PURE AND IMPURE CO_2 MINIMUM MISCIBILITY PRESSURE: COMPARING SIXTEEN CORRELATIONS

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ABSTRACT

Multiple contact miscible floods, involving the injection of relatively inexpensive gases into oil reservoirs, represent one of the most cost effective enhanced oil recovery processes currently available. The experimental displacement procedures available for determining the optimal flood pressure, referred to as the minimum miscibility pressure (MMP), are both costly and time consuming. Hence, the use of a correlation proven reliable over a large range of conditions is likely to be considered acceptable for the purposes of preliminary screening studies.

This paper evaluates 16 MMP correlations for pure and impure CO_2 miscible flooding published in the literature. A data set of 186 experimentally measured MMPs from the literature and corresponding gas/oil compositional information was constructed to evaluate the reliability of the MMP correlations. The accuracy of each correlation was evaluated by comparing the predicted versus measured MMPs and a complete statistical analysis is presented.

INTRODUCTION

CO_2 miscible flooding is among the most widely applied non-thermal enhanced oil recovery (EOR) techniques. Among gas injection processes, CO_2 is preferred over hydrocarbon gases because of its lower cost, high displacement efficiency, and the potential for concomitant environmental benefits through its disposal in the petroleum reservoir. Key factors that affect CO_2 flooding include the reservoir temperature, oil characteristics, reservoir pressure and the purity of injected CO_2 itself. Field case histories from CO_2 floods suggest that CO_2 purity should not be viewed as a rigid constraint as the use of low purity CO_2 stream could also be economical and effective in entrancing oil recovery.

Pure CO_2 is not always available as an injection gas. Impure CO_2 streams however are available from a variety of sources, including natural reservoirs and process plant waste streams. Typically, impure CO_2 contains a significant amount of nitrogen, H_2S, and hydrocarbons. Another potential source of impure CO_2 is the gas produced from wells in a field undergoing a CO_2 flood. Reinjection of produced gas could reduce the cost of CO_2 flooding because high-purity cleanup of the fluid is expensive.

The displacement efficiency of oil by gas is highly pressure dependent and miscible displacement is only achieved at pressure greater than a certain minimum. This minimum pressure is called the Minimum Miscibility Pressure (MMP). The CO_2 MMP is an important parameter for screening and selecting reservoirs for CO_2 injection projects. For the highest recovery, a candidate reservoir must be capable of withstanding an average reservoir pressure greater than the CO_2 MMP. Knowledge of the CO_2 MMP is also important when selecting a model to predict or simulate reservoir performance as a result of CO_2 injection.

A variety of correlations for the estimation of MMP have been developed from regressions of experimental data. However, few references Shokir [1] present a comparative analysis, the data set is not large and the comparison is only related to absolute average deviation. It was therefore necessary to carry out a more complete investigation.
This paper evaluates 16 MMP correlations, including pure and impure CO_2, published in the literature. A data set of 186 experimentally measured MMPs from the literature and corresponding gas/oil compositional information was constructed to evaluate the reliability of the MMP correlations. The accuracy of each correlation was evaluated by comparing the predicted versus measured MMPs and a complete statistical analysis is presented.

MMP CORRELATIONS

A variety of correlations for the estimation of MMP have been developed from regressions of experimental data. Although less accurate, correlations are quick and easy to use and generally require only a few input parameters. Hence, they are very useful for fast screening of reservoirs for potential CO_2 flooding. They are also useful when detailed fluid characterizations are not available. Table 1 summarizes independent variables of the selected correlations with MC_5^+ denote oil C_5^+ molecular weight, xvol volatile oil fraction (CH_4 and N_2), xint intermediate oil fraction (C_2 to C_4, H_2S and CO_2), °API gravity, M oil molecular weight, fra percentage of intermediate (C_2-C_6) in the oil.

Table 1: Independent variables with each correlation

Code correlation	Correlation	Independent variables
1[a]	Yellig e Metcalfe [2]	T
2[c]	Alston et al.[3]	T, MC_5^+,xvol,xint
3[b]	Sebastian et al. [4]	-
4[c]	Enick et al. [5]	T, MC_5^+,xvol,xint
5[a]	NPC [6]	T, °API
6[c]	Johson and Pollin [7]	T, °API, M
7[a]	Orr and Jensen [8]	T
8[a]	Holm and Josendal [9]	T, MC_5^+
9[c]	Eakin and Mitch [10]	T, MC_7^+
10[a]	Lange [11]	T, M
11[a]	Glaso [12]	T, MC_7^+, fra
12[a]	Cronquist [13]	T, MC_5^+, xvol
13[a]	PRI [14]	T
14[a]	Zuo et al.[15]	T, M, °API, xvol, xint
15[a]	Yuan et al. [16]	T, MC_7^+, fra
16[a]	Emera and Sarma [17]	T, MC_5^+, xvol, xint

a – only pure CO_2; b – only impure CO_2; c – pure and impure CO_2.

