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An Experimental and Modeling Approach to Estimate the Minimum Miscibility Pressure of Nitrogen-Crude Oil Using Dead Oil Samples

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Abstract

The Vanishing Interfacial Tension (VIT) technique is used to determine the Minimum Miscibility Pressure (MMP) of 5 dead crude oil samples using pure Nitrogen as injected gas. This technique is used to measure the Interfacial Tension for each oil sample in Nitrogen. NMMP can be estimated when there is no interface between oil and gas. As the experimental NMMPs are based on dead oil samples, and due to the risk involved with live oil, a new approach is introduced by using existing 30 experimental data sets available in the literature. The new correlation (SQU-NMMP model) is generated based on 20 data sets. The other 10 data sets were used to validate the SQU-NMMP model and other correlation models. The average error of SQU-NMMP model is 2.4% compared with 4.3% for Sebastian & Lawrence's model. Normalization is applied on each sample's fraction to convert it into dead condition. The coefficient is the ratio of MMPDead to NMMPLive. The standard deviation of the calculated coefficients is 0.2 with an average of 1.33. The NMMP of the 5 dead oil samples are estimated by the VIT experiment as well as by using the CMG WinProb software and then results are compared with each other resulting in an average error of 3.2%. The study proved the SQU-NMMP model works precisely with less error margin.

Keywords: Enhanced Oil Recovery, Minimum Miscibility Pressure, Vanishing Interfacial Tension, Interfacial Tension

1. Introduction

Miscible gas flooding application is one of the main Enhanced Oil Recovery (EOR) techniques. Gas is injected into the reservoir for miscible or immiscible displacement to enhance the recovery (Mario J et al., 2007). In gas flooding application, it is essential to look at the phase behavior that is if we mix two materials together, what will be the outcome mixture, is it one or two-phase mixture. Selection of gas type is also crucial in designing any gas flooding, some gases are expensive, and some are not available. CO2 injection is one of the successive & effective gas flooding techniques (Khalid Al-Hinai et al., 2014).

However, several disadvantages have been reported for CO2 injection. For instance, corrosion in production wells & surface equipment and asphaltene precipitation which is the main reason for formation damage, in addition to that cost encountered.

Nitrogen is selected as an alternative gas injection for gas flooding due to its low cost, no corrosive and availability. It can be extorted from atmospheric air by cryogenic processes (Vahidi A et al., 2007). Phase behavior depends on three parameters, Pressure, Temperature and Compositions. The pressure-temperature diagram shows the phase behavior of any mixture, depending on the fraction of each composition and from this diagram miscibility can be determined at which pressure.

Miscibility can be achieved by First Contact Miscibility (FCM) or Multi-Contact Miscibility (MCM). FCM is achieved when both gas & oil become miscible at any random ratio. Most of the gas flooding is not FCM, so miscibility is achieved by MCM. MCM can be achieved in vaporizing or condensing (Zick, 1986). In vaporizing, the amount of gas is high enough to vaporize the intermediate components of oil, and by several contacts the system will be forming a single gas phase. In condensing, the amount of gas is less, so it will dissolve in the oil (condensing), and by several contacts the oil becomes lighter forming a single liquid phase.

Minimum Miscibility Pressure (MMP) is the main parameter to determine if the gas injection can be applied for a specific oil field. MMP is the minimum pressure at which a gas can develop miscibility with a given reservoir oil at reservoir temperature (Stalkup, 1987).

The IFT is Zero at minimum miscibility pressure (Tathed, 2008), and no interface exists between the fluids so the displacing fluids and residual oil form one phase. To achieve a miscible gas flooding, the reservoir pressure should be maintained above the MMP of the injected gas.

MMP can be estimated using several experimental methods such as Slim-Tube experiment, rising-bubble apparatus (RBA) experiments (Holm et al., 1974; Zhou et al., 1998; Hoffman et al., 2019), mixing-cell experiments (Menzie, 1963; Teklu, 2012), and Vanishing Interfacial Tension (VIT) experiments (Ayatollahia et al., 2016). The rising-bubble apparatus (RBA) and the vanishing interfacial tension (VIT) technique are faster and cheaper methods for estimating the MMP (Rao et al., 2000). Experimental techniques are costly and time-consuming; therefore, many mathematical models are built to expedite the MMP calculation process.

