EVALUATION OF METHODS TO LOWER MMP OF CRUDE OIL IN GAS MISCIBLE DISPLACEMENT

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
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Approved by,

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July 2013

CERTIFICATION 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.

HEW ZHONG YING

ABSTRACT

As the crude oil production declining over the years, various efforts have undertaken to increase the oil recovery through implementation of EOR projects. Among several methods of EOR, gas injections were found to be the most favourable process. In this project, CO_2 miscible flooding is chosen for its volumetric sweep efficiency and lower minimum miscibility pressure (MMP). In the miscible displacement, minimum miscibility pressure is a key parameter to achieve miscibility between gas and oil. The key problem in this project is the initial reservoir pressure for Malaysia oil field is too low to achieve miscible displacement and thus it not recommended to implement CO_2 miscible flooding. Therefore, this project will focus on studying the potential methods to reduce minimum miscibility pressure to ensure miscible displacement can be achieved in Malaysia oil field.

In this study, the effects of injected gas composition on Dulang's crude oil are investigated through 1D Slim Tube simulation by ECLIPSE 300 reservoir simulator. Impure CO_2 gas streams and synthetic gas streams are investigated in this project. Studies has found that the addition of H_2S, C_2, C_3, C_4 and C_5 hydrocarbon components can lower the CO_2 minimum miscibility pressure (MMP) of crude oil. On the other hand, 16 synthetic gas samples were simulated and evaluated and the best synthetic gas sample will be selected. Gas 15 has provided lowest MMP which is around 1617 psia.

ACKNOWLEDGMENTS

There was a saying: "No one walks alone on the journey of life, just where you start to thank those that joined you, walked beside you, and helped you along the way". Hence, the author would like to take this opportunity to express her very great appreciation to Mr. Iskandar B Dzulkarnain for his continuous guidance and encouragement and support throughout from the initial until final stage of the project. He had been very kind and patient in guiding and assisting me from time to time in making this project successful.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY

The rising in crude oil price coupled with declining of oil production have fasten the effort prolong the production life of reservoir. Primary and secondary oil recovery methods are no longer adequate as they can only recover around one third of Original Oil In Place (OOIP) (Larry et al. 1992). Thus, enhance oil recovery (EOR) has become intense interest among petroleum industry experts. According to Samsudin (2005), the estimated oil-in-place from producing field in Malaysia as of January 2005 is about 17.0Bstb. On the other hand, the estimated ultimate recovery (EUR) of 5.62 Bstb turns to an average recovery factor of 33 percent for producing fields in Malaysia. Thus, it is suitable to implement EOR techniques to increase the oil production.

Among the enhance oil recovery (EOR) techniques, CO_2 flooding was identified as the most favourable process. Carbon dioxide is used for enhance oil recovery since 1950, several studies have found that carbon dioxide injection could become one of the important methods in tertiary oil recovery drives. Carbon dioxide flooding has received considerable attention in the petroleum industry due to its high displacement efficiency and relatively low cost (Yellig and Metcalfe 1980, Hui 1995, Jessen, Michelsen, and Stenby 1998). It has been implemented either as miscible, near-miscible or immiscible displacement while miscible displacement has been emphasized in recent years for its high oil recovery (Koch Jr. and Hutchinson Jr. 1958). Recent activity in miscible flooding has focused on the CO2 miscible process for its volumetric sweep efficiency and unit displacement efficiency and it is the best if applied to light and medium gravity crude oils (Azman Ikhsan 1997).

The mechanisms of CO_2 flooding that contribute to improve oil recovery are reduction in crude oil viscosity, oil swelling, interfacial tension reduction. In order to achieve miscible displacement, a pressure level in most reservoir oils is at a pressure greater a certain minimum (Stalkup 1978). This minimum pressure is known as minimum miscibility pressure (MMP) where it is defined as the lowest or minimum pressure where miscible displacement of reservoir oil can be achieved by CO_2 injection.

For the past decade, CO_2 was commonly separated from natural gas and vented. With the global concerns on green house gas (GHG) emissions, it has urged a considerable interest in CO_2 capture and sequestration (CCS) as a potential technology that can achieve significant CO_2 emission reductions while increasing oil production through CO_2 flooding. The IPCC has defined that enhanced oil and gas recovery via CO_2 injection as a recognized form of CCS (Sweatman et al. 2011).

1.2 PROBLEM STATEMENT

The minimum miscibility pressure (MMP) is always a key parameter in designing miscible flooding. Miscible displacement can be achieved when the miscible gas is injected into reservoir at a pressure higher than MMP and the MMP has to be lower than reservoir pressure. Hence, candidates' reservoir must be capable of withstanding at average reservoir pressure greater than MMP.

According to Hui (1995), the estimated CO_2 MMP for Malaysian crude oil is higher than reservoir pressure which is in a range of 2300 to 4380 psig. Additionally, equation of State (EOS) shows that the simulated CO_2 MMP for Dulang crude oil is estimated to be 3230 psig which were higher than its initial reservoir pressure of 1800 psig (Zain et al. 2001) and it is impossible to achieve miscibility under this condition.

As current reservoir pressure is lower than MMP, miscible flooding is rarely applied in Malaysia oil field. Thus, methods to reduce the MMP of crude oil are needed in order to achieve miscibility at Malaysian oil fields. Several injected gas compositions' scenarios have been studied to lower the MMP of crude oil in order to achieve miscible displacement. Thus, evaluation on effect of injected gas compositions to reduce MMP of crude oil is needed when screening for miscible flooding projects in Malaysia oil field.

1.2.1 Significant of Project

Study on the minimum miscibility pressure (MMP) of crude oil will be simulated to determine the reduction in MMP by varying the gas composition. The best injected gas composition and MMP is selected to accommodate feasibility of CO_2 miscible flooding in Malaysia oil field. ECIPSE 300 software will be used to perform studies on MMP determination and effect of gas composition on MMP.

1.3 OBJECTIVES AND SCOPE OF STUDY

The objectives of this project are:

- To investigate and evaluate the effects of injected gas composition on MMP.
- To determine the MMP of Malaysian crude oil samples at attainable temperature and varying pressure
- To learn ways to simulate with ECLIPSE 300 to determine MMP of crude oil.

1.3.1 The Scope Of Study

In this project, the minimum miscibility pressure (MMP) determination and evaluation of all known methods to reduce MMP are studied. The parameters and factors that influence MMP are identified. ECLIPSE 300 was used to simulate based on 1-D slim tube model where it is running in fully implicit mode. A data file from slim tube model is set as the base case and used to compare the result before and after simulation. Due to the time and information constrain, the author has decided that to limit the scope of study on the effects of injected gas compositions on MMP.

With known reservoir fluid composition, reservoir temperature and reservoir pressure, the simulation is run to investigate field recovery factor (FOE) by varying pressure and injected gas compositions. A function of pressure and FOE is plotted to determine the MMP.

1.4 RELEVANCY OF PROJECT

CO_2 flooding is one of the favourable Enhanced Oil Recovery (EOR) methods due to its high displacement efficiency and relatively low cost. Under CO_2 miscible flooding project, MMP is an important parameter in screening and selecting suitable reservoir. Thus, simulation study on miscible flooding is carried out to understand the effect of injected gas compositions on MMP. This project will assist the utilization of miscible flooding in Malaysia oil field.

1.5 FEASIBILITY OF THE PROJECT WITHIN THE SCOPE AND TIME FRAME

Final year project is divided into FYP I and FYP II and this project is expected to be completed within the time frame. The early phase of the project was mostly done on reading books, SPE papers, technical papers and journal papers to gain better understanding on the project. Initially, the author plans to accomplish this study through experimental work by using Slim Tube or Vanishing Interfacial Tension (VIT) apparatus. However, due to the circumstance of unexpected broken-down of apparatus, the research methodology has switched from experiment study to simulation study by using reservoir simulation software.

The research works will be continued by learning ways to simulate different case study using ECLIPSE 300 based on 1D Slim Tube functions. Different scenarios will be simulated with different injected gas compositions and then, the analysis on MMP of Dulang's crude oil will be done in order to select the best injected gas composition that can be implemented in Malaysia oil field.

CHAPTER 2

LITERATURE REVIEW

2.1 OVERVIEW OF GAS FLOODING

During the production lifetime of oil reservoir, the crude oil is produced through primary and then by secondary recovery methods. The effectiveness of oil recovery using primary and secondary recovery methods is considered unsatisfactory due to the high demand of crude oil; therefore tertiary recovery methods have been introduced to maximize the oil production. The major EOR techniques include thermal methods, gas methods and chemical methods. Among the EOR methods, gas injection is one the oldest EOR techniques and has increased recently. Four gas injection methods that applied in industry are hydrocarbon gas injection, carbon dioxide injection, nitrogen injection and flue gas injection.

Gas injection can be either miscible or immiscible. Miscible means that the injected gas goes into solution with the oil can mix together and become single phase. It also reduces the viscosity and surface tension of oil and rock. On the other hand, immiscible means that injected gas does not mix with oil and separated by a sharp interface.

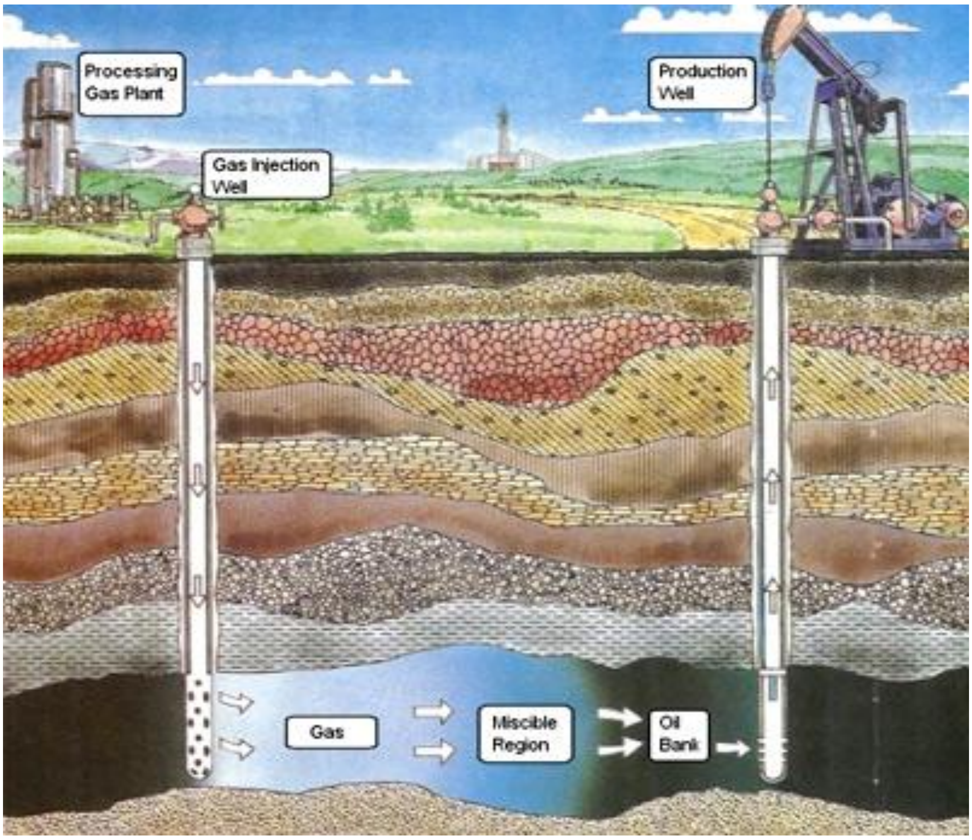

Figure 1 : Gas Injection & Production Well for Enhanced Oil Recovery (EOR) (Rigzone, 2013)

2.2 CARBON DIOXIDE FLOODING

The use of carbon dioxide for enhance oil recovery (EOR) in reservoir have been investigated since 1950 and it has been widely used in the 1970 and 1980 (Stalkup 1978). Carbon dioxide flooding has been used in EOR techniques as it helps to prolong the production period of the oil fields. Carbon dioxide flooding is preferred compared to the other gases like hydrocarbon gas, nitrogen and flue gas because it is cheaper, high sweep efficiency and provides environmental benefits in CO_2 capture and sequestration of the reservoir (Dong, Huang, and Srivastava 2000). Additionally, the hydrocarbon solvents are expensive and it would be uneconomical to carry out in gas flooding.

By using CO_2 as the injection gas, the miscibility of CO_2 and oil can be achieved at a lower pressure compared with hydrocarbon gases and nitrogen (Ghedan 2009, Yellig and Metcalfe 1980). Miscibility can be achieved with CO_2 gas by reducing or eliminating the interfacial tension, residual oil saturation to its lowest possible value.

Carbon dioxide flooding is more preferable as it affects reservoir as follows:

1. Reduction of oil viscosity and increasing mobility ratio
2. Promotes oil swelling to help displace oil out of reservoirs
3. Extraction or vaporization of oil into the CO_2 rich phase
4. Reduction in residual oil saturation due to reduction in CO_2 oil interfacial tension

Studies have shown that pure CO2 is not always available as an injection gas and Metcalfe (1982) has mentioned that the presence of impurities in gas streams can actually affect the pressure required to achieve miscibility displacement. Furthermore, Zhang et. Al. (2004) has stated that flue gas which contains a certain different gas concentrations from power plant is a ready stock for CO2; however CO2 extraction can be an issue that will increase the project cost. Hence, recycling produced gas stream is recommended to reduce the CO2 utilization and total cost.

2.3 MISCIBLE AND IMMISCIBLE DISPLACEMENT

Carbon dioxide flooding can be implemented in two different ways which is miscible and immiscible displacement. The miscible displacement is occurred when CO_2 is injected into reservoir at or above minimum miscibility pressure. Immiscible displacement is occurred when CO_2 is injected into the reservoir below minimum miscibility pressure.

Miscible displacement is defined as a condition in which two or more fluids substances (liquids or gases) that can mix in all proportion without the existence of an interface and form a single homogeneous phase. It can be achieved through two mechanisms, which are first contact and multiple contacts. First contact miscibility occurred when the injection fluids for miscible displacement mix directly with reservoir oil in all proportion. Multiple contact miscibility which consist vaporizing and condensing gas drive is achieved when a dynamic fluid-mixing process that resulting from repeated contact of oil and injection gas during the flow.

Immiscible displacement occurs when two or more fluids that does not mix and separated by a sharp interface. Immiscible displacement is more favourable when the reservoir pressure is too low and the oil density is too high. As it can cause swelling of oil, reduction in density, improving mobility and subsequently improve the oil recovery.

Stalkup (1978) has mentioned that ultimate recovery can achieved by immiscible gas flooding is limited by three factors: volumetric sweep out, displacement efficiency and capture of the displaced oil at the producing wells. With respond to the problems faced by immiscible displacement, recent activity in miscible flooding has focused on the CO_2 miscible process. On the other hand, the miscible process is more favourable than immiscible displacement due to the high oil recovery, high displacement efficiency, and as well as higher swelling factor in the miscible process (Yongmao & Italic, 2004).

Figure 2 shows that the miscible flooding process when CO_2 gas is injected into reservoir and mix with the oil, it creates a miscible zone. The CO_2 picks up the lighter hydrocarbon components, swelling the total volume of oil and reducing oil's viscosity and IFT to faster the oil moves towards producing well.

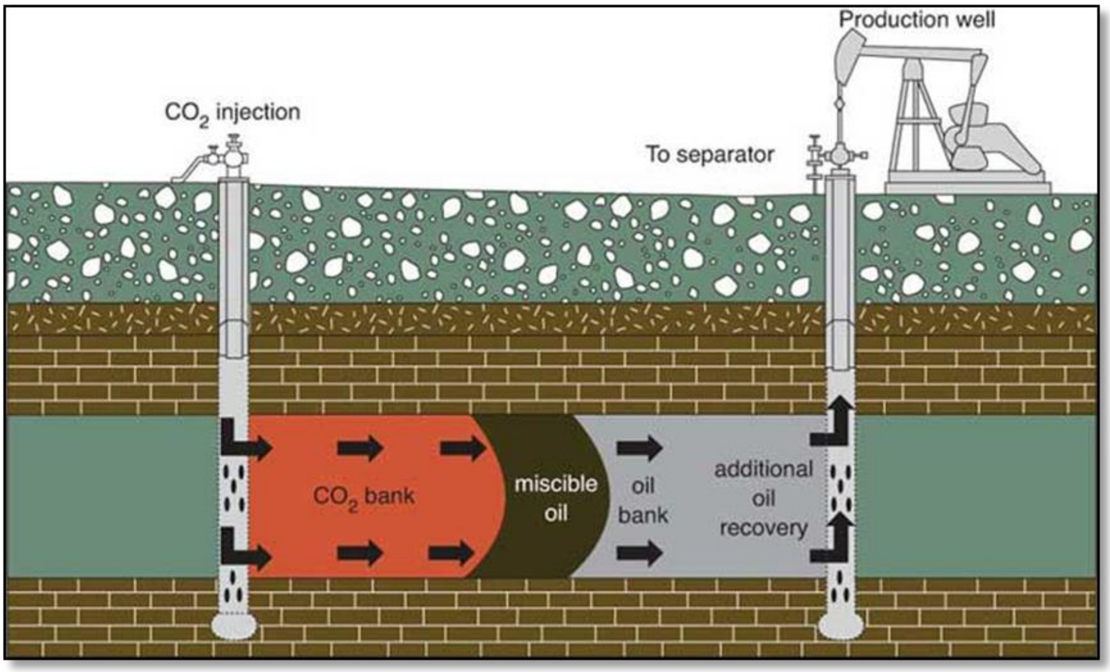

Figure 2 : CO2 Miscible Flooding (Kansas Geological Survey, 2005)

2.3.1 First Contact Miscible Process (FCM)

First contact miscible process is the most direct and simplest method to achieve miscibility displacement by injecting a solvent that mixes directly with oil in all proportions. However, FCM is only attainable for enriched gases or at high pressure which are too expensive to inject continuously. Stalkup (1978) mentioned that intermediate-molecular-weight- hydrocarbon solvent for first contact miscibility will also precipitate asphalt from asphaltic crudes where it may reduce permeability and affect well injectivities and productivities.

