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Research Article

An Improved CO_2-Crude Oil Minimum Miscibility Pressure Correlation

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Minimum miscibility pressure (MMP), which plays an important role in miscible flooding, is a key parameter in determining whether crude oil and gas are completely miscible. On the basis of 210 groups of CO_2-crude oil system minimum miscibility pressure data, an improved CO_2-crude oil system minimum miscibility pressure correlation was built by modified conjugate gradient method and global optimizing method. The new correlation is a uniform empirical correlation to calculate the MMP for both thin oil and heavy oil and is expressed as a function of reservoir temperature, C_{7+} molecular weight of crude oil, and mole fractions of volatile components (CH_4 and N_2) and intermediate components (CO_2, H_2S, and C_2~C_6) of crude oil. Compared to the eleven most popular and relatively high-accuracy CO_2-oil system MMP correlations in the previous literature by other nine groups of CO_2-oil MMP experimental data, which have not been used to develop the new correlation, it is found that the new empirical correlation provides the best reproduction of the nine groups of CO_2-oil MMP experimental data with a percentage average absolute relative error (%AARE) of 8% and a percentage maximum absolute relative error (%MARE) of 21%, respectively.

1. Introduction

CO_2 injection is one of the most effective methods to enhance oil recovery [1]. Generally, the oil recovery of miscible flooding is higher than nonmiscible flooding. The minimum miscibility pressure (MMP) at which the crude oil and CO_2 become miscible is a key factor because, in general, the CO_2 is not miscible at first contact with reservoir oils but may achieve dynamic miscibility through multiple contact [2]. At present, prediction of the MMP commonly contains three methods: experiment [3], empirical correlation [4], and equation of state [5, 6]. The slim tube test is one of the most commonly used test methods [3]; in addition, there are rising-bubble apparatus (RBA) method [7], steam density method [8], multiple contact method [9], and interfacial tension vanish method [10]. The experimental method is the standard method, but it needs to consume large amounts of time and money. Equation of state is precise and fast, but the miscibility function is difficult to give a clear judgment standard, because a characterization procedure of the plus-fraction must be used and such a characterization can have a huge influence on the calculated value. Thus, empirical correlation is usually used for predicting the MMP. Most the MMP empirical correlations are proposed based on the experimental data of CO_2-oil system, while these MMP empirical correlations of CO_2-oil system have certain constraints.

This study has two objectives. The first objective is to utilize the modified conjugate gradient and global optimization algorithm for establishing a four-parameter and improved MMP prediction model of CO_2-oil system, which has a wider range of application, taking advantage of 210 groups of CO_2-oil MMP experimental data tested by slim tube experiment in the literature. The second objective is to compare this model with the other eleven most popular and relatively high-accuracy CO_2-oil MMP correlations presented in the previous literature by using other nine groups of CO_2-oil MMP experimental data, which have not been used to develop the new correlation.

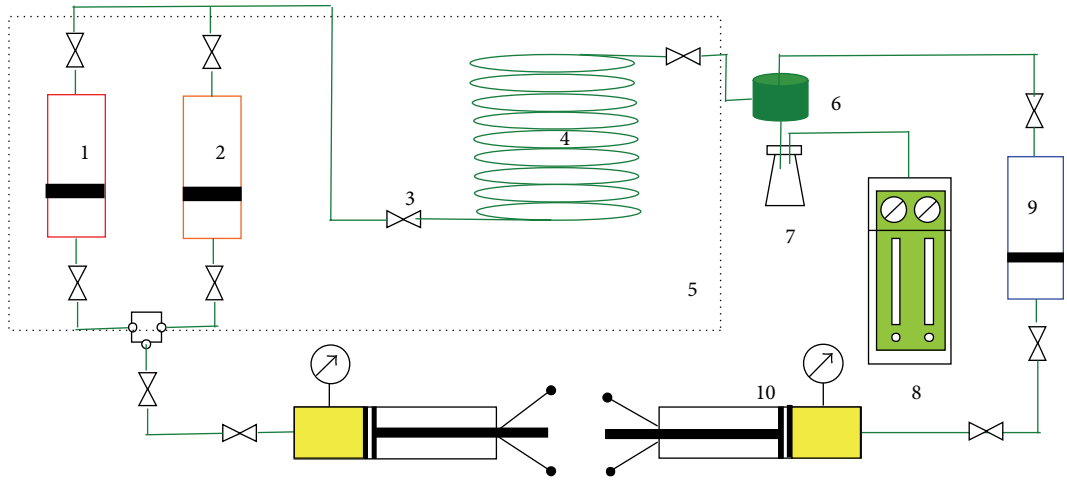

Figure 1: Schematic diagram of the slim tube experimental apparatus.

Table 1: Compositional analysis results of three oil samples with C_{7+} molecular weight in mole percentage.

