A STUDY OF WAG AND FAWAG INJECTION INDUCED ASPHALTENE PRECIPITATION IN LIGHT OIL RESERVOIR

By

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

SEPTEMBER 2012

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
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in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(PETROLEUM ENGINEERING)

Approved by,

____

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TRONOH, PERAK
SEPTEMBER 2012

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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TRONOH, PERAK

SEPTEMBER 2012

ABSTRACT

Petroleum is the backbone of world energy. We can’t live without it. From the efforts put in primary to tertiary recovery (Enhanced Oil Recovery, EOR), the ultimate objective is to maximize the recovery and to squeeze out the last drop of oil from reservoir.

. Asphaltene is an aromatic hetero-compound with aliphatic substitutions and asphaltene formed the most polar fraction of crude oil. The instability of asphaltene precipitation can causes permeability and porosity reduction, alteration of formation wettability, plugging of reservoir and fouling of surface facilities.

In this project, two EOR methods are being studied. The first objective is to investigate and compare the amount of asphaltene precipitated during Water-alternating-gas (WAG) injection and Foam-Assisted-Water-Alternating-Gas (FAWAG) injection. Through this experimental research, dynamic core flooding experiments is conducted to study the effect of WAG injection and FAWAG injection in inducing asphaltene precipitation in light oil reservoir. WAG injection is the mobility enhancement method of CO2 injection and it is believed that the presence of water could reduce the asphaltene precipitation. The amount of asphaltene precipitation in light oil will also be recorded for WAG and FAWAG injection. It is proven that FAWAG injection is able to further reduce asphaltene precipitation than WAG.

Core properties before and after displacement is being investigate to study the effect of on porosity, permeability and wettability alteration. Through the studies, it is found out that FAWAG has less effect on changing rock properties. FAWAG injection gives less asphaltene precipitation, less formation damage, and higher oil recovery compare to WAG injection.

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CHAPTER 1: INTRODUCTION

1.1. Project Background

Water-Alternating-Gas (WAG) injection is a popular Enhanced Oil Recovery (EOR) method in Malaysia. Brine and gas are alternatively pumped down-hole and used to force injected CO_2 to the oil rich zones. WAG improves sweep efficiency of the reservoir and leads to higher oil recovery. However, due to the low viscosity but high mobility of CO_2, CO_2 tends to seek the path of least resistance during injection process. Therefore, not all the residual oil is drawn out. The gas always finds a "quick-exit" and break through, leaving oil behind, causing reduced recovery.

Foam-Assisted-Water-Alternating-Gas (FAWAG) injection can be carried out after WAG operation. FAWAG is where foaming agent is added into the injection water in assisting the improvement of gas sweep efficiency. The mobility control of gas flow is increased by the assisting of foam, which eventually improves the well flow (Saleem *et al*, 2012).

Asphaltene precipitation is the fraction that separated from crude oil or petroleum related products when in contact with hydrocarbon solvents such as n-heptane (Speight, 1999).There are many researches stated that water in WAG is able to reduce the asphaltene precipitation. In this paper, the effect of WAG and FAWAG injection on asphaltene precipitation will be investigate to determine if the existing of foam will perform better in reducing the precipitation of asphaltene compare to water.

1.2. Problem Statement

1.2.1. Problem Identification

Asphaltene can cause problems in oil production, transportation, and processing (NMT ASPHALTENE**).** According to de Boer *et al*. (1995), small amount of asphaltene that exists in light oils is more likely to cause problems during production, compares to heavy oil with higher asphaltene fraction. With the existing of unstable asphaltene, plugging of reservoir can happened.

In order to minimize the precipitation of asphaltene, many researches on injection pressure and injection rate of WAG had been carried out. This paper will focus on the efficiency of WAG and FAWAG in minimizing the asphaltene precipitation. The performance of water and foam during the injection will be investigated. It is believed that foam will be able to reduce more asphaltene as compare to water, causing less formation damage and leads to higher oil recovery.

1.2.2. Significance of the Project

This project will focus on the performance of foam which is assumed that it will induce less asphaltene compare to water during the injection. Experiments will be carried out to compare WAG and FAWAG injection method performance in reservoir. The comparing factors will be focusing on their respective mobility control, sweep efficiency, oil recovery and asphaltene precipitation. The comparison will be based on the experiments results.

1.3. Objective

- To investigate and compare the asphaltene precipitation induced by Water-Alternating-Gas (WAG) injection and Foam-Assisted-Water-Alternating-Gas (FAWAG) injection
- To investigate the effects of asphaltene precipitation during WAG and FAWAG injection on core sample properties

1.4. Scope of Study

Two set of laboratory used Berea core samples were used in the experiments. The initial rock properties of the samples were being determined and recorded down. 1 set of crude oil and brine water were used. The injection gas for WAG and FAWAG was Carbon Dioxide (CO_2). The collections of asphaltene before and after the injection were recorded. The sweep efficiency and oil recovery will be further analysing and investigating.

1.5. The Relevancy of the Project

The study on efficiency of WAG and FAWAG in inducing asphaltene precipitation in light oil reservoir is important because the reservoirs in Malaysia are majority producing light oil while asphaltene precipitation produces more problems in light oil reservoir. WAG injection method is widely used nowadays, but through the study of FAWAG injection, the reservoirs will have higher oil recovery than WAG. Hence, this study is very relevant to current market need in Malaysia.

1.6. Feasibility of the Project within the Scope and Time Frame

In order to complete the research on time, full dedication and proper planning on the research schedule is very important. All the apparatus and materials used need to be prepared well before the experiment. Full concentration and hard work is needed in order to complete the tasks, together with the assistance from others.

CHAPTER 2: LITERATURE REVIEW

2.1 WAG and FAWAG Injection in Malaysia

Oil reserves in Malaysia were reported to be declining from year 1994 to year 2002 and if there were no new reserves, the production would end in 19 years time. The solution to increase the oil recovery in matured exploration and producing field like Malaysia is through the implementation of Enhanced Oil Recovery (EOR) projects. In year 2000, PETRONAS had conducted a screening study to identify the potential of EOR in Malaysia's oil field. (Y.Samsudin *et al*, 2005). It is important to implement EOR because oil production need to be accelerate, reserves need to be protect from smearing (Ezzam *et al*, 2011).Water-Alternating-Gas (WAG) injection and Foam-Assisted-Water-Alternating-Gas (FAWAG) injection are popular EOR method but WAG is more widely use in Malaysia.

2.1.1 WAG

WAG is one of the well-established methods for improving sweep efficiency and oil recovery. The WAG technique is a combination of two oil recovery processes: gas injection and water flooding (M.Dong *et al*, 2005), where alternating injection of CO2 is followed by water repeatedly over a number of cycles. WAG is good in controlling gas mobility and miscible process which will increase oil recovery (David H., 2009). With the presence of water in WAG injection, it is believed that the asphaltene precipitation will reduce. (Al-Qasim, 2011; Sarma, 2003; Walcot *et al*., 1989). However, in WAG injection, the Gas-Oil-Contact (GOR) will reduce with the presence of water and poor injectivity at carbonate reservoir (Viet Q.Le *et al*, 2008).

2.1.2 FAWAG

FAWAG is the improvement method from WAG, where foam is added into the WAG method to produce a better performance in oil recovery. Mobility control of gas flow is increased by foam and well flow performance is improved (Saleem *et al*, 2012). Foam can generate massive amount of trapped gas and high local pressure gradients that diffuse the gas phase (Viet Q.Le *et al*, 2008).

FAWAG tends to create a foam boundary that will delay the gas from moving upwards, but spread laterally in order to contact with the unswept parts in WAG.

The combination of foam and gas in the reservoir shows that the presence of foam reduces the mobility of carbon dioxide considerably. Foam reduced the mobility of carbon dioxide by 40% to 85% (F. Khalil & K. Asghari, 2006). In another field test, FAWAG method was used to improve recovery at operating pressures below the minimum miscibility pressure of carbon dioxide in the Wilmington field (Holm, L.W. & Garrison, W.H, 1998).

According to paper by F. Khalil & K. Asghari in year 2006, it stated that oil recovery efficiency of the project's field was increased when surfactant was used with carbon dioxide and that efficiency increased with flooding pressure. F. Khalil & K. Asghari presumed that the effectiveness of carbon dioxide miscible flooding could be increased by alternate injection of carbon dioxide and aqueous surfactant into the reservoir.