2.3.2 Multiple Contacts Miscible Process (MCM)

Multiple contact miscible process is a function of both temperature and pressure; but in isothermal reservoir, pressure is the only concern. There is a minimum pressure required to achieve multiple contact miscibility, called minimum miscibility pressure (MMP) which it is a key design/parameter in miscible flooding. MMP can be defined as the lowest or minimum pressure required when miscible recovery of reservoir oil can be achieved by CO2 displacement (Stalkup, 1978).

2.3.2.1 Vaporizing Gas Drive

Vaporizing Gas Drive is one of multiple contacts miscibility mechanism; it relies on vaporization of intermediate-molecular-weight hydrocarbon from the reservoir oil. According to Stalkup (1978), vaporizing gas drive miscibility can be achieved with flue gas, natural gas or nitrogen as injection gas, provided that the miscibility pressure is physically attainable in reservoir. The pressure required to achieve multiple contacts miscibility with CO_2 is usually lower than pressure required for other gases. On the other hand, CO_2 is able to extract higher molecular hydrocarbons than natural gas, flue gas and nitrogen.

2.3.2.2 Condensing Gas Drive

Injection gases with oil can miscibly displaced the reservoir oil even though they are initially immiscible. This mechanism creates a transition zone through condensation of the intermediate molecular weight hydrocarbons from gas to oil. Miscible transition is developed if sufficient gas/oil occurred. There are two variables that can affect condensing gas drive miscibility: reservoir pressure and gas composition. The increasing in reservoir pressure reduces the size of two phase region, and thus lower concentration of intermediate-molecular-weight hydrocarbon in injection gas (Stalkup 1987).

2.4 MINIMUM MISCIBILITY PRESSURE (MMP) DETERMINATION TECHNIQUES

At present, there are three approaches to measure and determine MMP: experimental, correlations and analytical models.

2.4.1 EXPERIMENTAL APPROACHES

2.4.1.1 SLIM-TUBE TEST

Figure 3 presents a schematic diagram of the apparatus. Slim-Tube test is considered to be the most accurate approach and the industry regards the slim tube apparatus as the standard method in measuring the MMP. The slim tube is constructed of ¼ inch OD stainless steel tube and 40ft long and packed with 160 to 200 mesh sand (Stalkup 1978). The purpose of slim tube test was to provide a medium for mixing oil and CO_2 in a flowing, multiple contact process. The test begins with a sand pack saturated with oil at a constant temperature. Carbon dioxide is injected at a given pressure and rate using positive displacement pump. The test will be terminated after 1.2 PV of CO_2 were injected.

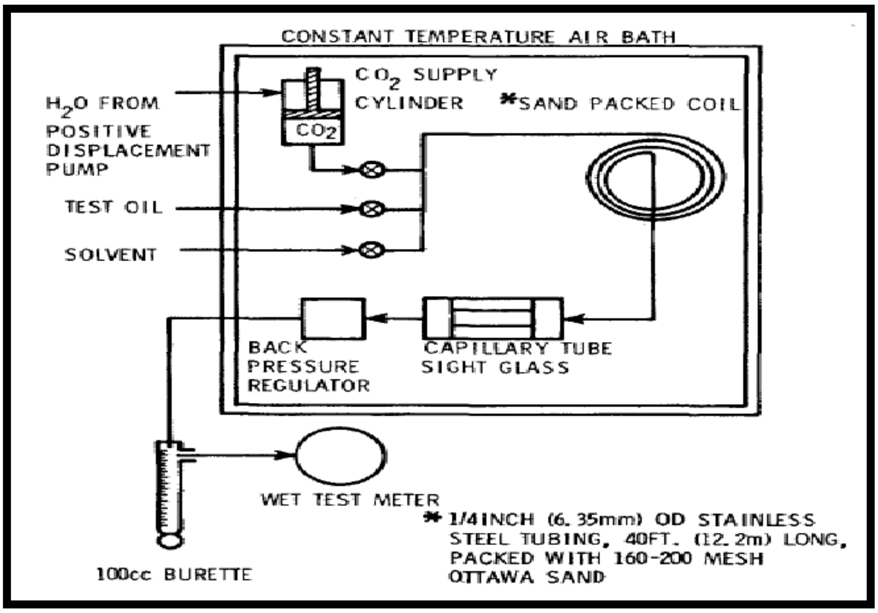

Figure 3 : Slim Tube Apparatus Schematic (Yellig and Metcalfe, 1980)

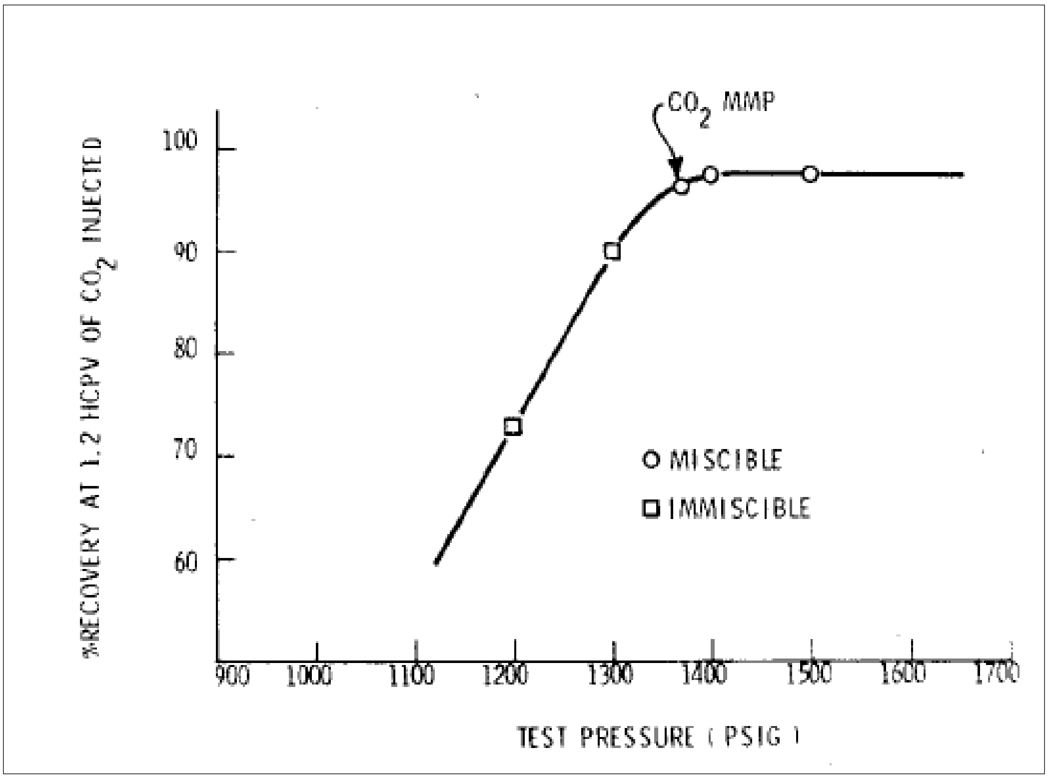

Figure 4 : Test Result for Fixed Oil Composition and Fixed Temperature (Yellig and Metcalfe, 1980)

Figure 4 shows the percent of oil recovery versus pressure for a series CO_2 flooding experiments in a slim tube test. The CO_2 MMP is determined by a sharp break or position of inflexion in the recovery curve with flooding pressure.

According to William et al. (1980), the minimum miscibility pressure (MMP) is commonly defined as the pressure where oil recovery being over 90% at 1.2PV CO_2 injection. The oil recovery increase with flooding pressure and the recovery range will become smaller as the pressure increases at the MMP or higher.

2.4.1.2 RISING BUBBLE APPARATUS (RBA)

The rising bubble apparatus was designed in the early 1980s, with features like a flat glass tube mounted vertically so that the evolution of shape of bubbles rising through the oil column can be observed clearly, and a hollow needle at the bottom is used to inject a bubble of gas, where the buoyant force of the gas will lift the gas bubble through the column and mix with oil.

Two advantages of using RBA to measure MMP is that RBA does not consume as much oil and gas as the slim tube method, and the RBA can visually demonstrate the pressure where miscibility occurs (Elsharkawy, Poettmann, and Christiansen 1992). Besides, RBA method is known as one of the cheapest and fast way in determines MMP (Christiansen and Haines 1987).

A bubble gas is formed at the tip of the hollow needle in water phase. The bubble was lifted by buoyant force and it rises through water, through water-oil interface, and up through the column of oil. The behaviour of rising bubble can be observed through sight gauge and recorded on video tape.

By using visual observation over a range of pressure in Figure 7and Figure 6, the MMP is determined at a constant temperature. Christiansen and Haines (1987) observed that below the MMP, gas bubble retains its initial near-spherical shape although it's slowly shrinks as the gas steadily dissolves in newly contacted oil. On the other hand, when the pressure at or above MMP, the bubble shape changed as it rises and dispersed more rapidly into column of oil.

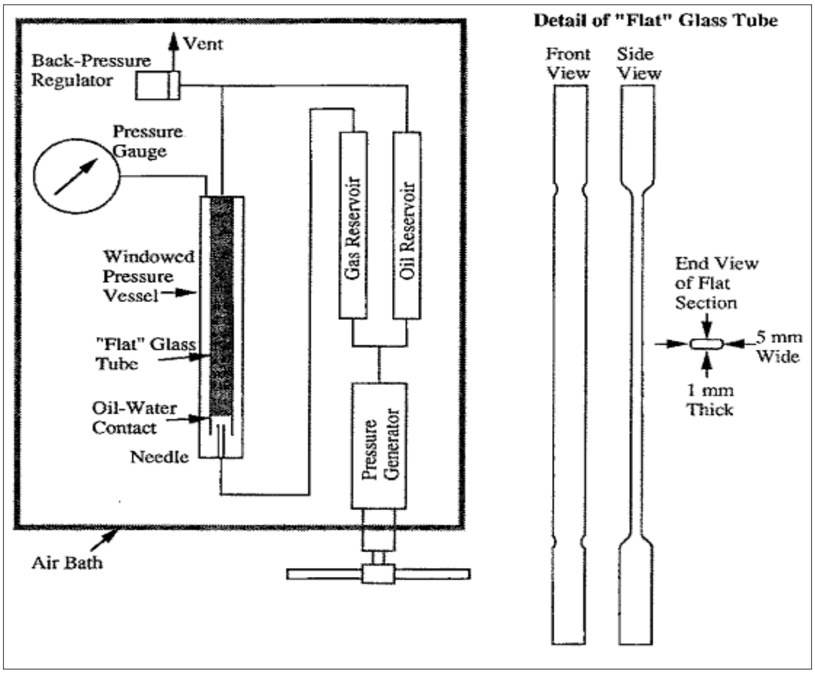

Figure 5: Schematic of Rising Bubble Apparatus
(Christiansen and Haines , 1987)

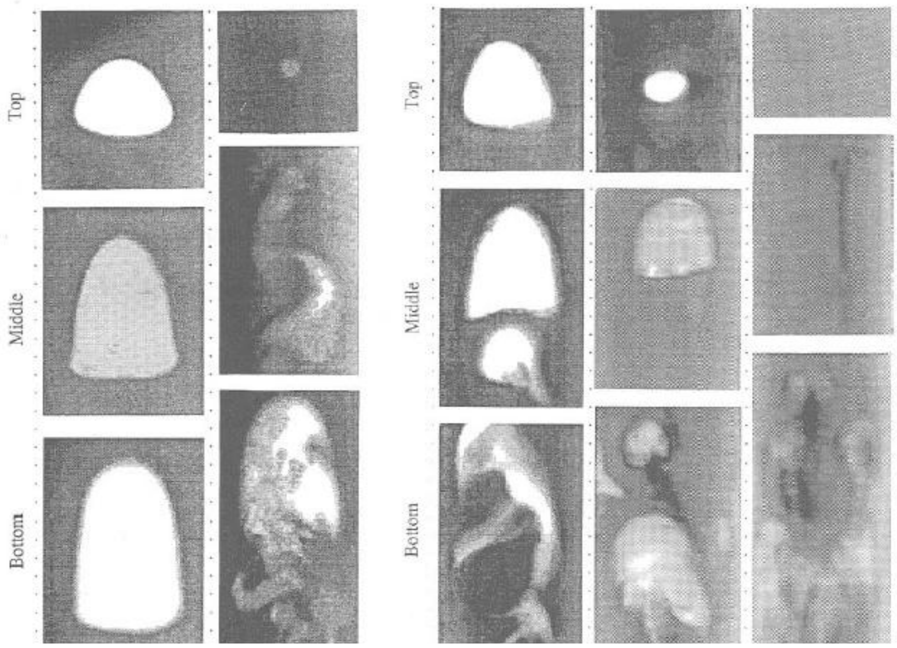

Figure 7 (Left) : Bubble Behavior for Vaporizing Gas Process
Figure 6 (Right) : Bubble Behavior for Condensing Gas Process
(Christiansen and Haines, 1987)

2.4.1.3 VANISHING INTERFACIAL TENSION

Rao and Lee (2003) claimed that miscibility requires the absence of an interface between the injected gas and crude oil at reservoir conditions. The VIT concept is based on the concept that the interfacial tension between two immiscible fluids will continuously diminish and become zero at the point of miscibility. VIT method relies on measuring interfacial tension to as low value as experimental allows due to zero interfacial tension is impossible to achieve.

VIT method is the most advanced and accurate method of measuring the IFT at large range of pressures and temperatures (Gu and Yang 2004). During the experiment, a pendant oil drop is produced at the tip of the syringe needle. By using an image acquisition system, the digital image of the drop is captured. Via computer digital image analysis and processing techniques, an accurate interfacial profile of the pendant drop is acquired. After that, by using the Laplace equation of capillarity, it will find the best fit for the numerically calculated interfacial profile to the physically observed drop profile, which will determine the IFT of the oil drop. The IFT measurements are repeated for at least four pendant drops to ensure that the results obtained are satisfactory.

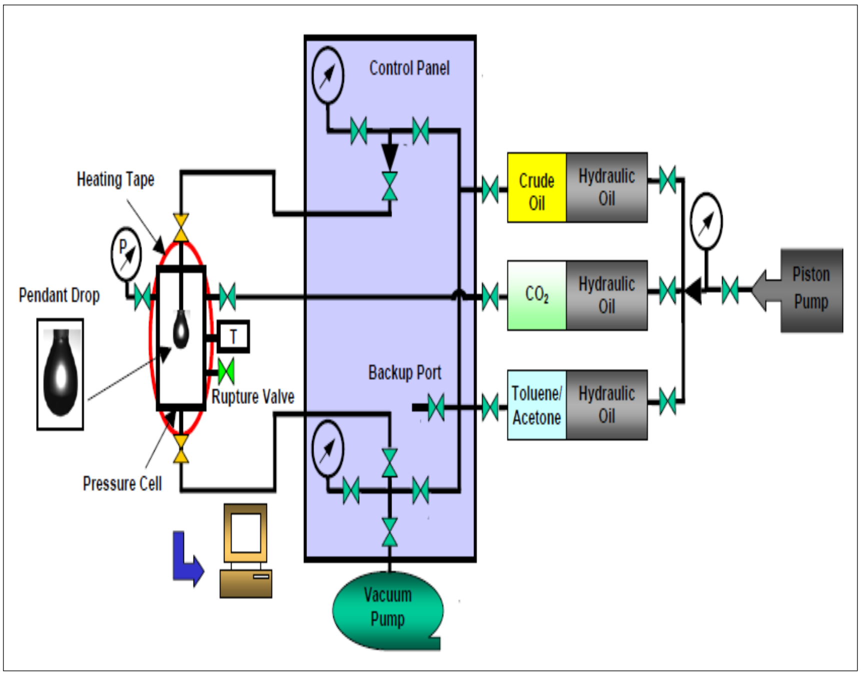

Figure 8 : Block Diagram of the Experimental Setup Used to Study the Interfacial Tension Interactions (Gu and Yang, 2004)

Figure 8 shows the block diagram of VIT apparatus. After determine the MMP, the point of zero interfacial tension was then identified by extrapolating the plot of IFT versus pressure to zero.

2.4.2 CORRELATION TECHNIQUES

Several correlation methods have been developed by different researchers to determine the MMP. Although it is less accurate, but these correlations are quick and easy to use. Most of empirical correlations predict MMP as a function of three variables: molecular weight of a plus fraction, mole fraction of a light component in the reservoir oil and temperature (Mogensen et al. 2009).

Yellig and Metcalfe (1980) have developed a MMP correlation for CO2 based on slim tube test from a group of light west Texas oils. Their correlation does not take the composition of oil into consideration. Apart from that, they assumed that if bubble point pressure of reservoir oil greater than CO2 MMP, then the bubble point is the MMP. However, their correlation may yield inaccurate result when heavy oils are present in the studies.