In this study, the Vanishing Interfacial Tension (VIT) technique is used to determine the Minimum Miscibility Pressure (MMP) of 5 crude oil samples (Dead Oil) using pure Nitrogen (N_2) as injected gas. The VIT technique is based on the pendant drop parameters of each oil sample in Nitrogen to determine the Interfacial Tension (IFT). The MMP can be estimated when the IFT between the injected gas and the reservoir oil, is zero.

CMG WinProb reservoir simulation software is used to calculate the MMPs of the dead oil samples. Component fractions of each dead oil sample, MW of heavy component, specific gravity of heavy component, and reservoir temperature are used as input. Results are generated and compared with the experimental MMPs and SQU-NMMP model.

2. State of the art

Recent studies on Nitrogen MMP are based on live oil samples. In this study, SQU-NMMP model is developed which is based on dead oil samples. Under normal circumstances, the NMMP from the dead oil samples cannot be estimated due to the volatility of light components. Furthermore, the risks involved with handling the live oil samples makes the process challenging. This project is aimed to develop a new method to measure the MMP of live oil samples from data extracted from dead oil samples. Moreover, a new correlation is derived for estimating the NMMP from existing live oil MMP data from various literature references.

3. Materials and Methods

As the experimental MMPs are based on dead oil samples, due to the risk involved with live oil, the work methodology is divided into the following stages:

- Collection of 30 existing live MMPs experiment data available in the literature in order to generate the SQU-NMMP model.
- SQU-NMMP model generated is based on 20 data sets. The other 10 data sets are used to validate the SQU-NMMP model and other correlation models.
- To obtain the conversion coefficient, normalization is applied on the live samples converting them to dead condition.
- Conduct the VIT experiments to estimate the NMMP of the 5 dead oil samples. And then convert the results into Live NMMP's using the conversion coefficient.
- The CMG WinProb software is used to calculate the NMMP and then the results are compared with the Live NMMPs which were obtained from the previous step.

3.1. Gas Chromatography

The crude oil compositions of the 5 dead oil samples are measured using the GC machine - model is Clarus 680 manufactured by PerkinElmer, Inc. Oil compositions will be one of the main parameters to calculate the Nitrogen MMP using the correlation models.

Figure 1. Gas Chromatography Machine

3.2. Oil Density Meter

Crude Oil Densities are measured for the 5 dead oil samples using Density Meter model: DMA 4500 M from Anton Paar GmbH.

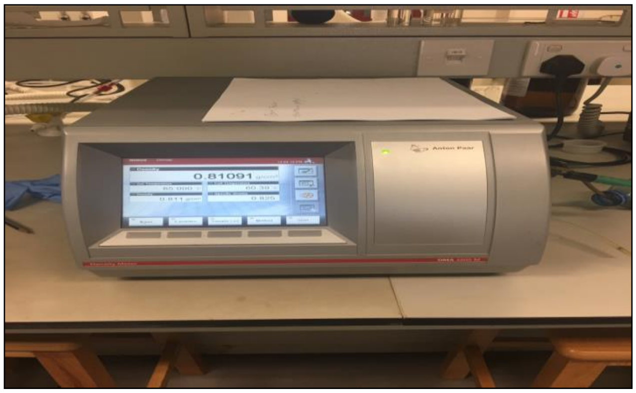

Figure 2. Oil Density Meter

3.3. Nitrogen Densities

Nitrogen density is measured at various pressures and temperatures of each sample using peace software.

3.4. VIT Meter

Interfacial Tension measurements are obtained using IFT-700 meter manufactured by VINCI Technologies, FRANCE. The pendant drop technique is one way to determine interfacial properties based on ADSA. Then parameters recorded from drop analysis are substituted in Laplace equation in order to measure the IFT. The schematic of a pendant drop is shown in Fig.1.The IFT is measured for each oil sample at different pressure values then plotted versus pressure. The estimation of MMP is done by extrapolating the IFT linear equation until IFT is zero.