2.2 Asphaltene

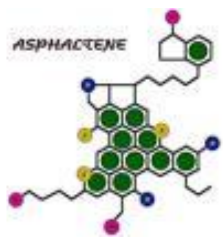


Figure 1: Asphaltene

Asphaltene precipitation is the fraction that separated from crude oil or petroleum related products when in contact with hydrocarbon solvents such as n-heptane (Speight, 1999). Asphaltene (as shown in figure above) is insoluble in n-pentane (or n-heptane) at a dilution ratio of 40 parts alkane to 1 part crude oil and re-dissolves in toluene. Asphaltene is an aromatic hetero-compound with aliphatic substitutions and asphaltene formed the most polar fraction of crude oil (NMT Asphaltene).

The deposition and precipitation of asphaltene can create big impact to reservoir and production. Problems will arise from permeability and porosity reduction, alteration of formation wettability, plugging of reservoir and fouling of surface facilities (Ghedan, 2009; Srivastava *et al.,* 1997).

The amount of asphaltene does not determine whether asphaltene will create problem or not, but asphaltene stability. The stability of asphaltene is depends on few factors, including the composition of the surrounding fluid – where how good a solvent the rest of the oil is for its asphaltene, pressure and temperature (Eduardo *etc al*, 2004). Operation such as gas injection, phase separation, incompatible chemicals and mixing of crude streams will change the composition and affect the asphaltene stability. In light oil reservoir, the asphaltene solubility is low and low solubility makes asphaltene unstable and easy to precipitate (Sima *et al*, 2011).

2.2.1 Asphaltene Stability Factor

As stated by de Boer et al. (1995), small amount of asphaltene that exists in light oils is more likely to cause problems during production, compares to heavy oil with higher asphaltene fraction. With the existing of unstable asphaltene, plugging of reservoir can happened. Therefore, we can say that stability of asphaltene is very crucial in affecting the performances of the crude oil. For asphaltene to precipitate there are few steps to go through. Step 1 is where the solid particles form a distinct phase as they come out from solution (crude oil). Then all the small solid particles will clump together and grow larger. This stage is called flocculation stage. Finally, all the clumped together particles will settle out on solid surface and deposited.

According to experimental researches and field experiences (de Boer et al.,1995), asphaltene stability is depends on few factors, which are pressure, temperature and composition of the surrounding fluid. Each factor will be discussed detailed. \

Factor 1: Pressure

Compared to temperature factor, pressure plays a more important role in affecting the asphaltene stability in crude oil. According to an experiment carried out by Sima *et al* in year 2011, by increasing the injection pressure of gas, less asphaltene would deposit as less permeability and porosity reduction were reported. This result is further proven by the experiment carried out by Eduardo et al in year 2004.

Depletion of pressure can destabilize asphaltene and cause precipitation. During the transportation of crude oil from one point to the other through pipeline, pressure dropped. This is mostly why asphaltene will deposited in well pipeline. Due to pressure drop, the density of the crude oil decreases and it caused the screening effect on asphaltene interactions arising from the presence of oil components drops, causing the interactions between asphaltene to become stronger, which in turn induces the precipitation (Eduardo et al, 2004).

Hammami et al. (2000) conducted an experiment to measure the APE for various Gulf of Mexico live oils through a series of isothermal pressure depletion experiments and he obtained the evidence that asphaltene will precipitate above its saturation pressure and asphaltene will show good solubility below the saturation pressure.

Factor 2: Temperature

There are many researches showed that the effect of temperature on asphaltene precipitation is not as influential as pressure changes or solvent composition. However, temperature changes will affect the solubility of the fluid. Solubility of fluid is directly affecting the precipitation of asphaltene. So we can say that temperature is still affecting the asphaltene stability.

Factor 3: Composition of the Surrounding Fluid

In a "good" solvent, asphaltene are not strongly attracted to one another. In a "poor" solvent, asphaltene attractive forces are enhanced (NMT Asphaltene). According to study by Eduardo et al, (2004), the effect of composition on asphaltene precipitation is generally believed to be stronger than the effect of temperature. Addition of paraffinic compounds shifts the solubility of asphaltenes in the bulk oil because its solvent power affects interactions among asphaltenes and resins. If the paraffinic compounds are good solvents for resins but not for asphaltenes, as the volume of diluents increases both the interaction between resins and asphaltenes and the capacity of the former to stabilize the asphaltene molecules as small aggregates becomes weak, causing asphaltenes to precipitate.

It is important to understand the basic mechanisms of asphaltene phase formation through experimental study of the effects of pressure, temperature, and composition on asphaltene precipitation. This study can also provide all the necessary input for development and validation of handling of asphaltene precipitation.

2.3 Effect of WAG Injection on Asphaltene Precipitation

In WAG, water is injected alternately with gas. The role of brine water helps to reduce precipitation of asphaltene. The increase in the brine concentration appears to reduce the asphaltene precipitation (Srivastava *et al.*, 1997). This research finding is also supported by Wolcot *et al.* (1989), who presented that the presence of injected fluid - brine could reduce the deposition but could not eliminate it at all (Wolcot *et al.,* 1989). Brine act as a medium to reduce the composition changes in reservoir, to further avoid the changes in asphaltene stability. However, WAG injection is more crucial for oil-wet reservoirs as compared to water-wet reservoir (Zahoor *et al,* 2011). Since brine cannot fully eliminate asphaltene, foam might play a better role in preventing asphaltene precipitation.

2.4 Effect of FAWAG Injection on Asphaltene Precipitation

According to research carried out by Viet *et al* (2008), the foam stabilized with gas soluble surfactants is more economical and technical advantages in controlling gas mobility in porous media (Viet *et al*, 2008). Other than reducing the gas mobility, foam also increase the differential pressure and diverted the flow into oil-saturated matrix (A. Haugen and A.Graue, 2012). In the experimental study by A. Haugen & A.Graue (2012), oil recovery during injection of pregenerated foam was improved significantly with up to 78% of OOIP produced (A. Haugen and A.Graue, 2012). Foam shows good potential in increasing oil recovery by high sweeping ability, less vicious fingering and gas diversion from high permeability or previously swept layers (A. Haugen and A.Graue, 2012; Bernard and Holm 1964; Rossen 1996).

Based on study by Blaker *et al* (2002), FAWAG on the Snorre field showed that foam efficiency is affected by surfactant absorption, critical surfactant concentration, and foam during effect, oil tolerance and foam strength. However, further studies will be done in this research to determine the role of FAWAG is light oil reservoir and the induction of asphaltene precipitation by foam.

2.5 Foaming Agent: Surfactant

2.5.1 Sodium Dodecyl Sulfate

According to J.F. Casteel and N.F. Djabbarah, the selections of a suitable foaming agent for a different reservoir condition need to be properly conducted. The requirement for the foaming agent included the capability in generating long lasting and ample foam in reservoir, low absorption and low decomposition losses. Other than that, a good foaming agent should be able to increase the CO2 sweep efficiency and recover more oil in porous media tests. The last requirement for the foaming agent is where it should be inexpensive and commercially available.

In this project, Sodium Dodecyl Sulfate - $CH_3(CH_2)_{11}OSO_3Na$ or sodium lauryl sulphate (SLS) is chosen as the foaming agent. Sodium Dodecyl Sulf is a negatively charged surfactant. It is commonly use as surfactant in tertiary recovery method –FAWAG. The foam stability is tested through bottle test and it is proven that the foam is stable and long lasting. It is also lower expenses compared to others. Sodium Dodecyl Sulfate is also an anionic wetting agent that reduced and lowers the surface tension of a liquid and the tension between two liquids.

From Figure below, it can be seen that in aqueous form, the polar part of the meolecule which consist of chain and the hydrophilic SO3 end. It has an amphiphilic part at the chain end.

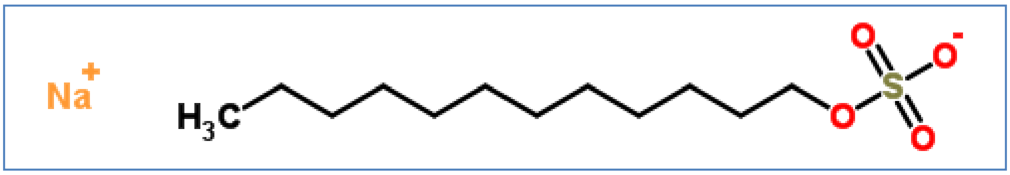


Figure 2: Sodium Dodecyl Sulfate

2.5.2 Alpha Olefin Sulfonate (AOS)

Normal alpha olefins are excellent intermediates for producing alpha olefin sulfonate (AOS) surfactants. These surfactants provide outstanding detergency, high compatibility with hard water, and good wetting and foaming properties. AOS is free of skin irritants and sensitizers, and it biodegrades rapidly. It is used in high-quality shampoos, light-duty liquid detergents, bubble baths, and heavy-duty liquid and powder detergents. It is also used in emulsion polymerization.

