Rheological Study of the Crude Oil

By

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(14423)

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CERTIFICATION OF APPROVAL

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

Approved by,

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(Dr Sia Chee Wee)
Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
SEPTEMBER 2014

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.

(AZRI BIN ABD SHUKOR)

ABSTRACT

The rheological study of the crude oil is very crucial in understanding the performance of the oil to efficiently produce from the reservoir. The rheological properties of the crude oil are measured for the practical importance for their transport properties, and pipeline and pump station design. The main objective of this project is to study the fluid behaviour of the crude oil. The parameters tested in this project are temperature and presence of wax in the crude oil. The two crude oil samples that were used for this study are Dulang Crude Oil and Arab Heavy Oil by using HPHT Viscometer. Newtonian Model and Bingham Model are used to determine the fluid behaviour of the crude oil samples. From the rheological test, only Arab Heavy Oil under the influenced of 40^{o}C is acting like a Newtonian fluid while Arab Heavy Oil with applied temperature of 40^{o}C deviate a little from Newtonian fluid class, acting slightly as a Bingham plastic fluid. On the other hand, Dulang Oil is completely behaving like a Bingham plastic fluid when both temperature of 40^{o}C and 70^{o}C are applied. It was observed that with the presence of wax, the crude oil has high probability to behave like a Bingham plastic fluid. From the experiment, the result also shows that high temperature will reduce the viscosity of the crude oil by a large margin.

ACKNOWLEDGEMENT

All praises to God, The Almighty, The Most Merciful, for giving me the health, strength and blessings throughout two tedious semesters to complete this Final Year Project research and report.

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Last but not least, I would like to extend a token of appreciation to my family, especially my parents and friends for their support and keen to know the outcome of my research throughout this project.

With that, I hoped all the experiences and knowledge that I have gained from this research will be a kick-start for my future career development.

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CHAPTER 1

INTRODUCTION

1.1 Background Study

Ronningsen (2012) stated that in petroleum industry, rheology plays a crucial role in two parts of field development cycle, which are drilling and production. Petroleum crude oils are consist of complex mixture of hydrocarbon compounds, ranging from simplest gases like methane to large asphaltenic molecules with molecular weights of thousands. These chemical variations induce a large variation in viscosities from the smallest value of fraction of a centipoise to the largest value of millions of centipoise. Not only that, it also ranging from perfectly Newtonian to very non-Newtonian rheological behaviour. This shows that description and rheological characterization of crude oils required a very broad variety of experimental techniques and modeling approaches.

Rheological properties of crude oil measurement have a lot of practical importance towards the industry. With difference rheological properties of the crude oil, transport properties, and pipeline and pump station design should be taken into account according to Malkin *et al.* (2006).

For this project, the fluids used for the study are two types of crude oils; light and waxy crude oil and heavy crude oil. The rheology of the crude oils under the effect of different temperatures and different type of oil is being investigated for this project.

1.2 Problem Statement

According to Society of Petroleum Engineers (2005), crude oil is a part of petroleum that exists in the liquid phase in natural underground reservoirs and remains liquid at atmospheric condition for both pressure and temperature. It may include a little amount of non-hydrocarbons produced with the liquids. Crude oil has several components which consist of maltenes, saturates, aromatics, resins and asphaltenes. Krohne (2013) stated that oil can be considered as one of the Newtonian fluids. However, as it is produced out of the well or transported through pipes, it mixes with other ingredients like air, water, salt, polymers or surfactants. Hence, the oil is no longer behaving as a simple Newtonian fluid. This statement means that many factors can affect the fluid behaviour of the crude oil which is opposite to the argument made by the assumption that oil is one of the Newtonian fluids. Besides that, there is little information regarding on the degree of how much the crude oil is behaving as a Newtonian fluid.

1.3 Objectives

The objectives of this project are:

- To investigate the effect of temperature on the fluid behaviour of the crude oil
- To investigate the effect of presence of wax on the fluid behaviour of the crude oil
- To study the degree of Newtonian of the crude oil as the crude oil affected by the presence of wax and temperature

1.4 Scope of Study

This project is oriented towards the understanding of the crude oil and its rheological properties. The scope of study for this project included the analysis of crude oil rheology. The rheology tests are conducted on the oil with different shear rates, ranging between 0 s^{-1} to 10 s^{-1}. This is sufficient enough in determining the fluid behaviour of the crude oil samples tested. From the test, shear stress, and n and K constants are also acquired for the determination on how Newtonian the tested crude oil samples. On the other hand, the effect of parameters such as temperature and presence of wax are also being tested on the rheological properties of the crude oil,

1.5 Project Relevancy and Feasibility

This project is very related to the author's field of study and important towards the oil and gas industry. By knowing the behaviour of the crude oil under certain circumstances, machine design and quality control of the fluid can be made to counter the effect that came out from the crude oil.

Moreover, this project is highly feasible as all the equipment required for running the experiment is available in UTP and the crude oil samples can be obtained through proper channel. The author is also has the capability as a final year student with the assistance from his supervisor and the lab technician to do this project. Thus, these factors can reduce the cost required for the project to begin with. On top of that, the experimental procedure in this research is the same as testing the rheological properties of the drilling mud. So, the procedure to run this experiment is known as the manual is available. The time taken to complete running the experiment is also within the time allocated for FYP research,

CHAPTER 2

LITERATURE REVIEW

2.1 Crude Oil Samples

The samples of the crude oil for the experiment were taken from two different oilfields which will represent each type of the crude oil; light and intermediate crude oil. For light crude oil, the sample that will be used is from Dulang oilfield from Malaysia while intermediate crude oil, the sample will be taken from Arab oilfield which come from Saudi Arabia.

2.1.1 Dulang Crude Oil (Waxy and Light)

Egbogah *et al.* (1992) stated that the Dulang oilfield is situated in the South China Sea, 130km offshore of Kuala Terengganu, on the east coast of Peninsular Malaysia. The water depth of the field is about 76 meters. Due to some major faults and fluid and pressure systems, the Dulang field is categorized into three main areas; Western Area, the Unit Area and the Eastern Area (Egbobah *et al.,* 1993).

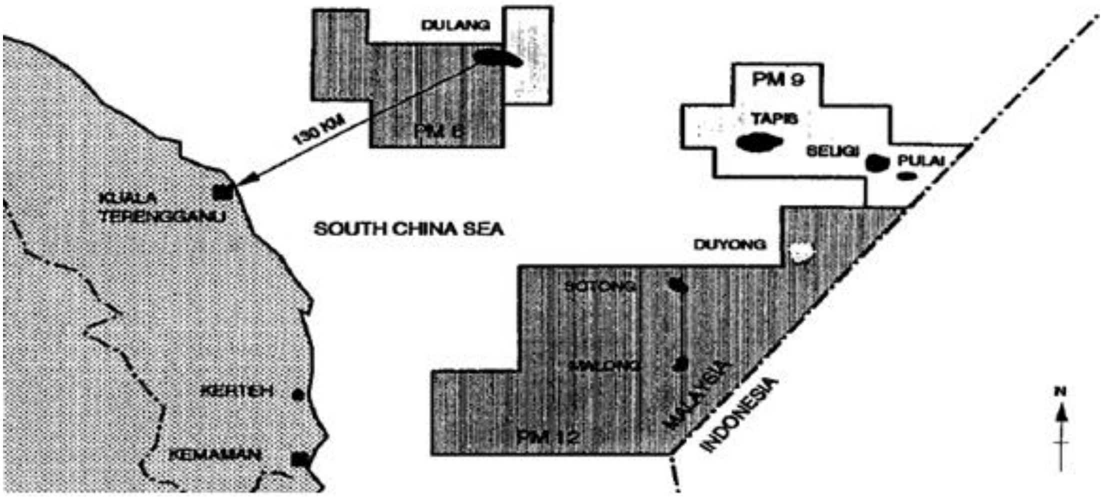

Figure 1: Location of Dulang Field (Egbogah et al., 1993)

