STUDY ON THE EFFECT OF VOIDS ON RESTART PUMPING OF GELLED CRUDE OIL IN PRODUCTION PIPELINE

by

Afildhatul Nashima Mustafa

Dissertation submitted in partial fulfilment of

the requirements for the

Bachelor of Engineering (Hons)

(Mechanical Engineering)

SEPTEMBER 2013

Universiti Teknologi PETRONAS

Bandar Seri Iskandar

31750 Tronoh

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

STUDY ON THE EFFECT OF VOIDS ON RESTART PUMPING OF GELLED CRUDE OIL IN PRODUCTION PIPELINE

by

Afildhatul Nashima Mustafa

A project dissertation submitted to the

Mechanical Engineering Programme

Universiti Teknologi PETRONAS

in partial fulfilment of the requirement for the

BACHELOR OF ENGINEERING (Hons)

(MECHANICAL ENGINEERING)

Approved by,

____

(Ir. Dr. Shaharin Anwar Sulaiman)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

May 2013

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or person.

AFILDHATUL NASHIMA MUSTAFA

ABSTRACT

Waxy crude oil can be found in many parts of the world for exploration and production purposed. The crystallisation of waxy crude oil during the transportation through pipeline may cause problems. The waxy crude oil may gel up during the platform shutdown and thus causes blockage in the pipeline. At a very high temperature at which it can reach up to 90°C especially in the reservoir, the waxy crude oil behaves as Newtonian fluid. When the temperature starts to decrease while flowing in the production pipeline, wax will form upon reaching the limit of Wax Appearance Temperature (WAT) as a result of cooling due to the low seabed temperature. The problem becomes more serious as the crude oil gelled up and clogs the pipeline as the temperature decreases and reaches the pour point temperature. Restarting the flow would be a problem because when the crude oil becomes gelled, it would be hard to initiate the flow of the oil and might damage the pipeline due to the gelled up crude oil that cannot be transported. The equation that has been used to calculate the restart pressure has be over predicted as it does not consider the compressibility characteristic of the crude oil. The gas voids formation during the transportation may also affect the compressibility of the oil. The objective of this work is to determine the effect of gas voids on the restart pressure the flow of gelled crude oil. The effect of gas voids was observed and compared by having the original sample and the second sample that is injected with air. The compressibility test was done to both of the sample. From the study it is shown that the gelled crude oil can be compressible and the pressure applied also affect the movement of the crude oil. The compressibility factor for the injecting air sample is higher compared to the original sample as it is the result of voids formation. The compressibility factor of the gelled crude oil from original sample (Sample 1) and injecting air (Sample 2) was 0.001 and 0.003 respectively for every 0.5 bar pressure applied.

ACKNOWLEDGEMENT

First and foremost, I would like to express my utmost gratitude to my supervisor, Ir. Dr Shaharin Anwar Sulaiman throughout the whole period in completing the project. Without his guidance and patience, I will not succeed to complete the project.

My appreciation is also extended up to individual that have taken the time and effort to assist the author in completing the project. Without the cooperation of these individuals, no doubt the author would have faced some minor complications throughout the courseeveryone that has given me all the supports and guidance throughout the whole period of completing the final year project. This is directly to UTP research scientist, Mr Mior Maarof B Mior Mokhtar, postgraduate student Mr Girma, Mr Azhar and other technicians for all their help, advice and assistance during the progress of my project.

Last but not least, big thanks to all my friends and families for their big support whether in giving opinions, providing ideas and also moral support in order to complete the project.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Background Study

Crude oil is a scientific name that is used to describe unprocessed oil that comes out from the ground. The crude oil is the complex mixture that contains different types of hydrocarbons such as paraffins, aromatics, asphaltenes, napthenic and resins. However, the crude oil that contain significantly high amount of paraffin is known as waxy crude oil (Ajienka *et al*., 1991). Paraffin has low solubility in crude oil when there is a decrease in temperature which results in solid and liquid composition.

In reservoir at a very high temperature, the waxy crude oil behaves as a Newtonian fluid where the wax dissolves completely. However, upon the transportation through a long pipeline, the crystallization of wax which results from the decreases in temperature might cause problem to the pipeline (Ekweribe *et al*., 2009). This is because during the shutdown of the pipeline, the crude oil will face extreme changes of the temperature as a consequence of the low seabed temperature. This will result in the wax crude oil will crystallise and turns into gelled or solidify texture in the pipeline as shown in Figures 1.1 and 1.2 that occurred in the real pipeline problems.

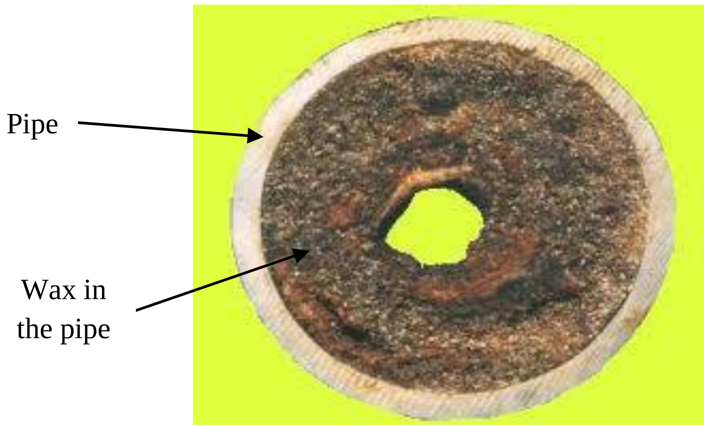

Figure 1.1: Wax deposition in pipeline from the Philip Petroleum Company

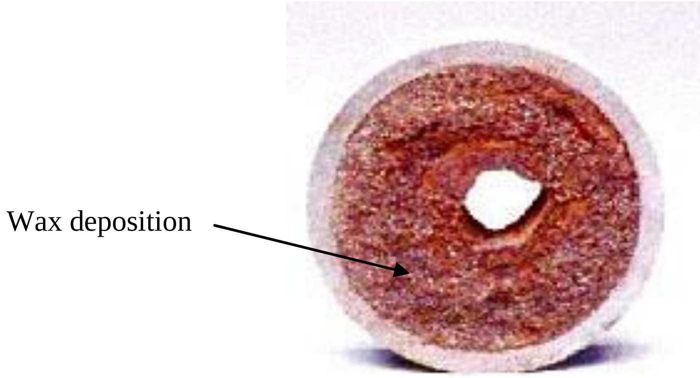

Figure 1.2: An example of plugging caused by wax deposition in a Niger Delta, Nigeria Crude Oil Pipeline

When the temperature cooled down below the wax appearance temperature (WAT), the oil will start to become wax. As the temperature decreases further reaching the pour point temperature, the wax crude oil will now turn to be gelled, solid like state (Karan *et al*., 2000). This gelled crude oil will block and clog the pipeline. Thus, the problem to restart the flow of the gelled crude oil in the pipeline will be the main concern.

