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**EOR SCREENING AND OPTIMIZING
STUDY ON SANDSTONE RESERVOIRS**

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10870

DISSERTATION REPORT

**PETROLEUM ENGINEERING
UNIVERSITI TEKNOLOGI PETRONAS
SEPTEMBER 2011**

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.



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CERTIFICATION OF APPROVAL

Multiphase Behaviour of CO₂, Hydrocarbon and Water Mixtures at Reduced Temperature

by

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ABSTRACT

CO₂ flooding is often applied as the tertiary recovery technique for light and medium oils after water flooding. Water flooding leaves high water saturation inside the reservoir. As a result, the reservoir fluid system consists of hydrocarbon and high water saturation. Therefore, for the CO₂ based EOR techniques, knowledge of multiphase behaviour and properties of CO₂ -reservoir fluids (hydrocarbon and water) mixture is important in order to determine the displacement efficiency, recovery evaluation, development, design and operation of the process.

It has been suggested that the high recovery of CO₂ flooding above certain pressure is a result of the formation of a dense CO₂ liquid phase that efficiently extract the C5+ fraction of the oil. From the CO₂ properties studies, CO₂ is in liquid phase when the temperature is under its critical temperature (31.1°C) and at certain pressure range. This study aims to investigate the phase behaviour of CO₂, hydrocarbon and high water content under low temperature (60°C to 30°C), so that we can predict the phases that is present and estimate the volume percentage of the phases.

This project consists of experimental work to predict the phase behaviour of two samples. The first sample is CO₂ and Dulang oil mixture (as the base case) and the second sample is CO₂, Dulang oil and water mixture. The temperature of wax formation is identified and the volume phases are measured at different low temperatures range (30°C to 60°C) and pressures of 2500psi to 500psi. The viscosity of CO₂ and hydrocarbon mixture is measured as additional properties analysis.

Results of the experiments show that, gas, CO₂-rich liquid and oil-rich liquid (G/L₁/L₂) occurred for CO₂-Crude oil mixtures at temperature below the CO₂ critical temperature (31°C) and at the pressure of around 900 psi. From compositional analysis, the CO₂-rich liquid phase (L₂) that occurred is resulted from the extracted C5+ component of the oil. This indicates that CO₂ can achieve miscibility with Dulang oil at temperature of 30°C. While for the CO₂, Dulang oil and water mixture, no formation of CO₂-rich liquid phase occurred. This may be due to the solubility of CO₂ in the water, leaving only little volume of CO₂ to react with the oil.

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CHAPTER 1

INTRODUCTION

1.1 Background of study

CO₂ miscible flooding is one of the principal EOR methods and developed on a commercial scale in many oil reservoirs. Since its development in 1970's, CO₂ flooding has become a leading EOR technique for light and medium oils. There are two major variations in miscible process that is first-contact-miscible (FMC) process and multiple-contact-miscible (MCM) process. CO₂ miscible flooding is one such process under the multiple-contact-miscible (MCM) (Green and Willhite, 1998). A key parameter in the design of CO₂ injection project is the minimum miscibility pressure (MMP), whereas local displacement efficiency from CO₂ injection is highly dependent on the MMP.

Petroleum reservoir fluid are mixtures of naturally occurring hydrocarbons that may exist in gaseous, liquid or in some rare cases solid state depending upon the prevalent pressure and temperature conditions in the petroleum reservoir. This particular state of the hydrocarbon mixture is primarily dictated or is a result of the pertinent pressure and temperature conditions that exist inside the reservoir. Therefore, the state of system can be predicted if only the pressure, temperature, chemistry and composition of CO₂ and hydrocarbon mixture are specified.

Mixing oil with CO₂ can produce multiple liquid and/or gas vapour phases in different pressure and temperature. Besides, according to Shelton and Yarborough, (1977), precipitation of solids phase is also probable when the reservoir oil is asphaltic. In order to understand better on the displacement behaviour of CO₂ inside the reservoir, the phase behaviour and its properties such as compressibility factors, density, viscosity and solubility need to be further evaluate.

Pressure and temperature are the two main variables that influence the behaviour and the properties of reservoir fluid. Therefore, relatively simple laboratory test that reflect the recovery of the hydrocarbon fluids are conducted by varying pressure and temperature, with primary emphasis on the volumetric data at reservoir and surface condition. This type of analysis that carried out on most reservoir fluid is called PVT analysis. Data measured from the PVT analysis is key elements of proper management of petroleum reservoirs, which include evaluation of

reserves, development of recovery plan and also determination of the quantity and quality of the produced fluids.

1.2 Problem Statement

Reservoir temperature is an important variable affecting the Minimum Miscibility Pressure (MMP) because its effect on the pressure required to achieve the CO₂ density required for miscible displacement (Yellig and Metcalfe, 1980). Higher miscibility pressure always results by the high reservoir temperature. High operating level of MMP may result in greatly inflated operation costs as well as occupational health concerns. Thus, reducing MMP by reducing the temperature of the system would bring significant economic benefits.

Besides, previous research on this Dulang field indicates that at the reservoir temperature of 215°F (101°C), CO₂ injection would not be able to achieve miscibility with the crude oil at the current reservoir pressure, or even if the pressure is increased to initial reservoir pressure (1800psi). CO₂ MMP for Dulang oil is estimated to be 2875psig at 215°F (101°C) and the process in the field will therefore be immiscible (Zahidah et al, 2001). This research is also conducted to see whether the CO₂ is able to achieve miscibility with Dulang oil at reduced temperature of the system.

After water flooding had been applied to the reservoir, the reservoir fluid system now consists of hydrocarbon and high saturated water system. To proceed with the tertiary recovery-EOR process, which in this case the CO₂ flooding, accurate data of CO₂, hydrocarbon and water mixture system are needed for CO₂ flooding phase behaviour prediction. This phase behaviour prediction is very important in order to determine the displacement efficiency, recovery evaluation, development, design and operation of the process. However, currently, there is not much literature data available on this multiphase behaviour of CO₂, hydrocarbon and water mixture, especially at reduced temperature.

Analysis of the mechanisms of CO₂ flooding is complicated by the fact that mixtures of CO₂ and most crude oils show complex phase behaviour (Orr Jr. et al 1981). It is important for the CO₂ and crude oil mixture to be miscible to obtain greater oil recovery. Besides, it has been suggested recently that the high recovery of CO₂ floods above a certain pressure is a result of the formation of dense CO₂ liquid phase that efficiently extract the C₅₊ fraction of the oil (Nghiem and Li, 1986). The

properties of CO₂ show that CO₂ liquid phase will occur below its critical temperature, 31.1°C and above certain pressure (above bubble point pressure). Therefore, investigation of CO₂ injection under low temperature is important to determine the liquid phase formation of the CO₂ and crude oil mixtures inside the reservoir.

1.3 Objectives

The objectives of the project are:

1. To identify the temperature of wax deposition and hydrates formation.
2. To observe the multiphase formation of the CO₂, hydrocarbon and water mixtures at reduced temperature.
3. To determine the viscosity of multiphase CO₂, hydrocarbon and water mixture under low temperature and different pressure.

1.4 Scope of study

This project is concentrate on the phase behaviour of CO₂, hydrocarbon and water mixture where the PVT analysis of the fluid mixture is conducted. Dulang crude oil which is light oil, CO₂ in the form of gas phase and distilled water are used in this experiment. Two samples are tested; Dulang crude oil and CO₂ mixture and another one are Dulang crude oil, CO₂ and water mixture. The samples are tested at constant mass condition and at four different low temperatures (30°C, 40°C, 50°C and 60°C). During the test, the mixture is pressurized at pressure range from 2500 psi to 500 psi. The behaviour of the phases present is observed and the total and phase volumes of the mixture are recorded at each pressure step.

The next experiment is to measure the fluid properties of the two samples mixture. The focus here is on the viscosity of the CO₂ and crude oil mixtures. Viscosity is measured using the capillary viscometer that attached to the PVT cell. The measurement is taken at the three different pressure; (1250, 1000 and 750psi) and same temperature range that is setup for the phase behaviour experiment before. Samples of the mixtures are also taken at temperature of 30°C and pressure of 800psi for the compositional analysis.

1.5 Relevancy and Feasibility

This project is relevant to the study of reservoir engineering as it is focused on the phase behaviour and the fluid properties of the CO₂, hydrocarbon and water mixtures. As mentioned before, the phase behaviour of CO₂, hydrocarbon and water mixtures that generated during the displacement is the important factors that affect the efficiency of a displacement of oil by CO₂. Thus, this project is a good work to add more literature data on the interpretation of CO₂, hydrocarbon and water mixture phase behaviour and its fluid properties under high pressure and low temperature.

For FYP 1, 10 weeks are optimized for the extensive research about the topic, study the available literature, gathering research materials and designing the experiment works. The gathering of research material that related to phase behaviour, viscosity, PVT analysis, and PVT experiment methodology are taken from the available petroleum engineering text books, journal, online technical papers and laboratory manual of the PVT equipments.

For FYP 2, the new PVT equipments in the PVT Lab are used and the materials required for the experiment which is crude oil sample, CO₂ gas and water are available in UTP as well. The experimental work is designed according to the specification of the PVT equipments. The experiments are planned to be conducted in the semester two, within the first seven weeks of the semester. Two samples are planned to be run for the main experiment, viscosity measurement and compositional analysis. For each sample measurement, CME test is estimated for two weeks, viscosity measurement is estimated for one week and compositional analysis is estimated for two days to be completed. Therefore, for two samples, about seven weeks are estimated to be enough and feasible within the time scope.

CHAPTER 2

THEORY & LITERATURE REVIEW

2.1 Theory:

2.1.1 Miscibility

Miscibility is the ability of two or more fluid substances (gases or liquids) to form a single homogeneous phase when mixed in all proportions. Miscibility is distinguished from “Solubility” which means the ability of one substance (fluid) to mix with a fluid or fluids and form a single homogeneous phase (Holm, 1987).

2.1.1 Miscible displacement processes

Miscible displacement process is a major branch of enhanced oil recovery (EOR). It is also called miscible gas drive, miscible drive or miscible flood. It is injection processes that introduce miscible gases into the reservoir to maintain reservoir pressure and improve oil displacement. The primary objective in miscible process is to displace oil with a fluid that is miscible with the oil (forms a single phase when mixed at all proportions with the oil) at the conditions existing at the interface between the injected fluid and the oil bank being displaced.

The injected gases include liquefied petroleum gas (LPG) such as propane, methane under high pressure, methane enriched with light hydrocarbon, nitrogen under high pressure and carbon dioxide under suitable reservoir condition of temperature and pressure. The fluid most commonly used for miscible displacement is carbon dioxide because it reduces the oil viscosity and is less expensive than liquefied petroleum gas.

There are two major variations in this process. The first one is called first-contact-miscible (FCM) process; the injected fluid is directly miscible with the reservoir oil at the conditions of pressure and temperature existing in the reservoir. The other variation of miscible process is the multiple-contact-miscible (MCM) process. In this process, the injected fluid is not miscible with the reservoir oil on first contact but under proper conditions of pressure, temperature and composition this composition modification will generate miscibility between the displacing and displaced phase.

2.1.3 CO₂ miscible process

The CO₂ miscible process illustrated in *Figure 1* is one such process of multiple-contact-miscible (MCM). A volume of relatively pure CO₂ is injected to mobilize and displace residual oil. Through multiple contacts between the CO₂ and the oil phase, intermediate- and higher-molecular-weight hydrocarbons are extracted into the CO₂-rich phase. Under proper condition, this CO₂-rich phase will reach a composition that is miscible with the original reservoir oil. From that point, miscible or near-miscible exist at the displacing front interface. Under ideal conditions, this miscibility condition will be reached very quickly in the reservoir and the distance required to established multiple-contact miscibility initially is negligible compared with the distance between wells. CO₂ volumes injected during a process are typically about 25% PV. The critical temperature of CO₂ is 87.7°F, and thus, in most cases it is injected as a fluid above its critical temperature. The viscosity of CO₂ at injection condition is small, about 0.06 to 0.10 cp, depending on reservoir temperature and pressure (Green and Willhite, 1998).

