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NEW MINIMUM MISCIBILITY PRESSURE (MMP) CORRELATION FOR HYDROCARBON MISCIBLE INJECTIONS

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ABSTRACT

This paper presents a new empirically derived correlation for estimating the minimum miscibility pressure (MMP) required for multicontact miscible (MCM) displacement of reservoir petroleum by hydrocarbon gas flooding. Only few empirical correlations exist for determining the MMP. These correlations are often used to estimate the MMP without considering the composition of the injected gas. On the other hand these correlations are based on a limited set of experimental data which are not quite applicable. In addition, in such correlations the complex condensing/vaporizing displacement process is not regarded. In this study, however, the derived correlation investigates the influence of the vaporizing/condensing drive mechanism and oil and gas composition on gas miscibility pressure. MMP has been correlated with temperature, oil composition and injection gas composition. Their effect on hydrocarbon gas MMP has been documented. MCM process was also modeled by compositional slim tube simulators. The modified Peng-Robison equation of state (PR3) was used to evaluate miscibility conditions. The new correlation is based on regression of widely experimentally measured MMP data in literature and data generated from validated compositional slim tube simulators. By comparing the calculated MMPs from the improved correlation data with currently used correlations and experimentally measured data, it was found that the novel correlation is significantly more accurate than other correlations.

KEYWORDS

Enhanced Oil Recovery, Miscible Gas Injection, Minimum Miscibility Pressure, Correlation, Gas Composition, Simulation

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1. INTRODUCTION

The application of miscible gas flooding as an enhanced oil recovery technique has increased rapidly. A large amount of gas is usually associated with oil in gathering center, which can be separated and reinjected into reservoir for miscible or immiscible displacement in order to enhance oil recovery. Generally, by using hydrocarbon gas as injecting fluid, the following mechanisms can be activated: immiscible displacement, miscible displacement, pressure maintenance, gravity enhancement and driving agent for miscible slug. In miscible displacement, lean gas can displace oil efficiently by developing a miscible bank through a multicontact miscibility (MCM) process. Minimum miscibility pressure (MMP) is needed to achieve the dynamic miscibility between oil and hydrocarbon gas. MMP is an important parameter for screening and selecting reservoirs for miscible gas injection projects and is defined as the minimum pressure at which oil and gas exist in one phase (**Stalkup, Jr., 1983**). Figure 1 shows compositional phase diagram for a definite temperature and pressure which is called ternary diagram. In thermodynamic criteria for defining the MMP by using ternary diagrams, the MMP is the pressure at which the limiting tie line passes through the point representing the oil composition.

In order to determine the MMP in gas injection processes, several methods are used. These methods include slim tube test (STD), rising bubble test, vapor-liquid equilibrium (VLE) studies, slim tube composition simulator, empirical correlation, among others. Application of correlation is the simplest method. Empirical correlations are used to obtain first-pass estimation or as a screening tool (**Stalkup, Jr., 1983**).

Stalkup, Jr. (**1983**) offered an empirical correlation for estimation of MMP with lean hydrocarbon gas. The MMP was correlated with the oil composition and oil saturation pressure. The correlation was developed from data of nine different oil compositions with average deviation of 260 psi and maximum deviation of 640 psi. **Firoozabadi and Aziz** (**1986**) reviewed twelve MMP data (experimentally measured data and simulator data) and proposed a correlation to estimate MMP for all vaporizing gas drive (VGD) processes. They correlated the MMP by oil composition without considering the injected gas composition. Their correlation was found as the most reliable MMP correlation for lean gas and nitrogen injection with standard deviations of 11.5 % and 23.5 % compared with other correlations reported in literature. Their correlation was developed from data, which contained more than 80 mol% methane. Large errors are produced when the methane content in the driving gas is significantly lower than 80 mole percent (**Danesh, 1997**).

When the injected gas is pure methane, the miscibility mechanism is considered to be vaporizing and is controlled by the original oil composition. Otherwise predicted MMPs cannot be trusted, unless both oil and gas compositions are regarded in the correlation (condensing/vaporizing gas drive).

