UNIVERSITI
TEKNOLOGI
PETRONAS

FINAL YEAR PROJECT

FINAL REPORT

Improvement in MMP Predictions Using Paraffin Number

Supervisor: Prof. Dr. Mariyamni bt Awang

Nur Fadzliana Azmi

11573

Petroleum Engineering

Improvement in MMP Predictions Using Paraffin Number

by

Nur Fadzliana Azmi

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Petroleum Engineering)

APRIL 2012

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATE OF APPROVAL

Improvement in MMP Predictions Using Paraffin Number

By

Nur Fadzliana Azmi

A project dissertation submitted to the
Petroleum & Geoscience Engineering Department
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(PETROLEUM ENGINEERING)

Approved by:

____

Prof Dr Mariyamni bt Awang
Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

April 2012

CERTIFICATE OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Nur Fadzliana Azmi

ABSTRACT

A high degree of accuracy is required for predicting the outcome of the gas injection process due to the high cost associated in the gas injection operation. Such accuracy includes preliminary screening parameters for gas miscible displacement, minimum miscibility pressure (MMP). Empirical correlations were often used to predict the MMP during the preliminary study. The aim of this study was to reduce the error of the prediction by the correlation. This study suggests incorporating the parafinicity factor into the correlation to further characterize the oil composition and reduce the error. For this purpose, a total of 79 MMP measurements from the literature and 4 measurements of MMP from this study were used to assess the Yuan (2004), Glaso (1985) Cronquist (1977) and Yellig (1980) correlations. Parafinicity factor was used to measure the limit of parafinicity that can fit in the correlations and to improve the correlation. It was demonstrated in this study that Yuan and Yellig correlations predictions will give huge error of predictions. In contrast, Glaso correlation was suitable for crude that has parafinicity factor value of more than 11.6 while Cronquist correlation was suitable for crude that has parafinicity factor value of more than 11.74 as the error was less significant. This indicates that Glaso and Cronquist correlations were applicable to paraffinic crude compared to asphaltenic crude. Glaso correlation can be further improved by including the parafinicity factor and reduce the average deviation error to 9.49% from 12.23%.

ACKNOWLEDGEMENT

The author would like to extend her deepest gratitude to Prof. Dr. Mariyamni Awang, who has been very kind to guide throughout the entire FYP 1 and FYP 2. The supervision and advice that were given truly help the progression of the study. The author also wishes to express her appreciation to the lab technologists Mr Redzuan and Mr. Shahrul from Reservoir laboratory for the assistance rendered during the course of this project. Last but not least, to Universiti Teknologi PETRONAS for providing the lab facilities to run the experiments.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

1.1 Background Study

MMP is the minimum pressure required to achieve single-phase miscibility when gas is injected into hydrocarbon fluid. Miscibility between the injection gas and the reservoir fluid is advantageous in EOR as it would eliminate the interfacial tension between injected gas and residual oil. Due to this, gas floods are often operated near the MMP.

MMP can be determined experimentally by slim-tube method. The problems with slim tube method are both costly and time consuming to perform and can give misleading results depending on the level of physical dispersion present. (Yuan, 2004) Due to this, correlations are often used to estimate the MMP. This is because correlations are proven reliable over a large range of conditions would likely be considered acceptable for the purposes of preliminary screening studies.

Most empirical correlations predict CO_2 MMP as a function of three variables: temperature, the molecular weight of a plus fraction and mole fraction of light component of reservoir fluid. Cronquist (1977) found that the molecular weight of the C_{5+} fraction was a good correlation parameter for MMP, whereas Yellig and Metcalfe (1980) developed a correlation which only varied as a function of temperature. Glaso (1985) observed that MMP is related with the molecular weight of the C_{7+} fraction, an idea also pursued by Yuan (2004).

It was observed that the previous correlation do not further characterized the C_{7+} fraction as they lump the heavy components in C_{7+} fraction. It became evident that proper characterization of heavier components was important for obtaining a reasonable prediction.

This study was conducted to find a method to reduce the error between the predicted MMP by these correlations and true MMP. Reducing the error is very important in order to achieve accurate prediction that will help in the designing of the model to be used in predicting or simulating reservoir performance as a result of CO_2 injection.

1.2 Problem Statement

A variety of correlations for the estimation of MMP have been developed from the regressions of slim tube 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 the fast screening of reservoirs for potential CO_2 flooding.

One significant disadvantage of current MMP correlations is that the regressions use MMPs from the slim tube data which are in themselves uncertain. (Yuan, 2004) Apart from that, these correlations are based on a limited set of experimental data and such are not widely applicable. Besides that, most correlation relies on the distribution of the molecular weight of C_{7+} fraction to characterize the reservoir fluid. Given same molecular weight, reservoir fluid might have different type of hydrocarbon such as paraffin, aromatic or naphthenes. Thus, these correlations always produce huge error when predicting the MMP.

Improvement on the correlations or development of a universal correlation that can fit to any type of the reservoir fluid and predict the minimum miscibility pressure with less error is important as it can save a lot of time and cost. Accurate prediction of MMP also helps in the development of the reservoir management strategies that can maximize the efficiency of gas injection performance.

1.3 Objectives

This research is aimed to study whether the existing empirical correlations can be improved by characterizing the C_{7+} fraction. This can be done by inculcate the parafinicity factor into the equation. The main objectives of this research were:

1. To assess the MMP correlations for both paraffinic crude and asphaltenic crude.
2. To reduce the error between the predicted MMP and true MMP.

1.4 Scope of the Study

This study will be focussing on the pure carbon dioxide injection and will be assessing four correlations namely: Cronquist (1977), Yellig and Metcalfe (1980) correlation, Glaso (1985) correlation and Yuan (2004). These correlations were used because these correlations are for pure CO_2 MMP correlations and often used as reported by Zahidah Md. Zain et al. (2011), J Bon et al. (2005) and K. Mogensen et al. (2009).

A data set of experimentally measured MMP's corresponding carbon dioxide/crude oil compositional information was constructed to evaluate the reliability of Yuan (2004), Glaso (1985), Cronquist (1977) and Yellig (1980) correlations. A total of 79 MMP measurements obtained from the literature and 4 points MMP of the experimental MMP from this current study were used as the data set.

This study involves a data set that had temperature range of 66^{o}F to 279^{o}F to represent a very low temperature reservoir and very high temperature reservoir. The data set also involve parafinicity factor of range 13.64 to 11.06 to represent high paraffin content to high aromatic content.

4 experiments were conducted to measure the MMP of Dulang and Dubai crude. Dulang crude (15% wax) were chosen as the experiment sample to represent paraffinic crude while Dubai crude (2.7% asphaltene) as asphaltenic crude. The aim of the experiments was to measure the MMP, thus vanishing interfacial technique was used because it is faster, cheap and had easy procedure. Plus, the MMP determined using the vanishing interfacial technique matched well (within 4-8%) with the reported slim tube miscibilities. (S.C Ayirala, D.N. Rao, 2006)

1.5 The Relevancy of the Project

This project was relevant to current situation of oil and gas industries that focused more on the EOR development. As CO_2 injection was more preferable to recover oil from mature oil field, more research is needed to improve the gas flooding technique. It is important to identify the CO_2 MMP for screening and selecting reservoirs for CO_2 injection projects since the candidate reservoir must be capable of withstanding an average reservoir pressure greater than the CO_2 MMP for obtaining the highest recovery. It also determines the model to be used in predicting or simulating reservoir performance as a result of CO_2 injection. Correlations were proven reliable to predict the CO_2 MMP. Having research on the minimum miscibility pressure correlation will help to improve the estimation of MMP for the paraffinic crude and asphaltenic crude by reducing the uncertainty in the correlations.

1.6 Feasibility of the Project

Based on the given time which is 7 months period (FYP 1 and FYP 2) this research is expected to be fully utilized within the scope of study and time frame. First few weeks will be concentrated on the study about the topic and equipment to be used. The sources will be the books, thesis, website, research paper and some journal. The next few weeks were focused on the detail of the design experiment. The experiment need to be designed carefully so that the result can be obtained within the limited time frame. The project can be done as all the materials and sources were in UTP such as the IFT Opman 700 and Anton Paar DMA. The time allocated for each experiments were designed so that it can accomplish the objectives of the research.

CHAPTER 2: LITERATURE REVIEW

This chapter will highlight the factors that affect the minimum miscibility pressure and how the existing correlations take into account these factors in their equation. From the literature review it showed that there was still a chance for improvement for the correlation to predict the MMP with less error and more accurate.

2.1 CO_2 Miscible Injection Flooding

CO_2 miscible injection is beneficial for EOR as it would eliminate the interfacial tension between the crude and gas, thus forming a single phase. CO_2 helps to improve the mobility ratio by viscosity reduction and hence volumetric conformance. Apart from that, CO_2 reduces the effective residual oil saturation by swelling effect. The volume of the crude will increase when saturated with CO_2. (Zahidah Md. Zain et al, 2011)

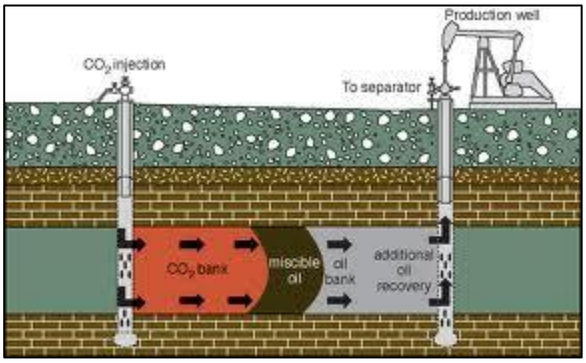


Figure 1: Carbon Dioxide Flooding

Figure 1 shows the miscible region between CO_2 and crude. The miscible region is highly dependent on the phase behaviour between carbon dioxide, water and reservoir oil. The CO_2-oil phase behaviour strongly affects fluid flow by altering mobility ratios, interfacial tensions, relative permeabilities and rates of mass transfer.

The miscible region is dependent on the minimum miscibility pressure. (Yuan et al, 2004) Minimum miscibility pressure is achieved through dynamic mass transfer interactions between reservoir crude oil and injected gas. At miscibility condition, capillary forces are eliminated that results in no capillary trapping of oil and consequently higher oil recoveries. To achieve the complete miscibility condition in the reservoir, displacement pressure should be higher than MMP. Therefore, accurate MMP prediction was important as the displacement efficiency was depending on MMP.

2.2 Factors Affecting Minimum Miscibility Pressure

CO_2 miscibility pressure depends on CO_2 purity, oil composition and reservoir temperature.

2.2.1 CO_2 Purity

Table 1: CO_2 Impurities and Its Effect on MMP

Injected gas impurities	Effect on minimum miscibility pressure
Nitrogen	Increase the MMP
Methane	Increase the MMP
Ethane, Propane, Butane, Pentane	Reduce the MMP
Hydrogen Sulfide	Reduce the MMP
Sulfur dioxide	Reduce the MMP

Table 1 shows the effect of CO_2 impurities towards MMP. Relatively small amounts of methane or nitrogen in CO_2 can increase substantially the pressure required for miscibility. (Stalkup, 1992) On the other hand, ethane and higher molecular weight hydrocarbons in CO_2 may reduce the pressure requirement. While the presence of H_2S and SO_x contribute towards lowering the MMP. (M.K. Emera et al, 2007)

2.2.2 Oil composition

A decrease in API oil gravity generally increases miscibility pressure, reflecting the reduced content of extractable hydrocarbons or, in other words MMP increases with the increase in oil molecular weight. This is because as high molecular weight will reduce the solubility of the hydrocarbon in CO_2. Lighter components from C_5 to C_{20} were comparably easy to be extracted. However, heavier components up to C_{36} may also be extracted though in a relatively small quantity. For heavy crude oil containing low intermediates of C_5 to C_{20}, the extraction was inefficient at all conditions. (Alston, R.B. et al.1985) This was supported by M.K Silva and F.M Orr Jr. (1987) which they reported that the distribution of molecular weight present in the oil is the most important factor that affect MMP. Higher molecular weight will reduce the solubility of the hydrocarbon inside CO_2.

Apart from molecular weight distribution, the development of CO_2/oil misicbility also depends on the chemical type of the heavy hydrocarbons such as paraffin, naphthenes and aromatics. (Wilburn, 1988) This finding was also investigated by M.K Silva and F.M Orr Jr. (1987).

Heavy hydrocarbon particularly hydrocarbons with seven and more carbon atoms can be divided into paraffin, naphthenes and aromatics. According to Wilburn (1988) and M.K Silva (1987), paraffin remain the most efficiently extracted by CO_2 followed by aromatics while naphthenes had detrimental effect on CO_2 solubility. Figure 2 summarize they type of hydrocarbon presents in the reservoir fluid.

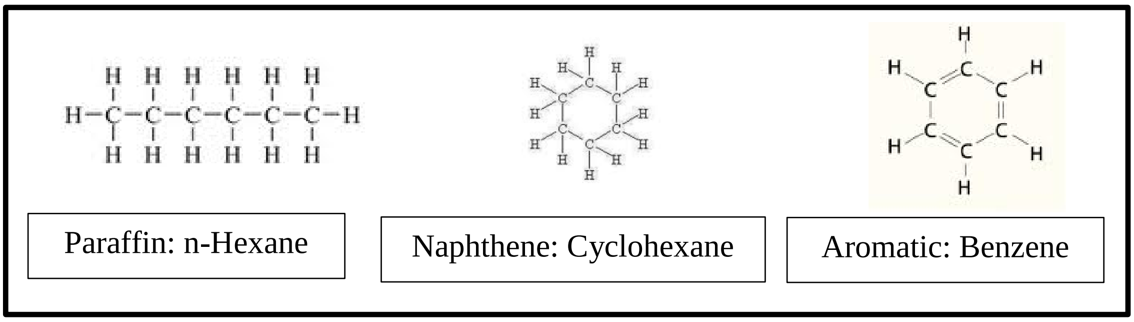


Figure 2: Example of Molecular Structure

Based on figure 2, given same carbon number the molecule can take different shape and this will affect the solubility of CO_2. MMP would be lowest for the branched paraffin, higher for the straight chain paraffin, still higher for the aromatics and highest for naphthenes. Aromatics hydrocarbons were extracted more effectively than the naphthenes. Naphthenes could have been extracted more efficiently if they had alkyl side chains in place of multiple ring structures.