Component	Oil sample 1	Oil sample 2	Oil sample 3
CO_2	2.076	0.889	0.38
N_2	0.887	1.962	0.56
C_1	31.744	14.96	13.21
C_2	8.217	8.545	2.55
C_3	7.86	5.563	3.66
IC_4	1.756	0.434	1.42
NC_4	3.222	1.072	3.78
IC_5	1.954	0.067	1.68
NC_5	1.531	0.165	2.74
FC_6	4.366	0	8.26
C_{7+}	36.387	66.343	61.79
Total	100.00	100.00	100.00
$M_{C_{7+}}$	183.69	245.36	229.17

2. Experimental Section

The slim tube test has become a standard method to measure the MMP in the petroleum industry. In this study, the CO_2-oil MMPs of three crude oil samples (i.e., oil 1, oil 2, and oil 3) are measured by using the slim tube test method. Table 1 shows the compositional analysis results of these three oil samples. It can be seen from the compositional analysis results that all these three oil samples used in this study have a large amount of volatile components (N_2 and CH_4) and C_{7+} fraction. The molecular weights of C_{7+} fraction for oil 1, oil 2, and oil 3 are measured to be 183.69 g/mol, 245.36 g/mol, and 229.17 g/mol, respectively.

The slim tube apparatus used in this study is a stainless steel fine tube (length of 20 m, inner diameter of 4.4 mm, and a total pore volume of 92.75 cm^3) filled with the 80~100 mesh quartz sand. Schematic diagram of the slim tube experimental apparatus is shown in Figure 1. The slim tube tests are performed on the recombined reservoir fluid with CO_2 at the given reservoir temperature. Once the slim tube is saturated with the crude oil sample, the CO_2 is introduced to displace the oil at an injection rate of 0.125 cm^3/min.

CO_2 displacement experiments are carried out at several pressures with the temperature being maintained constant at the reservoir temperature. For each test pressure, the pore volume of CO_2 injected, produced oil volume, and produced gas volume are recorded. Figure 2 plots the oil recovery factors measured at 1.20 pore volume of CO_2 injected as a function of operating pressure for oil sample 1. The acknowledged criterion for determining slim tube test to achieve miscibility is the oil recovery greater than 90% when 1.20 pore volume of CO_2 or other gases is injected, and with the displacement pressure increased, the displacement efficiency is no longer increasing [11, 12]. The CO_2-oil MMP at 130°C for oil sample 1 is determined to be 20.65 MPa by pinpointing the breakpoint of the oil recovery curve (see Figure 2). By applying the same methodology as for other temperature points (110°C, 90°C, and 70°C) for oil sample 1, the CO_2 flooding minimum miscibility pressure is 20.35 MPa, 19.95 MPa, and 19.3.8 MPa, respectively. As for oil sample 2 and oil sample 3 at 74.8°C and 89.7°C formation, the CO_2 flooding minimum miscibility pressure is 26.80 MPa and 22.65 MPa, respectively. A conservative error of 3% can be applied due to its complexity. Figures 2 and 3 indicate that crude oil recovery increases with injecting pressure and CO_2-crude oil minimum miscible increases with temperature.

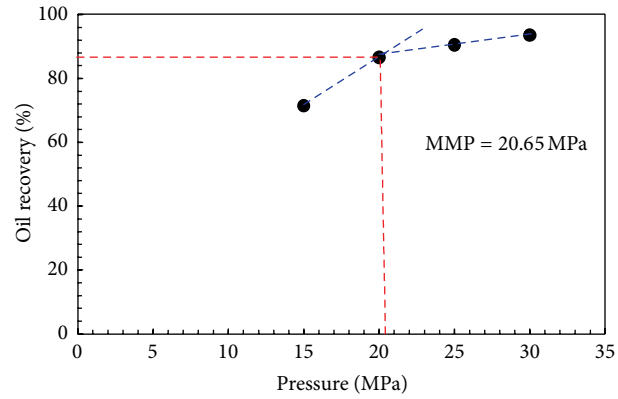

Figure 2: Variation of the oil recovery measured at 1.20 pore volume of CO_2 injected at various injection pressure for oil sample 1.

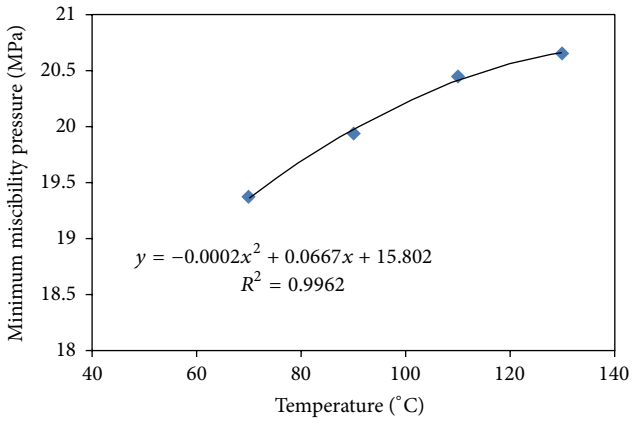

Figure 3: Variation of oil sample miscibility pressure with temperature.

3. Building of MMP Predicting Model

3.1. Existing Methods. Over the years, several empirical correlations have been developed for determining the MMP of CO_2-oil system. The most popular and relatively high-accuracy correlations applied for prediction of CO_2-oil MMP are those developed by Cronquist [4], Lee [13], Yelling-Metcalfe [14], Orr-Jensen [15], Glaso [16], Alston [17], Emera-Sarma [18], Yuan [19], Shokir [20], Chen [21], and Ju [22]. Table 2 shows the expression of the above correlations and its application restrictions.

