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Research Article

The Empirical and Theoretical Miscible Characterization Method in Gas-Enhanced Oil Recovery

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The determination of miscible characteristic is one of the key technologies for enhancing oil recovery of gas flooding. If the miscible characteristic at each development period of gas flooding can be known in real time, it will be helpful to guide gas flooding development scheme. The minimum miscible pressure (MMP) is mostly used to describe miscible characteristic. Currently, the MMP forecasting methods can be classified into two categories—the empirical method and theoretical calculation method. In this paper, the main controlling factors affecting MMP are analyzed combined with reservoir engineering method, phase equilibrium theory, reservoir numerical simulation technology, and so on. Based on this, new empirical and theoretical MMP forecasting model was built. Meanwhile, new ideas for improving forecasting accuracy through modifying miscible criterion were proposed. The calculation accuracies of the two MMP forecasting models can be improved to over 90% that is more accurate and adapted than other methods. This research result can supply new ideas for gas flooding MMP forecasting.

1. Introduction

Along with the world economic development, the demand for energy is more and more pressing. Many petroleum engineers try to find new resource to supply the demand of energy. Oil and gas reservoirs are the main research object. Many research institutions develop many evaluation models to analyze the optimal development mode to improve the oil and gas production in exploration, drilling, development, transportation, etc. [1–3]. There are many researches in fracturing works which try to improve the permeability of reservoirs, and great progress have been got [4–7]. Enhanced oil recovery (abbreviated EOR) is the most effective techniques for increasing the amount of crude oil that can be extracted from an oil field, like steam-assisted gravity drainage technology and gas flooding technology [8, 9].

Gas flooding is a very popular method to enhance oil recovery. And the MMP is a critical standard for judging the miscible characterization between injected gas and crude oil, which has a great impact on the implementation of gas flooding. According to the investigation results of MMP forecasting method internationally, the MMP forecasting methods can be classified into two categories— the empirical formula method and theoretical calculation method, shown in Table 1.

Theoretical calculation method includes state equation method, numerical simulation method, tie-line analytical method, and mix cell method. In these methods, the calculation results of theoretical calculation method are relatively reliable; however, more data including the composition of crude oil and injected gas, component critical parameters, and reservoir temperature are demanded. The empirical method concludes the MMP data of every oil field and combines the main controlling factors affecting MMP to determine the basic forecasting model, and eventually, MMP forecasting equation can be obtained through regression. This method needs relevant simpler data conditions, but still has some certain limitations.

Table 1: Current MMP forecasting methods [5–8].

Analytical forecasting method		Advantages	Disadvantages	Data conditions
Empirical formula method		Simple, convenient, and quick, apply for prescreening and feasibility study	Forecasting method has some certain limitations	Surface crude oil density, molecular weight of heavy component, critical pressure, critical temperature, etc.
Theory calculation method	State equation method	Suit for crude oil with relative few components and relative reliable result	Large calculation deviation for multicomponent system	Composition of crude oil and injected gas, component critical parameters, reservoir temperature
	Tie-line analytical method	Relative reliable result	Rely on the characteristics of fluid components, further improvement is needed in terms of multicomponent system	
	Mix cell methods	Relative reliable result	Rely on the characteristics of fluid components	
	Numerical simulation method	Relative reliable result	Based on experiment, time-consuming	Fluid pvt data, phase permeability, capillary pressure, reservoir temperature, composition of crude oil, and injected gas

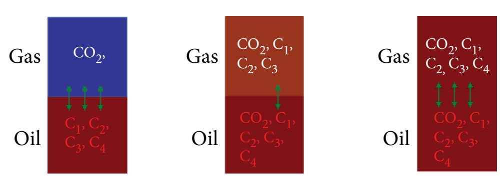

Figure 1: Basic theory of state equation.

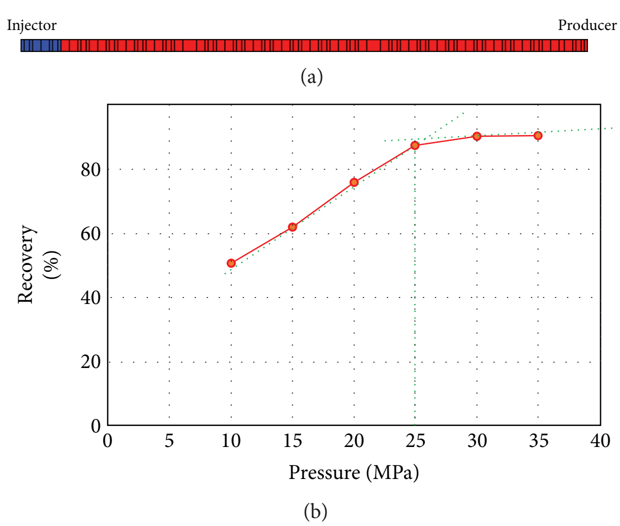

Figure 2: (a, b) Numerical simulation method forecasting MMP model.