Eventhough the effect of variations in the structure of the hydrocarbon molecules to the development of miscibility are smaller, it was believed that further characterization of heavier components were important to obtain accurate MMP prediction.

2.2.3 Reservoir Temperature

Higher reservoir temperatures result in higher miscibility pressure, other factors being equal. As the temperature decreases, the MMP of CO_2 decreases as well. (Glaso, 1985) Based on Figure 3, W. F. Yellig, R. S. Metcalfe (1980) experiment, increased temperature led to an increase in CO_2 MMP of approximately 15 psi/F (57 kPa/°C) over the range of 95 to 192°F (35 to 89°C)

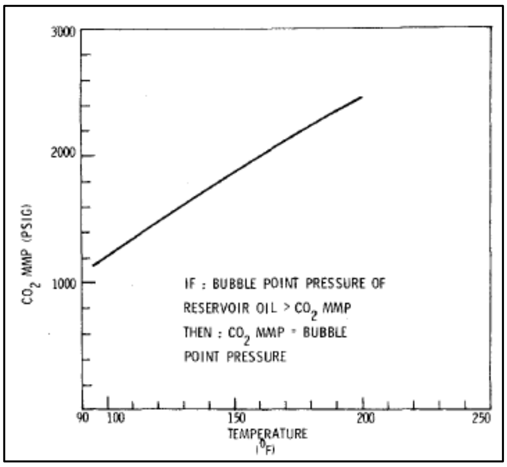


Figure 3: CO2 MMP vs. Temperature (W. F. Yellig, R. S. Metcalfe, 1980)

Holm and Josendal (1982) have pointed out an important fact that in order to achieve miscibility, a minimum CO_2 density is required to extract C_5 –C_{30} from the crude oil and the reservoir temperature is just a variable to determine the pressure needed to achieve the required CO_2 densities. This is because when the temperature decreases; the volume of CO_2 injected reduces, increasing the density of CO_2. Since the density of CO_2 is proportional to the amount of extracted hydrocarbon, this will reduce the MMP.

At temperatures not too far above the critical temperature of CO_2 [88°F (31°C)] mixtures of CO_2 and crude oil exhibit multiple liquid phases, and at some pressures L/L/V equilibrium were observed. (F.M Orr Jr et al, 1981) Figure 4 shows the presence of 3 phases at low temperature reservoir.

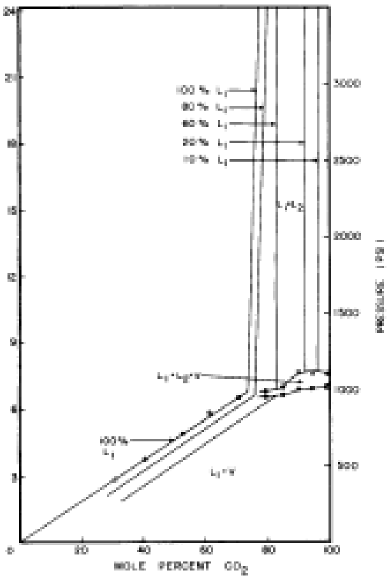


Figure 4: The Phase Behaviour of CO_2 and Maljamar Oil (F.M Orr et al. 1981)

The third phase is a second liquid phase high in CO_2 concentration, usually over 90% CO_2. This third phase occurs in a fairly narrow pressure region of from a few psi to about 200 psi. The reservoirs where a three-phase can occur are at relatively low temperatures (near the critical point of CO_2), has high CO_2 concentration (usually above 60 mole % CO_2). This phenomenon has not been reported above 120°F. (Reid B. Grigg, Ucok W. R. Siagian, 1998)

Low temperature oil displacement by CO_2 can achieve high displacement efficiency because CO_2 rich liquid phase can efficiently extract a certain range of hydrocarbon in the reservoir. CO_2 rich vapour phase extracts carbon number up to C_6 and CO_2 rich liquid phase can extract components as heavy as C_{30}. Swelling and stripping of hydrocarbons from the oil by a CO_2 rich liquid phase are the dominant mechanisms for tertiary recovery in low-temperature displacements in the L/L region. (F.M Orr Jr., A. D. Yu, C. L. Lien, 1981)

2.3 Parafinicity Factor

Molecular weight distribution was usually used to describe the hydrocarbon system. However, further characterization of heavier components can be done by using parafinicity factor.Whitson (1984) had developed a method to characterize the molar distribution and physical properties of petroleum fractions such as heptane-plus. The parafinicity factor was given as:

$$K_{C_{7+}} = 4.5579 \times {M_{C_{7+}}}^{0.15178} \times {\gamma_{C_{7+}}}^{-0.84573} \qquad (1)$$

Where;

M_{C7+} = molecular weight of C_{7+}

γ_{C7+} = specific gravity of C_{7+}

K defines relative parafinicity of a hydrocarbon fraction, with a typical range from 10.0 (highly aromatic) to 13.0 (highly paraffinic). The oil with a K factor more than 11.95 represents oil with high paraffin while oil with K factor less than 11.95 represents oil with high content of aromatic compounds.

2.4 MMP Correlations

To facilitate screening procedures and to gain insight into the miscible displacement process, many correlations relating the MMP to the physical properties of the oil and the displacing gas have been proposed. Table 2 summarize the correlations equation.

Table 2: Correlation That Were Evaluated In This Study

Correlation	Equation
Cronquist (1977)	$MMP = 15.988T^{0.744206+0.0011038\,M_{C5+}+0.0015279X_{C1}}$
W. F. Yellig and R. S. Metcalfe (1980)	$MMP_{pure} = 1833.717 + 2.2518055T + 0.01800674\,T^2 - \frac{103949.93}{T}$
Glaso (1985)	For mol fraction of $C_{2\text{-}6}$ > 18% $MMP_{pure} = 810 - 3.404M_{C7+} + 1.7 \times 10^{-9}{M_{C7+}}^{3.730}e^{786.8{M_{c7+}}^{-1.058}}T$ For mol fraction of $C_{2\text{-}6}$ < 18% $MMP_{pure} = 2947.9 - 3.404M_{C7+} + 1.7 \times 10^{-9}{M_{C7+}}^{3.730}e^{786.8{M_{c7+}}^{-1.058}}T - 121.2X_{C2-6}$
Yuan et al (2004)	$\mathrm{MMP_{pure}} = \mathrm{a_1 + a_2M_{C7+} + a_3X_{C2-6}} + \left(\mathrm{a_4 + a_5M_{C7+} + a_6\frac{X_{C2-6}}{M_{C7+}}}\right)\mathrm{T} + \left(\mathrm{a_7 + a_8{M_{C7+}}^2 + a_9{M_{C7+}}^2 + a_{10}X_{C2-6}}\right)\mathrm{T^2}$

Where;

T = reservoir temperature (°F)

M_{C5+} = molecular weight of C_{5+}

X_{C1} = sum of mol fraction of methane and nitrogen

M_{C7+} = molecular weight of C_{7+}

$X_{C2\text{-}6}$ = mol fraction of $C_{2\text{-}6}$

a_1 = -1.4634E+03

a_2 = 0.6612E-1

a_3 = -4.4979E+01

a_4 = 0.2139E+01

a_5 = 1.1667E+03

a_6 = 8.1661E+03

a_7 = -1.2258E-01

a_8 = 1.2883E-03

a_9 = -4.0152E-06

a_{10} = -9.2577E-04

Most empirical correlations predict CO_2 MMP as a function of three variables: temperature, the molecular weight of a plus fraction and the mole fraction of a light component in the reservoir oil. The authors used the molecular weight of the C_{7+} fraction to describe the hydrocarbon system. Through this method, thousands of components fall under C_{7+} fraction. These correlations lump together all the heavy components in the C_{7+} group. Given same molecular weight of C_{7+} fraction, some reservoir fluid might have different parafinicity and aromaticity. These oil compositions can affect the minimum miscibility pressure between the carbon dioxide with the reservoir fluid during the gas injection.

However, these correlations do not further characterize the components inside the C_{7+} fractions and as a result often produced inaccurate predictions of the minimum miscibility pressure.

Apart from that, these correlations are using their regional reservoir fluid as their data set during the development of the correlations. Thus the correlations can only fit the regional reservoir fluid and have a limited used when applied outside their data range.

2.4.1 W. F. Yellig and R. S. Metcalfe (1980)

Yellig and Metcalfe correlation is based on the reservoir temperature only. Their data was limited to West Texas crude and reservoir temperature range of 95 to 192°F. This correlation was used during the preliminary screening due to the simplicity of the correlation that needs only the reservoir temperature parameter.

2.4.2 Glaso (1985)

Glaso correlation is a result of curve fitting on Benham et al. (1960) data. The absolute deviation of the fit is less than 1%. Glaso (1985) studies shows that for hydrocarbon systems, paraffinicity has an effect on MMP. In the equations, the C_{7+} molecular weight of the oil is corrected to a K factor of 11.95, thereby accounting for varying paraffinicity. This correlation was compared with North Sea hydrocarbon system and temperature range of 71°F to 234 °F.

2.4.3 Yuan (2004)

Yuan et al approach is to use the developed analytical theory for multi component multiphase flow MMP calculations from equation of state to generate MMP correlations for displacements by pure and impure CO_2. The advantage of this approach is that MMP for a wide range of temperatures and reservoir fluids can be calculated quickly.

2.5 Laboratory Methods to Measure MMP

There were three methods to measure MMP found in the literature namely; slim tube method, rising bubble method and vanishing interfacial method. However, only slim tube method and vanishing interfacial tension technique will be reviewed as the two methods were used to develop the data set.

2.5.1 Slim Tube Method

The slim tube test was conducted by saturating the porous media inside coil with oil at desired temperature and pressure. Then, the CO_2 was injected into the porous media using positive displacement pump. After 1.2 pore volume of CO_2 were injected, the test was terminated. Final recovery at 1.2 pore volume CO_2 injected was determined.

Flow experiments offer the most reliable method to determine the pressure required for miscibility with CO_2, N_2, and hydrocarbon gas. The slim-tube method has been most widely used to determine miscibility.

Figure 5 shows MMP by slim tube test that was defined as the lowest pressure at which a distinct point of maximum curvature when recovery of oil is plotted against pressure at 1.2 pore volume gas injected. When a distinct point of maximum curvature is not apparent, the 95 % recovery of oil at 1.2 pore volume injected gas is used to define the MMP.

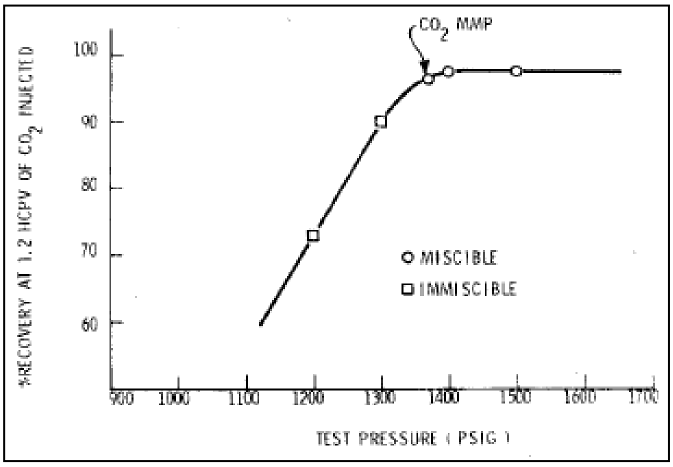


Figure 5: %Recovery vs Pressure (W. F. Yellig, R. S. Metcalfe, 1980)

2.5.2 Vanishing Interfacial Tension Technique

Determination of MMP using interfacial tension technique is based on the measurement of the interfacial tension between the injected gas and the oil at the constant temperature and varying pressure. The miscibility of the injected gas and the oil is evaluated on the basis of the vanishing IFT between the two phases. The IFT between the phases was extrapolated to zero IFT to get the MMP. (Nor Idah Kechut, 1999) Pendant drop method is used to measure interfacial tension. The IFT values is determine from the profile of the static pendant drop for a given density difference.

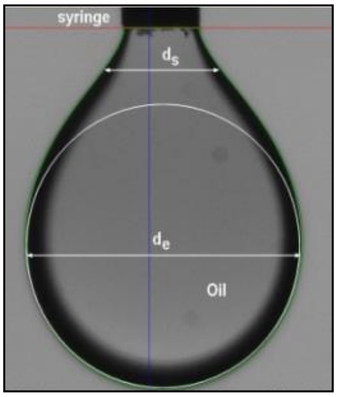


Figure 6: IFT measurement by pendant drop method (Dandekar, 2006)

IFT is determining based on the assumption that the drop is symmetric about a central vertical axis. IFT is calculated based on the equation:

$$\sigma = \frac{\Delta\rho g d_e}{f} \qquad (2)$$

Where;

σ = interfacial tension, mN/m

g = gravity acceleration, m/s^2

f = Drop shape factor, ratio of d_s/d_e dimensionless

d_e = equatorial diameter, m

d_s = diameter of the drop at the height d_e above the bottom of drop, m

ΔP = density difference between two fluids. kg/m^3

CHAPTER 3: METHODOLOGY

To evaluate the Yuan (2204), Glaso (1985), Cronquist (1977) and Yellig (1980) correlations, a total of 83 MMP data were collected whereby 79 MMP measurements were collected from the literature review and 4 MMP data from this study experiment. The error between the predicted MMP and true MMP were calculated and reported.