RESULTS

A data set of experimentally measured MMPs and corresponding gas/oil compositional information was constructed to evaluate the reliability of the MMP correlations. A total of

186 MMP measurement obtained from the literature was used as a data set. Due to lack of space here a detailed description of the experimental set data is impossible.
It is important to note that it was not always possible to calculate the MMP for every system within each data set using the appropriate correlations. This was due to the fact that specific gas and /or oil compositional information required by individual correlations was not available in certain cases. Calculations results are summarized in Table 2, where the number of MMPs evaluated, average absolute deviation (AAD), standard deviation (SD) and correlation coefficient (CD) for each correlation are listed.

Table 2: Correlation Statistical Analysis

Code correlation	Number of MMPs evaluated	AAD	SD	CC	Solvent
1	90	15,96	22,08	0,58	Pure CO_2
2	53	21,65	31,34	0,6	Pure CO_2
2	122	29,31	66,38	0,3	Pure and impure CO_2
3	73	8,76	12,47	0,82	Impure CO_2
4	119	17,94	23,82	0,69	Pure and impure CO_2
5	38	37,23	54,23	0,02	Pure CO_2
6	38	34,69	45,98	0,36	Pure and impure CO_2
7	89	19,24	28,95	0,5	Pure CO_2
8	45	17,58	21,28	0,79	Pure CO_2
9	44	46,5	59	0,75	Pure CO_2
9	118	44,72	60,91	0,23	Pure and impure CO_2
10	49	14,94	19,27	0,55	Pure CO_2
11	37	33,61	55,67	0,5	Pure CO_2
12	35	20,71	27,87	0,76	Pure CO_2
13	90	18,07	26,97	0,5	Pure CO_2
14	20	20,91	27,41	0,52	Pure CO_2
15	37	23,58	28,33	0,52	Pure CO_2
16	21	20,21	28,89	0,6	Pure CO_2

The correlation 1 was exclusively developed for pure CO_2 and temperature was the only independent variable so we can apply it for 90 oils. It is important to emphasize the high correlation coefficient, which demonstrates the great importance temperature in MMP correlation for pure CO_2. For the highest MMPs, the correlation calculated values were in most cases underestimated.
It was possible to apply correlation 2 for 122 oils from which in 53 oils the solvent is pure CO_2. Despite the correlation 1 consider only temperature as independent variable, and the correlation 2 takes more variable into account, a comparison between the two correlations regarding to the correlation coefficient, absolute medium deviation and standard deviation, demonstrated a clear advantage for the first one. The correlation 2 behavior shows functional dependence not very appropriate of the temperature as well as the other variables.
A comparison between the only pure CO_2 results and the total group which contain pure and impure CO_2 experimental data reveals an accented correlation coefficient decrease and a significant increase of the dispersion. The results demonstrated that neither the pseudocritical temperature, used as correction factor of MMP pure CO_2 for MMP impure CO_2 an adequate

correction factor nor its functional form which is linked does not seem to be the possible best choice.
The correlation 3 is different from the previous ones since it only allows calculating the relationship between MMP for an impure CO_2 stream and MMP for a corresponding pure CO_2. In this investigation to realize a judicious evaluation of this correlation, we used only experimental CO_2 MMPs. As consequence, the evaluation is concerning to the correlation capacity to calculate the influence impurity in CO_2 stream. The results of this evaluation (73 oils) show a very good correlation coefficient, as well as the other evaluation parameters. This behavior implies that the use of the critical temperature, obtained from molar fraction, as well as it functional form is much appropriated.
As the correlation 4 calculations were realized under a graphic form, there is a high inaccuracy. For this correlation our experimental database allows 119 oils to be employed, with the results presented in the Table 2. The results indicated that, in most of the studied oils the MMP is underestimated and also the deviation increases with the pressure increase. The same independent variables of this correlation were used previously in the correlation 2. A comparison allows concluding that the correlation 4 is superior in all statistical aspects. A fundamental difference is regarding to the fact that correlation 4 has an important theoretical basis while the correlation 2 it is an experimental adjustment data only.
In the correlation 5 the only independent variables are density of the oil and its temperature. There is not a relationship between the variables but only a range of independent variables. For these known properties, our database allows the application in 38 oils; and in all cases the solvent is pure CO_2. As expected since there is a range of variables and there is not a functional relationship, the behavior of the correlation is very bad and all the statistical evaluations demonstrate this fact.
With the correlation 6 the oil independent variables are its molecular weight and density. For the injection gas the used variables are composition, temperature, pressure and component critical volumes. An important point to detach is the great number of variables involved in the impure CO_2 description. As a consequence the behavior would be better than the other one. This correlation was applied for 38 oils with pure CO_2 and 32 systems with impure CO_2. Despite the size of our data base due to the fact that the only impurities allowed in the correlation are N_2 and C_1 even than their composition must be less than 0,2 the analyzed sample university is small. As occurred in the other correlations the deviation increase with the increase of the experimental pressure and there is a systematic pressure underestimated.
For the correlation 7, the only independent variable is the temperature, originally developed for pure CO_2, could be applied for 89 oils and it can be compared with the correlation 1. The results demonstrate that the correlation 1 is superior with regard to the correlation coefficient. This fact can be explained as its superior functional relationship in the temperature. Another observation is that on keeping this functional form more variables should be involved in the correlation 7.
The correlation 8 was developed for pure CO_2 and it is presented under graphic form. Due to the available independent variables for its application it can be used with 47 oils. The results demonstrated the correlation 8 with a high correlation coefficient value despite the fact the correlation under graphic form. A comparison between this correlation and the correlation 1, display a practically equal result. As a consequence we can conclude that the inclusion of the fraction C_5^+ molecular weight in the correlation did not corresponded to great advantages. On the other hand, we compare the correlation 8 with the correlation 2 which besides the molecular weight of the fraction C_5^+ and temperature, it contains as important variable the ratio between the volatile and intermediate components percentage. The results allow to verify