Figure 3. IFT-700 meter

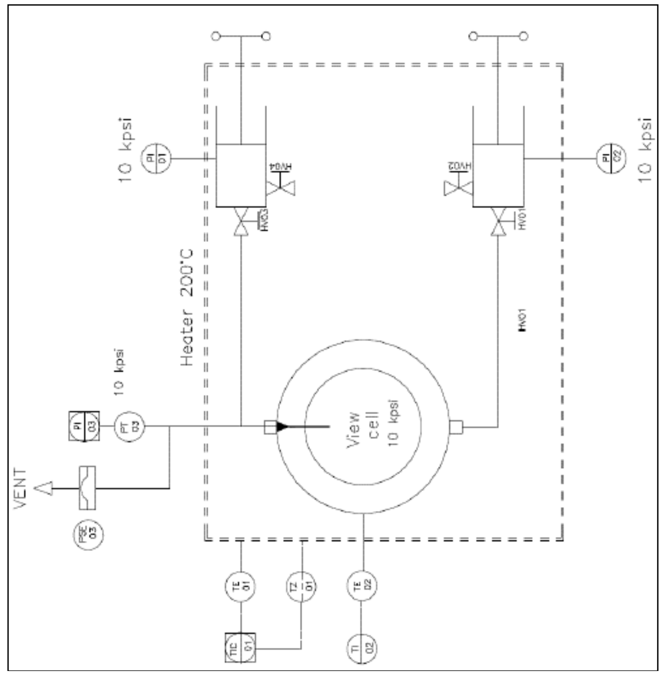

Figure 4. Schematic of a pendant drop.

3.5. Correlation Models:

In this study, four different models are used to validate the collected oil data sets, which are:

- Sebastian and Lawrence NMMP model.
- Hanssen NMMP model.
- Hudgins NMMP model.
- Firoozabadi and Aziz NMMP model.

4. Results and Discussion

The 30 live oil samples' data (Sebastian et al., 1986; Hanssen, 1988; Hudgins, 1990; Firoozabadi et al., 1986; Koch, 1958; Akram, 2007; Wang, 1998) are used to estimate the MMP with Nitrogen using the above models, and to generate the SQU-NMMP model. Each sample has its own composition fractions, and these fractions are used later on for normalizing and converting the samples into dead condition, in order to determine the conversion factor coefficient. The data is given in Table.1.

Table 1. 30 data sets of NMMPS

Sample	NMMP (psi)	Sample	NMMP (psi)
1	5947	16	6400
2	6164	17	6850
3	6382	18	4902
4	6527	19	3800
5	6017	20	7600
6	5500	21	4500
7	7000	22	3873
8	6800	23	8850
9	6500	24	8949
10	6000	25	8900
11	6599	26	6800
12	5050	27	8400
13	8500	28	6400
14	9000	29	4800
15	6700	30	5845

4.1. Generating SQU-NMMP Model

The SQU-NMMP model is generated using Non-Linear Regression. Table 2 shows the fraction summary of the 5 dead oil samples which are used in generating the SQU-NMMP model. The main parameters that affect the MMP are:

- Reservoir Temperature (°F).
- Mole fraction of C_1.
- Mole fraction of C_2-C_6.
- Molecular weight of C_{7+}.

The given parameters seem to affect the MMP of a reservoir fluid with N2. The amount of intermediates enhances the development of miscibility. Another factor is the volatility of the reservoir oil. The more volatile the oil is, the more vaporization will be at the lower pressure. Hence, C1 fraction and C7+ molecular weight are taken into account. Finally, the effect of temperature is also an important factor, as the increase in temperature will reduce the viscosity of the oil and enhance the vaporization.

The authors should illustrate here the main findings of this paper and provide a short discussion. The discussion should spell out the major conclusions and interpretations of the work, including some explanation on the importance and relevance of the dataset and analysis. It should not be restatement of the analyses done and their basic conclusions.

SQU-NMMP model is produced based on 20 live NMMPs and validated using the other 10 live NMMPs. The generated model is shown in Equation 1.

$$MMP = 4032 + 27.1(T) - 0.0025(T^2) + 3.8(MW_{C7+}) - 29.23(C_1) - 15.43(C_{INT}) + 71.85\left(C_1.\frac{T}{MW_{C7+}}\right) - 166.7\left(C_{INT}.\frac{T}{MW_{C7+}}\right) - 16956.4\left(C_1.\frac{T}{MW^2_{C7+}}\right) + 18417.3\left(C_{INT}.\frac{T}{MW^2_{C7+}}\right) \quad (1)$$

Some models showed higher errors, however the validation of SQU-NMMP model showed an average absolute error of 2.4% as compared to 4.3% for Sebastian & Lawrence model as shown in Figure 5.