1.1. Research Status of Theoretical Calculation Method. State equation method is a simple and practical MMP forecasting method [10–12]. The basic theory is that the vapor-liquid phase occurs interphase mass transfer in the contact process which changes the properties of the two phases. When the property of vapor phase is similar with the property of crude oil, the vapor-liquid interface will disappear, at which time miscible state is deemed to be achieved, and the miscible process is shown in Figure 1. The selection of critical parameters and state equation determine the accuracy of forecasting results. However, the determination of critical parameters needs the support of PVT experiment and the result reliability of PVT experiment determines the precision of critical parameters. State equation is mainly used to conduct flash calculation to determine the composition of gas and liquid phases. Currently, PR3 is relatively widely utilized among various state equations.

The numerical simulation method is a crucial method for studying miscible displacement effect and designing miscible flooding. Simulating slime-tube experiment utilizing numerical simulation method can predict the MMP value. When using the numerical simulation method to simulate slime-tube experiment, simplify the oil layer into one-dimension model at maximum limit, as shown in Figure 2(a). Its effect is to supply a consecutive contact environment in porous medium for reservoir crude oil and injected gas and exclude some adverse influence factors. Slime-tube experiment can obtain data as recovery and composition of exit output fluid, through analyzing the relationship between injected pressure and recovery to determine MMP, as shown in Figure 2(b). This method

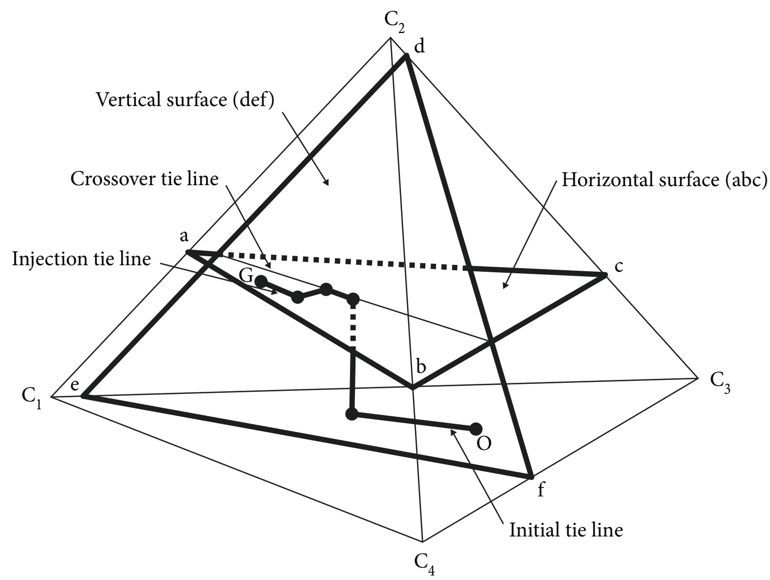

Figure 3: Quaternary system tie line.

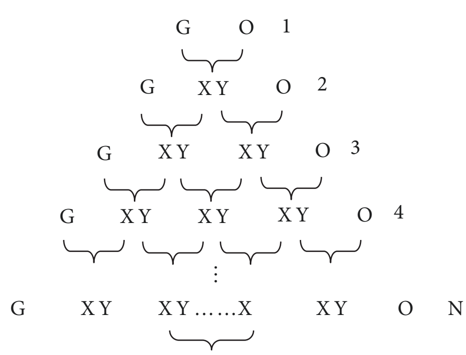

Figure 4: Principle of mix cell method.

is similar with slime-tube physical simulation experiment. Porosity and permeability simulated by slime tube are not required to be exactly the same with reservoir conditions, and the obtained recovery is not the crude oil recovery of reservoir miscible displacement development, but the MMP measured can represent the measured oil-gas system.

