concluded that the CO<sub>2</sub> purity range corresponding to near miscible flooding in E5 well is 64%–100%, which indicates that the potential space of impure CO<sub>2</sub> near miscible flooding in the target reservoir is relatively large.

**Table 4.** Near miscible pressure region under different CO<sub>2</sub> content

CO <sub>2</sub> content, %	Low limit of near miscible pressure, MPa	Slim –tube test/simulation, MPa	Up limit of near miscible pressure, MPa
100	26.85	30.33	33.21
85	28.47	32.96	35.43
70	31.80	35.01	36.87
55	33.38	37.96	41.08
40	34.95	39.78	42.72



**Fig. 3.** Pressure region of near miscible under different CO<sub>2</sub> purity

### 5 Development Effect of Different Miscibility Degree

A three-dimensional reservoir model was built by Eclipse software by the target reservoir characteristics. The grid is divided into 20 × 20 × 3, the grid size is 10 × 10 × 1 m.

The reservoir pressure is 33 MPa and oil saturation is 60%. The injection wells and production wells are located at two opposite corners of the model respectively. The change of oil saturation at the same time of gas flooding was calculated by numerical simulation under different CO<sub>2</sub> purity, as shown in Fig. 4. CO<sub>2</sub> purity of 40% represents immiscible flooding, CO<sub>2</sub> purity of 80% represents near miscible flooding, and CO<sub>2</sub> purity of 100% represents miscible flooding. It can be seen that the sweep range and displacement efficiency of CO<sub>2</sub> near miscible flooding are closer to miscible flooding. The cumulative recovery of immiscible flooding, near miscible flooding and miscible flooding was 42.27%, 54.8% and 58.68% respectively. The recovery degree of near miscible flooding is 1.29 times of that of immiscible flooding, which is only 3.88% lower than that of miscible flooding, it indicates that the development effect of CO<sub>2</sub> near miscible flooding is closer to that of miscible flooding. Considering the difficulty and cost of CO<sub>2</sub> separation and purification, and miscible flooding is very limited to improve oil recovery, so the feasibility is very high by near miscible flooding with 80% CO<sub>2</sub> purity.

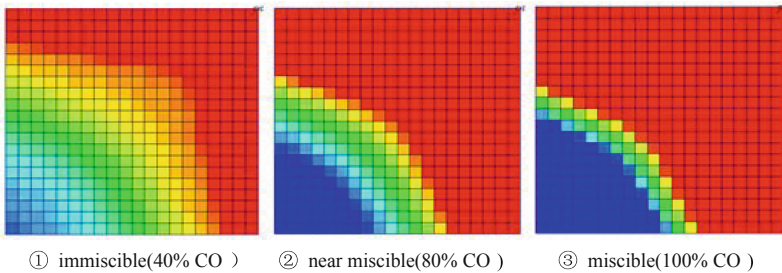


Fig. 4. Oil saturation of gas flooding with different CO<sub>2</sub> purity

## 6 Conclusions and Suggestions

- 1) The main influencing factors of miscibility degree of CO<sub>2</sub> flooding is as flowing: reservoir temperature, C<sub>7+</sub> mole fraction in crude oil, content of volatile components (CH<sub>4</sub> + N<sub>2</sub>), (C<sub>2</sub>-C<sub>4</sub>) and (C<sub>5</sub>-C<sub>6</sub>), content of CH<sub>4</sub>, N<sub>2</sub>, H<sub>2</sub>S and intermediate components (C<sub>2</sub>-C<sub>6</sub>) in injected gas.
- 2) An empirical formula for calculating the pressure region of pure/impure CO<sub>2</sub> miscible flooding is established. The relative error is less than 10%, which can quickly evaluate the feasibility of impure CO<sub>2</sub> near miscible flooding in low permeability reservoirs.
- 3) The lower limit of CO<sub>2</sub> purity of near miscible flooding is more than 64%, the recovery degree of near miscible flooding is 1.29 times of that of immiscible flooding, which is only 3.88% lower than that of miscible flooding, the feasibility is very high by near miscible flooding.



- 4) The implementation of near miscible flooding not only reduces the pressure requirements, but also relaxes the requirements of gas source purity, and reduces the operation cost, which is conducive to promoting the implementation of CO<sub>2</sub> near miscible flooding technology.

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