According to Yong Bai and Qiang Bai (2005), the relation used to for the restart pressure prediction is:

$$\Delta p = 4\tau_y L / D \qquad (1.1)$$

The components involved in the equation 1.1 are; τ_y is the yield stress needed to break the gelled crude oil, L is the length of the pipe and D is the diameter of the pipe.

The minimum pressure needed at the pipe inlet determined the restart pressure of the gelled up crude oil (Vinay *et al.*, 2009). The current equation that is used to predict the pressure needed to restart the gelled up crude oil is believed to be over predicted. They seem to be over predicted because some of the gelled crude oil characteristics are not taken into consideration which results in higher pressure used to restart the pipeline.

1.2 Problem Statement

During the transportation from the reservoir, the waxy crude oil behaves as Newtonian fluid because of the high temperature surrounding. However, during the transportation, the waxy crude oil face extreme changes in temperature where the wax crystal starts to appear when the temperature decreases below Wax Appearance Temperature (WAT).

The result from the pipeline shutdown and the different in seabed temperature which decreases upon pour point temperature, the wax crystal increases and the gel structure starts to form and groups together and finally become gelled and clog the pipeline. The blockage of the pipeline is the effect of the gelled up crude oil. This will affect the operation of the pipeline as much more time is needed for the shutdown to take place. The production loss during the shutdown will result in higher cost whether for replace or maintenance purpose. Furthermore, the pipeline blockage must be avoid because the cost for high restart pressure, maintenance or abandoned pipelines result in worth millions of dollars. For example, in the Lasmo Field at United Kingdom, the wax deposition was so severe and frequent that the entire field was abandoned at a cost over USD 100 million (Lee , 2008).

The gas voids formation in the gelled crude oil will result in compressibility factor. Injecting air to the system might increase gas void formation which will reduce the restart pressure. Thus, the main problem is the gelled up waxy crude oil that might clog the pipeline affect the restart pressure after shutdown.

As the pumping and restart pressure cost is significantly high, the prediction of the restart pressure of the gelled crude oil is important in order to reduce the capital expenditure (CAPEX) of the oil production. The compressibility characteristic of gelled up crude oil that has not been considered causes much waste in producing excess pressure during the restart process. The study of compressibility of the gelled up crude oil and the effect of gas voids would give better prediction of the restart pressure.

1.3 Objectives

The objective of this project is to study the effect of pressure of gas voids gelled waxy crude oil on ease of restart pumping for the pipeline. Then, the compressibility test was done to show the effect of voids to the crude oil quantitatively.

1.4 Scope of Study

The project was focused on the study of the characteristic of the compressibility of gelled crude oil and gas voids formation in waxy crude oil with the effect of injecting air. It is about running the waxy crude oil into flow loop to simulate the seabed condition. In order to accomplish the project, some early experiments such as Wax Appearance Temperature (WAT) and Pour Point Temperature (PPT) experiment were conducted to identify the minimum point for the crude oil to turn wax and gelled consequently. Then, the data were analysed and the crude oil was injected with air to check on the compressibility and the effect of gas void formation. However, the apparatus used for injecting air need to be selected carefully as it might affect the result. The version of the crude oil that is used in this study is Sepat 7. The Sepat 7 crude oil is the crude oil produce by Petronas. The Sepat 7 crude oil that is used have characteristic of high pour point of 36°C with API gravity of 35.3°C.

CHAPTER 2

THEORY AND LITERATURE REVIEW

2.1 Theory

2.1.1 Crude Oil & Waxy Crude Oil

Crude oil contains the hydrocarbons such as paraffin, asphaltnes, aromatics, napthenic and resins. The different lengths of carbon chain for the hydrocarbon differentiate the state or condition of the crude oil. The longer the carbon chain, the heavier the molecule is. The heavier molecules tend to appear as solid or liquid while molecules with much lesser carbon appear to be in gaseous (Sequeira, 1994).

The crude oil is known as waxy crude oil when their content of paraffin is relatively high range from 1% to 50% (Ajienka, 1991). They are like long-chain alkanes with 20 to 50 carbon atoms and have slight quantities of branched and cyclic hydrocarbons (Siljuberg, 2012). The temperature affects the solubility of the paraffin waxes. The waxy crude oil that eventually becomes gelled up crude oil when extreme changes in lower temperature seabed which is lower than the pour point affect the transportation and production pipeline.

2.1.2 Wax Appearance Temperature

The Wax Appearance Temperature (WAT) also known as cloud point temperature. It is the limit temperature at where the wax develops. This means that the solubility of the paraffin reaches the maximum limit of solubility which results in the appearance of the waxy crude oil (Thomasan, 2000). As for the study, experiment on WAT was done to know the WAT limit point and is used to indicate the right temperature used for the heating and cooling during the experiment.

2.1.3 Pour Point Temperature

Same function as WAT, Pour point temperature is the limit temperature where the gel structure is formed from the crude oil (Venkatessan *et al.*, 2002). Without any stress, this is also known as gelation temperature as it is the temperature where the gel is formed. The gelation temperature is defined to occur between the WAT and pour point temperature. This is where the state of waxy crude oil starts to change from fluid to solid state.

2.2 Literature Review

Crude oil is a very complex mixture that combines many types of hydrocarbon and is called waxy crude oil as the content of the paraffin inside the crude oil becomes high. As crude oil becomes huge production in today's world, there is big concern to how it is transport and produce upon having problems and challenges of wax deposition, increase viscosity, and pressure drop at temperature below the cloud point, and high restart pressure for gelled oil in pipeline at temperature below the pour point. Such transportation is very expensive in terms of pumping cost and any things that lead to pumping failure and re-start pressure add further to these costs (Benkreira *et al.*, 2011).

At reservoir surroundings where involved the high temperatures ranges from 70°C to 150°C with high pressures within 50 to 100 MPa, the level of the solubility of the paraffin in the oil is very high where it completely dissolved the wax structure which results in the crude oil behaves as a low viscosity Newtonian fluid (Singh *et al.*, 2000).

When the temperature drops to the minimum limit, the wax will be deposited. The deposition rates is caused by so many factors such as paraffin content, fluid viscosity, flow rates, gas and oil ratio and the overall heat transfer coefficient (Golczynski and Kempton 2006). Thus, at that point the solid gelled like structure will interface at the pipe wall. The wax deposition affects in significant reduction of production due to plugging of wells and pipelines. Thus, in any extreme situation the wax and gelled crude oil can cause a pipeline or production facility to be abandoned (Singh *et al*., 2011).

The main principal in the gelled formation is the pour point temperature. The pour point defines the minimum temperature where the wax turns into gelled form. Below the pour point, the crude oil has a yield shear stress. This indicates that the oil would not flow unless a minimum shearing force like pumping acts on it (Time, 2011). When there is shutdown that might take longer time, the crude oil will be cooled down to ambient temperature which results in a blockage of the pipeline and difficulties to restarted the operation (Golczynski and Kempton 2006).

