UNIVERSITI
TEKNOLOGI
PETRONAS

FINAL YEAR PROJECT

FINAL REPORT

Improvement of CO_2 MMP Correlations by Incorporating Paraffinicity Factor

Supervisor: Mr. Iskandar Dzulkarnain

Muhammad Syahmi Azri Md Zanil
12087
Petroleum Engineering

Improvement of CO_2 MMP Correlations by Incorporating Paraffinicity Factor

by

Muhammad Syahmi Azri bin Md Zanil

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

SEPT 2012

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATE OF APPROVAL

Improvement of CO_2 MMP Correlations by Incorporating Paraffincity Factor

By

Muhammad Syahmi Azri bin Md Zanil

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:

Mr Iskandar Dzulkarnain

UNIVERSITI TEKNOLOGI PETRONAS TRONOH,
PERAK
September 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.

____

Muhammad Syahmi Azri bin Md Zanil
12087, Petroleum Engineering

ABSTRACT

Enhanced Oil Recovery (EOR) implies oil recovery technique beyond the conventional recovery stages of primary or secondary recovery. Out of several extensive methods, miscible gas displacement has been widely used in some of the field in Malaysia. Due to the location at the offshore, CO_2 gas injection was chose to be employed as the EOR technique. The key to successful gas displacement efficiency is to have a reservoir pressure greater than a minimum miscibility pressure (MMP). The MMP has been defined as the minimum pressure at which the injected gas and the oil become miscible with each other. A high degree of accuracy is needed for predicting the outcome of the gas injection process for it is known as a very costly operation. Empirical correlations were often used to predict the MMP during the preliminary study. The aim of this study is to reduce the error of the prediction by correlation. To alleviate the error of prediction, parafinicty factor is incorporated into the correlation. In order to develop accurate predictive compositional models, it is necessary to have at one's disposal many experimental data. This study suggests incorporating the parafinicity factor into the correlation to further characterize the oil composition and reduce the error. A total of 72 MMP measurements from the literature were used to assess the Maklavani (2001), Sebastian (1985), Cronquist (1977) and Yellig (1980) correlations. Parafinicity factor was used to further characterize the correlation which will increase accuracy.. It was demonstrated in this study that some correlations predictions would give huge error of predictions. Several correlations are eliminated from improvement and Yellig et Metcalfe is finally chosen for improvement.

ACKNOWLEDGEMENT

Alhamdullilah, praise be upon Allah, with His will and permission, this Final Year Project has been completed successfully. The author truly feel it is a great learning and a gesture towards the success of the Department to produce well rounded and highly capable Petroleum Engineers.

The author would like to take this opportunity to convey his upmost gratitude to my:

Project Supervisor; Mr Iskandar Dzulkarnain for his relentless support and guidance since first day the project given. His effort and time spent in making sure my project runs smoothly are truly appreciated .His enthusiasm and dedication had inspired the author to strive harder in completing this project.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

1. BACKGROUND STUDY

This study is to help engineers attain miscibility at a more accurate pressure. CO_2 injection is one of the techniques fall under EOR (Enhanced Oil Recovery), which involves injection of miscible gas into the reservoir to help it sweep the remaining oil. Out of several extensive methods, miscible gas displacement has been widely used in some of the field in Malaysia. The key to successful gas displacement efficiency is again relies on the accuracy of determining the MMP (Minimim Miscibility Pressure). To briefly describe MMP, it is the pressure at which the injected gas and the oil become miscible with each other.

MMP has been widely determined by several methods; i.e the experimental method, analytical method, and the correlations. In this paper, the various correlations are studied and modified to give a better accuracy at predicting the MMP.

Correlations for predicting MMP have been proposed by a number of investigators [1-3.] Most of the methods are localized and are to be used at the particular reservoir at which the investigator did the experiment. 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 most authors.

From the previous studies, most authors often neglect the heavier components in C_{7+} fraction. It became evident in a study by Yellig and Metcalfe that a 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. Apart from the correlation, the renowned Slimtube experiment is also used to determine the miscibility pressure. This technique is however consumed so much time and costly.

1.1 Problem Statement

Various correlations for MMP estimation have been developed from the regression of slim tube data. Correlations are quick and easy to use though usually less accurate. Enrich et al. (1988) pointed out that several critical points to be considered when performing correlation process; - a) ideally, any correlation should account for each parameter known to affect the MPP; b) the correlation should be based on thermodynamic or physical principles that affect the miscibility of fluids; c) should be directly related to the multiple contact miscibility process. For screening purposed, they gave a fair first guess depending on the data used. Moreover, they are inexpensive and can be detained by simple hand calculation. However, the success of the correlations is usually limited to the composition range in which these correlations were developed.

On top of that, a very significant weakness of current MMP correlations is that the regressions use MMPs from slim tube experiment which are themselves uncertain (Yuan, 2004). 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 hydrcarbon such as paraffin, aromatic or napthenes. The existence of this C_{7+} has altered the correct MMP and the calculated value produce huge error.

There is a need for further improvement of current correlations. Development of a universal correlation that can fit to any type of the reservoir and accurate MMP is very essential as it can save a lot of time and cost.

1.2 Objectives

The ultimate aim of this project is to improvise the correlations we obtained from several authors. This paper serves as the platform to compare and contrast the best correlation to be used prior to gas fluid injection. Several CO_2 MMP correlations have been published, but none of these can be used with enough confidence for final project design. They are however very helpful for screening and preliminary work.

The fundamental idea of this paper is to:

- Reduce the error between the predicted MMP by these correlations and true MMP.
- Introduce the parafinicity factor to further characterize the composition of crude oil.

1.3 Feasibility Of Project

The allocated time for my Final Year Project is in the 7 months period (FYP1 and FYP2). This research fully utilized the given the short timeframe while maintaining credibility of the results. Several weeks prior to proposal is the brainstorming of idea. Books from the library are used for better understanding of the topic. Aside from that, the accumulation of idea is assisted by the thesis, websites, research paper and journal obtained from the Internet. The selection of best correlations to be used is the job came after the selection of topic. Thorough analyses of every correlation are made. The following weeks were fulfillled with the complex regression analysis of the datapoints obtained.

CHAPTER 2

2. LITERATURE REVIEW

In this section, previous studies have shown several attempts of predicting MMP. Some had shown very good results while some are not. From the literature review, there is room for improvement for the correlation of MMP.

2.1 Miscible Injection

From studies of displacing oil from reservoir rock by gas, we have learned that a portion of the oil is left as residual when immiscible conditions are present because capillary and viscous forces form interfaces. Eliminating the interfaces allows complete displacement of the oil. The potential for achieving attractive economics was first reported by Whorto and Kieschnich(December 1952) ; they found that natural gas at sufficiently high pressures would miscibly displace crude oil. Of all the availabe gas to be injected, CO_2 is chosen due to its economical and ease of handling.

2.1.1 CO_2 Miscible Injection

Carbon dioxide is used to generate a miscible displacement in a reservoir. Although CO_2 is not miscible with reservoir oils, it will generate a miscible solvent in-situ through a mechanism similar to that using high-pressure gas. 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 depicts the idea of CO_2 injection.

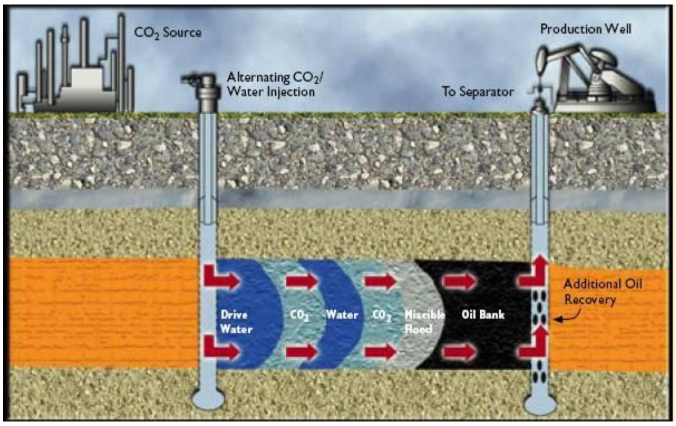


Figure 1: CO^2 Miscible Gas Injection

2.2 Factors Affecting Minimum Miscibility Pressure

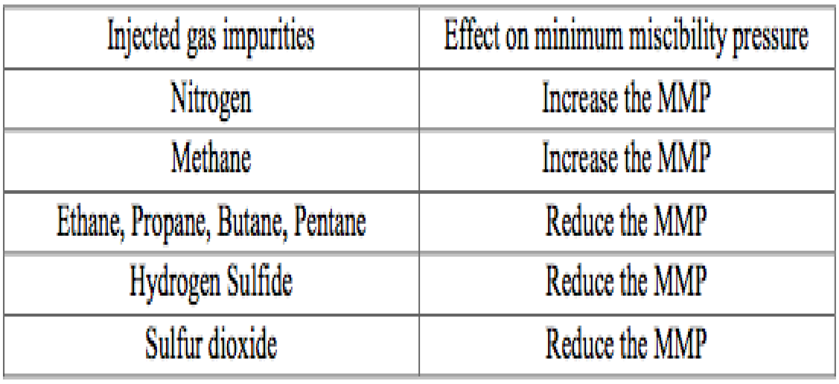
In this section of this paper, the factors affecting the Miscibility Pressure are discussed upon. CO_2 miscibility pressure depends on CO_2 purity, oil composition and reservoir temperature.

2.2.1 CO_2 Purity

Pure CO_2 is not always available as an injection gas. Impure CO_2 streams however available from a variety of sources, including natural reservoirs and process plant waste streams. Now we should revise the effect of impurity of CO_2 towards MMP.

A recent study by Ahmadi (1990) shows that suppose we have impure CO_2 injection, where CO_2 is contaminated with methane. The MMP for displacement of oil with mixtures of these two components can change nonlinearly over its entire range from 0 to 100% methane contamination. At low contamination levels, however, the MMP changes linearly with the methane mole fraction in the gas.

Table 1 : The effect of CO2 impurities on MMP (Ahmadi 1990)



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

2.2.2. Oil composition

Oil composition plays a major role in fluctuating the resultant MMP reading. 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. The logic behind this is that a higher molecular weight will reduce the solubility of hydrocarbon in CO_2.

The Lighter components that range 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

As we go along the sequence of molecular weight, we will finally reach the C_{7+} section that will play a role in MMP correlation. Paraffin, naphthenes and aromatics are what made up this C_{7+} .(Wilburn, 1988) .According to Wilburn (1988) and M.K Silva (1987), paraffin remains the most efficiently extracted by CO_2 followed by aromatics while naphthenes had detrimental effect on CO_2 solubility.
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 is important to obtain accurate MMP prediction.