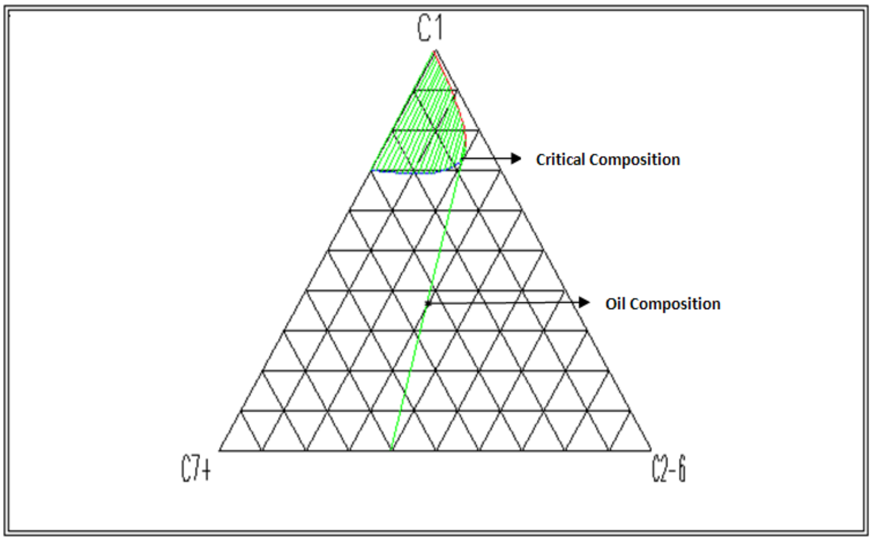

Figure 1. Ternary phase diagram for a hydrocarbon system: the limiting tie line passes through the oil composition at MMP.

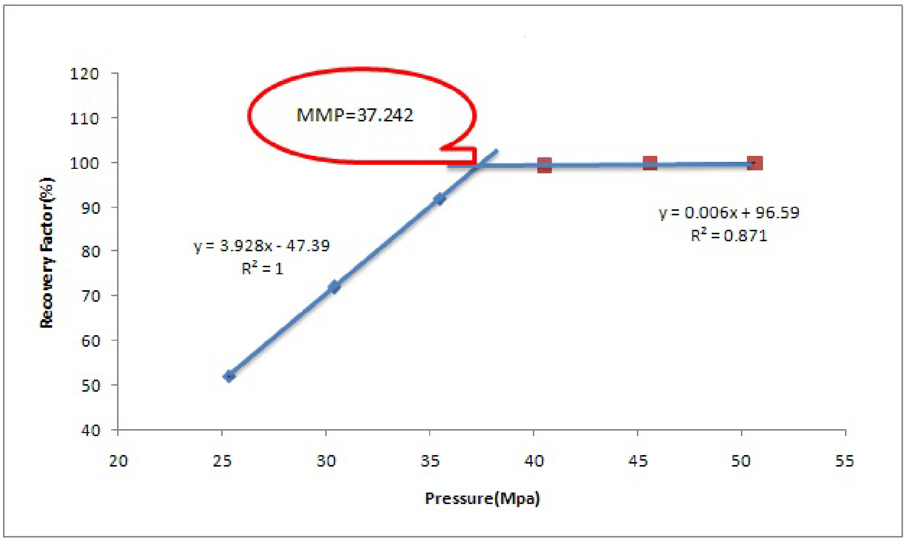

Figure 2. MMP calculated by model for oil A **(Michelsen and Stenby, 1998).**

2. METHODOLOGY

2.1 Slim Tube Simulator

As mentioned above, there are several methods for determining the MMP of miscible gas flooding. These methods include slim tube test (STD), rising bubble test, vapor-liquid equilibrium (VLE) studies, mixing cell methods and slim tube simulators. Mixing cells and rising bubble methods are not so common in oil and gas industry. VLE studies are not convenient and applicable in that they require an enormous amount of calculation (**Danesh, 1997**).The thermodynamic miscibility conditions in mixing cells and rising bubble predict richer solvent than the conventional slim-tube tests indicated (**Williams and Zana, 1980**).

The most common method to calculate MMP involves a slim tube experiment in the oil and gas industry. Using the slim tube method is costly and time consuming and somehow the use of the slim tube compositional simulator is preferred. In this study, slim tube has been modeled in one dimensional rectangular reservoir with 20-m length and cross sectional area of 0.000025 m^2. Hydrocarbon gas is injected at 2.77×10^{-9} m^3/s (10 cm^3/h). Porosity and permeability are set to 20% and 1000 md, respectively. The model is initially saturated with oil at the reservoir temperature above the bubble point pressure. The reservoir fluid was modeled by tuned PR3_EOS parameters and imported into the simulator (**Thomas and Okazawa, 1996**). A typical relative permeability curve was used for this model. The type of relative permeability curve does not change the result of MMP. Generally, the pressure drop across the slim tube is small, so the entire displacement process is considered to be at constant pressure. This model has 500 blocks, which is a typical number of blocks in compositional slim tube simulators. Before using this model to generate MMP, it should be validated and calibrated using known oil MMP and PVT data.