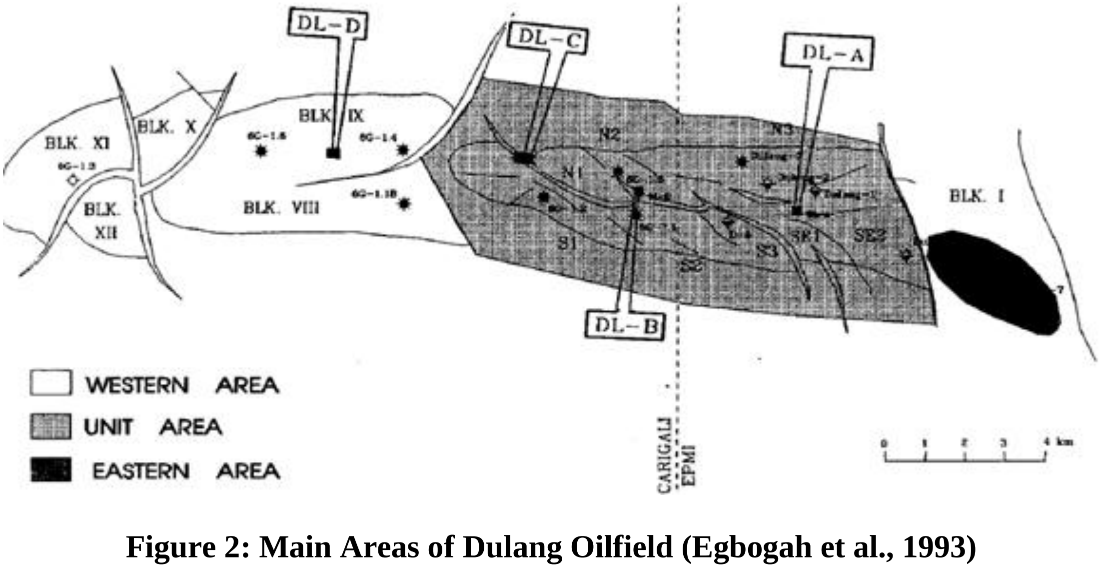

Figure 2: Main Areas of Dulang Oilfield (Egbogah et al., 1993)

The table below shows the list of reservoir and fluid properties of the Dulang oilfield:

Table 1: Dulang Field Reservoir & Fluid Properties (Egbogah *et al.*, 1992)

Reservoir & Fluid Properties	**Value**
Average Water Saturation	39%
Average Permeability	200 mD
Average Porosity	30%
Initial Reservoir Pressure	1800 psig
Reservoir Temperature	96°C
Bubble Point Pressure	1,600 psig
Oil Viscosity (at 96°C)	0.625 cp
Oil Pour Point	40°C
Gas Viscosity	0.016 cp
Oil Stock Tank Density	0.8347 gm/cc
API	37.4°API
Solution Gas-Oil Ratio	400 scf/stb
Oil Formation Volume Factor	1.279 rb/stb

2.1.2 Arab Crude Oil (Intermediate)

In Facts Global Energy (2014), around 30% of Saudi Arabia's total crude oil production capacity consists of intermediate and heavy crude oil. These crude oils which mainly come from the offshore fields are considered sour, containing quite a high levels of sulfur according to U.S. Energy Information Administration (2014). Major heavy oil fields are listed in the table below:

Table 2: Major Heavy Oilfields in Saudi Arabia (U.S. Energy Information Administration, 2014)

Field	Location	Capacity (as of 2012)
Safaniya	Offshore	1.2 million bbl/d
Manifa	Offshore	0.9 million bbl/d (after completion at end of 2014)

Croft *et al.* (2009) stated that Safaniya Field was discovered in 1951 and is the world's largest offshore oil field. Two major sands, the Safaniya and the Khafji contribute to the production of the Arab Heavy crude oil. Table 3 below shows the reservoir rock and fluid information about Safaniya Field Reservoir.

Table 3: Safaniya Field Reservoir Parameters (Saudi Aramco, 1980)

Reservoir	Safaniya	Khafji
Net Thickness (ft)	136	137
Oil Gravity	27	27
Viscosity (cp) (Temperature is not stated)	6.4	4.55
Sulfur Content (%)	2.93	2.84
Porosity (%)	26	25
Permeabilty (md)	5,700	6,250

Meanwhile, the Manifa Field lies between the northen and southern producing areas and produces Arab Heavy from the carbonate reservoirs (Croft *et al.*, 2009). The Manifa Field's reservoir description is explained briefly in the table below:

Table 4: Manifa Field Reservoir Parameters (Saudi Aramco, 1980)

Reservoir	U. Ratawi	L. Ratawi	Manifa
Net Thickness (ft)	50	188	71
Oil Gravity	31	26	29
Viscosity (cp) (Temperature is not stated)	2.6	4.4	2.8
Sulfur Content (%)	2.77	3.66	2.97
Porosity (%)	17	22	20
Permeabilty (md)	50	600	300

Figure 3: Location of Safaniya and Manifa Field (Edgell, 1992)

2.2 Rheological Measurement Units

Rao (1999) defined rheology as the study of the deformation and flow of matter. To study the rheological behaviour of the fluid, knowledge of the compositions of the fluid is very helpful. The rheological properties are determined based on the flow and the deformation responses of the fluid when subjected to stress. There are two type of shear; simple shear and steady simple shear (Dealy and Wang, 2013). In applied rheology, simple shear is more importance than steady simple shear.

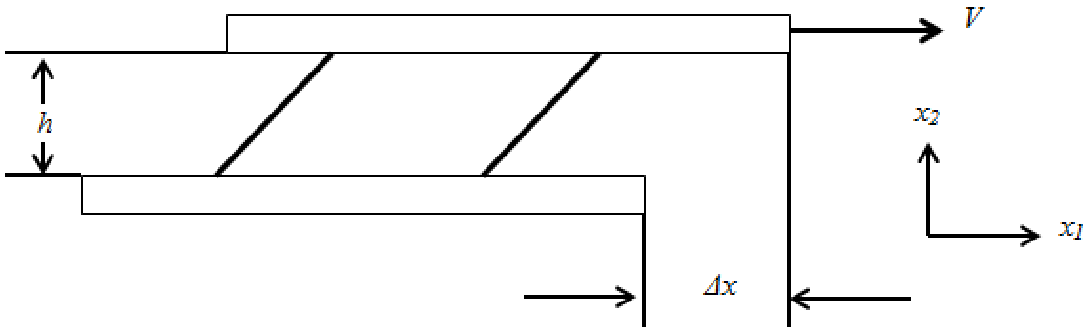

Figure 4: Simple Shear Flow in x_1 Direction

2.2.1 Shear Stress

The definition of the shear stress is the force that causing the fluid to deform by slippage along a plane or planes parallel to the imposed stress according to Encyclopaedia Britannica (n.d). This statement can be illustrated better in the **Figure 4** above.

$$\tau = \frac{F}{A}$$

Where τ= Shear stress, N/m^2 or Pa

F= Applied force, N

A= Cross-sectional area of the fluid parallel to the applied force, m^2

2.2.2 Shear Rate

Dealy and Wang (2013), shear rate $\dot{\gamma}$ is the derivative of the shear strain with respect to time and shear strain, denoted as γ. So, the velocity of the moving plate divided by the gap between two plates as shown in the **Figure 4** before, represent the shear rate. The equation below can explain the argument better.

$$\gamma = \frac{\Delta X}{h}$$

$$\frac{d\gamma}{dt} = \frac{1}{h}\frac{dX}{dt} = \frac{V}{h}$$

Where	V	=	velocity of the upper plate, m/s
	v_1	=	velocity of the fluid in the x_1 direction
	h	=	gap between two plates, m

Simple shear is a uniform deformation such as that each fluid element subjected to the same deformation and the strain and strain rate are independent of position in space. Meanwhile, in steady simple shear, the strain rate is constant with time, thus the strain rate of every fluid element is the same.