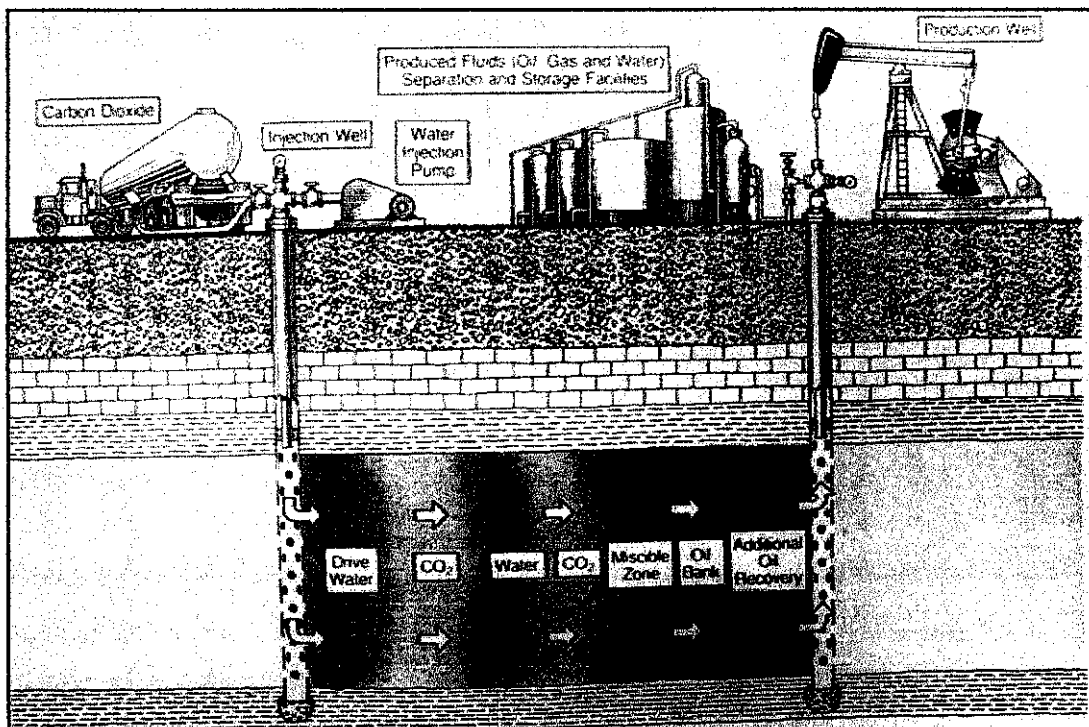


Figure 1: CO₂ Miscible Process (Green and Willhite, 1998)

2.1.4 CO₂ properties and phase behaviour

Phase Diagram of Carbon Dioxide:

The critical point of carbon dioxide occurs at 31.1°C and 1070.741psi. Below this temperature, the gas and liquid phase of the CO₂ can be clearly differentiated by the saturation line. Above the critical temperature, the CO₂ will be in fully supercritical fluid state (if $P > P_c$) or in partially supercritical vapour-like appearance (if $P < P_c$).

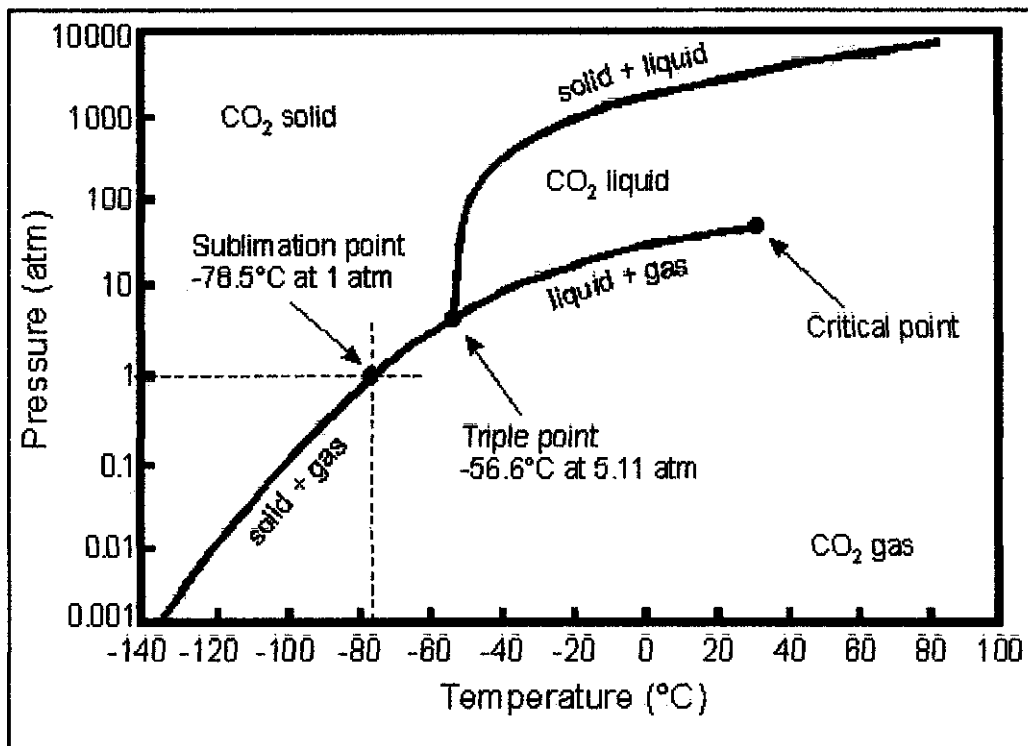


Figure 2: Phase diagram of CO₂.

2.1.5 Viscosity (Black oil and Volatile oil) variation with pressure and temperature

Oil viscosity, denoted by μ_o usually specified in centipoises, or cp, like other physical properties is affected by pressure as well as temperature. An increase in temperature causes a decrease in viscosity. Ordinarily, a decrease in pressure causes a decrease in viscosity and vice versa, provided that the only effect of pressure is to either decompress or compress the oil. The relationship between the viscosities of a black oil as a function of pressure at constant temperature is shown in *Figure 3* below. Viscosity for multicomponent system (Oil and CO₂ mixture) is discussed more under the literature review part.

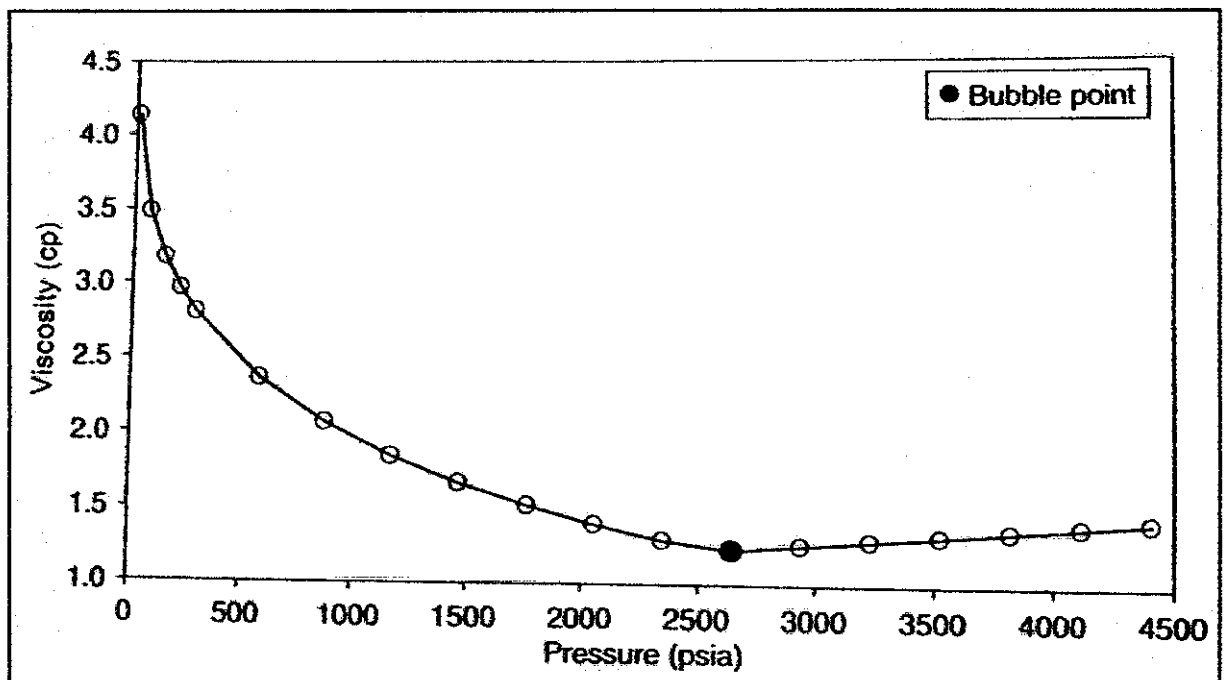


Figure 3: Variation in the viscosity of a black oil with pressure at constant reservoir temperature (Dandekar, 2006).

2.1.6 Mobility and Mobility ratio

Darcy equation which describes the flow of fluids in a porous medium, relates the velocity of fluid to the pressure gradient by a proportionality factor as displayed in equation below:

$$\mu_i = \frac{k_i dp}{\mu_i dx}$$

Where,

u = superficial velocity, cm/s

k = permeability, md

p = pressure, atm

x = length, cm and

μ =viscosity, cp

The subscript i represent a particular fluid. The proportionality factor is termed the mobility of the fluid and is the measure of the facility with which the fluid flows through the rock – i.e., how mobile it is. From equation above, the mobility of fluid i , λ_i , is defined as the effective permeability of the rock to fluid i divided by its viscosity, k_i/μ_i . For example, the mobility of oil is k_o/μ_o and the mobility of a miscible solvent is k_s/μ_s .

When one fluid displaces another, the mobility ratio, M of the displacement is defined as the mobility of the displacing fluid divided by the mobility of displaced fluid. Mobility ratio is one of the most important parameters of a miscible displacement and has a profound influence on volumetric sweepout of the solvent and on the integrity of the solvent slug.

2.2 Literature Review:

2.2.1 Efficiency of displacement oil by CO₂

Orr Jr. et al (1981) point out that the efficiency of a displacement of oil by CO₂ depends on a variety of factors including phase behaviour of CO₂ - crude oil mixture generated during the displacement, densities and viscosities of the phase present, relative permeability to individual phases, and a host of additional complications such as dispersion, viscous fingering, reservoir heterogeneities and layering.

Therefore, it is generally acknowledged that phase behaviour and attendant compositional effect on fluid properties strongly influence displacement of oil by CO₂.

2.2.2 Effect of low temperature reservoir on phase behaviour of CO₂ and crude oil mixture

Orr Jr. et al (1981) identified that at temperature not too far above the critical temperature of CO₂ (88°F or 31°C), mixtures of CO₂ and crude oil exhibit multiple liquid phases, and at some pressures L/L/V equilibria are observed.

Table 1 summarizes data reported for CO₂/Crude oil mixtures. Of the 10 system studied by Orr Jr. et al (1981), all those at temperature above 120°F (50°C) show only L/V equilibria while those below 120°F (50°C) exhibit L/L/V separations.

Crude Oil	Temperature (°F)	Phase Behavior
West Texas Oil ₇	90	L ₁ /L ₂ /V
Oil B ₈	94	L ₁ /L ₂ /V
Wasson ₅	105	L ₁ /L ₂ /V
Oil A ₁	190	L ₁ /L ₂ /V
Oil A ₉	130	L/V
Rangley ₁₀	160	L/V
Painter ₁₁	164	L/V
Oil C ₁	186	L/V
Weeks Island ₁₂	225	L/V
Oil B ₉	225	L/V

Table 1: Summary of CO₂/Crude oil systems for which phase behaviour has been reported by Orr Jr. et al (1981).

The occurrence of L/L and L/L/V phase behaviour on CO₂/Crude oil mixture is consistent with similar behaviour reported for binary and ternary mixtures of CO₂ with alkanes at temperature not too far above the critical temperature of CO₂. CO₂ also show immiscibility with hydrocarbons heavier than C₁₃ at temperature above 88°F (31°C).

2.2.3 Phase behaviour representation of CO₂ miscible process

The phase behaviour representation of this process is more complicated than the hydrocarbon injection process. *Figure 4* indicates the enrichment in C₅ to C₃₀ hydrocarbons that required to achieve the miscible displacement fronts.

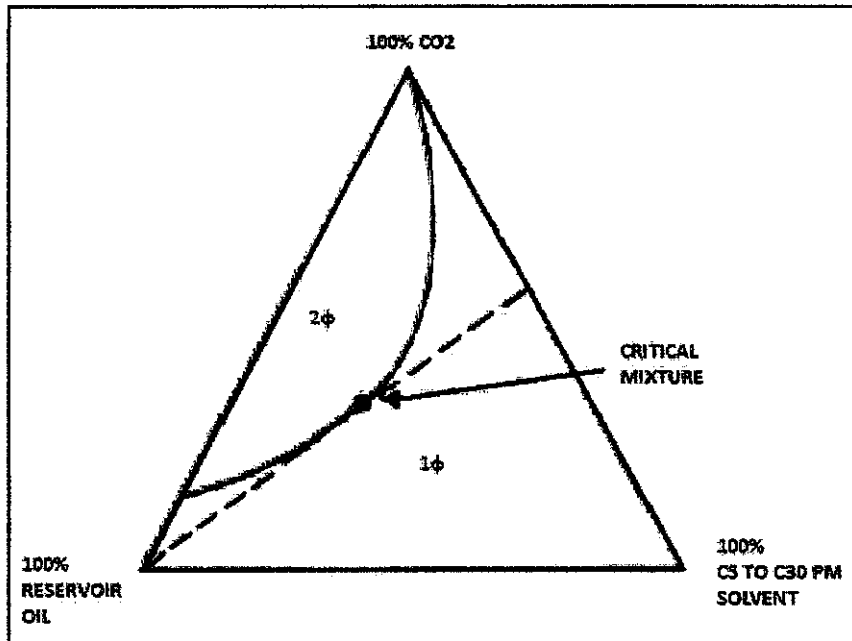


Figure 4: Postulated phase diagram for fluid at displacement front after CO₂ has extracted hydrocarbons in-situ from reservoir oil, contacted at miscible pressure, P_m (Holm, 1987).