The slim tube model was tested for a real reservoir oil (named here as oil A) (**Michelsen and Stenby, 1998**) with a known MMP of 37.500 MPa. The MMP calculated from the model is 37.242 MPa (Figure 2) with error of 0.68 %.

2.2 Factors Influencing the MMP

Most correlations in the literature predict a nearly linear behavior of MMP with respect to temperature (**Yuan et al., 2005**). The trend of MMP as a function of temperature was investigated for oil A as shown in Figure 3. As other correlations in the literature, three parameters of oil composition are selected for estimation of MMP, namely the molecular weight of C_{7+}, the mole fraction of C_{2-6} and the mole fraction of methane **(Firoozabadi and Aziz, 1983)**.

Since condensing-vaporizing gas drive dominates the enriched gas injection, the MCM process is more complicated. Two parameters from gas stream are selected for estimation of MMP: mole fraction of C_{2+} and molecular weight of C_{2+} (**Michelsen and Stenby, 1998**). As mentioned in the literature (**Kuo, 1985**), the MMP will decrease with increasing C_{2+} mole fraction. The trend of MMP as a function of MC_{2+} (content of C_{2+} in the injection gas in terms of molecular weight) was investigated for one of the Iranian southwest oil reservoirs. The results as shown in Figure 4, indicate that the MMP decreases slightly by increasing the MC_{2+}. Figure 5 also shows that the C_{2+} content in the injection gas causes significant reduction in the MMP.

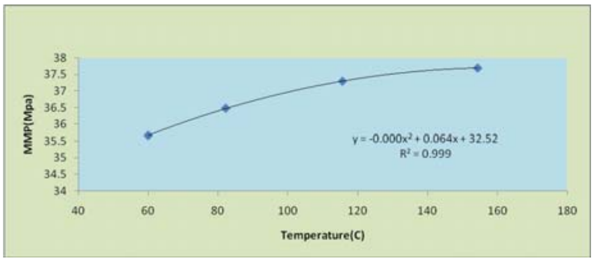

Figure 3. MMP as a function of temperature for Oil A and a typical gas.

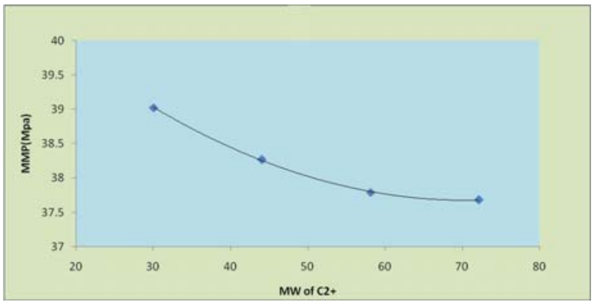

Figure 4. . MMP as a function of M_{C2+}.

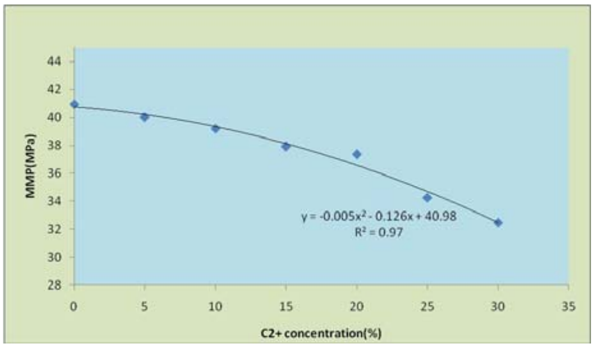

Figure 5. . MMP vs. C_{2+} content in the injection gas.

3. RESULTS AND DISCUSSION

3.1 Correlation for MMP

By summarizing the findings presented above, an improved MMP correlation was generated including the following criteria:

- As temperature increases, the hydrocarbon gas MMP increases for any type of oil;
- The hydrocarbon gas MMP also increases as the C_{7+} molecular weight increases;
- The hydrocarbon gas MMP decreases as the mole fractions of methane and C2-6 increase in the oil composition.
- By increasing the mole fraction and molecular weight of C_{2+}, the MMP is reduced.