Tie-line analytical method is based on tie-line analytical theory. It describes the changing process of multistage contact miscible and fluid mass transfer process according to tie-line pattern change to forecast MMP [13, 14]. Tie-line analytical method is a MMP forecasting method raised by John and Orr in 1993, which is based on one-dimension component model and two-phase fluid flow in pore. Assuming that there is no effect on proliferation and mass transfer during flow process, initial conditions and boundary conditions together with principle of mass conservation constituting a Riemann problem and this Riemann problem have an analytical solution. In accordance with these assumptions, the analytical solution can be achieved through determining the algebra and geometry forms of a series of principal tie line. Once the principal tie line is determined, the displacement process of multi-contact miscible can be described by geometry form and critical track, and further, the MMP can be elicited through the geometry form of principal tie line. In the tie-line analytical method, the composition of crude oil is defined as initial tie line, and the composition of injection gas is defined as injection tie line. Besides, cross tie line is defined, which connects with initial tie line and injection tie line and intersects with them, as shown in Figure 3. When the length of any tie line reaches 0, it is deemed that miscible state is achieved.

Mix cell method is based on tie-line analytical method. Multistage mix cell method is suitable for predicting the miscible pressure of three-phase or multiphase system while tie-line analytical method limits to two-phase system of any components. The calculation steps of this method are as follows (Figure 4):

(1) Preset the initial temperature and pressure (pressure lower than MMP)

(2) Calculate based on two cells (cells of injected gas and crude oil). Equilibrium gas phase composition y and liquid phase composition x are obtained through flash calculation

(3) Equilibrium gas phase and equilibrium liquid phase occur contact flash again with the oil phase and injected gas of the adjacent cell, respectively, and the new equilibrium liquid phase and gas phase are obtained, as shown in Figure 2, until Nc-1 principal tie line appears and meets the convergence requirement. The formation of principal tie line can mainly be judged by whether the slopes of the three adjacent consecutive grids are zero or not

(4) Calculate the length of principal tie line in step 3 and reserve the smallest one

Table 2: Light constituent, oil component, and MMP of China typical reservoirs [19].

Oil sample	T (°C)	MW_{C5+} (g/mol)	y_{vol} (%)	y_{int} (%)	$\frac{y_{vol}}{y_{int}}$	MMP (MPa)
1	98.9	248.2	18.71	11.78	1.59	22.3
2	97.3	265.9	19.01	11.97	1.59	22.1
3	108.4	277.5	26.82	6.80	3.94	27.9
4	76	259.0	25.35	8.74	2.90	20.2
5	83.9	288.8	11.48	2.76	4.16	20.3
6	112	271.6	14.33	5.68	2.52	22.9
7	71	227.3	13.71	6.66	2.06	16.7
8	74.8	237.2	36.33	9.76	3.72	26.1
9	45	350.3	19.22	2.95	6.52	29.8
10	53	272.4	42.75	7.12	6.01	19.1
11	64	372.0	44.48	4.71	9.44	42.5
12	62.2	249.3	30.35	4.33	7.01	21.6
13	92	224.9	26.67	17.33	1.54	19.8
14	71.6	233.4	18.79	15.65	1.20	19.5

(5) Increase pressure gradually and repeat steps 2~4. The pressure amplification cannot be oversized, and 0.5Mpa is generally selected

(6) Repeat steps 2~5 until the length of one principal tie line is zero, and the corresponding pressure at this time is MMP

Among the four theoretical calculation methods, the state equation method only considers the process of multiphase mass transfer without considering the flow features in the fluid medium. The numerical simulation method considers relativity comprehensively; however, it needs more parameters and the operation time is relatively long, which is detrimental to the quick forecasting of MMP. Tie-line analytical method not only has relative comprehensive consideration by considering characteristics like multiple-contact miscible changing process, fluid mass transfer process, and flow in the two-phase fluid medium but also has the features of convenient and quick calculation, which compensate the disadvantages of the state equation method and numerical simulation method. Mix cell method is based on tie-line analytical method with some calculation optimization. This study refers to mix cell method, amends its miscible criterion, and establishes a new theory of MMP forecasting method.

1.2. Research Status of Empirical Equation Forecasting Method. The empirical equation method is also an important method to calculate MMP. Its application is simple and time-saving, which makes it the most direct method to obtain MMP. Currently, there are plenty of empirical equations to determine MMP, some typical ones will be introduced here.