As discussed in the CO₂ miscible contact section, through multiple contacts between the CO₂ and oil phase, intermediate and higher molecular weight hydrocarbon are extracted into the CO₂-rich phase. Under proper condition (pressure and temperature), this CO₂-rich phase will reach a composition that is miscible with the original reservoir oil.

2.2.4 Pressure-Composition requirement for CO₂ miscible process

The reservoir pressure at which miscible displacement can occur are similar to those for the first-contact or enriched-gas processes (1000 to 2000 psi) because of the high solvency of the dense, supercritical CO₂ at these pressures and most reservoir temperature (<200°F).

According to Holm (1987) lower miscibility pressures are achieved at lower temperature. The CO₂ miscible process is dependent on the C₅ to C₃₀ content of the oil. At a given reservoir temperature, miscibility displacement with CO₂ is achieved at lower pressures where the C₅ to C₃₀ content is higher.

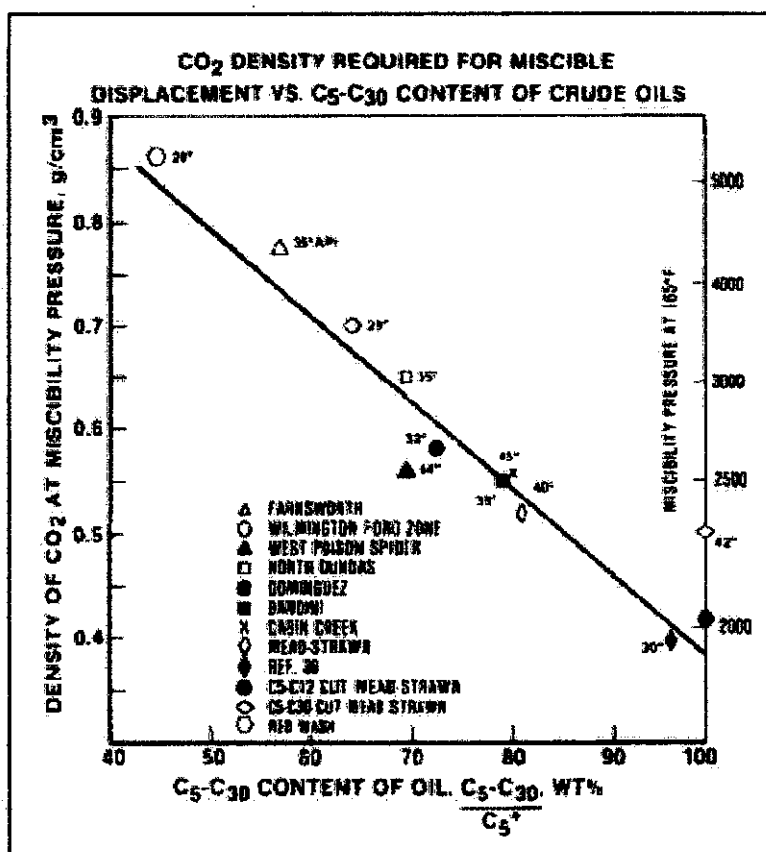


Figure 5: CO₂ density required for miscible displacement vs C₅ to C₃₀ content of various crude oils. MMP's at 165°F for the same crude oils (Holm, 1987).

2.2.5 Effect of temperature on MMP (Minimum Miscibility Pressure)

Yellig and Metcalfe (1980) state that reservoir temperature also plays a role in MMP. *Figure 6* below shows the variation of MMP (and the corresponding density) with temperature and oil composition. From the figure, we can see that the lower temperature and the lower molecular weight of C_{2+} , the lower the minimum miscibility pressure value.

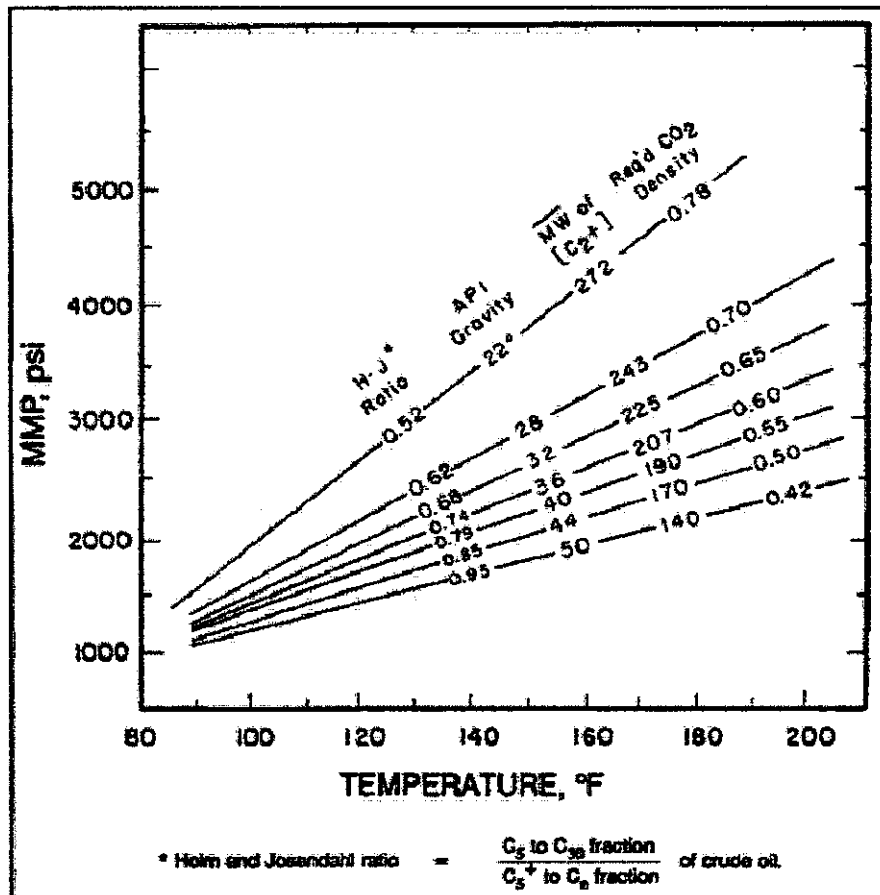


Figure 6: Correlations for CO_2 MMP (Heller and Taber, 1986)

2.2.6 Viscosity of CO₂ and hydrocarbon mixture

Prediction of viscosity for multicomponent system:

Mathematical models used to predict the field performance of a CO₂ flood employ viscosity correlation based on CO₂-hydrocarbon mixture viscosity databases (Lansangan, 1990).

In 1964, the LBC (Lohrenz-Bray-Clark) method appeared and thereafter became accepted as an industry-wide standard for estimating the viscosity of crude oil and natural gas/crude oil mixtures, requiring only input data that are readily available. The procedure was developed by adapting a pure-component viscosity correlation for mixture via combinatorial rules to obtain the correlation parameters for a multicomponent system.

$$\mu_o = \frac{\sum_{i=1}^n Z_i \mu_{oi} MW_i^{1/2}}{\sum_{i=1}^n Z_i MW_i^{1/2}}$$

Where Z_i is general representation of the mole fraction of component i in the mixture, which could be single-phase vapour or liquid, or the equilibrated vapour phase of liquid phase.

Effect of viscosity on mobility ratio:

Stalkup Jr. (1992) states that a disadvantage of CO₂ flooding compared with water flooding result from the low viscosity of CO₂ relative to that of oil. The low viscosity of CO₂ causes the mobility ratio in most CO₂ flood to be unfavourable and unfavourable mobility ratio affect sweepout adversely.

The citation above shows the important of viscosity determination in order to estimate the favourable mobility ratio for better sweepout. For example, at a reservoir temperature of 110°F, CO₂ viscosity is about 0.03cp at 1500 psi, whereas as 2500 psi, the viscosity is about 0.06cp.

2.2.7 Effect of temperature on viscosity of CO₂ and hydrocarbon mixture

Stalkup Jr., (1992) found out that at temperatures of interest in miscible flooding, CO₂ viscosity is more gas-like than liquid like. As a result, oil/CO₂ viscosity ratio will be unfavourable from the standpoint of viscous fingering.

Below figure shows the viscosity of pure CO₂ versus temperature and pressure. Viscosities values for this figure were calculated from a correlation published by Kennedy and Thodos (1961). Here we can conclude that, the viscosity of CO₂ in single phase liquid form decrease as the temperature increase while the value of viscosity decrease as the pressure decrease.

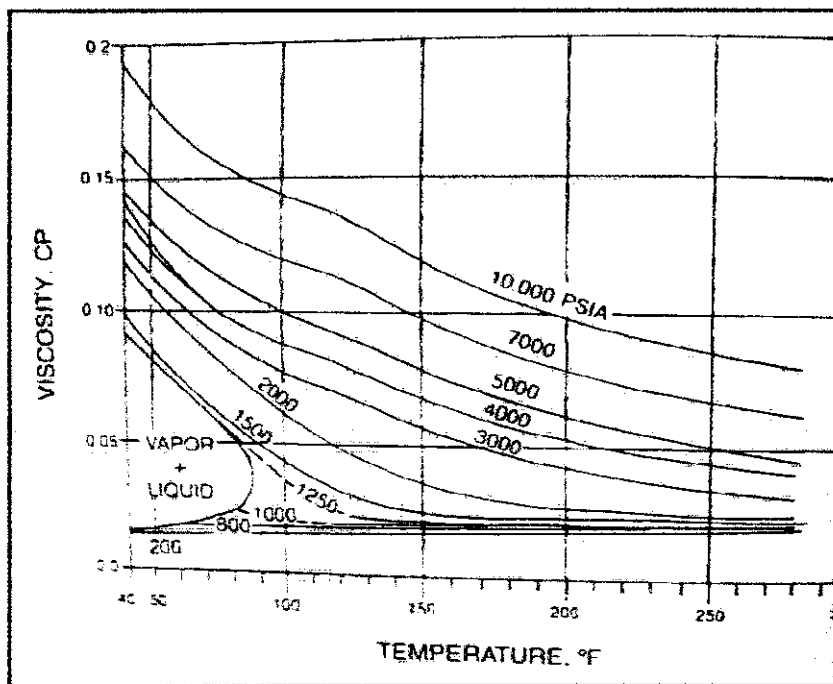


Figure 7: Viscosity of CO₂ (Kennedy and Thodos, 1961).

CHAPTER 3

METHODOLOGY

3.1 Equipments and materials

Below are the equipments and software that needed for the experiment of this project. These equipments are categorized under the PVT equipments and available in the PVT lab in building academic 15-00-02.

1. Fluid-Eval Standard (Main Equipment)

The Fluid-Eval Standard is a PVT instrument for the study of thermodynamic properties and phase behaviour of black oil, volatile oil and gas condensates. It consists of PVT cell that is enclosed by the piston at one end. The piston is equipped with a magnetic driven stirrer for homogenous agitation of the fluid sample. For this experiment, visual head is used as this head has larger glass window that permit full observation of the fluid located inside the PVT cell. Full specification of this equipment is available in the Appendices and the Fluid Eval Standard: Operation & Maintenance Manual v3.2.

2. Recombination Cell Apparatus

The recombine apparatus is used to combine gas and liquid samples at pressure and temperature of reservoir conditions or a fluid mixture at a specified bubble point pressure. It provides sample homogeneity (mixing) while reducing fluid preparation time.

3. Capillary Tube Viscometer

The capillary tube viscometer is one of the PVT equipments that can be attached to the Fluid-Eval Standard (PVT cell). It is a capillary viscometer which is designed for the determination of viscosity of single phase fluids at reservoir conditions for both vapour and liquid sample. Capillary tube range of 0.1 to 1 cp is used in the measurement.