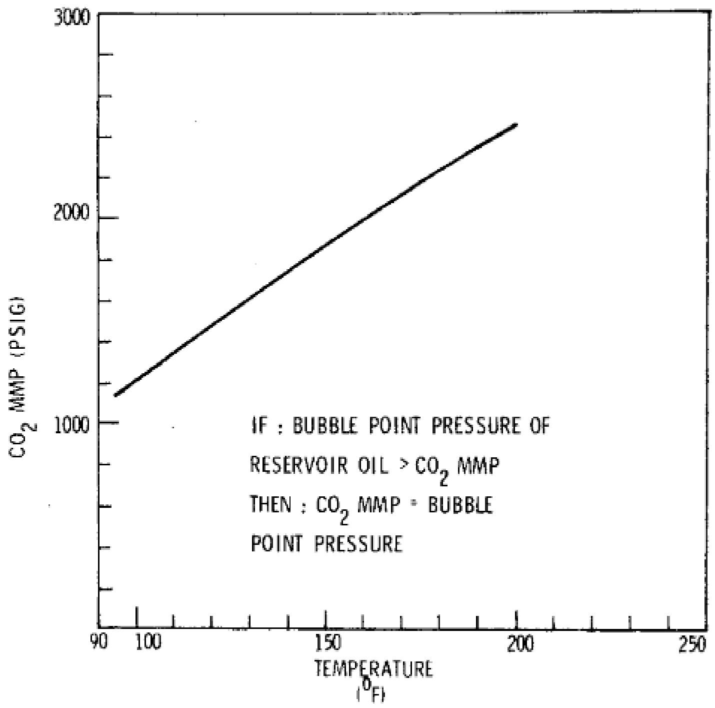

Figure 9 : Temperature/ Bubble Point Pressure of CO2 MMP (Yellig and Metcalfe, 1980)

Figure 9 shows the correlation on reservoir temperature on CO_2 MMP. Yellig and Metcalfe (1980) mentioned that the temperature dependence of CO_2 MMP have a very significant effect on the CO_2 MMP determined for a given reservoir oil.

Cronquist has found that the molecular weight of C_{5+} was a good correlation parameter for MMP. Thus, Cronquist (1978) proposed a correlation that takes reservoir temperature, molecular weight of C_{5+} and mole percent of C_1which covers wide range of API and temperature.

Glass (1985) has observed that the MMP correlated with the molecular weight of plus fraction. A MMP correlation for hydrocarbon, CO_2 and N_2 gas has been developed based on Benham et al.'s work. Input parameters that required in Glaso correlation are mole % of $C_2 - C_6$ intermediate content, molecular weight of C_{7+} and reservoir temperature.

Another correlation for multi component multiphase flow MMP calculations from equation of state is developed to generate MMP correlations for displacements by pure and impure CO2 (Yuan et al. 2005). The advantage of this approach is that MMP for a wide range of temperatures and reservoir fluids can be calculated quickly.

Mogensen et al. (2009) discussed that empirical correlations are generally over predicting the MMP for light oils and underestimating the MMP for heavy oils. His studies indicated that the correlations had limited use when applied outside the range of data to which they were fitted.

2.4.3 ANALYTICAL MODELS

Mathematical models use phase equilibria and EOS to estimate MMP. Johns and Wang have developed a generalized n-component phase equilibrium approach to estimate the MMP for two phase system (Johns et al.1996, Wang et al. 1998). An EOS is used to calculate the partitioning of the components between the phases that are present. This mathematical methods may not satisfactory predict the MMP. Hence, additional information should be collected to fine-tune the EOS and improve the estimation of MMP.

2.4.3.1 Key Tie-Line Approach

The key tie-line approach was developed by Johns et al. (1996), Wang et al. (1998) and Jessen et al.(1998). Monroe et al. (1990) has examined the analytical theory that showed the existence of a third key tie line in the displacement path, called the crossover tie line. The existing of crossover tie line is confirmed and constructs a key tie-line approach to control miscibility in a multi-component system. The MMP is determined at the lowest pressure where the length of one of the key tie-lines becomes zero.

2.4.3.2 Method of Characteristics (MOC)

An analytical model based on the method of characteristics is presented by Dumore, Hagoort, and Risseeuw (1984) for the calculation of one-dimensional, three-component condensing and vaporizing gas drive. MOC was used to describe the composition path from initial gas composition to initial oil composition Mogensen et al. (2009). Monroe et al. (1990) has examined the analytical theory that showed the existing of a third key tie line in the displacement path, called the crossover tie line. Current MOC for MMP determination has its disadvantages, which it may provide an overestimation MMP value.

2.4.3.3 1D Slim Tube Simulation

1D Slim Tube simulation is a numerical approach that imitates the flow in porous media that occurs in slim-tube experiments to simulate the multiphase flow displacement and phase behaviour. 1D slim tube simulation is used to predict MMP that are consistent with slim tube test data, provided with fluid phase behaviour characterization and consideration of numerical dispersion effect. The MMP is determined from an arbitrary bend in the recovery curves versus pressure (Jarrell 2002). Better accuracy of MMP was obtained by repeating the simulations, but it is time-consuming to perform this simulation.

2.4.3.4 Multiple Mixing Cell Method

Multiple mixing cell method a simulation that consist of a series of PVT cell ranging from 5 to 500 cells that are connected and are initially filled with oil. The gas is mixed with in repeating cell contacts, resulting in a new equilibrium composition (Ahmadi and Johns 2008). They have developed a new mixing-cell method to determine the MMP for systems with any number of components. Their method relies on performing PT flash calculations using any EOD, and on moving the injected and equilibrium gas ahead of the equilibrium liquid in each cell.

2.5 FACTORS AFFECTING MISCIBILITY PRESSURE

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

2.5.1 Carbon Dioxide 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	Reduce the MMP
Hydrogen Sulphide	Reduce the MMP
Sulphur dioxide	Reduce the MMP

Table 1 shows the effects of CO_2 impurities towards MMP. The presence of H_2S, SO_x, and intermediate hydrocarbons components (such as C_2, C_3 and C_4) in injected gas can reduce the MMP. On the other hand, Emera and Sarma (2007) found that the presence of C_1 and N_2 in CO_2 can increase the MMP.

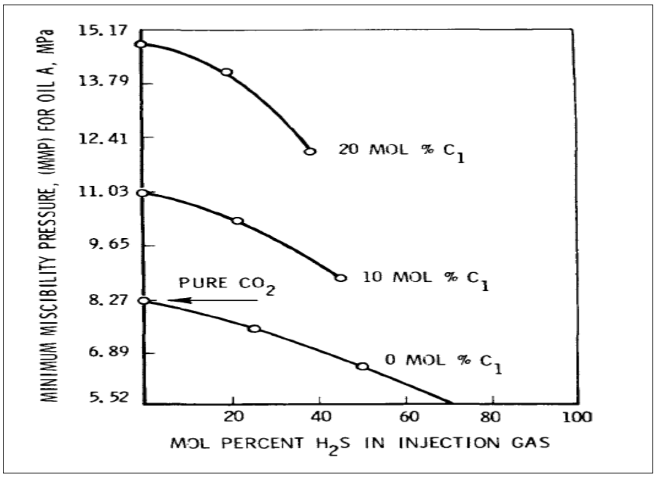

Figure 10 : Effect of Impurities on MMP for CO2 (Metcalfe, 1982)

2.5.2 Oil Composition

Oil composition is playing an important role in miscible displacement. A decrease in API oil gravity resulted increasing in MMP, reflecting the reduced content of extractable hydrocarbons. 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 1985). This was supported by Silva and Orr Jr. (1987) which they reported that the distribution of molecular weight present in the oil is the most important factor that affects MMP. Higher molecular weight will reduce the solubility of the hydrocarbon inside CO_2.

Miscibility Pressure vs Gravity

Gravity (°API)	Miscibility Pressure (psi)
<27	4,000
27 to 30	3,000
>30	1,200

Correction for Reservoir Temperature

Temperature (°F)	Additional Pressure Required (psi)
<120	None
120 to 150	+200
150 to 200	+350
200 to 250	+500

Figure 11 : Effect of API Oil Gravity on MMP (National Petroleum Council, 1976)

2.5.3 Reservoir Temperature

National Petroleum Council (1976) has proved that higher reservoir temperature result in higher minimum miscibility pressure, all others being equal. As shown in Figure 12, Yellig and Metcalfe (1980) have stated that for every 50 °F drop in temperature, the CO_2 MMP decreases by about 600-700 psia.

Furthermore, Holm (1986) have pointed out that 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.

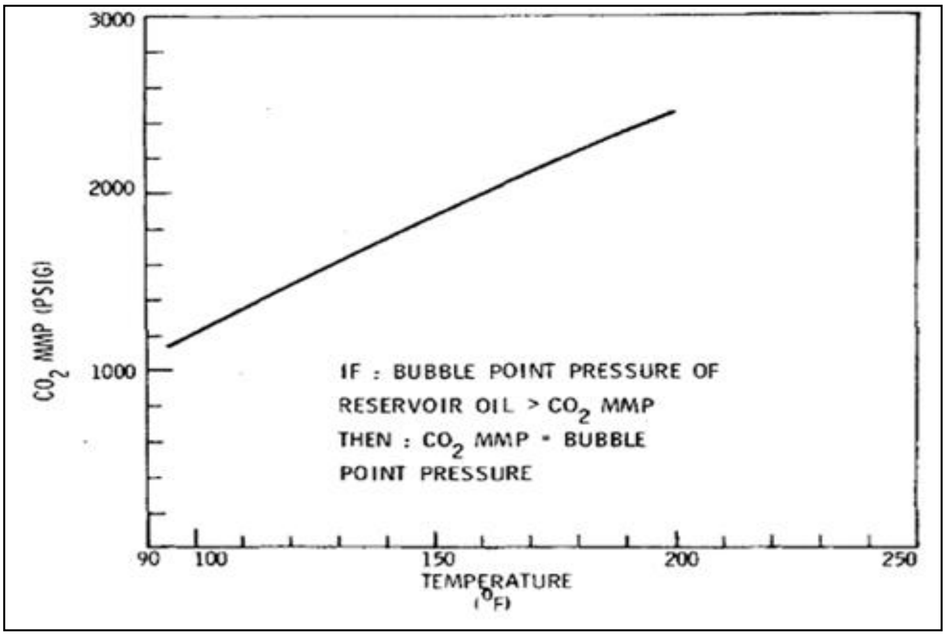

Figure 12 : Effect of Reservoir Temperature on MMP (Yellig and Metcalfe, 1980)

2.6 KNOWN METHODS TO REDUCE MMP

For a miscible displacement to occur, a minimum pressure at a given temperature must attain to ensure miscible conditions between oil and injected gas. This minimum pressure is known as the minimum miscibility pressure (MMP). If the reservoir pressure is lower than MMP, miscible displacement will not occur. In order to achieve miscibility in low pressure reservoir, several methods have been studied to reduce the MMP.

The changes in CO_2 MMP are direct functions of temperature. A study by Yellig and Metcalfe (1980) shown that the MMP decreases by about 600-700 psia for every 50 $^{\circ}$F drops in temperature. Winston (1984) has invented a method to reduce MMP by injecting a coolant into the formation. This method can lower the formation temperature between injections well and production well and thus lowers the MMP.

Additionally, it is possible to reduce the MMP by blending CO_2 with solvent such as ethane, propane and butane (Hui 1995). Besides, Metcalfe (1982) concluded that CO_2 streams containing H_2S, C_{2+} hydrocarbon can reduce the MMP's than do pure CO_2 streams. Lastly, Nizar F. Djabbarah (1988) found that alcohol can lower the MMP when injected along with CO_2.

CHAPTER 3

METHODOLOGY

3.1 RESEARCH METHODOLOGY

Initially, this research project was planned to be performed experimentally. Simulation studies have been carried out instead of experimental work due to unforeseen circumstances of broken down VINCI Technologies Interfacial Tensometer.

Literature review is done prior to this project to gain a better understanding on the project's topic such as gas flooding which focuses on the CO_2 flooding. The author has done intensive studies on the parameters and factors that would affect minimum miscibility pressure (MMP) and the known methods to reduce the MMP. Apart from that, the author also done some reading on the ECLIPSE software's manual and then continues with software familiarization. The objectives and frameworks of the project were clearly identified. Then, simulation work will begin at the middle stage of FYP I to the whole time period for FYP II. The results obtained from reservoir simulation will be discussed and analysed. The best simulation case will be selected. Lastly, the author will compile all the required information into project's final report.

3.1.1 Data Gathering

In this project, the simulation investigation was started by collecting the parameters and input data for reservoir and fluid properties. The parameters for such as injection pressure and injected gas composition will be altered at constant reservoir temperature to investigate their effect on MMP and oil recovery factor.

The base case is obtained from Slim Tube Model in ECLIPSE 300 simulator. The crude oil properties and reservoir properties are obtained from Zain et. Al. (2001). The initial reservoir pressure of Dulang field is 1800 psia and average reservoir temperature is 215 °F. The reservoir fluid composition with 37 °API and saturation pressure of 1525 psia. Characterization of the reservoir fluid sample is carried out using a compositional simulator known as Pressure-volume-temperature analysis software (PVTi).

3.1.2 Simulation Modelling

The summary of required input is summarized in the following table.

Table 2 : Essential Keywords and Description in ECLIPSE for Slim Tube Simulation

RUNSPEC	
FULLIMP	Fully Implicit Solution option. This is required for runs with very high flow rate and default for Blackoil.
MISCIBLE	It activated dependence of relative permeability and capillary pressure on surface tensions according to the PARACHOR values.
PROPS	
EOS	Equation of States
CNAMES	Component Names
MISEXP	Miscibility Exponent
BIC	Binary Coefficients
PCRIT	Critical Pressure
TCRIT	Critical Temperature
ZCRIT	Critical Z-factor
MW	Molecular Weight
ACF	Accentric Factors
ZCRITVIS	Critical Z-Factors for Viscosity Calculation
VCRITVIS	Critical Volumes for Viscosity Calculation
OMEGAA	Omega A
OMEGAB	Omega B
PARACHOR	Component Parschors

SOLUTION	
XMF	Specifies cell initial oil composition
TSCRIT	Time Stepping Criteria
WELLSTRE	Compositions of Injection Gas Stream
WINJGAS	Specify the Nature of Injection Gas
SGFN	Gas Saturation Functions
SOF2	2 Phase Oil Saturation Functions

In this project, the Peng-Robinson equation of state (EOS) was used to characterize the reservoir fluid composition by using PVTi module of the ECLIPSE simulation software. The critical fluid properties of reservoir fluid are obtained and exported to ECLIPSE 300 to simulate the fluid behaviour.

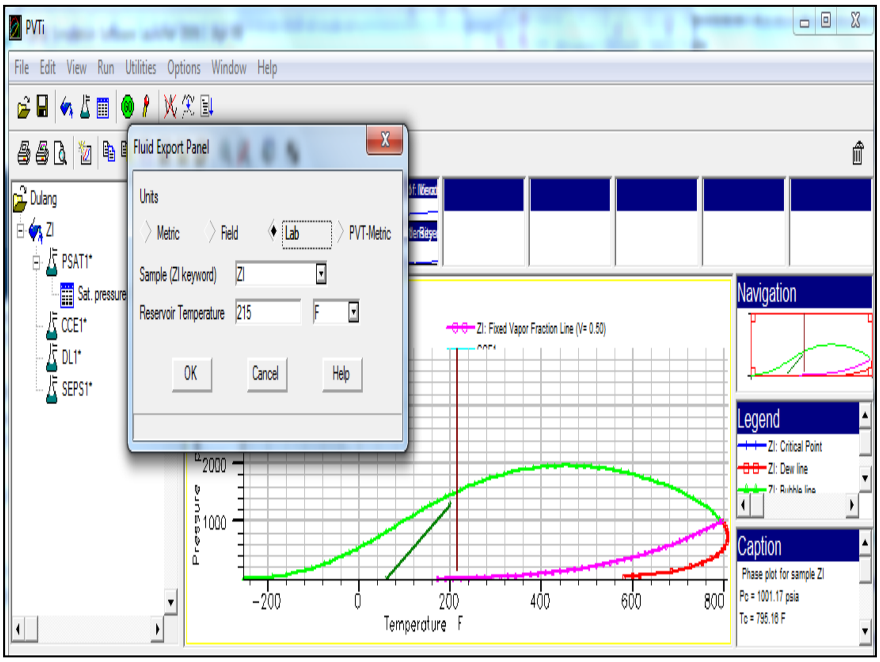

Figure 13 : Exporting Critical Fluid Properties from PVTi (PVTi 2009.1)