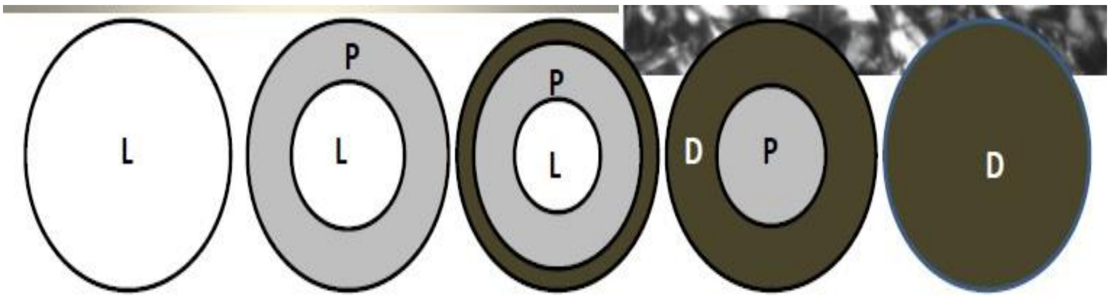

Figure 2.1: The evolution of wax formation in a pipe

The Figure 2.1 shows the changes that the oil undergoes upon shutdown and extreme changes of temperature. Firstly, the oil changes from liquid (L) to as liquid-precipitate (L-P) state. Then, a bit of deposited (D) area start to form which form (L-P-D) phase. After a while, the liquid will all turn into only deposited and precipitate state (D-P). Finally, the oil becomes deposited (D). The differences phase of the crude oil upon reaching the WAT point can be seen in Figure 2.2.

Figure 2.2: Crude oil sample above WAT (left) and
Crude oil sample below WAT (right)

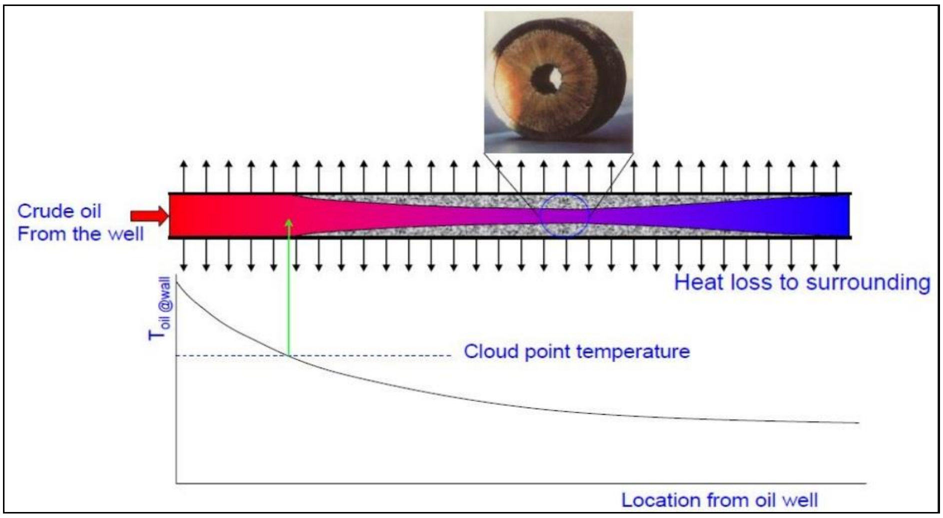

Figure 2.3: Overview of the general mechanism of the wax deposition

Figure 2.3 shows the simple overview on how the temperatures affect the structure of the crude oil along the pipelines. The red area indicates the high temperature from the reservoir meanwhile the blue part shows the extreme decreases of the temperature in the pipeline which finally results in the waxy gelled crude oil formation. During the whole process, the paraffin that is deposited into wax and gel will slowly ages becomes thicker and harder as time increases which will then reduce the pipe diameter, clogging it and weakening its flow efficiency (Civan, 2003).

As the gel form, the gel yield stress will surely be high, beyond the maximum allowable pressure that the pipe can withstand (Ekweribe *et al*., 2009). The shutdown or experience great changes in temperature upon cooling results in the waxy crude oil to become gelled and delay the transportation and production process from offshore platforms (Henaut *et al.*, 1999). When the pipeline temperature drops below the pour point of the temperature, the incompressible waxy crude oil undergoes thermal shrinkage. The restart pressure to restart the flow becomes harder due to the gelled up crude oil (Benkreira *et al.*, 2011).

Without doubt, the situation affect the economic loss for the operator as the flow cannot be started and everything need to be rejected. Some alternatives can be consider to overcome the clog problem such as sending the divers manually to remove the pipeline blockage, mechanical pigging, application of chemical, cold flow and melting deposit by heat generate by a chemical reaction (Nguyen *et al.*, 2001).

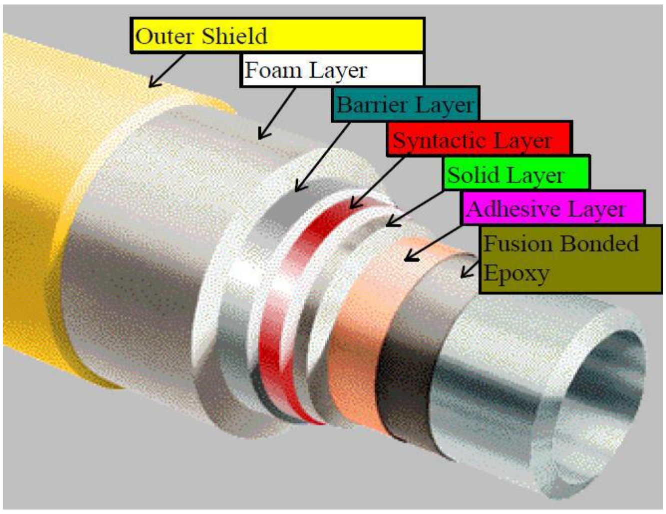

Figure 2.4: Example approach heat application or thermal insulation method

The heat application for example usually use approaches such as hot oil, hot water or steam injection. These methods are using thermal insulation concept. Figure 2.4 shows the heat application using thermal insulation method. The most advance technology that almost used the same concept is known as Direct Electric Heating System (DEHS). The basic principle is that DEHS will pass large electric current to the entire pipeline to generate heat.

It used an alternating current (AC) through a metallic conductor to generate the heat needed (Kullbotten and Lervik, 2007). Example of the DEHS system where it is installed in North Sea Lines is shown in Figure 2.5 (Lenes *et al.*, 2005).