MJP correlation is an amendment for J-P correlation. Cronquist applies light components and intermediate components in the crude oil into J-P correlation [15]. On the basis of the prediction plate of Benham et al., Glaso gave out that MMP is a function about reservoir temperature, oil C_{7+} molecular mass, molar mass of methane in the injected gas, and molecular mass of intermediate components (C_2~C_6) [16]. Kovarik put forward two correlations to calculate MMP, one thought that MMP was a function about the mole fraction of CO_2 including impurities (such as N_2 and CH_4); the other recognized that MMP was a function about the critical properties of the injected gas [17]. Cronquist thought that MMP was related to reservoir temperature T, relative molecular mass of penthane and heavier fraction $M_{C_5^+}$, and mole percent between methane and nitrogen $y_{C_1\&N_2}$. Correlation of Yelling and Metcalfe only considered the impact of temperature on MMP, and the relation between MMP and temperature was simplified into a linear relation, which makes the result to be unreliable. According to CO_2 vapor pressure curve, PRI1 empirical equation was raised, and this correlation only considered the effect of reservoir temperature T on MMP. Stalkup thought that the MMP was related to the critical temperature of $CO_2 T_c$, mass percent of total C_{6+} hydrocarbon in the crude oil $x_{C_6^+}$ (alkane plus arene) except reservoir temperature T, and molar percentage of methane in the injected gas y_{c1} [18]. Yuan and Johns proposed MMP correlation of pure CO_2 flooding and flooding of CO_2 with impurities according to the analytical theory of application state equation determining MMP [19]. Holm and Josendal raised a MMP forecasting correlation related to temperature T and the average molar mass of C_{5+} based on Benham correlation. Emera and Sarma proposed two correlations to forecast MMP in 2004 and 2006, respectively, on the basis of genetic algorithm, and the considered parameters included reservoir temperature T, average molar mass of $C_{5+}M_{C_5^+}$, the specific value (X_{vol}/X_{int}) between the molar numbers (X_{vol}, X_{int}) of the volatile fraction in crude oil components (N_2 and C_1) and intermediate oil fracture (C_{2-4}, CO_2, and H_2S). Empirical equations for predicting C_{5+} are plenty, but they all have limitations, and the influence factors considered were not comprehensive, which are mainly used for prescreening and feasibility study.

Although there are many empirical equations, every equation is regressed and matched under some specific reservoir characteristics and fluid properties. So these empirical equations apply only to some specific reservoir and have great limitations. This study optimizes empirical equation method on the basis of former studies, and a new empirical equation method is proposed.

2. Miscible Pressure Influence Factor Analysis

2.1. Effect of MMP on Crude Oil Components. Through wide literature investigation [17, 19], it can be known that the main influence factors on MMP include reservoir temperature, crude oil components (molecular mass of C5+ (MWC5+)), volatile components, intermediate components, and the components of the injected gas.

The study used MMP as objective function and studied the sensitivity of MMP to the mole fraction of volatile

Table 3: Literature reported light oil constituent and MMP [16].

No.	T (°C)	MW_{C5+} (g/mol)	y_{vol} (%)	y_{int} (%)	$\frac{y_{vol}}{y_{int}}$	MMP_{pure} (MPa)
15	34.4	212.56	16.78	10.76	1.56	10
16	118.3	171.1	34.2	28.6	1.20	23.45
17	67.8	203.81	31	22.9	1.35	16.9
18	71.1	221	41.27	6.99	5.90	23.45
19	102.2	205	51.28	9.84	5.21	28.17
20	80	240.7	53.36	8.60	6.20	26.76
21	112.2	213.5	32.70	28.10	1.16	24.15
22	99	190.7	40.14	2.95	13.61	30.28
23	49	187.25	34.34	22.82	1.51	11.04

components and intermediate components, reservoir temperature, and MW_{C5+}. 23 sets of light oil data (Tables 2 and 3) and 29 sets of nonlight oil data (Table 4) were adopted, and the analysis results are shown in Figure 5.

Through the analysis of MMP sensitivity, the MMP of the two types of oil (nonlight oil and light oil) increases with volatile components, MW_{C5+}, and reservoir temperature and decreases with increasing intermediate components. This trend is the same with the former results. However, the effect of light oil components (volatile components, intermediate components, and MW_{C5+}) on MMP is larger than that of nonlight oil while the effect of reservoir temperature is smaller than that of nonlight oil. Former study based on nonlight oil thinks that the effect of reservoir temperature is the most prominent, and this article has verified this point (sensitivity coefficient is 0.776). For light oil, MW_{C5+} is the most significant influence factor but not the temperature with the sensitivity coefficient to be 0.85. As the light oil contains relative high light dydrocarbon content and relative low content of heavy components which are sensitive to temperature, the physical properties of light oil (density, viscosity, etc.) are relatively low, and these properties changes little with temperature which further lead to MMP's relative narrow fluctuation range with temperature.

2.2. Effect of Injected Gas Components on MMP. Injected gas components (such as CH_4, H_2S, N_2, and intermediate components) have significant impact on MMP. Dong et al. noticed that the existence of H_2S in the injected gas components and intermediate components led to relative high injected gas pseudocritical temperature and relative low MMP. Meanwhile, through analyzing the P-T phase figure of elementary gas (Figure 6), gases able to lower MMP, such as H_2S, C_2H_6, C_3H_8, C_4H_{10}, and CO_2, all have relative high critical temperature while gases detrimental to MMP, such as N_2 and CH_4, possess relative low critical temperature. For mixed gases, some researches think that the pseudocritical temperature and pseudocritical pressure of injected gas have a great impact on MMP and should be analyzed as influence factors.