3.2 PROJECT WORKFLOW

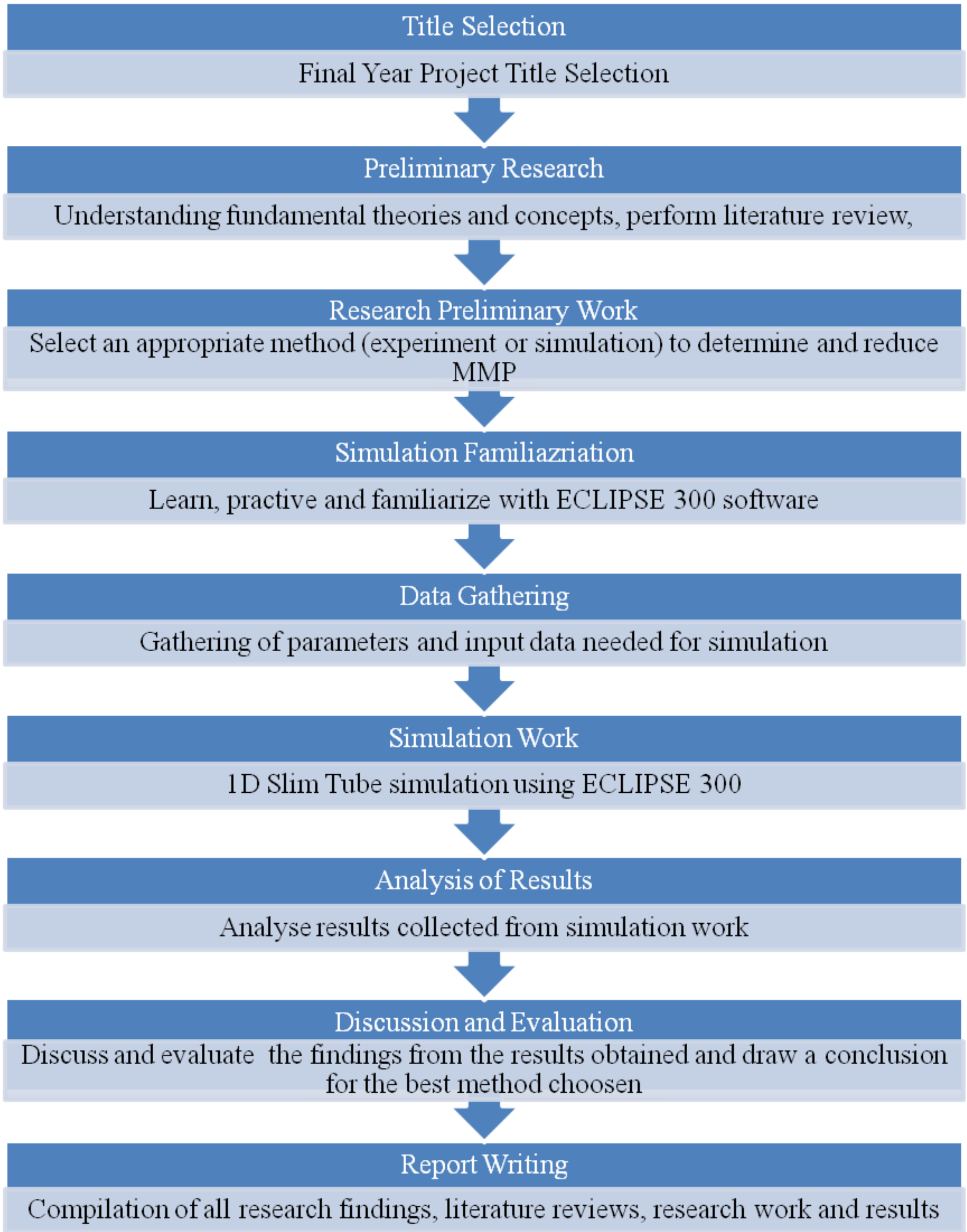

Figure 14 : Project Workflow

3.2.1 Simulation Workflow

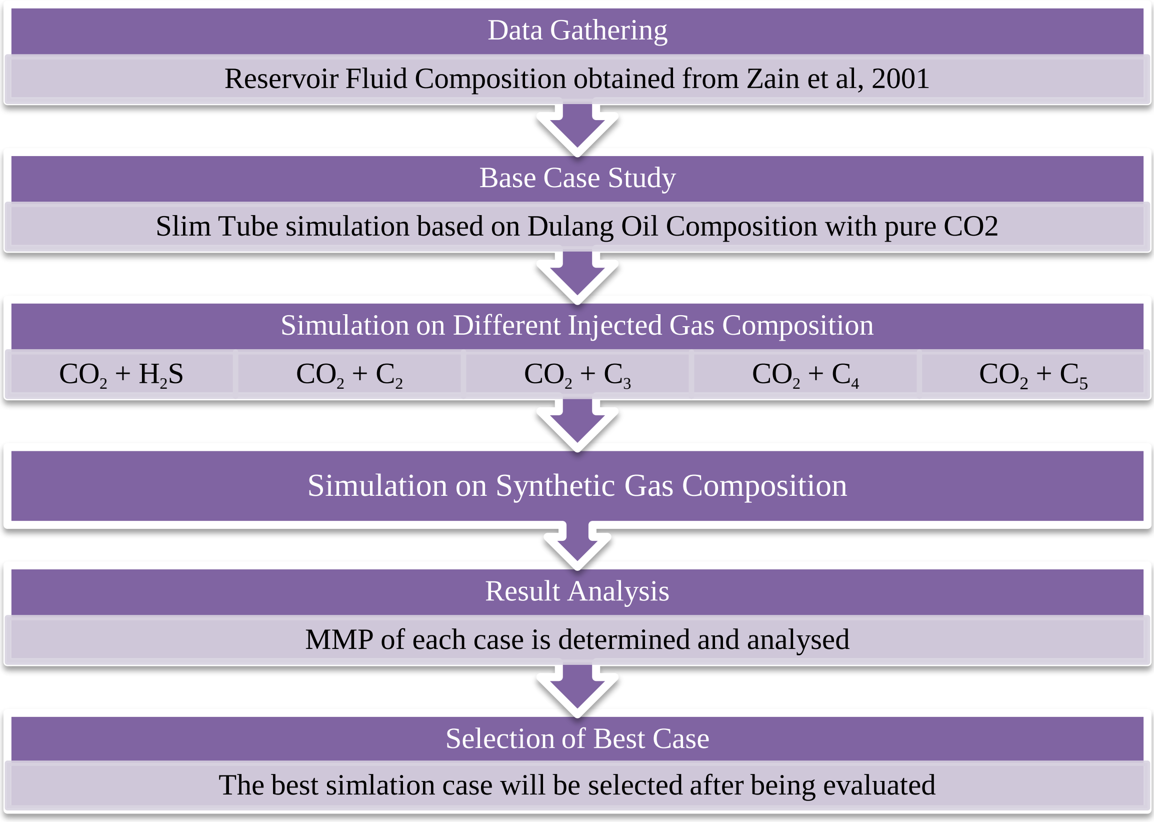

Figure 15 : Simulation Workflow

3.2.2 Studied Cases

The base case used pure carbon dioxide as injection gas to determine the minimum miscibility pressure (MMP) of Dulang crude oil. In the first scenario, impure CO_2 gases were made by mixing with different mol % of H_2S, C_2, C_3, C_4 and C_5. Then, the effects of impure CO_2 gases on MMP are determined and analysed. In the second scenario, the synthetic produced gases were made by alternating the gas compositions. In these synthetic gas streams, CO_2 still retained a relatively high mol % in it where other hydrocarbon components starting from C_6 were removed. This study was done to simulate a possible gas stream that can lower the MMP below Dulang's initial reservoir pressure. The composition of synthetic gases can be found in Table 3.

Table 3: Synthetic Gas Composition

Gas Sample	Compositions
Gas 1	94% CO_2 + 3% N_2 + 3%H_2S
Gas 2	90% CO_2 + 3% N_2 + 7% H_2S
Gas 3	85% CO_2 + 8% N_2 + 7%H_2S
Gas 4	80% CO_2 + 10% N_2 + 10% C_2
Gas 5	80% CO_2 + 10% H_2S + 10% C_2
Gas 6	80% CO_2 + 10% C_2 + 10% C_3
Gas 7	80% CO_2 + 10% H_2S + 10% C_3
Gas 8	80% CO_2 + 10% H_2S + 5% C_2 + 5% C_3
Gas 9	80% CO_2 + 10% H_2S +10% C_4
Gas 10	80% CO_2 + 10% C_3 +10% C_4
Gas 11	80% CO_2 + 5% C_3 +15% C_4
Gas 12	80% CO_2 + 5% H_2S +15% C_4
Gas 13	80% CO_2 + 5% H_2S + 5% C_3 + 10% C_4
Gas 14	75% CO_2 + 5% C_3 + 20% C_4
Gas 15	70% CO_2 + 5% C_3 + 25% C_4
Gas 16	80% CO_2 + 10% C_4 + 10% C_5

3.3 KEY MILESTONES

Table 4 : Key Milestones

Activities	Week		Progress
Project Approval and Identification	**Week 3**	**Semester 1**	**Completed**
Literature Research	**Week 5**		**Completed**
Submission of Extended Proposal	**Week 7**		**Completed**
Proposal Defence	**Week 8**		**Completed**
Submission of Interim Report	**Week 14**		**Completed**
Simulation Work Continues	**Week 12**	**Semester 2**	**Completed**
Submission of Progress Report	**Week 8**		**Completed**
Pre-SEDEX	**Week 11**		**Completed**
Submission of Dissertation & Technical Paper	**Week 13-14**		**Completed**

3.4 GANTT CHART

Details	**Week**														
	1	2	3	4	5	6	7		8	9	10	11	12	13	14
Project Approval and Identification	■	■						Mid Semester Break							
Preliminary Research Work		■	■	■											
Literature Research			■	■	■	■									
Submission of Extended Proposal							●								
Proposal Defence										●					
Continuation of Project Progress									■	■	■	■	■	■	■
Submission of Interim Report														●	

Figure 16: Gantt Chart for FYP I

Details	**Week**														
	1	2	3	4	5	6	7		8	9	10	11	12	13	14
Project Work Continues	■	■	■	■	■	■		Mid Semester Break							
Submission of Progress Report									●						
Project Work Continues										■	■				
Data Analysis										■	■	■			
Pre-SEDEX												●			
Submission of Draft Report													●		
Submission of Dissertation & Technical Paper														●	
Oral Presentation															●
Submission of Project Dissertation															●

Figure 17: Gantt Chart for FYP II

3.5 TOOLS REQUIRED

1. **ECLIPSE 300 Software (2009.1)**

ECLIPSE reservoir simulation software provides a complete and robust set of numerical solutions for fast and accurate prediction of dynamic behaviour – for all types of reservoirs and degrees of complexity, including structure, geology, fluids and development schemes. ECLIPSE 300 used to solves the reservoir flow equations for compositional hydrocarbon description and thermal simulation

Figure 18: ECLIPSE Launcher 2009.1

2. **PVTi Software**

   ECLIPSE PVTi is a compositional PVT equation-of-state-based program used to characterize a set of fluid samples for use in ECLIPSE simulator.

3. **Microsoft Excel, Word, Power Pont 2007**

   To prepare results, graphs, reports and presentation slides for Final Year Project.

CHAPTER 4

RESULT AND DISCUSSION

4.1 RESERVOIR FLUID CHARACTERIZATION

ECLIPSE PVTi is used to define the fluid properties of the reservoir fluid. The reservoir fluid is generated based on reservoir temperature of 215 °F and saturation pressure of 1525 psia. The fluid properties are tabulated in 5,6 and 7.

Table 5: Composition and Properties of Reservoir Fluid

Component	ZI (mol %)	Molecular Weight (MW)
CO_2	20.743	44.01
N_2	0.109	28.013
H_2S	0.000	34.076
C_1	15.062	16.043
C_2	3.007	30.07
C_3	2.710	44.097
iC_4	1.032	53.124
nC_4	0.854	58.124
iC_5	0.415	72.151
nC_5	0.283	72.151
C_6	2.917	84
C_7	2.833	96
C_8	1.285	107
C_9	2.470	121
C_{10}	2.357	134
C_{11+}	43.923	215.2

Table 6 : Fluid Compenent Properties I

Component	Critical Temperature (K)	Critical Pressure (ATM)	Critical Volume (cc/gm-mole)	Critical Z Factor
CO_2	304.7	72.9	94	0.274077797
N_2	126.2	33.5	90	0.291151404
H_2S	373.6	88.2	98	0.281954299
C_1	190.6	45.44	98	0.284729477
C_2	305.43	48.2	148	0.284634795
C_3	369.8	41.9	200	0.27616462
iC_4	408.1	36	263	0.282736959
nC_4	425.2	37.47	255	0.273855549
iC_5	460.4	33.45	308	0.272710872
nC_5	469.6	33.26	311	0.268438914
C_6	507.5	29.71	351	0.250417485
C_7	548	29	392	0.252810108
C_8	575	28.42	433	0.260816494
C_9	603	25.96	484	0.253935644
C_{10}	626	23.88	534	0.248251667
C_{11+}	743.2783001	15.90912189	881.0693514	0.229824211

Table 7 : Fluid Component Properties II

Component	Acentric Factors	Parachor	OMEGAA	OMEGAB
CO_2	0.225	78	0.457236	0.077796
N_2	0.04	41	0.457236	0.077796
H_2S	0.1	80	0.457236	0.077796
C_1	0.013	77	0.457236	0.077796
C_2	0.0986	108	0.457236	0.077796
C_3	0.1524	150.3	0.457236	0.077796
iC_4	0.1848	181.5	0.457236	0.077796
nC_4	0.201	189.9	0.457236	0.077796
iC_5	0.227	225	0.457236	0.077796
nC_5	0.251	231.5	0.457236	0.077796
C_6	0.299	271	0.457236	0.077796
C_7	0.3	312.5	0.457236	0.077796
C_8	0.312	351.5	0.457236	0.077796
C_9	0.348	380	0.457236	0.077796
C_{10}	0.385	404.9	0.457236	0.077796
C_{11+}	0.727524	578.4901	0.457236	0.077796

4.2 EFFECTS OF GAS COMPOSITION ON MINIMUM MISCIBILITY PRESSURE (MMP)

Minimum Miscibility Pressure (MMP) is an essential criterion for screening and selecting for the miscible flooding process. Pressure at which oil recovery reached 90% of recovery is chosen as the criterion for determining MMP in this project. Several cases were run at different displacement pressure in order to determine the MMP for each gas stream. The case study is divided into 2 main categories, impure CO_2 gas stream and synthetic produced gas stream. The recovery factor (FOE) is then plotted versus displacement pressure (psia) to determine the MMP of crude oil.

4.2.1 Pure CO2

Preliminary simulation has been done to determine the CO_2 MMP of Dulang crude oil. As shown in Figure 19, the MMP for 100% CO_2 injection is about 3528 psia. The MMP is about 1728 psia higher than initial reservoir pressure of 1800 psia. This indicates that miscible displacement is not feasible under this condition as the MMP is higher than initial reservoir pressure. In order to achieve CO2 miscible flooding, the methods to reduce MMP and effects of different injected gas composition are studied.

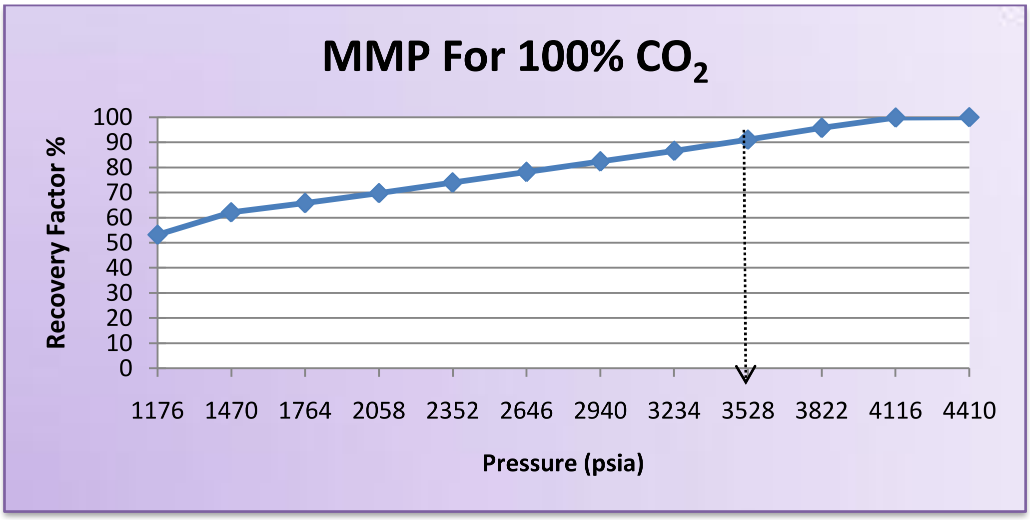

Figure 19: MMP for 100% CO_2

4.2.2 Hydrogen Sulphide (H_2S)

The same procedure was repeated to determine the effects of adding 10 mol%, 20 mol% and 30 mol% of H_2S into the CO_2 gas stream. From Figure 20, we can observe that the MMP reduced when the mole percentage of H2S increased in CO_2 gas stream. First test was carried out with 10 mol% of H2S; the MMP has decreased 441 psia to 3087 psia. 20 mol% of H_2S is then added into gas stream, the MMP decreased further by 294 psia to 2793psia. Lastly, with 30 mol % of H_2S in gas stream; the MMP has reduced significantly to 2499psia, which is 1029 psia compared to pure CO_2 gas stream.

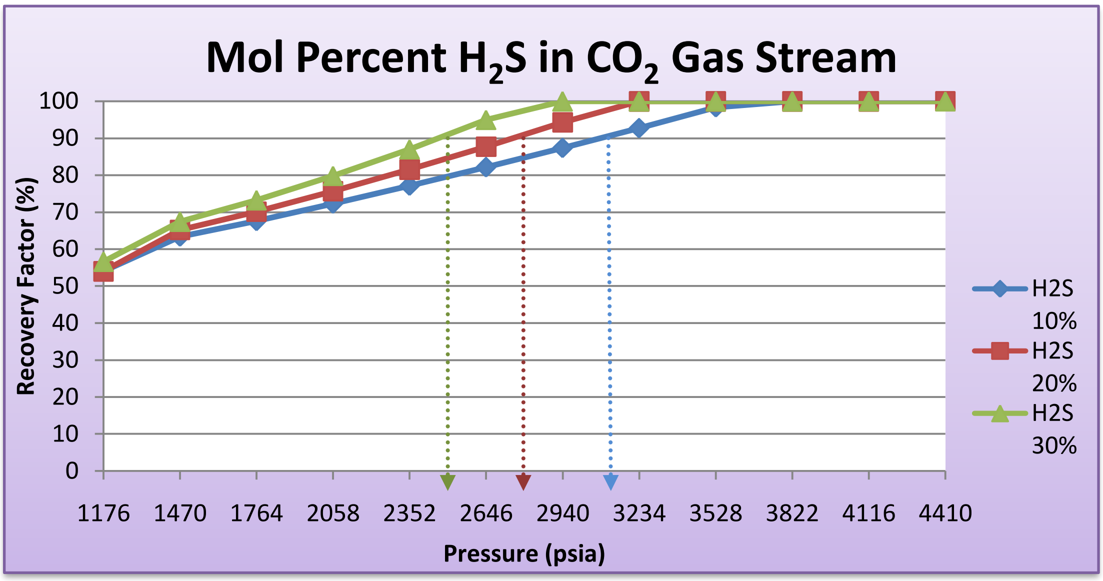

Figure 20: Mol Percent H2S in CO2 Gas Stream

4.2.3 Ethane (C_2)

10, 20 and 30 mol% of ethane have been added into CO_2 gas stream. The MMP has lowered as the result of the addition of methane as shown in Figure 21. By adding 10 mol% C2 into CO2 gas stream for each test, the MMP has decreased from 3234 psia to 2793 psia with the percentage reduction about 13.6%.