2.2.3. Reservoir Temperature

The reservoir temperature is one of the parameters that will easily affect the MMP. It is best known that higher reservoir temperatures result in higher miscibility pressure, other factors being equal. (Glaso, 1985). Yellig, R. S. Metcalfe (1980) experiment shows that an increase in 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). He also produces a correlation that only takes into account the temperature factor only. Figure 2 shows the correlation of MMP with Temperature. This correlation is very helpful in very early stage of planning. It helps in preliminary project.

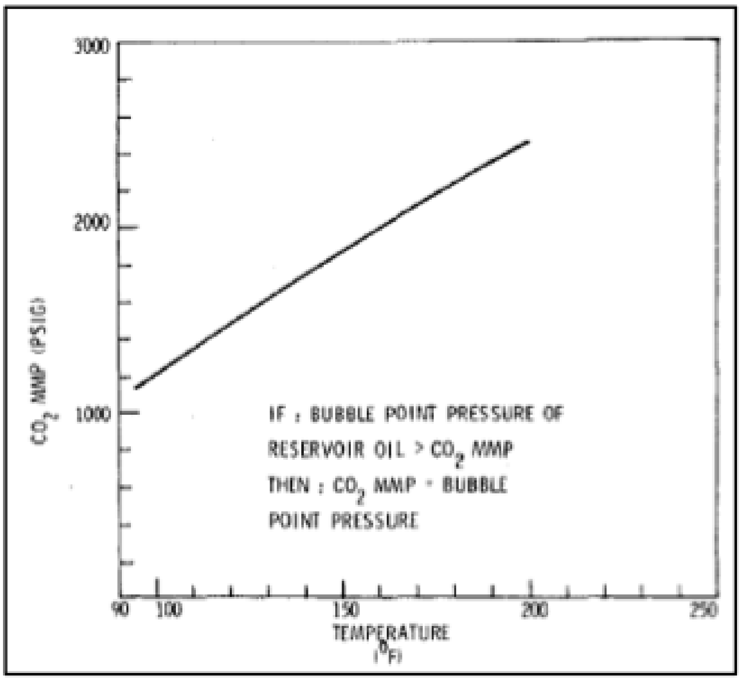


Figure 2: CO2 MMP vs Temperature (W.F Yellig)

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 C5 –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.

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.

2.2.4. Parafinicity Factor

A study 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. 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:

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

Where;
$M_{C_{7+}}$ = molecular weight of C_{7+}
γ_{C7+} = specific gravity of C_{7+}

2.3 Methods Of Estimating MMP

There are several experimental and computational methods for estimating MMP. The focus of this dissertation is on computational methods.

2.3.1 Experimental methods for estimating MMP

MMP can be estimated through a number of experiments: slim-tube experiments, mixing-cell experiments, rising bubble/falling drop experiments, and vanishing interfacial tension experiments. This section reviews these experiments and describes some of their shortcomings. Although the cost and the time of conducting many of these experiments are prohibitive, if carefully performed, such experiments can duplicate the complex

2.3.2 Slim-tube experiments

The slim-tube experiment is the widely accepted experimental method for estimating MMP. A slim-tube is a long, narrow tube packed with glass beads or sand. The length of the tube is between 5 and 120 ft (Elsharkawy et al. 1992; Orr et al. 1982), and the diameter varies from 0.12 to 0.63 in, with 0.25 in as a typical diameter (Danesh 1998; Elsharkawy et al. 1992). Because of this large length-to-diameter ratio, the slim- tube experiment comes close to a one-dimensional displacement, thus isolating the effect of phase behavior on displacement efficiency.

In slim-tube experiments, gas is injected into a slim-tube that is saturated with oil. The injection temperature and pressure are kept constant (pressure is generally kept constant by a back-pressure regulator). The rate of gas injection is such that it does not induce a large pressure gradient. The slim-tube displacement velocity is typically between 120 and 200 ft/D (Danesh 1998).

To determine MMP, three or more slim-tube experiments are performed. In each experiment, oil recovery and pore-volume of injected gas are recorded. The recovery data are then used to estimate MMP using a number of criteria. The most common criterion is the break-over pressure in a plot of recovery versus pressure, when recovery is recorded after typically injecting 1.2 pore volume of gas (Danesh 1998; Yellig and Metcalfe 1980). Other MMP criteria are 80% recovery at gas breakthrough (Holm and Josendal 1974) and 90%–95% of ultimate recovery (Glaso 1990; Hudgins et al. 1990; Jacobson 1972).

Slim-tube experiments, however, have significant drawbacks. These drawbacks partly stem from the lack of standards both in conducting the test and in interpreting its results. Elsharkawy et al. (1992) published a thorough review of slim-tube procedures in the early 90s. These procedures, which have not changed since, are time-consuming and expensive to conduct. Each experiment involves extensive procedures to clean and restore the slim-tube before the next test, and the cleaning can be especially complicated if asphaltene is precipitated during the experiment. Furthermore, the results of a slim- tube experiment can be uncertain because of the lack of data points and because of the impact of dispersion (Walsh and Orr Jr. 1990; Johns et al. 2002). Orr et al. (1982) raise concerns about whether the results of one slim-tube experiment are reproducible with another slim-tube. Despite these shortcomings, slim-tube experiments remain the most reliable experimental method of estimating MMP in the industry, because they can replicate the actual interaction of oil and gas in a one-dimensional porous medium.

The literature reveals other experimental methods of determining MMP, the most cited of which are multiple-contact mixing experiments, rising-bubble experiments (Christiansen and Haines 1987), and vanishing interfacial tension experiments; the following sections briefly review each of these methods.

2.3.3 Multiple-contact experiment (mixing cell experiment)

Multiple-contact experiments can accurately estimate MMP under certain conditions. The main purpose of a multiple-contact test is to study the phase behavior of injection gas and oil (Bryant and Monger 1988; Menzie and Nielsen 1963; Turek et al. 1988). Nevertheless, such tests, as they are currently designed, can measure MMP only if the displacement type is a condensing or a vaporizing drive, not a condensing/vaporizing one.

The multiple-contact test relies on contacts between oil and gas. In each contact, oil and gas are mixed at a specified ratio in a pressure-volume-temperature (PVT) cell and brought to equilibrium. A single PVT cell or a series of cells is used to make repeated contacts between oil and gas in a *forward* or a *backward* manner. In a *forward* contact, after each contact the equilibrium gas is retained while the equilibrium oil is replaced with fresh oil. Consequently, at each stage, the equilibrium gas from the previous stage contacts fresh oil. In a *backward* contact, equilibrium oil is retained and the gas is replaced with fresh injection gas. The contacts are repeated until there is no further change in the composition of the phases. These experiments are repeated at several pressures until the repeated contacts result in a single phase (seen visually from the window on the cell).

The main drawback of multiple-contact tests is their inability to measure MMP for a condensing/vaporizing drive. These experiments can be a fast and cheap alternative to slim-tube experiments when the miscibility mechanism is known beforehand to be either condensing or vaporizing.

2.3.4 Rising bubble /falling drop experiment

Christiansen and Haines (1987) first introduced the rising bubble experiment as a rapid alternative to slim-tube experiments. The experiment is based on the visible appearance of a gas bubble as it rises through the oil column; this consists of a high- pressure transparent tube eight inches long that is filled with oil and kept at a desired pressure and temperature. Gas is introduced through a needle at the bottom of the tube, which then forms a bubble and rises through the column. Christiansen and Haines (1987) describe how the shape of the rising gas bubble is used to assess the MMP criteria.

Although rapid and cheap compared to slim-tube experiments, the rising bubble method suffers from major limitations, the most important of which is its unreliability in predicting MMP for condensing and condensing/vaporizing gas drives. The rising gas bubble attempts to duplicate the forward contact of gas and oil in reservoirs. As gas rises, it makes contact with fresh oil at any stage of the experiment. As a result, the gas becomes richer and richer as it gets closer to the top, similar to the advancing gas front in the reservoir, but not necessarily the same. If miscibility develops, therefore, it will do so at the front of the advancing gas. Thus, rising bubble experiments can likely predict the MMP for a vaporizing gas drive, but not for a condensing drive (Zhou and Orr 1998). Whether such experiments can accurately determine the MMP for a condensing/vaporizing drive remains to be determined (Zhou and Orr 1998).

The falling drop experiment is a modified version of the rising bubble experiment and is used for predicting MME (Christiansen 1986; Zhou and Orr 1998) and MMP in a condensing gas drive. The principle of the experiment is the same as the rising bubble, the difference being that a bubble of oil is introduced into a gas-filled chamber. As with the rising bubble experiment, it is unclear whether the falling drop method can accurately predict the MMP for a vaporizing/condensing gas drive, and therefore it is not commonly used in the industry (Zhou and Orr 1998).

2.3.5 Vanishing interfacial tension (VIT) experiment

Rao (1997) proposed the vanishing interfacial tension (VIT) experiment as a method for determining MMP (or MME). This method is based on measuring the interfacial tension (IFT) between oil and injected gas at various pressures and at a fixed temperature. It consists of a high-pressure, high-temperature cell filled with the injection gas. A drop of crude oil (about 10% of the cell volume) is then introduced into the cell through a capillary tube (Rao and Lee 2002). The IFT between the oil drop and the gas is determined by analyzing the shape of the hanging oil drop and the densities of the oil and the gas. The pressure is then increased by introducing more gas into the cell and the IFT measurement is repeated. The MMP is approximated by extrapolating the plot of IFT versus pressure (or enrichment, for MME) to zero. Ayirala and Rao (2006) presented a modified version of the experiment in which the overall composition in the cell is kept constant and IFT is measured with both a capillary rise method and with a shape analysis of the hanging oil drop. For more information about different variation and applications of the VIT method, see Jessen and Orr (2008) and the references therein.

Orr and Jessen (2007) analyzed the VIT method through a series of ternary and quaternary systems and concluded that a VIT estimate of MMP is highly dependent on the overall composition of the cell and can be significantly different from the analytically calculated MMP (see section 2.2.2 for details). It is not clear which overall composition gives a reasonable MMP. The VIT method, however, is fundamentally limited in that "it investigates mixture compositions that are linear combinations of the initial oil and injection gas that are quite different from the critical mixture that forms at the MMP in a gas–oil displacement in a porous medium" (Orr and Jessen 2007, page 99). Jessen and Orr (2008) further extended their analysis to a multi-component mixture and observed that the mixtures created in VIT cells do not generally lead to reliable estimates of MMP. They concluded that VIT experiments may not be a dependable method of determining MMP for multi-component oil mixtures.