3.2. Main Factors Influencing the MMP. Reviewing published MMP slim tube test data and previously presented empirical models indicates the existence of the following [21, 22]:

(1) The MMP of CO_2-oil system is determined by the reservoir temperature, the components in the injected gas, and the components and properties of oil.

(2) On the constant condition of the components in the injected gas and the components and properties of oil, the MMP increases with increasing the reservoir temperature.

(3) On the constant condition of the components in the injected gas and the reservoir temperature, the higher the content of C_2~C_6 and the lower the molecular weight in the crude oil, the smaller MMP. On the contrary, the more the heavy components in the crude oil are, the less favorable it will be for miscibility.

(4) On the constant condition of the reservoir temperature and the components and properties of oil, the MMP decreases with increasing the content of intermediate components (CO_2, H_2S, and C_2~C_6) and increases with increasing the content of volatile components (CH_4 and N_2) in the injected gas.

The paper is focused on building an improved MMP model of pure CO_2-oil system, so the influence of injection gas components on MMP has been taken into account. Based on the shortages of the above empirical formula in Table 2 and the sensitive factors proposed in Section 3.2 influencing the MMP, we selected the four sensitive factors including reservoir temperature, relative molecular weight of C_{7+}, the volatile components (CH_4 and N_2), and intermediate components (CO_2, H_2S, and C_2~C_6) of crude oil to develop an improved MMP prediction correlation with four parameters by using the modified conjugate gradient and global optimization algorithm regression theory.

3.3. Mathematical Model. The determined MMP of CO_2-crude oil system is the result of multiple factors interaction. Therefore, we should take full account of the sensitive factors in Section 3.2 and then maximize and utilize the experimental data. However, when the independent variable and dependent variable uncertainty or error is larger, prediction results by the traditional least squares linear regression method are very low. Thus, the optimization and regression algorithm can solve the problem well. In this paper we use the modified conjugate gradient and global optimization algorithm to establish a prediction model for the MMP of CO_2-oil system.

And the prediction model, based on Emera-Sarma model, also consists of four affecting factors (reservoir temperature, C_{7+} molecular weight of crude oil, mole fractions of volatile components (CH_4 and N_2), and mole fractions of intermediate components (CO_2, H_2S, and C_2~C_6) in the crude oil) and four parameters; the following improved correlation was developed:

$$P_{m,\min,\text{pure}} = a\left[\ln(1.8T+32)\right]^b\left[\ln\left(M_{C_{7+}}\right)\right]^c\left(1+\frac{x_{\text{VOL}}}{x'_{\text{MED}}}\right)^d. \quad (1)$$

On the basis of Emera-Sarma model, reservoir temperature, $M_{C_{7+}}$ in crude oil, mole content of volatile component (CH_4 and N_2), and mole content ratio of intermediate components (CO_2, H_2S, and C_2~C_6) in crude oil were modified. The term $\ln(1.8 \times T + 32)$ is used to suppress temperature effect on the hydrocarbon gas-oil MMP when the reservoir temperature is relatively high. The reason why $M_{C_{7+}}$ instead of $M_{C_{5+}}$ is used in the correlation is partially because $M_{C_{7+}}$ is a routine measurement item in a typical compositional analysis

Table 2: Correlations for CO_2-oil MMP.

