Empirical Formula for Minimum Miscible Pressure of CO₂-oil System in China

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Abstract. MMP of CO₂ and system in China oilfields is generally higher than that of other oilfields aboard. By abundant investigations the reason and the prediction of MMP is systematic analyzed. Based on the statistical data of reservoir characteristics, oil physical properties, injection gas components from dozens of oilfields in China, a correlation formula was regressed and derived. Compared to some other empirical formula, predicting results of this new empirical formula is relatively satisfactory.

1. Introduction
With the growing influence of greenhouse gases on humans and the growing demand of enhancing oil recovery, CO₂ flooding has become an increasing concern by people. In general, it is divided into miscible flooding and immiscible flooding. Compared with immiscible flooding, miscible flooding got more attention because of the higher oil recovery. Minimum miscible pressure (MMP) is the most important parameter to determine whether miscible flooding could be achieved [1]. However, MMP of CO₂-oil system in china is generally higher than that of abroad, which has brought a lot of inconvenience to the promotion of CO₂ miscible flooding.

There are mainly three methods to determine MMP: experimental method, theoretical method, and empirical formula method. Slime-tube displacement test is the standard method which is widely recognized. But it is costly and time-consuming. Empirical formula method is lowest accuracy and has certain fields of application in these three methods, but at the same time, it is the simplest method, which could reduce experimental numbers and pre-select the suitability of CO₂ flooding.

In 1960, Benham et al first published a correlation for predicting MMP of rich gas flooding. In 1978, Yelling et al presented a correlation used for determining MMP of impure CO₂ streams [2]. In 1979, PRII correlation was proposed according to saturation vapor pressure curve. In 1980, Holm and Rosendale correlation can only be used for a certain scope of molecular weight. Based on the predicting charts of Benham et al, Orr and Taber correlation is mainly used for predicting the effect of CO₂ purity. Johnson and Pollin correlation was only suitable for binary mixed gases. In 1985, Glaso proposed a correlation considering the effect of intermediate component to MMP [3]. Sebastian presented a correlation considering the effect of purity of CO₂. Alston proposed a correlation for impure streams and live oil systems [4]. In 1986, Kovarik summarized a correlation using impure CO₂ and West Texas oil systems. Given that the effect of the molecular weight distribution to MMP is
much greater than that of hydrocarbon structure; Silva raised a new correlation which MMP is regarded as a function of molecular weight distribution [5]. However, most empirical formulas used in China are cited from other countries. In sum, the accuracy is not as good as that used in other countries. This paper analyze the reason why MMP of CO$_2$-oil system is higher in China. By analyzing statistical data of reservoir and oil physical properties, injection gas components from dozens of oilfields in China, a new empirical method to determine MMP of CO$_2$-oil system was derived.

2. Higher MMP of CO$_2$-oil System in China

2.1. Sedimentary Environment

As table 1 shows, most oilfields in China belong to continental sedimentary deposition, which is relatively complex in oil types and constitution. The main characteristics of the crude oil in China are high wax content and high solidification point. Apart from some specific reservoirs, the gasoline fraction is very limited, and residual oil account for nearly one third.

| Basin           | sedimentary characteristic                  |
|-----------------|---------------------------------------------|
| Songliao        | shallow lake facies, delta facies           |
| Jiyang Depression | shallow lake facies, delta facies         |
| Huanghua Depression | delta facies                      |
| Sichuan         | shallow lake facies                         |
| Shan-Gan-Ning   | river dominated delta facies, offshore lake facies |
| Junggar         | alluvial fan facies                         |
| Turpan-Hami     | braided river delta facies, alluvial fan facies |
| Jiuquan         | shore-shallow lake facies                   |
| Qaidam          | delta facies, fluvial facies                |
| Tarim           | fluvial facies, offshore lake facies, littoral facies, delta facies |

2.2. Oil Component

The main CO$_2$ flooding project worldwide is concentrated in Texas of United States. While the main CO$_2$ flooding project of China is in Jilin oilfield. MMP of the crude oil in West Texas is mainly between 8MPa to 9MPa, while in Jilin oilfield, it is over 20MPa.

Fig. 1 is the contrast of the carbon distribution of crude oil sample between these two oilfields. It is obvious that compared with the oil sample in West Texas, mole fraction of some components like CH$_4$, N$_2$, and C$_{10+}$, which are not beneficial for forming miscible, is significantly higher in Jiling oilfield, while for the mole fraction of C$_2$–C$_{10}$, especially C$_2$ and C$_3$, which can achieve super critical state and significantly improve mass transfer rate like CO$_2$, is significantly lower in Jiling oilfield.
To achieve the general law of the carbon distribution of crude oil sample, this paper investigated a great deal of data from 21 oilfields abroad. Results show that C$_2$-C$_{10}$ is widely higher in these oilfields than that of Jilin oilfield.

2.3. **Colloid & Asphaltene**

Fig.2 is the relationship between oil density, colloid & asphaltene. For the oil samples of Jilin oilfield, as oil density increases, colloid and asphaltene increases much more obviously than those in other countries. In other words, colloid and asphaltene content in china is much higher than that in other countries for the same oil density. This may be one of the reasons why MMP of CO$_2$-oil system in china is much higher than in that in other countries.