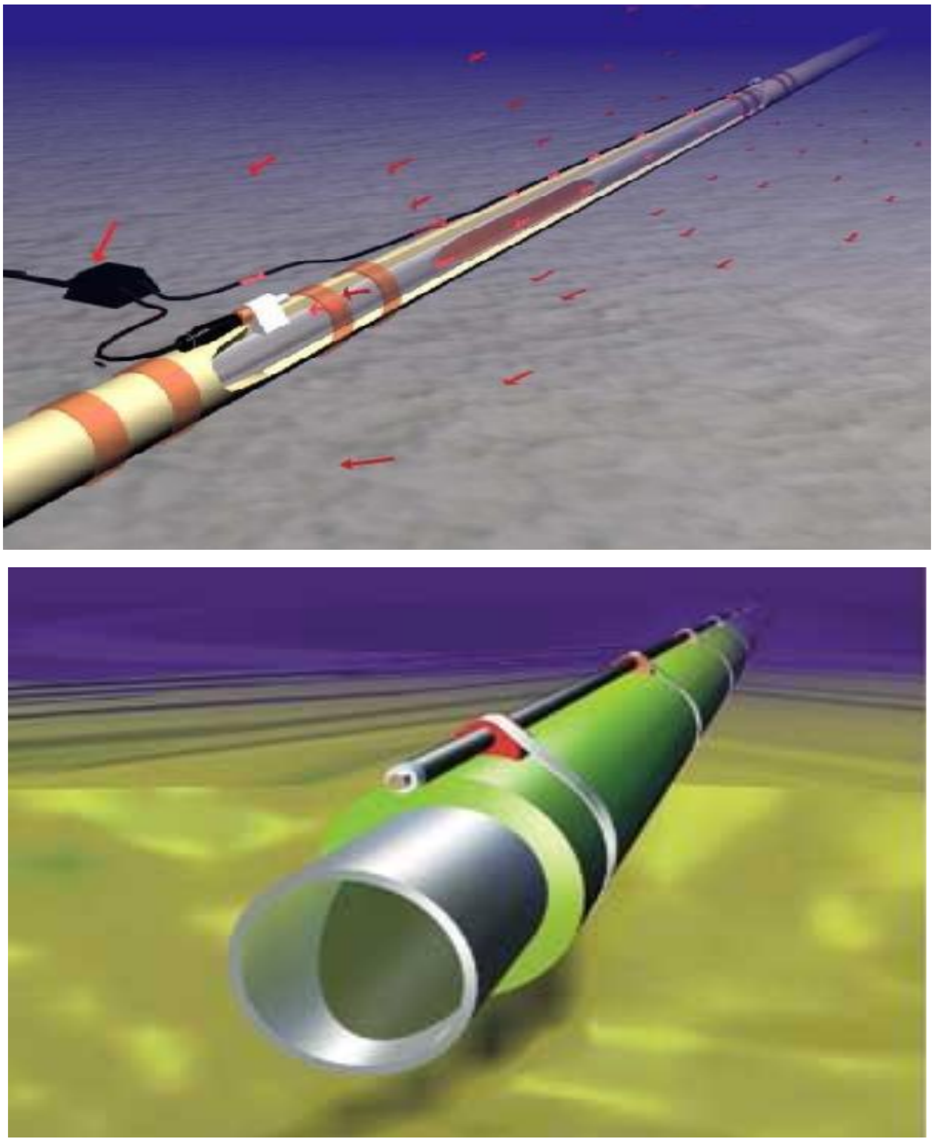

Figure 2.5: Example DEHS on seabed

The mechanical pigging method is a method that used pipeline inspection gauges or ‘pigs’ to perform the maintenance. The pigs will running through the pipeline to scrap off the wax and gelled that deposited on the internal wall of the pipeline. The mechanical pigging function is to the pipe cleaning. Besides that, it is also used to removed liquid accumulation in the pipeline, removes the salts and also scale. Figure 2.6 show the working principal of the pigging method meanwhile in Figure 2.7 illustrates the basic diagram of the process.

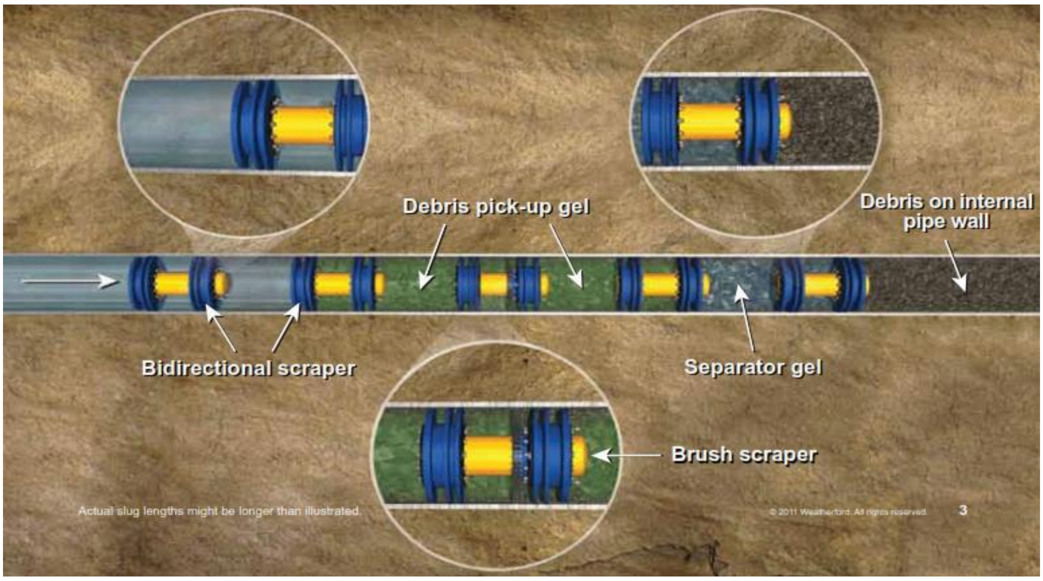

Figure 2.6: Example of pipeline pigging method

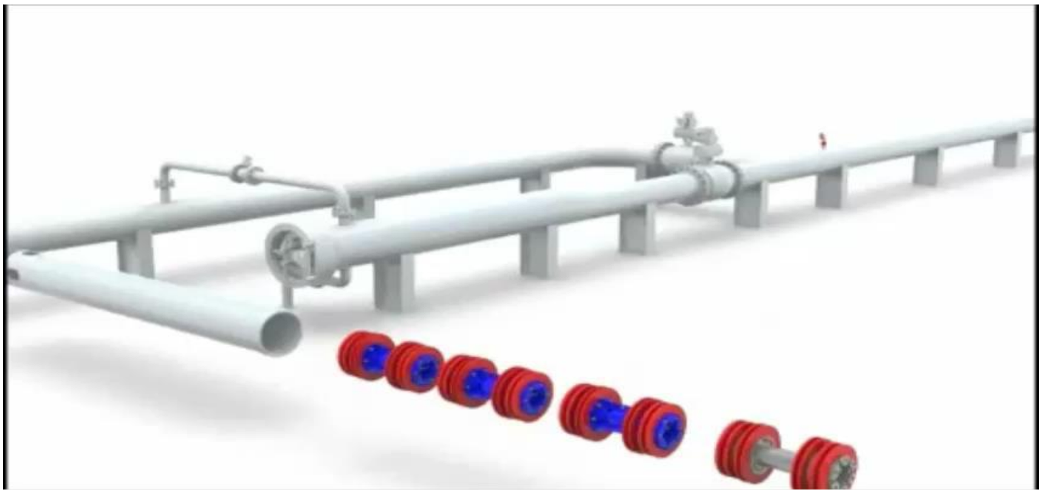

Figure 2.7: The basic pigging diagram application

Another approach is the application by chemical or chemical injection method. This is a well-known method and widely used in the industry (Lederhos *et al.*, 1996). In this method, the inhibitor is added into the pipeline to inhibit the wax formation. The inhibitor substance is used to water wet the pipe surface to avoid the adhesion of paraffin to the pipe wall (Al-Yaari. 2011). The two main categories of the inhibitor are thermodynamic hydrate inhibitor (THI) and low-dosage hydrate inhibitor (LDHI) (Paez *et al.*, 2001).