Using MMP as the objective function, the sensitivity of MMP to the pseudocritical temperature and pseudocritical pressure of injected gas is studied. 23 sets of light oil data

Table 4: Literature reported nonlight oil constituent and MMP [18].

No.	T (°C)	MW_{C5+} (g/mol)	y_{vol} (%)	y_{int} (%)	$\frac{y_{vol}}{y_{int}}$	MMP_{pure} (MPa)
1	54.4	171.2	29.48	31.82	0.93	11
2	71.1	207.9	4.4	13.9	0.32	15.52
3	32.2	187.77	10.5	14.28	0.74	6.9
4	40.6	187.77	10.5	14.28	0.74	8.28
5	57.2	187.77	10.5	14.28	0.74	11.86
6	48.9	205.1	12.5	22.62	0.55	10.59
7	110	180.6	32.51	35.64	0.91	20.21
8	59	205	5.45	11.35	0.48	12.8
9	54.4	185.83	5.4	38.4	0.14	9.48
10	61.1	185.83	5.4	38.4	0.14	10.35
11	54.4	185.83	5	7.5	0.67	10.35
12	54.4	185.83	22.9	38.4	0.60	10.35
13	57.8	202.61	0.5	1.2	0.42	11.72
14	54.4	235.56	5.4	35.5	0.15	12.76
15	110	180.6	32.51	35.64	0.91	20.21
16	71.1	207.9	4.4	13.9	0.32	15.52
17	54.4	171.2	29.48	31.82	0.93	11
18	42.8	196.1	19.35	26.8	0.72	10.62
19	32.2	187.77	10.5	14.28	0.74	6.9
20	40.6	187.77	10.5	14.28	0.74	8.28
21	57.2	187.77	10.5	14.28	0.74	11.86
22	57.2	182.6	0	5.11	0.00	13.1
23	87.8	182.6	0	5.11	0.00	17.24
24	54.4	170.5	0	1.57	0.00	12.07
25	42.8	204.1	17.07	20.95	0.81	10.35
26	59	205	5.45	11.35	0.48	12.8
27	48.9	205.1	12.5	22.62	0.55	10.59
28	137.22	136.17	24.68	39.37	0.63	19.38
29	73.89	231	0	0.002	0.00	22.83

(Tables 2 and 3) and 29 sets of nonlight oil data (Table 4) were adopted, and the analytical results are exhibited in Figure 7. Through sensitivity analysis, the MMP of the two oil types (nonlight oil and light oil) increases with pseudocritical pressure of injected gas and decreases with the increasing pseudocritical temperature. This trend is the same with the former research results. Pseudotemperature of injected gas almost has the same impact on the MMPs of light oil and nonlight oil, and the sensitivity coefficients are −0.534 and −0.531, respectively. However, the MMP of light oil is quite insensitive to the pseudocritical pressure of injected gas with the sensitivity coefficient to be only 0.02, which has great difference with the impact of pseudocritical pressure on the MMP of nonlight oil (the sensitivity coefficient is 0.295).

3. Amended MMP Forecasting Method

3.1. Amended Empirical Equation Method. According to the development process of MMP empirical equation, which

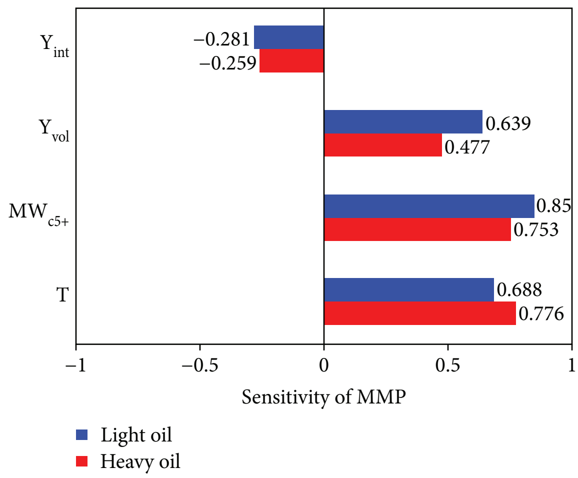

Figure 5: MMP sensitivity analysis of crude oil.