Author	Published empirical correlation	Remarks
Cronquist [4]	(a) $P_{m,\min,\text{pure}} = 0.11027\,(1.8T + 32)^{0.744206+0.0011038M_{C_5}+0.0015279x_{VOL}}$	(i) The tested oil gravity ranged from 23.7 to 44.8°API (ii) The tested T ranged from 21.67 to 120.8°C (iii) The tested experimental MMP ranged from 7.4 to 34.5 MPa
Lee [13]	(b) $P_{m,\min,\text{pure}} = 7.3924 \times 10^{2.772-[1519/(492+1.8T)]}$	(i) Based on equating MMP with CO_2 vapor pressure when $T < CO_2$ critical temperature, while using the corresponding correlation when $T \geqslant CO_2$ critical temperature (ii) If MMP < P_b, P_b is taken as MMP
Yelling-Metcalfe [14]	(c) $P_{m,\min,\text{pure}} = 12.6472 + 0.01553(1.8T + 32) + 1.24192 \times 10^{-4}\,(1.8T + 32)^2 - \dfrac{716.9427}{(1.8T + 32)}$	Limitations: $35.8 \leq T < 88.9$°C (i) If MMP < P_b, P_b is taken as MMP
Orr-Jensen [15]	(d) $P_{m,\min,\text{pure}} = 0.101386 \exp\left[10.91 - \dfrac{2105}{255.372 + 0.5556\,(1.8T + 32)}\right]$	(i) Based on extrapolated vapor pressure (EVP) method (ii) Used to estimate the MMP for low temperature reservoirs ($T < 49$°C)
Glaso [16]	When $x'_{\text{MED}} < 18$ mol%, (e1) $P_{m,\min,\text{pure}} = 5.58657 - 2.3477 \times 10^{-2} M_{C_{7+}} + 1.1725 \times 10^{-11} M_{C_{7+}}^{3.73} \exp^{786.8M_{C_{7+}}{}^{-1.058}} (1.8T + 32)$ When $x'_{\text{MED}} > 18$%, (e2) $P_{m,\min,\text{pure}} = 20.33 - 2.3477 \times 10^{-2} M_{C_{7+}} + 1.1725 \times 10^{-11} M_{C_{7+}}^{3.73} \exp^{786.8M_{C_{7+}}{}^{-1.058}} (1.8T + 32) - 0.836 \times x'_{\text{MED}}$	Considers the effect of intermediates (C_2–C_6) only when x'_{MED} (C_2–C_6) < 18 mol%
Alston [17]	When $P_b \geq 0.345$ MPa (f1) $P_{m,\min,\text{pure}} = 6.0536 \times 10^{-6}\,(1.8T + 32)^{1.06} \left(M_{C_{5+}}\right)^{1.78} \left(\dfrac{x_{\text{VOL}}}{x_{\text{MED}}}\right)^{0.136}$ When $P_b < 0.345$ MPa (f2) $P_{m,\min,\text{pure}} = 6.0536 \times 10^{-6}\,(1.8T + 32)^{1.06} \left(M_{C_{5+}}\right)^{1.78}$	If MMP < P_b, P_b is taken as MMP
Emera-Sarma [18]	When $P_b \geq 0.345$ MPa (g1) $P_{m,\min,\text{pure}} = 5.0093 \times 10^{-5}\,(1.8T + 32)^{1.164} \left(M_{C_{5+}}\right)^{1.2785} \left(\dfrac{x_{\text{VOL}}}{x_{\text{MED}}}\right)^{0.1073}$ When $P_b < 0.345$ MPa (g2) $P_{m,\min,\text{pure}} = 5.0093 \times 10^{-5}\,(1.8T + 32)^{1.164} \left(M_{C_{5+}}\right)^{1.2785}$	Limitations: $40.8 < T < 112.2$°C; $8.28 < P_{m,\min,\text{pure}} < 30.2$ MPa; $166.2 < M_{C_{5+}} < 267.5$ g/mol
Yuan [19]	(h) $P_{m,\min,\text{pure}} = a_1 + a_2 M_{C_{7+}} - a_3 x'_{\text{MED}} + \left(a_4 + a_5 M_{C_{7+}} + a_6 \dfrac{x'_{\text{MED}}}{M_{C_{7+}}{}^2}\right)(1.8T + 32) + \left(a_7 + a_8 M_{C_{7+}} - a_9 M_{C_{7+}}{}^2 - a_{10} x'_{\text{MED}}\right)(1.8T + 32)^2$ $a_1 = -9.8912$; $a_2 = 4.5588 \times 10^{-2}$; $a_3 = -3.1012 \times 10^{-1}$; $a_4 = 1.4748 \times 10^{-2}$ $a_5 = 8.0441 \times 10^{-4}$; $a_6 = 5.6303 \times 10^{1}$; $a_7 = -8.4516 \times 10^{-4}$; $a_8 = 8.8825 \times 10^{-6}$ $a_9 = -2.7684 \times 10^{-8}$; $a_{10} = -6.3830 \times 10^{-6}$	Limitations: $21.7 < T < 148$°C; $P_{m,\min,\text{pure}} < 70$ MPa; $139 < M_{C_{7+}} < 319$ g/mol

Table 2: Continued.

Author	Published empirical correlation	Remarks
Shokir [20]	(i1) $P_{m,\min,\text{pure}} = -0.068616Z^3 + 0.31733Z^2 + 4.9804Z + 13.432$ (i2) $Z = \sum_{i=1}^{4} Z_i$ (i3) $Z_i = a_i + b_i x_i + c_i {x_i}^2 + d_i {x_i}^3$ $a_1 = -2.9182$; $a_2 = -3.1227 \times 10^{-1}$; $a_3 = -4.9485 \times 10^{-2}$; $a_4 = 25.430$ $b_1 = 7.5340 \times 10^{-2}$; $b_2 = -7.9169 \times 10^{-3}$; $b_3 = 4.2165 \times 10^{-2}$; $b_4 = -3.9750 \times 10^{-1}$ $c_1 = -5.5996 \times 10^{-4}$; $c_2 = 1.3644 \times 10^{-3}$; $c_3 = -2.7853 \times 10^{-3}$; $c_4 = 1.9860 \times 10^{-3}$ $d_1 = 2.3660 \times 10^{-6}$; $d_2 = -1.3721 \times 10^{-5}$; $d_3 = 3.5551 \times 10^{-5}$; $d_4 = -3.1604 \times 10^{-6}$	Limitations: $32.2 < T < 112.2^{\circ}$C; $6.9 < P_{m,\min,\text{pure}} <$ 30.28 MPa; $185 < M_{C_{5+}} < 268$ g/mol
Chen [21]	(j) $P_{m,\min,\text{pure}} = 3.9673 \times 10^{-2} T^{0.8293} \left(M_{C_{7+}}\right)^{0.5382} \left(x_{C_1+N_2}\right)^{0.1018} \left(x_{C_2-C_6}\right)^{-0.2316}$	Limitations: $32.2 < T < 118.3^{\circ}$C; $6.9 < P_{m,\min,\text{pure}} <$ 28.17 MPa; $185 < M_{C_{7+}} < 249$ g/mol
Ju [22]	(k1) $P_{m,\min,\text{impure}} = -0.04562S^3 + 0.33399S^2 + 4.9811S + 13.569$ (k2) $S = \sum_{i=1}^{8} S_i$ (k3) $S_i = a_i + b_i x_i + c_i {x_i}^2 + d_i {x_i}^3$ The detailed parameters refer to [18]	Limitations: $P_{m,\min,\text{pure}} < 40$ MPa