Next, the recently alternative method used is the cold flow. The cold flow is a new technology that is used to clear the blockage in the pipeline. The basic principle of the method is the wax formation is allowable through cooling down process fluid, but the wax can still be carried by the fluid stream in the slurry (solid-liquid) form. This will avoid more accumulation of the wax particles that might plug and block the pipeline. Figure 2.8 shows the components involved in the cold flow method.

Research shows that this method can be used for longer distance transfer that reach more than 200 km from the wellhead platform to the facilities centre on seabed (Wolden, 2008). For example, it can be apply to the long distance application in Arctic with the cold tough environment include Skrugard which is 200 km offshore of Northern Norway in Barents Sea and Mizzen that is 500 km offshore of Newfoundland, Canada (Hoffmann, 2012).

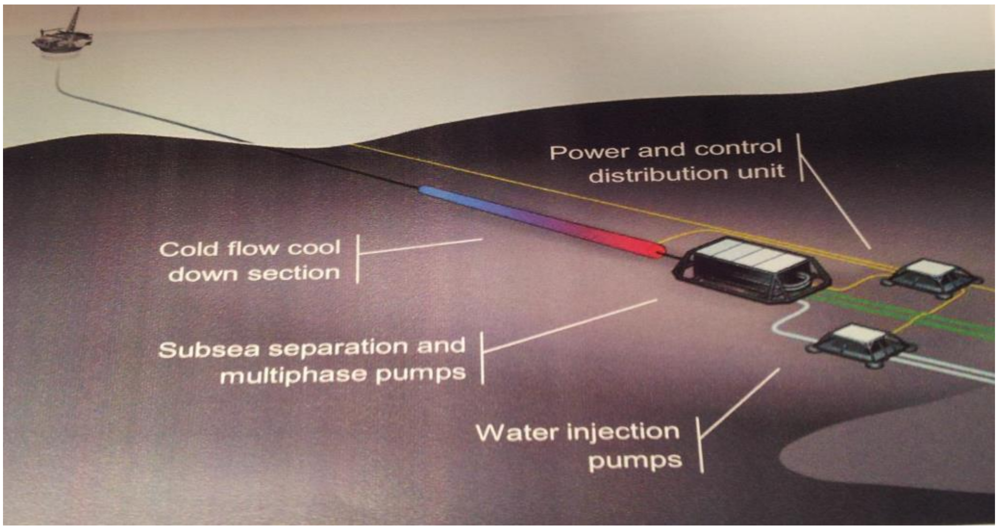

Figure 2.8: The Cold Flow components

However, seems those methods have its own disadvantages which make it hard to overcome the problem. For example, sending the divers manually to remove the pipeline blockage is a very high risk as the high pressure down the sea might be harmful to the diver. The DEHS method has no shutdown limitation and more friendly compared to chemical injection. However, there is high possibility of cable failure which can damage the pipelines and form the short circuit. The long distance pipeline also required high power consumption but currently the application is limited to distance up to 50 km only.

For mechanical pigging, if the gel strength is truly high the pig might get stuck in the pipeline result in more losses and maintenance to overcome. In chemical injection method, the methanol used can enhanced corrosion rate and reduces the efficacy of some corrosion inhibitors due to the dissolve oxygen in it (Scott-Hagen, 2010). The price of advanced inhibitor also is extremely high.

The cold flow method is said to be cost effective. However, the balance of heat might be the main problem. The subsea pipelines that used a steel-reinforced concrete layer to ensure the pipe to stay fixed at the bottom can result in a low overall heat transfer coefficient (Gudmundsson, 2012). Furthermore, this method has not proven field wise yet. The summary on some of the technologies can be found in Table 2.1.

In Table 2.1, it shows the comparison between the four methods which are chemical injection, Direct Electric Heating System (DEHS), cold flow and mechanical pigging. The four alternatives were analysed based on seven criteria which are the system application, viscosity, pipeline distance range, chemical requirements, infrastructures, waste issue, and the cost. Those are the crucial factors that need to be considered and seen before any alternative from the method is chosen.

Table 2.1: The summary of qualitative analysis of the methods

	Chemical Injection (Inhibitor-Methanol)	**DEHS**	**Cold Flow**	**Mechanical Pigging**
System application	Oil, gas & condensate, multiphase	Oil, gas & condensate, multiphase	Oil, gas & condensate, multiphase	Oil, gas & condensate, multiphase
Viscosity	Up to 30%, but not problematic	No effect	High pressure drop may lead to difficulty in transportation with high viscosity.	No effect
Pipeline distance range	10-200 km (With insulation)	Currently up to 50 km. 200 km (maximum)	200 km and above. Extra pipeline for cooling loop	1-150 km
Chemical requirements	10% to 60% by volume	Not required	Not required	Only for intelligence pigging
Important Infrastructures	Regeneration /reclamation facility, large storage tank, umbilical, high horse power pump.	Power source	Non-insulated pipeline, reactor, splitter, pump.	The shaft and pigging gauge
Waste issue pollution	Toxic & contaminates oil	No pollution, but large energy demand	High energy demand to break the slurry. No chemical, no pollution	No
CAPEX and OPEX	Very High	Medium	Low	Low

Figure 2.9: Gelled plug removed through pigging

As the gel hardness increases, more restart pressure is needed to start the flow after shutdown. The shear yield stress determines the strength of the gel. Numerous studies has been done to analyses the yield strength of waxy crude oil for many condition eventually the pressure required to restart the gelled up crude oil (Thomason, 2000; Borghi *et al*., 2003; Davidson *et al.*, 2004). Figures 2.9 and 2.10 shows some problem related to the gelled crude oil that occurred in Nigeria pipeline.

Figure 2.10: The scrapper coated with wax in Nigeria pipelines

The wax or gelled crude oil issue is very important as it affect the production and the oil flow greatly. It can gives great significant especially to the profit and loss of the production. Some of the bad impacts of the situation are to construct chemical and mechanical pigging operations, reduced production, well shut-in, less utilisation of capacity, chocking of the flowlines, equipment failure, extra horse power requirement, and increased manpower attention.