2.2.3 Viscosity

From Rao (1999) point of view, viscosity is the internal friction of a fluid or its tendency to resist flow. The symbol for the viscosity is denoted as η for Newtonian fluids whose viscosity is independent from the shear rate and η_a , also known as apparent viscosity for non-Newtonian fluids as its viscosity dependent towards the shear rate. Apparent viscosity is very important as its wide applications in characterizing the fluids. The preferred units of viscosity are mPa s or cp. Dealy and Wang (2013) stated most viscosity of the fluid are influenced by three factors; shear rate, temperature and pressure.

$$\eta_a = \frac{\text{Shear Stress}}{\text{Shear Rate}} = \frac{\sigma}{\gamma}$$

2.3 Petroleum Wax

Majority of crude oils found in the reservoir may contain high molecular weight paraffinic components which, at low temperatures, can be categorized as a wax phase. According to Fasano *et al.* (2003), the presence of a solid (wax) phase can affect the whole rheological behaviour of the crude oils. The paraffin content in the crude oil may vary from 1% to 15% and its solubility depends on several factors such as chemical composition, pressure and temperature. However, pressure gives a little effect on the paraffin solubility. When the equilibrium temperature (Cloud Point or WAT, Wax Appearance Temperature) is reached wax begins to crystallize entrapping the oil in a gel structure. Thus, cloud point can be defined as the temperature at which dissolved solids (paraffin wax) in the oil begin to form and separate from the oil.

Fasano *et al.* (2003) also stated that wax crystallization in the crude oils produces a non-Newtonian behaviour, whereas for a very high temperatures which in return causing the absence of the wax, the oil usually behaves as a Newtonian fluid. A high concentration of paraffin content results primarily in an increase of viscosity by several of magnitude. Besides that, the crystallization of wax leads to a wide range of non-Newtonian characteristics such as yield stress, pseudoplasticity (shear thinning), time dependency, shear and thermal history (Wardhaugh *et al.*, 1988). The consequence of this is that a wide range of viscosity exist at a given temperature and rate of shear.

2.4 Type of Fluid Flow Behaviour

Fluid, in term of rheology is a substance that continuously deform in the face of tangential (shear stress) irrespective of the magnitude of shear stress according to Biswas and Som (n.d). Continuous deformation of the fluid under the influence of the shear stress will cause the fluid to flow.

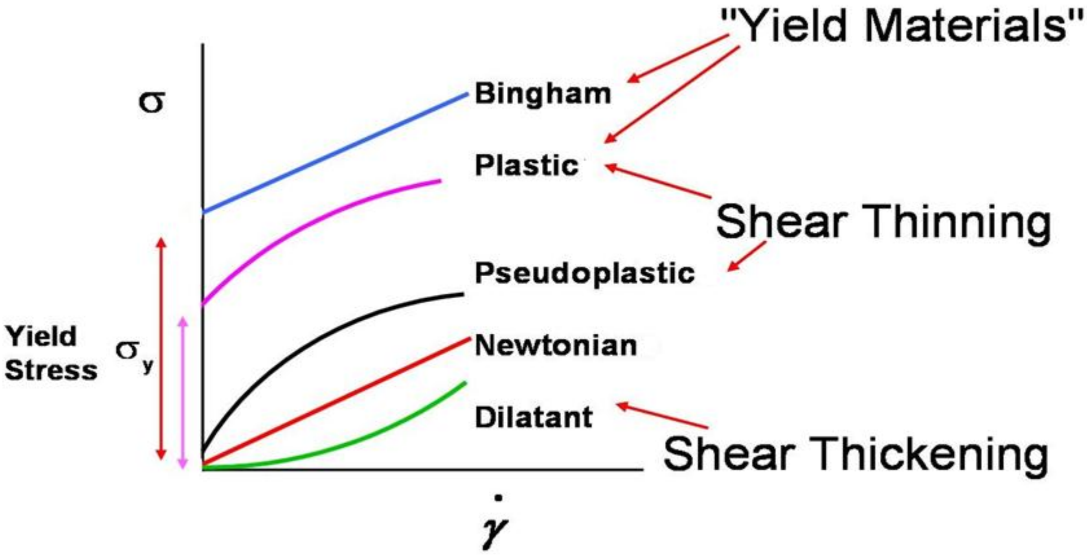

Figure 5: Behaviour of the Fluids (Alcantara, n.d.)

2.3.1 Newtonian Fluid

Newtonian fluid is defined as that for all shear stresses below those giving increment to turbulence, the relationship between unit shear stress and rate of shear is linear (Govier and Ritter, 1963). Newton's equation represented this relationship by defining the consistency property called viscosity. The equation will represents a straight line through the origin on an arithmetic plot of unit shear stress versus rate of shear. If the slope of the straight line is equivalent to 1, the fluid is behaving like a Newtonian fluid.

$$\eta = \frac{\sigma}{\dot{\gamma}}$$

Where η = viscosity, Pa s or cp

σ = shear stress, Pa

$\dot{\gamma}$ = shear rate, s^{-1}

Meriem-Benziane *et al.* (2011) had conducted an experiment concerning the rheological properties of light crude oil. In this experiment, four different samples of light crude oil were obtained from different oil fields in Algeria. The samples were characterized as follows:

Table 5: Crude Oil Properties of Algeria Light Crude Oil

(Meriem-Benziane *et al.*, 2011)

Crude Oil Properties	Value
Temperature	20°C
Pressure	2.5 bar
Density	806 kg/m^3
Specific gravity	36-44°API

The rheological behaviour of different samples was studied by using the rheometer performance (RheoStress 600, type Z40 DIN, Germany). The result for crude oil at 0% of water content is shown in the figure below:

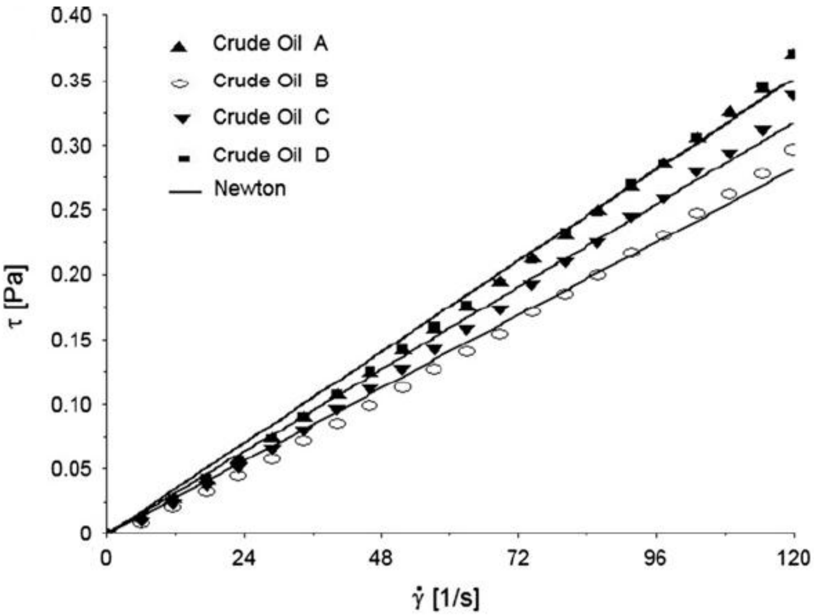

Figure 6: Fluid Behaviour of Pure Light Crude Oil

(Meriem-Benziane *et al.*, 2011)

From the results obtained from the experiment held by Meriem-Benziane *et al.* (2011), pure crude oils (in this case, no water content) act like a Newtonian fluid. This observation support the statement made by Krohne (2013) which is crude oil is one of the Newtonian fluid.