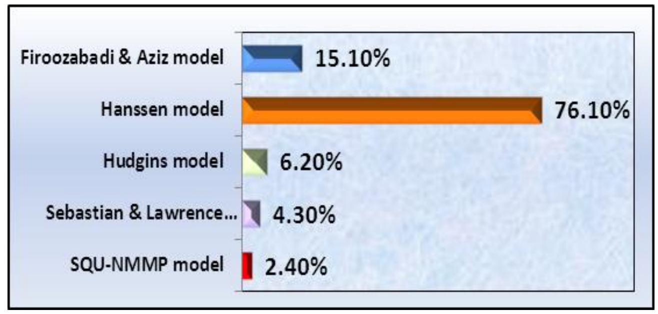

Figure 5. APRE% for 10 Live samples

4.2. Normalization of live Oil samples

The idea is to apply ZERO to volatile components and distribute their actual fraction to the remaining components. Figure 6 & Figure 7 illustrate the mole fractions of C_2-C_6 & C_{7+} respectively, before and after normalization.

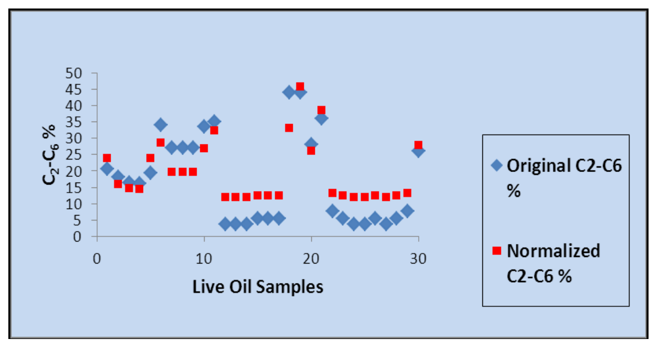

Figure 6. C_2-C_6 Normalization

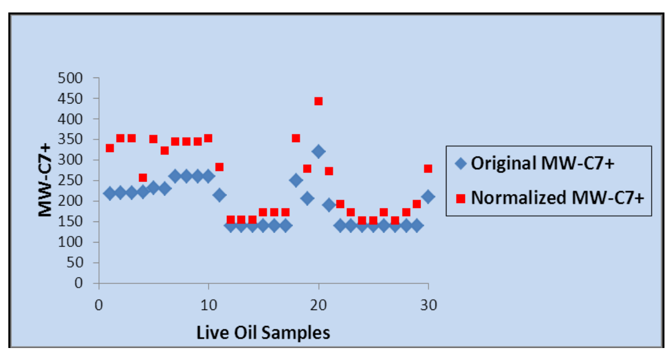

Figure 7. MWC_{7+} Normalization

4.3. Determination of MMPDead/MMPLive coefficient

A coefficient is obtained for each sample by dividing MMP_{Dead} sample over MMP_{Live} sample. The standard deviation is obtained for the calculated coefficients of SQU-NMMP and Sebastian & Lawrence model to be to be 0.2 & 0.27 respectively, with an average coefficient equal to 1.33 for SQU-NMMP model and 1.44 for Sebastian & Lawrence model. The average of these coefficients will be used later on as a conversion factor of any dead MMP to live MMP.

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A coefficient is obtained for each sample by dividing MMPDead sample over MMPLive sample. The standard deviation is obtained for the calculated coefficients of SQU-NMMP and Sebastian & Lawrence model to be to be 0.2 & 0.27 respectively, with an average coefficient equal to 1.33 for SQU-NMMP model and 1.44 for Sebastian & Lawrence model. The average of these coefficients will be used later on as a conversion factor of any dead MMP to live MMP.

4.5. NMMP Experiments

Miscibility is achieved when there is no interface between the two phases, in another word, the IFT between the two phases is zero, and therefore extrapolating the IFT curve to zero IFT would lead to estimate the MMP. The objective of this section is to estimate the NMMP for 5 dead oil samples.