2.4 Correlations

2.4.1 Yellig and Metcalfe (1980)

An experimental study was undertaken to obtain a better understanding of the effects of temperature and oil composition on the CO_2 MMP determined for an oil. In this paper, CO_2 MMP's were determined using the sand-packed coil (or slim-tube) method. Results of this study were used by the author to develop a correlation for predicting the CO_2 MMP for the oil.

The purpose of this paper is to present the correlation for predicting CO_2 MMP's that was developed from this study. Another purpose is to propose that the sand-packed coil method be used as a standard method of experimentally determining the CO_2 MMP for an oil.

Two variables were considered in this study: **oil composition and temperature**. Oils were considered to consist of three fractions: a light fraction consisting primarily of C1 and small amounts of N2 and CO_2 an intermediate fraction consisting of hydrocarbons with molecular weights between C2 and C6 ; and a heavy fraction (C7 +) consisting of hydrocarbons with molecular weights equal to or greater than normal C7 .

The CO_2 MMP's obtained in this study were determined· using the sand-packed coil or slim-tube test apparatus as described by Smith and Yarborough. The purpose of using a sand-packed coil was to provide a medium for mixing and oil in a flowing, multiple-contact process. It was not intended to simulate reservoir rock. Coil test data, especially from immiscible tests, should not be considered indicative of the ultimate recovery, sweep, transition zone length, etc., to be achieved on a reservoir scale for actual oil reservoirs.

MMP's for the oils used in this study are tabulated in Table 2 and presented graphically in Figure 3. Considering experimental uncertainty, recombined oil composition had little or no effect on the MMP at the lower temperatures and only a minor effect at the higher temper- atures [150 and 192°F (66 and 89°C)].

Table 2 : Experimental MMPs for Test Oils

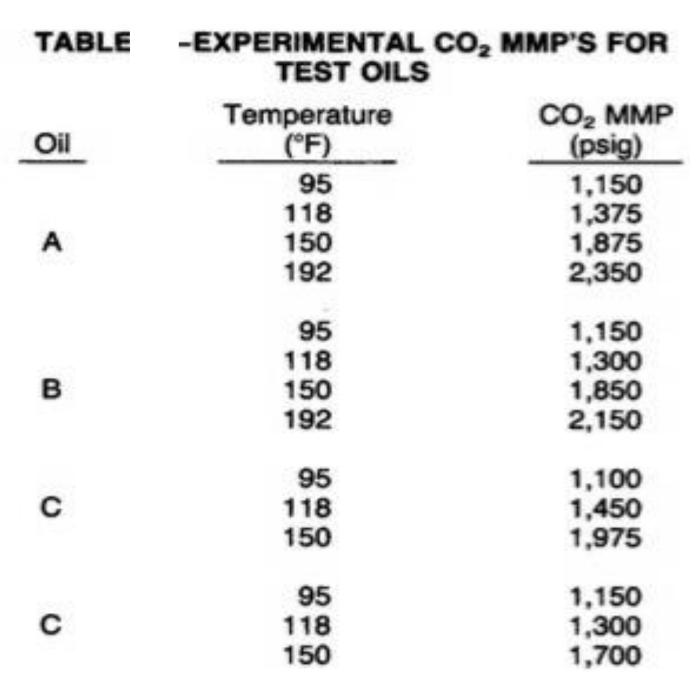


TABLE -EXPERIMENTAL CO_2 MMP'S FOR TEST OILS

Oil	Temperature (°F)	CO_2 MMP (psig)
A	95	1,150
	118	1,375
	150	1,875
	192	2,350
B	95	1,150
	118	1,300
	150	1,850
	192	2,150
C	95	1,100
	118	1,450
	150	1,975
C	95	1,150
	118	1,300
	150	1,700

This result is somewhat surprising, since it had been postulated that light and intermediate components in the reservoir oil should significantly affect the MMP determined for that oil.

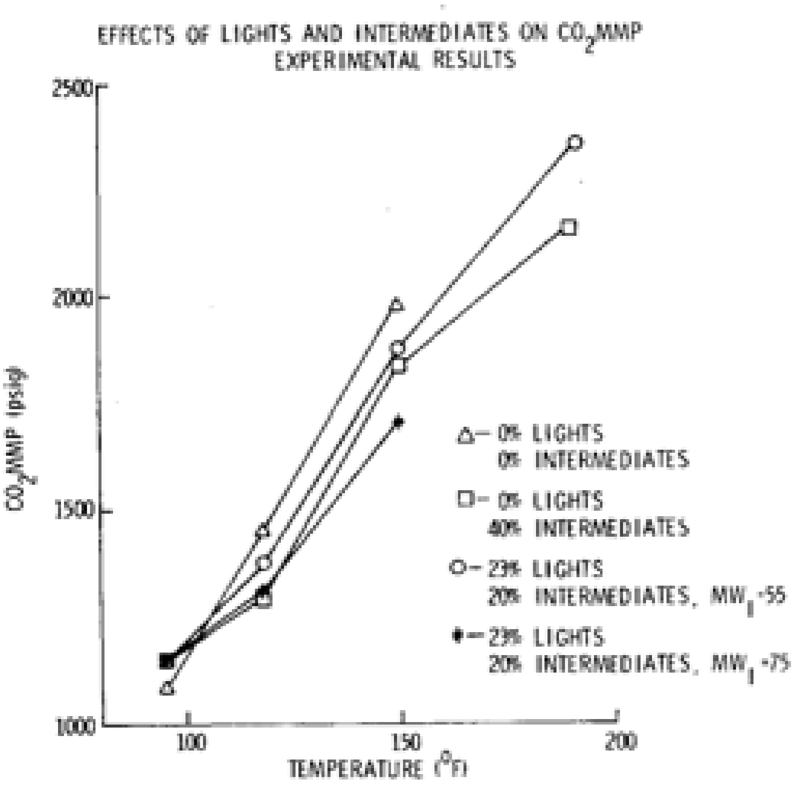


Figure 3 : Results of Correlation (Yellig)

As a result of this study, a correlation was developed for predicting the CO_2 MMP's for reservoir oils. The correlation shown in Figure 3 uses temperature as the parameter, and a correction is applied when the saturation pressure of the oil exceeds the predicted CO_2 MMP.

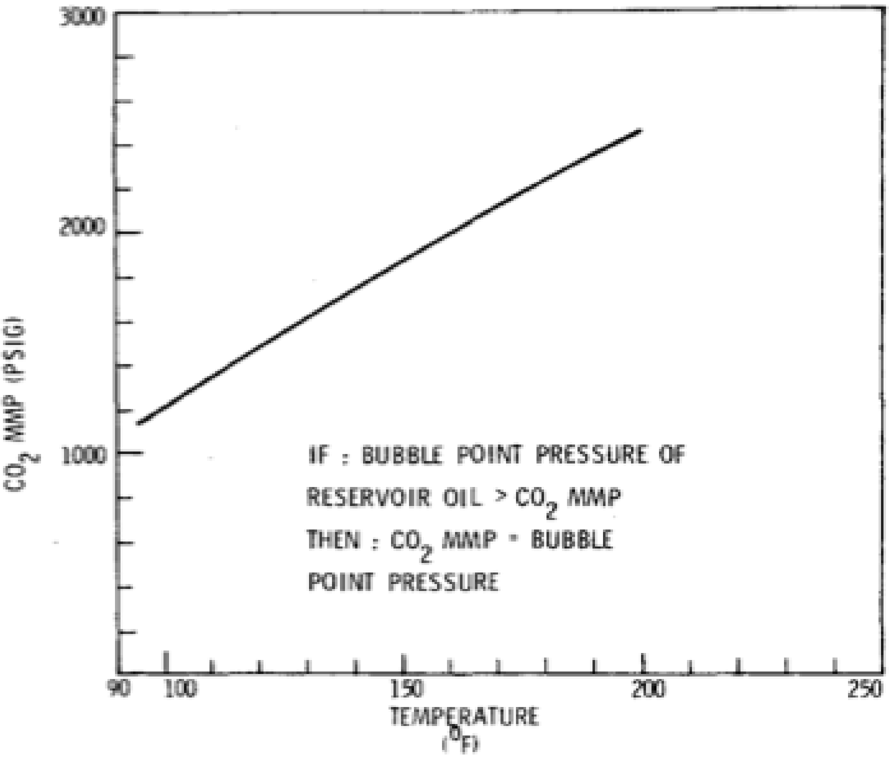
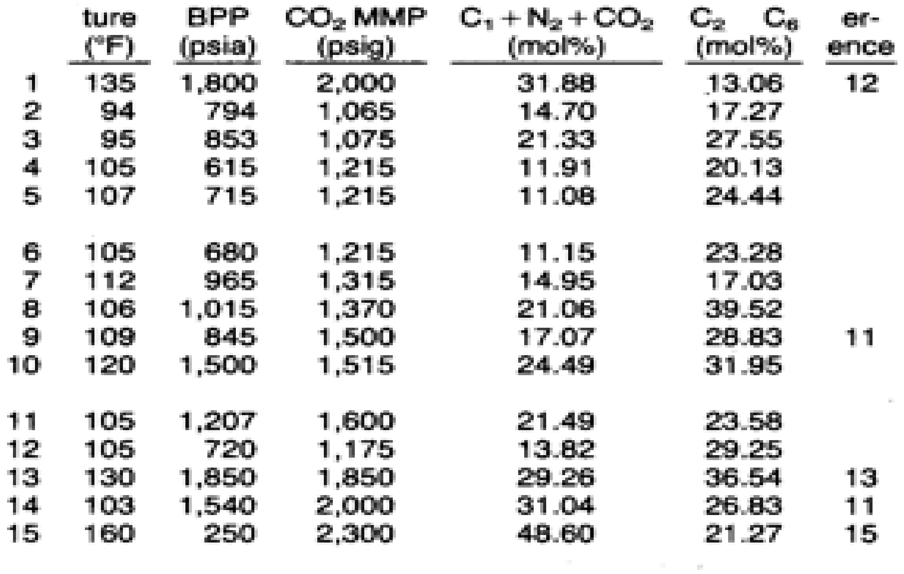


Figure 4: Temperature/bubble-point pressure of CO2 MMP

The data shown in Figure 3 demonstrate that temperature had the greatest effect on CO_2 MMP for the oils and temperatures used in this study. The CO_2 MMP's given in Table 1 were correlated as a function of temperature. This temperature correlation was then used to predict known reservoir oil CO_2 MMP's. The correlation was resonably accurate for oils with bubble-point pressures (BPP's) lower than the predicted CO_2 MMP. However, inaccuracies were found when the oil BPP exceeded the predicted CO_2 MMP.