4. Model Arnel 3023 Simulated Distillation Analyzer

- Liquid sample composition analysis

5. Model Arnel 2008 PPC Natural Gas Analyzer

- Gas sample composition analysis

6. Software:

- i. Appli Lab: for the Fluid-Eval Standard control system
- ii. VAquisition: for the visualisation camera setting and positioning

Materials used in the experiment are:

- i. Crude oil sample: Dulang crude oil
- ii. CO₂ gas (from the CO₂ gas tank)
- iii. Water: Distilled water

3.2 Research Methodology

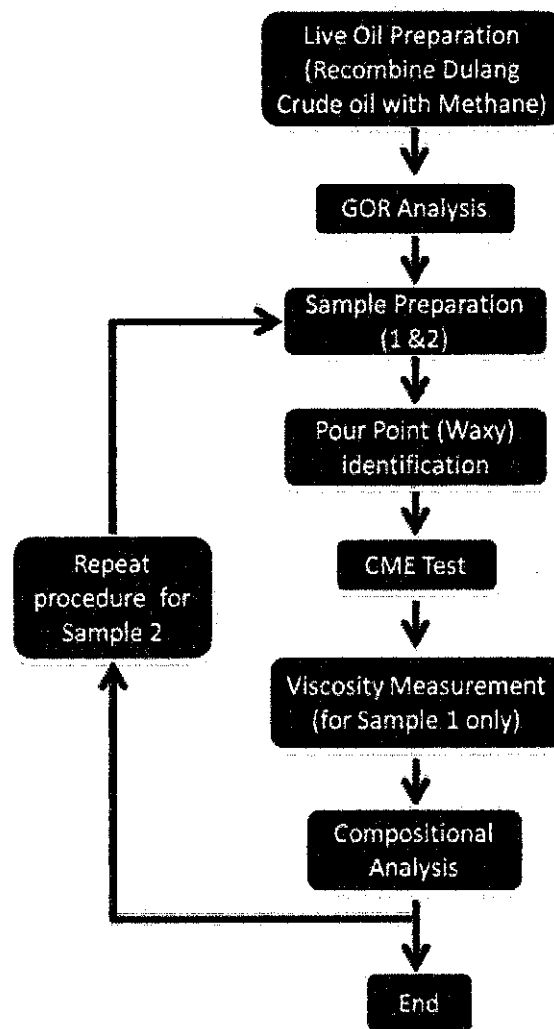
Multiphase behaviour of CO₂ and hydrocarbon mixture experiment at various temperatures:

- a. Manipulated variables: Temperature, Pressure and Water volume
- b. Responding variables: Volume of each phase, viscosity, composition of gas samples and liquid samples.
- c. Constant variables: CO₂ volume (20%)

Samples:

- Sample 1: CO₂ (20% or 10cc) and Dulang crude oil (40cc)
- Sample 2: CO₂ (20% or 10cc), Dulang crude oil (24.4cc) and water (39% or 15.6cc)

Workflow of the experiment:



A known amount of crude oil is combined with CO₂ gas in the PVT cell. Then, the temperature of the oven of the PVT cell is set to the wanted temperature. The overall composition of the reservoir fluid sample or its original mass always remains constant because no fluids, either gas or liquid, is removed from the PVT cell during the experiment. The mixture sample is then pressurized to a value greater than its bubble point pressure which is estimated in this experiment to be 2500psi. After the pressure and temperature condition are stabilize, a pressure depletion procedure is carried out by increasing the volume in increment until the pressure drop to 500psi. The PVT cell is agitated regularly by the stirrer to ensure that the cell content is equilibrium. The total and phase volumes of the fluid mixture are recorded at each pressure step. The fluid inside the cell can be visually observed or video/picture recorded while conducting the pressure depletion procedure. After the completion of the test, the same sample is run at other three different temperatures. The same steps are repeated for second sample (with water) at the same temperatures

and pressure depletion steps. The measurement of the viscosity of the equilibrium phases is achieved by passing the fluids through an analysis loop (in this case, port E) that consists of a capillary tube viscometer. The viscosity measurement is taken at three pressures, 1250, 1000 and 750psi and at four different temperatures. Oil and gas sample from the two mixtures are taken at temperature of 30°C and pressure interest (below than 1000psi) for compositional analysis.

3.3 Project Activities

For the first semester, FYP 1 the project activities is more on to the research and literature review of the selected topic, multiphase behaviour of CO₂ and hydrocarbon mixtures. Many references from reservoir engineering and fluid properties text books, journal and technical papers had been studied in order to find problem statement and come out with relevant objectives. Beside, the research is done to find the important information that can relate to the expected result. The final stage of the first semester is come out with a relevant and feasible experiment design that will be conducted in the second semester, FYP 2.

The major activities that had been done in the second semester (FYP 2) were conducting the experiment work based on the methodology that design during FYP1. PVT equipments are used to do the main experiments and viscosity measurement as well. After getting data from the experiments, analysis and discussion of the results is done. The final stage of the experiment is come out with conclusion that is relevant to the objectives of the project.

3.4 Key Milestone

Below table show the key milestone and the estimated completion date of the overall project. Currently the project is at the end of the Semester 2 which is in the submission of this final report and the final presentation.

Milestone	Estimated completion dates
Start experiment works	30/5/2011
Progress report submission	15/7/2011
Finished experiment	29/7/2011
Pre-EDX	1/8/2011
Final presentation	22/8/2011
Final Interim Report Submission	5/9/2011

Table 2: Key milestone for FYP 2 and the estimated completion dates

3.5 Gantt chart

No	Project details/Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
1	Selection of Project Topic																													
2	Preliminary Research Work:																													
	Research on the basic concept of phase behavior																													
	Research on the fluid properties																													
	Determine the problem statement and objective																													
3	Submission of Extended Proposal Defence																													
4	Continue Research Work:																													
	Continue on phase behavior of CO ₂ and crude oil																													
	Finding related literature review on multiphase behavior of CO ₂ and crude oil																													
5	Proposal Defence presentation																													
6	Continue Project work:																													
	Research methodology & Experiment design																													
	PVT equipment training																													
7	Submission of Interim Draft Report																													
8	Submission of Interim Report																													

Gantt Chart (Continue)

No	Project details/Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
9	Project Work Continues (FYP 2):																													
	Material and equipment preparation																													
	Recombine reservoir oil preparation (Sample 1 & 2)																													
	CME Experiment (Sample 1) at Temp 60°C																													
	CME Experiment (Sample 1) at Temp 50°C																													
	CME Experiment (Sample 1) at Temp 40°C																													
	CME Experiment (Sample 1) at Temp 30°C																													
	Viscosity measurement and compositional analysis for sample 1																													
	CME Experiment (Sample 2) at Temp 60°C																													
	CME Experiment (Sample 2) at Temp 50°C																													
	CME Experiment (Sample 2) at Temp 40°C																													
	CME Experiment (Sample 2) at Temp 30°C																													
	Viscosity measurement and compositional analysis for sample 2																													

Gantt Chart (Continue)

No	Project details/Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
10	Submission of Progress Report																													
11	Data analysis on the experiment result																													
12	Come out with final conclusion of the project																													
13	Poster and presentation preparation																													
14	Pre-EDX																													
15	Submission of Draft Report																													
16	Submission of Dissertation (soft bound)																													
17	Submission of Technical Paper																													
18	Oral Presentation																													
19	Submission of Project Dissertation (Hard Bound)																													

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Phase behaviour

4.1.1 CO₂ and Dulang oil system

Tables below show results of experiments for sample 1 (CO₂ and hydrocarbon without water) at four different temperatures.

Pressure (psig)	Phase observed @ 60°C			Phase observed @ 50°C			Phase observed @ 40°C			Phase observed @ 30°C		
	G	L ₁	L ₂	G	L ₁	L ₂	G	L ₁	L ₂	G	L ₁	L ₂
2500	√	√		√	√		√	√		√	√	
2300	√	√		√	√		√	√		√	√	
2100	√	√		√	√		√	√		√	√	
1900	√	√		√	√		√	√		√	√	
1700	√	√		√	√		√	√		√	√	
1500	√	√		√	√		√	√		√	√	
1250	√	√		√	√		√	√		√	√	
1000	√	√		√	√		√	√		√	√	
750	√	√		√	√		√	√		√	√	√
500	√	√		√	√		√	√		√	√	√

Table 3: Phase observed for sample 1 at temperature of 60, 50, 40 and 30°C.

Figure 8 to 11 below show the phase behaviour of CO₂ and Dulang oil mixture at pressure of 750psi and four different temperatures.

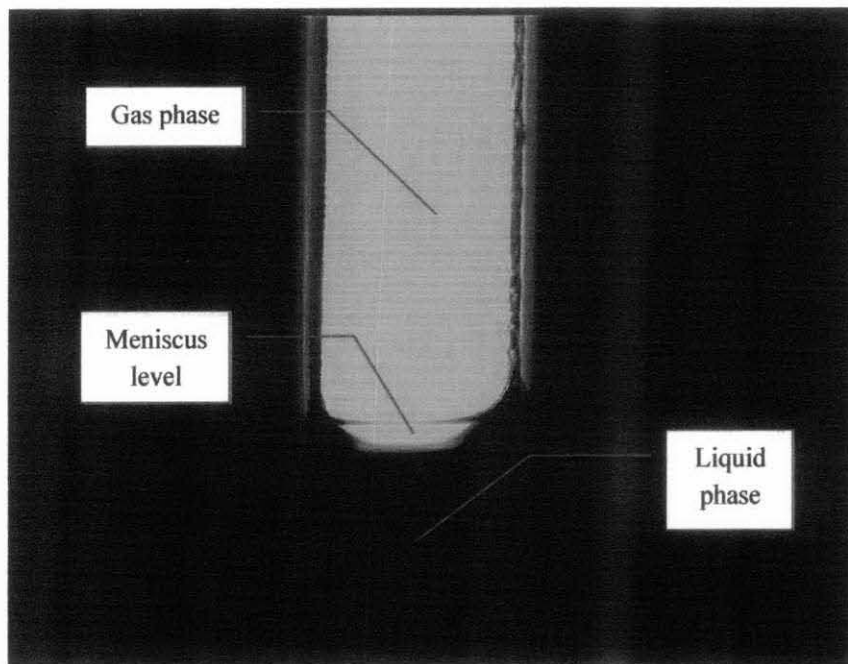


Figure 8: Phase behaviour of sample 1 at 750 psi and 60°C

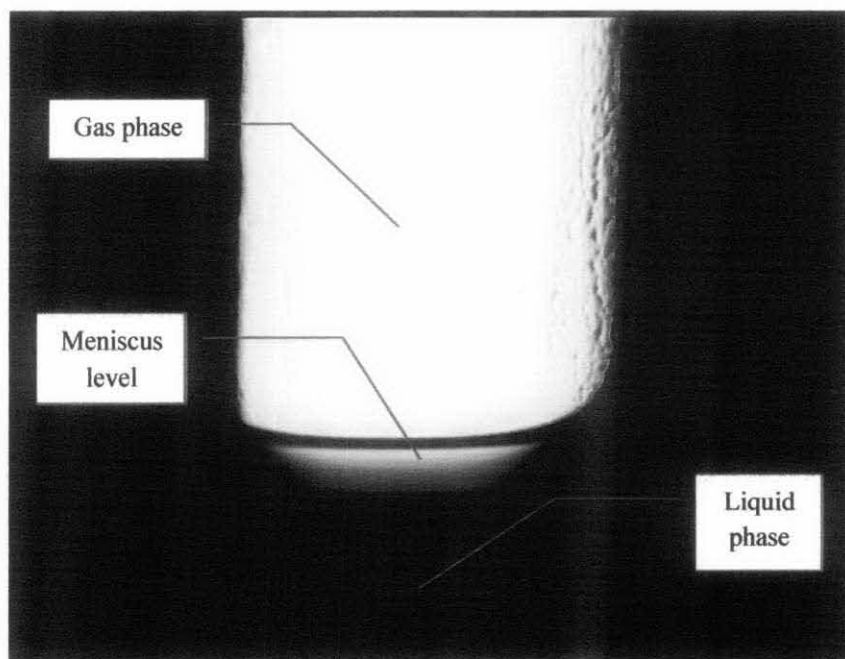


Figure 9: Phase behaviour of sample 1 at 750 psi and 50°C

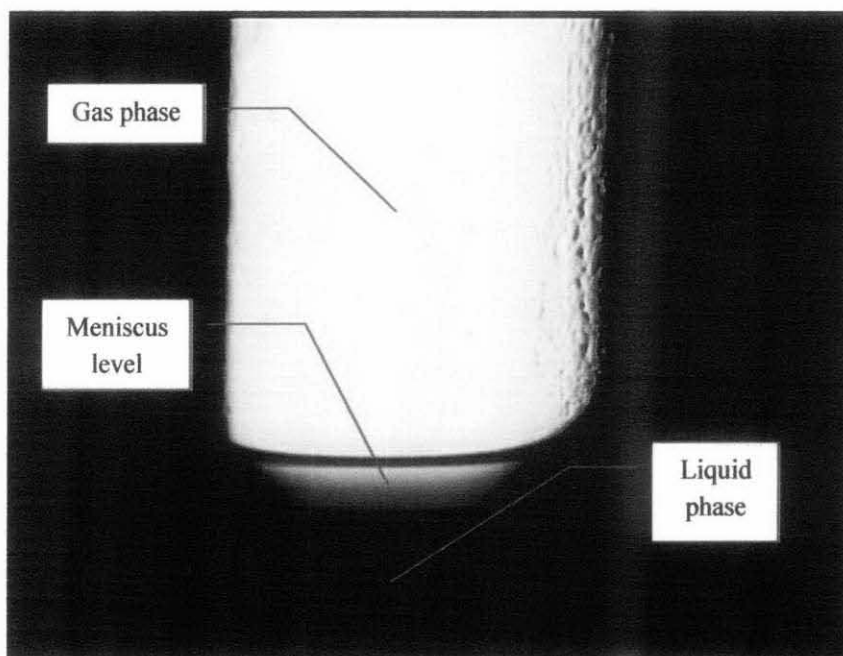


Figure 10: Phase behaviour of sample 1 at 750 psi and 40°C

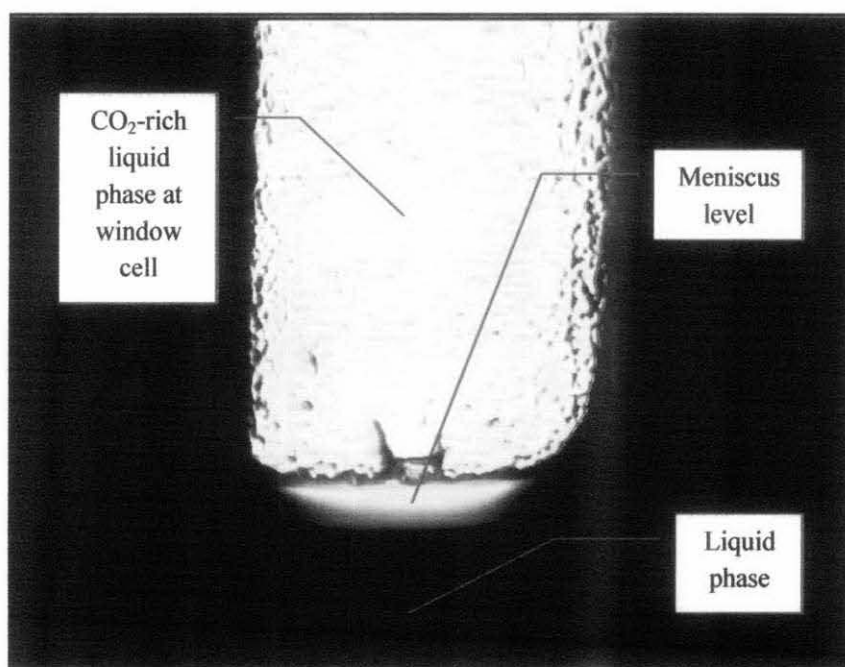


Figure 11: Phase behaviour of sample 1 at 750 psi and 30°C

Phase observed for sample 1 at 30°C shows the occurrence of light yellow colour liquid (CO₂-rich liquid) at window cell starting from pressure of 886psi and below. Sequence of the CO₂-rich liquid formation is shown in the *Figure 12* below:

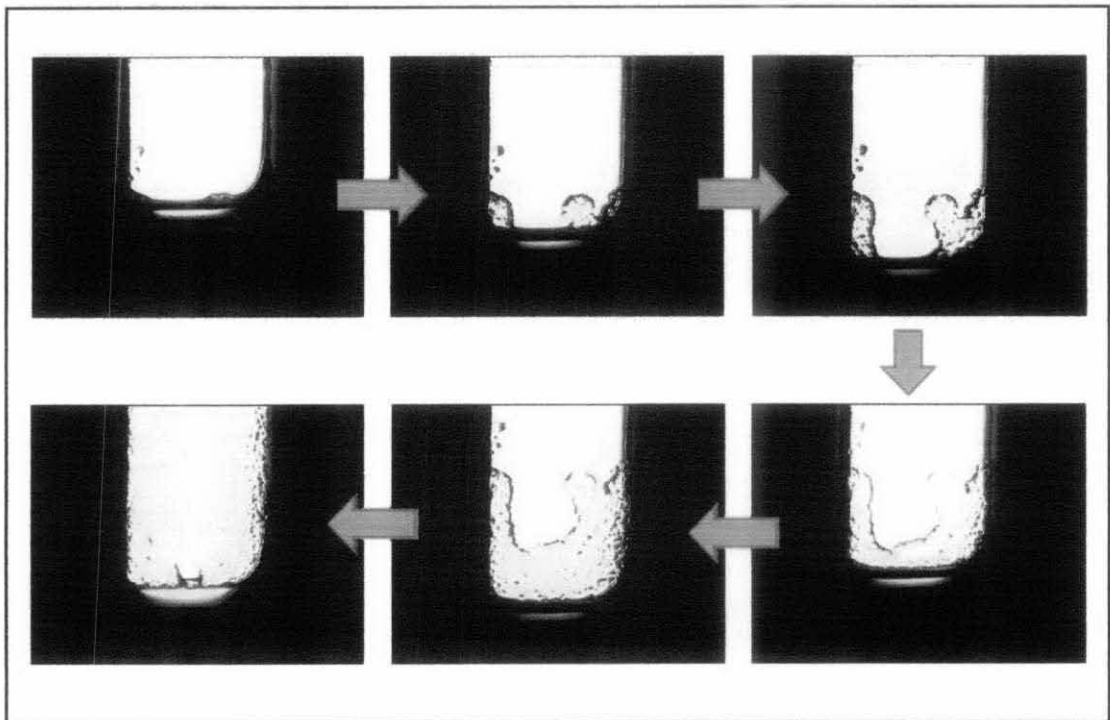


Figure 12: Phase behaviour of sample 1 at 30°C and pressure from 886psi to 750psi.

4.1.2 CO₂, Dulang oil and water system

Table 4 below shows the results of experiments for sample 2 (CO₂, hydrocarbon and water) at four different temperatures.

Pressure (psig)	Phase observed @ 60°C			Phase observed @ 50°C			Phase observed @ 40°C			Phase observed @ 30°C		
	G	L ₁	L ₂	G	L ₁	L ₂	G	L ₁	L ₂	G	L ₁	L ₂
2500	√	√		√	√		√	√		√	√	
2300	√	√		√	√		√	√		√	√	
2100	√	√		√	√		√	√		√	√	
1900	√	√		√	√		√	√		√	√	
1700	√	√		√	√		√	√		√	√	
1500	√	√		√	√		√	√		√	√	
1250	√	√		√	√		√	√		√	√	
1000	√	√		√	√		√	√		√	√	
750	√	√		√	√		√	√		√	√	
500	√	√		√	√		√	√		√	√	

Table 4: Phase observed for sample 2 at temperature of 60, 50, 40 and 30°C.

Figure 13 to 16 below show the phase behaviour of CO₂, Dulang oil and water mixture at pressure of 750psi and four different temperatures.

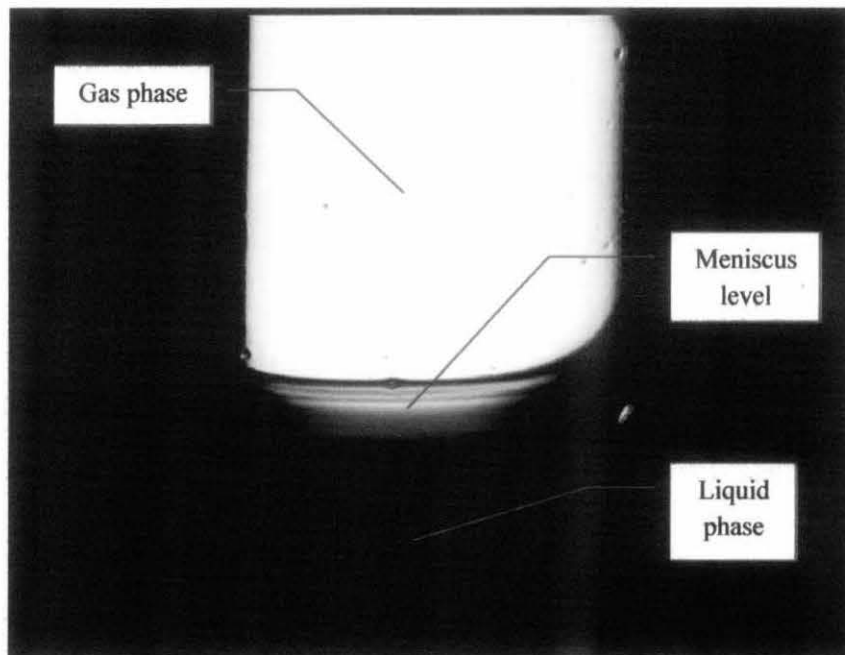


Figure 13: Phase behaviour of sample 2 at 750 psi and 60°C

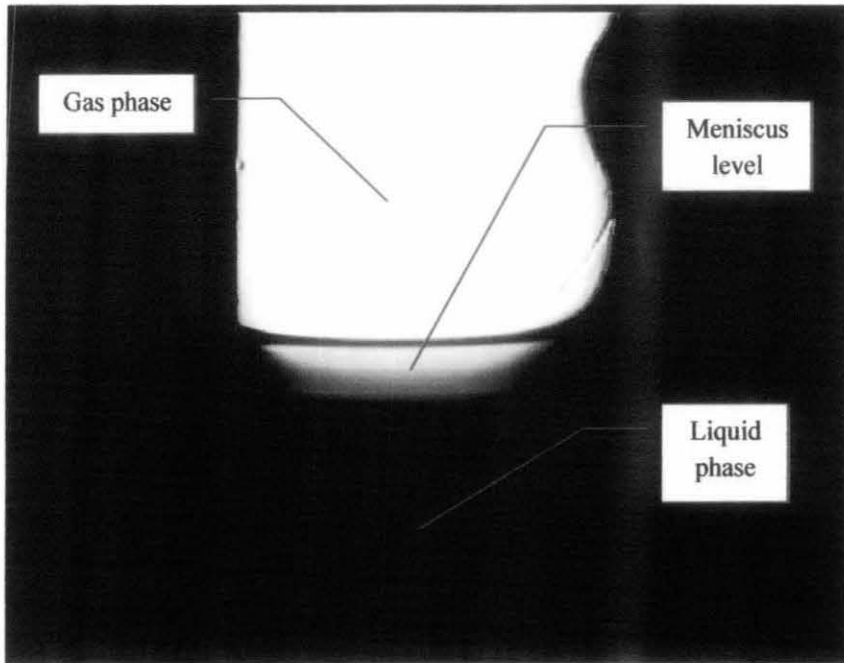


Figure 14: Phase behaviour of sample 2 at 750 psi and 50°C

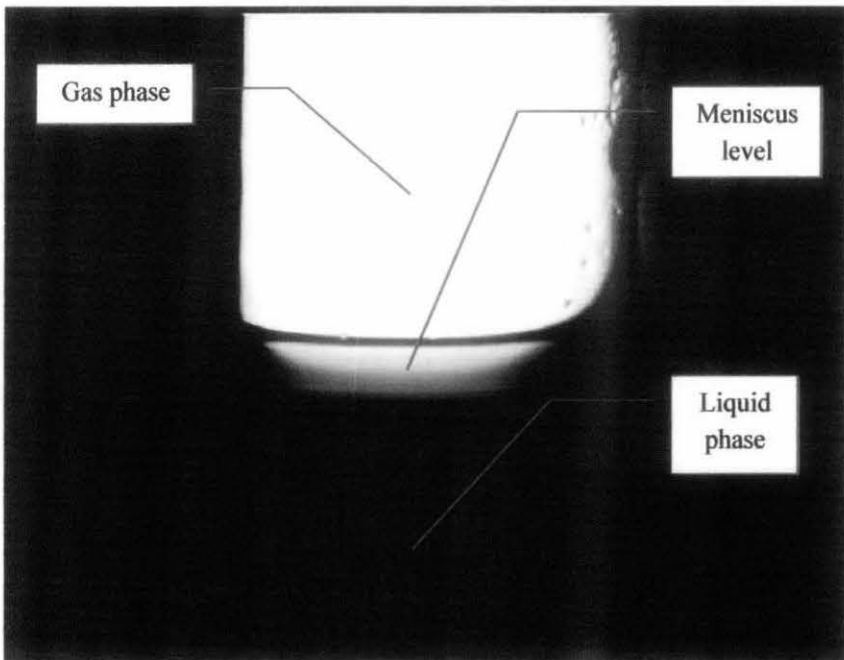


Figure 15: Phase behaviour of sample 2 at 750 psi and 40°C

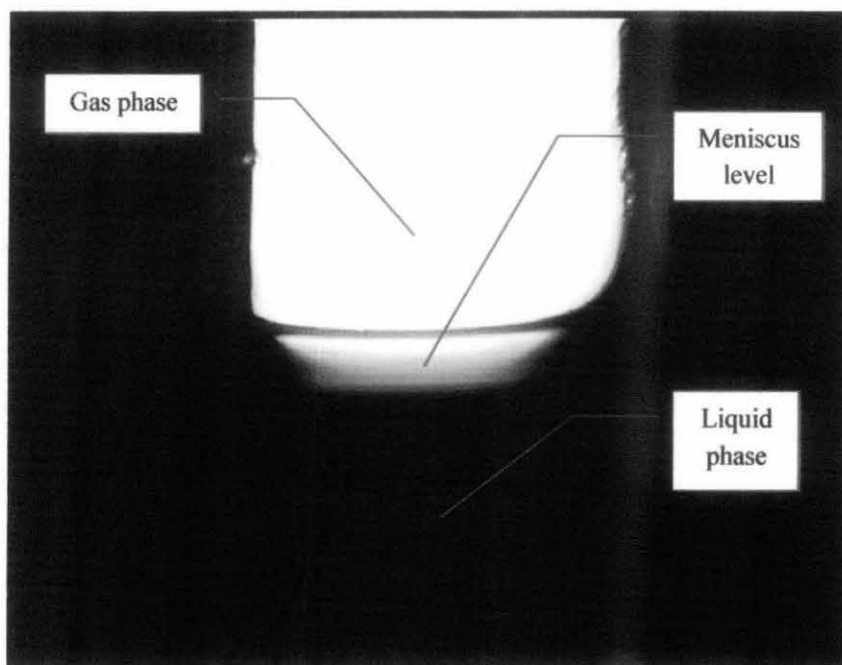


Figure 16: Phase behaviour of sample 2 at 750 psi and 30°C

Formation of black particles which are strongly belief as asphaltenes:

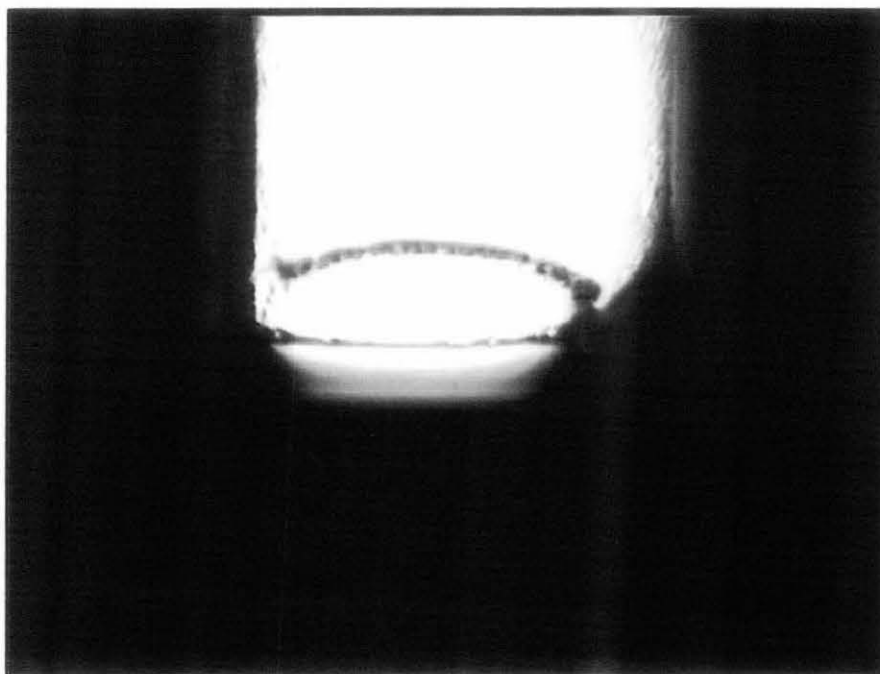


Figure 17: Formation of asphaltenes at temperature 40°C and 1000psi.