By considering the criteria above, the following correlation was developed, using the experimentally measured MMP data in the literature and data collected in this work (Table 1). For generating the correlation, nonlinear regression was used.

$$MMP = 43.664 - 4.542\alpha + 0.689\alpha^2 - 0.132\beta \qquad (1)$$

$$\alpha = \frac{X_{C2-C6}^{1.72785} \times X_{C1}^{0.1}}{(1.8T + 32)^{0.5} \times M_{C7+}} \qquad (2)$$

$$\beta = Y_{C2+}^{(1.064 + 0.00686 M_{C2+})} \qquad (3)$$

In equations 1 to 3, one has:

- MMP: Minimum Miscibility Pressure(MPa)
- $X_{C2\text{-}6}$: Intermediate composition in the oil containing $C_{2\text{-}6}$, CO_2 and H_2S, in mole %;
- X_{C1}: Amount of methane in the oil (%);
- T: Temperature (°C);
- M_{C7+}: Molecular weight of C_{7+} (g/mol);
- Y_{C2+}: Mole percent of C_{2+} composition in injected gas (%);
- M_{C2+}: Molecular weight of C_{2+} in injected gas.

The proposed correlation has two main parameters: α and β. Parameter α includes oil composition parameters that are used in Aziz and Firoozabadi's correlation for miscible lean hydrocarbon gas injection with different power and additional parameter (methane content). In Aziz and Firoozabadi's correlation, gas composition effects were not considered. The parameter β refers to the gas composition effect on the MMP. It is evident that MMP decreases with increasing C_{2+} content and molecular weight in the injection gas, but the effects of M_{C2+} are too small compared with C_{2+}.

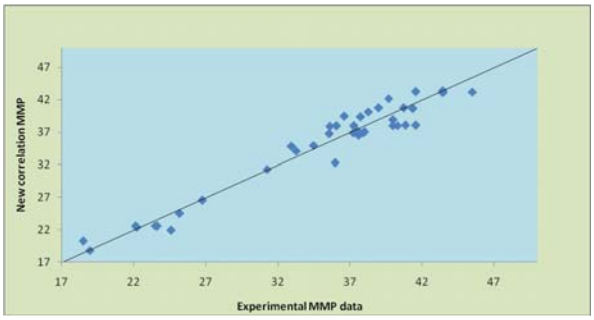

Figure 6. Comparison of experimental MMP with new correlation MMP.

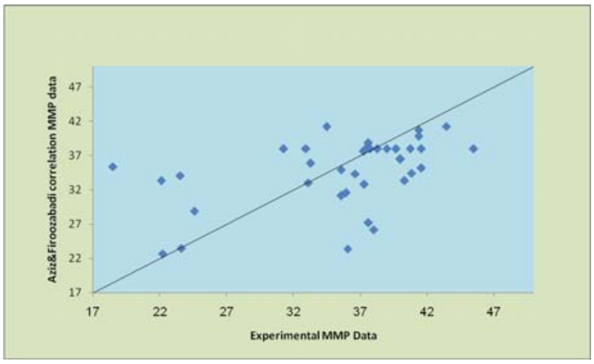

Figure 7. Comparison of MMP predicted by Aziz and Firoozabadi's correlation with the available MMP Data.

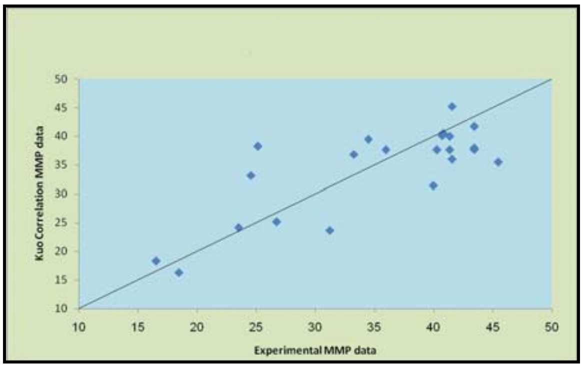

Figure 8. Comparison of MMP predicted by Kuo's correlation with the available MMP data.