Table 3: Regression parameters.

Parameters	Value
a	8.3397×10^{-5}
b	3.9774
c	3.3179
d	1.7461×10^{-1}

report, while $M_{C_{5+}}$ normally need to be calculated from $M_{C_{7+}}$. In addition, it is found in this study that the use of $M_{C_{7+}}$, rather than $M_{C_{5+}}$, even leads to a slightly better performance of (1) in terms of the correlation coefficient R^2. Meanwhile, $M_{C_{7+}}$ is replaced by $\ln(M_{C_{7+}})$ to reduce the influence of $M_{C_{7+}}$ on the MMP of CO_2-oil system when $M_{C_{7+}}$ is larger. And x_{VOL}/x'_{MED} is replaced by $(1 + x_{VOL}/x'_{MED})$ to avoid the fact that x_{VOL}/x'_{MED} approaches to zero because of too fewer volatile components in heavy oil which result in great differences between the parameters.

The objective optimization function contains four parameters ($m = (m_1, m_2, m_3, m_4)$). The CO_2-oil MMP database used in this study includes a total of 210 MMP measurements from the literature, among which the temperature has a range of 21.67°C~191.97°C and C_{7+} molecular weights range from 130 g/mol to 402.7 g/mol [2, 20–37]. In addition, it should be noted that 176 out of the 210 measurements are obtained from overseas data in the literature, while the remaining 34 measurements are obtained from domestic data in the literature. The CO_2-oil MMP database is used to determine the tuned coefficients ($m = (m_1, m_2, m_3, m_4)$) in (1) by regression fitting using the modified conjugate gradient and global optimization algorithm. The regression fitting has been conducted by using the Matlab programming. The tuned coefficients are given in Table 3 and (1) generates a fit with $R^2 = 0.9488$ (Figure 4).

Step 1. Given the constant $\sigma_1 \in (0, 1/2)$, $\sigma_1 < \sigma_2 < 1$, $\varepsilon > 0$, pick the initial point $m_0 \in R^4$, $d_0 = -g_0$, and place $k = 0$.

Step 2. If $\|g_k\| < \varepsilon$, algorithm stops and m_k in $f(m)$ is to be obtained; otherwise, algorithm turns to Step 3. g_k, the conjugate gradient of $f(m)$ at m_k, represents $g_k = \beta_k \times f(m_k)$, in which $\|g_k\|$ is the norm of g_k and β_k is the parameter. Generally, two expression forms include $\beta_k^{FR} = \|g_k\|^2/\|g_{k-1}\|^2$ and $\beta_k^{PR} = g_k^T(g_k - g_{k-1})/\|g_{k-1}\|^2$ [22]. In this paper, $\beta_k = \max\{0, \beta_k^{FR} + \min\{0, g_k^T g_{k-1}/g_{k-1}^T d_{k-1}\}\}$, in which g_k^T is the transposed conjugate gradient.

Step 3. Step length α_k is determined by 1D linear search.

Step 4. Place $m_{k+1} = m_k + \alpha_k d_k$, in which d_k is the conjugate gradient search direction and is determined as follows:

$$d_k = \begin{cases} -g_k & k = 0, \\ -\theta_k g_k + \beta_k d_{k-1} & k \geq 1, \end{cases} \tag{2}$$

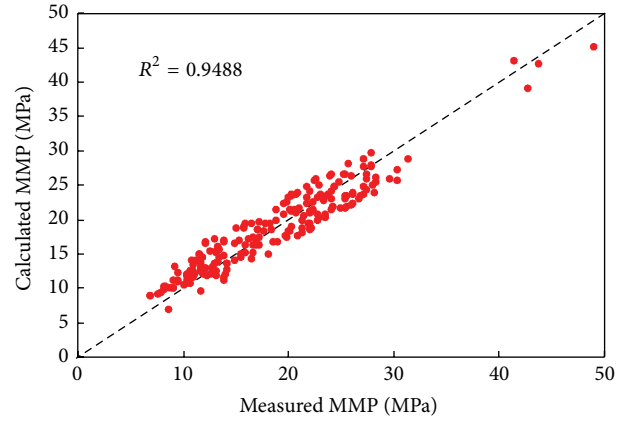

Figure 4: Resulted CO_2-oil MMP from the new correlation versus the experimental measurements.