Table 5 shows the summary of the phase behaviour of these two samples system:

Temperature (°C)	Phase behaviour	
	CO ₂ and Dulang oil system	CO ₂ , Dulang oil and water system
60	G/L ₁	G/L ₁
50	G/L ₁	G/L ₁
40	G/L ₁	G/L ₁
30	G/L ₁ /L ₂ (at P < approx 900psi)	G/L ₁

Table 5: Summary of phase behaviour for Sample 1 and Sample 2.

4.1.3 Discussion on phase behaviour

Generally, the Dulang crude oil becomes wax at temperature of below 30°C, where it is not suitable for the experiment. From the observation, the pour point of the two samples (with and without water) is identified at same temperature, approximately 27°C. Therefore, injection of CO₂ at temperature below the pour point (27°C) is not suitable as the oil will become wax. Besides, no hydrates formation occurs for sample 2 (CO₂, Dulang oil and water mixture).

However, for sample 2 (with water) there are some black particles appeared and deposited between the liquid oil and liquid water phases during the first run of the experiment at 30°C and 2500psi. As the pressure drop, the black particle still exist and permanently sticking at the window cell throughout all experiments. It is strongly believed that these particles are the asphaltenes that formed due to the pressure change and fluid composition change. Zahidah et al (2001) also reported that asphaltenes appeared and randomly dispersed throughout the sample of her CCE (Constant Composition Expansion) experiment for Dulang oil.

At CO₂ concentration of 20% and temperature of 60, 50 and 40°C, Sample 1 (CO₂ and Dulang oil mixture) exhibit two phase behaviour which are gas and oil-rich liquid (G/L₁) at all pressure range from 2500psi to 500psi. While at temperature of 30°C, two phase region are observed which are gas and oil-rich liquid (G/L₁) from pressure of 2500psi to 1000psi. Three phase region; gas, oil-rich liquid and CO₂-rich liquid phase (G/L₁/L₂) occurred from pressure of approximately 886psi to 500psi as shown in *Figure 12*. However, the formation of this CO₂-rich liquid phase (L₂) is very little and as pressure drop, the CO₂-rich liquid phase is sticking at the window of the cell.

At temperature of 30°C, (below the critical temperature of CO₂) the CO₂ in the system is in liquid form from 2500psi to about 1000psi. Due to this formation of dense CO₂ liquid phase, the C5+ fractions of the oil are extracted forming the CO₂-rich liquid phase (L₂). According to Green and Willhite (1998), this formation of CO₂-rich liquid phase (L₂) is very important as it will reach miscibility with the original reservoir oil. As pressure decrease below the saturation pressure of CO₂ (approximately 1000psi at 30°C), the less dense CO₂-rich liquid phase is separated from the denser oil-rich liquid phase (L₁) as in *Figure 12*.

No CO₂-rich liquid phase (L₂) appeared at other temperatures (40, 50 and 60°C) and pressure from 2500psi to 500psi because these temperatures are above the critical temperature of CO₂ which is 31.1°C. Above this critical temperature, CO₂ are in fully supercritical, fluid state ($P > P_c$) or partially supercritical, vapour-like appearance ($P < P_c$). For pure component, the critical temperature may also be defined as the temperature above which the gas cannot be liquefied, regardless of the applied pressure. Therefore, the CO₂ above this temperature cannot become liquid phase at any pressure and cannot achieved miscibility with the hydrocarbon.

For sample 2 (CO₂, Dulang oil and water mixture), only two phase behaviour and water phase are observed throughout the experiment (at all temperature and pressure, 2500psi to 500psi). These two phases are gas and oil liquid phase (G/L₁). No formation of CO₂-rich liquid phase occurred for this (with water) system. This may be due to the present of water, where the CO₂ tends to dissolve in it rather than reacting with the oil and forming CO₂-rich phase. According to Stalkup Jr. (1992), CO₂ is partially soluble in water, and a portion of the CO₂ injected in miscible flooding will be dissolved, either by formation of water or by the water that injected with the CO₂ for mobility ratio improvement. This reduces the volume of CO₂ available for miscible displacement of the oil.

From the analysis of this multiphase behaviour, the occurrence of CO₂-rich liquid phase shows that the CO₂ gas can achieve miscibility with Dulang oil at temperature of 30°C (below the critical temperature of CO₂). Therefore, the CO₂ miscible flooding is possible to be applied to Dulang field but at a very low temperature of CO₂ injection, 30°C. However, the low temperature injection cannot be less than the pour point of the Dulang oil to prevent the wax formation.

4.2 Compositional Analysis (Results and Discussion)

Samples of gas and liquid are taken from both sample 1 and sample 2 at temperature of 30°C and 800psi. These pressure and temperature is chosen because of the formation of CO₂-rich liquid phase that occurred at this temperature and pressure during the experiment. *Table 6* shows the compositional analysis results for the two samples.

Component	CO ₂ and Dulang oil system	CO ₂ , Dulang oil and Water system
	Gas Sample (Mole %)	Gas Sample (Mole %)
CO ₂	6.85	9.30
N ₂	0.00	0.00
O ₂	0.70	1.21
C1	93.37	82.00
C2	0.00	0.00
C3	0.00	0.00
i-C4	0.00	0.00
n-C4	0.00	0.00
i-C5	0.01	0.00
n-C5	0.01	0.00
C6	0.00	0.00
C7	0.00	0.00
C8	0.00	0.00
C9	0.00	0.00
C10+	0.00	0.00
Total	100.94	92.51

Table 6: Sample 1 & 2 Compositional analysis results

For the gas sample of CO₂ and Dulang oil system, there are occurrence of 0.01 % of i-C₅ and 0.01% of n-C₅ gases which indicate the formation of CO₂-rich liquid phase that extracted by the CO₂. As the pressure drop, the extracted C₅ liquid (which initially contained in the CO₂-rich liquid) vaporized to become gas. However, the compositional analysis of the liquid sample data is not available due to the liquid sample GC is having technical problems during that experiment time.

4.3 Viscosity Measurement

Result:

Figure 18 shows the results of viscosity versus pressure of CO₂ and Dulang oil mixture. The viscosity of Dulang oil with 20% CO₂ concentration increase as the pressure is decrease. While increase in temperature result decrease in the viscosity values. The viscosity measurement is taken at pressure of 1250, 1000 and 750psi which are below the bubble point pressure of the system. Viscosity measurement for sample 2 (CO₂, hydrocarbon and water system) cannot be done as the liquid phase is not homogeneous (separated from the oil). The water liquid phase which is denser than the oil is located at the bottom of the cell. Only water is expected to flow into the capillary tube if the valve from the cell is opened. Therefore, the comparison between sample 1 and sample 2 viscosities cannot be done.

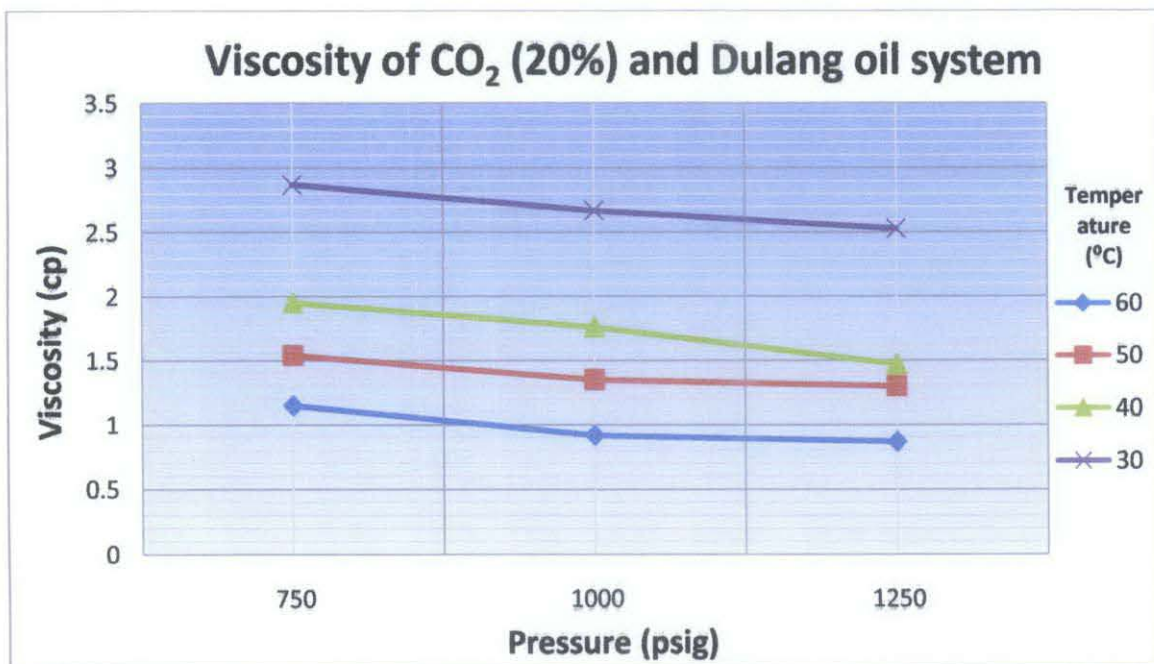


Figure 18: Viscosity vs pressure of Dulang oil with 20% CO₂ concentration

Pressure/Temperature (psi/°C)	60°C	50°C	40°C	30°C
	Viscosity,cp			
750	1.15	1.54	1.95	2.87
1000	0.92	1.35	1.76	2.67
1250	0.87	1.3	1.47	2.53

Table 7: Viscosity of Dulang oil with 20% CO₂ concentration

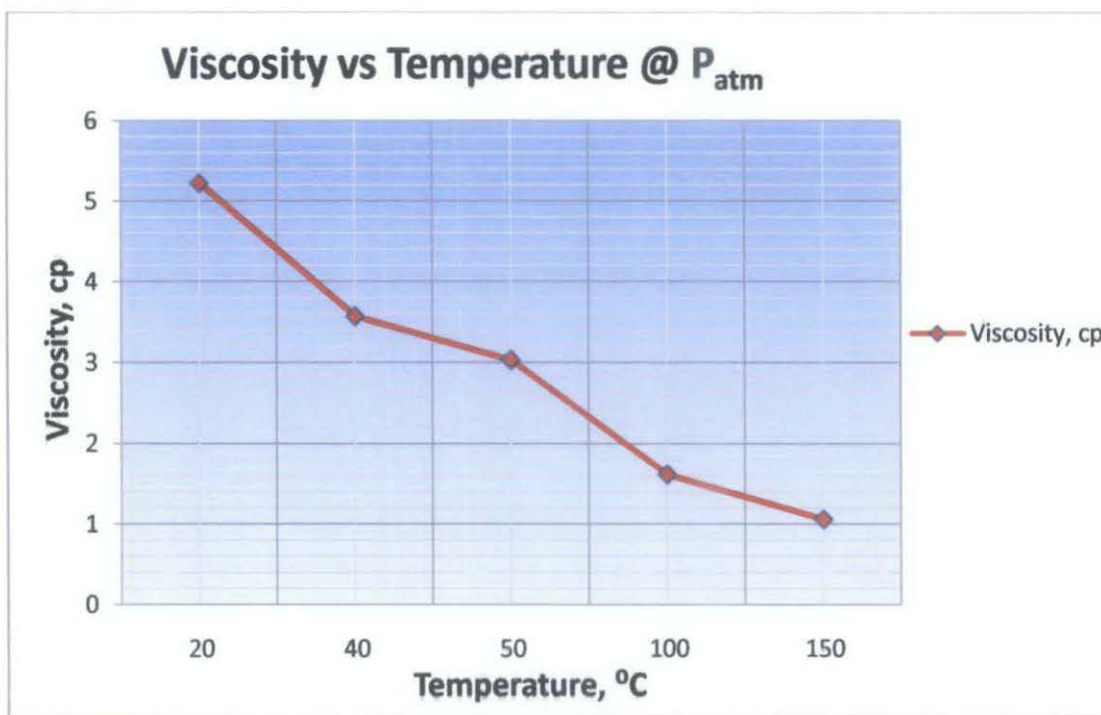


Figure 19: Viscosity of Dulang oil versus temperature at atmospheric pressure.