Many cases had happened and showed that the problem is very critical. For example, the Lasmo Oilfield in United Kingdom had to be abandoned because of the recurring plugging problems at a cost over USD 100 million. Then, 17 pipelines were plugged in the Gulf of Mexico in 1994 and since that the number increases. One of the cases in Gulf, Mexico was shown in Figure 2.11. The remediation of pipeline blockage in deep water as deep as 400 m can costs more than USD 2.5 million. Furthermore, the forecasters expected that by 2017, the oil production from deep sea areas will exceed 8 million barrels per day which is about three times greater than in 2002 (Vankatesan *et al.*, 2002).

Figure 2.11: Critical gelled crude oil that stuck in pipeline in Gulf, Mexico

In order to restart the flow, the main concern would be to determine the minimum pressure at the entrance tube in order to overcome the gel strength (Mendes *et al.*, 2011). The restart pressure is a very high concern as the operator might face high cost to replace the pipeline. Moreover, the proper study of the characteristics of the gelled up crude oil is important to reduce the Capital Expenditure Cost (CAPEX Cost) and ensuring a constant flow of crude (Borghi *et al.*, 2003). This is because the study of those characteristics might read new restart pressure that will be more affective for the flow to restart.

The original equation that is used to calculate the pressure that needs to be used for the restart flow might be over predicted as it only includes the yield stress of the gel without concerning the compressibility characteristic of the gel crude oil. The compressibility characteristic leads to a strong pressure drop at the upstream of a pipe (Vinay *et al.*, 2009).

Thus, this shown that the restart pressure calculation is supposed to include the compressibility factor. It proves that gas voids formation actually affect the compressibility of the gelled up crude oil which could reduce the restart pressure of the operation. Thus, further study of the formation of gas voids and injecting air might give better results for the outcome.

Based on Table 2.2, those are summary on few of the researches work. For example, in the "Prediction and Scale up of Waxy Oil Restart Behaviour", Borghi states that most models used to predict the start-up pressure will assume that the crude oil is incompressible. The research shows different types of waxy crude oil and the prediction of its gellation pressure to break the hardness. Meanwhile, Benkreira mentioned in "Rheology and Start-up Pipeline Pressure of Waxy Crude Oil", because of the complexity in yielding behaviour of the wax-oil gel, many studies have been carried out to estimate the yield strength of the wax-oil gel for various conditions and, ultimately, the pressure required to restart the gelled pipelines in the field shows that the restart of pipeline may break the gelled structure which lead to losses in pipeline restart, abandoned pipelines or scrapped process equipment.

Table 2.2: Summary of related work

Research	Finding/Observation
Ekweribe et al.2009	Struggling to restart the pipeline flow required the breaking of paraffin plug by overcoming the gel strength. The gel yield stress can be extremely high, exceeding the maximum allowable pressure that the pipe can bear
Nguyen et al., 2001	As the microstructure of the crude oil are influenced by temperature and cooling rate, the yield stress also changes. Thus there will be problem to the gelled up crude oil in the pipeline. There were some techniques available to overcome the problem such as sending the divers to manually remove the pipeline blockage, mechanical pigging and melting the deposit by heat generate by a chemical reaction
Borghi et al. 2003	In the "Prediction and Scale up of Waxy Oil Restart Behaviour" states that most models used to predict the start-up pressure, assumes that the gelled up crude acts like an incompressible, high viscous fluid. The journal shows the experiment by using different types of waxy crude oil with different approach of the model.
Benkreira et al. 2011	In "Rheology and Start-up Pipeline Pressure of Waxy Crude Oil" shows that the restart of pipeline may break the gelled structure which lead to losses in pipeline restart, abandoned pipelines or scrapped process equipment.

CHAPTER 3
METHODOLOGY

3.1 Project Planning

3.1.2 The overview of the project flow

The journey of the project begins with the selection of title where the student will be given opportunity to choose their favour title. However, the selection is based on first come first serve basis and it was assigned to the student according to the availability of the title. Then the project is started with the research on the project, basically the literature review part. In this project the compressibility and gas void formation of gelled up waxy crude oil is the main part that need to be studied. As many researches have been done before for the study, a literature review finding will help a lot on the project progress later.

Next, the experiments that were done for the study are Pour Point Temperature (PPT) experiment, Wax Appearance Temperature (WAT) and compressibility experiment to check the effect of the gas voids formation. The experiments were conducted to determine the PPT and WAT of the crude oil. From the experiment, recorded data was used to analyse the formation of gas void in waxy crude oil under thermal shrinkage and determine the characteristics of waxy crude oil. The whole work planned for the first phase which is from the beginning up until the experiment is shown in Table 3.1.

The design flow loop was used during the experiment to study further about the gas void formation and characteristic of waxy crude oil. The main function of the designed flow loop is to apply the same situation or condition of the seabed temperature. It is also used to simulate the production pipeline situation of gelled crude oil during the experiment. Last but not least, the test section from the flow loop will be used to test the compressibility factor of the crude oil before and after injecting air. This phase of planning is shown in Table 3.2. Figure 3.1 shows the project flow process based on the project planning.