in which $\theta_k = 1 + (g_k^T d_{k-1}/\|g_k\|^2)\beta_k$. It can be inferred that $d_k = -g_k - (g_k^T d_{k-1}/\|g_k\|^2)\beta_k g_k + \beta_k d_{k-1}$, where g_k^T is to be multiplied at both sides to obtain the following expression:

$$\begin{aligned} g_k^T d_k &= -\|g_k\|^2 - \frac{g_k^T d_{k-1}}{\|g_k\|^2}\beta_k \|g_k\|^2 + \beta_k g_k^T d_{k-1} \\ &= -\|g_k\|^2 < 0. \end{aligned} \tag{3}$$

It is obvious that $g_k^T d_k$ is always less than 0 and g_k^T is greater than 0, which results in downward search direction. Moreover, if $\beta_k \neq 0$, $-g_k^T g_{k-1}/g_{k-1}^T d_{k-1} \geq 0$, $\beta_k = \beta_k^{FR}$, the modified conjugate gradient method is FR conjugate gradient method [38]. Otherwise, combining correlation ((c), see Table 2), we can draw that

$$\begin{aligned} \beta_k &= \beta_k^{FR} + \frac{g_k^T g_{k-1}}{g_{k-1}^T d_{k-1}} = \frac{\|g_k\|^2}{\|g_{k-1}\|^2} - \frac{g_k^T g_{k-1}}{\|g_{k-1}\|^2} \\ &= \frac{g_k^T (g_k - g_{k-1})}{\|g_{k-1}\|^2} = \beta_k^{PR}. \end{aligned} \tag{4}$$

It is called FR conjugate gradient method. It is indicated that the FR conjugate gradient method takes in excellent global convergence of FR algorithm and excellent numerical result of PR algorithm.

Step 5. d_k is determined, and place $k = k + 1$. Process turns to Step 2.

Finally, the modified MMP correlation of CO_2-crude oil is as follows:

$$\begin{aligned} f(m) = P_{m,\min,pure} &= 8.3397 \\ &\times 10^{-5} [\ln(1.8T + 32)]^{3.9774} \left[\ln\left(M_{C_{7+}}\right)\right]^{3.3179} \\ &\cdot \left(1 + \frac{x_{VOL}}{x'_{MED}}\right)^{0.17461}. \end{aligned} \tag{5}$$

Table 4: The nine oil samples components, properties, and MMP data for the new correlation validation.

T (°C)	$M_{C_{7+}}$	$M_{C_{5+}}$	x_{MED}	x'_{MED}	x_{VOL}	Experimental data (MMP) (MPa)	Reference
60.00	149.690	136.470	39.370	46.160	24.680	11.138	[39]
80.00	149.690	136.470	39.370	46.160	24.680	14.152	[39]
137.22	149.690	136.470	39.370	46.160	24.680	18.379	[39]
100.00	151.740	138.530	26.760	37.950	13.530	14.634	[40]
80.00	170.080	160.590	2.630	7.100	12.150	16.062	[41]
130.00	183.690	165.262	23.131	30.982	32.631	20.650	Current work
74.80	245.690	229.085	16.501	16.733	16.922	26.800	Current work
89.70	229.170	211.213	11.790	24.470	13.770	22.630	Current work
53.00	205.740	182.800	12.933	25.333	18.706	13.090	[42]

Compared with the other 11 correlations in Table 2, the correlation has broader application (pressure range: 0~70 MPa, temperature range: 21.67~191.97°C, and relative molecular weight of C_{7+}: 130~402.7 g/mol).

4. Calculation Results and Analysis

Generally, the absolute error (6), the absolute relative error (7), and the average absolute relative error (8) are used to express the deviation between the calculated MMP by the empirical correlation and optimize the most appropriate empirical correlation for predicting the MMP of CO_2-oil system:

$$\mathrm{AE} = \mathrm{Cal} - \mathrm{Exp}, \tag{6}$$

$$\mathrm{ARE}\,(\%) = \sum_{i=1}^{N} \left| \frac{\mathrm{Cal} - \mathrm{Exp}}{\mathrm{Exp}} \right|_i \times 100, \tag{7}$$

$$\mathrm{AARE}\,(\%) = \frac{1}{N} \sum_{i=1}^{N} \left| \frac{\mathrm{Cal} - \mathrm{Exp}}{\mathrm{Exp}} \right|_i \times 100. \tag{8}$$