2.3.2 Non-Newtonian Fluid

Non-Newtonian fluid is all types of fluid which shear stress-shear rate plot is not linear or the plot given is not begin at the origin or that the fluid shows a time-dependent rheological behaviour as a result of the structural changes (Rao, 1999). There are several types of non-Newtonian fluid behaviour; Bingham plastic, shear-thinning, shear-thickening, and time-dependent behaviour. Same like Newtonian fluid, Shear-thinning or pseudoplastic fluid has a viscosity that appears to decrease as the applied shear rate increases. Shear-thickining or dilatant fluid is the opposite to the shear-thinning fluid, appears to increase when the shear rate increases.

Rao (1999) also stated that Bingham plastic has a linear shear stress-shear strain relationship but required a finite yield stress before they can begin to flow. The Bingham Plastic model has an equation as shown below:

$$\sigma - \sigma_0 = \eta'\dot{\gamma}$$

Where	σ	=	Measured shear stress, Pa
	σ_0	=	Shear stress when shear rate = 0 (also known as yield point, Pa
	η'	=	Bingham plastic viscosity, cp
	$\dot{\gamma}$	=	Shear rate, s^{-1}

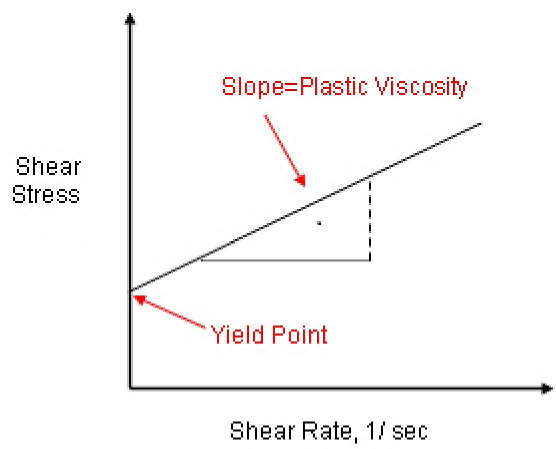

Figure 7: Bingham Plastic Model (Rachain and Coleman, 2010)

Meriem-Benziane *et al.* (2011) also investigate the effect of water content to the rheological behaviour of the Algerian light crude oil. The emulsions were prepared with different percentage of water (30%, 50% and 70%). The perfect homogenization between the water and crude oil was achieved by stirring the solution for 10 minutes with a magnetic bar.

The effect of different percentage of water content towards the rheological behaviour of the light crude oil is expressed in the **Figure 8**, **Figure 9**, and **Figure 10**.

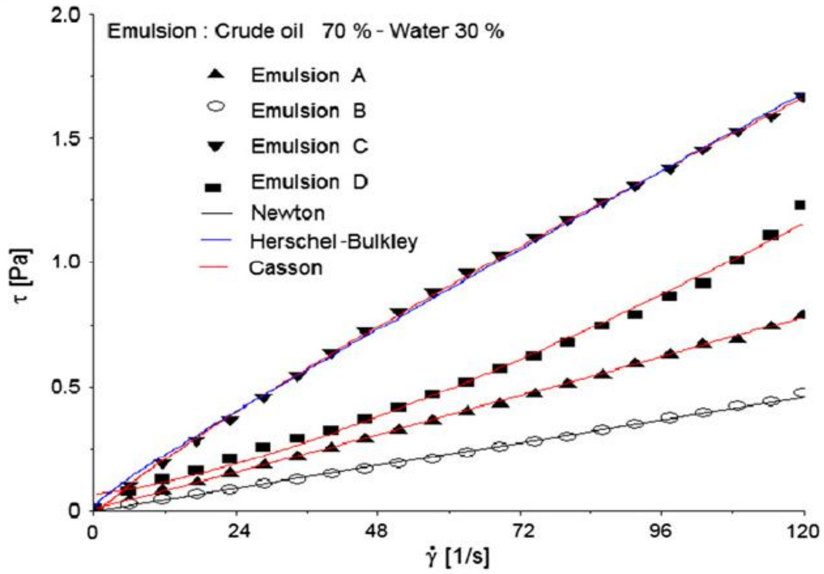

Figure 8: The Effect of 30% Water Content on Rheological Behaviour of Light Crude Oil (Meriem-Benziane *et al*., 2011)

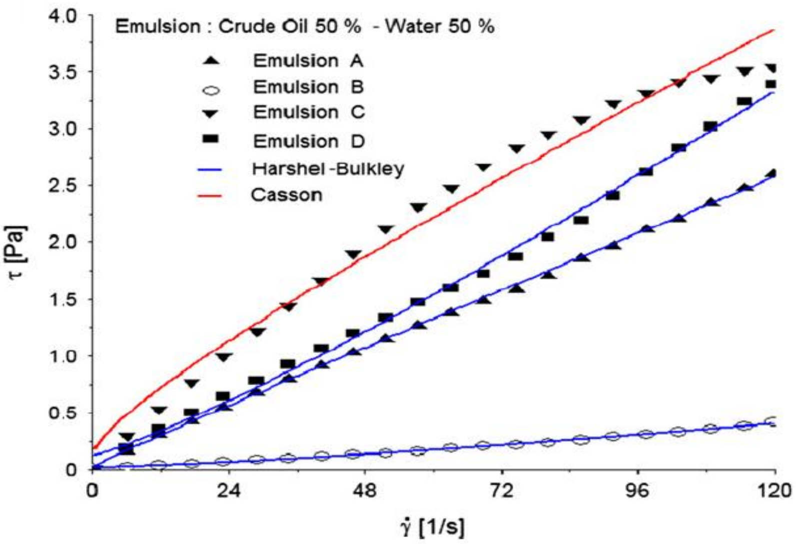

Figure 9: The Effect of 50% Water Content on Rheological Behaviour of Light Crude Oil (Meriem-Benziane *et al*., 2011)

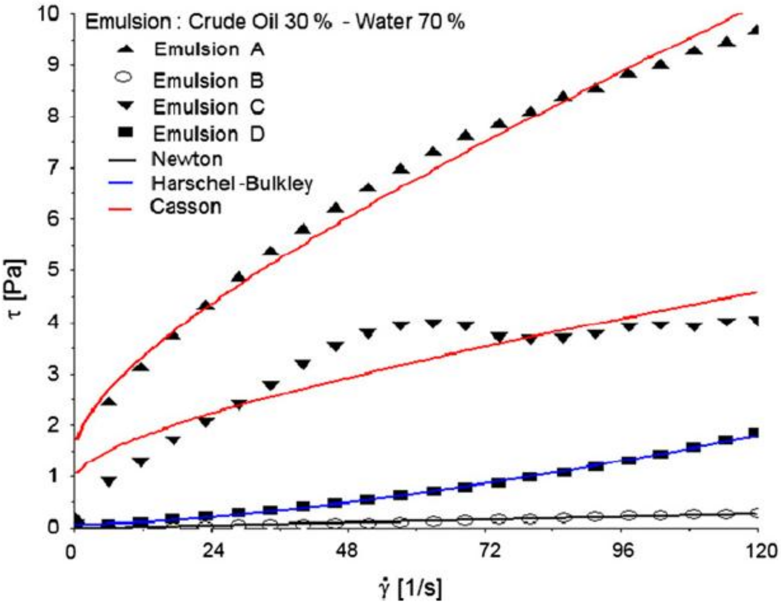

Figure 10: The Effect of 70% Water Content on Rheological Behaviour of Light Crude Oil (Meriem-Benziane *et al*., 2011)

The results show that the existence of impurity such as water content in the crude oil will change the fluid behaviour of the crude oil. Crude oil will no longer act like a Newtonian fluid. As the percentage of water content increase from 30% to 70%, four Algerian light crude oil become more and more like a non-Newtonian fluid, shear thinning and shear thickening to be exact.