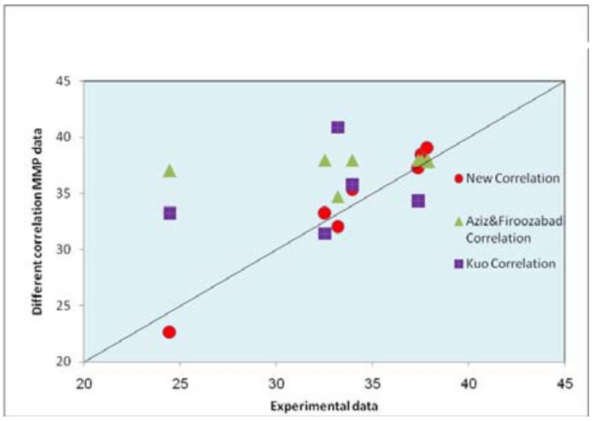

Figure 9. Comparison of different correlation results using data from Table 2.

3.2 Correlation Accuracy and Limitation

Figure 6 shows a comparison between the MMP calculated with the new correlation and the available MMP data. The average absolute deviation was determined to be about 4.4 %. A comparison is also given in Table 1. A comparison between the MMP calculated by Aziz and Firoozabadi's correlation and available MMP data (Table 1) is also shown in Figure 7, with an average absolute deviation of 16.53 %, which has low precision compared with new correlation.

Another correlation which is commonly used for calculation of MMP of enriched gas is Kuo's empirical correlation (**Kuo, 1985**). This correlation is also compared with new correlation in its limited range of influencing parameters. Comparison shows that Kuo's correlation has average absolute deviation of 13.14 %, which is higher than the current correlation deviation (Figure 8). A new correlation validation is also performed with more MMP data (Table 2). These MMP data have not been used in the new correlation. Different correlation results are compared in Figure 9 by using the MMP data from Table 2. The Average Absolute Deviations (AAD) for the current correlation, Aziz and Firoozabadi's correlation and Kuo's correlation are 3.3 %, 10.9 % and 15.17 %, respectively. These results indicate that the current correlation is significantly more precise than the other correlations.

Table 1. Reservoir oil and injection gas properties and MMP data.

C1 %	C_2-C_6 %	MWC_{7+}	T / °C	C_{2+}	MWC_{2+}	Exp MMP(MPa)	Reference	calc MMP(MPa)
55	22	209	98.33	14	37.25	39.990	Firoozabadi and Aziz, 1986	38.871
50	22	250	121.11	10	33.51	41.369	Firoozabadi and Aziz, 1986	40.682
49	23	250	121.11	0	0	43.437	Firoozabadi and Aziz, 1986	43.321
57	26	183.6	84.22	0	0	43.437	Firoozabadi and Aziz, 1986	43.114
55	22	209	98.33	16	37.71	39.990	Firoozabadi and Aziz, 1986	37.994
50	23	250	121.11	10	34.01	41.369	Firoozabadi and Aziz, 1986	40.632
49	23	250	121.11	0	0	43.437	Firoozabadi and Aziz, 1986	43.321
46	25	240.68	115.93	18	39.77	37.235	Michelsen and Stenby, 1998	36.875
42	1	302	150.00	35	44.1	26.752	Kuo, 1985	26.551
42	1	302	150.00	38	44.1	25.166	Kuo, 1985	24.516
42	1	302	150.00	46	44.1	18.961	Kuo, 1985	18.804
33	24	215	101.67	47	39.91	16.547	Kuo, 1985	20.199
33	24	215	101.67	47	39.91	18.478	Kuo, 1985	20.249
39	27	258	125.56	24	38.19	33.274	NIOC, 1998	34.120
31	27	271	132.78	23	37.34	32.922	NIOC, 1998	34.859
37	25	294.97	146.09	23	37.34	34.474	Arya et al., 2001	34.943
31	27	271	132.78	23	37.34	32.922	Arya et al., 2001	34.859
44	31	231	110.56	27	38.73	35.954	Glass, 1985	32.305
33	26	121.91	49.95	15	37.37	36.051	Wang and Orr, 2000	37.943
23	33	141.74	60.97	41	41.86	22.201	Jean-Noel et al., 2001	22.397
24	30	141.99	61.11	41	41.86	23.601	Jean-Noel et al., 2001	22.559
54	24	132.12	55.62	17	39.77	38.001	Jean-Noel et al., 2001	37.019
22.92	32.08	257.7	125.39	41.47	42	22.105	Jean-Noel et al., 2001	22.573
23.64	30.36	254.4	123.56	41.47	42	23.504	Jean-Noel et al., 2001	22.614
45.85	24.68	143.7	62.06	18.12	39.89	37.611	Jean-Noel et al., 2001	36.517
26.57	30.25	245.43	118.57	12	39.43	36.611	Jean-Noel et al., 2001	39.428
54.26	24.12	238.15	114.53	17.88	40	37.907	Jean-Noel et al., 2001	36.903
6	28	175	79.44	43	41.34	24.580	Pedrood, 1995	21.944