A new correlation validation is performed with more MMP data (Table 4). These MMP data have not been used to develop the new correlation. The comparative results of the calculated MMP by the correlation proposed in this study and the other eleven most popular and relatively high-accuracy correlations presented in the previous literatures are shown in Figure 5 and Table 5. The average absolute relative errors (AARE) for the correlation proposed in this study, Cronquist's correlation, Lee's correlation, Yelling-Metcalfe's correlation, Orr-Jensen's correlation, Glaso's correlation, Alston's correlation, Emera-Sarma's correlation, Yuan's correlation, Shokir's correlation, Chen's correlation, and Ju's correlation are 8%, 16%, 37%, 20%, 32%, 19%, 20%, 13%, 27%, 21%, 14%, and 29%, respectively. The maximum absolute relative errors (MARE) for the proposed correlation in this study, Cronquist's correlation, Lee's correlation, Yelling-Metcalfe's correlation, Orr-Jensen's correlation, Glaso's correlation, Alston's correlation, Emera-Sarma's correlation, Yuan's correlation, Shokir's correlation, Chen's correlation, and Ju's correlation are 21%, 31%, 73%, 46%, 78%, 50%, 39%, 25%, 58%, 52%, 28%, and 57%, respectively. These results indicate that the proposed correlation in this study is significantly more precise than the other correlations. The results of the calculated MMP by the correlation proposed in this study, the measured MMP by slim tube test, and the absolute error (AE) are shown in Figures 5 and 6. From Table 5, it is clearly seen that the absolute errors (AE) of the calculated MMP by the model proposed in this study of many oil samples are less than 1.5 MPa, which are very close to the experimental data.

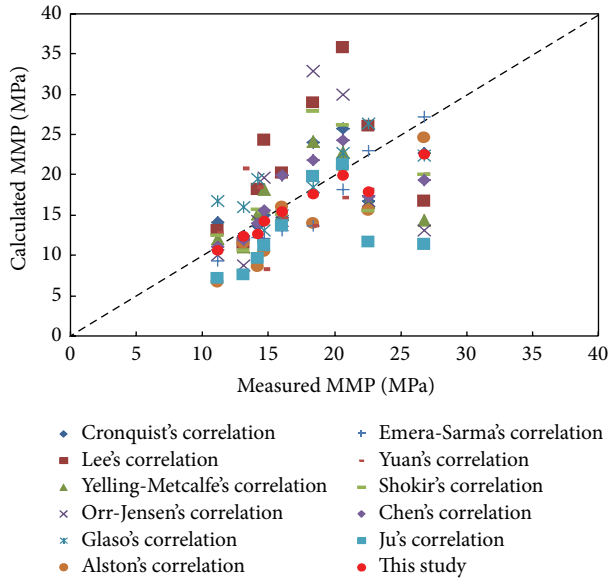

Figure 5: The resulted nine-oil-sample MMP from the new correlation proposed in this study versus the calculated nine-oil-sample MMP from Cronquist's correlation, Lee's correlation, Yelling-Metcalfe's correlation, Orr-Jensen's correlation, Glaso's correlation, Alston's correlation, Emera-Sarma's correlation, Yuan's correlation, Shokir's correlation, Chen's correlation, and Ju's correlation.

5. Conclusions

(1) Four sensitive factors are determined for affecting the MMP of CO_2-oil system, which includes the reservoir temperature, C_{7+} molecular weight of oil, mole fractions of volatile components (CH_4 and N_2), and mole fractions of intermediate components (CO_2, H_2S, and C_2~C_6) of oil. Based on the above sensitive factors, a four-parameter and improved MMP prediction model of CO_2-oil system is

Table 5: Comparison of predicted MMPs for nine oil samples by the correlation proposed in this study and other eleven literature correlations.

Exp. (MMP) (MPa)	Correlation proposed in this study		Cronquist's correlation		Lee's correlation		Yelling-Metcalfe's correlation	
	MMP (MPa)	ARE, %	MMP (MPa)	ARE, %	MMP (MPa)	ARE, %	MMP (MPa)	ARE, %
11.138	10.594	4.881	14.062	26.251	13.055	17.214	12.135	8.947
14.152	12.619	10.833	13.693	3.241	18.143	28.201	15.154	7.080
18.379	17.548	4.522	24.043	30.816	28.968	57.614	24.077	31.004
14.634	14.243	2.673	15.050	2.844	24.340	66.325	18.139	23.954
16.062	15.387	4.203	14.645	8.820	20.143	25.408	15.154	5.654
20.650	19.990	3.196	25.722	24.561	35.810	73.416	22.870	10.752
26.800	22.551	15.853	22.616	15.613	16.716	37.627	14.381	46.338
22.630	17.864	21.060	16.765	25.919	26.007	14.921	16.594	26.673
13.090	12.399	5.278	12.419	5.129	11.525	11.959	11.014	15.860
AARE, %		8.055		15.910		36.965		19.585
MAARE, %		21.060		30.816		73.416		46.338
Exp. (MMP) (MPa)	Orr-Jensen's correlation		Glaso's correlation		Alston's correlation		Emera-Sarma's correlation	
	MMP (MPa)	ARE, %	MMP (MPa)	ARE, %	MMP (MPa)	ARE, %	MMP (MPa)	ARE, %
11.138	10.002	10.196	16.679	49.746	6.756	39.342	9.362	15.945
14.152	14.306	1.087	19.472	37.593	8.611	39.155	12.214	13.695
18.379	32.845	78.712	18.464	0.462	14.032	23.650	13.738	25.251
14.634	19.691	34.556	13.128	10.290	10.462	28.512	12.071	17.513
16.062	14.306	10.934	14.973	6.779	15.941	0.751	13.032	18.863
20.650	29.963	45.097	22.617	9.525	20.944	1.423	18.150	12.105
26.800	13.087	51.170	22.328	16.687	24.636	8.074	27.222	1.575
22.630	16.777	25.863	26.327	16.337	15.512	31.454	23.042	1.820
13.090	8.734	33.279	16.029	22.452	11.524	11.963	12.102	7.550
AARE, %		32.321		18.874		20.481		12.702
MAARE, %		78.712		49.746		39.342		25.251
Exp. (MMP) (MPa)	Yuan's correlation		Shokir's correlation		Chen's correlation		Ju's correlation	
	MMP (MPa)	ARE, %	MMP (MPa)	ARE, %	MMP (MPa)	ARE, %	MMP (MPa)	ARE, %
11.138	12.775	14.699	12.549	12.669	11.002	1.218	7.091	36.332
14.152	18.512	30.809	15.783	11.522	13.967	1.309	9.539	32.598
18.379	13.735	25.266	27.908	51.845	21.849	18.878	19.767	7.554
14.634	8.304	43.255	15.366	5.004	15.543	6.210	11.280	22.921
16.062	14.568	9.302	15.191	5.420	19.961	24.274	13.697	14.727
20.650	17.164	16.879	26.111	26.445	24.313	17.739	21.215	2.734
26.800	20.033	25.250	20.132	24.881	19.328	27.879	11.409	57.428
22.630	18.113	19.960	15.509	31.468	17.374	23.226	11.615	48.674
13.090	20.738	58.425	10.647	18.664	11.973	8.531	7.577	42.116
AARE, %		27.094		20.880		14.363		29.454
MAARE, %		58.425		51.845		27.879		57.428