CHAPTER 3: METHODOLOGY

3.1 Key Milestones and Elaboration

The figure below describes the overall milestones and general of this project.

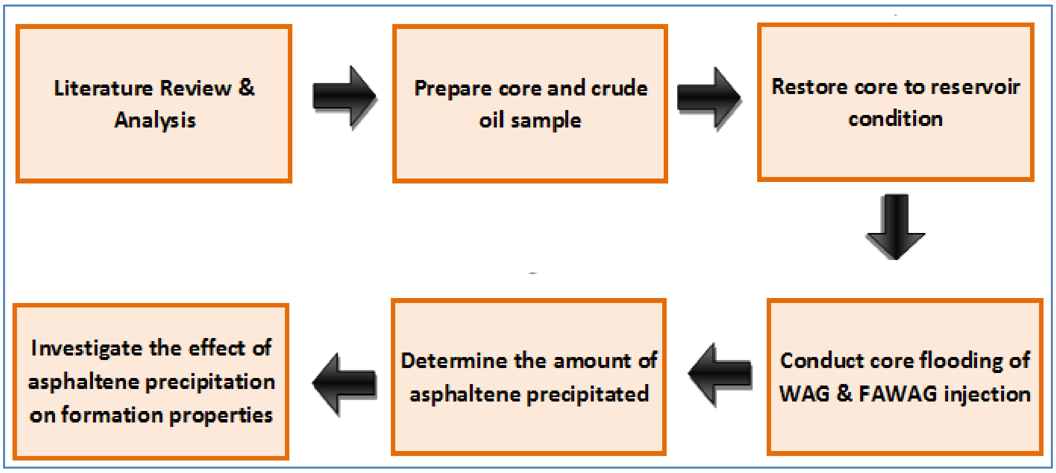


Figure 3: Research Methodology

Table 1: Elaboration on the Key Milestones

Steps	Activity
Literature Review & Analysis	To obtain information regarding the project and its elements such as fundamental theories and concept, equipments and others. Literature study able to enhance the knowledge about previous studies done on asphaltene.
Prepare core and crude oil sample	Measure porosity and permeability of core sample using PoroPerm System. Rock Wettability was measured using IFT 700
Restore core to reservoir condition	Saturated core with 5000ppm brine follow by oil to restore the initial oil in place and irreducible water saturation. Water flooding was conducted to restore the residual oil saturation in core.
Conduct core flooding of WAG & FAWAG injection	Using Relative Permeability System to conduct core flooding experiments for WAG and FAWAG. Effluent was collected every 25 minutes.
Determine the amount of asphaltene precipitated	The collected crude effluent was tested using ASTM standard D3279-07 to measure the asphaltene content.
Investigate the effect of asphaltene precipitation on formation properties	Measure the changes in porosity, permeability and wettability of core samples to determine the degree of changes brought by asphaltene precipitation

3.2 Research Methodology

Table 2: Core Properties Measurement

Core Properties Measurement

Equipment:

Oven, Poro-Perm System

Chemical:

Nitrogen Gas

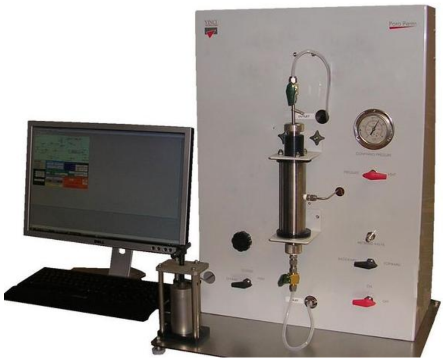


Figure 4: PoroPerm System

Procedure:

1. The core sample loaded into the core holder.
2. The length and diameter of samples were measured with digital caper and subsequently bulk volume was determined automatically from system.
3. Nitrogen gas was filled into core chamber to fully saturate the samples.
4. Using suitable confining pressure of 400 Psia, the effective porosity and gas absolute permeability can be obtained.
5. The Klinkenberg gas slippage effect is corrected using the build in klinkenberg correction software.

Calculation:

Porosity is a measure of storage capacity of a reservoir. The porosity is calculated as ratio of the pore volume to the bulk volume of the core sample.

$$Porosity = \frac{Pore..Volume}{Bulk..Volume} = \frac{Bulk..volume - Grain..Volume}{Bulk..Volume}$$

Bulk Volume:

$$V_b = \pi r^2 L$$

where: r = radius of the core
L = length of the core

Porosity:

$\emptyset$=Vp/Vb x 100%

where: Vb = bulk volume of the core
Vp = pore volume of the core

Table 3: Core Flooding

Core Flooding

Equipment:

Relative Permeability System,

Chemical:

Crude Oil Sample, Brine water (5000 ppm), 99.99% Pure CO_2 Gas,

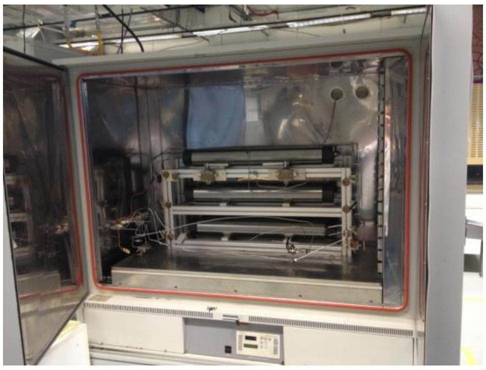


Figure 5: Relative Permeability System

Procedure:

1. The core sample was flooded with brine follow by crude oil to obtain initial oil in place and irreducible water saturation restoration. The original oil in place was determined through the amount of water dispersed.
2. The core was then flooded with brine and the amount of produced oil was measured to obtain the residual oil saturation. The process was conducted until a stable residual oil was established. This is when only water is being produced at the outlet.
3. To determine the WAG injection on the asphaltene precipitation, CO_2 gas and water were injected alternatively into the core 0.2 cc/min injection rates. The amount effluent oil was collected every 25 minutes to obtain the recovery factor and phase saturation change. Step was repeated until no more oil was recovered.
4. The above step was repeated for FAWAG injection under same injection rate. The injection length for brine and CO_2 gas injected were 10 minutes each.

Calculation:

Initial Oil Saturation:

$$S_{oil\ initial} = \frac{Voil\ initial}{Vpore}$$

where: *Voil initial = Initial Oil Volume*
Voil = Volume of Oil
Vpore = Pore Volume

Residual Oil Saturation:

$$S_{oil\ residual} = \frac{V_{oil\ initial} - V_{oil}}{V_{pore}}$$

Table 4: Asphaltene Content Measurement

Asphaltene Content Measurement

Equipment : Gooch Crucible, , Filter Paper, Heating Flask, Suction Flask, Reflux Condenser, Hot Plate, Magnetic Stirrer, Dessicator, Hood, Oven

Chemical: n-Heptanes, crude oil sample

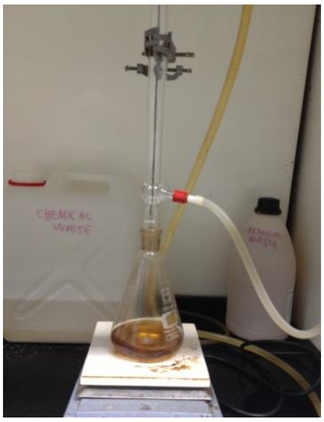


Figure 6: Experiment setup for Asphaltene Measurement

Procedure:

1. The sample was weighted to the nearest 1.0 g (B) and 100 ml of solvent per 1.0 g of sample was added into the heating flask.
2. With the magnetic stirrer added, the flask was heated on the hot plate at 70^{o}C under the reflux condenser for about 20 minutes and cool down.
3. The filter paper was placed into the gooch crucible and put into oven at about 107^{o}C for 15 minutes. The gooch crucible was allowed to cool down in Dessicator and the weight was measured.
4. The gooch crucible was pre-filtered with n-heptane and the mixture in the heating flask was poured into the suction flask through the gooch crucible.
5. The gooch crucible was put into oven at about 107^{o}C for 15 minutes. The gooch crucible was then allowed to cool down in Dessicator and the weight was measured. The amount of insoluble inside is denoted as (A).