CHAPTER 3

METHODOLOGY

3.1 Preliminary Study

The project started by doing a background research on the topic related to understand more about it. Information on what type of fluid flow behaviour and rheological properties that can be found through experiment with different parameters involved is very important for this topic. Besides that, a background study on the crude oil sample is a top priority as this sample will influence the experiment later. Sources for this information are usually obtained through journal and article from the website and also through borrowed book from the UTP library.

3.2 Pre-experimental work

This section represents the preparation of the samples and listing out the parameters involved in the experiment. Below are the lists of parameters proposed for the experiment:

- Type of crude oil : Light and Intermediate
- Ambient Pressure : 14.7 psia
- Temperature : 25^oC, 40^oC and 70^oC
- Shear Stress ($dynes/cm^2$)
- Shear Rate (s^{-1})
- Viscosity (cp)
- Rotation per minute (RPM)

3.3 Experimental Work

There are two parts for this section: sample preparation and experimental designs. Both parts begin on the FYP II.

3.3.1 Sample Preparation

Before starting the experiment, crude oil samples were obtained. Two crude oils were chosen for this experiment, Dulang Crude Oil and Arab Heavy Oil. Dulang crude oil is a waxy, light crude oil with API value of 37.4° while Arab Heavy Oil is a intermediate oil with 27.3°API, non-waxy and has a sulphur content of about 2.95%. For Dulang oil, the sample was required to be heated in the oven first due to its unique waxy characteristic. After collecting the crude oil samples, the beaker had to tightly closed by using aluminium foil as the crude oil can be contaminated if left open for a long period of time.

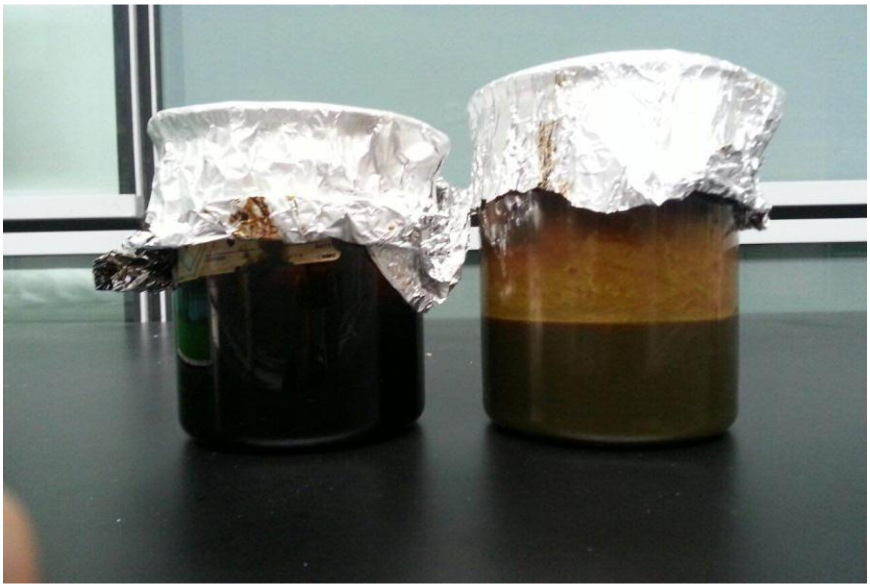

Figure 11: Arab Heavy (left) and Dulang Oil (right)

3.3.2 Experimental Designs

After obtaining the samples, the crude oil is load into the viscometer to find the rheological properties of the oil itself by using a syringe. The amount of crude oil required for the test is around 52 mL only. For the ambient pressure and temperature (14.7 psia and 25^{o}C), the FANN (Model 35A) Viscometer is used while for the ambient pressure and different temperature, High Pressure High Temperature (HPHT) Viscometer is used.

3.3.2.1 FANN (Model 35A) Viscometer (Manufacturer: FANN)

Below are the steps that need to be followed to use this equipment:

1. The crude oil samples are placed in the cup until it reached the scribed line.
2. The knurled knob between the rear support posts is turned to raise or lower the rotor sleeve until it is immersed in the sample.
3. The sample is stirred for around 5 seconds at 600 RPM and later the desired RPM is selected.
4. The dial reading is waited to stabilize.
5. The dial reading and RPM is recorded.
6. Repeat step 1-5 by using different crude oil sample.
7. The apparatus is cleaned up at the end of the experiment.

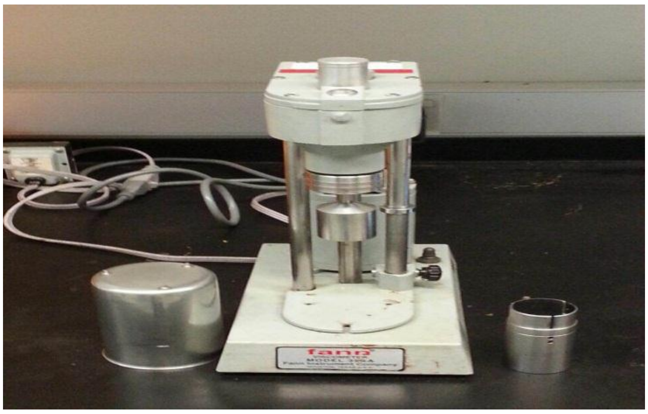

Figure 12: FANN (Model 35A) Viscometer

3.3.2.2 HPHT Viscometer (Manufacturer: OFI Testing Equipment, Inc.)

Below are the steps that need to be followed to use this equipment:

1. By using a syringe, approximately 52 mL of crude oil sample is loaded into the sample cup.
2. The sample cup nut is screwed tightly before running the test.
3. In the software used for the equipment, set the temperature and parameters (shear stress, shear rate, RPM, etc.) desired from the experiment.
4. The test is run and waited until the temperature is stabilized to the value desired.
5. The results obtained are recorded and analysed.
6. Repeat step 1-5 by using different crude oil sample.
7. The apparatus is cleaned up at the end of the experiment.

Figure 13: HPHT Viscometer

3.4 Overall Flowchart

Below is the flowchart for the project, categorized in terms of week by week and the activities done in every week.