Then, parafinicity factor was calculated for every data by using equation (1). For improved equation, parafinicity factor was included in the Glaso equation. Next, the improved equation was fit into the data set and the improved equation was compared with the Glaso equation in terms of the average deviation error.

The experiment methodology for the determination of 4 MMP data will be further explained in section 3.1 and 3.2.

3.1 Experiment Samples

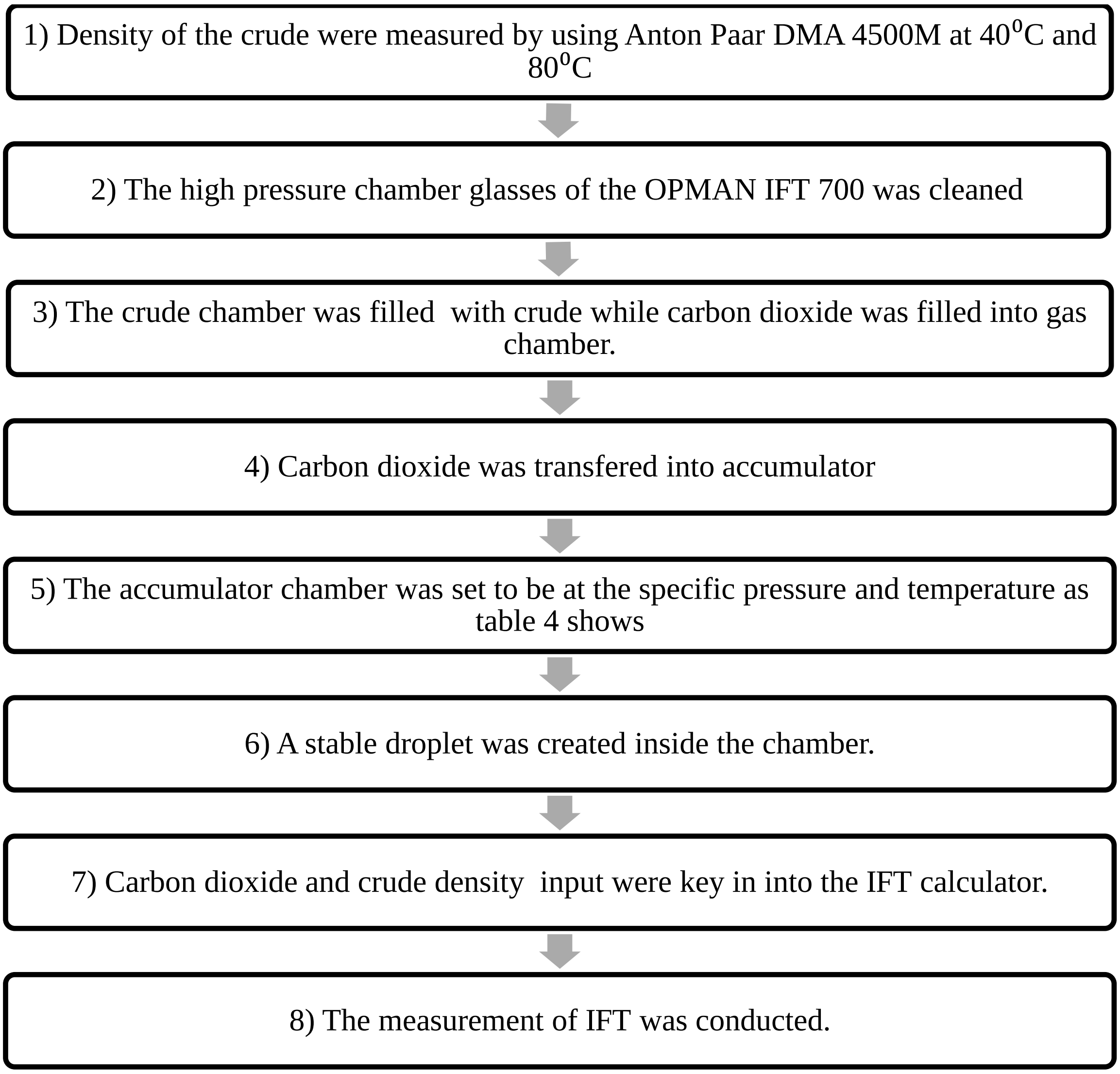
The 4 MMP data that were measured in this study were based on vanishing interfacial technique. Table 3 summarize the detail of the samples that were used in the experiment.

Table 3: Properties of crude (Zainuri, 2011)

	Dulang crude (Paraffinic crude)	Dubai crude (Asphaltenic crude)
Wax Content (%)	15	4.6
Asphaltene Content (%)	0.47	2.7
API	37.8°	30°
Density at 40°C (g/cc)	0.818	0.864
Density at 80°C (g/cc)	0.787	0.833

The procedures of the experiment were explained in Figure 7.

3.2 Experiment Procedure



1) Density of the crude were measured by using Anton Paar DMA 4500M at 40^{o}C and 80^{o}C

2) The high pressure chamber glasses of the OPMAN IFT 700 was cleaned

3) The crude chamber was filled with crude while carbon dioxide was filled into gas chamber.

4) Carbon dioxide was transfered into accumulator

5) The accumulator chamber was set to be at the specific pressure and temperature as table 4 shows

6) A stable droplet was created inside the chamber.

7) Carbon dioxide and crude density input were key in into the IFT calculator.

8) The measurement of IFT was conducted.

Figure 7: IFT Experiment Workflow

Interfacial tension between Dulang and Dubai crude with carbon dioxide were measure based on the Figure 7 workflow. A total of 16 measurements were conducted based on the Table 4 summary.

Table 4: Pressure and Temperature Used In IFT Measurements

Temperature (^{o}C)	40			
Pressure (psi)	1000	1400	1500	1600
Temperature (^{o}C)	80			
Pressure (psi)	1000	1400	1800	2200

3.3 Equipment

There are two major equipment used during this study, namely:

1. Density meter

Figure 8: Anton Paar DMA 4500M

Anton Paar was used to determine the density of the crude at specific temperature. The measurement is based on the proven oscillating U-tube principle ensuring highly accurate density values.

2. IFT apparatus

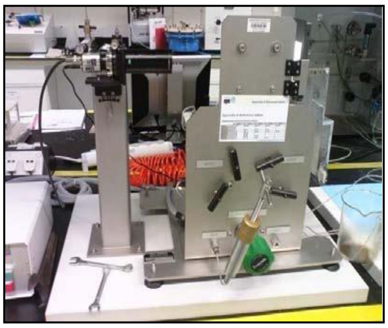


Figure 9: IFT OPMAN 700

IFT OPMAN 700 was used to measure IFT between crude and CO2. Microscope camera was used to capture the digital images of the pendant drop.

3.4 Gantt Chart for Project Activities

Table 5: Project Time Line for FYP 1

Project time line (FYP 1)														
Activities /Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Project topic selection	■	■												
Literature review on: 1. Basic EOR 2. Miscible gas injection 3. MMP at reduced temperature 4. Paraffinic crude and asphaltenic crude 5. MMP measurement experiment 6. MMP correlation	■	■	■	■	■	■	■	■						
Submission of proposal report						■								
Proposal defence									■					
Experiment design to measure the MMP by vanishing interfacial technique										■	■			
Submission of interim draft report												■		
Submission of interim report													■	
Confirmation of sample availability: 1. Dulang crude 2. Dubai crude 3. IFT OPMAN 700 availability 4. Density Anton Paar DMA 4500M availability													■	■

Table 6: Project Time Line for FYP 2

Project time line (FYP 2)														
Activities /Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Experiment to measure Dulang and Dubai crude density at 40^{0}C and 80^{0}C.	▨													
Experiment to measure MMP of Dulang and Dubai crude at 40^{0}C 80^{0}C by vanishing interfacial technique.		▨	▨											
Compilation of MMP measurements from literature review				▨										
Comparison between the predicted MMP with true MMP for the 83 data					▨									
Improvement on the correlation to reduce the error						▨	▨							
Submission of progress report								■						
Analysis result									▨	▨				
Pre-EDX											■			
Compilation of the report and completion of the report											▨	▨	▨	▨
Submission of draft report												■		
Submission of soft dissertation													■	
Submission of technical paper													■	
Oral presentation														■
Submission of project dissertation														■

3.5 Key Milestone

Table 7: Key milestone for FYP 1

Details/Month	September	October	November	December
Literature review on the topic: 1. Factors that affect MMP 2. Types of crude 3. Slim tube procedure 4. Correlation of the MMP	■	■		
1. Decision on what crude will be used for the experiment 2. Familiarization with the density Anton Paar DMA 4500M and IFT OPMAN 700 equipment			■	
Experiment design and the commencement of experiment				■

Table 8: Key milestone for FYP 2

Details/Month	January	February	March	April
Density and MMP measurement of Dulang and Dubai crude at 40°C and 80°C.	■			
Compilation of MMP measurements from literature review and comparison with the correlation		■		
Analysis of the result and discussion			■	
Finalizing result and discussion				■

CHAPTER 4: RESULT AND DISSCUSION

4.1 Results of MMP by Vanishing Interfacial Tension

The MMP of Dulang and Dubai crude at 40°C and 80°C were determined by vanishing interfacial technique. The IFT vs. Pressure graph were extrapolated to zero IFT to determine the MMP. Figure 10 and Figure 11 show the result.

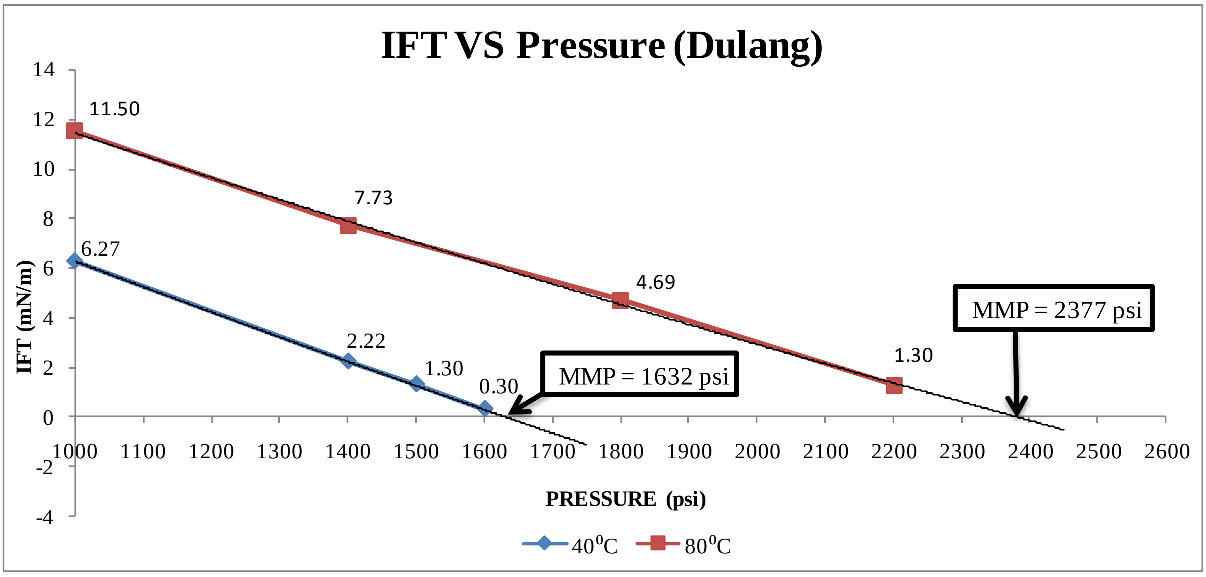


Figure 10: MMP of Dulang Crude at 40°C and 80°C

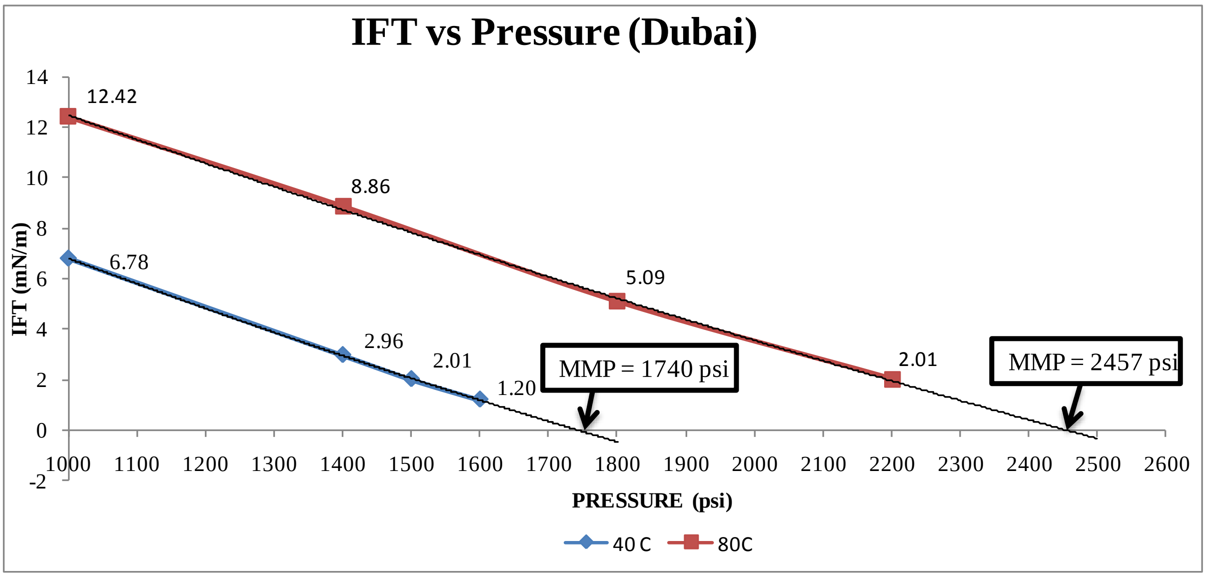


Figure 11: MMP of Dubai Crude at 40°C and 80°C

Based on Figure 10 and Figure 11, the MMP of Dulang were 1632 psi and 2377psi at 40°C and 80°C respectively. While for Dubai crude the MMP were 1740 psi at 40°C and 2457psi at 80°C.