In this experiment, the author pointed out that there is an effect of reservoir oil composition on CO_2 MMP at the higher temperatures. Based on the results of this study, these compositional effects are considered to be minor. However, they are a source of error since they are neglected by the proposed correlation. The different C_{7+} fractions in the various reservoir oils given in Table 3 also may attribute to an error in the correlation. At the present time, there is no unique method of characterizing the C_{7+} fraction. The average molecular weight of this fraction is used typically as a correlating parameter. Various other parameters might be used to characterize this fraction: density, aromatic content, carbon-to-hydrogen ratio, nonhydrocarbon content, as- phaltene content, etc. At the present time, the data are not available to determine whether these would yield a better correlation of the available CO_2 MMP data.

Table 3: CO2 MMPs for various reservoir oils



	ture (°F)	BPP (psia)	CO_2 MMP (psig)	$C_1 + N_2 + CO_2$ (mol%)	C_2 C_6 (mol%)	er- ence
1	135	1,800	2,000	31.88	13.06	12
2	94	794	1,065	14.70	17.27	
3	95	853	1,075	21.33	27.55	
4	105	615	1,215	11.91	20.13	
5	107	715	1,215	11.08	24.44	
6	105	680	1,215	11.15	23.28	
7	112	965	1,315	14.95	17.03	
8	106	1,015	1,370	21.06	39.52	
9	109	845	1,500	17.07	28.83	11
10	120	1,500	1,515	24.49	31.95	
11	105	1,207	1,600	21.49	23.58	
12	105	720	1,175	13.82	29.25	
13	130	1,850	1,850	29.26	36.54	13
14	103	1,540	2,000	31.04	26.83	11
15	160	250	2,300	48.60	21.27	15

1. The slim-tube method used in this study has proven to be a useful and reproducible technique for determining the CO_2 MMP for a reservoir oil.

2. For the oils considered and the experimental proce- dure used in this study: (a) temperature increases CO_2 MMP by approximately 15 psi/OF (57 kPal°C) over a temperature range from 95 to 192°F (35 to 89°C), and (b) there is little or no significant effect of oil composition on the CO_2 MMP.

2.4.2 H. Yuan (2004)

This paper presents new MMP correlations for the displace- ment of multicomponent oil by CO_2 and impure CO_2. The ap- proach is to use recently developed analytical theory for MMP calculations from equations of state (EOSs) to generate MMP cor- relations for displacements by pure and impure CO_2. The ad- vantage of this approach is that MMPs for a wide range of tem- peratures and reservoir fluids can be calculated quickly and accu- rately without introducing uncertainties associated with slimtube MMPs and other numerical methods. The improved MMP correlations are based solely on the reservoir temperature, the molecular weight of C_{7+}, and the percentage of intermediates (C2–C6) in the oil. The MMPs from the improved correlations are compared to currently used correlations and 41 experimentally measured MMPs.

The MMP is an important optimization parameter in CO_2 floods. Recoveries from slimtube experiments often give a slope change at the MMP. Above the MMP, slimtube recoveries (or local displacement efficiencies) typically do not increase signifi- cantly with enrichment. Thus, the accurate determination of MMP is important in gasflood design.

Four primary methods have been used in recent years to deter-mine MMPs for specific fluid displacements: slimtube experi-ments, compositional simulation, mixing-cell models, and analytical methods. Each of these methods has advantages and disadvantages. Slimtube experiments use real fluids but are expensive and time consuming to perform and can give misleading results depending on the level of physical dispersion present. Fine- grid compositional simulations and mixing-cell models can suffer from numerical-dispersion effects and are also time consuming to perform. Dispersion-free analytical methods are often very fast, but like simulation and mixing-cell models, they rely on an accurate fluid characterization by an EOS.

A variety of correlations for the estimation of the MMP have been developed from regressions of slimtube data. Although less accurate, correlations are quick and easy to use and generally require only a few input parameters. Hence, they are very useful for fast screening of reservoirs for potential CO_2 flooding. They are also useful when detailed fluid characterizations are not avail- able. One significant disadvantage of current MMP correlations is that the regressions use MMPs from slimtube data, which are themselves uncertain. This paper uses the analytical theory developed for multicom- ponent multiphase flow to calculate MMPs for a variety of fluid characterizations, reservoir temperatures, and injection composition. The primary advantage in this approach is that the analytical calculation is fast and accurate, and, thus, a wider range of input parameters can be considered. The correlations for pure- and impure CO_2 injection are developed from regressions of the calcu- lated MMPs. Available MMPs estimated from slimtube experi- ments are compared to those predicted from the new correlations.

2.4.3 Maklavani (2010)

Malavani recently wrote another paper on miscibility pressure. In the paper, he presents a new empirically derived correlation for estimating the minimum miscibility pressure (MMP) required for multicontact miscible (MCM) displacement of reservoir petroleum by hydrocarbon gas flooding. These correlations are often used to estimate the MMP without considering the composition of the injected gas. In his paper, he did a study on how the composition of injected gas affects the miscibility. This is however irrelevant to my study but the correlations he came out with is somewhat general and applicable to be used anytime. From his findings, it is found that :

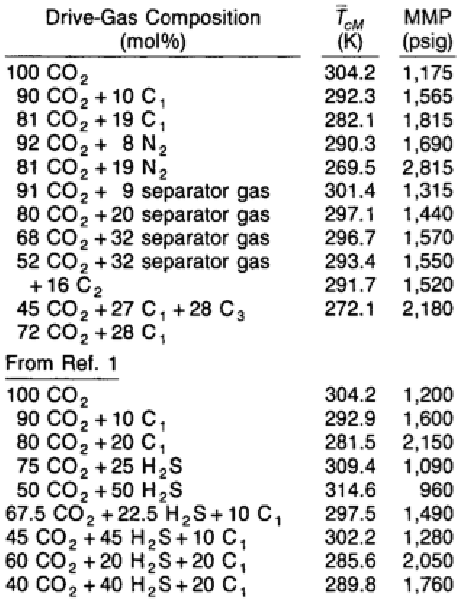
- As temperature increases, the hydrocarbon gas MMP increases for any type of oil;
- The hydrocarbon gas MMP also increases as the C7+ molecular weight increases;
- The hydrocarbon gas MMP decreases as the mole fractions of methane and C2-6 increase in the oil composition.
- By increasing the mole fraction and molecular weight of C2+, the MMP is reduced.

In conclusion, Maklavan had produced a novel MMP correlation for hydrocarbon gas injection on the theory of multicontact miscibility (MCM) process. The correlation is significantly more accurate than the currently used correlations. In this correlation, a wide range of parameters that affect the MMP are taken into account. The new empirically derived miscibility correlation for hydrocarbon gas drive considers oil and gas composition. The MMP data calculated by slim tube simulators show that the MMP increases with increasing temperature and decreases slightly with increasing C2+ molecular weight in the gas stream.

2.4.4 Sebastian et al

In his study, Sebastian suggests that for optimal displacement efficiency CO_2 flooding should be conducted at displacement pressures greater than a certain minimum defined previously as the CO 2 MMP. He also takes into account the effect of injection gas composition. He did an experimental study using Slim-tube apparatus. A series of at least five displacements at different pressure was cinducted with each drive oil system. In these tests, the outlet pressure and flow rate remained constant so that the pressure at the inlet and at the displacement front decreased gradually, while the less viscous drive gas displaced the oil.

Table 4: Drive-Gas Composition (Sebastian)



Drive-Gas Composition (mol%)	$\bar{T}_{cM}$ (K)	MMP (psig)
100 CO_2	304.2	1,175
90 CO_2 + 10 C_1	292.3	1,565
81 CO_2 + 19 C_1	282.1	1,815
92 CO_2 + 8 N_2	290.3	1,690
81 CO_2 + 19 N_2	269.5	2,815
91 CO_2 + 9 separator gas	301.4	1,315
80 CO_2 + 20 separator gas	297.1	1,440
68 CO_2 + 32 separator gas	296.7	1,570
52 CO_2 + 32 separator gas	293.4	1,550
+ 16 C_2	291.7	1,520
45 CO_2 + 27 C_1 + 28 C_3	272.1	2,180
72 CO_2 + 28 C_1		
From Ref. 1		
100 CO_2	304.2	1,200
90 CO_2 + 10 C_1	292.9	1,600
80 CO_2 + 20 C_1	281.5	2,150
75 CO_2 + 25 H_2S	309.4	1,090
50 CO_2 + 50 H_2S	314.6	960
67.5 CO_2 + 22.5 H_2S + 10 C_1	297.5	1,490
45 CO_2 + 45 H_2S + 10 C_1	302.2	1,280
60 CO_2 + 20 H_2S + 20 C_1	285.6	2,050
40 CO_2 + 40 H_2S + 20 C_1	289.8	1,760

The data in Table x is used to develop a correlation to predict the change in MMP resulting from the impuritiies in the CO_2 drive gas. In some cases, the use of the weight fraction average can overstate the effectiveness of intermediate components in reducing the MMP of a complex gas mixture. From Sebastian et al, it can be conlcuded that :

- Sebastian's correlation has been developed relating the MMP of an impure drive gas to the MMP of pure CO_2 , This correlation uses a mole average critical temperature as a correlating parameter, which is superior to other parameters tested. It has been tested mainly with west Texas oils, which should be noted when it is used with different types of oils, especially heavy, viscous oils.
- The correlation is useful as a screening guide for estimating the MMP of gases containing up to 55 mol % impurities.
- The correlation works whether the impure stream is a binary or a multicomponent mixture. The present correlation is applicable to a wider range of drive gases than others previously reported.
- The correlation indicates that the detrimental effect of light gases-such as nitrogen and methane can be balanced against the beneficial effects of intermediate components to maintain a relatively stable MMP.