Calculation:

The weight percentage of asphaltene content, Wt= A/B x 100%

Table 5: Wettability Measurement – IFT 700

Wettability Measurement – IFT 700

Equipment:

IFT 700

Material/Chemical:

Brine, Thin Core slices, light crude oil

Figure 7: IFT 700

Procedure:

1. A degreaser and air-blower were used to clean the chamber cell to remove any impurities.
2. A small piece of core sample was inserted into the sample holder and load into the chamber cell.
3. The cell was then pressurized to 3000 Psi at constant temperature of 100oC to resemble the core flooding conditions.
4. By slowly controlling the inlet/ outlet pressure of the oil tank, a single droplet of oil was injected into the pressure cell.
5. The oil droplet image adhere on the core surface was observed from the computer through the microscopic camera.
6. The position and the resolution of camera were adjusted to give clear image.
7. The results with low contact angle (0 to 90oC) indicate water wet properties while the large contact angle (90 oC to 180 oC) represent oil wet properties.

Calculation:

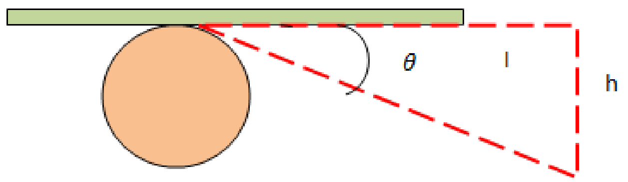


Figure 8: Contact Angle

Contact Angle, θ:
$< 90^o$ = water wet
$> 90^o$ = oil wet

3.3 Project Activities

The figure below is the overview of the project activities:

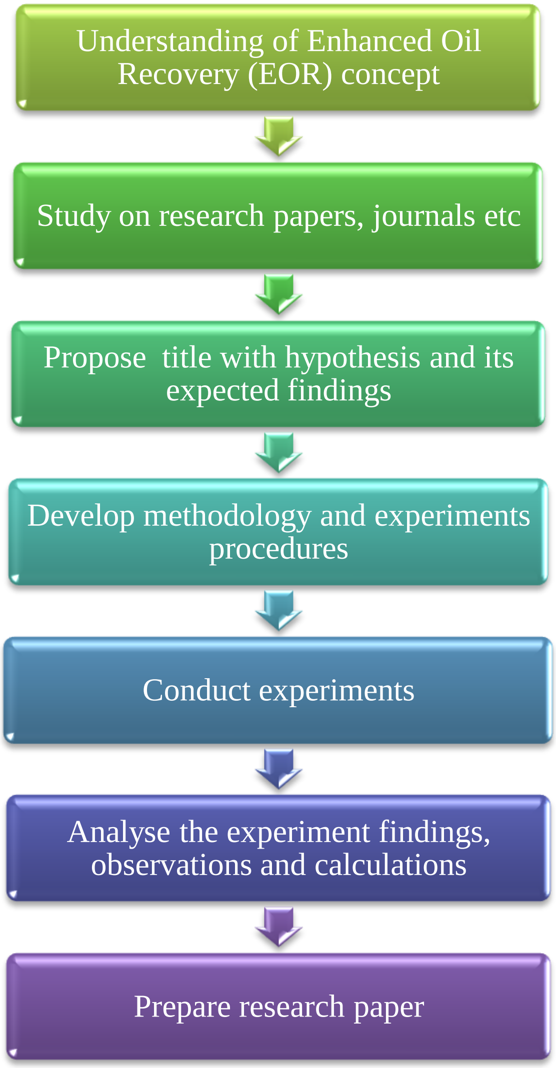


Figure 9: Project Activities

3.4 Gantt Chart

Table below is the Gantt chart for the project:

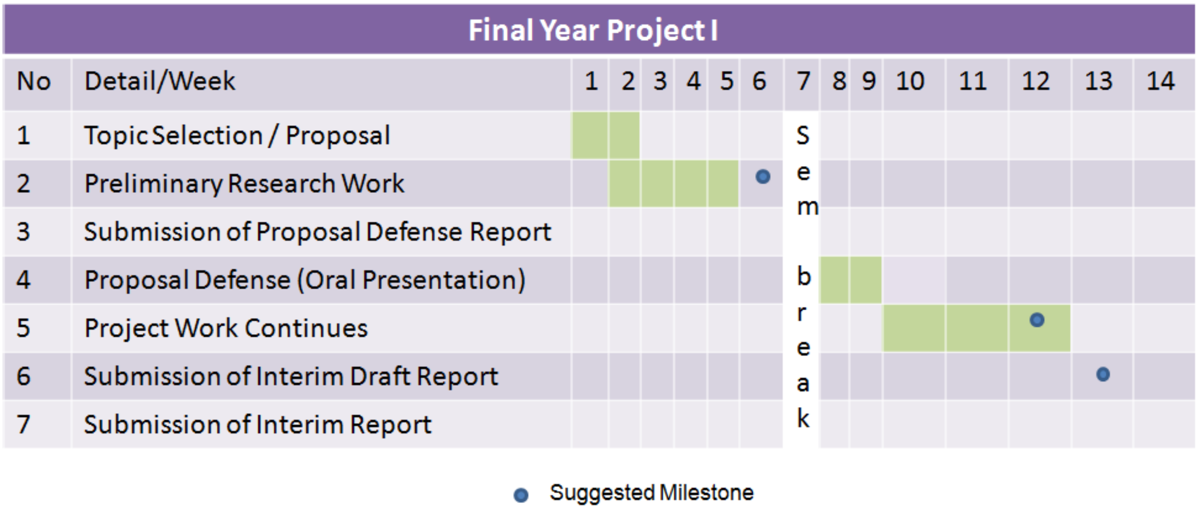


Figure 10: Gantt Chart FYP I

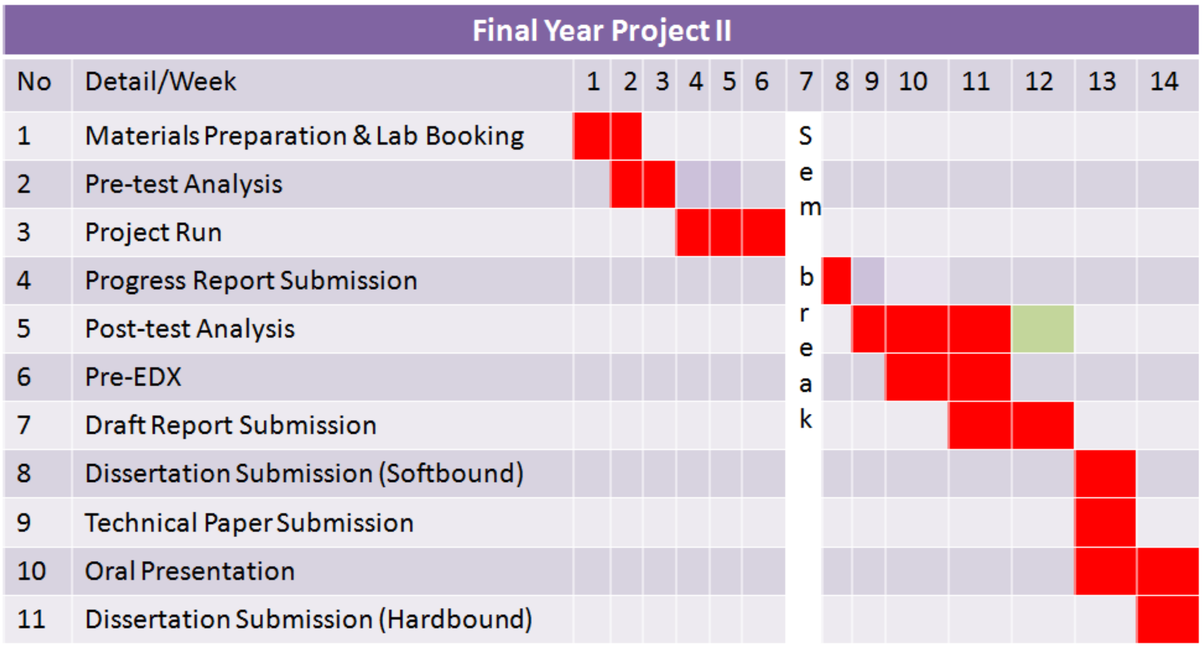


Figure 11: Gantt Chart FYP II

3.5 Tool, Material and Equipment

The list of tools and equipments that will be used for the project:

Table 6: List of Tools/Materials

Tools/ Materials	Function
2 Sample core plug	Core flooding
Sample crude oil	Core flooding
99.99% pure CO2 gas	CO2 & WAG injection
Brine	Core restoration/ WAG injection
Toluene	Core cleaning
n-heptanes	Core cleaning, Asphaltene content
Surfactant	Foam Injection

Table 7: List of Equipments

Equipments	Function
Relative Permeability Test System	To conduct core flooding
Soxhlet Extractor	Core cleaning
Drying oven	Core cleaning
Poro-perm system	To determine core properties measurement
Dessicator	Asphaltnene content measurement
Densitometer	To measure crude oil density
IFT 700	Interfacial Tension measurement – to determine the effect of asphaltene precipitation on Wettability alteration

CHAPTER 4: RESULTS AND DISCUSSION

Below are the summaries of results obtained from each experimental phases. Details results from each experiment are presented in Appendix for reference.