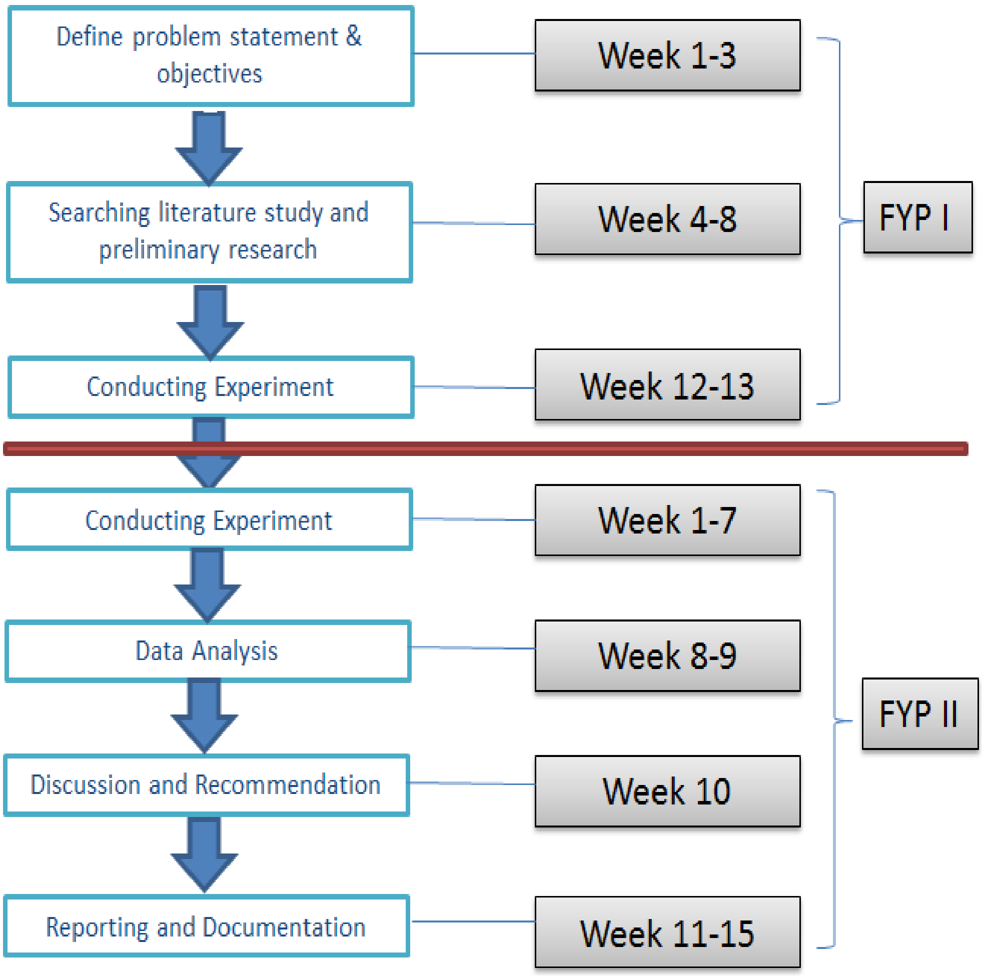

Figure 14: Project Activities Flowchart

3.5 Project Timeline

Table 6: Ganttz Chart for FYP I

Activities	Week No.																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Selection of Project Topic	■	■	■												Study Week	Final Examination Week	
Preliminary Research Work				■	■	■	■										
Submission of Extended Proposal								●									
Proposal Defense									■	■							
Continue with Project Work										■	■	■	■				
Submission of Interim Draft Report													●				
Submission of Interim Report														●			

Progress ■   ● Milestones

Table 7: Ganttz Chart for FYP II

Activities	Week No.																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Project Work Continuation	■	■	■	■	■	■	■										
FYP II Briefing		■															
Submission of Progress Report							●										
Project Work Continuation								■	■	■	■	■					
Pre-SEDEX									●								
Submission of Final Draft Report												●					
Submission of Technical Paper												●					
SEDEX												●					
Viva														●			
Submission of Hardbound Copies																●	

■ Progress

● **Milestones**

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Rheological Properties Measurement

4.1.1 Ambient Pressure and Ambient Temperature

Due to the unique composition of Dulang crude oil, which is the presence of the wax, the test is unable to run using the FANN (Model 35 A) Viscometer at ambient temperature (25^{o}C). The Dulang oil has a pour point of 40^{o}C, meaning that below that temperature, the oil become semi solid, thus loses its flow characteristics. With the absent of hot cup, FANN Viscometer unable to give any readings for Dulang crude oil. In conclusion, all tests are required to be run by using HPHT Viscometer at minimum 40^{o}C.

Figure 15: Waxy Dulang Oil

4.1.2 Ambient Pressure and Different Temperature

By using HPHT Viscometer, the experiment can be completed within the period of time given. The rheological properties that wanted from the experiment are shear rate, shear stress and the viscosity of the crude oil. The parameters tested in this experiment are the presence of wax and the temperature which is 40^{o}C and 70^{0}C.

4.1.2.1 Dulang Crude Oil

To determine the rheological measurement of the crude oil, several revolution per minute (RPM) were tested against the oil, starting with 3 RPM, 6 RPM, 30 RPM, 60 RPM, 100 RPM, and 200 RPM. The experiment followed the manual procedure stated in the ISO 17025 for HPHT Viscometer. All the results obtained from the experiment for the Dulang Crude Oil are tabulated in the following tables:

Table 8: Rheological Properties for Dulang Oil at 40^{o}C

RPM	Shear Rate (s^{-1})	Shear Stress (Pa)	Viscosity (cp)
3	2.6	4.1	955.1
6	5.1	4.2	485.7
30	25.5	4.3	100.7
60	51	4.5	52.6
100	85	4.8	33.8
200	170.1	5.2	18.3

Table 9: Rheological Properties for Dulang Oil at 70°C

RPM	Shear Rate (s^{-1})	Shear Stress (Pa)	Viscosity (cp)
3	2.6	3	691.3
6	5.1	3	345.6
30	25.5	3	70.4
60	51	3.1	35.8
100	85	3.5	24.2
200	170.1	3.9	13.6

From **Table 8** and **Table 9**, the results show that as the shear rate increase, the viscosity of the Dulang crude oil obtained during each RPM tests decreased. This is due to the presence of wax or paraffin in the oil. The presence of wax required a lot of force for the crude oil to flow. That is the reason why as the shear rate increase, the viscosity of the Dulang oil will decrease significantly, with the evidence of **Figure 16**. On the other hand, by comparing the results in **Table 8** and **Table 9**, the difference in temperature play an important role towards the viscosity of the oil. As the temperature increase, the viscosity decrease a lot faster as the shear rate increases.

The results obtained can also be used to plot a graph of shear stress vs shear rate, illustrated in the **Figure 17**. From the graph, Dulang Crude Oil acts like a Bingham Plastic fluid. By testing at different temperature, the crude oil will has different yield point. The yield point of the Dulang oil tested at 40°C is about 4.2 Pa and it decrease as the temperature rise to 70°C to 2.9 Pa. The main reason for the yield point to decrease as the temperature increase is because the intermolecular forces between the wax molecules becomes weaker, thus the molecular bond between them can easily broke up. Thus, this will make the crude oil to flow much easier at higher temperature with the same shear stress.