4.2 Results of the Comparison between the True MMP with the Predicted MMP

A data set of experimentally measured MMP's corresponding carbon dioxide/crude oil compositional information was constructed to evaluate the reliability of Yuan, Glaso, Cronquist and Yellig correlations. A total of 79 MMP measurements obtained from the literature and four points MMP of the current study were used as the data set. Compositional information for each of these 83 carbon dioxide/oil pairs and corresponding literature reference sources were available in the Appendix 3. Table 9 tabulate the comparison between the experimental MMP and predicted MMP. The bold error was above 25% indicating significant deviation from the true MMP.

Table 9: Comparison between the Experimental MMP and Predicted MMP

REFERENCE	T (F)	TRUE MMP (PSI)	YUAN	ABS ERROR	GLASO	ABS ERROR	CRONQUIST	ABS ERROR	YELLIG	ABS ERROR
[13]	66	1100	397.95	**63.82**	898.96	18.28	1011.93	8.01	485.77	**55.84**
[13]	70	1130	488.94	**56.73**	947.67	16.14	1072.63	5.08	594.58	**47.38**
[33]	71	1250	959.00	23.28	1289.00	3.12			620.00	**50.40**
[18]	88	1175	1495.00	**27.23**	1221.00	3.91	1339.00	13.96	990.00	15.74
[38]	90	1100	1176.00	6.91	1188.00	8.00	1244.00	13.09	1027.00	6.64
[16]	90	1100	1752.88	**59.35**	1768.57	**60.78**			1027.23	6.62
[13]	95	1290	1007.20	21.92	1252.14	2.93	1451.28	12.50	1115.94	13.49
[51]	95	1150	1063.00	7.57	1245.00	8.26			1116.00	2.96
[26]	98	1129	1297.50	14.92	1314.74	16.45			1166.62	3.33
[4]	100	2400	2695.00	12.29	3303.00	**37.63**	1687.00	**29.71**	1199.00	**50.04**
[21]	103	2000	1428.00	**28.60**	1376.00	**31.20**	1703.00	14.85	1247.00	**37.65**
EXPERIMENT	104	1740	1067.06	**38.67**	1375.15	20.97	1284.57	**26.17**	1263.15	**27.41**
EXPERIMENT	104	1632	1217.08	**25.42**	1433.66	12.15	1420.86	12.94	1263.15	22.60
[5]	104	1316	1404.00	6.69	1384.00	5.17	1700.00	**29.18**	1263.00	4.03
[20]	104	1274	1252.00	1.73	1355.00	6.36	1432.00	12.40	1263.00	0.86
[38]	105	1200	1492.00	24.33	1368.00	14.00	1444.00	20.33	1279.00	6.58
[5]	109	1822	1910.00	4.83	1494.00	18.00	1861.00	2.14	1339.00	**26.51**
[21]	109	1550	1583.00	2.13	1450.00	6.45	1708.00	10.19	1339.00	13.61
[19]	110	1572	1384.00	11.96	1792.00	13.99	1790.00	13.87	1354.00	13.87
[31]	110	1300	1542.83	18.68	1421.90	9.38			1354.30	4.18
[51]	118	1375	1527.00	11.05	1516.00	10.25			1469.00	6.84
[26]	119	1650	2087.29	**26.50**	1679.31	1.78			1483.15	10.11
[26]	119	1440	1266.60	12.04	1519.39	5.51			1483.15	3.00
[43]	120	1700	1240.00	**27.06**	1716.00	0.94			1497.00	11.94
[20]	120	1535	1744.00	13.62	1610.00	4.89	1960.00	**27.69**	1497.00	2.48
[13]	122	1500	1469.38	2.04	1580.97	5.40	1859.09	23.94	1524.40	1.63
[25]	130	3970	3084.00	22.32	3067.00	22.75			1631.00	**58.92**
[33]	130	2450	2026.00	17.31	2458.00	0.33			1631.00	**33.43**
[4]	130	1375	1176.78	14.42	1644.75	19.62	1690.66	22.96	1631.15	18.63
[4]	130	1850	1545.59	16.45	1807.05	2.32	2208.48	19.38	1631.15	11.83
[4]	130	1500	1176.78	21.55	1644.75	9.65	1925.65	**28.38**	1631.15	8.74
[4]	130	1500	1757.16	17.14	1601.05	6.74	1633.65	8.91	1631.15	8.74

[46]	130	1550	1368.00	11.74	1652.00	6.58	1871.00	20.71	1631.00	5.23
[24]	130	1550	1499.00	3.29	1653.00	6.65			1631.00	5.23
[7]	130	1708	1424.00	16.63	1645.00	3.69	1847.00	8.14	1631.00	4.51
[28]	132.5	1750	2043.00	16.74	2151.00	22.91	2353.00	**34.46**	1664.00	4.91
[28]	133	3925	2519.00	**35.82**	2560.00	**34.78**	2974.00	24.23	1670.00	**57.45**
[28]	135	1950	2330.00	19.49	1907.00	2.21	2064.00	5.85	1696.00	13.03
[28]	135	1505	1942.00	**29.04**	1808.00	20.13	1889.00	**25.51**	1696.00	12.69
[33]	135	1900	2253.00	18.58	2024.00	6.53	1683.00	11.42	1696.00	10.74
[26]	135	1599	1744.38	9.09	1790.42	11.97			1695.88	6.06
[38]	135	1720	2056.00	19.53	1728.00	0.47	1842.00	7.09	1696.00	1.40
[4]	136	1900	1872.30	1.46	2034.29	7.07	1863.64	1.91	1708.68	0.51
[33]	137	1850	1801.57	2.62	1722.82	6.87			1721.42	6.95
[41]	138	1700	2244.42	**32.02**	1871.65	10.10	2035.51	19.74	1734.13	2.01
[4]	142	1500	1345.19	10.32	1781.50	18.77	1839.81	22.65	1784.52	18.97
[41]	142	1711	1680.75	1.77	1782.42	4.17	1855.35	8.44	1784.52	4.30
[33]	150	2300	2070.99	9.96	2020.34	12.16			1883.64	18.10
[27]	150	2030	1706.00	15.96	2101.00	3.50			1884.00	7.19
[51]	150	1875	2079.00	10.88	1893.00	0.96			1884.00	0.48
[4]	154	2450	2477.00	1.10	1971.00	19.55	2676.00	9.22	1933.00	21.10
[4]	160	3400	3392.00	0.24	3423.00	0.68	3317.00	2.44	2005.00	**41.03**
[43]	160	1900	1840.00	3.16	2179.00	14.68			2005.00	5.53
[43]	160	1900	1861.00	2.05	2179.00	14.68			2005.00	5.53
[12]	160	2100	1945.52	7.36	2139.73	1.89	2290.73	9.08	2005.29	4.51
[44]	164	3500	3281.00	6.26	3199.00	8.60	3397.00	2.94	2053.00	**41.34**
[33]	165	2600	2567.68	1.24	2558.00	1.62			2065.50	**53.06**
[33]	165	3200	1822.68	**43.04**	2481.88	22.44			2065.50	**39.25**
[33]	165	3000	2084.82	**30.51**	2295.44	23.49			2065.50	**31.15**
[33]	165	2450	2216.46	9.53	2043.62	16.59			2065.50	15.69
[33]	171	2600	1949.59	**25.02**	2112.00	18.77			2137.42	17.79
[4]	176	3880	3657.00	5.75	3542.00	8.71	4514.00	16.34	2197.00	**43.38**
EXPERIMENT	176	2457	1920.36	21.84	2278.30	7.27	2111.27	14.07	2197.19	10.57
EXPERIMENT	176	2377	2236.06	5.93	2237.17	5.88	2362.10	0.63	2197.19	7.56
[11]	180	3250	2923.00	10.06	2452.00	24.55	2516.11	22.58	2245.00	**30.92**
[6]	180	3190	2149.48	**32.62**	2988.42	6.32	3360.51	5.35	2244.96	**29.63**
[6]	180	3095	1665.58	**46.18**	2346.32	24.19	2943.57	4.89	2244.96	**27.46**
[33]	185	3050	2322.58	23.85	2485.43	18.51			2304.69	24.44
[21]	186	5000	3548.00	**29.04**	2909.00	**41.82**	4658.00	6.84	2317.00	**53.66**
[55]	188	2500	2543.00	1.72	2337.00	6.52			2341.00	6.36
[33]	190	2750	2611.32	5.04	2360.38	14.17			2364.50	14.02
[51]	192	2350	2637.00	12.21	2388.00	1.62			2388.00	1.62
[4]	210	4390	4023.00	8.36	4452.00	1.41			2716.00	**38.13**
[59]	215	2875	2761.00	3.97	3414.00	18.75	2978.00	3.58	2667.00	7.23
[4]	216	4085	3864.00	5.41	3652.00	10.60	4490.00	9.91	2679.00	**34.42**
[7]	220	3190	2425.00	23.98	3543.00	11.07	3152.00	1.19	2718.00	14.80
[4]	230	2930	2678.00	8.60	2770.00	5.46	3544.00	20.96	2852.00	2.66
[4]	234	3502	3111.00	11.17	3032.00	13.42	4402.00	**25.70**	2902.00	17.13
[6]	240	3705	1417.41	**61.74**	4033.40	8.86	4519.33	21.98	2978.21	19.62
[6]	240	3670	1619.10	**55.88**	3108.05	15.31	3929.67	7.08	2978.21	18.85
[52]	245	3400	2294.96	**32.50**	3006.24	11.58	3636.55	6.96	3041.98	10.53
[2]	250	3100	2753.82	11.17	3438.79	10.93	3307.93	6.71	3106.00	0.19
[23]	279	2810	2995.00	6.58	3440.00	22.42	3026.00	7.69	3492.00	24.27
			AVERAGE	17.79		12.23		13.93		17.82

Empty tables indicate MMP could not be calculated due to the insufficient compositional data. For easier comparison, Table 9 was translated into graph form. Figure 12, Figure 13, Figure 14 and Figure 15 show the result.