4.1 Sample Properties

The density and viscosity of the crude oil sample used in WAG and FAWAG injection is shown in table below.

Table 8: Light Crude Oil Properties

Sample Name	Malaysia Light Oil
Viscosity(cst) @ 98°C	1.51
Viscosity(cp) @ 98°C	0.80
Density (g/cm^3)	0.52

The properties for core samples that used for WAG and FAWAG injection were measured using PoroPerm System before core flooding operation, as shown in Table 9 below:

Table 9: Original Core Sample Properties

Parameter	Core 1 (WAG injection)	Core 2 (FAWAG injection)
Diameter (mm)	38.17	36.94
Length (mm)	70.09	77.76
Weight (g)	174.91	182.55
Bulk volume (cc)	80.082	83.337
Pore volume (cc)	13.932	15.473
Kair (mD)	53.278	58.615
K (mD)	48.715	52.674
Porosity (%)	17.398	17.529

4.2 Foam Stability Test: Sodium Dodecyl Sulfate (SDS) and Alpha Olefin Sulfonate (AOS)

Two surfactants were used as received and screened in Bottle Test for foam with 5000ppm brine based on Defoaming Time. The surfactants are Sodium Dodecyl Sulfate (SDS) and Alpha Olefin Sulfonate (AOS), see Table 10 for surfactant properties.

Table 10: Surfactant Chemical Description

Name	Chemical Description
Surfactant 1	Alpha Olefin Sulfonate
Surfactant 2	Sodium Dodecyl Sulfate

Surfactant solutions were prepared by adding 0.5 wt% surfactant in the same brine solution and shaking to generate foam. This is to inspect the ability of the solution to foam and the stability of the generated foam. The foam conditions were visually inspected to determine the most stable foam over the time. However, foam behaviour during static tests does not necessarily predict the behaviour at flooding conditions.

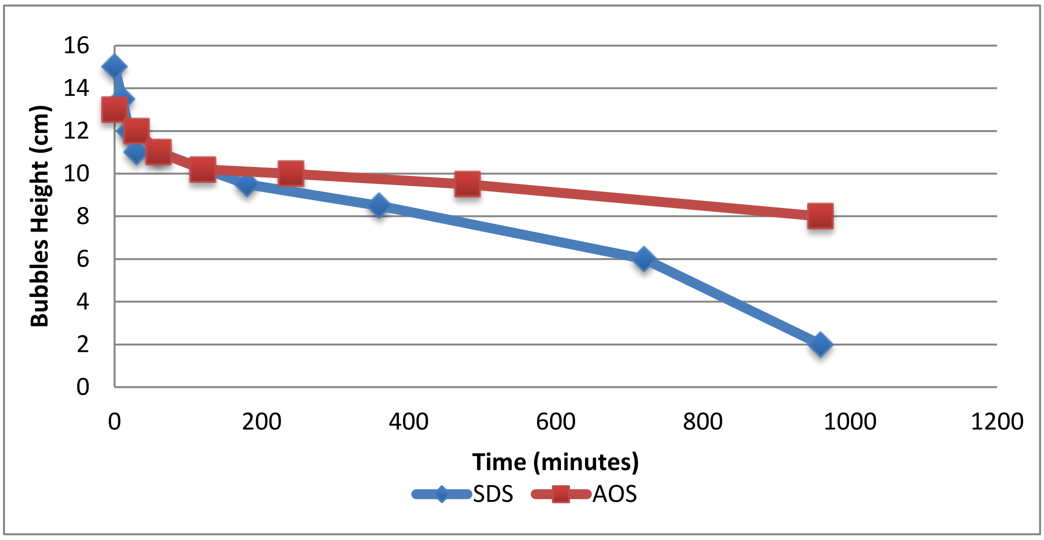


Figure 12: Defoaming Time Of AOS And SDS @ Atmospheric Temperature And Atmospheric Pressure

Figure 13 above showed the results of bubble height over time carried out at atmospheric temperature and pressure condition. AOS showed better foam stability compared to SDS. At the time 16 hours, there was still 8cm of AOF bubbles left in the test tube but SDS on left 2cm of bubbles. After much consideration, the project will use AOF as foaming agent in FAWAG injection. Further details can refer to Appendix 1.

4.3 Dynamic Core Flooding Test

Dynamic displacement experiments – Core Flooding test were carried out using Relative Permeability System to determine the effect of WAG and FAWAG injection on asphaltene precipitation. Figure 13 shows simple schematic diagram of Relative Permeability System.

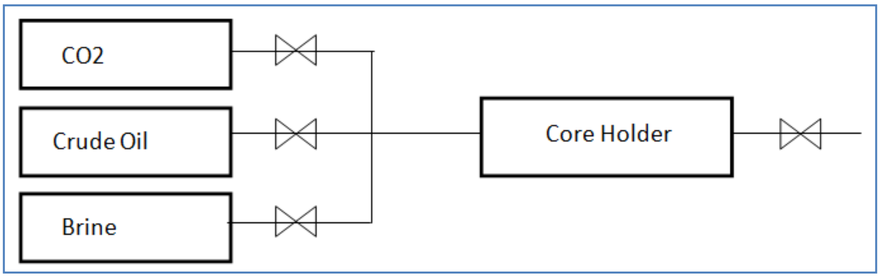


Figure 13: Simple Schematic of Core Flooding Equipment

The formation was fixed at 3000 Psi and 100°C to simulate near reservoir condition. The injection rate was 0.2 cc/min with 2000 Psi injection pressure. For WAG injection, it was a injection cycle of gas alternate 5000ppm brine with 10 minutes of injection time each. Each cycle took 20 minutes and the cycle was repeated until no more oil was produced. The effluent were collected every 25 minutes interval for both WAG and FAWAG injection in order to measure the changes in asphaltene content. Details were recorded in Table 11 below.

Table 11: Dynamic Core Flooding Test Parameters

Parameter	Value
Injection rate (cc/min)	0.2
Inlet Pressure (Psia)	2000
Confining Pressure (Psia)	3000
Temperature (°C)	100
Brine concentration (ppm)	5000
Effluent collection interval (min)	25
WAG injection	
Water injection length (min)	10
Gas injection length (min)	10
FAWAG injection	
Surfactant injection length (min)	10
Gas injection length (min)	10

4.4 Analysis on Asphaltene Precipitated during WAG and FAWAG Injection

From the effluent that collected throughout WAG and FAWAG core flooding test, the asphaltene content was measured. During the injection operation, changes in reservoir condition, pressure instability and changes in composition induced asphaltene precipitation. This condition is often happened in Malaysia light crude oil field which induced the precipitation of asphaltene during production. Both injection methods caused asphaltene precipitation, but FAWAG performed better based on the core flooding test. Further details can refer to Appendix 3.