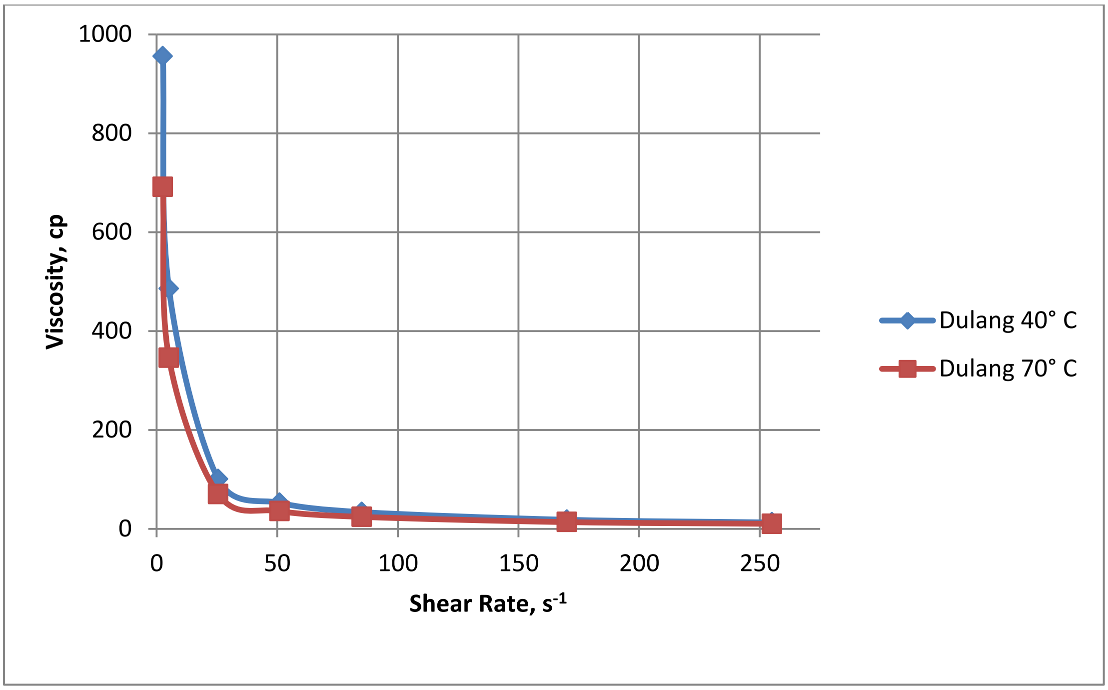

Figure 16: Effect of Shear Rate to the Oil Viscosity for Dulang Crude Oil Sample

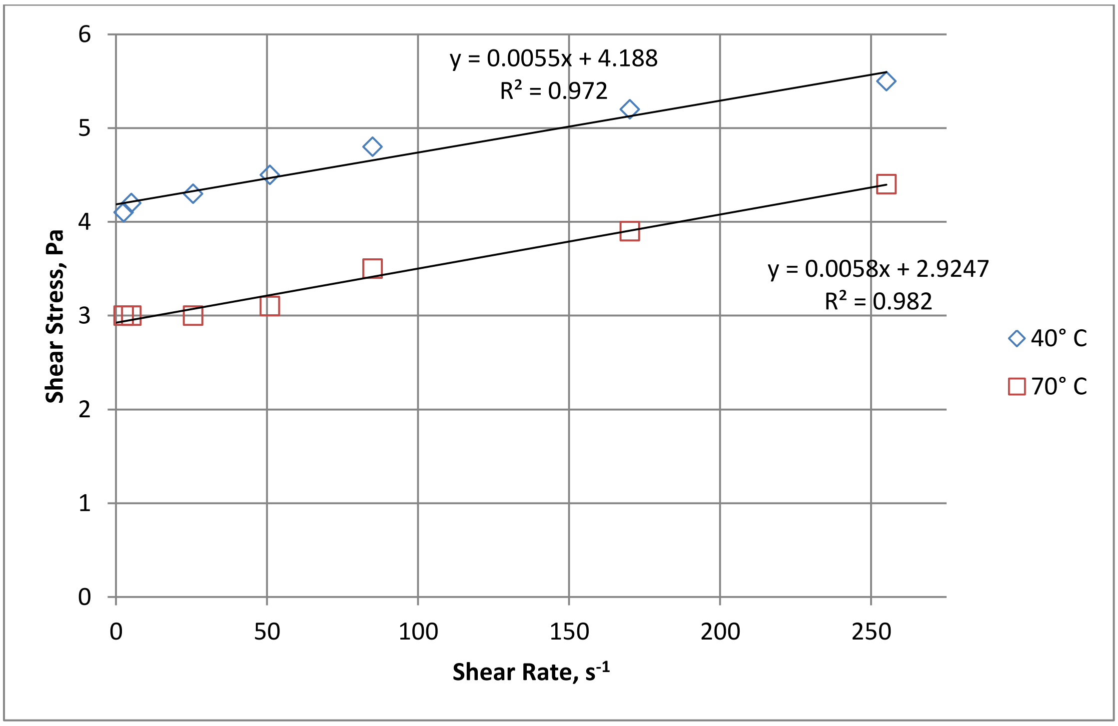

Figure 17: Effect of Temperature to Rheological Measurement for Dulang Crude Oil

4.1.2.2 Arab Heavy Crude Oil

Comparing the **Table 10** and **Table 11**, it is found that as the temperature increase from 40^{o}C to 70^{o}C, the shear stress applied to the Arab Heavy oil is in decreasing manner as the RPM increased, thus the viscosity of the crude oil decreased from 30 cp to 12.3 cp. According to Glert (1998), as temperature rises, the viscosity of a simple liquid will decrease. This is due to the increment effect of average speed of the molecules in the liquid and less amount of time for the molecules to come "in contact" with another nearest molecules. Thus, as the temperature increases, the intermolecular forces between the molecules decrease. This statement is very applicable to this experiment.

Table 10: Rheological Properties for Arab Heavy at 40^{o}C

RPM	Shear Rate (s^{-1})	Shear Stress (Pa)	Viscosity (cp)
3	2.6	0.00	0
6	5.1	0.00	0
100	85	0.49	34.6
200	170.1	0.86	30
300	255.1	1.29	30.1
600	510.2	2.60	30.3

Table 11: Rheological Properties for Arab Heavy at 70°C

RPM	Shear Rate (s^{-1})	Shear Stress (Pa)	Viscosity (cp)
3	2.6	0.00	0
6	5.1	0.00	0
100	85	0.00	0
200	170.1	0.02	0.8
300	255.1	0.53	12.3
600	510.2	1.05	12.3

From the graph plotted in the **Figure 18** below, at 40°C the Arab Heavy Oil is acting like a Newtonian fluid. It began to deviate slightly to Bingham Plastic fluid when the temperature is rising to 70°C, which require 47 s^{-1} of shear rate for the oil to start to flow.