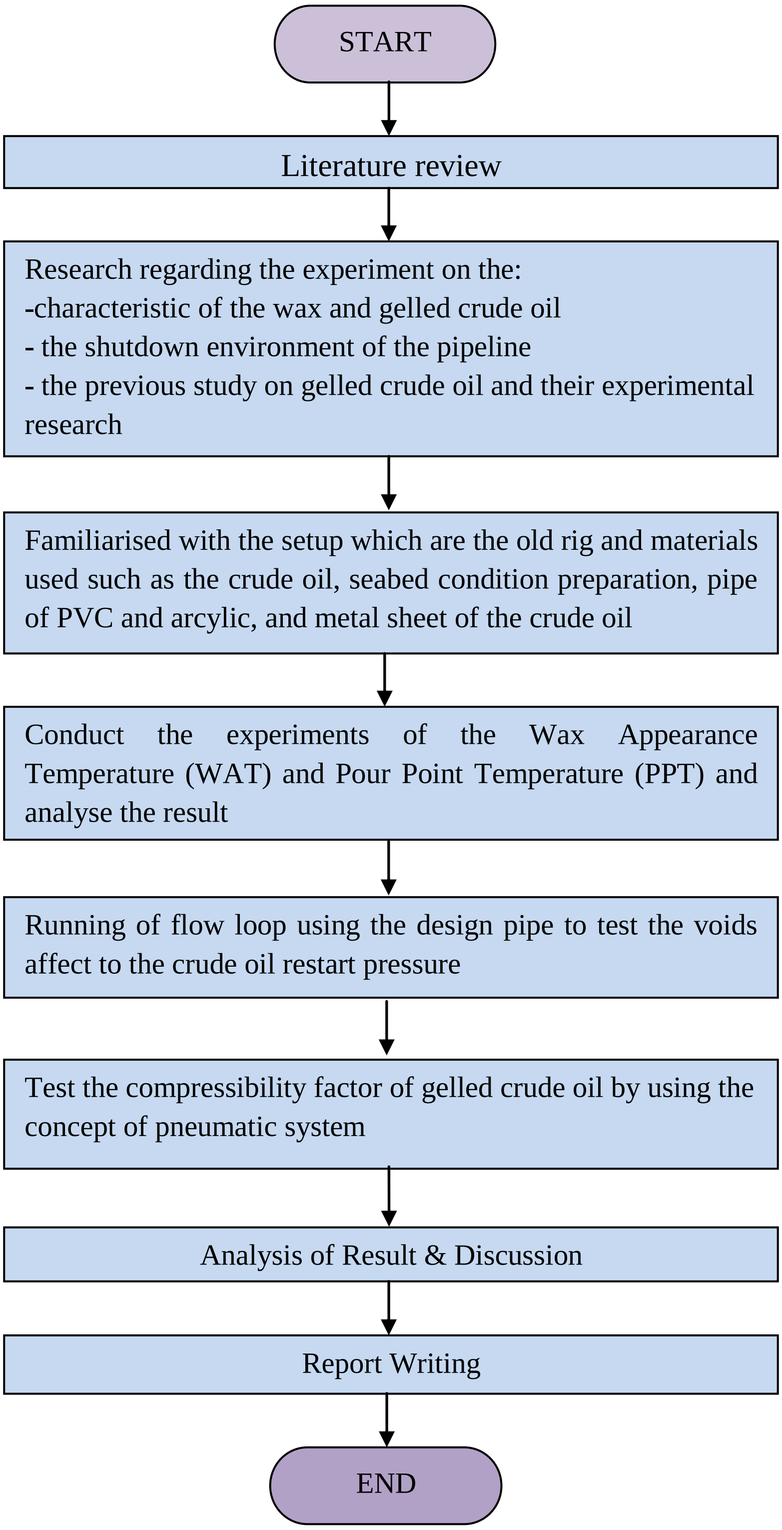

Figure 3.1: Project flow diagram

3.1.2 Understanding the Working rig

As the project involved in the working rig, some knowledge on how the rig worked is very essential. From here, it is important to identify the basic information and principle of the project. For example, get to know the characteristic of the liquid and the working principle of the old and new rig. As the project require for the injecting air and compressibility study, the next step is to identify the right way to undergo the alternatives that have been chosen to inject air and to do the compressibility analysis. The flow in the Figure 3.2 shows the main idea on how the experiment was done basically. However, on the third stage where the test section is in seabed condition, the experiment will be done with and without injecting air to figure out the effect of the voids formation.

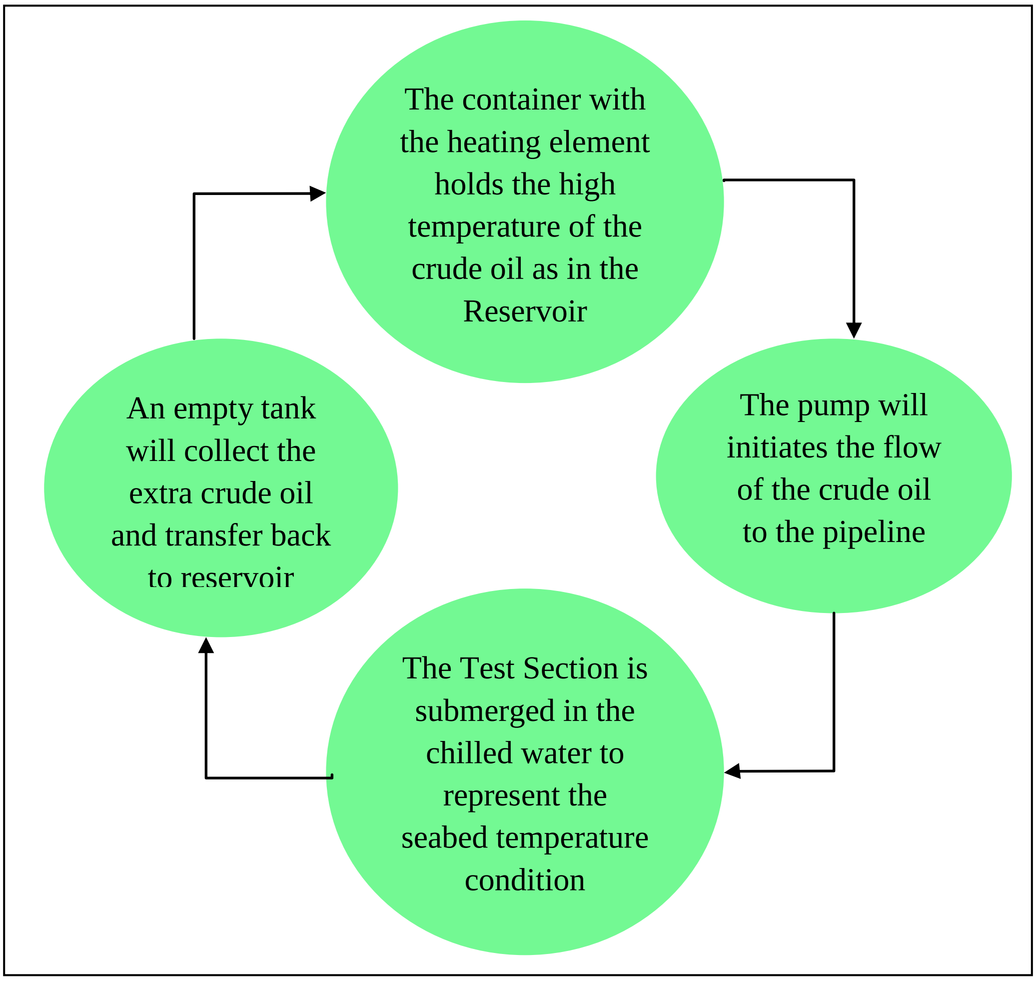

Figure 3.2: The basic process of the flow

3.1.3 Gantt Chart

Table 3.1: Gantt chart for FYP 1

No	Activities/ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Selection of Project Title								MID SEM BREAK							
2	Initial research work / Literature Review															
3	Research on WAT and PPT Experiment															
4	Submission of Extended Proposal															
5	Proposal defence															
6	Proposed the WAT and PPT Experiment															
7	Conduct the WAT and PPT Experiment															
8	Analysis of Experiment Result															
9	Submission of Interim Draft Report															
10	Submission of Interim Report															

Table 3.2: Gantt chart for FYP

No	Activities/ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
1	Revised Literature Review								MID SEM BREAK								
2	Data analysis																
3	Identify on way to conduct compressbility experiment																
4	Test the flow loop																
5	Submission of Progress report																
6	Pre-SEDEX																
7	Compressibility experiment																
8	Submission of Dissertation (soft bound)																
9	Submission of Technical report																
10	Project presentation (VIVA)																
11	Submission of Dissertation																

3.2 Wax Appearance Temperature (WAT) and Pour Point Determination

For this project, both temperatures were identified using one experiment. The objectives of this experiment are to determine the Wax Appearance Temperature and Pour Point Temperature. The crude oil used is Sepat 7. The setup in Figure 3.4 shows the setup for WAT experiment.