Table 1. Continuation.

C1 %	C_2-C_6 %	MWC_{7+}	T / °C	C_{2+}	MWC_{2+}	Exp MMP(MPa)	reference	calc MMP(MPa)
33	26	209.81	98.78	16	36.75	40.300	Current work	37.983
33	26	209.81	98.78	16	36.75	35.584	Current work	37.853
33	26	209.81	98.78	16	36.75	37.280	Current work	37.954
33	26	209.81	98.78	16	36.75	40.838	Current work	38.038
33	26	209.81	98.78	16	36.75	41.568	Current work	38.073
32	25	252.21	122.34	0	0	41.575	Current work	43.214
32	25	252.21	122.34	10	30.07	38.976	Current work	40.738
32	25	252.21	122.34	10	44.1	38.273	Current work	40.125
32	25	252.21	122.34	10	58.12	37.735	Current work	39.359
32	25	252.21	122.34	5	30.07	39.672	Current work	42.188
31	27	270	132.22	0	0	45.492	Current work	43.193
31	27	270	132.22	10	30.07	40.734	Current work	40.718
31	27	270	132.22	20	30.07	37.418	Current work	37.223
46	25	240.68	115.93	18	39.77	35.563	Current work	36.739
46	25	240.68	115.93	18	39.77	37.618	Current work	36.925
32	25	252.21	122.34	28	41.53	31.247	Current work	31.319

Table 2. MMP data for new correlation validation.

C1 %	C_2-C_6 %	MWC_{7+}	T(°C)	C_{2+}	MWC_{2+}	Exp MMP(MPa)	Reference	Calc MMP(MPa)	Error (%)
50	22	197.3	82.22	25	45.48	33.198	**Pedrood, 1995**	32.005	3.59
26.15	29.75	274.5	121.11	43.07	40.21	24.476	**Rahimpour and Kharrat,2002**	22.613	7.61
32	25	252.21	98.89	10	72.15	37.570	Current work	38.403	2.22
32	25	252.21	98.89	20	30.07	37.397	Current work	37.244	0.41
32	25	252.21	98.89	30	30.07	32.536	Current work	33.222	2.11
32	25	252.21	98.89	25	30.07	33.950	Current work	35.288	3.94
32	25	252.21	98.89	15	30.07	37.852	Current work	39.071	3.22

This correlation investigates MMP calculation for oil and gas systems which include the temperatures from 54 to 149 °C, methane concentration from 6 to 55 mole percent, C_{7+} molecular weight from 120 to 302 g/mol, oil C_{2-6} concentration from 1 to 63 mole percent, injection gas C_{2+} concentration from 0 to 48 mole percent and injection gas C_{2+} molecular weight from 0 to 72. Comparing with other similar correlations, this correlation has larger applicable ranges, but in any case care must be taken when extrapolating beyond the range of data used to develop the correlation.

4. CONCLUSIONS

A novel MMP correlation for hydrocarbon gas injection has been developed based on the theory of multicontact miscibility (MCM) process. The correlation is significantly more accurate than the currently used correlations. In this correlation, a wide range of parameters that affect the MMP are taken into account. The new empirically derived miscibility correlation for hydrocarbon gas drive considers oil and gas composition. The MMP data calculated by slim tube simulators show that the MMP increases with increasing temperature and decreases slightly with increasing C_{2+} molecular weight in the gas stream.

ABBREVIATIONS

AAD	Average Absolute Deviation
EOS	Equation of State
MCM	Multicontact Miscible
MMP	Minimum Miscibility Pressure
PR3	Modified Peng-Robison Equation of State
STD	Slim Tube Test
VGD	Vaporizing Gas Drive
VLE	Vapor-Liquid Equilibrium

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