The selected correlations to be studied is as follows:

Correlation	Equation
W.F Yellig and R. S. Metcalfe (1980)	MMP_{pure}= 1833.717 + 2.2518055T + 0.01800674T^2- $\frac{103949.93}{T}$
Sebastian et al (1985)	$MMP_{pure\ CO2}$ = 1.0 -2.13 $\times\ 10^{-2}$ (T_{cM}- 304.2) + 2.52 $\times\ 10^{-4}$ (T_{cM}- 304.2)^2 - 2.35 $\times\ 10^7$ ($T_{cM} - 304.2)^3$ Where $T_{cM} = \sum w_i \ \times T_{ci}$
Cronquist	MMP = 15.988$T^{0.744206+0.0011038M_{c5+}+0.0015279XC1}$
A. M. Maklavani (2001)	MMP = 43.664 – 4.542α + 0.689α^2 - 0.132β $\alpha = \frac{X_{c2-c6}^{1.72785} \times X_{C1}^{0.1}}{(1.8T+32) \times M_{C7+}}$ $\beta = Y_{C2+}^{(1.064+0.00686M_{C2+}}$

Where:

T – reservoir temperature (F°)

TcM = pseudocritical temperature

Wi= mole craction of component i

Ti= critical temperature of component i

MC5+ = molecular weight of C5+

XC1 = sum of mol fraction of methane and nitrogen

MC2-6 = mol fraction of C2-6

MC7+ = molecular weight of C7+

CHAPTER 3

3. METHODOLOGY

Out of the 16 (sixteen) correlations, a few that are simple are chosen. Generous amounts of datapoints are available in hand collected from the litearture review. This study will be assessing four correlations namely: Sebastian (1985), Maklavani (2001), Cronquist (1977) and Yellig (1980) correlations. The equation can be seen in Table X. These correlations were used because these correlations include the Temperature in the equation.

A data set of experimentally measured MMP's corresponding carbon dioxide/crude oil compositional information was constructed to evaluate the reliability of the correlations. A total of 72 MMP measurements obtained from the literature were used as the data set. Compositional information for each of these 72 carbon dioxide/oil pairs and corresponding literature reference sources were available in the APPENDIX.

The 72 MMP measurements data were compared to the MMP calculated from the correlations. The error between the predicted MMP and true MMP were calculated and reported. The data were arranged according to its parafinicity factor from 13.64 to 11.06 to represent high paraffin content to high aromatic content.

In the latter part, the parafinicity factor was calculated for every data by using Eq. (1). For improved equation, parafinicity factor was included in the Yellig et Metcalfe equation. Next, the improved equation was fit into the data set and the improved equation was compared with the true MMP data. The average error and standard deviation is plotted to graphically show the improvement on the correlation.

result and discussion

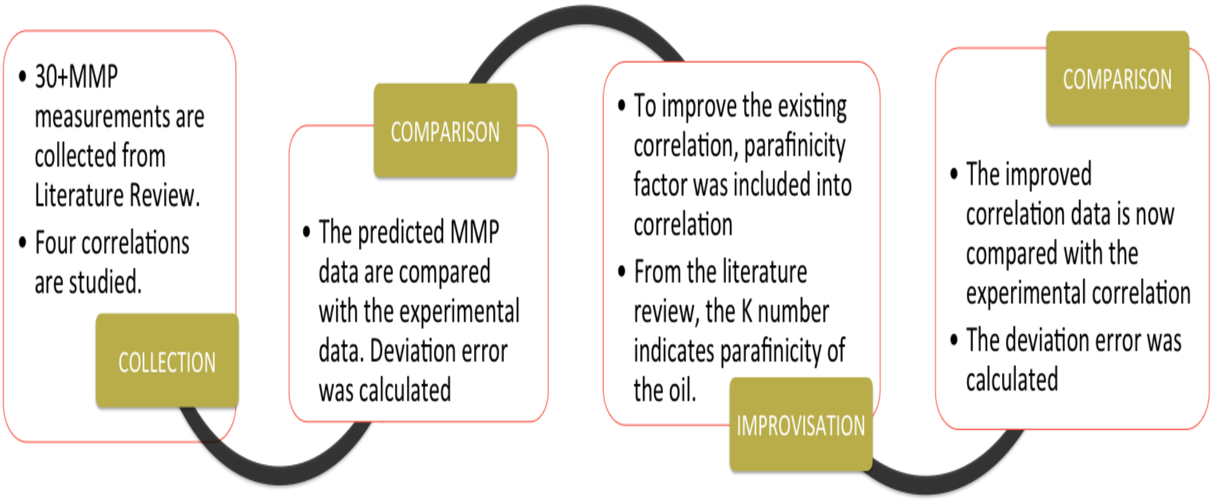


Figure 5: Methodology Workflow

3.1 Gant Chart

Table 5: FYP I Timeline

TIMELINE FYP I														
Activities/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Project topic selection	🟨													
Thorough research on topic		🟨												
Topic Finalization			🟨											
1. Literature Review of Topic			🟨	🟨	🟨	🟨	🟨							
2. EOR (Gas Miscible Injection)			🟨	🟨	🟨	🟨	🟨							
3. Minimum Miscibility Pressure			🟨	🟨	🟨	🟨	🟨							
4. Factors affecting MMP			🟨	🟨	🟨	🟨	🟨							
5. MMP Correlations			🟨	🟨	🟨	🟨	🟨							
6. Analytical and Experimental Method of determining MMP			🟨	🟨	🟨	🟨	🟨							
7. Parafinnicity			🟨	🟨	🟨	🟨	🟨							
Submisson of Extended Proposal						🟨								
Proposal Defence								🟨	🟨					
Elaborate research on selected Correlations										🟨	🟨			
Regression Analysis of 100 datapoints												🟨		
Submission of Interim Draft													🟨	
Submission of Interim Report														🟨

Table 6: FYP II Timeline

TIMELINE FYP II														
Activities/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Compliation of measurements from Lit Review	🟨	🟨	🟨											
Comparison between calculated MMP with true MMP			🟨	🟨	🟨	🟨								
Improvement on the correlation to reduce the error					🟨	🟨	🟨	🟨						
Submission of progress report									🟨					
Analysis result										🟨				
Poster Presentation										🟨				
Completion of the report											🟨			
Submission of Technical Paper											🟨			
Submission of softbound report												🟨		
Oral presentation (VIVA)													🟨	
Submission of Project Dissertation														🟨

3.4 Key Milestone

Table 7: Key Milestone for FYP I

Details/Month	May	June	July	August
Literature review of the topic 1. Factors that affect MMP 2. Available correlations 3.Gathering of datapoints	▨	▨		
1. Selection of Correlations 2. Detailed study on each correlations 3. Gathering Relevant Datapoints for each correlations		▨	▨	
1. Tabulation of various data for comparisons				▨

Table 8: Key Milestone for FYP II

Details/Month	September	October	November	December
1. Translation of data into graph	▨			
2. Analysis of calculated MMP against experimental MMP	▨			
3. Analysis on the standard deviation an error	▨			
1. Analysis of C7+		▨		
2. Incorporation of Parafinicity into correlation		▨		
1. Study on the new improved correlation			▨	
2. Analyzing result and discussion			▨	
3. Finalizing result and discussion				▨

CHAPTER 4

4. RESULTS AND DISCUSSIONS

4.1 Comparison between 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 Cronquist, Yellig, Maklavani and Sebastian et al correlations. A total of 72 MMP measurements obtained from the literature were used as the datapoints. Compositional information for each of these carbon dioxide/oil pairs is tabulated into a table for easy comparison. Table 9 tabulates the comparison between the experimental MMP and predicted MMP.

REFERENCE	SLIM TUBE TRUE MMP	MAKLAVANI	ERROR	SEBASTIAN	ERROR	CRONQUIST	ERROR	YELLIG	ERROR
[4]	2770	3887	40.32490975	2621.897382	5.346664899			2581.375134	6.809561951
[4]	3500	4068	16.22857143	3628.641512	3.67547177			3103.704188	11.32273748
[23]	3160	4567	44.52531646	4790	51.58227848	4732	49.74683544	3106	1.708860759
[23]	2100	3556	69.33333333	3303	57.28571429	1687	19.66666667	1199	42.9047619
[23]	2120	2990	41.03773585	3542	67.0754717	4514	112.9245283	2197	3.632075472
[12]	1850	2090	12.97297297	1807.054817	2.321361224	2208.481113	19.37735744	1631.150099	11.82972439
[12]	3502	3222	7.995431182	3032	13.42090234	4402	25.69960023	2902	17.13306682
[12]	1700	3424	101.4117647	3890.207973	128.8357631	1863.644678	9.626157554	1708.676751	0.510397095
[12]	2450	2555	4.285714286	1971	19.55102041	2676	9.224489796	1933	21.10204082
[12]	1500	2144	42.93333333	1781.504798	18.7669865	1839.811813	22.65412084	1784.518719	18.96791462
[21]	2930	2544	13.17406143	2770	5.460750853	3544	20.9556314	2852	2.662116041
[21]	2032	3650	79.62598425	3199	57.43110236	3397	67.17519685	2053	1.033464567
[21]	1550	1598	3.096774194	1653	6.64516129			1631	5.225806452
[21]	2719	3435	26.33321074	3543	30.30525929	3152	15.92497242	2718	0.036778227
[21]	1708	1708	0	1645	3.68852459	1847	8.138173302	1631	4.508196721
[6]	2100	2344	11.61904762	2139.72992	1.891900942	2290.728679	9.082318038	2005.290338	4.509983929
[6]	1100	1124	2.181818182	1313.03351	19.36668271	1526.877304	38.80702762	1199.46525	9.042295455
[6]	1130	2455	117.2566372	1678.395563	48.53058078	1979.742143	75.19841975	1631.150099	44.34956627