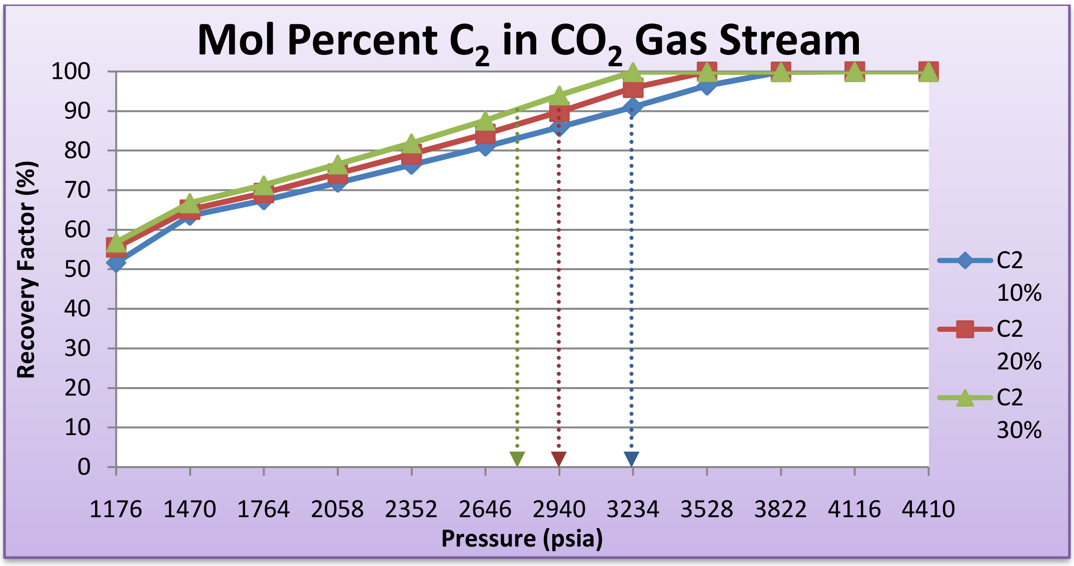

Figure 21: Mol Percent C_2 in CO_2 Gas Stream

4.2.4 Propane (C_3)

The effect of adding C_3 into CO_2 gas stream is even more effective in reducing MMP than H_2S and C_2. The reduction in MMP caused by adding 10 mol % C_3 is equivalent to 20mol % C_2. As shown in Figure 22, the MMP has been reduced from 2940 psia to 2058 psia where the percentage of reduction is about 30%.

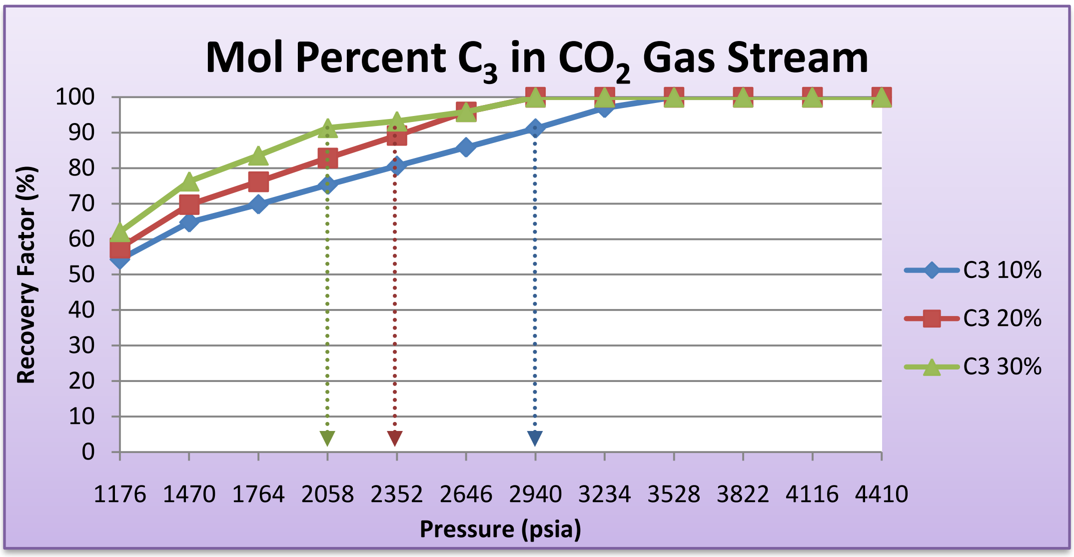

Figure 22: Mol Percent C_3 in CO2 Gas Stream

4.2.4 Butane (C_4)

The simulation continues study the effect of butane with Dulang crude oil. 10, 20 and 30 mol% of C_4 is added into CO_2 gas stream. In this study, the MMP was lower compared to C_3. By adding 30 mol % of C4 into CO_2 gas stream, it managed to lower the MMP from 2646 psia to 1617 psia which is lower than initial reservoir pressure. The MMP has been reduced from 2646 psia to 1617 psia where the percentage of reduction is about 38.89%. The larger MMP reduction in C_4 has indicated that butane is more effective agent for CO_2 than propane.

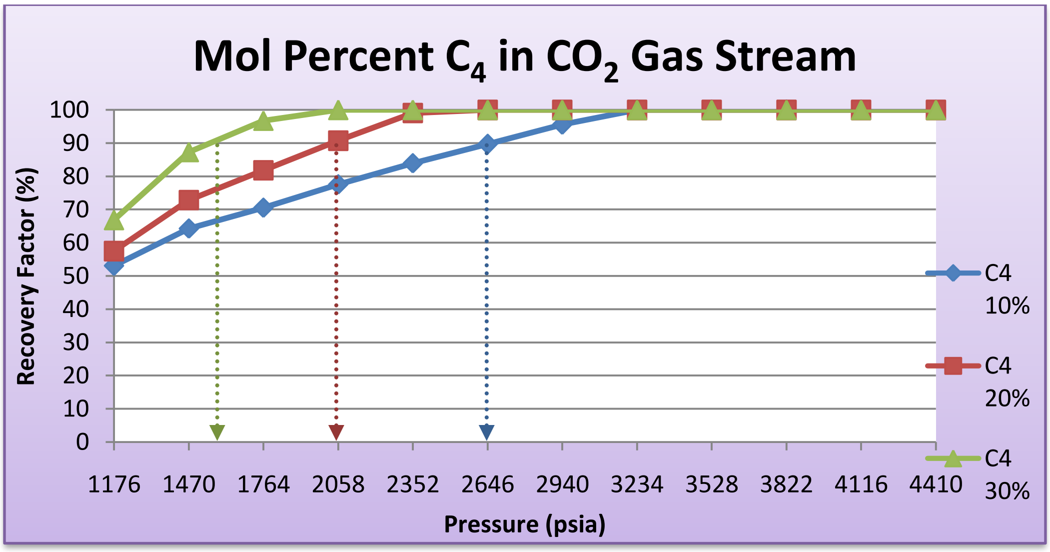

Figure 23 : Mol Percent C_4 in CO_2 Gas Stream

4.2.5 Pentane (C5)

Figure 24 shows the effect of pentane on MMP of Dulang crude oil. This study showed that the reduction of MMP by adding 10 mol % of C_5 is equivalent to by adding 10 mol % of C_4. However, the MMP reduced drastically to 1911 psia when 20 mol% of C_5 is added. Nevertheless, the MMP has managed to reach 1470 psia after 30 mol% of C_5 is added into CO_2 gas stream. From the results above, we can observe that C_5 is a good MMP reducing agent compare to other hydrocarbon components. The MMP has been reduced from 2646 psia to 1470 psia where the percentage of reduction is about 44.44%.

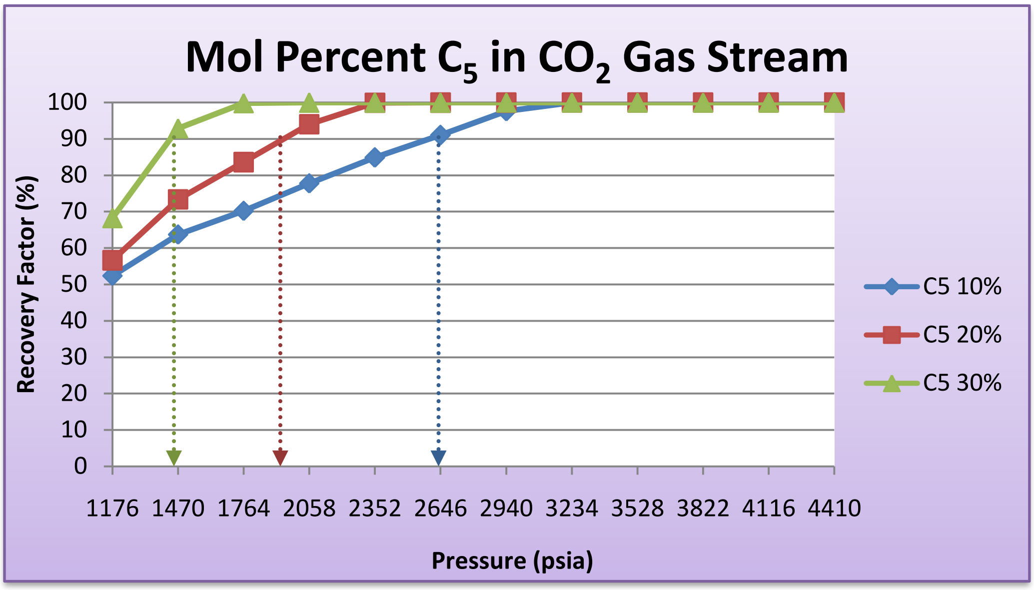

Figure 24: Mol Percent C_5 in CO2 Gas Stream

4.3 EFFECT OF SYNTHETIC GAS COMPOSITION ON MINIMUM MISCIBILITY PRESSURE (MMP)

Due to the lack information on produced gas composition from Dulang field, synthetic gas is used in this study. The gas composition was altered to simulate its effect on MMP. This gas will be treated as recycling produced gases as it could reduce the operational cost and save time in gas transportation. 16 synthetic gases was made and these gases are primarily made up of CO_2 and mix with some other hydrocarbon components. Due to the time constraint, only 7 hydrocarbon compositions were altered in sixteen synthetic gases samples. All samples are simulated at constant reservoir temperature of 215 ℉. The results are summarized in Table 8.

Table 8: MMP for Synthetic Gas Samples

Gas Composition	MMP (psia)
Gas 1 (94%CO_2+3%N_2+3H_2S)	3528
Gas 2 (90%CO_2+3%N_2+7%H_2S)	3381
Gas 3 (85%CO_2+8%N_2+7%H_2S)	3822
Gas 4 (80%CO_2+10%N_2+10%C_2)	3822
Gas 5 (80%CO_2+10%H_2S+10%C_2)	2940
Gas 6 (80%CO_2+10%C_2+10%C_3)	2646
Gas 7 (80%CO_2+10%H_2S+10%C_3)	2646
Gas 8 (80%CO_2+10%H_2S+5%C_2+5%C_3)	2646
Gas 9 (80%CO_2+10%H_2S+10%C_4)	2352
Gas 10 (80%CO_2+10%C_3+10%C_4)	2205
Gas 11 (80%CO_2+5%C_3+15%C_4)	2058
Gas 12 (80%CO_2+5%H_2S+15%C_4)	2205
Gas 13 (80%CO_2+5%H_2S+5%C_3+10%C_4)	2352
Gas 14 (75%CO_2+5%C_3+20%C_4)	1911
Gas 15 (70%CO_2+25%C_4+5%C_3)	1617
Gas 16 (80%CO_2+10%C_4+10%C_5)	2058

In review of the results of simulation studies above, 16 gas samples have shown the effects of raising or lowering the MMP. By adding 3% N_2 and 3%H_2S in Gas 1, the MMP remain unchanged compare to pure CO_2, which is about 3528psia. Furthermore, the MMP rose to 3822psia in Gas 3 and Gas 4 with the contamination of higher N_2 in gas streams. This indicates that the presence of N_2 in gas stream has increased the MMP of crude oil.

On the other hand, the presence of H_2S, C_3, and C_4 in CO_2 gas streams can lower the MMP of crude oil. However, a small reduction in MMP was observed when C_5 is added with C_4 and CO_2; it has just lowered the MMP by 1470 psia from 3528 psia. In additional, the MMP has reduced to 2205 psia by adding 10 mol% of C_3 and 10 mol% of C_4 into CO_2 gas stream. Furthermore, the MMP of crude oil has decreased to 1911 psia for the addition of 5mol% C_3 and 20 mol% C_4. The increment of C_4 to 25 mol% has further lower the MMP to 1617 psia where it is below the initial reservoir pressure.

Therefore, Gas 15 has been selected as the best injected synthetic gas where it has a MMP value that lower than reservoir pressure. By injecting this gas into the reservoir, it can leads to miscible displacement and resulting in higher oil recovery.

4.4 DISCUSSION

The implementation of CO_2 flooding requires a large amount of CO_2 gas supply. It will be a big challenge to provide and transport this large amount of CO_2 to offshore platform. Furthermore, CO_2 sources are rarely pure; it is normally contain a certain concentration of other gas composition. Purifying the impure CO_2 will increase the cost significantly. To reduce the operation cost, it is expected that the produced CO_2 from field can be recycled and re-injected without purification. Hence, Malaysia might be very fortunate because CO_2 is naturally in abundance, and work to synchronize there areas with EOR (Samsudin, 2005).

With the high demand of hydrocarbon gas demand as it provides the feedstock for MLNG plant and critical gas supply to the running of gas pipeline that supply most of the power producers' demand, EOR gas injection projects are forced to compete with sales gas demand which are equally important.

Furthermore, existing surface facilities limitation is one of the challenges faced for CO_2 EOR project. Therefore, a proper planning to design this project is needed for future. Additional cost need to be accounted such as pipeline, compression of injection gas stream and surface facilities. The cost for various options in CCS and CO_2 EOR are illustrated in Figure 25. It shows a wide range costs for transport, storage, caption and potential revenue from EOR, as sourced from the US, DOE, NETL and other organization (Sweatman et. Al. 2011).

Costs in 2009 S/T CO_2 stored	*Capture + Compression*	*Transportation*	*Storage*	*Total Cost (revenue)*
Low Cost	Gas processing $10-25	At site $0	EOR or EGR ($10 to 60 revenue)	($50 revenue) to $15 cost
Medium Cost	Coal power plants $60-120	30-200 miles $2 - 10	Depleted oil/gas field $5 - 10	$70 to $140
High Cost	Refining, Air $100-1000+	>500 miles $15 - 25	Off-shore saline $20 - 30	$140+ *Likely >$500*

Figure 25: Wide Ranges of CCS Costs with EOR Benefits (Sweatman, 2011)

	7/19/13	7/12/13	% Change
NGLs ($/gallon)			
Ethane	$ 0.258	$ 0.246	5%
Propane	$ 0.963	$ 0.930	3%
Butane	$ 1.253	$ 1.258	0%
Isobutane	$ 1.338	$ 1.320	1%
Natural Gasoline	$ 2.143	$ 2.143	0%

Figure 26: Price of NGL (Ingrid Pan, 2013)

Figure 26 shows that the market price for ethane, propane, butane. The price increased from ethane to butane, hence an economic analysis should be done to prevent excessive cost invest in the CO_2 miscible flooding.

Solid precipitation can occur with the increasing of H2S in the content of injection gas. Some solvent wash have to be use in order to dissolve them. When H2S is present along with CO_2, sour well corrosion occurs, which will bring severe problem to the well and pipelines. Same goes to CO_2; it will form corrosive carbonic acid when dissolved in water. Hence, CO_2 dehydration is required prior transporting to prevent excessive corrosion.

Most projects have experienced early CO_2 breakthrough, usually after injection of 0.05 to 0.2 hydrocarbons PV of total fluid (Stalkup, 1978). This happened when gas moves through a reservoir more easily than oil and caused CO_2 searching for a “quick-exit”, leaving the oil behind (Bon and Sarma, 2005). WAG (Water Alternate Gas) scheme was implemented to prevent gas breakthrough and helps to maintain a stable front for the CO_2 flood.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

Minimum miscibility pressure (MMP) determination using ECIPSE 300 reservoir simulation has been conducted on Dulang crude oil. The MMP of Dulang's crude oil is estimated to be 3528 psia at 215 ℉ which is about 1728 psia higher than initial reservoir pressure. In order to lower the MMP of crude oil, this study is carried out using different gas composition. Based on the results above, the author has identified that addition of H_2S, C_2, C_3, C_4 and C_5 in CO_2 gas; they give a lower MMP compare to pure CO_2. Furthermore, it is seen that C_2 has the same effectiveness in reducing MMP as H_2S. In addition, C_3 is more effective than H_2S and C_2, while C_5 is slightly effective than C_4. After simulate all 16 synthetic gas samples, the lowest MMP for Dulang crude oil has been identified. Gas 15 has provided the lowest MMP and the MMP is below the initial Dulang reservoir pressure. Therefore, miscible flooding is achievable or feasible in Malaysia oil field by using Gas 15 as injection gas into the reservoir.

In the nutshell, the author is able to complete this dissertation within given time frame. All the workflows for FYP I and FYP II were completed and met the relevant objectives.

5.2 RECOMMENDATIONS FOR FUTURE WORK

This simulation work is only focuses based on slim tube model; hence it is recommended that a real full field data is used to determine the minimum miscibility pressure (MMP) if time permits. A detailed economic analysis should be done to have a close look whether it is economic feasible to implement CO2 flooding in that particular field.