established by using the modified conjugate gradient and the global optimization algorithm.

(2) The nine groups of CO_2-oil MMP experimental data, which have not been used to develop the new correlation, were calculated by the empirical correlation proposed in this study and other eleven most popular and relatively high-accuracy empirical correlation presented in the literature to validate the new correlation. It can be seen from the comparative results that the accuracy of the empirical correlation proposed in this study is significantly more precise than the other eleven most popular and relatively high-accuracy empirical correlations presented in the literature. The range of the absolute error is less than 1.5 MPa, which corresponds to the requirement of engineering design of CO_2 displacement.

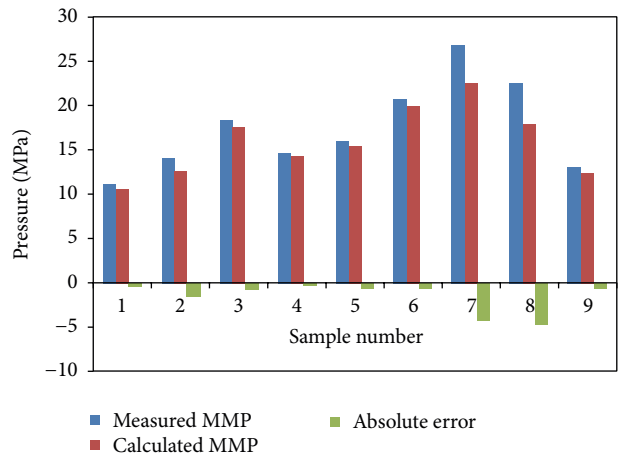

Figure 6: The MMPs of the system of nine CO_2-oil samples and their errors predicted by the correlation proposed in this paper.

Nomenclature

$M_{C_{5+}}$: Molecular weight of C_{5+} in the crude oil, g/mol
T: Reservoir temperature, °C
$M_{C_{7+}}$: Molecular weight of C_{7+} in the crude oil, g/mol
x_{VOL}: Mole fraction of volatile components ($CH_4 + N_2$) in the crude oil, mol%
x_{MED}: Mole fraction of intermediate components (CO_2, H_2S, and C_2~C_4) in the crude oil, mol%
x'_{MED}: Mole fraction of intermediate components (CO_2, H_2S, and C_2~C_6) in the crude oil, mol%
$P_{m,min,pure}$: Minimum miscibility pressure by pure CO_2 injection, MPa
$P_{m,min,impure}$: Minimum miscibility pressure by impure CO_2 injection, MPa
x_1: Reservoir temperature, °C
x_2: Mole fraction of volatile components ($CH_4 + N_2$) in the crude oil, mol%
x_3: Mole fraction of intermediate components (CO_2, H_2S, and C_2~C_6) in the crude oil, mol%
x_4: Molecular weight of C_{5+} in the crude oil, g/mol
x_5: Mole fraction of volatile components (C_1) in the injection gas, mol%
x_6: Mole fraction of intermediate components (C_2~C_4) in the injection gas, mol%
x_7: Mole fraction of volatile components (N_2) in the injection gas, mol%
x_8: Mole fraction of volatile components (H_2S) in the injection gas, mol%
$x_{C_1+N_2}$: Mole fraction of volatile components ($CH_4 + N_2$) in the crude oil, mol%
$x_{C_2-C_6}$: Mole fraction of intermediate components (C_2~C_6) in the crude oil, mol%
AE: Absolute error
%ARE: Percentage absolute relative error
%AARE: Percentage average absolute relative error
%MARE: Percentage maximum average absolute relative error.

Conflict of Interests

Here, all the authors solemnly declare that there is no conflict of interests regarding the publication of this paper.

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