[7]	1290	1432	11.00775194	1313.03351	1.785543398	1526.877304	18.36258169	1199.46525	7.018197674
[7]	1500	1432	4.533333333	1580.965682	5.397712133	1859.091665	23.93944433	1524.400387	1.626692483
[7]	1550	1543	0.451612903	1652	6.580645161	1871	20.70967742	1631	5.225806452
[7]	3670	3421	6.784741144	3108.054451	15.31186783	3929.671127	7.075507549	2978.211532	18.84982203
[9]	2134	3111	45.78256795	2346.320838	9.949430082	2943.56851	37.9366687	2244.959459	5.19959976
[22]	2330	3723	59.78540773	2988.421452	28.25843143	3360.508075	44.22781436	2244.959459	3.649808631
[19]	3100	3677	18.61290323	4033.40327	30.1097829	4519.330695	45.78486112	2978.211532	3.928660269
[11]	1300	3211	147	1421.899783	9.376906407			1354.297311	4.176716259
[20]	1100	1232	12	1768.568403	60.77894571			1027.234543	6.615041566
[16]	1800	3872	115.1111111	3067	70.38888889			1631	9.388888889
[24]	1572	1654	5.216284987	1792	13.99491094	1790	13.86768448	1354	13.86768448
[13]	1274	1243	2.433281005	1355	6.357927786	1432	12.40188383	1263	0.863422292
[11]	1535	1334	13.09446254	1610	4.885993485	1960	27.68729642	1497	2.475570033
	1250	1244	0.48	1289	3.12			620	50.4
[14]	1900	2413	27	2024	6.526315789	1683	11.42105263	1696	10.73684211
	1850	2111	14.10810811	1722.824712	6.874339908			1721.423493	6.950081478
[12]	2300	2522	9.652173913	2020.338893	12.15917855			1883.639042	18.10265036
[12]	2314	3211	38.76404494	2676.522083	15.66646858			2065.497739	10.73907782
46]	2400	3223	34.29166667	2382.90252	0.712395004			2065.497739	13.9375942
[6]	2100	2111	0.523809524	2295.443422	9.306829621			2065.497739	1.642964798
[6]	2450	2135	12.85714286	2043.61811	16.58701593			2065.497739	15.69396983
[6]	2600	2121	18.42307692	2111.995496	18.76940401			2137.415328	17.79171816
[6]	2400	2542	5.916666667	2485.432635	3.559693127			2304.688811	3.971299521
[31]	2750	2890	5.090909091	2360.377335	14.1680969			2364.49702	14.01829017
[14]	2450	2541	3.714285714	2458	0.326530612			1631	33.42857143
[25]	1505		100	1808	20.13289037	1889	25.51495017	1696	12.6910299
[15]	1950		100	1907	2.205128205	2064	5.846153846	1696	13.02564103
[17]	1750		100	2151	22.91428571	2353	34.45714286	1664	4.914285714
[17]	1800		100	2560	42.22222222	2974	65.22222222	1670	7.222222222
[33]	1100		100	1188	8	1244	13.09090909	1027	6.636363636
[33]	1200		100	1368	14	1444	20.33333333	1279	6.583333333
[33]	1720		100	1728	0.465116279	1842	7.093023256	1696	1.395348837
[33]	1700		100	1716	0.941176471			1497	11.94117647
[33]	1900		100	2179	14.68421053			2005	5.526315789
[33]	1900		100	2179	14.68421053			2005	5.526315789
[33]	1711		100	1782.415763	4.173919497	1855.349819	8.436576189	1784.518719	4.296827542
[33]	1700		100	1871.647711	10.0969242	2035.505563	19.73562137	1734.125391	2.007375969

[33]	2500		100	2909	16.36	4658	86.32	2317	7.32
[33]	2000		100	1376	31.2	1703	14.85	1247	37.65
[33]	1150		100	1245	8.260869565			1116	2.956521739
[31]	1375		100	1516	10.25454545			1469	6.836363636
[31]	1875		100	1893	0.96			1884	0.48
[31]	2350		100	2388	1.617021277			2388	1.617021277
[31]	2270	4332	90.83700441	3616.889257	59.33432852			3093.380378	
[31]	2280	4311	89.07894737	2238.932526	1.801204983		28.87880812	2280.791378	0.03470958
[32]	2680	3799	41.75373134	2621.897382	2.168008123			2581.375134	3.680032315
[32]	4136	4063	1.764990329	3616.889257	12.55103343			3093.380378	25.20840479
[32]	3100	4332	39.74193548	3616.889257	16.67384701			3093.380378	0.2135362
[32]	2675	2655	0.747663551	4478.028493	67.40293433			2965.52228	10.86064597
[32]	2516	2451	2.583465819	4478.028493	77.98205459			2965.52228	17.86654529
[27]	1894	1880	0.739176346	4478.028493	136.4323386			2965.52228	56.57456598
[43]	1654	2019	22.06771463	2725.171434	64.76248089			2642.269703	59.75028437
[43]	1847	2024	9.583107742	2725.171434	47.5458275			2642.269703	43.05737431
AVERAGE ERROR			47.1249253		22.84452718		14.87880812		12.04943659

Table 9: Comparison between Calculated MMP and True MMP

Empty tables show that the MMP could not be computed due to insufficient of data. This table is translated into scatter plot for easy comparison. The Figures below show the result:

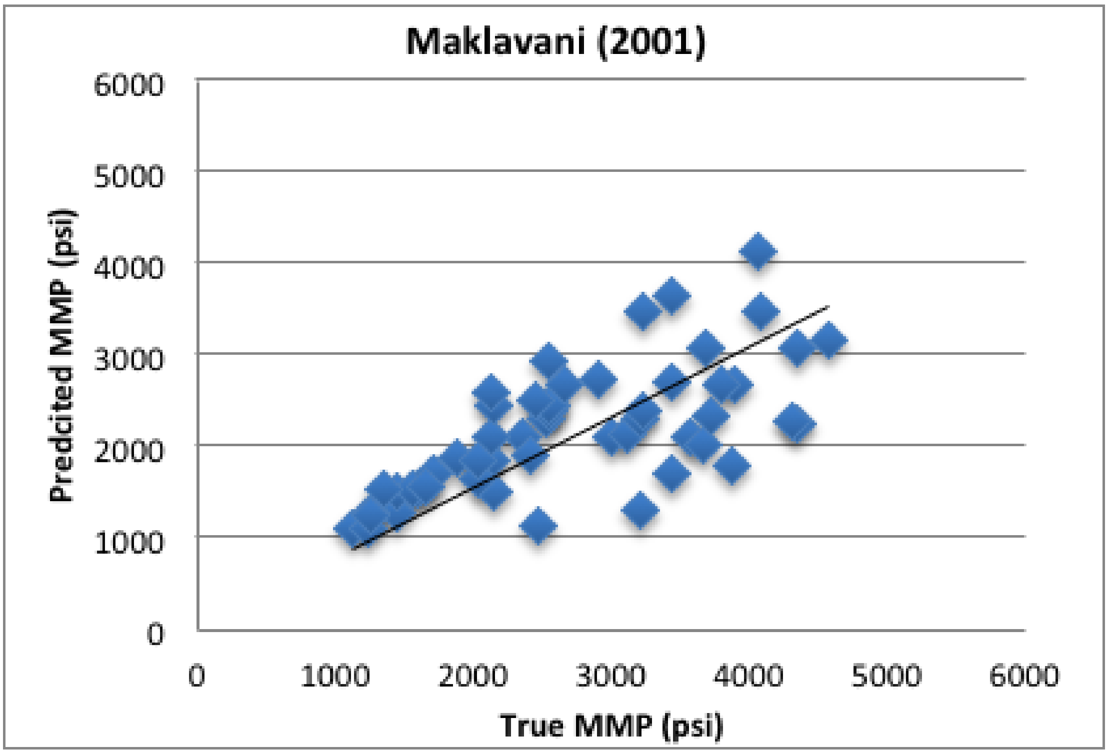


Figure 6: Maklavani's correlation predicted vs True MMP

Figure 6 shows a comparison between the MMP calculated with the MMP correlation. The average absolute deviation was determined to be about 47% which is considered as the least precision compared with the other correlations. This is due to the fact that Maklavani was formulated to be used with impure CO_2 injetion. In the calculation the datapoint for injected gas is ignored and is assumed to be 100% CO_2 without any trace elements. In this correlation the parameter β refers to the gas composition effect on the MMP. It is evident that MMP decreases with increasing C_{2+} content but the effects of MC_{2+} are too small compared with C_{2+}.

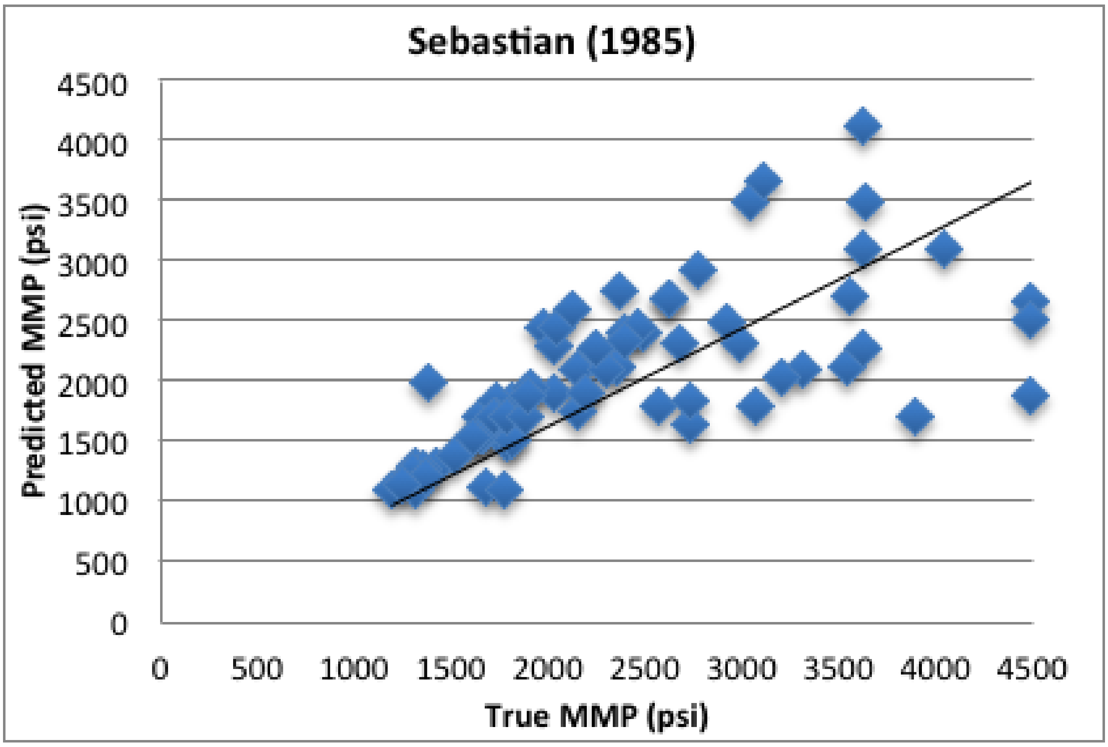


Figure 7: Sebastian Correlation's predicted MMP vs True MMP

Based on Fig. 7, quarter of the 72 data had error beyond 22.84% for Sebastian correlation. This is because the Sebastian is used to correlate impure drive gas to the MMP of pure CO_2. The correlation is useful as a screening guide for estimating the MMP of gases containing up to 55mol % impurities. Thus, Sebastian also appeared not applicable to be used to predict the MMP.