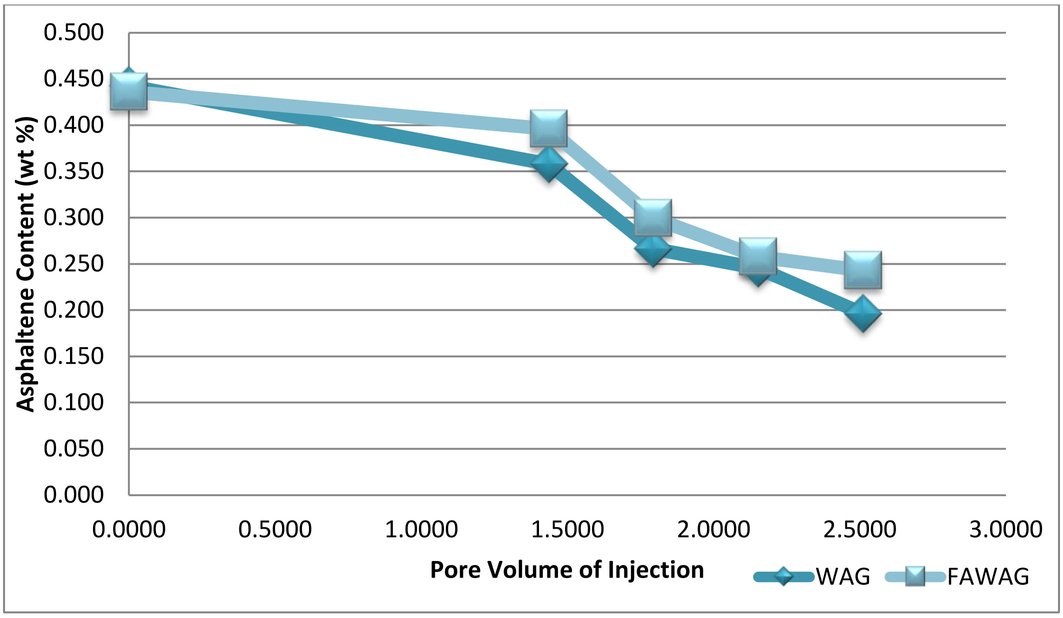


Figure 14: Asphaltene Content of Collected Effluent vs. Pore Volume of Injection

Figure 14 above shows the amount asphaltene content in effluent throughout the injection. The weight percentage of asphaltene in the effluent oil were measured based on ASTM D3279-07 Standard Test Method. Based on the graph it was observed that the asphaltene content in the collected effluent for FAWAG injection was more that WAG injection. The initial asphaltene content in the crude oil for WAG was 0.442wt% while FAWAG was 0.436 wt%. At the end of effluent collection, the asphaltene content in WAG method's crude was 0.196 wt% while FAWAG was 0.243wt%. The reduction of asphaltene weight indicates precipitation inside the core. WAG method had higher reduction. This meant that more asphaltene was precipitated inside the core sample. FAWAG method had lower precipitation as the reduction of asphaltene in effluent collect was lower.

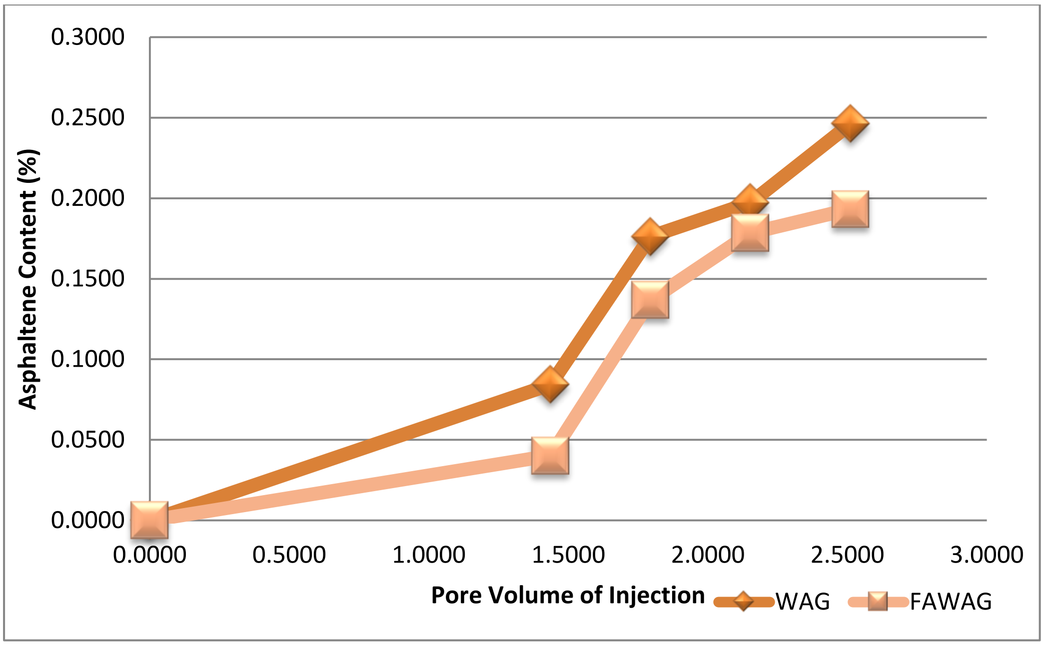


Figure 15: Asphaltene Content in Core Sample vs. Pore Volume of Injection

Figure 15 showed the asphaltene content inside the core sample over the injection for WAF an FAWAG. Based on the results obtained, it showed that for WAG injection, active asphaltene precipitation was occurred inside the core sample based to the high asphaltene weight percentage compared to FAWAG injection as the injected pore volume increased. At 1.4360 pore volume, where first effluent oil was collected, the amount of asphaltene precipitation was 0.0844 wt%. Over the time, the weight percentage of asphaltene at pore volume 2.1530 was 0.1967 wt%. At the end of core flooding test, it was found that 0.2464 wt% of asphaltene was precipitated inside the core when the pore volume was 2.5120.

As for FAWAG injection, it was observed that the amount of asphaltene precipitation was lower than WAG injection. At pore volume of 1.4360, 0.0402 wt% of asphaltene was measured. At same value of pore volume, FAWAG injection had 50% less asphaltene precipitation compared to WAG. FAWAG injection finished collection of effluent at pore volume 2.5120 with 0.1933 wt% asphaltene precipitated inside the core sample.

Based on the results obtained, the hypothesis of this project was proven. Foaming agent in FAWAG injection provided a more stable environment which reduced the asphaltene precipitation throughout the injection. Gas mobility was well controlled by foam, which reduced the changes of fluid composition for reservoir.

4.5 The Influence of Asphaltene Precipitation on Rock Properties – Porosity and Permeability

The deposition and precipitation of asphaltene can create big impact to reservoir and production. One of the possible problems is permeability and porosity reduction. The amount of asphaltene does not determine whether asphaltene will create problem or not, but asphaltene stability.

After dynamic core flooding test, each core sample was treated with n-heptane to remove all impurities but only leave asphaltene inside the core. This was to indicate the changes of porosity and permeability due to the presence of asphaltene. In table below, it showed that the initial porosity and permeability of each core sample and after displacement test. The differences occurred indicate formation damage induced by asphaltene precipitation.

Table 12: Core Sample Porosity and Permeability Before and After Displacement Test

		Porosity (%)	Difference (%)	Permeability (mD)	Difference (%)	Pore Volume (cc)
WAG Injection	Before Displacement	17.398	9.78	53.278	62.36	13.932
	After Displacement	15.696		20.055		12.584
FAWAG Injection	Before Displacement	17.529	3.13	58.165	39.93	14.563
	After Displacement	16.981		34.939		14.067

Based on the above findings, the differences in porosity and permeability were plotted as graph, as showed in Figure 16 and Figure 17. From the plot, It is proved that asphaltene precipitation would cause reduction in porosity and permeability. However, it was observed that a bigger alteration in porosity and permeability for core sample used in WAG injection. This indicated that a more critical degree of formation damage brought by WAG injection to the rock properties. The reduction in porosity and permeability was high possibility due to the clogging of pore space by small particles of the precipitated asphaltene during the injection.