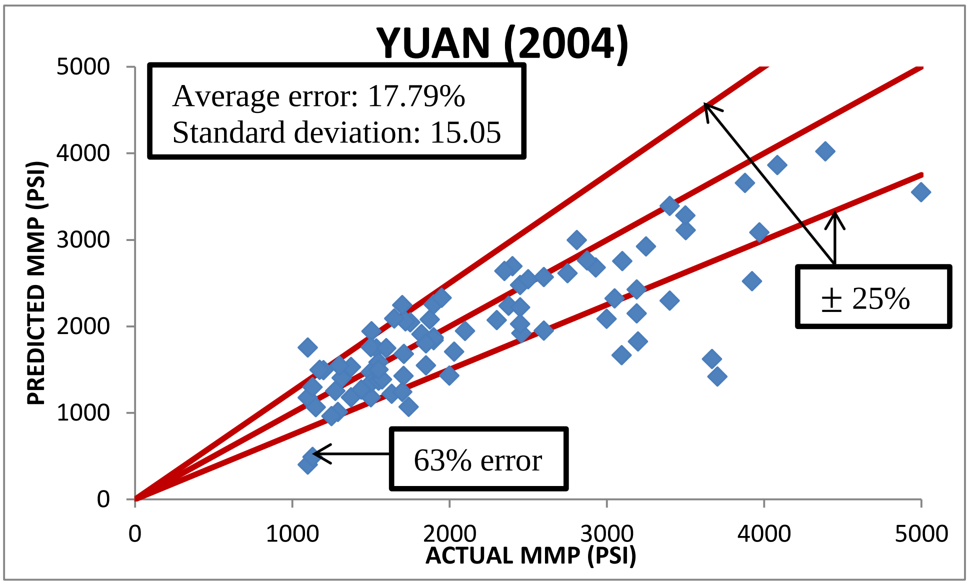


Figure 12: Yuan correlation’s predicted vs. actual MMP

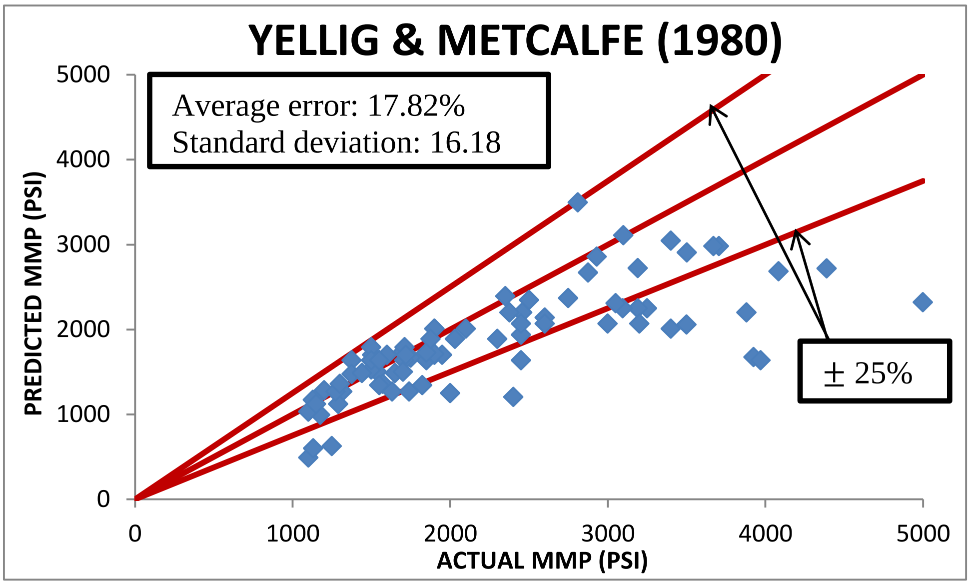


Figure 13: Yellig & Metcalfe correlation’s predicted vs. actual MMP

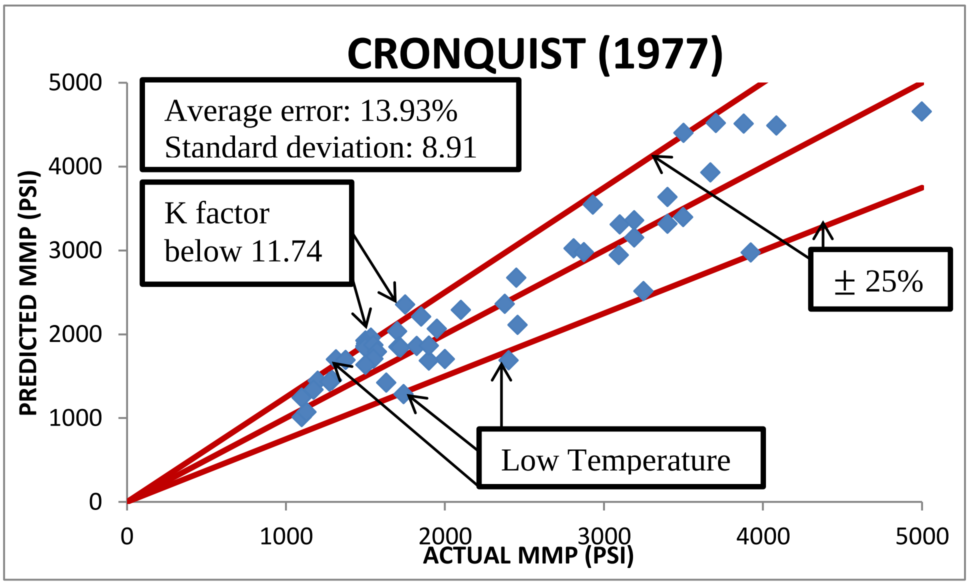


Figure 14: Cronquist correlation's predicted vs. actual MMP

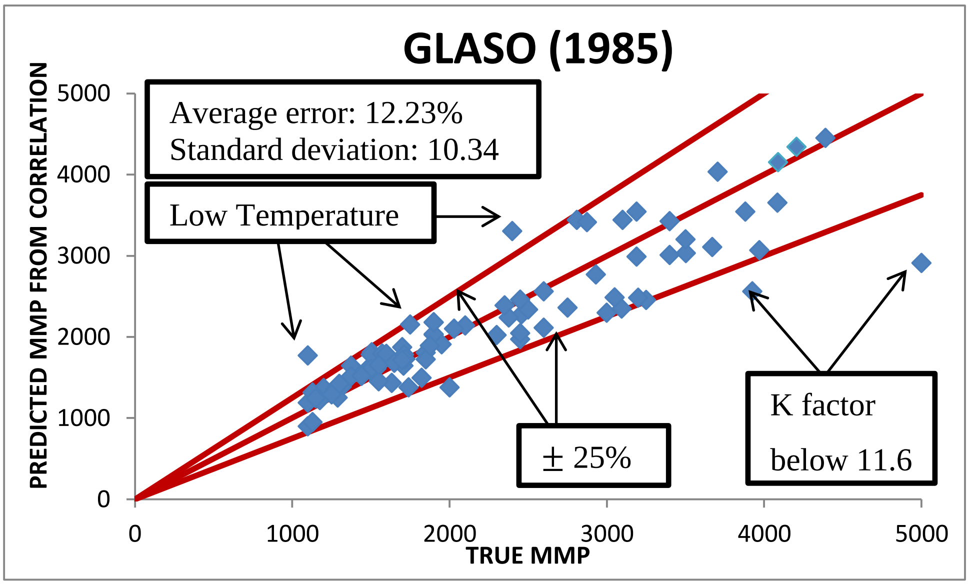


Figure 15: Glaso correlation's predicted vs. actual MMP

Figure 12, Figure 13, Figure 14 and Figure 15 were illustrated along with a unit slope line indicates a perfect match between predicted and actual MMP's and ±25% deviation lines.

Based on Figure 12, 13, 14 and 15 it is evident that with an average deviation between 12.23% and 17.82%, none of the correlations perform very well.

With highest error which was 63% and quarter from the 83 data had error above 25%, it is worth noting that Yuan correlation appears not applicable to predict the MMP. It was speculated that the percent of error Yuan correlation may be caused by the quadratic function involving the molecular weight of the plus fraction.

Quarter of the 83 data had error beyond 25% for Yellig and Metcalfe correlation. This is because the Yellig and Metcalfe correlation only accounts for temperature as a variable and hence predict a constant MMP for case that had same temperature. However, experimental investigations in the past have clearly shown that compositional effects must be considered also. Thus, Yellig and Metcalfe also appear not applicable to be used to predict the MMP.

Among the empirical correlations, Glaso and Cronquist seems to be more reliable as a first estimate as the average deviation were 12.23% and 13.93% respectively which were the least among the four correlations. Most of the data fall inside the ±25% deviation line. There were several points fall outside the ±25% deviation line and the reasons for that were explained in section 4.3.

4.3 Effect of Parafinicity Factor towards MMP

Further analysis was conducted by grouping the 83 data according to its parafinicity factor. This data were divided to its K factor value to determine the limit of parafinicity factor that can fit in the correlation and to determine whether the correlations can be used for paraffinic and asphaltenic crude.

The oil with a K factor more than 11.95 represents oil with high paraffin while oil with K factor less than 11.95 represents oil with high content of aromatic compounds.

The 83 data were divided into two groups whereby 23 data having parafinicity factor of more than 11.95 while 60 data having parafinicity factor of less than 11.95. Table 10 and Table 11 summarize the data.

Table 10: Oil with a K Factor More Than 11.95

REFERENCE	T (F)	K FACTOR	TRUE MMP (PSI)	YUAN	ABS ERROR	GLASO	ABS ERROR	CRONQUIST	ABS ERROR	YELLIG	ABS ERROR
[43]	120	13.64	1700	1240.00	27.06	1716.00	0.94			1497.00	11.94
[43]	160	13.64	1900	1840.00	3.16	2179.00	14.68			2005.00	5.53
[43]	160	13.64	1900	1861.00	2.05	2179.00	14.68			2005.00	5.53
[44]	164	13.51	3500	3281.00	6.26	3199.00	8.60	3397.00	2.94	2053.00	41.34
[59]	215	13.18	2875	2761.00	3.97	3414.00	18.75	2978.00	3.58	2667.00	7.23
EXPERIMENT	104	13.01	1632	1217.08	25.42	1433.66	12.15	1420.86	12.94	1263.15	22.60
EXPERIMENT	176	13.01	2377	2236.06	5.93	2237.17	5.88	2362.10	0.63	2197.19	7.56
[2]	250	12.88	3100	2753.82	11.17	3438.79	10.93	3307.93	6.71	3106.00	0.19
[16]	90	12.87	1100	1752.88	59.35	1768.57	**60.78**			1027.23	6.62
[13]	66	12.37	1100	397.95	63.82	898.96	18.28	1011.93	8.01	485.77	55.84
[13]	70	12.37	1130	488.94	56.73	947.67	16.14	1072.63	5.08	594.58	47.38
[13]	95	12.37	1290	1007.20	21.92	1252.14	2.93	1451.28	12.50	1115.94	13.49
[13]	122	12.37	1500	1469.38	2.04	1580.97	5.40	1859.09	23.94	1524.40	1.63
[28]	135	12.32	1505	1942.00	29.04	1808.00	20.13	1889.00	25.51	1696.00	12.69
[28]	135	12.18	1950	2330.00	19.49	1907.00	2.21	2064.00	5.85	1696.00	13.03
[19]	110	12.09	1572	1384.00	11.96	1792.00	13.99	1790.00	13.87	1354.00	13.87
[25]	130	12.08	3970	3084.00	22.32	3067.00	22.75			1631.00	58.92
[26]	119	12.07	1440	1266.60	12.04	1519.39	5.51			1483.15	3.00
[4]	100	12.05	2400	2695.00	12.29	3303.00	**37.63**	1687.00	**29.71**	1199.00	50.04
[4]	176	12.05	3880	3657.00	5.75	3542.00	8.71	4514.00	16.34	2197.00	43.38
[52]	245	12.05	3400	2294.96	32.50	3006.24	11.58	3636.55	6.96	3041.98	10.53
[4]	130	12.02	1850	1545.59	16.45	1807.05	2.32	2208.48	19.38	1631.15	11.83
[7]	220	12.01	3190	2425.00	23.98	3543.00	11.07	3152.00	1.19	2718.00	14.80
			AVG ERROR		20.64		14.18		11.48		19.95

Based on Table 10, as the K factor increase, the true MMP is reduced. This indicates that the parafinicity of oil affects the MMP. This is because high K factor value demonstrate that the reservoir fluid contain more paraffin content. Paraffin is more soluble in carbon dioxide during the gas injection and lowering the minimum miscibility pressure between the crude and carbon dioxide.

Yuan and Yellig correlation seems to be not reliable on the K factor value as the deviation of the predicted MMP from the true MMP is quite significant and does not show any significant trend. In contrast, Glaso and Cronquist correlation seems to be reliable on the parafinicity of the crude as the deviation of the predicted from the true MMP is small for this group of data. This also indicates that Glaso and Cronquist correlation were applicable for paraffinic crude.

However, two data that has large error in Glaso correlation which are 60.78% and 37.63% happened to be at the low temperature, 90°F and 100°F respectively. This phenomenon was also observed with Cronquist correlation where one of its data had error of 29.71% happened to be at 100°F. This signified that both correlations have a limited use at low temperature. This is suspected due to present of multiple liquid phases when CO_2 mix with crude oil at low temperatures.

This was supported by F.M Orr Jr et al (1981) where they had reported that at temperatures not too far above the critical temperature of CO_2 [88°F (31°C)] mixtures of CO_2 and crude oil exhibit multiple liquid phases, and at some pressures L/L/V equilibrium are observed. Low temperature oil displacement by CO_2 achieves high displacement efficiency because CO_2 rich liquid phase can efficiently extract a certain range of hydrocarbon in the reservoir. Therefore, MMP at low temperature is much lower compared to the predicted MMP. This also points out that the Glaso and Cronquist correlation is suitable for the two phase miscibility (liquid and gas) that occur above 120°F.