Temperature, °C	Viscosity, cp
20	5.22
40	3.57
50	3.03
100	1.62
150	1.06

Table 8: Viscosity of Dulang oil at atmospheric pressure and various temperatures

Figure 19 and Table 8 above show the viscosity of Dulang crude oil (Source from Exxon Mobil, Global Crude Oil: Dulang) at P_{atm} and various temperatures. From initial comparison, the sample 1 (CO_2 and Dulang oil mixture) viscosity shows lower value than the viscosity of original Dulang crude oil. The addition of 20% CO_2 concentration is proved to give viscosity reduction on Dulang oil.

Discussion:

As reservoir pressure falls below the bubble point of the mixture, the overall original composition of the oil changed. The gas that evolves takes the lighter components from the oil, leaving the remaining oil with relatively larger concentration of heavier components. This changing composition cause a larger increase in the viscosity of the oil as pressure continues to fall below the bubble point pressure. At temperature of 30°C, the viscosity measurement is higher than the other values because the wax is starting to form at low temperature.

Viscosity of the CO₂ and hydrocarbon mixture is important as it affect the mobility ratio. For idealized situation where solvent (in this case CO₂) displaced oil at the irreducible water saturation and where mixing of solvent with the oil is negligible. Mobility ratio is simply the ratio of oil and solvent viscosity, μ_o / μ_s . In real situation, mixing of solvent and oil does occur during the course of displacement, which can result in an effective viscosity ratio that is less than the ratio of pure component viscosity. Besides, effective mobility ratio becomes more complicated and uncertain when mobile water is present. As for example, in tertiary recovery, water is injected with the solvent as a technique to reduced solvent mobility.

CHAPTER 5

CONCLUSIONS & RECOMMENDATION

5.1 Conclusions

This project is an experimental base work which is conducted to identify and observe the multiphase behaviour of the CO₂, hydrocarbon and water mixture and measure the viscosity of the fluid mixture. From the interpretation and discussion of the data, it can be concluded that:

1. Wax formation of Dulang oil occurs at temperature below 30°C (approximately 27°C) for both with water and without water system.
2. Three phase behavior; gas, oil-rich liquid and CO₂-rich liquid (G/L₁/L₂) occurred for CO₂-hydrocarbon mixture at temperature below the critical temperature of CO₂ (31°C) and at pressure around 900psi and below. CO₂-rich liquid phase is formed by the extracted intermediate and higher molecular weight of the oil by the CO₂ liquid at miscible condition. While at higher temperature than critical temperature of CO₂, only gas and oil liquid (G/L₁) phases are observed.
3. However, no formation of CO₂-rich liquid phase occurred in CO₂-hydrocarbon-water mixture due to the solubility of CO₂ in the water, leaving only little volume of CO₂ to react with the oil. No formation of hydrate is observed for this sample 2 (with water) as well.
4. At the experiment condition, the 20% CO₂ concentration was capable of extracting heavier component (C₅+) of the oil to form L₂ phase, the CO₂-rich liquid phase at the temperature of 30°C.
5. The occurrence of CO₂-rich liquid phase shows that the CO₂ gas can achieve miscibility with Dulang oil at temperature of 30°C (below the critical temperature of CO₂). Therefore, the CO₂ miscible flooding is possible to be applied to Dulang field but at a very low temperature of CO₂ injection, 30°C.

5.2 Recommendation

Extended experiments and evaluation are recommended, so that the project will be more informative and reliable. Experiments such as slim-tube or core displacement can be done to evaluate more on the displacement efficiency and the displacement behaviour of the CO₂ and crude oil inside the reservoir condition.

Furthermore, brine water can also be used in this experiment as the water phase to represent more realistic condition of the reservoir. Besides, the experiment can be conducted at other water volume percentage and CO₂ concentration as well. So that the effect of water percentage and CO₂ concentration on the multiphase behaviour of this CO₂, hydrocarbon and water mixture can be observed and further evaluate.

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<http://webbook.nist.gov/chemistry/#Top>
6. Phase diagram of CO₂:
<http://www.science.uwaterloo.ca/~cchieh/cact/c123/phasesdgm.html>

APPENDICES

Fluid-Eval Standard (Technical Specification)

The Fluid-Eval Standard is a PVT instrument for the study of thermodynamic properties and phase behaviour of black oil, volatile oil and gas condensates. The chamber is enclosed at one end by the piston of the embedded pump and at the other end by a dedicated cell head. The piston is equipped with a magnetic driven stirrer for homogenous agitation of the fluid sample. The PVT cell can be configured either for oil studies with a liquid head or for gas condensates studies with a gas condensates head. For this experiment, the liquid or oil head will be used as this head can be used for the mixture of liquid and gas studies.

The liquid head consists of a stainless steel cap equipped with a high pressure sight glass mounted at the top of it. The top cap incorporates an integral zero dead volume sampling valves located at the junction of the inner surface of the glass window. This permits observation of fluids which enter and leave through the outlet sampling valve.

Technical Specifications of Fluid-Eval Standard:

- i. Volume capacity: 500cc
- ii. Operating pressure: 1000Bar – 15000Psi
- iii. Operating temperature: ambient to 200°C and option cooling system down to -20°C
- iv. Chamber material: Stainless steel
- v. Connections: 1/8" LP Autoclave or Butech type (15000psi)
- vi. Power requirement: 240 VAC 50/60Hz single phase plus ground power – 6kW
- vii. Dimensions: 1200mm x 960mm x 2300mm (LxWxH)
- viii. Weight: 700kg

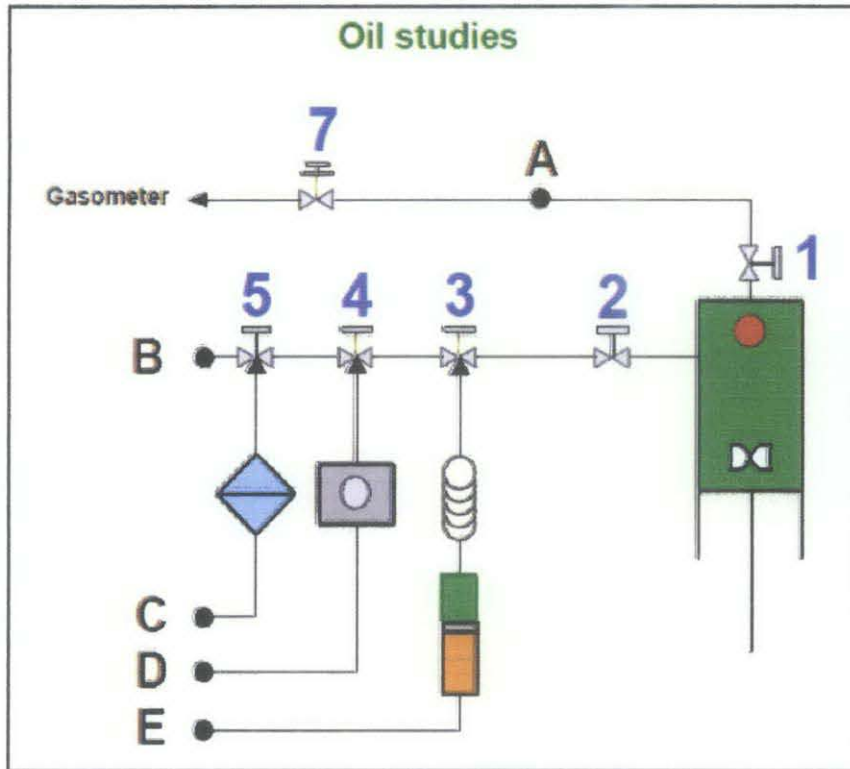


Figure 20: Flow schematic of Fluid-Eval Standard for oil studies

Ports:

A: Inlet/outlet to/from PVT cell

B: Gas inlet

C: to Organic Solid Filter

D: to HPM (High Pressure Microscope)

E: to Viscometer

Capillary Tube Viscometer

The capillary tube viscometer is based on the Poiseuille's law which defines fluid viscosity as a function of the pressure drop in a fluid flowing laminarily through a capillary. It includes 5 range of capillary tube viscometer:

- i. 0.1 to 1 cp
- ii. 1 to 10 cp
- iii. 10 to 100 cp
- iv. 100 to 500 cp
- v. 500 to 3000 cp

Live oil preparation.

Volume of gas at Loading Pressure calculation:

* For this case the recombination is done under non-isothermal system.

Assuming Isothermal and z=1		Description
$GOR = V_{gas@atm} / V_{oil@atm}$		
GOR (cc/cc)	300	Wanted GOR
V_{oil} (cc)	150	
P_{max} / P_{load} (BAR)	140	
1. V_{gas} @ atm, (cc)	45000	
2. V_{gas} @ P load, (cc)	325.6875	Ammount of gas that need to be load in to recombination cell
If process is not isothermal:		
$(P_{atm} \times V_{atm} / T_{atm}) = (P_{load} \times V_{load} / T_{load})$		
T @ atm (°C)	24	
Recombination T (°C)	100	
V gas @ P load & T recombination (cc)	1357.03125	Ammount of gas that need to be load in to recombination cell
Fill by technician		
automatic calculation		

GOR Analysis (for the Dulang live oil)

Measured data:

GOR Oil pycnometer (tare weight) = 613.16g

GOR Oil pycnometer (gross weight) = 632.87g

Volume of gas (measured by gasometer) = 3663.9cc

Volume of GOR Liquid Trap = - cc

Oil density = 0.873g/cc

Formula used for Calculation:

Weight of oil = GOR Oil pycnometer (gross weight) - GOR Oil pycnometer (tare weight)

Volume of oil = weight oil / oil density

GOR = Volume of gas / volume of oil

For this analysis, GOR value is 222.09. The GOR gain is lower than the targeted GOR (300) due to only methane is used as the recombined gas.

CO₂ properties

Carbon dioxide gas is formed from the combination of two elements: carbon and oxygen. CO₂ gas has a slightly irritating odour, is colourless and heavier than air. In an aqueous solution it forms carbonic acid, which is too unstable to be easily isolated. The triple point of carbon dioxide occurs at a pressure of 5.11 atm (5.177 bar) and 216.5 K (-56.6°C). At temperature of 197.5 K (-78.5°C), the vapor pressure of solid carbon dioxide is 1 atm (760 torr).

PROPERTIES	VALUE
1. Molecular Weight	
Molecular weight	44.01 g/mol
2. Solid phase	
Latent heat of fusion (1,013 bar, at triple point)	196.104 kJ/kg
Solid density	1562 kg/m ³
3. Liquid phase	
Liquid density (at -20 °C (or -4 °F) and 19.7 bar)	1032 kg/m ³
Liquid/gas equivalent (1.013 bar and 15 °C (per kg of solid))	845 vol/vol
Boiling point (Sublimation)	-78.5 °C
Latent heat of vaporization (1.013 bar at boiling point)	571.08 kJ/kg
Vapor pressure (at 20 °C or 68 °F)	58.5 bar
4. Critical point	
Critical temperature	31.1 °C
Critical pressure	73.825 bar
Critical density	464 kg/m ³
5. Gaseous phase	
Triple point temperature	-56.6 °C
Triple point pressure	5.185 bar
6. Miscellaneous	
Gas density (1.013 bar at sublimation point)	2.814 kg/m ³
Gas density (1.013 bar and 15 °C (59 °F))	1.87 kg/m ³
Compressibility Factor (Z) (1.013 bar and 15 °C (59 °F))	0.9942
Specific gravity (air = 1) (1.013 bar and 21 °C (70 °F))	1.521
Specific volume (1.013 bar and 21 °C (70 °F))	0.547 m ³ /kg
Heat capacity at constant pressure (C _p) (1.013 bar and 25 °C (77 °F))	0.037 kJ/(mol.K)
Heat capacity at constant volume (C _v) (1.013 bar and 25 °C (77 °F))	0.028 kJ/(mol.K)
Ratio of specific heats (Gamma:C _p /C _v) (1.013 bar and 25 °C (77 °F))	1.293759
Viscosity (1.013 bar and 0 °C (32 °F))	0.0001372 Poise
Thermal conductivity (1.013 bar and 0 °C (32 °F))	14.65 mW/(m.K)
Solubility in water (1.013 bar and 0 °C (32 °F))	1.7163 vol/vol
Concentration in air	0.03 vol %

Table 9: Properties of carbon dioxide (Source from Gas Encyclopaedia)

Dulang reservoir and fluid properties

Reservoir/Fluid properties	Value
Location	130km from offshore Terengganu
Water depth	76m in South China Sea
Dulang field anticline	Approx, 24km long and 3.5km wide
Average hydrocarbon column	100m
Reservoir temperature	215°F/101°C
Initial reservoir pressure	1800psig
Sand porosity range	16 to 36%
Average porosity	30%
Average permeability	200mD
Oil permeability	2mD to 800mD
Initial water saturation	19 to 61%
Average water saturation	39%
Solution GOR	400 scf/stb
Oil formation volume factor	1.279 rb/stb
Oil stock tank density	0.8347 g/cc
API	37.4°API
Oil viscosity at 96°C	0.625cp
Gas viscosity	0.016cp
Bubble point pressure @ T_R 101°C & GOR 280 scf/bbl (laboratory measurement)	1525psig
Multiple contact miscibility pressure for CO ₂ (laboratory measurement)	3230psig
Multiple contact miscibility pressure for produced hydrocarbon gas (laboratory measurement)	3340psig
Vaporisation by pure CO ₂ (laboratory measurement)	15% of stock tank oil

Source: Gain from research papers [1], [2] & [14].