4.6. IFT Results

IFT experiment is conducted on the 5 dead oil samples using the IFT-700 meter. Pendant drop shapes given in Figure 8.

Oil densities are measured at reservoir temperature of each sample. Nitrogen densities are obtained from Peace Software at different pressures. Both oil and Nitrogen densities are key parameters in calculating the IFT in addition to the injection pressure and oil temperature.

The relationship between the injected N2 pressure and IFT is linear. The IFT for L-721 reduces from 21.98 mN/m to 21.1 mN/m. For L-722 the IFT reduces from 22.1 mN/m to 21.12 mN/m. For F-299 the IFT reduces from 21.3 mN/m to 20.48 mN/m. For N-166 the IFT reduces from 22.3 mN/m to 21.36 mN/m. For MLM-182 the IFT reduces from 22.2 mN/m to 21.23 mN/m.

NMMP is estimated for each dead oil sample by extrapolating the IFT curve to zero pressure, as shown in Figures 9 to 13. The resulted NMMP is higher than the reservoir pressure of each oil sample, thus Nitrogen cannot be used for the given reservoirs. Another technique can be used as an alternative. It is also proving that Nitrogen is used for deep reservoir with much higher reservoir pressure.

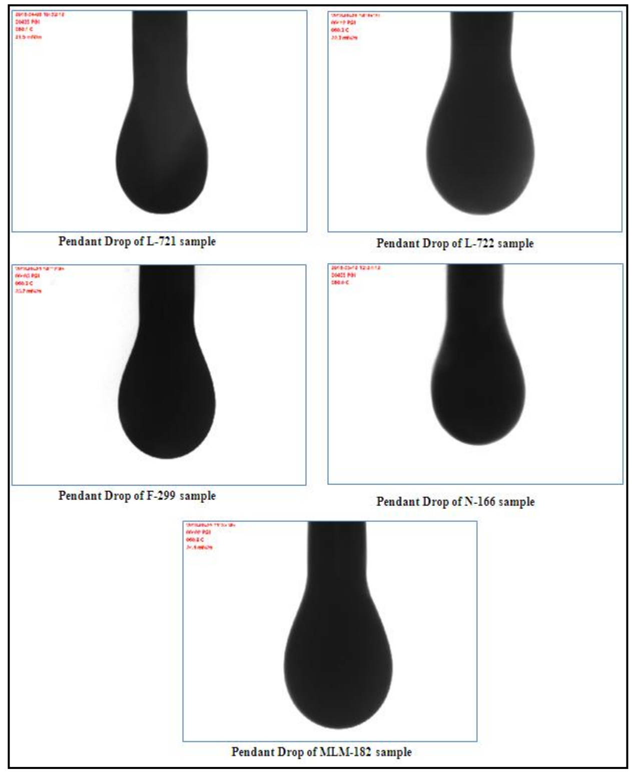

Figure 8. Pendant Drop test for the 5 dead oil samples

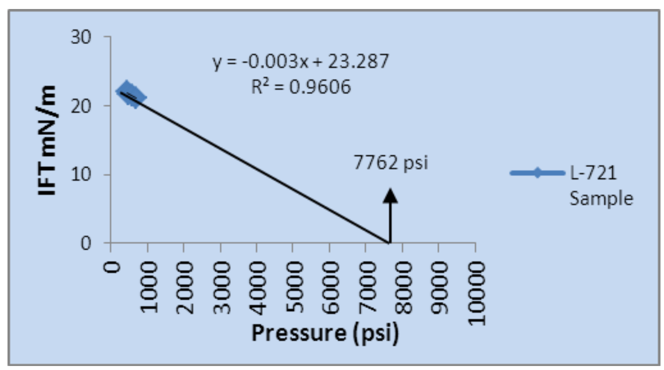

Figure 9. MMP estimation for N2-L721 dead oil system

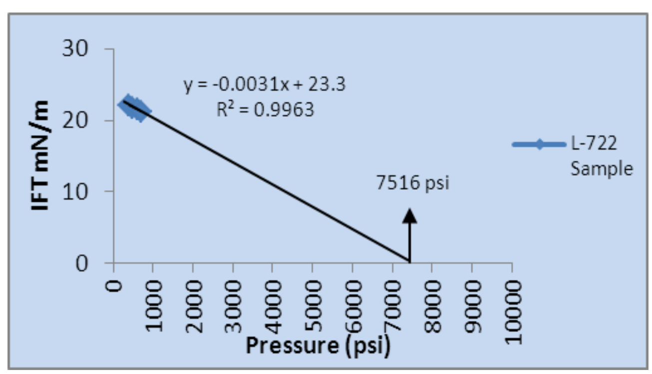

Figure 10. MMP estimation for N2-L722 dead oil system

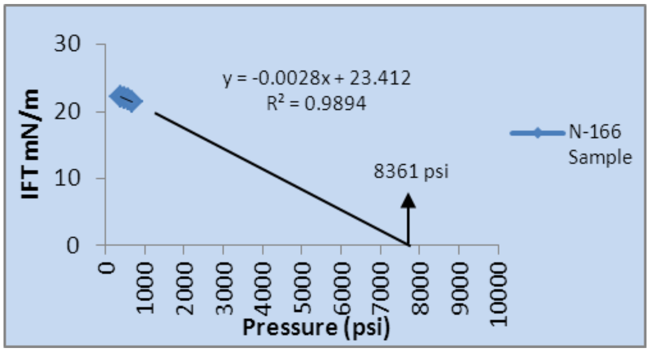

Figure 11. MMP estimation for N2-N166 dead oil system

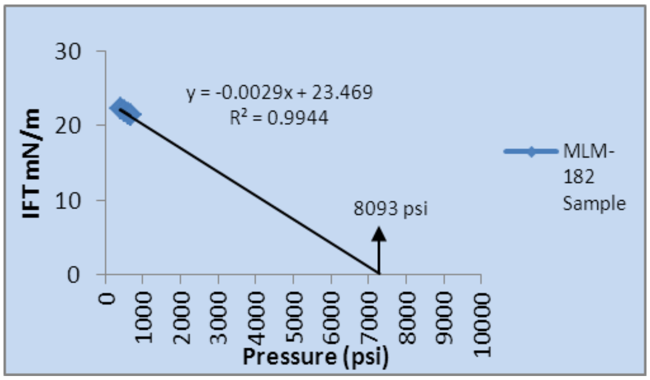

Figure 12. MMP estimation for N2-MLM-182 dead oil system

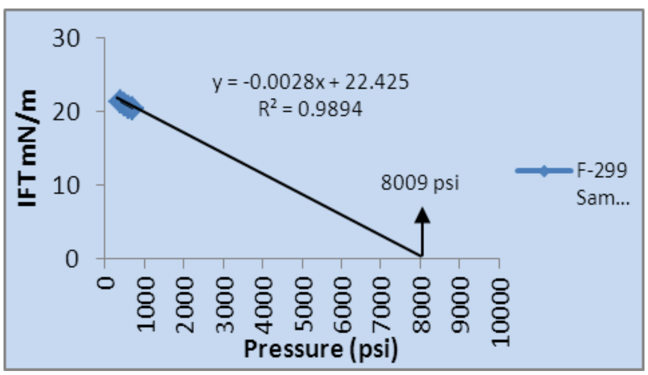

Figure 13. MMP estimation for N2-F299 dead oil system

Table 2. Estimated NMMP from the 5 dead oil samples

Sample	Reservoir Pressure (psi)	Temperature (C)	NMMP (psi)
L-721	1999	63	7762
L-722	1999	63	7516
F-299	904	69	8009
N-166	1300	78	8361
MLM-182	1973	90	8093

Component fractions are given in Table 3, for the 5 oil samples. The experimental NMMP's are validated using the existing correlation models, SQU-NMMP model, and CMG software. This is to ensure that the procedure for the experiment is followed properly, and results obtained from the experiment have the least margin of error as showing in Table 4.