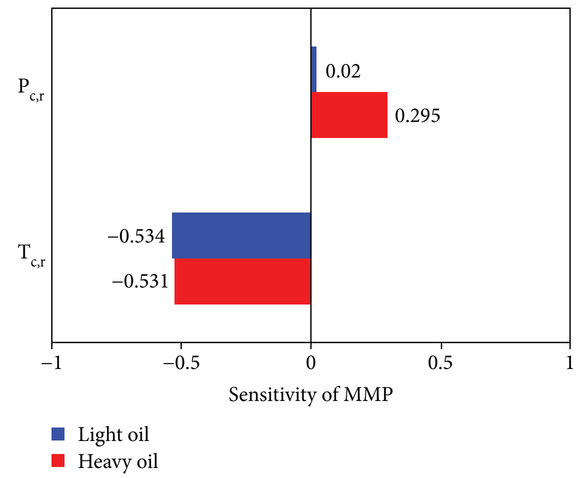

Figure 7: Sensitivity analysis of MMP between injected gas components and crude oil.

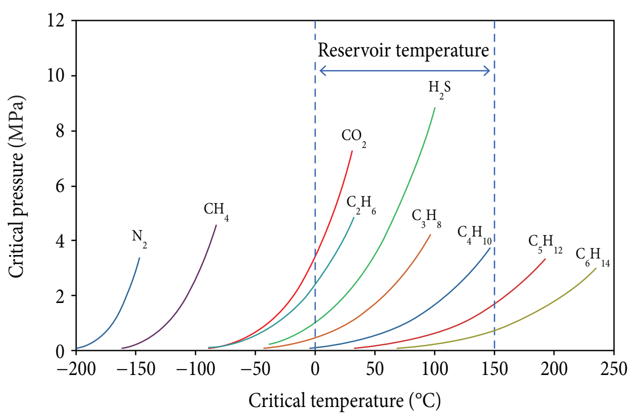

Figure 6: P-T phase diagram of elementary gas.

was mentioned before, that compared with theoretical analysis method, it needs relatively simple and easily obtained materials, which make it widely utilized internationally. However, it also has some limitations. Its application is always regional, and for reservoir beyond the region, the accuracy of MMP forecasting is relatively low.

Referring to Yuan's empirical equation method, on which basis, a new empirical method for predicting MMP is raised [20, 21].

The forecasting method of empirical calculation equation raised by Yuan et al. can be divided into 2 steps. Firstly, the MMP of pure CO_2 is calculated, as shown in

$$\begin{aligned} \mathrm{MMP}_{\mathrm{pure}} = {} & \alpha_1 + \alpha_2 M_{C7+} + \alpha_3 P_{C2-6} \\ & + \left(\alpha_4 + \alpha_5 M_{C7+} + \alpha_6 \frac{P_{C2-6}}{M_{C7+}^2}\right) T \\ & + \left(\alpha_7 + \alpha_8 M_{C7+} + \alpha_9 M_{C7+}^2 + \alpha_{10} P_{C2-6}\right) T^2. \end{aligned} \quad (1)$$

The relation of MMP between nonpure CO_2 and pure CO_2 is as follows:

$$\frac{\mathrm{MMP}_{\mathrm{imp}}}{\mathrm{MMP}_{\mathrm{pure}}} = 1 + m\left(P_{CO_2} - 100\right), \quad (2)$$

where $\mathrm{MMP}_{\mathrm{pure}} = P_{CO_2}$ is the MMP of pure CO_2 (Psi), $P_{C_{2-6}}$ is the mole percentage of crude oil C2–C6, constant, M_{C7+} is the molar mass of C7 plus in the crude oil (g/mol), T is the reservoir temperature (°F), and a (Table 5) is the relevant coefficient, constant.

This study amends the MMP relation between nonpure CO_2 and pure CO_2 (relative MMP) in Yuan's method. The amendment process is as below: take MMP value as objective function and pseudocritical temperature of injected gas as independent variable, then build relative MMP forecasting model by data fitting and regression. The forecasting model is stated in the following:

$$\mathrm{MPP}_r = \frac{\mathrm{MMP}_{\mathrm{impure}}}{\mathrm{MMP}_{\mathrm{pure}}}, \quad (3)$$

$$\mathrm{MMP}_r = 27.6178 - 65.9478 T_{cr} + 54.0497 T_{cr}^2 - 14.7556 T_{cr}^3, \quad (4)$$

where $\mathrm{MMP}_{\mathrm{pure}}$ is the relative MMP, decimals, and $\mathrm{MMP}_{\mathrm{imp}}$ is the MMP between nonpure CO_2 and crude oil, MPa.

As shown in (1), the forecasting model of nonpure CO_2 MMP still adopts the method raised by Yuan.