At the moment, there is neither a standard design, nor a standard set of criteria for obtaining MMP's with slim tube plot (Mogensen et al. 2009). Hence, in order to increase the accuracy of the results, it is recommended that the result obtained from simulation should be compared or verified with result obtained from other sources such as other simulation software, experimental and correlation.

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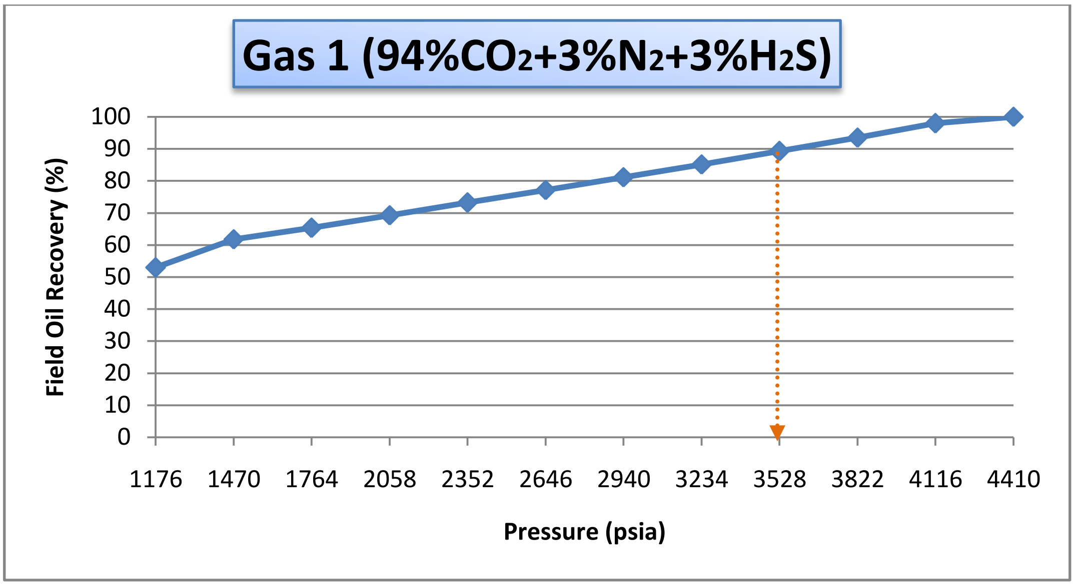
APPENDICES

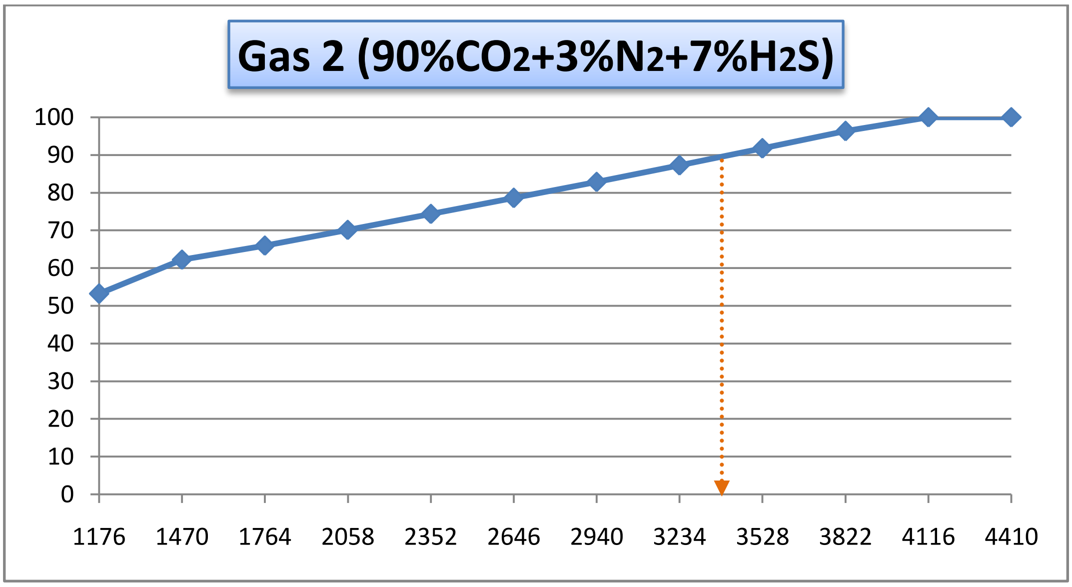
Appendix A

Effect Of Synthetic Gas Composition On Minimum Miscibility Pressure (MMP)

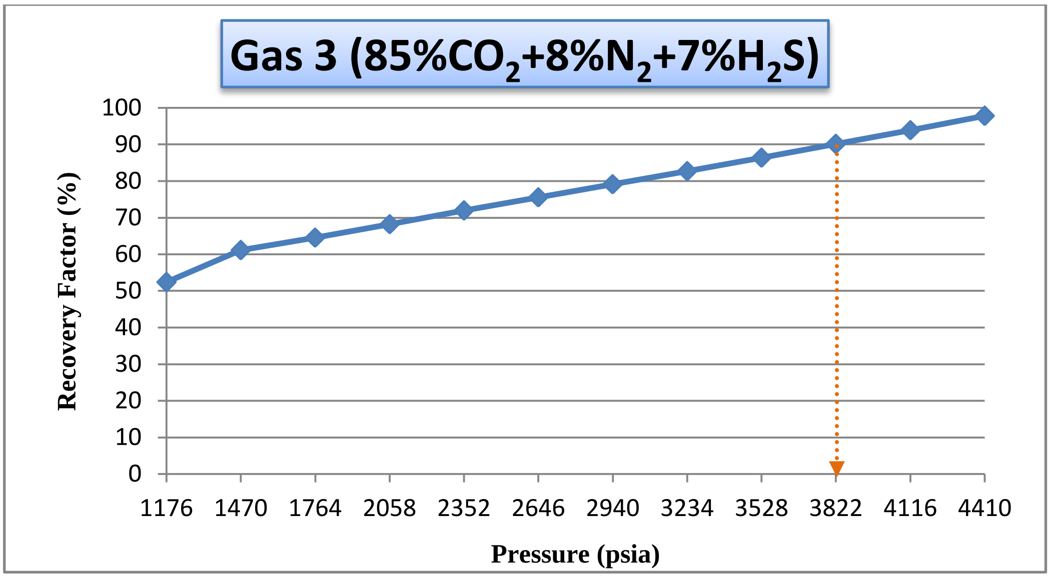
1. **Gas 1 (94%CO_2+3%N_2+3%H_2S)**



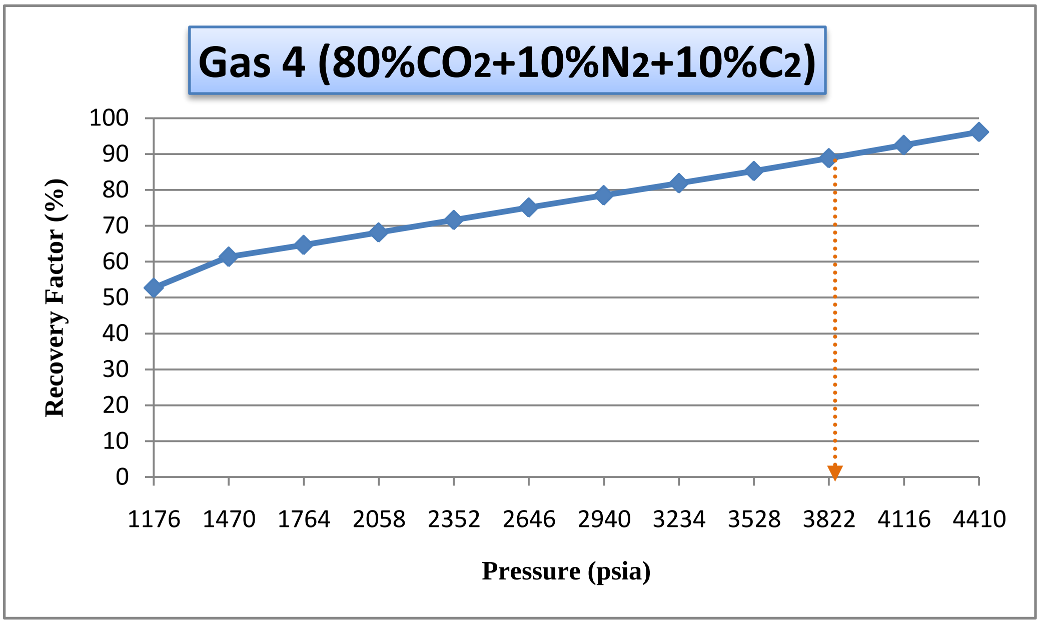
2. **Gas 2 (90%CO_2+3%N_2+7%H_2S)**



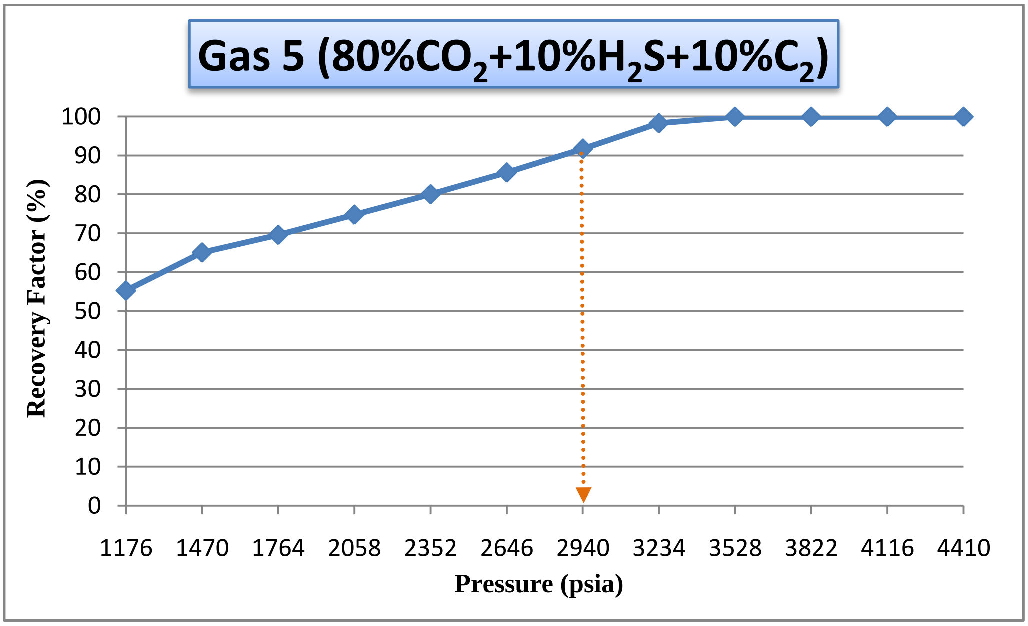
3. Gas 3 ($85\%CO_2+8\%N_2+7\%H_2S$)



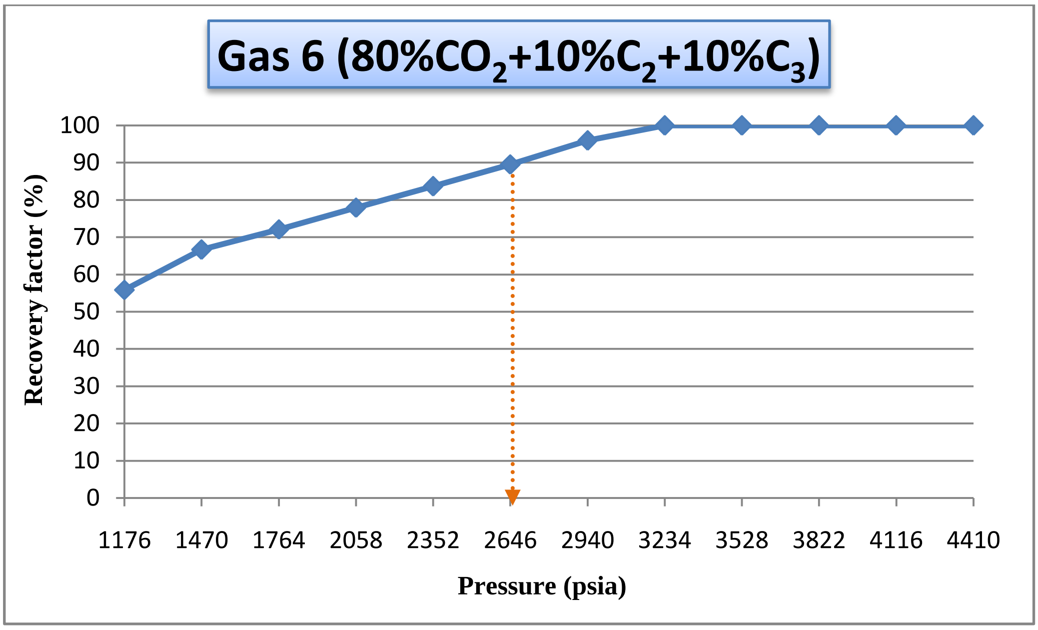
4. Gas 4 ($80\%CO_2+10\%N_2+10\%C_2$)



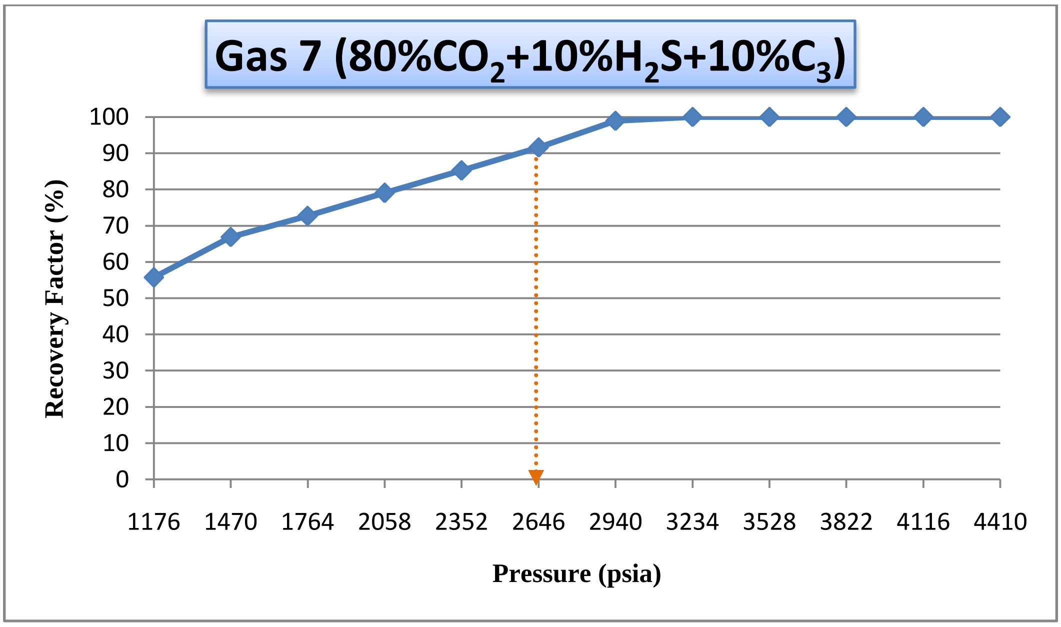
5. Gas 5 (80% CO_2+10% H_2S+10% C_2)



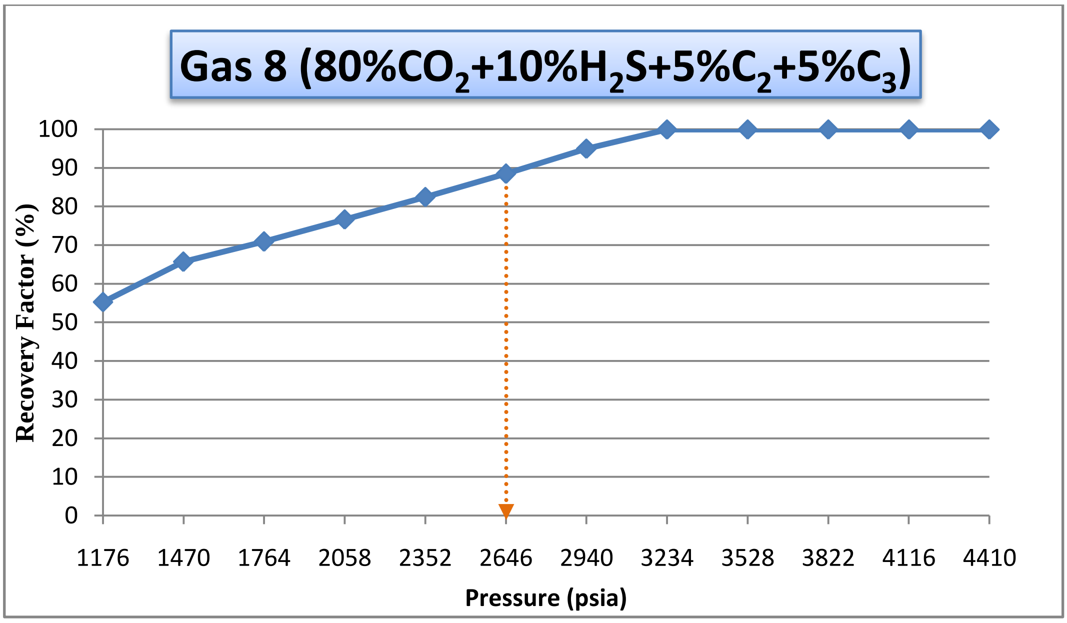
6. Gas 6 (80% CO_{2+}10% C_2+10% C_3)