Table 3. Component fractions for the 5 oil samples

Component	L-721	L-722	N-166	MLM-182	F-299
C1	0.00%	0.00%	0.00%	0.00%	0.00%
C2	0.00%	0.00%	0.00%	0.00%	0.00%
C3	0.00%	0.00%	0.21%	0.00%	0.00%
C4	2.97%	5.26%	1.99%	0.41%	1.89%
C5	6.47%	7.96%	6.79%	11.10%	8.90%
C6	3.61%	3.89%	2.22%	1.78%	3.35%
C7+	86.94%	82.89%	88.79%	86.71%	85.86%

Table 4. NMMPDead from VIT, CMG, SQU model, and Sebastian & Lawrence model

Sample	NMMP (psi) VIT	NMMP (psi) CMG	NMMP (psi) SQU model	NMMP (psi) Sebastian & Lawrence model
L-721	7762	7255	7487	8482
L-722	7516	7445	7343	8277
F-299	8009	7875	7545	8381
N-166	8361	8195	7981	8805
MLM-182	8093	7695	8043	8613

4.7. Validation of Dead oil NMMPs

The first validation is performed with CMG WinProb software by simulating the MMP of each dead oil sample, and compares them with the experimental NMMPs of the 5 oil samples. The results are shown in Figure 14. The simulation results show that N2 gas achieved MCM with reservoir oils by vaporization of the light components and with absolute error percentage ranging from 0.94% to 6.53%, and with average absolute error of 3.2%.

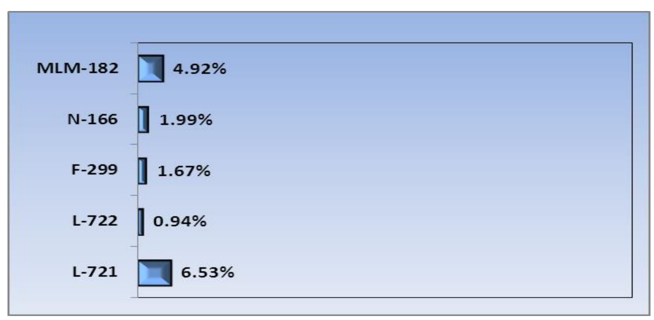

Figure 14. APRE % for CMG $NMMP_{Dead}$ and VIT Experimental $NMMP_{Dead}$

The second validation is conducted with SQU-NMMP model and compares the results along with the experimental NMMPs of the 5 oil samples. The results show a positive agreement with experimental data. The absolute error percentage is ranging from 0.6% to 5.8% with an average absolute error percentage of 3.3% as shown in Figure 15.

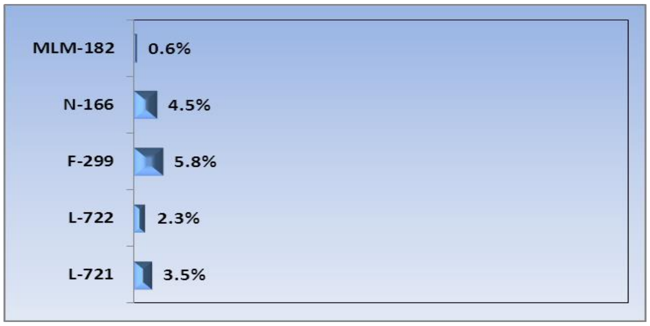

Figure 15. APRE % for SQU- $NMMP_{Dead}$ and VIT Experimental $NMMP_{Dead}$

The third validation is executed with the Sebastian & Lawrence model. The absolute error % is ranging from 4.64% to 10.13% with an average absolute error percentage of 7.1% as shown in Figure 16.

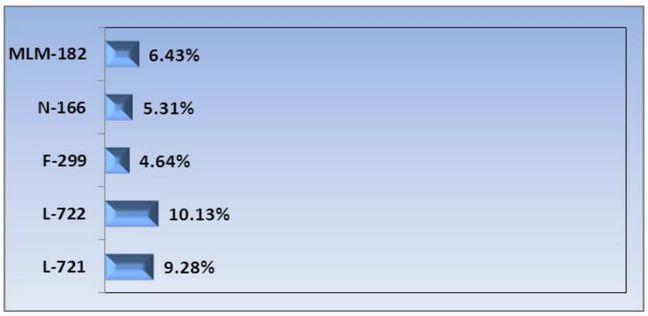

Figure 16. APRE % for Sebastian & Lawrence- $NMMP_{Dead}$ and VIT Experimental $NMMP_{Dead}$

The estimated NMMPs from SQU-NMMP model are compared with the ones measured by CMG simulation software to evaluate the SQU-NMMP model as shown in Figure 17. The absolute error % is ranging from 1.37% to 4.52%, with an average absolute error of 3.18%. This shows that SQU-NMMP model can be a useful tool for screening reservoir fluids in the first evaluation phase, to estimate the MMP for Nitrogen-Oil system.