Applying this MMP empirical equation calculation method (Y-Z model) and the predicted results are exhibited in Table 6, from which it is easy to see that the calculation accuracy of new model is significantly improved compared with other widely utilized forecasting models currently, and the deviation is controlled within 10%.

Table 5: a coefficient table.

a_1	$-1.4634E+3$	a_6	$8.1661E+3$
a_2	$0.6612E+1$	a_7	$-1.2258E-1$
a_3	$-4.4979E+1$	a_8	$1.2283E-3$
a_4	$0.2139E+1$	a_9	$-4.0152E-6$
a_5	$1.1667E-1$	a_{10}	$-9.2577E-4$

3.2. Amended Theoretical Calculation Method. The key parameters of MMP theoretical calculation method include state equation, critical parameters, and miscible criterion. Currently, some scholars improve the accuracy of MMP forecasting model through amending state equation, and the critical parameters are generally acknowledged as relatively precise. However, current researches all ignore the effect of miscible criterion on the MMP. State equation method thinks that the equilibrium K values of all the components around the critical point is kin to 1, and there is no interface between the two phases, which means that the two phases become one phase and forming miscible. Then, the miscible criterion of state equation method is raised, as stated in

$$F_{\mathrm{M}} = -\sum_{i=1}^{n}\left[\frac{z_i(K_i-1)}{K_i}\right], \tag{5}$$

where F_{M} is the miscible function, z_i is the total mole fraction of component i in the system, and K_i is the equilibrium K value of component i in the system.

Equation (6) states that component z_i changes with the injection of injected gas and reaches critical state, at which time the miscible function decreases progressively to 0.

However, tie-line analytical method and mix cell method also have a parameter analogous to miscible criterion, which is defined as tie-line length, as shown in

$$L_n = \sqrt{\sum_{i=1}^{N}(y_i^n - x_i^n)^2}, \quad n = 1L\,N-1, \tag{6}$$

where L_n is the tie-line length, y_i is the gas mole composition, and x_i is the oil mole composition.

When the miscible state is achieved, the tie-line length is approximate to 0. Tie-line length and miscible criterion have the same physical significance. In the current MMP calculation methods, during the process of MMP determination, it is recognized that the injected gas and crude oil components are similar and the interface disappears at miscible state, at which time the tie-line length or miscible criterion is deemed to be less than a minimal value and defaults to 0.001 in the practical program calculation. The MMP forecasted by the above miscible criterion is unstable and still has relative large deviation with the MMP measured by slime-tube test. In this study, method of improving calculation accuracy through changing miscible criterion and minimal value is attempted. The miscible criterion raised by this study is shown in (7). Minimal value is determined to be 0.01 to offset the deviation between experimental and theoretical calculations brought by physical similarity criterion. This forecasting method is adopted to predict the data obtained through collection and investigation, as shown in Table 7. It can be seen that the calculation accuracy of the amended model has the minimum deviation which is controlled within 10%.

$$F_{\mathrm{m}} = \sqrt{\sum_{i=1}^{N}\left(y_i^2 - x_i^2\right)}. \tag{7}$$

3.3. The Standard of Empirical and Theoretical Miscible Characterization Method. In some oilfields, there are limited data of fluid property and no MMP experiment which results in the difficulty to select the right MMP calculation method and to forecast MMP. The first condition is that only the basic physical property data of crude oil is available, then the empirical method could be considered. The second condition is that the detailed PVT data or crude oil composition data is available, and the theoretical calculation method could be used. The theoretical calculation method can be used in light oil, heavy oil, and so on.

4. Discuss

Currently, there are many MMP forecasting methods. However, experimental methods always are used to evaluate the reliability of MMP forecasting methods. MMP experimental tests like slime-tube test have some deviations caused by human factors in determining MMP value, such as naked eye recognition capability and drawing technique of the curve slope. However, the theoretical calculation method bases on miscible principle, and the calculation result is more incline to theorization. The MMP could be classified into two types: one is experimental MMP, which reflects near-miscible or miscible state, but I prefer that the experimental MMP should reflect near-miscible state, and the other is theoretical MMP value, which reflects pure miscible state. This explains the differences between theoretical calculation value and the experimental value that reflect different miscible states. In gas flooding process, displacement efficiency at near-miscible state is already close to miscible state. Hence, the experimental value also has significant guidance for the design of injected gas development scheme. A mountain of work still is needed to consummate the conclusion about the causes and amendment of differences between the miscible pressures predicted by experiment and theory.