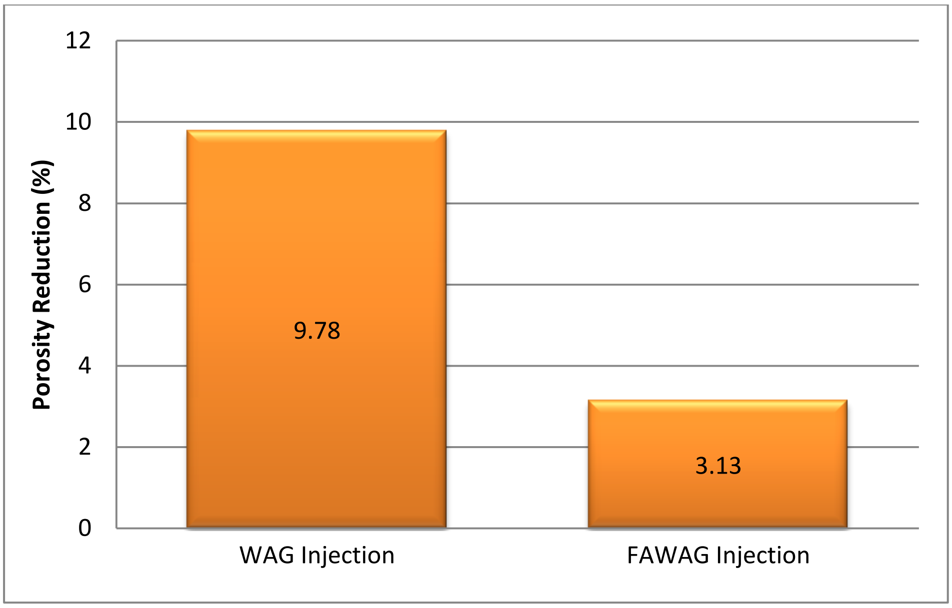


Figure 16: Porosity Reduction due to WAG and FAWAG Injection

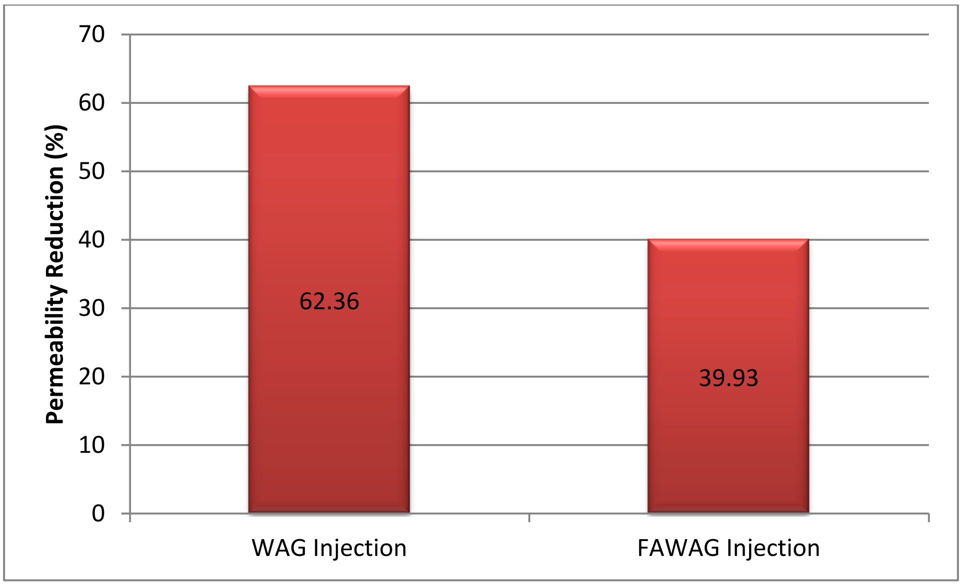


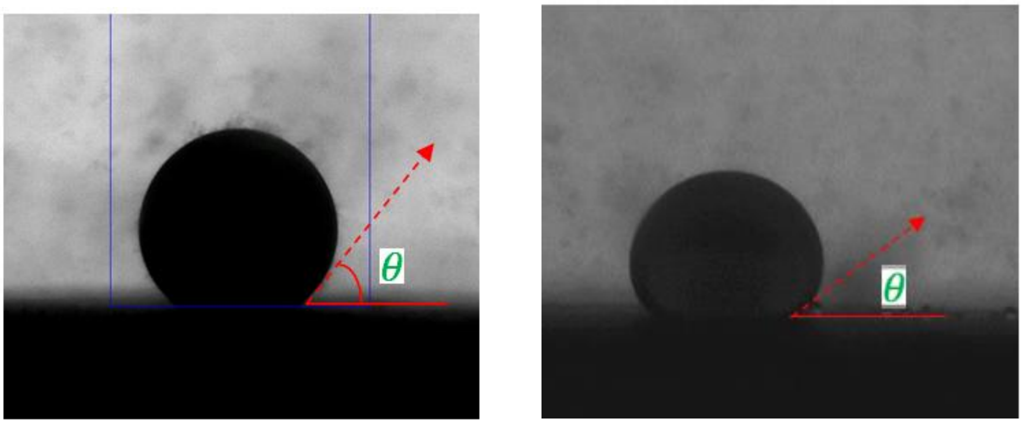
Figure 17: Permeability Reduction due to WAG and FAWAG Injection

Based on Figure 16 and Figure 17, an obvious reduction trend was presented. For porosity, the differences brought by WAG injection was 9.78% while for FAWAG injection, it was 3.13%. WAG injection had higher effect on porosity reduction as more asphaltene was precipitated during the operation. As for permeability, FAWAG showed 39.93% differences for changes between before displacement and after displacement. Compared to 62.30% by WAG injection, FAWAG once again showed a better performance than WAG. This was due to stable reservoir condition provided by the injected foam during the test.

4.6 The Influence of Asphaltene Precipitation on Rock Wettability

The interaction between a rock surface and a fluid such as oil and water determines its wetting characteristics, whether it is oil-wet or water-wet. Based on principle of thermodynamics, all surfaces try to reach their lowest possible surface energy in a specific fluid phase (Stumm, 1992). Water, surfactant and asphaltene are polar compounds that have the capability to change the energy of surface, causing changes in wettability. There are also other factors that determine rock wettability.

The core sample wettability was determined using IFT 700 - sessile drop method, where the contact angle between oil droplet and core slide was measured. The angle of the denser fluid (brine) to the rock surface of less than 90^{o} indicate a water wet condition while an angle of more than 90^{o} indicated oil wet. Figure 8: Contact Angle explained the condition.



Before WAG Injection:

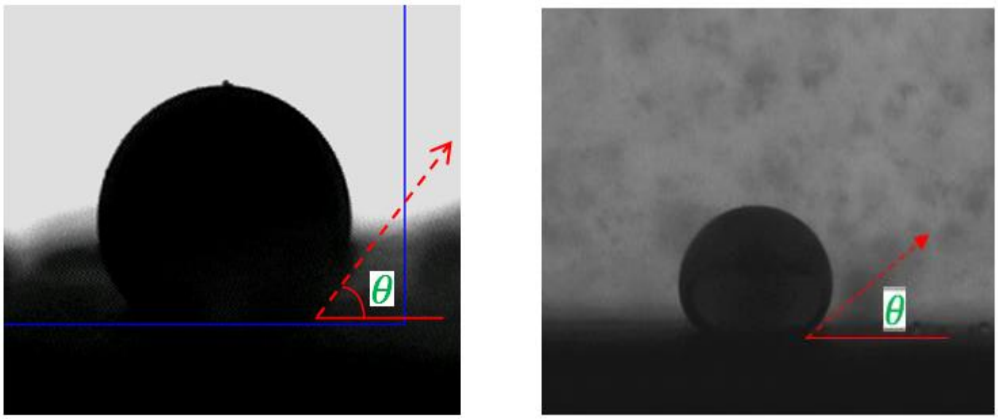
Contact Angle = 45^{o} ; Water Wet

After WAG Injection:

Contact Angle = 33^{o} ; Water Wet

Figure 18: Contact Angle for WAG Injection - Before and After

For WAG injection, the initial rock wettability condition was water wet, where the contact angle, θ was 40^{o}. After the core flooding test, the contact angle, θ was changed to 33^{o}, in which the wettability of the rock moving towards more water wet. The injection of water provided a protective layer to the rock surface from interaction with the asphaltene particles. However, when compared with FAWAG injection, where surfactant wad injected, it seems like a stronger shield was formed to resist the changes brought by precipitated asphaltene. Refer to Figure 19 for the effect of FAWAG injection on contact angle between rock surface and crude oil.



Before FAWAG Injection:

Contact Angle = 40^o ; Water Wet

After FAWAG Injection:

Contact Angle = 28^o ; Water Wet

Figure 19: Contact Angle for FAWAG Injection - Before and After

During FAWAG injection, foam was formed inside the core to provide a better reservoir condition to enhance oil recovery and reduce the interfacial tension between crude oil and injected fluid. The contact angle before core flooding test was 40^o and measurement after core flooding test showed that contact angle was 28^o Primary and waterflood oil recovery is affected by the wettability of the system. A water-wet system will exhibit greater primary oil recovery.