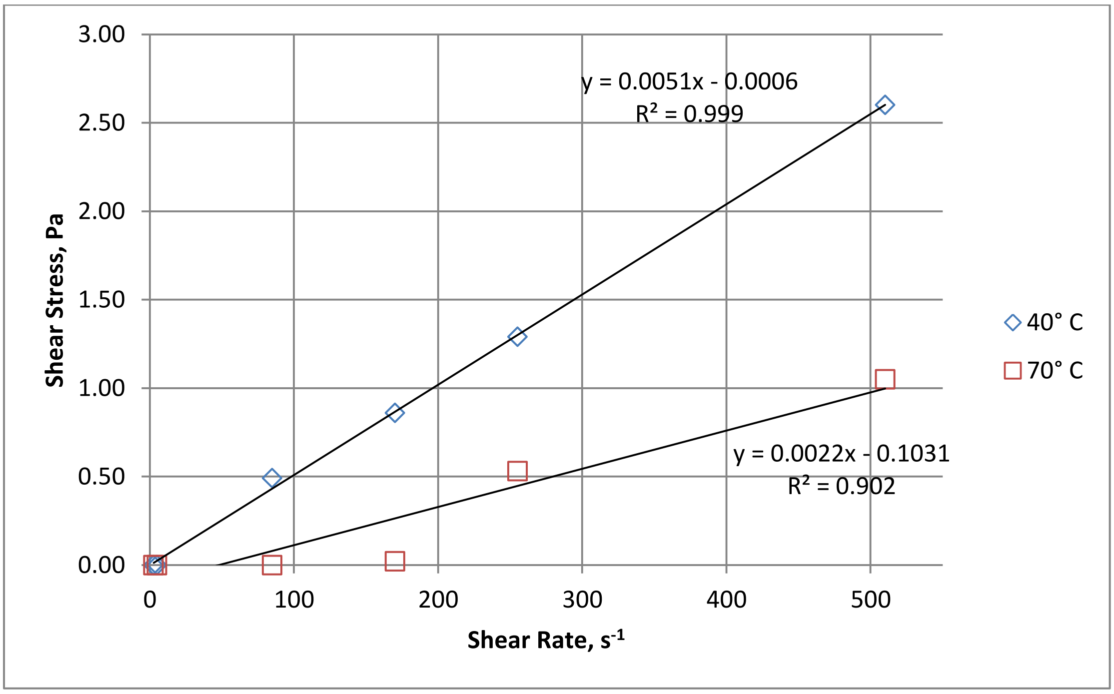

Figure 18: Effect of Temperature to Rheological Measurement for Arab Heavy Oil

4.1.3 Ambient Pressure and Presence of Wax

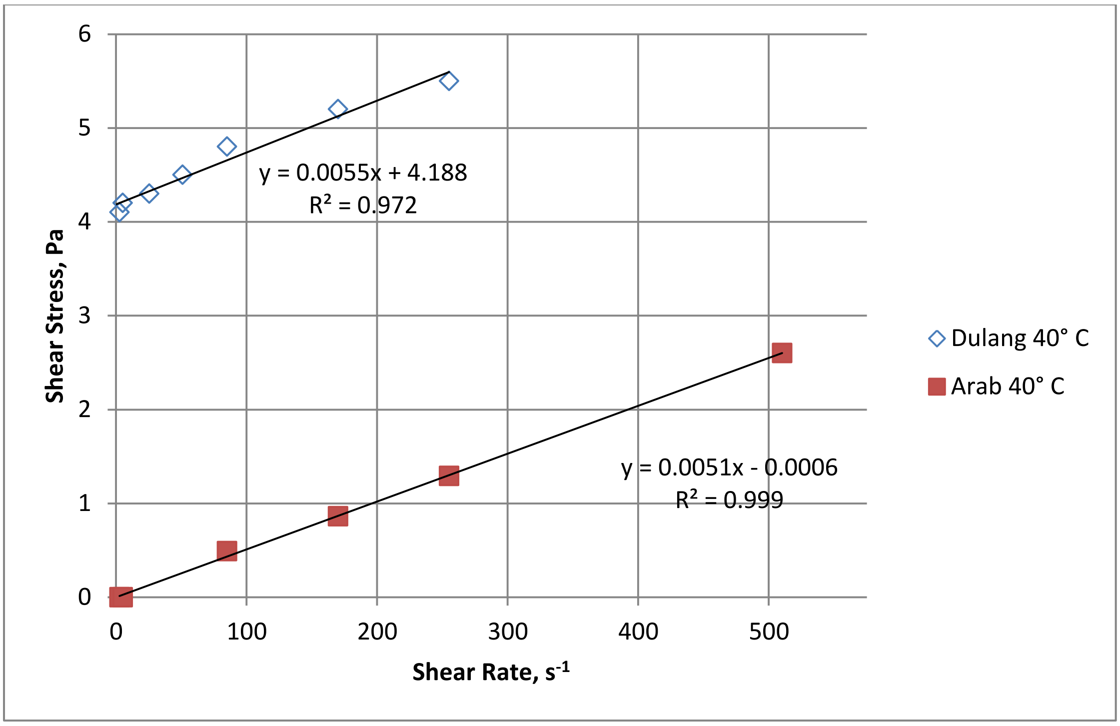

Figure 19: Effect of Presence of Wax to Rheological Measurement to Crude Oil at 40°C for Dulang Crude Oil and Arab Heavy Oil

As shown in the figure above, Dulang Crude Oil is acting likes a Bingham Plastic fluid while Arab Heavy Oil is behaving likes a Newtonian fluid. The difference between these two crude oil is that Dulang Oil has a unique characteristic, which is the oil is waxy below 40°C while Arab Heavy does not has this characteristic. Dulang Oil required a certain amount of shear stress for it to start flowing. Arab Heavy Oil started to flow as soon as the shear stress is applied to it.

4.1.4 Dulang vs Arab Heavy (Overall)

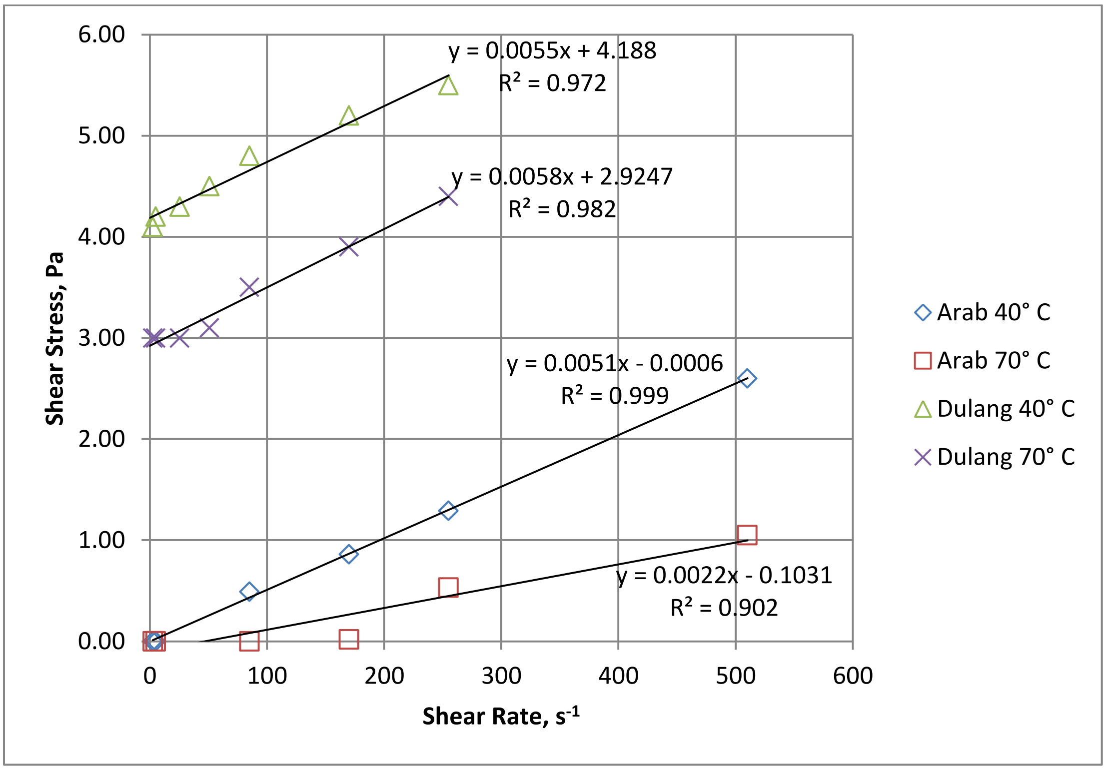

Figure 20: Overall Fluid Behaviour of Arab Heavy Oil and Dulang Crude Oil at 40°C and 70°C

From **Figure 20**, the only Newtonian fluid behaviour can be seen is the Arab Heavy oil when 40°C was applied. When the temperature increased to 70°C, Arab Heavy oil began to behave slightly Bingham plastic fluid. Dulang Oil behave completely like Bingham Plastic fluid at both 40°C and 70°C due to the presence of wax. The only difference between them is the yield point of the oil.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In conclusion, the crude oil only behaves like a Newtonian fluid when a certain condition is passed. High percentage of wax deviates the crude oil from behaving like a Newtonian fluid and applying high temperature to the crude oil is preferred to lower the viscosity of the crude oil to ensure the oil to flow easily. The findings from this experiment will help engineers to design their machine according to the behaviour of the crude oil and make quality control over the produced crude oil in the field. The objectives of the project are achieved successfully.

5.2 Recommendation

Due to the main factor, time as limitation in doing further research on the rheological studies of the crude oil, there are several parameters that have not been covered and tested. Below are the lists of recommendation on what can be done for the experiment upon the rheological properties of the crude oil:

5.2.1 Addition of Pressure Parameters

Although pressure gives a little effect on the viscosity of the crude oil, changes still occurs. Though it required high pressure to see the changes in the viscosity value, the fluid behaviour of the crude oil can be determined whether the crude oil can maintain its Newtonian behaviour or not.

5.2.2 Addition of Water Content Effect

As the crude oil produced to the surface, it commonly mix together with the produced water, low percentage of the water may miscible in the crude oil. Thus, the crude oil is not entirely pure in the real case scenario. From this statement, the effect of water content on the fluid behaviour of the crude oil can be investigated further.

5.2.3 Addition of Asphaltene Effect

Asphaltene presence can cause additional difficulties related to transport and processing due to an increased crude oil viscosity. As the percentage of asphaltene content in the crude oil is varied, an experiment can be conducted to investigate its effect to the rheological properties of the crude oil.

5.2.4 Additon of Wax Content Effect

The experiment tested only considered the presence of wax in the crude oil (waxy Dulang Oil and non-waxy Arab Heavy Oil). Further study on the effect of wax content at different percentage to the rheological behaviour of the crude oil can be done. The outcome of the experiment can determine how much yield stress required for the crude oil to flow, which in return solutions such as heating the crude oil at certain temperature or adding some additive to the crude oil can be made to counter this problem.

5.2.5 Increase the Number of Temperature Data

Due to time constraint, only two temperatures (40^{o}C and 50^{o}C) can be tested upon the crude oil sample. The experiment can be further developed in the future by testing against the variety number of temperature values, especially at the reservoir temperature. By doing this, the real fluid behaviour of the crude oil can be found.

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