Table 11: Oil with a K Factor Less Than 11.95

REFERENCE	T (F)	K FACTOR	TRUE MMP (PSI)	YUAN	ABS ERROR	GLASO	ABS ERROR	CRONQUIST	ABS ERROR	YELLIG	ABS ERROR
[6]	240	11.92	3670	1619.10	55.88	3108.05	15.31	3929.67	7.08	2978.21	18.85
[6]	180	11.92	3095	1665.58	46.18	2346.32	24.19	2943.57	4.89	2244.96	27.46
[20]	104	11.91	1274	1252.00	1.73	1355.00	6.36	1432.00	12.40	1263.00	0.86
[26]	130	11.90	1550	1499.00	3.29	1653.00	6.65			1631.00	5.23
[33]	190	11.87	2750	2611.32	5.04	2360.38	14.17			2364.50	14.02
[26]	135	11.86	1599	1744.38	9.09	1790.42	11.97			1695.88	6.06
[33]	171	11.86	2600	1949.59	25.02	2112.00	18.77			2137.42	17.79
[33]	185	11.86	3050	2322.58	23.85	2485.43	18.51			2304.69	24.44
[26]	119	11.85	1650	2087.29	26.50	1679.31	1.78			1483.15	10.11
[23]	279	11.83	2810	2995.00	6.58	3440.00	22.42	3026.00	7.69	3492.00	24.27
[4]	234	11.81	3502	3111.00	11.17	3032.00	13.42	4402.00	25.70	2902.00	17.13
[26]	98	11.81	1129	1297.50	14.92	1314.74	16.45			1166.62	3.33
[33]	165	11.81	2450	2216.46	9.53	2043.62	16.59			2065.50	15.69
[33]	165	11.81	2600	2567.68	1.24	2558.00	1.62			2065.50	53.06
[11]	180	11.81	3250	2923.00	10.06	2452.00	24.55	2516.11	22.58	2245.00	30.92
[33]	165	11.81	3000	2084.82	30.51	2295.44	23.49			2065.50	31.15
[33]	165	11.81	3200	1822.68	43.04	2481.88	22.44			2065.50	39.25
[33]	137	11.81	1850	1801.57	2.62	1722.82	6.87			1721.42	6.95
[33]	150	11.81	2300	2070.99	9.96	2020.34	12.16			1883.64	18.10
[33]	71	11.81	1250	959.00	23.28	1289.00	3.12			620.00	50.40
[33]	135	11.81	1900	2253.00	18.58	2024.00	6.53	1683.00	11.42	1696.00	10.74
[51]	95	11.80	1150	1063.00	7.57	1245.00	8.26			1116.00	2.96
[51]	118	11.80	1375	1527.00	11.05	1516.00	10.25			1469.00	6.84
[51]	150	11.80	1875	2079.00	10.88	1893.00	0.96			1884.00	0.48
[51]	192	11.80	2350	2637.00	12.21	2388.00	1.62			2388.00	1.62
[12]	160	11.79	2100	1945.52	7.36	2139.73	1.89	2290.73	9.08	2005.29	4.51
[41]	142	11.78	1711	1680.75	1.77	1782.42	4.17	1855.35	8.44	1784.52	4.30
[4]	136	11.77	1900	1872.30	1.46	2034.29	7.07	1863.64	1.91	1708.68	0.51
[4]	154	11.77	2450	2477.00	1.10	1971.00	19.55	2676.00	9.22	1933.00	21.10
[4]	216	11.77	4085	3864.00	5.41	3652.00	10.60	4490.00	9.91	2679.00	34.42
[46]	130	11.77	1550	1368.00	11.74	1652.00	6.58	1871.00	20.71	1631.00	5.23
[28]	132.5	11.74	1750	2043.00	16.74	2151.00	22.91	2353.00	34.46	1664.00	4.91
[55]	188	11.69	2500	2543.00	1.72	2337.00	6.52			2341.00	6.36
[4]	160	11.68	3400	3392.00	0.24	3423.00	0.68	3317.00	2.44	2005.00	41.03
[20]	120	11.68	1535	1744.00	13.62	1610.00	4.89	1960.00	**27.69**	1497.00	2.48
[6]	180	11.68	3190	2149.48	32.62	2988.42	6.32	3360.51	5.35	2244.96	29.63
[6]	240	11.68	3705	1417.41	61.74	4033.40	8.86	4519.33	21.98	2978.21	19.62
[18]	88	11.67	1175	1495.00	27.23	1221.00	3.91	1339.00	13.96	990.00	15.74
[4]	210	11.64	4390	4023.00	8.36	4452.00	1.41			2716.00	38.13
[41]	138	11.62	1700	2244.42	32.02	1871.65	10.10	2035.51	19.74	1734.13	2.01
[5]	104	11.61	1316	1404.00	6.69	1384.00	5.17	1700.00	**29.18**	1263.00	4.03
[28]	133	11.60	3925	2519.00	35.82	2560.00	34.78	2974.00	24.23	1670.00	57.45
[21]	186	11.60	5000	3548.00	29.04	2909.00	41.82	4658.00	6.84	2317.00	53.66
[5]	109	11.60	1822	1910.00	4.83	1494.00	18.00	1861.00	2.14	1339.00	26.51
[4]	130	11.60	1375	1176.78	14.42	1644.75	19.62	1690.66	22.96	1631.15	18.63
[4]	130	11.60	1500	1176.78	21.55	1644.75	9.65	1925.65	28.38	1631.15	8.74
[21]	103	11.60	2000	1428.00	**28.60**	1376.00	**31.20**	1703.00	14.85	1247.00	37.65
[4]	130	11.60	1500	1757.16	17.14	1601.05	6.74	1633.65	8.91	1631.15	8.74
[4]	142	11.59	1500	1345.19	10.32	1781.50	18.77	1839.81	22.65	1784.52	18.97
EXPERIMENT	104	11.56	1740	1067.06	38.67	1375.15	20.97	1284.57	26.17	1263.15	27.41
EXPERIMENT	176	11.56	2457	1920.36	21.84	2278.30	7.27	2111.27	14.07	2197.19	10.57
[21]	109	11.55	1550	1583.00	2.13	1450.00	6.45	1708.00	10.19	1339.00	13.61
[4]	230	11.55	2930	2678.00	8.60	2770.00	5.46	3544.00	20.96	2852.00	2.66
[33]	130	11.51	2450	2026.00	17.31	2458.00	0.33			1631.00	33.43
[31]	110	11.36	1300	1542.83	18.68	1421.90	9.38			1354.30	4.18
[7]	130	11.31	1708	1424.00	16.63	1645.00	3.69	1847.00	8.14	1631.00	4.51
[38]	90	11.24	1100	1176.00	6.91	1188.00	8.00	1244.00	13.09	1027.00	6.64
[38]	105	11.24	1200	1492.00	24.33	1368.00	14.00	1444.00	20.33	1279.00	6.58
[38]	135	11.24	1720	2056.00	19.53	1728.00	0.47	1842.00	7.09	1696.00	1.40
[27]	150	11.06	2030	1706.00	15.96	2101.00	3.50			1884.00	7.19
	AVERAGE DEVIATION				16.70		11.49		15.05		17.00

Table 11 summarized data that has parafinicity factor of less 11.95. Based on Table 11, Glaso prediction had a good agreement with the true MMP up until the K factor value was 11.6, where the deviation of error starts to increase to 34.78%. While, Cronquist correlation had a good agreement with the true MMP up until K factor value was 11.74, where the deviation of error start to be significant.

Three data that had been bold in Glaso correlation where the huge deviation occurs at K factor of 11.6. At K factor of 11.6 and below, 50% of Glaso prediction were less than the true MMP. Inaccurate Glaso correlation prediction was suspected due to the hydrocarbon plus fraction term. Glaso correlation did not characterize the hydrocarbon plus fraction and lump together thousands of compounds with a carbon number higher than six. Glaso only depend on the molecular weight of C_{7+} fraction to do the prediction. Insufficient characterization of heavier hydrocarbon (eg; heptanes and heavier) reduces the accuracy of MMP predictions.

On the other hand, Cronquist correlation lump all the heavy components in the C_{5+} compounds. Only the molecular weight of C_{5+} was used as one of the parameters to determine the MMP. At K factor of 11.74 and below Cronquist correlation starts to have huge deviation from the true MMP. It is also suspected that Cronquist correlation inaccuracy is due to insufficient characterization of heavier hydrocarbon.

K factor of 11.95 and below has high content of aromatics and less content of paraffin. Low value of K factor indicates that the reservoir fluid had high content of aromatic compounds that increase the MMP measurement due to the fact that aromatic compounds are less soluble in carbon dioxide. MMP correlations should further characterize the hydrocarbon plus fraction to produce a reliable and improve the MMP prediction.

It was also observed that at low temperature especially below 120°F, Glaso and Cronquist correlation prediction had a significant deviation from the true MMP. Two of the data for Cronquist correlation had large errors which were 29.18% and 27.69% that were occurred at 104°F and 120°F respectively. One of the Glaso data had error of 31.2% that had occurred at temperature of 103°F.

4.4 Improvement on Empirical Correlation

Based on Table 10 and Table 11, it was suspected insufficient description of heavier hydrocarbon cause the deviation error between the prediction and true MMP. Volatile oil phase behaviour is particularly sensitive to the composition and properties of the heaviest components. Thus, to improve the MMP prediction by the empirical correlation, it was suggested to include the parafinicity factor into the empirical correlation. To verify the suggestion, this study had included the parafinicity factor in Glaso correlation to reduce the error between the prediction and true MMP.

Parafinicity factor gives information regarding the paraffin content in the hydrocarbon plus fraction. Parafinicity factor of more than 11.95 represents oil with high paraffin while oil with parafinicity factor of less than 11.95 represents oil with high content of aromatic compounds.

Glaso equation was used as the base equation as Glaso correlation had the least deviation error compared to Cronquist, Yuan and Yellig correlation. Parafinicity factor had been included in the Glaso equation and deviation error between the improved correlation and true MMP was compared. Table 12 summarized the result.

Table 12: Average Deviation Error between the Improved Correlation and true MMP

Group	Improved equation	Average deviation error
Mol of C_2-C_6 more than 18%	$MMP_{pure} = 810 - 3.404M_{C7+} + 1.7 \times 10^{-9}{M_{C7+}}^{3.730}e^{786.8{M_{c7+}}^{-1.058}}T - K^{1.74}$	9.78
Mol of C_2-C_6 less than 18%	$MMP_{pure} = 2947.9 - 3.404M_{C7+} + 1.7 \times 10^{-9}{M_{C7+}}^{3.730}e^{786.8{M_{c7+}}^{-1.058}}T - 121.2X_{C2-6} - K^{1.45}$	8.12

By including the parafinicity factor in the Glaso correlation, the deviation of error between the prediction and true MMP had been reduced to 9.78 and 8.12 for the two groups respectively. Even though the reduction is small, it can be resolved that by including the parafinicity factor into the correlation can improve the correlation.

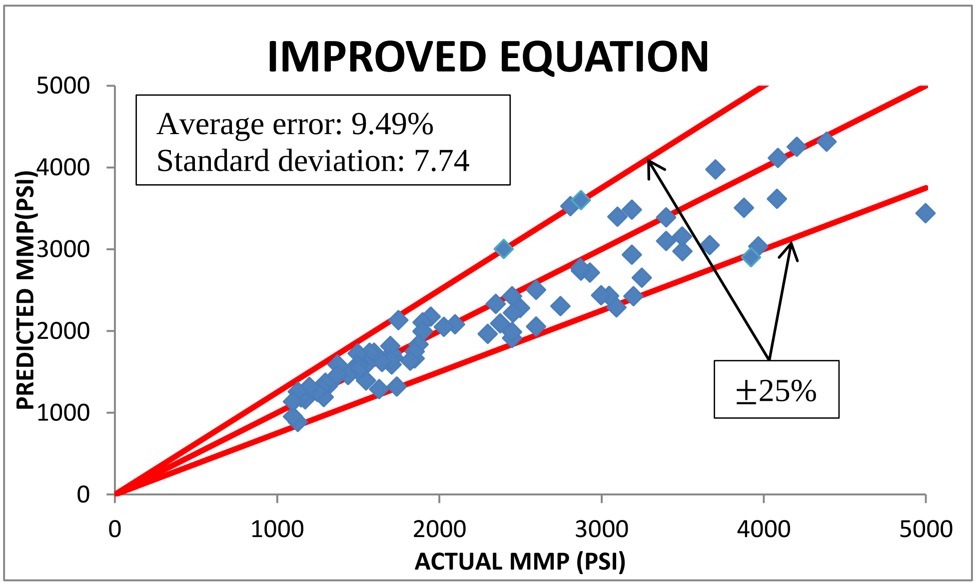


Figure 16: Improved Equation Prediction vs. Actual MMP

By comparing Figure 16 and Figure 15, the improved equation had reduced the error to 9.49% from 12.23%.

K factor was added into the Glaso correlation and the term of K factor in the equation was manipulated to fit in the data available. The data that were used to fit in the improved correlation were collected from different parts of the world. The data were from:

1. North Sea
2. United States especially from Texas, SACROC project, Colorado, Louisiana
3. Dulang field, Malaysia basin
4. Natuna Sea, Indonesia
5. Cooper Basin, Australia
6. Saskatchewan, Canada
7. Middle East (Dubai, Iraq and Qatar)
8. China (Ordos basin, ShengLi field)

It was believed that the improved correlation was more comprehensive as the data used was widespread and extensive. Thus the improved correlation was estimated to fit in to any type of fluid.

Apart from that, the improved correlation can be used for a broad temperature range of 66°F to 279°F. The improved correlation can be used for a very low temperature reservoir and high temperature reservoir.

Besides that, the improved correlation can be applied for a wide-range of K factor from 13.64 to 11.06. It was believed that the improved correlation can predict the MMP for the paraffinic and asphaltenic crude. Table 13 and Table 14 tabulate the result of the improved correlation.

Table 13: Improved Correlation for Hydrocarbon that has Mol of C_2-C_6 Less Than 18%

REFERENCE	T (F)	K FACTOR	TRUE MMP (PSI)	IMPROVED EQUATION (PSI)	ABS ERROR (%)
[33]	71	11.81	1250	1253.64	0.29
[4]	130	11.60	1500	1566.11	4.41
[25]	130	12.08	3970	3031.35	23.64
[33]	130	11.51	2450	2424.20	1.05
[33]	135	11.81	1900	1989.02	4.69
[4]	136	11.77	1900	1998.58	5.19
[4]	160	11.68	3400	3388.84	0.33
[44]	164	13.51	3500	3155.78	9.83
[4]	176	12.05	3880	3506.31	9.63
[21]	186	11.60	5000	3437.77	31.24
[4]	210	11.64	4390	4313.32	1.75
[4]	216	11.77	4085	3616.79	11.46
[2]	250	12.88	3100	3398.11	9.62
[57]	258	12.31	4090	4113.22	0.57
			AVERAGE ERROR		8.12

Table 14: Improved Correlation for Hydrocarbon that has Mol of C_2-C_6 More Than 18%

REFERENCE	T (F)	K FACTOR	TRUE MMP (PSI)	IMPROVED EQUATION (PSI)	ABS ERROR
[13]	66	12.37	1100.00	950.50	13.59
[13]	70	12.37	1130.00	884.21	21.75
[18]	88	11.67	1175.00	1163.37	0.99
[38]	90	11.24	1100.00	1134.10	3.10
[13]	95	12.37	1290.00	1188.68	7.85
[51]	95	11.80	1150.00	1186.46	3.17
[26]	98	11.85	1129.00	1255.63	11.22
EXPERIMENT	104	13.01	1632.00	1287.19	21.13
EXPERIMENT	104	11.56	1740.00	1318.42	24.23
[20]	104	11.91	1274.00	1295.41	1.68
[5]	104	11.61	1316.00	1326.76	0.82
[38]	105	11.24	1200.00	1314.01	9.50
[21]	109	11.55	1550.00	1393.72	10.08
[5]	109	11.60	1822.00	1636.74	10.17
[31]	110	11.36	1300.00	1366.79	5.14
[19]	110	12.09	1572.00	1730.95	10.11
[51]	118	11.80	1375.00	1457.47	6.00
[26]	119	12.07	1440.00	1458.46	1.28
[26]	119	11.86	1650.00	1620.12	1.81
[20]	120	11.68	1535.00	1551.91	1.10
[43]	120	13.64	1700.00	1641.66	3.43
[13]	122	12.37	1500.00	1517.51	1.17
[4]	130	12.02	1850.00	1746.58	5.59
[4]	130	11.60	1375.00	1587.72	15.47
[4]	130	11.60	1500.00	1587.72	5.85
[24]	130	11.90	1550.00	1593.12	2.78
[20]	130	11.31	1708.00	1590.01	6.91
[46]	130	11.77	1550.00	1593.32	2.79
[28]	132.5	11.74	1750.00	2132.38	21.85
[26]	135	11.87	1599.00	1731.15	8.26
[28]	135	12.18	1950.00	2173.08	11.44
[38]	135	11.24	1720.00	1673.84	2.68
[33]	137	11.81	1850.00	1664.05	10.05
[41]	138	11.62	1700.00	1814.41	6.73
[4]	142	11.60	1500.00	1724.47	14.96
[41]	142	11.78	1711.00	1723.85	0.75
[33]	150	11.81	2300.00	1961.56	14.71
[52]	150	11.06	2030.00	2047.87	0.88
[51]	150	11.80	1875.00	1834.51	2.16
[4]	154	11.77	2450.00	1912.20	21.95