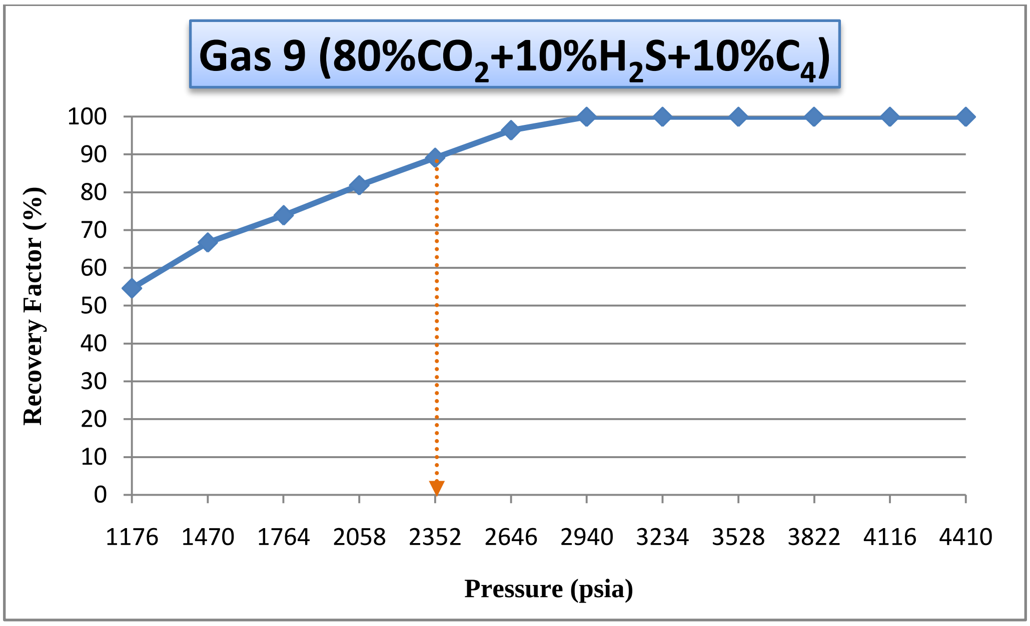
7. **Gas 7 ($80\%CO_2+10\%H_2S+10\%C_3$)**



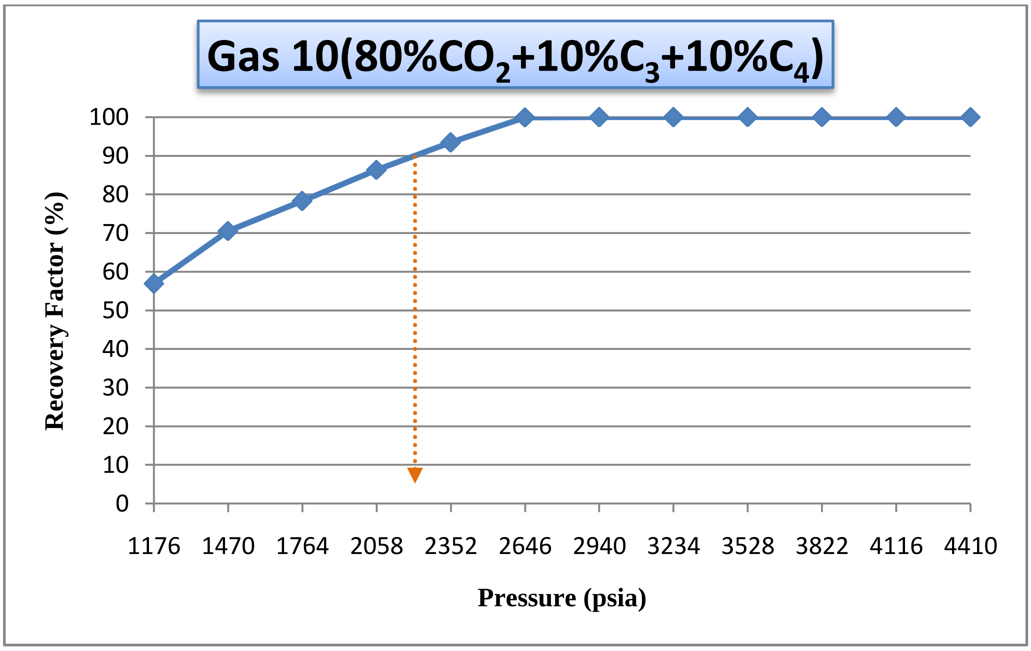
8. **Gas 8 ($80\%CO_2+10\%H_2S+5\%C_2+5\%C_3$)**



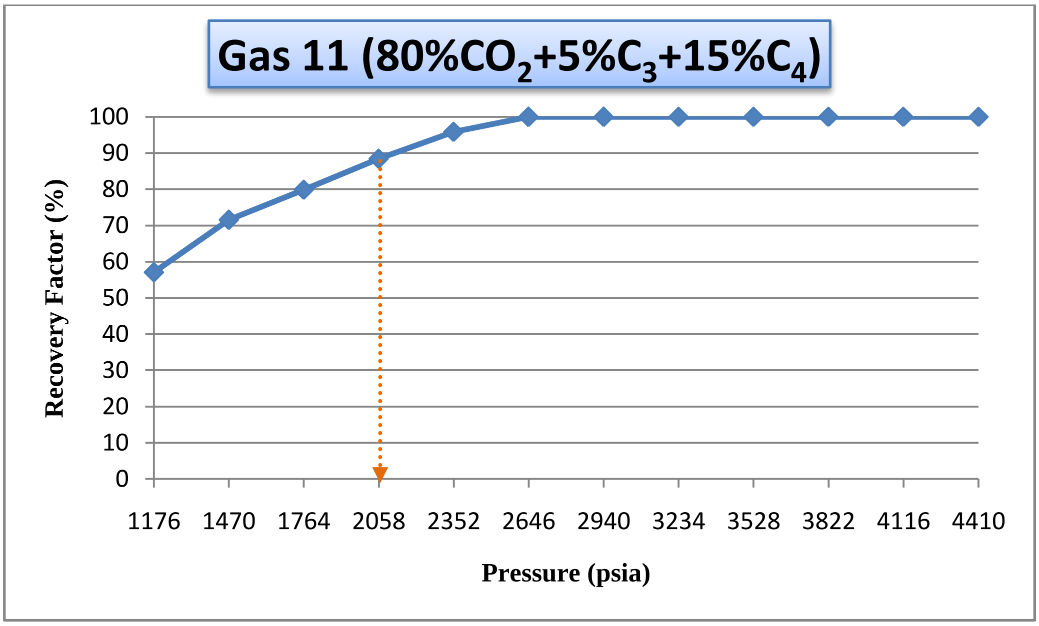
9. **Gas 9 ($80\%CO_2+10\%H_2S+10\%C_4$)**



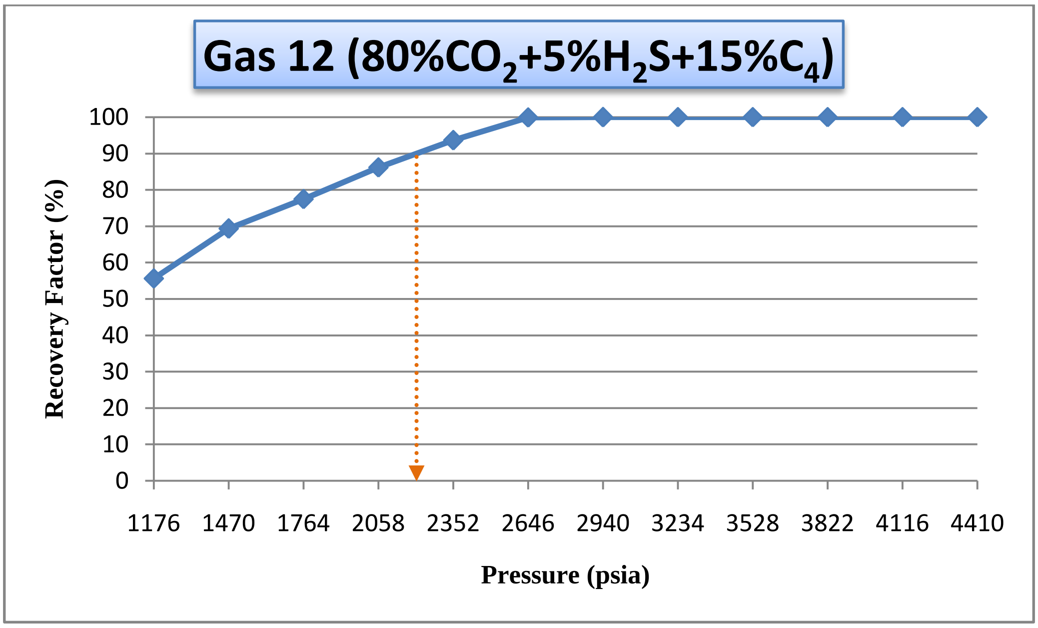
10. **Gas 10 ($80\%CO_2+10\%C_3+10\%C_4$)**



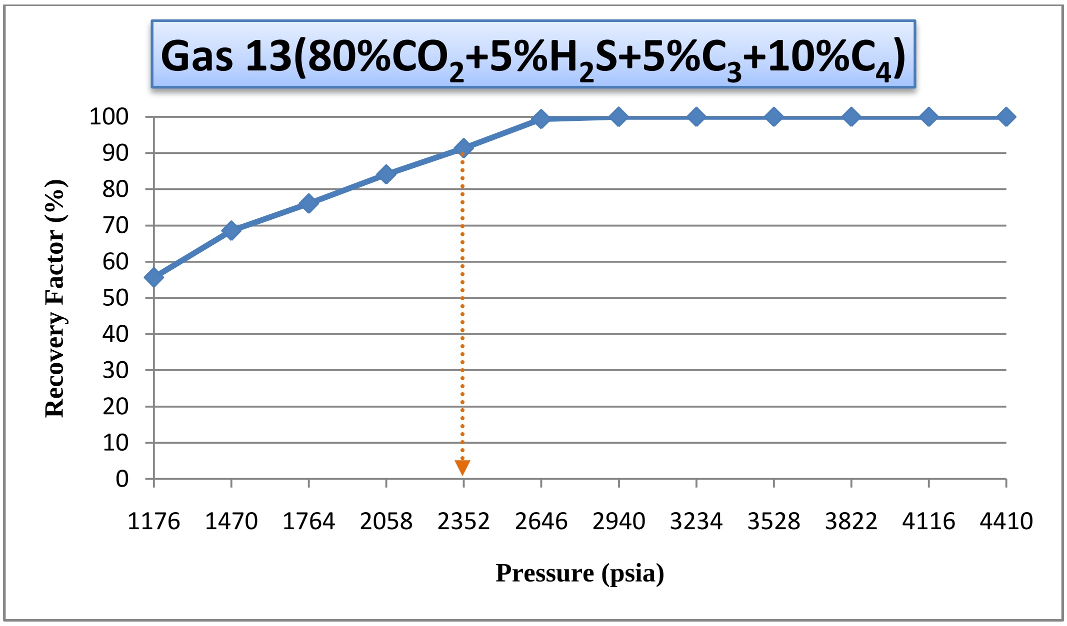
11. Gas 11 (80% CO_2+5% C_3+15% C_4)



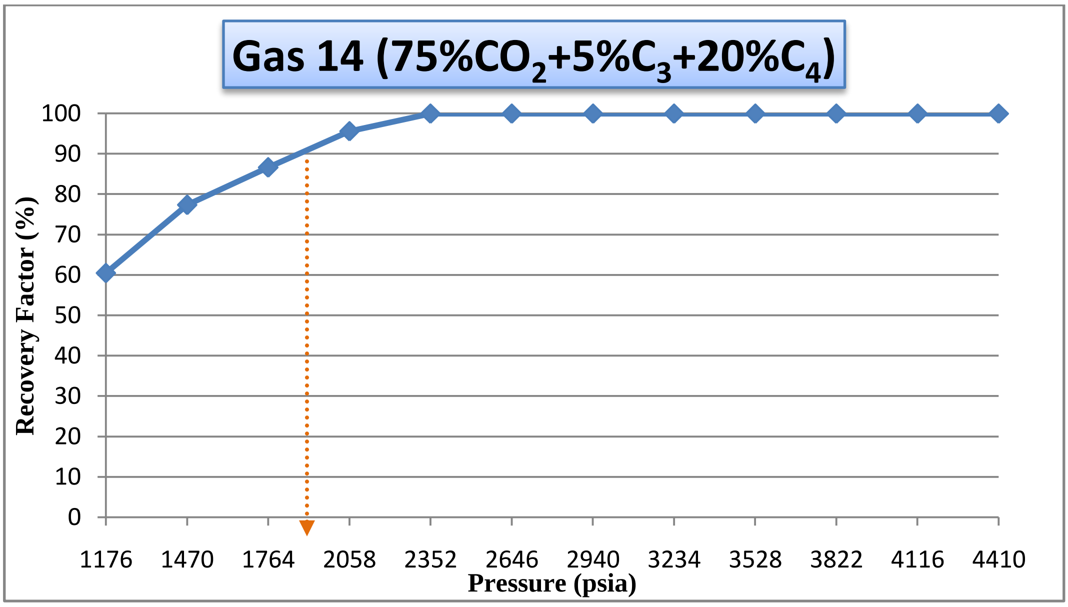
12. Gas 12 (80% CO_2+5% H_2S+15% C_4)



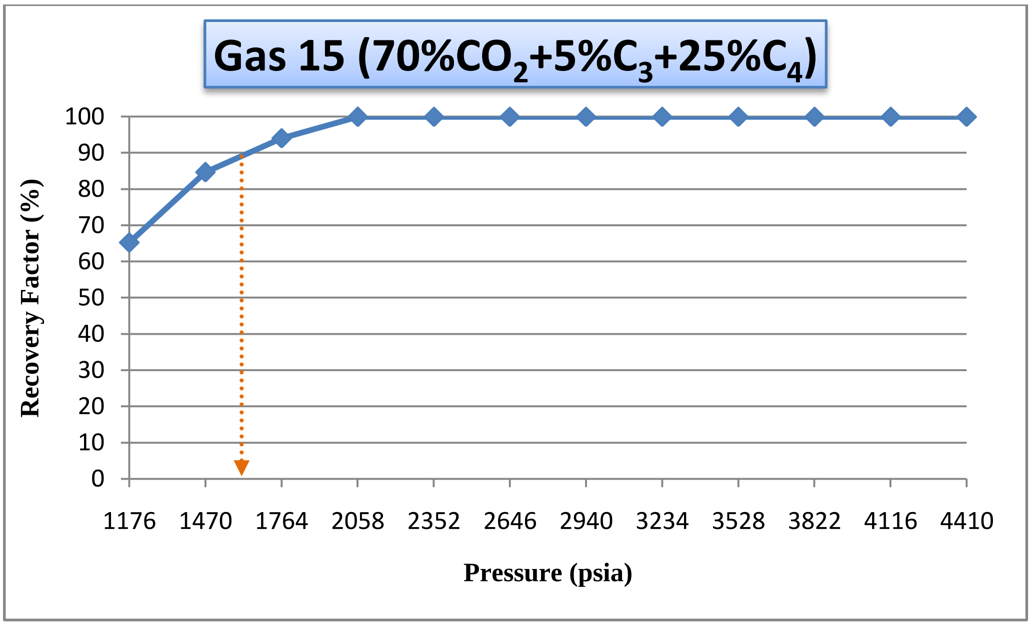
13. Gas 13 (80% CO_2+5% H_2S+5% C_3+10% C_4)



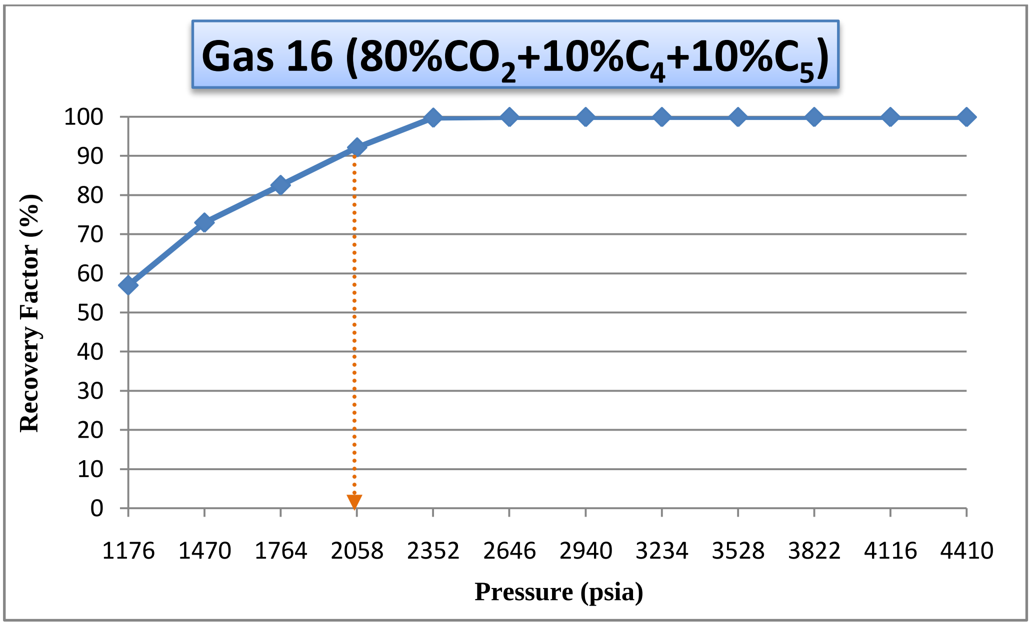
14. Gas 14 (75% CO_2+5% C_3+20% C_4)