### Table 2. Component of the crude oil (mol%)

| Components  | Flash oil, % | Flash gas | well flows | Components  | Flash oil | Flash gas | well flows |
|-------------|--------------|-----------|------------|-------------|-----------|-----------|------------|
| CO$_2$      | 0            | 1.428     | 0.481      | C$_{17}$    | 3.126     | 0         | 2.072      |
| N$_2$       | 0            | 6.315     | 2.129      | C$_{18}$    | 3.413     | 0         | 2.262      |
| C$_1$       | 0            | 73.247    | 24.691     | C$_{19}$    | 3.169     | 0         | 2.101      |
| C$_2$       | 0            | 11.031    | 3.718      | C$_{20}$    | 3.031     | 0         | 2.009      |
| C$_3$       | 0            | 4.824     | 1.626      | C$_{21}$    | 2.785     | 0         | 1.846      |
| iC$_4$      | 0            | 0.505     | 0.17       | C$_{22}$    | 2.581     | 0         | 1.711      |
| nC$_4$      | 0.48         | 1.443     | 0.805      | C$_{23}$    | 2.33      | 0         | 1.544      |
| iC$_5$      | 0.866        | 0.224     | 0.65       | C$_{24}$    | 2.378     | 0         | 1.576      |
| nC$_5$      | 1.74         | 0.518     | 1.328      | C$_{25}$    | 2.114     | 0         | 1.401      |
| C$_6$       | 1.695        | 0.294     | 1.223      | C$_{26}$    | 2.096     | 0         | 1.389      |
| C$_7$       | 2.495        | 0.152     | 1.706      | C$_{27}$    | 1.609     | 0         | 1.067      |
| C$_8$       | 3.693        | 0.019     | 2.454      | C$_{28}$    | 1.79      | 0         | 1.187      |
| C$_9$       | 5.459        | 0         | 3.619      | C$_{29}$    | 1.555     | 0         | 1.031      |
| C$_{10}$    | 4.976        | 0         | 3.299      | C$_{30}$    | 1.336     | 0         | 0.885      |
| C$_{11}$    | 5.292        | 0         | 3.508      | C$_{31}$    | 1.195     | 0         | 0.792      |
| C$_{12}$    | 5.522        | 0         | 3.66       | C$_{32}$    | 1.064     | 0         | 0.705      |
| C$_{13}$    | 4.763        | 0         | 3.157      | C$_{33}$    | 1.031     | 0         | 0.684      |
| C$_{14}$    | 4.387        | 0         | 2.908      | C$_{34}$    | 0.883     | 0         | 0.585      |
| C$_{15}$    | 4.945        | 0         | 3.278      | C$_{35}$    | 0.857     | 0         | 0.568      |
| C$_{16}$    | 4.171        | 0         | 2.765      | C$_{36+}$   | 11.173    | 0         | 7.407      |

Molecular Weight of C$_{36+}$: 674.9
Relative Density of C$_{36+}$: 0.8861
Gas oil ratio: 36.65 m$^3$/m$^3$

3. **A New Empirical Method**

Based on the statistical data of reservoir characteristics, oil physical properties, injection gas components from dozens of oilfields in China, a correlation formula was derived as Eq.1 shows. Pseudo-critical temperature $T_{cm}$ was introduced to consider the effect of the injection gas to MMP of the CO$_2$-oil system.

$$\text{MMP pure}=17.02T+99.20A+21.39B-53.53T_{cm}$$ (1)
Where, $MMP_{pure}$—MMP of pure CO$_2$ and oil system, psia; $T$—Reservoir temperature, F; $A$—intermediate/volatile; $B$—C$_5$+. Molecular Weight, g/mol; $T_{cm}$—Average critical temperature of component gas, K

4. Application of the new empirical formula

4.1. Forecasting of MMP of pure CO$_2$-oil system

Table 2 is the oil component of XX reservoir. Reservoir temperature is 108.4°C. Taking the MMP measured by slim tube test as standard, results calculated by different empirical formulas including Eq.1 are shows in table 3. Relative error of the results using this new empirical formula is less than 10%, absolute error is less than 2MPa. From the point of accuracy, Eq.1 > Yelling & Metcalfe > Cronquist > PRI 2 > Mungan > NPC. NPC method and Y-M correlation just considered the effect of reservoir temperature; parameters such as the characteristics of the gas, oil composition, molecular weight, and distribution were all neglected, so the results using these two methods are not very satisfactory. Mungan method just based on oil density, molecular weight of C$_5$+ to determine MMP, so the relative error is much bigger than the others. Cronquist correlation considered parameters like reservoir temperature, mole fraction of CH$_4$ and molecular weight of C$_5$+ in the oil, which were very important for determining miscible pressure.

Table 3. Comparison of MMP of CO$_2$ and oil system using different methods

| Empirical formula | Predicted MMP, MP a | Measured MMP, MP a | Relative error, % |
|-------------------|---------------------|-------------------|------------------|
| NPC               | 10.35               |                   | 62.92            |
| Mungan            | 20.5                |                   | 26.52            |
| PRI 2             | 21.32               |                   | 23.57            |
| Cronquist         | 31.37               |                   | 12.44            |
| Yelling & Metcalfe| 25.61               |                   | 8.22             |
| New empirical method | 26.23             | 27.90             | 5.99             |

5. Conclusion

Continental sedimentary environment, higher oil components like CH$_4$N$_2$ and C$_{10+}$, and higher Colloid & Asphaltene maybe the reason why MMP of CO$_2$ and system in China oilfields is significantly higher than that of other oilfields aboard. There are many empirical formulae used for determining MMP of CO$_2$ and oil system, but almost all correlations just considered part of influential factors. What’s more, every correlation was derived or regressed from characteristic of specific reservoirs and fluid properties. Based on the specific characteristic of reservoirs in China, a new empirical formula was regressed to determine MMP of CO$_2$ and oil system in China. Predicting results is relatively satisfactory compared to some other empirical formula.

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