[11]	160	11.79	2100.00	2081.14	0.90
[43]	160	13.64	1900.00	2104.84	10.78
[43]	160	13.64	1900.00	2104.84	10.78
[33]	165	11.81	3000.00	2436.97	18.77
[33]	165	11.81	3200.00	2423.10	24.28
[33]	165	11.81	2450.00	1984.84	18.99
[33]	165	11.81	2600.00	2500.22	3.84
[33]	171	11.81	2600.00	2053.22	21.03
EXPERIMENT	176	13.01	2377.00	2090.70	12.04
EXPERIMENT	176	11.56	2457.00	2221.56	9.58
[6]	180	11.92	3095.00	2286.64	26.12
[6]	180	11.68	3190.00	2930.71	8.13
[11]	180	11.83	3250.00	2650.85	18.44
[33]	185	11.81	3050.00	2426.65	20.44
[55]	188	11.69	2500.00	2279.12	8.84
[33]	190	11.81	2750.00	2301.60	16.31
[51]	192	11.80	2350.00	2329.39	0.88
[58]	197.6	13.64	2871.00	2766.06	3.66
[59]	215	13.18	2875.00	2735.61	4.85
[20]	220	12.01	3190.00	3482.95	9.18
[4]	230	11.55	2930.00	2713.31	7.40
[4]	234	11.86	3502.00	2972.71	15.11
[6]	240	11.92	3670.00	3048.38	16.94
[6]	240	11.68	3705.00	3975.69	7.31
[14]	240.8	13.24	4206.00	4251.13	1.07
[27]	245	12.05	3400.00	3100.54	8.81
[23]	279	11.86	2810.00	3527.03	25.52
			AVERAGE ERROR		9.78

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusions

The objective of this study was to assess the Yuan (2004), Glaso (1985), Cronquist (1977) and Yellig (1980) correlations. As a general observation, none of the MMP correlations evaluation in this study would appear sufficiently accurate. However, the following generalizations can be made:

1. The correlations presented in literature could be used helpfully as a screening tool and they are not adequate for final design. Laboratory tests are the most reliable source of information.
2. Yuan correlation produces erroneous prediction due to its quadratic function involving the molecular weight of the plus fraction.
3. Yellig correlation is not applicable to predict the MMP as the correlation only accounts for temperature as a variable and hence predict a constant MMP for case that had same temperature. Yellig correlation can be used within its data range only.
4. Glaso correlation can be used for crude that has K factor value of more than 11.6 while Cronquist correlation can be used for crude that has K factor value of more than 11.74 as the deviation from the true MMP is less significant. Glaso and Cronquist correlation are more applicable to paraffinic crude.
5. The use of Glaso and Cronquist correlation at low temperature (below 120°F) must be used with precaution as the prediction can lead to deviation up to 60% error. The prediction of MMP at low temperature deserves further analysis in order to establish stronger correlation.
6. Glaso correlation can be further improved by including the parafinicity factor and reduce the error to 9.49% from 12.23%.

5.2 Recommendations

There were several recommendations that can be applied to get a better and more accurate result. They were:

1. In future, this project should be continued by increase the crude samples to present more variety of asphaltene content in crude samples. It is important to see the trend of the MMP for different content of asphaltene and paraffin so that the effect of asphaltene and paraffin content in the crude could be correlated.
2. Other than that, more drops need to create at specific temperature and pressure to increase the accuracy of the MMP measurement from the vanishing interfacial tension technique.
3. It is also desirable to measure the minimum miscibility pressure by using slim tube apparatus as slim tube was considered as industry standard of MMP measurement.
4. Next, add more MMP data from different part of the world during the development of the correlation so that the correlation is more global and can fit any type of fluid.
5. Add more MMP data from different part of the world during the development of the correlation so that the correlation is more global and can fit any type of fluid.
6. Include the phase behaviour parameter in the development of the correlation for the low temperature CO2 injection to take into account the three phase behaviour below 120^0F.

7. Separate the MMP measurements according to its methods used in comparing the experimental MMP with predicted MMP.
8. Last but not least, develop a new MMP correlation as a function of parafinicity factor.

REFERENCES

1. *TOTSA*. (18 July, 2001). Retrieved 10 October, 2011, from Crude Assay: www.totsa.com

2. Abdassah D, Siregar S, Kristanto D,. (2000). *The Potential of Carbon Dioxide Gas Injection Application in Improving Oil Recovery.* Beijing, China: Society of Petroleum Engineers (SPE 64730).

3. Ahmad, T. (1997). *A Generalized Methodology for Minimum Miscibility Pressure.* Rio de Janeiro: Society of Petroleum Engineers (SPE 39034).

4. Alston, R.B., Kokolis, G.P. and James, C.F. (1985). CO2 Minimum Miscibility Pressure: A correlation for Impure CO_2 Streams and Live Oil Systems. *SPE Journal, Vol. 25, No. 2,*, 268-274.

5. Andrew P. Spence, Jr. and Robert W. Watkins. (1980). *The effect of microscopic core heterogeneity on miscible flood residual oil saturation*. Dallas, Texas: SPE 9229.

6. B.E. Eakin and F.J. Mitch. (1988). *Measurement and Correlation of Miscibility Pressures of Reservoir Oils.* Houston: SPE 18065.

7. Chaback, J. (1988). *Phase Equilibria for Enhanced Oil Recovery in an n-Butane Enriched Carbon Dioxide + Black Oil System.* Tianjin, China: SPE 17621.

8. D. E. Menzie, R.F. Nielsen. (1963). *A Study of the Vaporization of Crude Oil by Carbon Dioxide Repressuring.* Oklahoma: Journal of Petroleum Technology (SPE 568).

9. D. L. Katz, A. Firoozabadi. (1978). Predicting Phase Behaviour of Condensate/Crude-Oil Syatems using Methane Interaction Coefficients. *Journal Petroleum Technology*, 1649 - 1655.

10. Dandekar, A. Y. (2006). *Petroleum Reservoir Rock and Fluid Properties.* United States: Taylor & Francis Group.

11. Dengen Zhou, Clair Jensen and Ray Tang and Hozef Arif. (1999). *A New Formulation for Simulating Near-Miscible Displacement Processes.* Houston, Texas: SPE 56623.

12. Dennis J. Graue, E. T. Zana. (1981). Study of a Possible CO_2 Flood in Rangely Field. *Journal of petroleum technology*, 1312-1318.

13. Dhia M. Kassim, Mohamed Salah Hameed, Faiz I. Paulus. (1988). *A Laboratory Study for Determination of Miscibility Under Certain Conditions of Temperature and Pressure.* USA: SPE 17646.

14. Erik Lindeberg, Torleif Holt. (1994). *EOR by Miscible CO_2 Injection in the North Sea.* Oklahoma: SPE 27767.

15. F.M Orr Jr., A. D. Yu, C. L. Lien. (1981). Phase behavior of CO_2 and Crude Oil in Low Temperature Reservoir. *SPE 8813*, 480-492.

16. Franklin M. Orr, Matthew K. Silva, Cheng-Li Lien. (1983). Equilibrium Phase Compositions of CO_2/Crude Oil Mixtures-Part 2: Comparison of Continuous Multiple-Contact and Slim-Tube Displacement. *SPE Journal (10725)*, 281-291.

17. Glaso. (1985). Generalized Minimum Miscibility Pressure. *Society of Petroleum Engineers Journal*, 927-934.

18. H.M. Sebastian, R.S. Wenger, T.A. Renner. (1985). Correlation of Minimum Miscibility Pressure for Impure CO2 Streams. *Journal of petroleum technology*, 2076-2082.

19. Hamoodi. (September 1986). Discussion of Generalized Minimum Miscibility Pressure Correlation. *SPEREE*, 535.

20. Henry R.L and Metcalfe R.S. (1983). Multi-phase Generation During Carbon Dioxide Flooding. *SPEJ*, 595-601.

21. J. J Rathmel, F. I. (1971). *A Laboratory Investitagion of Miscible Displacement by Carbon Dioxide.* Texas: SPE.

22. J. L Creek, J. Sheffled. (1991). Phase Behavior, Fluid Properties and Displacement Characteristics of permian Basin reservoir fluid/CO_2 System. *Society of Petroleum Engineers Rservoir Engineering*, 34-42.

23. J.Bon, H. K. Sarma, A. M. Theophilos. (2005). *An Investigation of Minimum Miscibility Pressure for* CO_2 *Rich Injection Gases with Pentane-Plus Fraction.* Kuala Lumpur: SPE 97536.

24. J.J. Chaback, M.L. Williams. (1988). Phase Equilibria in the SACROC Oil/$C0_2$ System. *SPE Reservoir Engineering*, 103-111.

25. James P. Frimodig, Norman A. Reese, Craig A. Williams. (1983). Carbon Dioxide Flooding Evaluation of High Pour-Paraffinic Red Wash Reservoir Oil. *Society Of Petroleum Engineers Journal*, 587-594.

26. James P. Johnson and James S. Pollin. (1981). *Measurement and Correlation Of* CO_2 *Miscibility Pressure*. Okalahoma: SPE 9790.

27. John B. Desch, Wayne K. Larsen, Robert F. Lindsay, Robert L. Nettle. (1984). Enhanced Oil Recovery by CO_2 Miscible Displacement in the Little Knife Field, Billings County, North Dakota. *Journal Of Petroleum Technology*, 1592-1602.

28. K. Mogensen, P Hood, N. Lindeloff, R Noman. (2009). *Minimum Miscibility Pressure Investigation for a Gas Injection EOR Project in Al Shaheen Field, Offshore Qatar*. New Orleans, Louisiana: SPE 124109.

29. Karen Schou Pedersen, Peter L. Christensen. (2007). *Phase Behavior of Petroleum Reservoir Fluids*. Danvers: Taylor & Francis Group.

30. Kaveh Ahmadi, Russell T. Johns. (2008). *Multiple Mixing Cell Method for MMP Calculations*. Colorado: SPE 116823.

31. Kovarik, F. (1985). *A Minimum Miscibility Pressure Study Using Impure* $C0_2$ *and 'West Texas Oil System: Data Base, Correlations and Compositional Simulation*. Lubbock,Texas: SPE 14689.

32. L. W. Holm, V. A. Josendal. (1974). Mechanism of Oil Displacement By Carbon Dioxide. *Journal of Petroleum Technology*, 1427 - 1438.

33. LeRoy W.Holm, Virgil A. Josendal. (1982). Effect of Oil Composition on Miscible-Type Displacement by Carbon Dioxide. *Society of Petroleum Engineers Journal*, 87-98.

34. M.K Silva, F.M Orr Jr. (1987). *Effect of Oil Composition on Minimum Miscibility Pressure: Part 1 Solubility of Hydrocarbons in Dense CO_2.* SPERE 14149.

35. M.K. Emera, H.K. Sarma. (2007). Genetic Algorithm (GA)-Based Correlations Offer More Reliable Prediction of Minimum Miscibility Pressures (MMP) Between Reservoir Oil and CO_2 or Flue Gas. *JCPT Volume 46, No. 8,* 19-25.

36. Marcel Latil, Charles Bardon, Jacques Burger, Pierre Sourieau. (1980). *Enhanced Oil Recovery.* Paris: Institut Francais Du Petrole Publications.

37. McCain, W. D. (1990). *The Properties of Petroleum Fluids 2nd Edition.* Oklahoma: PennWell Publishing Company.

38. Metcalfe, R. (April 1982). Effects of Impurities on Minimum Miscibility Pressures and Minimum Enrichment Levels for CO_2 and Rich-Gas Displacements. *Society of Petroleum Engineers Journal*, 219-225.

39. Mohammed K. Emera, Hemanta K. Sarma. (2006). *A Reliable Correlation to Predict the Change in Minimum Miscibility Pressure when CO2 in Diluted with other Gases.* Manama , Bahrain: SPE Reservoir Evaluation & Engineering.

40. Nor Idah Kechut, Zahidah Md. Zain, Noraini Ahmad, DM Anwar Raja DM Ibrahim. (1999). *New Experimental Approaches in Minimum Miscibility Pressure (MMP) Determination.* Kuala Lumpur: SPE.

41. P.Y. Zhang, S. Sayegh, X.L. Zhou. (2004). *Effect of CO_2 Impurities on Gas-Injection EOR Process.* Oklahoma: Society Petroleum Engineers (SPE 89477).

42. R. Okuno, R. T. Johns and K. Sepehrnoori. (2010). *Mechanism for High Displacement Efficiency of Low Temperature CO2 Floods.* Oklahoma: SPE 129486.