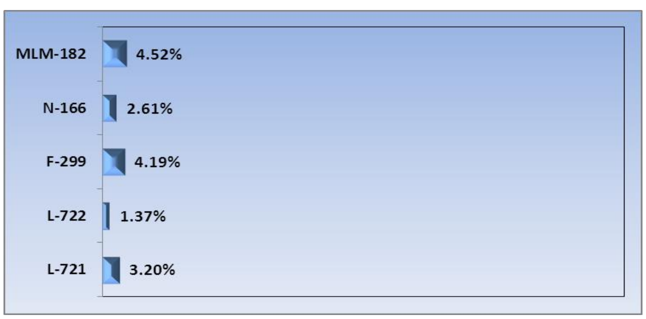

Figure 17. APRE % for SQU-NMMPDead model with CMG MMP's

4.8. Live NMMP determination

The last step is to convert the Experimental Dead NMMPs into live NMMPs using the conversion factor obtained from the 30 experimental MMPs, which were collected from different published papers. The conversion factor from SQU-NMMP and Sebastian & Lawrence models is 1.33 and 1.43 respectively. Data are tabulated in Table 5, and shown in Figure 18.

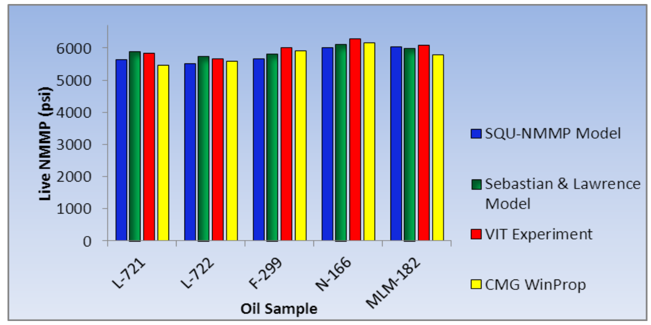

Figure 18. Live MMPs from SQU-NMMP - S & L conversion factors

From the results obtained, the Live NMMPs are found to be greater than 5000 psi, which are much higher than the reservoir pressures. Hence Nitrogen injection cannot be applied on these 5 wells. But the same technique of obtaining the live NMMP from Dead oil samples can be used for any different oil reservoir.

5. Conclusions

The sensitivity analysis of the proposed SQU-NMMP model is conducted by testing 10 data sets that were not used in the development of the new correlation. The evaluation process shows an outstanding agreement among the measured NMMPs and the ones calculated from proposed model. From the VIT experiment, the IFT measurements show that the IFT decreases by increasing the pressure at the same temperature. The dead NMMP is estimated for the 5 dead oil samples by extrapolating the IFT curve to Zero IFT. The new correlation (SQU-NMMP model) is more accurate than the other correlations in the literature. Live NMMPs are calculated and the results are found to be greater than 5000 psi, which are much higher than the reservoir pressures. Hence, nitrogen injection cannot be applied on these 5 wells, but the same technique of obtaining the live MMP from Dead oil samples can be used for any different oil reservoir. Moreover, the study proved that the NMMP is much greater than the CO2 MMP.

Table 5. Experimental dead NMMPs converted into Live

	VIT Experiment		SQU-NMMP Model		Sebastian & Lawrence Model		CMG WinProp	
Oil Sample	NMMP-Dead (psi)	NMMP-Live (psi)	NMMP-Dead (psi)	NMMP-Live (psi)	NMMP-Dead (psi)	NMMP-Live (psi)	NMMP-Dead (psi)	NMMP-Live (psi)
L-721	7762	5836	7487	5629	8482	5890	7255	5455
L-722	7516	5651	7343	5521	8277	5748	7445	5598
F-166	8009	6022	7545	5673	8381	5820	7875	5921
N-166	8361	6286	7981	6001	8805	6115	8195	6162
MLM-182	8093	6085	8043	6047	8613	5981	7695	5786

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