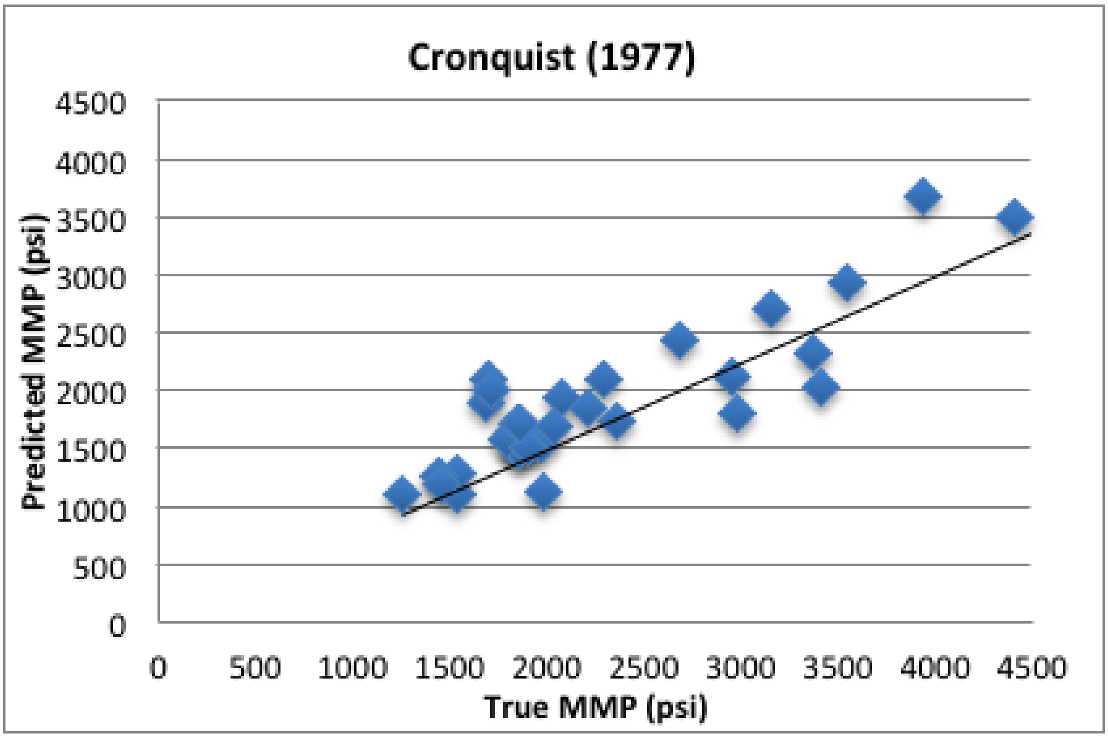


Figure 8: Cronquist Correlation's predicted MMP vs True MMP

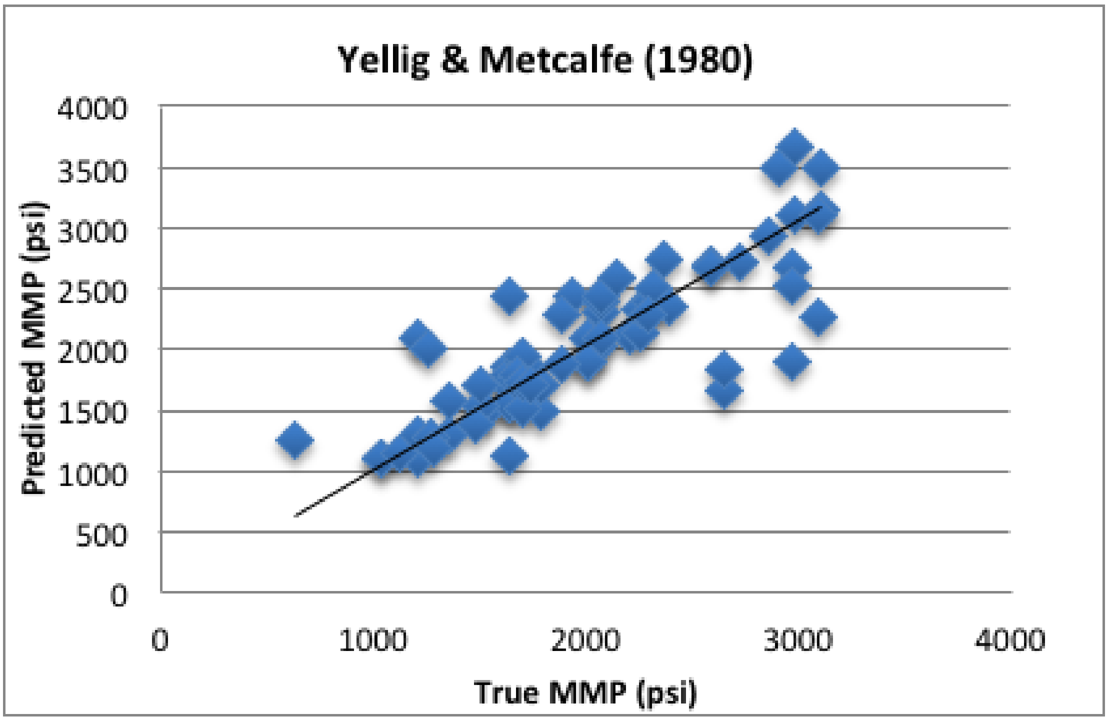


Figure 9: Yellig Correlation’s predicted MMP vs True MMP

Among the empirical correlations, Cronquist and Yellig seems to be more reliable as a first estimate as the average deviation were 14.23% and 12.01% respectively which were the least among the four correlations. Not many data found in the literature review can correlate to Cronquist, as it wants specific number of C_5. Most of the data found lump the number of C_5 together with several other C+s. But the result obtained for Cronquist is very promising though it is not really precise.

Cronquist and Yellig correlation seems to be reliable on the parafinicity of the crude as the deviation of the predicted from the true MMP is small for high parafinicity factor crude. This also indicates that Yellig and Cronquist correlation were applicable for paraffinic crude. It was suspected that insufficient description of heavier hydrocarbon caused the deviation error between the prediction and true MMP. Volatile oil phase behavior is particularly sensitive to the composition and properties of the heaviest components. Cronquist correlation only depends on the molecular weight of heavy fraction to do the prediction, while Yellig only depends on the Temperature. Inadequate characterization of heavier hydrocarbon reduces the accuracy of MMP predictions. It would be very fitting to characterize the heavier components of the hydrocarbons (C_{7+}) and incorporate it into Yellig. Incorporation of the Parafinnic characteristic will be fully explained later in 4.2 sections.

4.2 Incorporating Paraffinicity into correlation

As planned before, to characterize the heavier components (C_{7+}), K factor is used. Equation (1) is used and parafinicity factor for every crude oil is calculated. 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. From the literature review, it is found that paraffinic crude oil affects the MMP, and in this study, varying number of K factor is used to confirm the hypothesis.

The newly found K factor is then incorporated into Yellig et Metcalfe correlation resulting to this equation:

$$MMP_{pure} = 1833.717 + 2.2518055T + 0.01800674T^{2} - \frac{103949.93}{T} + K^{2.622}$$

Where:
T = Temperature (°F)
K = Paraffinicity (refer to equation (1))

The result of the new improved correlation is tabulated into a table. It significantly shows that a higher number of K factor affects the MMP reading. The results is in accordance to a study by Fadzliana (2011), which shows that paraffnicity of oil affects the MMP. This is because high K factor indicates a high number of paraffin content which is more solubke in carbon dioxide, hence loweing the number of MMP between the crude and injected gas.

Table below summarizes the comparison between the experimental MMP and Predicted MMP for improved equation:

Table 10: Comparison between the experimental MMP and Improved MMP

REFERENCE	K FACTOR	SLIM TUBE TRUE MMP	YELLIG	ERROR	CORRECTED	ERROR
[4]	11.76546586	2770	2581.375134	6.809561951	2670.633685	0.719937373
[4]	12.08973159	3500	3103.704188	11.32273748	3197.495617	8.64298237
[23]	13.16954518	3160	3106	1.708860759	3215.611963	1.759872244
[23]	12.05271682	2100	1199	42.9047619	2134.54	1.644761905
[23]	12.05271682	2120	2197	3.632075472	2290.268885	8.03155117
[12]	12.01505565	1850	1631.150099	11.82972439	1723.888666	6.816828843
[12]	11.85742098	3502	2902	17.13306682	2992.533689	14.54786726
[12]	11.77399289	1700	1708.676751	0.510397095	1798.053202	5.76783541
[12]	11.77399289	2450	1933	21.10204082	2022.376451	17.45402239
[12]	11.59648969	1500	1784.518719	18.96791462	1500	0
[21]	11.54964537	2930	2852	2.662116041	2938.297871	0.283203773
[21]	13.51450745	2032	2053	1.033464567	2167.899464	6.687965768
[21]	11.89819502	1550	1631	5.225806452	1722.101711	11.10333619
[21]	12.012509	2719	2718	0.036778227	2810.702757	3.372664829
[21]	11.31127797	1708	1631	4.508196721	1714.080341	0.35599188

[6]	11.7867917	2100	2005.290338	4.509983929	2094.843886	0.245529239
[6]	12.37119706	1100	1199.46525	9.042295455	1297.273201	17.9339274
[6]	12.37119706	1130	1631.150099	44.34956627	1728.95805	53.00513719
[7]	12.37119706	1290	1199.46525	7.018197674	1297.273201	0.563814066
[7]	12.37119706	1500	1524.400387	1.626692483	1622.208339	8.147222579
[7]	11.76941469	1550	1631	5.225806452	1720.313141	10.9879446
[7]	11.91942845	3670	2978.211532	18.84982203	3560	2.997275204
[9]	11.91940459	2134	2244.959459	5.19959976	2336.357273	9.482533899
[22]	11.67984158	2330	2244.959459	3.649808631	2333.038003	0.130386393
[19]	11.67984158	3100	2978.211532	3.928660269	3066.290076	1.087416912
[11]	11.35786127	1300	1354.297311	4.176716259	1438.002105	10.61554657
[20]	12.86657403	1100	1027.234543	6.615041566	1132.295522	2.935956587
[16]	12.08001077	1800	1631	9.388888889	1724.654071	4.185884947
[24]	12.08592327	1572	1354	13.86768448	1447.737605	7.904732478
[13]	11.91	1274	1263	0.863422292	1354.266465	6.300350471
[11]	11.68	1535	1497	2.475570033	1585.080721	3.262587668
	11.81	1250	620	50.4	0	0
[14]	11.81	1900	1696	10.73684211	1785.875085	6.006574481
	11.81	1850	1721.423493	6.950081478	1811.298578	2.091968783
[12]	11.81	2300	1883.639042	18.10265036	1973.514127	14.19503798
[12]	11.81	2314	2065.497739	10.73907782	2155.372824	6.855106996
46]	11.81	2400	2065.497739	13.9375942	2155.372824	10.192799
[6]	11.81	2100	2065.497739	1.642964798	2155.372824	2.636801148
[6]	11.81	2450	2065.497739	15.69396983	2155.372824	12.02559902
[6]	11.81	2600	2137.415328	17.79171816	2227.290413	14.33498413
[6]	11.81	2400	2304.688811	3.971299521	2394.563896	0.226504319
[31]	11.81	2750	2364.49702	14.01829017	2454.372105	10.75010527
[14]	11.51	2450	1631	33.42857143	2534.733	3.458489796
[25]	12.32158151	1505	1696	12.6910299	1793.094422	19.1424865
[15]	12.17832839	1950	1696	13.02564103	1791.047512	8.151409628
[17]	11.92612849	1750	1664	4.914285714	1755.491776	0.313815796
[17]	11.60381327	1800	1670	7.222222222	1757.036723	2.386848708
[33]	11.24	1100	1027	6.636363636	1109.12894	0.829903661
[33]	11.24	1200	1279	6.583333333	1361.12894	13.42741169
[33]	11.24	1720	1696	1.395348837	1778.12894	3.379589551
[33]	13.63742131	1700	1497	11.94117647	1613.810578	5.069965992
[33]	13.63742131	1900	2005	5.526315789	2121.810578	11.67424095
[33]	13.63742131	1900	2005	5.526315789	2121.810578	11.67424095
[33]	11.78420041	1711	1784.518719	4.296827542	1874.036399	9.528720001
[33]	11.62123888	1700	1734.125391	2.007375969	1821.400405	7.141200292
[33]	11.6000012	2500	2317	7.32	2403.984634	3.84061466
[33]	11.59071229	2000	1247	37.65	1333.857765	33.30711176
[33]	11.8	1150	1116	2.956521739	1205.736477	4.846650208
[31]	11.8	1375	1469	6.836363636	1558.736477	13.3626529
[31]	11.8	1875	1884	0.48	1973.736477	5.265945461
[31]	11.8	2350	2388	1.617021277	2477.736477	5.435594783
[31]	12.01244676	2270	3093.380378		3186.082259	40.35604667
[31]	11.21164374	2280	2280.791378	0.03470958	2362.543201	3.620315845