43. R. S. Metcalfe, Lyman Yarborough. (1979). The Effect of Phase Equilibria on the CO_2 Displacement Mechanism. *Society Of Petroleum Engineers Journal* , 242-252.

44. R.L. Cardenas, R.B. Alston, A.J. Nute, G.P. Kokolis. (1984). Laboratory Design of a Gravity-Stable Miscible CO_2 Process. *Journal Of Petroleum Technology*, 111-118.

45. Reid B. Grigg, Ucok W. R. Siagian. (1998). *Understanding and Exploiting Four-Phase Flow in Low Temperature CO2 Floods.* Texas: SPE 39790.

46. Roy M. Dicharry, T. L, Perryman, J. D. Ronquille. (1973). Evaluation and Design of CO_2 Miscible Flood Project - SACROC Project, Kelly-Snyder Field. *Journal Of Petroleum Technology*, 1309-1318.

47. S.C Ayirala, D.N. Rao. (2006). *Comparative Evaluation of a New MMP Determination Technique.* Oklahoma: SPE 99606.

48. Silva, Z. A. (25 May, 2002). *Petronas*. Retrieved 10 October, 2011, from Our Business: www.petronas.com.my

49. Stalkup, F. I. (1992). *Miscible Displacement.* Texas: Society of Petroleum Engineers.

50. Ucok W. R. Siagian, Reid B. Grigg. (1998). *The extraction of Hydrocarbon from Crude Oil by High pressure* CO_2. Oklahoma: Society of Petroleum Engineers (SPE 39684).

51. W. F. Yellig, R. S. Metcalfe. (1980). Determination and Prediction of CO_2 Minimum Miscibility Pressures. *Journal of Petroleum Technology*, 160 - 168.

52. Whitson, C. H. (AUGUST 1983). Characterizing Hydrocarbon Plus Fractions. *Society Of Petroleum Engineers Journal*, 683-694.

53. Wischnewski, B. (June, 2009). *Peace Software*. Retrieved 29 January, 2012, from Online Calculation - Carbon dioxide: http://www.peacesoftware.de/einigewerte/co2_e.html

54. Wilburn D.L, Bankston B.A, Monger T.G (1988). *An Experimental Investigation Into the Effects of Chemical Tye on* CO_2 */ Heavy-Hydrocarbon Phase Behavior.* SPERE 16272

55. Yuan, H. J. (2004). *Improved MMP Correlations for CO_2 Floods Using Analytical Gas Flooding Theory*. Oklahoma: SPE.

56. Yu-Feng Hu,Shi Li, Ning Liu, Yan-Ping Chu, Sang J. Park, G.Ali Mansoori and Tian-Min Guo. (2004). Measurement and corresponding states modeling of asphaltene precipitation in Jilin reservoir oils. *Journal of Petroleum Science and Engineering*, 199-212.

57. Yang Xu, Bo Ren, Baolun Niu, Shaoran Ren, Xiangliang Li, Ping Guo, Xinwang Song. (2011). *Laboratory Assessment and Field Pilot of near Miscible CO_2 Injection for IOR and Storage in a Tight Oil Reservoir of ShengLi Oilfield China.* Kuala Lumpur: SPE144108

58. Y Zhou, X Ran, X Liao. (2012) *An Assessment of a CO_2 Flood for EOR and Sequestration Benefits in the Ordos Basin, Northwest China.* Florida: CMTC150272

59. Zahidah Md. Zain, Nor Idah Kechut, Ganesan Nadeson, Noraini ahmad, Dr. DM Anwar Raja. (2011). *Evaluation of CO_2 Gas Injection For Major Oil Production Fields in Malaysia - Experimental Approach Case Study: Dulang Field.* Kuala Lumpur: SPE.

60. Zainuri, Z. D. (20 September, 2011). Asphaltenic crude and paraffinic crude. (F. Azmi, Interviewer)

APPENDICES

APPENDIX 1: Composition of Dulang Crude and Dubai Crude

The composition of Dulang crude is based on the report dated 25th May 2002 and it is provided by the PETRONAS website at www.petronas.com.my/our_business.

While the composition of Dubai crude is based on the report dated 18th July 2001 and it was provided by the TOTAL Oil Trading at www.totsa.com.

Figure 17 show the oil composition of Dulang and Dubai crude.

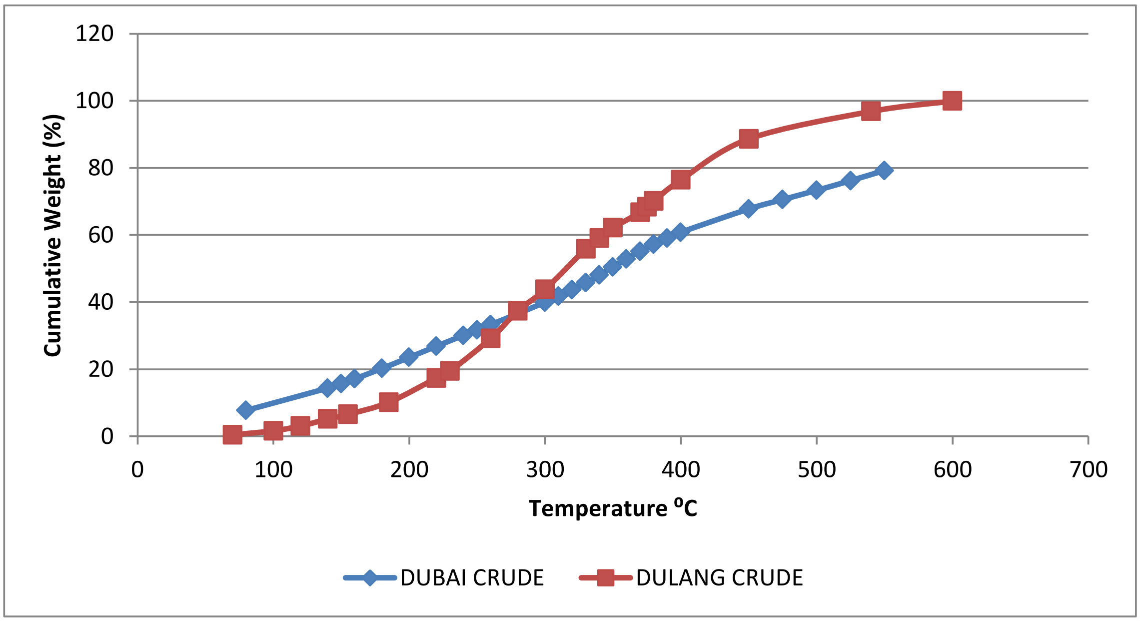


Figure 17: Dulang and Dubai crude composition from true boiling point distillation data

APPENDIX 2: Dulang and Dubai Crude Parameters for Correlation

To apply the mentioned correlations, knowledge about the molecular weight distribution for undefined components above C_{7+} is required. In this study, mole fractions were calculated from true boiling point distillation (TBP) data while molecular weight was calculated from the correlation by (D. L. Katz, A. Firoozabadi, 1978). Figure 17 shows the Katz and Firoozabadi correlation and Table 16 summarize the input variable for the MMP correlation.

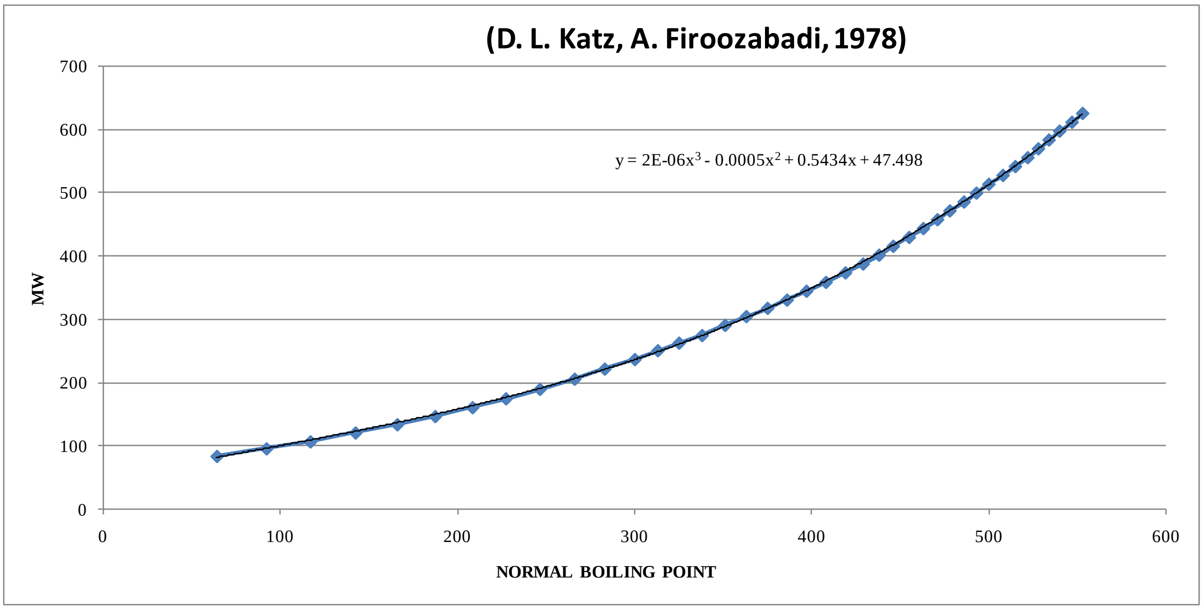


Figure 18: Katz and Firoozabadi correlation

Table 16: Input variables of Dulang and Dubai crude for correlation calculation

Crude	Dubai	Dulang
MW of C_{7+}	217.2126	180.5167
MW of C_{5+}	181.4031	201.0735
Mol % C_1	2.2758	
Mol % C_2-C_6	34.4588	20.1559

APPENDIX 3: Properties of Crude Found In the Literature

REFERENCE	T (F)	MOLE % C1	MOLE % C2-C6	MW C5+	MW C7+
[13]	66	20.00	30.00	195.00	210.00
[13]	70	20.00	30.00	195.00	210.00
[33]	71		15.00		193.00
[18]	88	12.00	24.20	205.00	240.00
[16]	90		30.00	323.00	330.00
[38]	90	11.00	25.00	188.00	206.00
[13]	95	20.00	30.00	195.00	210.00
[51]	95		20.00		201.00
[26]	98		27.00		224.30
[4]	100	4.90	2.00	236.00	245.00
[21]	103	28.00	30.00	200.00	223.00
EXPERIMENT	104	2.28	34.46	181.40	217.21
EXPERIMENT	104		20.16	201.07	180.52
[20]	104	8.30	31.00	191.00	205.00
[5]	104	24.00	30.70	202.00	221.00
[38]	105	11.00	25.00	188.00	206.00
[21]	109	17.00	28.80	204.00	222.00
[5]	109	17.00	23.40	221.00	235.00
[31]	110		20.00		201.00
[19]	110	54.00	43.50	160.00	284.00
[51]	118		20.00		201.00
[26]	119		20.00		245.00
[26]	119		30.00		190.00
[20]	120	16.00	31.00	214.00	227.00
[43]	120		21.00		142.00
[13]	122	20.00	30.00	195.00	210.00
[4]	130	5.40	38.40	185.83	190.00
[4]	130	5.40	35.50	235.56	240.00
[4]	130	22.90	38.40	185.83	190.00
[4]	130	5.00	18.00	180.00	185.00
[7]	130	30.00	37.30	169.00	190.00
[24]	130		36.60		198.00
[46]	130	29.00	40.40	171.00	197.40
[25]	130		13.40		319.70
[33]	130		11.00		175.00
[28]	132.5				284.00
[28]	133				284.00
[33]	135	2.00	15.00	183.00	193.00
[26]	135		30.00		223.60
[28]	135				284.00
[28]	135				284.00
[38]	135	11.00	25.00	188.00	206.00

[4]	136	0.50	15.00	202.61	180.00
[33]	137		20.00	171.00	185.00
[41]	138	5.00	20.00	210.00	232.00
[4]	142	5.40	38.40	185.83	190.00
[41]	142	10.00	28.00	181.00	191.00
[33]	150		27.00	219.00	230.00
[27]	150		20.00		139.00
[51]	150		20.00		201.00
[4]	154	31.00	23.00	204.00	210.00
[4]	160	41.00	7.00	221.00	227.00
[12]	160	29.50	31.80	171.20	227.94
[43]	160		30.00		142.00
[43]	160		25.00		142.00
[44]	164	49.00	8.84	210.00	218.00
[33]	165		20.00	267.00	267.00
[33]	165		35.00	254.00	260.00
[33]	165		30.00	214.00	240.00
[33]	165		20.00	171.00	190.00
[33]	171		30.00	172.00	190.00
[4]	176	53.00	9.00	241.00	245.00
EXPERIMENT	176	2.28	34.46	181.40	217.21
EXPERIMENT	176		20.16	201.07	180.52
[6]	180	6.35	26.09	250.00	281.00
[6]	180	33.00	40.76	190.00	220.00
[11]	180	6.00	24.00	200.00	234.00
[33]	185		27.00	219.00	230.00
[21]	186	45.00	13.00	248.00	268.00
[55]	188		31.10		200.00
[33]	190		18.50	183.00	200.00
[51]	192		20.00		201.00
[4]	210		3.00		195.00
[59]	215	9.80	31.90		196.00
[4]	216	51.00	10.00	205.00	210.00
[7]	220	43.00	30.80	154.00	273.00
[4]	230	33.00	36.00	181.00	185.00
[4]	234	33.00	28.00	214.00	220.00
[6]	240	6.35	26.09	250.00	281.00
[6]	240	33.00	40.76	190.00	220.00
[52]	245	36.34	30.72	169.20	200.00
[2]	250	0.50	18.00	200.00	240.00