15. Gas 15 (70% CO_2+25% C_4+5% C_3)



16. Gas 16 (80% CO_2+10% C_4+10% C_5)



Appendix B

Data File for Scenario 1

```
-->Simulation of a 10 metre slimtube
using lab units
-- 5 components
-- Peng-Robinson EoS
-- Grid dimensions 200x1x1
-- FULLIMP solution method
-- LAB units
-- OIL GAS only, no water
-------------------------------------------------
RUNSPEC
==============================
OIL
GAS

FULLIMP

DIMENS
200  1  1  /

-- Cartesian co-ord system
CART

-- Units: Lab
LAB

-- Number of components: implies
compositional run
COMPS
16 /

MISCIBLE

GRID
==============================
DX
200*5 /

--Cross section is 1 square cm

DY
200*1.0 /

DZ
200*1.0 /

-- Porosity and permeability
PORO
200*0.1 /
PERMX
200*2000.0 /

PERMY
200*2000.0 /

PERMZ
200*2000.0 /

--Depth of cell centres
MIDS
200*100.0 /

PROPS
==============================
-- Properties section: PVT data from
INCLUDE file

EOS
PR    /

CNAMES
  'CO2'
  'N2'
  'H2S'
  'C1'
  'C2'
  'C3'
  'IC4'
  'NC4'
  'IC5'
  'NC5'
  'C6'
  'C7'
  'C8'
  'C9'
  'C10'
  'C11+'
/

MISCEXP
0.2 /
```

```
BIC
-- Binary Interaction Coefficients
(Reservoir EoS)
-0.012
   0.096   0.176
     0.1     0.1    0.05
     0.1     0.1    0.05       0
     0.1     0.1    0.05       0       0
     0.1     0.1    0.05       0       0       0
     0.1     0.1    0.05       0       0       0
0
     0.1     0.1    0.05       0       0       0
0       0
     0.1     0.1    0.05       0       0       0
0       0       0
     0.1     0.1    0.05  0.0279    0.01
0.01       0       0       0       0
     0.1     0.1    0.05 0.03308    0.01
0.01       0       0       0       0
         0
     0.1     0.1    0.05  0.0363    0.01
0.01       0       0       0       0
         0       0
     0.1     0.1    0.05 0.03896    0.01
0.01       0       0       0       0
         0       0       0
     0.1     0.1    0.05 0.04092    0.01
0.01       0       0       0       0
         0       0       0       0
     0.1     0.1    0.05 0.04903125    0.01
0.01       0       0       0
         0       0       0       0       0       0
/

PCRIT
-- Critical Pressures (Reservoir EoS)
          72.9
          33.5
          88.2
         45.44
          48.2
          41.9
            36
         37.47
         33.45
         33.26
         29.71
            29
         28.42
         25.96
         23.88
  15.9238855729396
/

TCRIT
-- Critical Temperatures (Reservoir EoS)
--
         304.7
         126.2
         373.6
         190.6
        305.43
         369.8
         408.1
         425.2
         460.4
         469.6
         507.5
           548
           575
           603
           626
  743.034515766089
/

MW
-- Molecular Weights (Reservoir EoS)
--
         44.01
        28.013
        34.076
        16.043
         30.07
        44.097
        58.124
        58.124
        72.151
        72.151
            84
            96
           107
           121
           134
      223.5035
/

ACF
--
-- Acentric Factors (Reservoir EoS)
--
         0.225
```

0.04
0.1
0.013
0.0986
0.1524
0.1848
0.201
0.227
0.251
0.299
0.3
0.312
0.348
0.385
0.726851247067162
/

ZCRIT
-- Critical Z-Factors (Reservoir EoS)
0.274077797373227
0.291151404389918
0.281954299174958
0.284729476628582
0.284634795100356
0.276164620041118
0.28273695875079
0.273855549100576
0.272710871582637
0.268438914149838
0.250417484943592
0.252810107997845
0.260816494200699
0.253935643949794
0.248251667320208
0.229898071770294
/

ZCRITVIS
-- Critical Z-Factors for Viscosity Calculation (Reservoir EoS)
0.274077797373227
0.291151404389918
0.281954299174958
0.284729476628582
0.284634795100356
0.276164620041118
0.28273695875079
0.273855549100576
0.272710871582637
0.268438914149838
0.250417484943592
0.252810107997845
0.260816494200699
0.253935643949794
0.248251667320208
0.229898071770294
/

OMEGAA
--
-- EoS Omega-a Coefficient (Reservoir EoS)
--
0.457235529
0.457235529
0.457235529
0.457235529
0.457235529
0.457235529
0.457235529
0.457235529
0.457235529
0.457235529
0.457235529
0.457235529
0.457235529
0.457235529
0.457235529
0.457235529
/

OMEGAB
-- EoS Omega-b Coefficient (Reservoir EoS)
--
0.077796074
0.077796074
0.077796074
0.077796074
0.077796074
0.077796074
0.077796074
0.077796074
0.077796074
0.077796074
0.077796074
0.077796074
0.077796074
0.077796074
0.077796074
0.077796074
/

```
PARACHOR
--
-- Component Parachors
--
        78
        41
        80
        77
       108
      150.3
      181.5
      189.9
       225
      231.5
       271
      312.5
      351.5
       380
      404.9
  577.975378345
/

STCOND
15.0 1.0 /

GRAVITY
1* 1.01 1* /

-- Reservoir temperature: Deg C
RTEMP
101.666666666667 /

-- Rock and properties
ROCK
136.0  0.000004  /

SGFN
0.00  0.0000  0.0
0.10  0.0156  0.0
0.20  0.0625  0.0
0.30  0.1406  0.0
0.40  0.2500  0.0
0.50  0.3906  0.0
0.60  0.5625  0.0
0.70  0.7656  0.0
0.80  1.0000  0.0  /

SOF2
0.20  0.0000
0.30  0.0278
0.40  0.1109
0.50  0.2500
0.60  0.4444
0.70  0.6944
0.75  0.8403
0.80  1.0000 /

SOLUTION
=============================
--  Solution section: define explicitly

PRESSURE
200*80.0 /

SGAS
200*0.0 /

XMF
200*0.20743
200*0.00109
200*0.00000
200*0.15062
200*0.03007
200*0.0271
200*0.01032
200*0.00854
200*0.00415
200*0.00283
200*0.02917
200*0.02833
200*0.01285
200*0.0247
200*0.02357
200*0.43923 /

YMF
200*0.20743
200*0.00109
200*0.00000
200*0.15062
200*0.03007
200*0.0271
200*0.01032
200*0.00854
200*0.00415
200*0.00283
200*0.02917
200*0.02833
200*0.01285
200*0.0247
200*0.02357
200*0.43923 /
```

```
--  Calculate initial oil and gas in place
at surface conditions
FIELDSEP
1 15.0 1.0 /
/

RPTSOL
PRES  SOIL  SGAS  /

OUTSOL
PRES  SOIL  SGAS /

SUMMARY
=============================
WOPR
PRODUCER  /

FOPR

WOPT
PRODUCER  /

WGOR
PRODUCER  /

-- field Recovery factor
FOE      /

RUNSUM

RPTONLY

SCHEDULE
=============================
CVCRIT
-0.001 /

SEPCOND
SEPP  G2  1  15.0  1.0 /
/

--2000a WELLSPEC is used for back-
compatibility, prefered keyword is
WELSPECS
--WELLSPEC
--INJECTOR G1  1 1 1*       /
--PRODUCER G2 200 1 1* SEPP  /
WELSPECS
INJECTOR G1   1 1 1* GAS  /
PRODUCER G2 200 1 1* OIL  /
/

--2000a uses WELSEPC to associate
separator with wells
WSEPCOND
PRODUCER SEPP /
/

--2000a WELLCOMP is for back-
compatibility, prefered keyword is
COMPDAT
--WELLCOMP
--INJECTOR  1 1  1  1  1 1* 5000 /
--PRODUCER 200 1  1  1  1 1* 5000 /
COMPDAT
INJECTOR   1 1  1  1  OPEN 1 5000 /
PRODUCER 200 1  1  1  OPEN 1 5000/
/

WELLSTRE
FLUE  0.9  0  0  0.1 /
/

--Total pore volume is 100ccs, inject
1/10 PV per hour

--2000a WELLINJE is for back-
compatibility, prefered keyword is
WCONINJE
--WELLINJE
--INJECTOR  STREAM  LEANGAS
RV  5* 10.0 /
WCONINJE
INJECTOR  GAS OPEN RESV 1* 10.0/
/

WINJGAS
INJECTOR STREAM FLUE /
/

--2000a WELLPROD is for back-
compatibility, prefered keyword is
WCONPROD
--WELLPROD
--PRODUCER  BHP  4*  136.0  /
WCONPROD
PRODUCER  OPEN BHP  5*  80.0  /
/

RPTPRINT
1 1 1 1 1   1 1 1 0 0 /

RPTSCHED
PRESSURE  SOIL  SGAS /
```

--Limit max step to get at least 500
timesteps per 10 hours = 1 PV injected

TSCRIT
0.001 0.0001 0.02 /

--Run for 12 hours - ie 1.2 pore volumes
injected

TIME
1 2 3 4 5 6 7 8 9 10 11 12 /

END

Appendix C

Data File for Scenario 2

```
-->Simulation of a 10 metre slimtube
using lab units
-- 5 components
-- Peng-Robinson EoS
-- Grid dimensions 200x1x1
-- FULLIMP solution method
-- LAB units
-- OIL GAS only, no water
--------------------------------------------------

RUNSPEC
==============================
OIL
GAS

FULLIMP

DIMENS
200  1  1  /

-- Cartesian co-ord system
CART

-- Units: Lab
LAB

-- Number of components: implies
compositional run
COMPS
16 /

MISCIBLE

GRID
==============================
DX
200*5 /

--Cross section is 1 square cm

DY
200*1.0 /

DZ
200*1.0 /
-- Porosity and permeability
PORO
200*0.1 /
PERMX
200*2000.0 /

PERMY
200*2000.0 /

PERMZ
200*2000.0 /

--Depth of cell centres
MIDS
200*100.0 /

PROPS
==============================
-- Properties section: PVT data from
INCLUDE file

EOS
PR    /

CNAMES
   'CO2'
   'N2'
   'H2S'
   'C1'
   'C2'
   'C3'
   'IC4'
   'NC4'
   'IC5'
   'NC5'
   'C6'
   'C7'
   'C8'
   'C9'
   'C10'
   'C11+'
/

MISCEXP
0.2 /
```

```
BIC
-- Binary Interaction Coefficients
(Reservoir EoS)
 -0.012
   0.096   0.176
     0.1     0.1    0.05
     0.1     0.1    0.05       0
     0.1     0.1    0.05       0       0
     0.1     0.1    0.05       0       0       0
     0.1     0.1    0.05       0       0       0
0
     0.1     0.1    0.05       0       0       0
0       0
     0.1     0.1    0.05       0       0       0
0       0       0
     0.1     0.1    0.05  0.0279    0.01
0.01       0       0       0       0
     0.1     0.1    0.05 0.03308    0.01
0.01       0       0       0       0
         0
     0.1     0.1    0.05  0.0363    0.01
0.01       0       0       0       0
         0       0
     0.1     0.1    0.05 0.03896    0.01
0.01       0       0       0       0
         0       0       0
     0.1     0.1    0.05 0.04092    0.01
0.01       0       0       0       0
         0       0       0       0
     0.1     0.1    0.05 0.04903125    0.01
0.01       0       0       0
         0       0       0       0       0       0
/

PCRIT
-- Critical Pressures (Reservoir EoS)
          72.9
          33.5
          88.2
         45.44
          48.2
          41.9
            36
         37.47
         33.45
         33.26
         29.71
            29
         28.42
         25.96
         23.88
   15.9238855729396
```

```
/
TCRIT
-- Critical Temperatures (Reservoir EoS)
--
         304.7
         126.2
         373.6
         190.6
        305.43
         369.8
         408.1
         425.2
         460.4
         469.6
         507.5
           548
           575
           603
           626
   743.034515766089
/

MW
--
-- Molecular Weights (Reservoir EoS)
--
         44.01
        28.013
        34.076
        16.043
         30.07
        44.097
        58.124
        58.124
        72.151
        72.151
            84
            96
           107
           121
           134
      223.5035
/
```

```
ACF
-- Acentric Factors (Reservoir EoS)
--
       0.225
        0.04
         0.1
       0.013
      0.0986
      0.1524
      0.1848
       0.201
       0.227
       0.251
       0.299
         0.3
       0.312
       0.348
       0.385
  0.726851247067162
/

ZCRIT
-- Critical Z-Factors (Reservoir EoS)
--
  0.274077797373227
  0.291151404389918
  0.281954299174958
  0.284729476628582
  0.284634795100356
  0.276164620041118
  0.28273695875079
  0.273855549100576
  0.272710871582637
  0.268438914149838
  0.250417484943592
  0.252810107997845
  0.260816494200699
  0.253935643949794
  0.248251667320208
  0.229898071770294
/

ZCRITVIS
-- Critical Z-Factors for Viscosity
Calculation (Reservoir EoS)
--
  0.274077797373227
  0.291151404389918
  0.281954299174958
  0.284729476628582
  0.284634795100356
  0.276164620041118
  0.28273695875079
  0.273855549100576
  0.272710871582637
  0.268438914149838
  0.250417484943592
  0.252810107997845
  0.260816494200699
  0.253935643949794
  0.248251667320208
  0.229898071770294
/

OMEGAA
-- EoS Omega-a Coefficient (Reservoir
EoS)
--
  0.457235529
  0.457235529
  0.457235529
  0.457235529
  0.457235529
  0.457235529
  0.457235529
  0.457235529
  0.457235529
  0.457235529
  0.457235529
  0.457235529
  0.457235529
  0.457235529
  0.457235529
  0.457235529
/

OMEGAB
-- EoS Omega-b Coefficient (Reservoir
EoS)
  0.077796074
  0.077796074
  0.077796074
  0.077796074
  0.077796074
  0.077796074
  0.077796074
  0.077796074
  0.077796074
  0.077796074
  0.077796074
  0.077796074
  0.077796074
```

```
  0.077796074
   0.077796074
   0.077796074
/
 PARACHOR
-- Component Parachors
            78
            41
            80
            77
           108
          150.3
          181.5
          189.9
           225
          231.5
           271
          312.5
          351.5
           380
          404.9
   577.975378345
/
STCOND
15.0 1.0 /

GRAVITY
1* 1.01 1* /

-- Reservoir temperature: Deg C
RTEMP
101.666666666667 /

-- Rock and properties
ROCK
136.0  0.000004  /

SGFN
0.00  0.0000  0.0
0.10  0.0156  0.0
0.20  0.0625  0.0
0.30  0.1406  0.0
0.40  0.2500  0.0
0.50  0.3906  0.0
0.60  0.5625  0.0
0.70  0.7656  0.0
0.80  1.0000  0.0  /

SOF2
0.20  0.0000
0.30  0.0278
0.40  0.1109
0.50  0.2500
0.60  0.4444
0.70  0.6944
0.75  0.8403
0.80  1.0000 /
SOLUTION
=============================
--  Solution section: define explicitly

PRESSURE
200*80.0 /

SGAS
200*0.0 /

XMF
200*0.20743
200*0.00109
200*0.00000
200*0.15062
200*0.03007
200*0.0271
200*0.01032
200*0.00854
200*0.00415
200*0.00283
200*0.02917
200*0.02833
200*0.01285
200*0.0247
200*0.02357
200*0.43923 /

YMF
200*0.20743
200*0.00109
200*0.00000
200*0.15062
200*0.03007
200*0.0271
200*0.01032
200*0.00854
200*0.00415
200*0.00283
200*0.02917
200*0.02833
200*0.01285
200*0.0247
200*0.02357
200*0.43923 /
```

```
--  Calculate initial oil and gas in place
at surface conditions
FIELDSEP
1 15.0 1.0 /
/


RPTSOL
PRES  SOIL  SGAS  /

OUTSOL
PRES  SOIL  SGAS /

SUMMARY
=============================
WOPR
PRODUCER  /

FOPR

WOPT
PRODUCER  /

WGOR
PRODUCER  /

-- field Recovery factor
FOE      /

RUNSUM

RPTONLY

SCHEDULE
=============================
CVCRIT
-0.001 /

SEPCOND
SEPP  G2  1  15.0  1.0 /
/

--2000a WELLSPEC is used for back-
compatibility, prefered keyword is
WELSPECS
--WELLSPEC
--INJECTOR G1  1 1 1*       /
--PRODUCER G2 200 1 1* SEPP  /
WELSPECS
INJECTOR G1   1 1 1* GAS  /
PRODUCER G2 200 1 1* OIL  /
/

--2000a uses WELSEPC to associate
separator with wells
WSEPCOND
PRODUCER SEPP /
/

--2000a WELLCOMP is for back-
compatibility, prefered keyword is
COMPDAT
--WELLCOMP
--INJECTOR  1 1  1  1  1 1* 5000 /
--PRODUCER 200 1  1  1  1 1* 5000 /
COMPDAT
INJECTOR   1 1  1  1  OPEN 1 5000 /
PRODUCER 200 1  1  1  OPEN 1 5000/
/

WELLSTRE
FLUE  0.8  0  0.1  0  0.05  0.05/
/

--Total pore volume is 100ccs, inject
1/10 PV per hour

--2000a WELLINJE is for back-
compatibility, prefered keyword is
WCONINJE
--WELLINJE
--INJECTOR  STREAM  LEANGAS
RV  5* 10.0 /
WCONINJE
INJECTOR  GAS OPEN RESV 1* 10.0/
/

WINJGAS
INJECTOR STREAM FLUE /
/

--2000a WELLPROD is for back-
compatibility, prefered keyword is
WCONPROD
--WELLPROD
--PRODUCER  BHP  4*  136.0  /
WCONPROD
PRODUCER  OPEN BHP  5*  80.0  /
/

RPTPRINT
1 1 1 1 1   1 1 1 0 0 /
```

```
RPTSCHED
PRESSURE  SOIL  SGAS /


--Limit max step to get at least 500
timesteps per 10 hours = 1 PV injected

TSCRIT
0.001 0.0001 0.02 /

--Run for 12 hours - ie 1.2 pore volumes
injected

TIME
1 2 3 4 5 6 7 8 9 10 11 12 /

END
```