great supremacy of the first one regarding to all aspects, including the correlation coefficient relationship. We can explain these comparison results, as being not appropriate influence evaluation of the ratio between the volatile and intermediate components and/or a poor functional dependence of the other two independent variables.

For the correlation 9 the independent variables are temperature and fraction C_7^+ molecular weight and with regard to the solvent its composition, critical pressure and temperature of the components. For pure CO_2 the correlation was used with 44 oils of our database and the results indicate that, spite the good correlation coefficient, bad absolute average deviation and standard deviation. The correlation 9 can be compared with the correlation 8, since the independent variable difference for pure CO_2, is the molecular weight of the fraction C_7^+ to the first one and the fraction C_5^+molecular weight to the second. The results demonstrated that the correlation coefficient is very close, however the average absolute deviation and the standard deviation with the first one is larger than the second correlation. When we apply this correlation with pure and impure CO_2, it was possible to accomplish it in 118 oils and the correlation behavior was very bad with relation to all relevant analysis items. The correlation coefficient decreases to an extremely low value which demonstrates the poor characterization solvent, mainly its functional form.

For all implemented correlations being the solvent pure CO_2 the correlation 10 presented the best behavior in standard deviation and average absolute deviation terms, as it can be seen in the Table 2. However, its correlation coefficient was very low, despite the fact this correlation was developed based on a strong physical theory, and not is an empiric correlation. As other mentioned correlations, the deviation increases with the pressure increase.

The correlation 11 was developed having pure CO_2 as solvent. The independent variables are: temperature, molecular weight of the fraction C_7^+ and C_2-C_6 molar percentage in the oil. With these characteristics 44 oils were selected to compare the results of this correlation with the correlation 1. We conclude that the simpler correlation 1 with the temperature as the only independent variable have a superior performance. This fact demonstrates that the addition of these independent variables do not correspond an improvement.

The independent variables of the correlation 12 are: temperature, molecular weight of the fraction C_5^+, molar percentage of methane and nitrogen. This correlation can be applied in 35 oils. The results demonstrate that, in most examined oils the correlation 12 provide MMP above the experimental values. The comparison between correlation 12 with the correlation 8 allow to detach that the correlation coefficients are very similar; however few superior average absolute deviation and standard deviation. The comparison of this correlation with the correlation 6 demonstrates a great advantage for the first one .When we compare this correlation with the correlation 1; we observed that the only advantage of the first is regarding to the correlation coefficient.

For the correlation 13, the only independent variable is the temperature and it can be applied in 90 oils. The results demonstrated as usually the increase deviation of the MMP calculated with regard to the experimental value with the increase of the pressure. We observed that so this correlation, as the correlation 1 and correlation 7, they have temperature as the only independent variable. A comparison among the 3 allows to verify that the correlation 13 is extremely similar the correlation 7 in all of the evaluation criteria. The correlation 1 however presents slight superior performance with respect to the other ones.

In the correlation 14 the independent variables are temperature, molecular weight of the fraction C_7^+, molar fraction of light and intermediate components. With our database this correlation can be applied in 20 oils. When we compared this correlation with correlation 6 we verified a great improvement in all evaluated levels. Table 2 shows that the behavior of this correlation and the correlation 13, despite the fact that correlation 14 uses more variables than the correlation 13

In the correlation 15 the independent variables are: molecular weight of C_7^+, molar percentage of C_2-C_6 and temperature, it could be applied in 37 oils, and the results presented in the Table 2.

For the correlation 16, the independent variables are: temperature, molecular weight of C_5^+, volatile oil fraction and intermediate oil fraction. This correlation was developed for pure CO_2, could be applied for 21 oils, being the results presented in the Table 2.

CONCLUSIONS

16 MMP correlations for pure and impure CO_2 miscible flooding published in the literature were studied. A data set of 186 experimentally measured MMPs from the literature and corresponding gas/oil compositional information was constructed to evaluate the reliability of the MMP correlations. As conclusion there is not an agreement in the literature regarding to the mains factors affecting the MMP except the temperature .For the examined correlation we detach the very low correlation coefficient as a consequence more independent variables should influence MMP.

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