[32]	12.39807035	2680	2581.375134	3.680032315	2679.570539	0.016024683
[32]	11.79352815	4136	3093.380378	25.20840479	3183.027202	23.04092839
[32]	10.73395256	3100	3093.380378	0.2135362	3168.897272	2.22249265
[32]	13.7378259	2675	2965.52228	10.86064597	3083.904535	15.28615085
[32]	13.7378259	2516	2965.52228	17.86654529	2515.25	0.029809221
[27]	13.7378259	1894	2965.52228	56.57456598	1987.57	4.940337909
[43]	11.89904611	1654	2642.269703	59.75028437	2341.42	41.56106409
[43]	11.89904611	1847	2642.269703	43.05737431	2063.53	11.72333514
AVERAGE ERROR				12.04943659		8.610196443

Table 11: Improved Correlation MMP vs True MMP

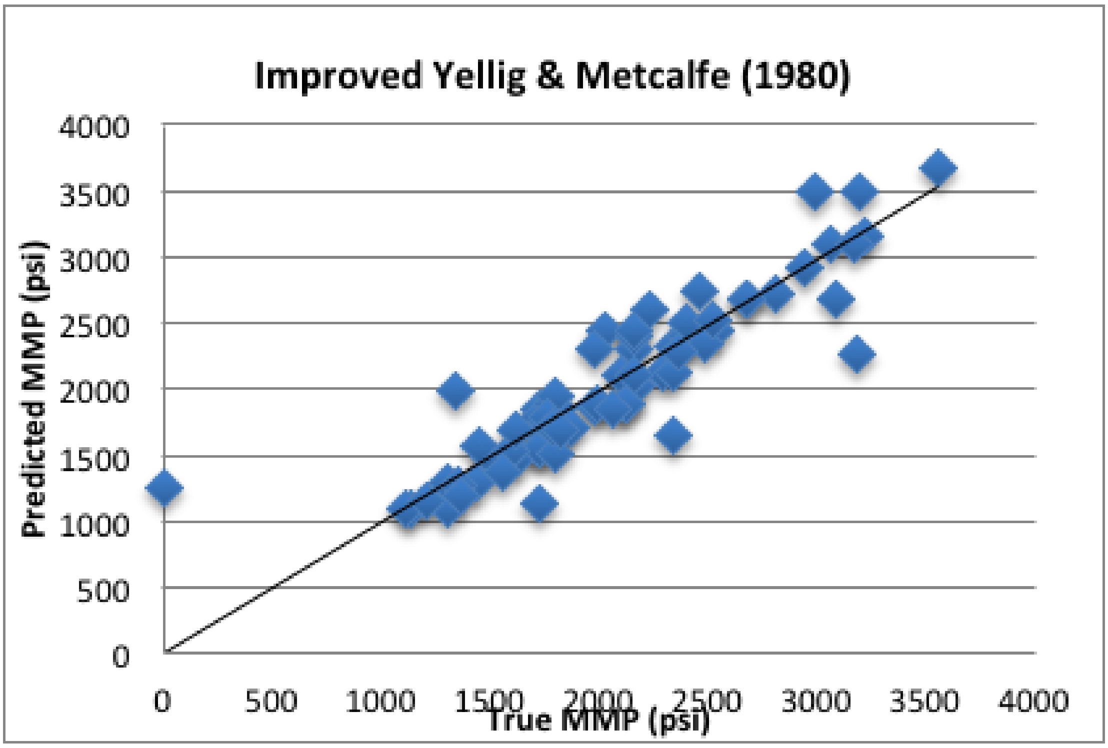


Figure 9: Improved Correlation vs True MMP

Based on Fig. 5, the improved equation had reduced the error to 8.61% from 12.01%. It was believed that the improved correlation was more comprehensive as the data used was widespread and extensive. Characterizing the heavy components provides an added value to the available Yellig et Metcalfe correlation. Even though the reduction is small, it can be resolved that by including the parafinicity factor into the correlation can improve the correlation.

CHAPTER 5

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The objective of this study was to assess the Maklavani (2001), Cronquist (1977) and Yellig (1980) and Sebastian et al (1985) correlations. From a holistic observation, none of the MMP correlations evaluation in this study would appear sufficiently accurate. All four correlations produce deviation from the true MMP. 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. Maklavani correlation produces erroneous prediction due to its purpose is to correlate impure CO_2 instead of pure.
3. The use of Yellig and Cronquist correlation at low temperature (below 1200F) 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.
4. Yellig correlation can be further improved by including the parafinicity factor and reduce the error to 8.61% from 12.01%.

The study achieved the objective which are to reduce error from availabe correlation and to incorporate paraffinicity into availble correlation.

5.2 Recommendations

It is suggested that more datapoints from different part of this world is added during the development of correlation so that the correlation is more global and can fit any type of fluid. Apart from that, the next study should explore the effect of

Asphaltic and Aromatic characteristic C_{7+} to MMP calculation. It is hoped that an experimental procedure can be done alongside correlation study to further improve the calculation.

CHAPTER 6

6. REFERENCE:

1. 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).
2. Ahmadi, T. (1997). A Generalized Methodology for Minimum Miscibility Pressure. Rio de Janeiro: Society of Petroleum Engineers (SPE 39034).
3. Alston, R.B., Kokolis, G.P. and James, C.F. (1985). CO_2 Minimum Miscibility Pressure: A correlation for Impure CO_2 Streams and Live Oil Systems. SPE Journal, Vol. 25, No. 2,, 268-274.
4. 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.
5. B.E. Eakin and F.J. Mitch. (1988). Measurement and Correlation of Miscibility Pressures of Reservoir Oils. Houston: SPE 18065.
6. Benham. A.L., “Miscible Fluid Displacement- Prediction of Miscibility”, The Ohio Oil.Co.
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. Cronquist, C.: (1977). Carbon Dioxide Dynamic Miscibility with Light Reservoir Oils, Proc., Fourth Annual U.S. DOE Symposium, Tulsa (1977).
9. 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).
10. Enrich H.E.,(1986) : A Combined Condensing/Vaporizing Mechanism in the Displacement of Oil by Enriched Gas, paper SPE 15493 presented at the 1986 SPE Annual Technical Conference and Exhibition, New Or- leans, 5–8 October.

11. Glaso, O.: (December 1985) .Generalized Minimum Miscibility Pressure Correlation, SPEJ 927.
12. Jaubert J.N., Laurent A. (2001). A crude oil data bank containing more than 5000 PVT and gas injection data: Journal of Petroleum Science and Engineering.
13. Johnson, J.P and Colling, J.S,: Measurement and Correlation of CO_2 Minimum Miscibility Pressure,Paper SPE 9790.
14. Jacobsen, H.A.: “ Acid Gases and Their Contribution to Miscibility, “ J. Cdn. Pet.Tech 56.
15. Johns, R.T. “ Miscible Gas Displacement of Multicomponent Oils”. Soc. Of Petroleum Engineer 30798-PA
16. Kechut, Nor Idah., “New Experimental Approaches in Minimum Miscibility (MPP) Determination”, Soc. Of Petroleum Engineers.
17. K. Luo and G. Chen, “ application of the Gas-Oil Interfacial tension to Determine Minimum Miscibility Pressure”, SPE Paper, 2001-135-EA
18. Metcalfe, R.S.: “Effects of Impurities on Minimum Miscibility Pressure and Minimum Enrichment Levels for CO_2 and Rich Gas Displacements,” SPE 9320 Soc. Of Petroleum Engineers.
19. Stalkup, F.I., (1980) *Miscible Displacement; Monograph Volume 8,* Soc. Of Petroleum Engineers.
20. Sebastion, H.M.,Correlation of Minimum Miscibility Pressure for Impure CO_2 Streams, Soc. Of Petroleym Engineers.
21. Whorton L.w., “ Multicontact Miscibility of CO_2 gas injection”, Soc of Petroleum Engineers
22. Whorto, L.P., Kieschne E.R., and Dyes, A.B. (December 1952).: Method for Pro- ducing Oil by Means of Carbon Dioxides, U.S. Patent No. 2,623,596
23. 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
24. Yellig, W.F. and Metcalfe, R.S: “Determination and Prediction of CO_2 minimum miscibility pressures”, J. Pet. Technol.
25. Yellig, W.F., Metcalfe, R.S.(1990), Mechanism of Oil Displacement by Carbon Dioxide, Soc. Of Petroleum Engineers.

26. Yuan H.., (2006). Improved MMP Correlations for CO_2 Floods using Analytical Gasflooding Technique. SPE, Petrotel Inc.
27. Zahidah Md. Zain, Noraini Ahmad, DM Anwar Raja DM Ibrahim. (1999). New Experimental Approaches in Minimum Miscibility Pressure (MMP) Determination. Kuala Lumpur: SPE