4.7 Oil Recovery Factor of WAG and FAWAG injection

Based on the results from core flooding test, the recovery factor for WAG method and FAWAG method were calculated. Refer to Table 13 and Figure 20 below for the calculation results:

Table 13: Recovery Calculation Results

	Water Flooding (%OOIP)	EOR (%OOIP)
WAG	50.87%	43.50%
FAWAG	43.13%	48.95%

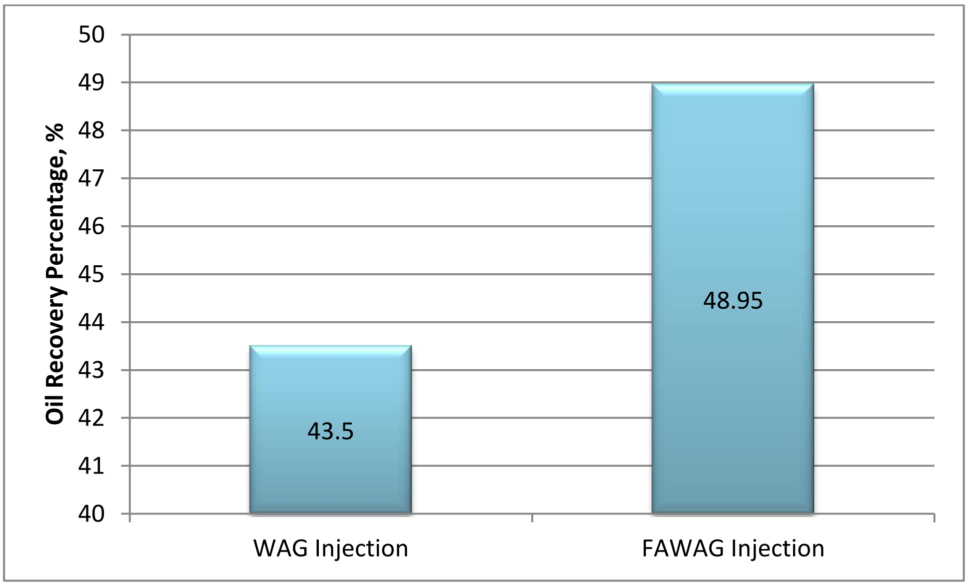


Figure 20: Oil Recovery for WAG and FAWAG

For WAG Injection, the recovery percentage during Water Flooding was 50.87% while for FAWAG it was 43.13%. Core sample for WAG injection had a slightly higher recovery percentage during water flooding stage. As for the tertiary recovery stage, the recovery for WAG was 43.50% while FAWAG was slightly higher than WAG, which was 48.95%. Basically both method had high recovery factor and performed well in this core flooding test. Detail calculation and information can be obtained in Appendix 2.

Both WAG and FAWAG injection are efficient enhanced oil recovery method. From the results obtained, it showed that both methods had significantly high water recovery factor. For WAG, Brine is pumped down-hole and used to force injected CO_2 to the oil rich zones. WAG improves sweep and leads to higher oil recovery. However, during injection, CO_2 tends to seek the path of least resistance so that not all the residual oil is drawn out due to low viscosity of high mobility CO_2. This will cause reduction in term of recovery.

For FAWAG injection, the recovery was slightly higher than WAG. FAWAG is the improvement method from WAG, where foam is added into the WAG method to produce a better performance in oil recovery. Mobility control of gas flow is increased by foam and well flow performance is improved. FAWAG tends to create a foam boundary that will delay the gas from moving upwards, but spread laterally in order to contact with the unswept parts in WAG. Foaming agent will will further enhanced the role of gas in contracting with the crude inside the reservoir by efficiently diverts gas bubbles from the high to the low permeability zones

CHAPTER 5: CONCLUSION AND RECOMMENDATION

This study had successfully achieved the objectives that set. This study has proven that both WAG and FAWAG injection caused asphaltene precipitation but FAWAG is less induced the precipitation as compared to WAG injection. FAWAG injection provides a more stable condition for the crude in the reservoir. Amount of asphaltene does not determine the degree of precipitation, but the stability. The stability of asphaltene is very crucial. Stability depends not only on the properties of the asphaltene fraction, but also on how good a solvent to asphaltene. FAWAG injection performed better in this part.

Asphaltene particles caused reduction to porosity and permeability and changes in wettability. This is due to the precipitated asphaltene particles have clogged the pore volumes and reduced the porosity of core sample. During the injection progress, interfacial tension between the injected medium and core sample rock surface also induced changes to the rock wettability. the water wet condition of the rock retained. the wettability of the rock moving towards more water wet after WAG and FAWAG test

Other than focusing on determining the optimum condition to reduce asphaltene precipitation, it is recommended to place the focus on foaming agent for FAWAG injection. Further studies are suggested in determining the best foaming agent for Malaysia field condition; choose the optimum concentration of surfactant to be injected with respect to suitable brine concentration, which can give less asphaltene precipitation and higher recovery factor.

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APPENDIX

Appendix 1:

Surfactant 1: 5000ppm Brine, 0.5 wt% of AOS

Time (minutes)	Height of Bubble (cm)	Remarks
0	13	Bubbles are small and compact
30	12	Bubbles remains similar condition
60	11	Bubbles still compact
120	10.2	Bubbles become bigger
240	10	Bubbles on top looks weak with big gap
480	9.5	Bubbles near solution are stable
960	8	Bubbles still exists well after 16 hours

Surfactant 2: 5000ppm Brine, 0.5 wt% of SDS

Time (minutes)	Height of Bubble (cm)	Remarks
0	15	Bubbles are small and compact
10	13.5	Bubbles still compact
20	12	Bubble become bigger
30	11	Bigger bubbles with gap
60	11	Gap between Bubbles become bigger
180	9.5	Bubbles become even bigger with larger gap
360	8.5	Large bubble with huge gap
720	6	Less obvious bubbless
960	2	Left 2cm of bubble above the solution

Appendix 2:

Core Flooding Results

Parameter	**WAG Flooding**	**FAWAG Flooding**
Pore Volume (ml)	13.932	14.563
Initial Oil Volume (ml)	9.770	9.97
Initial Oil Saturation	70.13%	68.46%
Initial Water Volume (ml)	4.162	4.593
Initial Water Saturation	29.87%	31.54%

Water Flooding		
Oil Produced (ml)	4.970	4.3
Residual Oil Volume (ml)	4.800	5.67
Residual Oil Saturation	35.67%	38.93%
Residual Water Volume (ml)	9.132	8.893
Residual Water Saturation	64.33%	61.07%

Oil Recovery Factor	50.87%	43.13%

WAG Flooding Results

Time (minutes)	Toal Vp of Injection	Oil Produced (ml)
25	25.000	0
50	75.000	0
75	1.077	0
100	1.436	2.8
125	1.794	0.7
150	2.153	0.3
175	2.512	0.2
200	2.871	0.1
225	3.230	0.1
250	3.589	0.03
275	3.948	0.02
300	4.307	0
	Total oil produced(ml)	**4.25**
	Oil Recovery Factor	**43.50%**

FAWAG Flooding Results

Time (minutes)	Toal Vp of Injection	Oil Produced (ml)
25	25.000	0
50	75.000	0
75	1.077	0
100	1.436	3.2
125	1.794	0.8
150	2.153	0.3
175	2.512	0.4
200	2.871	0.1
225	3.230	0.05
250	3.589	0.02
275	3.948	0.01
300	4.307	0
	Total oil produced	4.88
	Oil Recovery Factor	48.95 %

Appendix 3:

WAG

Sample	Pore Volume of Injection	Sample Weight (B)	Weight Before Filtration	Weight After Filtration	Weight Difference btw Before and After Fitration (A)	Asphaltene Weight Percentage, (A/B)x100%	Asphaltene left behind in core sample
Initial	0.0000	1.1301	19.8121	19.8171	0.0050	0.442	0.0000
S 1	1.4360	0.4189	19.4010	19.4025	0.0015	0.358	0.0844
S2	1.7940	0.4132	19.8122	19.8133	0.0011	0.266	0.1762
S 3	2.1530	0.3670	19.4000	19.4009	0.0009	0.245	0.1972
S 4	2.5120	0.1020	23.2180	23.2182	0.0002	0.196	0.2464

FAWAG

Sample	Pore Volume of Injection	Sample Weight (B)	Weight Before Filtration	Weight After Filtration	Weight Difference btw Before and After Fitration (A)	Asphaltene Weight Percentage, (A/B)x100%	Asphaltene left behind in core sample
Initial	0.0000	1.1921	19.7837	19.7889	0.0052	0.436	0.0000
S 1	1.4360	1.0100	19.4011	19.4051	0.0040	0.396	0.0402
S2	1.7940	0.4342	19.8152	19.8165	0.0013	0.299	0.1368
S 3	2.1530	0.4268	19.4011	19.4022	0.0011	0.258	0.1785
S 4	2.5120	0.1235	19.8152	19.8155	0.0003	0.243	0.1933