5. Conclusion

(1) Factors affecting MMP were analyzed, and on the basis of the current MMP empirical equation method, a new miscible pressure forecasting model was built and the forecasting accuracy was improved

(2) Key problems of the current MMP theoretical calculation method were concluded, and the idea of

Table 6: Results of MMP forecasting model.

No.	Experiment value MPa	New model MPa	New model Deviation	Kovarik model MPa	Kovarik model Deviation	Sabaiastian model MPa	Sabaiastian model Deviation	Alston model MPa	Alston model Deviation	Yuan model MPa	Yuan model Deviation
1	19.69	19.7	0.11	20.12	2.16	20.41	3.65	18.73	−4.89	26.80	36.11
2	18.62	19.1	2.65	20.85	11.97	21.01	12.85	19.62	5.36	25.09	34.77
3	18.62	18.1	−2.81	17.60	−5.48	18.44	−0.99	16.78	−9.89	27.24	46.30
4	10.07	10.5	4.44	10.94	8.69	10.96	8.84	10.91	8.29	11.02	9.48
5	9.31	9.0	−3.75	7.73	−16.93	9.59	3.02	8.87	−4.73	11.97	28.60
6	7.9	8.3	4.46	4.84	−38.72	8.54	8.16	7.78	−1.58	12.88	63.00
7	9.66	10.4	7.99	10.88	12.67	10.93	13.17	10.85	12.36	11.04	14.31
8	7.93	7.9	−0.71	4.46	−43.74	8.42	6.18	7.66	−3.35	13.00	63.93
9	13.04	12.9	−1.02	13.44	3.10	13.45	3.15	13.38	2.63	13.53	3.76
10	11.04	11.0	−0.39	10.23	−7.31	11.77	6.62	10.89	−1.40	14.69	33.09
11	8.97	10.1	12.91	7.34	−18.16	10.49	16.90	9.54	6.38	15.80	76.18
12	12.88	12.8	−0.60	13.38	3.91	13.42	4.17	13.32	3.42	13.55	5.21
13	10.5	9.7	−7.97	6.96	−33.70	10.33	−1.59	9.41	−10.42	15.95	51.94
	Average	3.83		15.89		6.87		5.75		35.90	

Table 7: MMP calculation deviation table.

No.	Experiment value MPa	Amended mix cell method MPa	Amended mix cell method Deviation	State equation method MPa	State equation method Deviation	Tie-line analytical method MPa	Tie-line analytical method Deviation	Numerical simulation method MPa	Numerical simulation method Deviation	Mix cell method MPa	Mix cell method Deviation
1	10	9.13	−8.71	6.95	−30.52	11.03	10.27	9.76	−2.36	10.14	1.39
2	23.45	22.39	−4.53	19.16	−18.31	19.97	−14.85	22.37	−4.60	23.33	−0.50
3	16.9	16.00	−5.32	12.24	−27.60	16.96	0.35	16.28	−3.65	16.60	−1.78
4	23.45	22.16	−5.50	12.68	−45.91	24.91	6.23	22.02	−6.09	22.19	−5.38
5	28.17	28.36	0.68	16.88	−40.06	29.45	4.54	28.17	0.01	27.65	−1.83
6	26.76	26.79	0.11	13.88	−48.12	32.30	20.72	27.42	2.48	27.07	1.14
7	24.15	25.82	6.90	18.28	−24.30	28.10	16.37	27.58	14.21	25.05	3.73
8	30.28	29.67	−2.03	16.44	−45.69	28.67	−5.32	27.79	−8.23	23.53	−22.29
9	11.04	11.22	1.60	9.52	−13.81	11.37	3.03	11.14	0.90	12.56	13.81
10	22.3	25.47	14.22	16.43	−26.32	34.19	53.30	30.14	35.17	24.45	9.63
11	22.1	24.75	11.99	16.21	−26.64	38.08	72.33	32.22	45.79	23.88	8.07
12	27.9	28.53	2.26	17.75	−36.39	51.27	83.77	41.70	49.45	26.24	−5.95
13	20.2	24.45	21.04	13.35	−33.93	31.75	57.19	26.25	29.97	21.67	7.29
14	20.3	23.01	13.35	14.40	−29.04	44.10	117.26	34.20	68.48	16.99	−16.33

improving forecasting accuracy through changing miscible criterion was raised. Through the amendment of miscible criterion, the forecasting accuracy of mix cell method was significantly improved with the accuracy to be above 90%

(3) The two methods can be used in different data conditions. If the reservoir temperature, mole composition of crude oil, and injected gas are available, Y-Z model can be selected. If more detailed data, such as fluid high-pressure physical property data and critical parameters, is available, then the modified mix cell method can be selected and utilized

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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