Raw data of Sample 1:CO₂ and Dulang oil system experiment (CME Test)

Pressure	Phase observed			Total Cell Volume Corr	Phase volume (gas)	Phase volume (liquid)
	(psig)	G	L ₁			
2500.3	√	√		50.952	12.56	38.392
2299.7	√	√		53.042	14.64	38.402
2100.1	√	√		55.757	17.12	38.637
1900.2	√	√		59.236	20.71	38.526
1699.9	√	√		63.713	25.11	38.603
1500.3	√	√		69.585	30.62	38.965
1250	√	√		79.858	40.31	39.548
999.8	√	√		95.441	56.07	39.371
750.5	√	√		121.826	81.41	40.416
500.3	√	√		174.972	129.02	45.952

Table 10: CME test for sample 1 at temperature of 60°C

Pressure	Phase observed			Total Cell Volume Corr	Phase volume (gas)	Phase volume (liquid)
	(psig)	G	L ₁			
2500.3	√	√		49.069	8.79	40.279
2300.6	√	√		50.540	8.97	41.570
2100.1	√	√		53.359	10.37	42.989
1899.5	√	√		56.589	13.06	43.529
1700.1	√	√		60.648	17.02	43.628
1500.3	√	√		66.134	21.92	44.214
1250	√	√		75.626	31.75	43.876
999.8	√	√		90.186	46.39	43.796
750.5	√	√		114.936	70.38	44.556
500.3	√	√		164.961	119.22	45.741

Table 11: CME test for sample 1 at temperature of 50°C

Live oil preparation.

Volume of gas at Loading Pressure calculation:

* For this case the recombination is done under non-isothermal system.

Assuming Isothermal and z=1		Description
$GOR = V_{gas@atm} / V_{oil@atm}$		
GOR (cc/cc)	300	Wanted GOR
V_{oil} (cc)	150	
P_{max} / P_{load} (BAR)	140	
1. V_{gas} @ atm, (cc)	45000	
2. V_{gas} @ P load, (cc)	325.6875	Amount of gas that need to be load in to recombination cell
If process is not isothermal:		
$(P_{atm} \times V_{atm} / T_{atm}) = (P_{load} \times V_{load} / T_{load})$		
T @ atm (°C)	24	
Recombination T (°C)	100	
V gas @ P load & T recombination (cc)	1357.03125	Amount of gas that need to be load in to recombination cell
Fill by technician		
automatic calculation		

Pressure	Phase observed			Total Cell Volume Corr	Phase volume (gas)	Phase volume (liquid)
	(psig)	G	L ₁			
2499.3	√	√		50.454	11.67	38.784
2300.6	√	√		51.73	12.07	39.66
2100.1	√	√		53.625	12.69	40.935
1899.5	√	√		56.417	15.38	41.037
1699.9	√	√		60.885	19.73	41.155
1499.4	√	√		65.979	24.46	41.519
1250	√	√		74.88	33.31	41.57
999.8	√	√		88.818	47.58	41.238
750.5	√	√		112.291	70.26	42.031
500.3	√	√		159.87	117.43	42.44

Table 12: CME test for sample 1 at temperature of 40°C

Pressure	Phase observed			Total Cell Volume Corr	Phase volume (gas)	Phase volume (liquid)
	(psig)	G	L ₁			
2499.3	√	√		49.124	13.76	35.364
2299.7	√	√		50.575	14.71	35.865
2101	√	√		52.742	18.83	33.912
1900.4	√	√		55.532	19.54	35.992
1699.9	√	√		59.385	20.1	39.285
1500.3	√	√		64.324	18.59	45.734
1250	√	√		73.032	37.39	35.642
1000.7	√	√		86.662	50.95	35.712
749.6	√	√	√	109.941	74.77	35.171
499.4	√	√	√	156.916	121.74	35.176

Table 13: CME test for sample 1 at temperature of 30°C

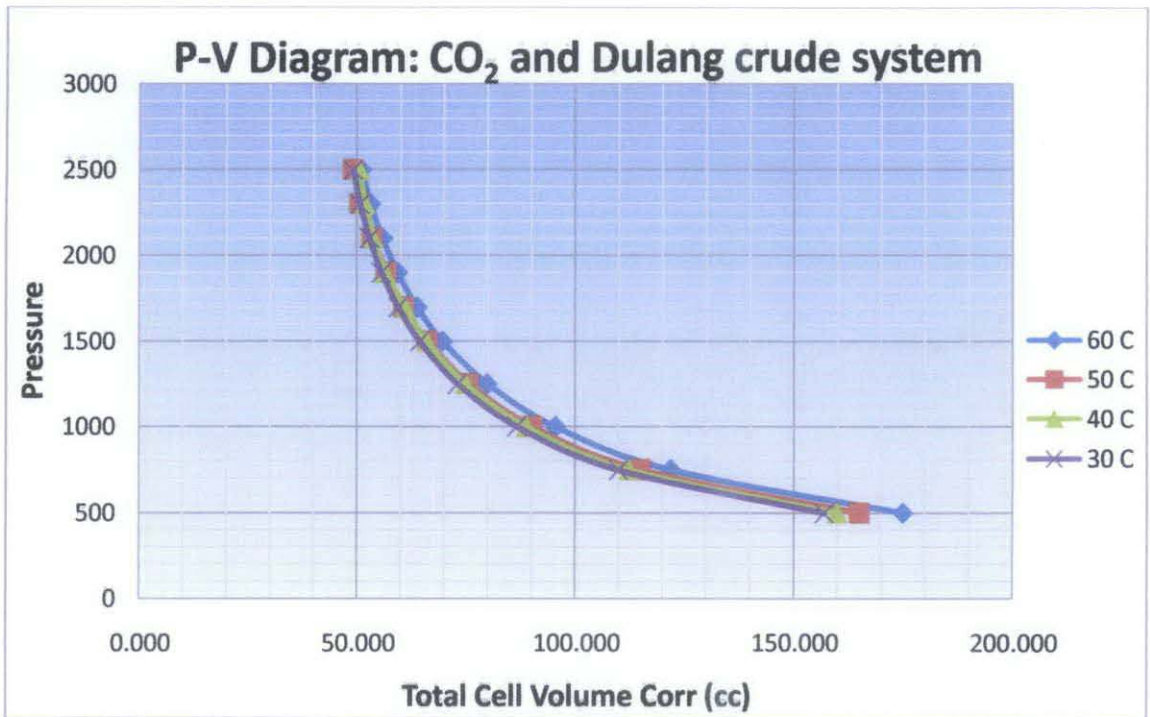


Figure 21: P-V Diagram of CO₂ and Dulang oil system at different temperature

Raw data of Sample 2: CO₂, Dulang oil and water system experiment (CME Test)

Pressure (psig)	Phase observed			Total Cell Volume Corr (cc)	Phase volume (gas) (cc)	Phase volume (liquid) (cc)
	G	L ₁	L ₂			
2499.6	√	√	√	45.573	6.64	38.933
2299.7	√	√	√	46.152	6.91	39.242
2100.1	√	√	√	47.349	7.86	39.489
1900.4	√	√	√	48.940	9.32	39.620
1699.9	√	√	√	51.323	11.38	39.943
1500.3	√	√	√	54.281	14.04	40.241
1250	√	√	√	59.770	19.26	40.510
999.8	√	√	√	68.327	27.54	40.787
749.1	√	√	√	83.519	42.16	41.359
500.3	√	√	√	113.076	71.21	41.866

Table 14: CME test for sample 2 at temperature of 60°C

Pressure	Phase observed			Total Cell Volume Corr	Phase volume (gas)	Phase volume (liquid)
	(psig)	G	L ₁			
2500.3	√	√	√	44.265	5.54	38.725
2299.7	√	√	√	45.050	6.1	38.950
2101.9	√	√	√	46.201	6.95	39.251
1899.5	√	√	√	47.675	8.31	39.365
1699.9	√	√	√	49.718	9.97	39.748
1500.3	√	√	√	52.839	12.93	39.909
1250	√	√	√	57.773	17.31	40.463
1000.3	√	√	√	65.881	24.99	40.891
749.6	√	√	√	79.797	38.65	41.147
500.3	√	√	√	107.883	66.07	41.813

Table 15: CME test for sample 2 at temperature of 50°C

Pressure	Phase observed			Total Cell Volume Corr	Phase volume (gas)	Phase volume (liquid)
	(psig)	G	L ₁			
2500.3	√	√	√	43.773	5.56	38.213
2300.6	√	√	√	44.317	5.9	38.417
2101	√	√	√	45.364	6.59	38.774
1899.5	√	√	√	46.772	7.74	39.032
1700.6	√	√	√	48.634	9.11	39.524
1500.3	√	√	√	51.153	11.23	39.923
1250	√	√	√	56.252	15.8	40.452
1000.7	√	√	√	63.581	22.39	41.191
749.1	√	√	√	76.782	35.32	41.462
500.3	√	√	√	103.647	61.97	41.677

Table 16: CME test for sample 2 at temperature of 40°C

Pressure (psig)	Phase observed			Total Cell Volume Corr (cc)	Phase volume (gas) (cc)	Phase volume (liquid) (cc)
	G	L ₁	L ₂			
2500.3	√	√	√	43.301	5.66	37.641
2299.7	√	√	√	43.826	5.92	37.906
2100.1	√	√	√	44.819	6.54	38.279
1899.5	√	√	√	46.128	7.71	38.418
1699.9	√	√	√	47.899	9.07	38.829
1499.4	√	√	√	50.271	10.71	39.561
1250	√	√	√	54.564	14.86	39.704
999.8	√	√	√	61.41	21.21	40.2
750.5	√	√	√	73.872	33.2	40.672
500.3	√	√	√	99.549	58.6	40.949

Table 17: CME test for sample 2 at temperature of 30°C

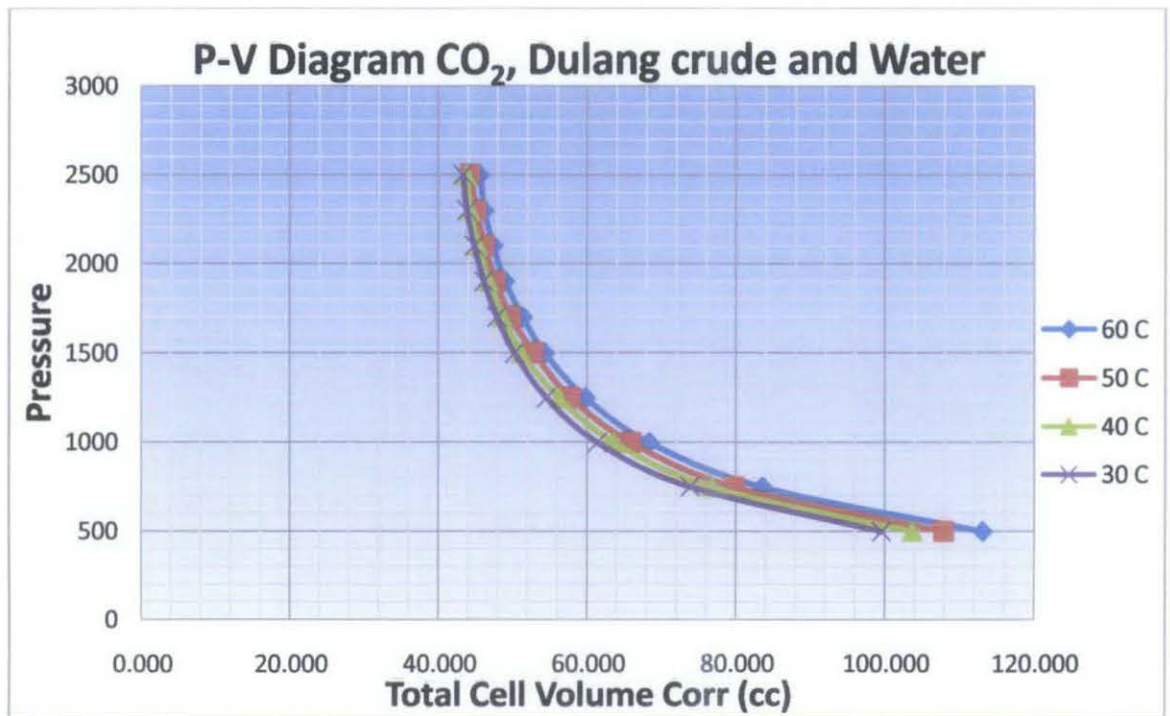


Figure 22: P-V Diagram of CO₂, Dulang oil and water system at different temperature