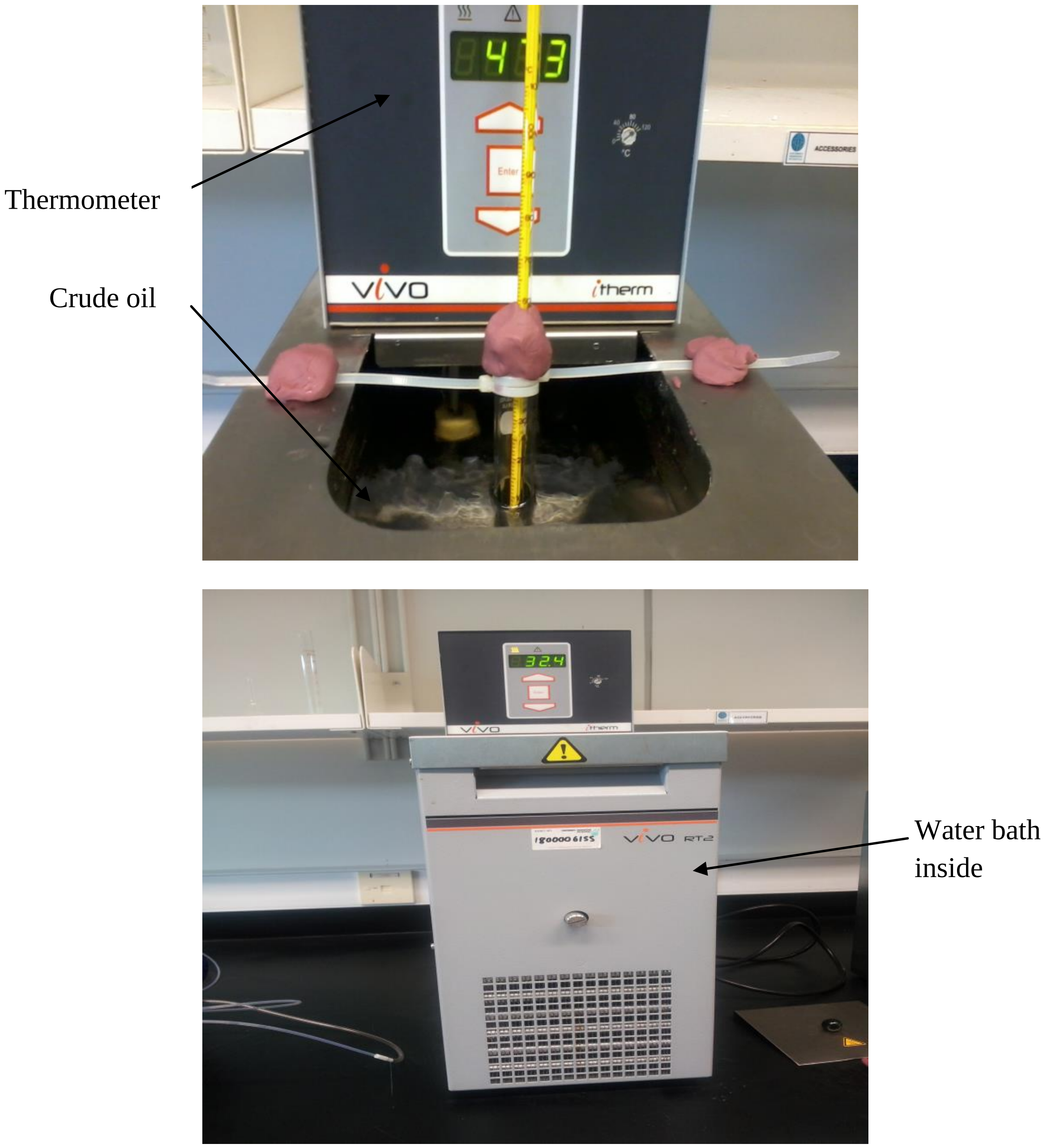

Figure 3.3: The setup of the experiment

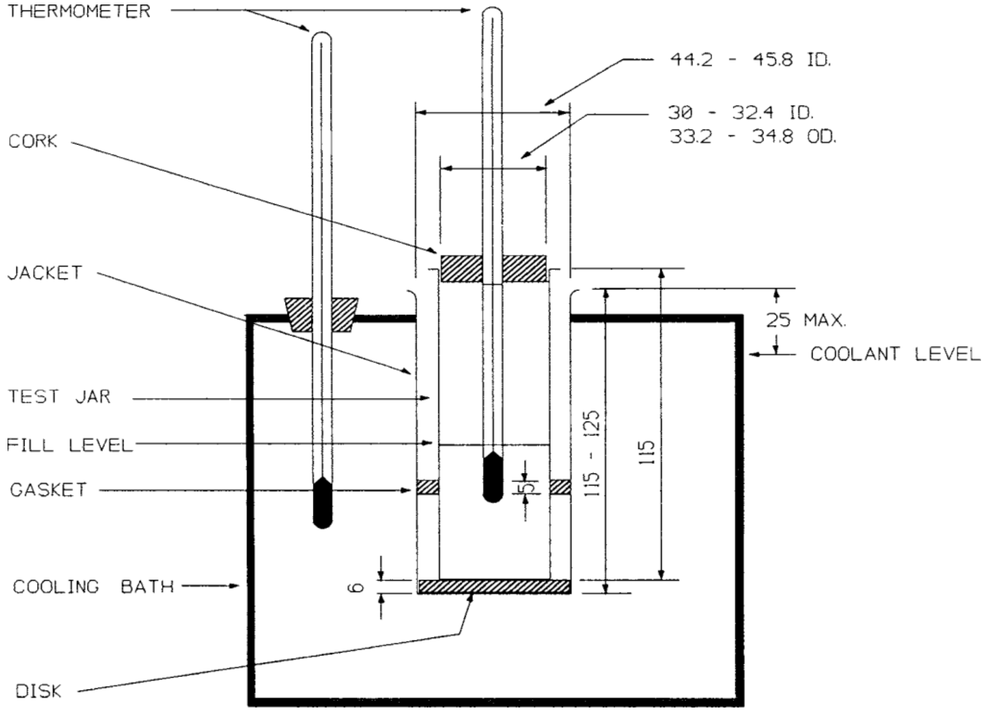

Figure 3.4: Example of schematic diagram of the experiment from lab

The specimen was heated without stirring to 9°C above the expected pour point, but to at least 45°C, in a bath maintained at 12°C above the expected pour point, but at least 48°C. Test jar was put in water bath maintained at 24°C and the pour point temperature was observed. The appearance of the specimen was observed when the temperature of the specimen is 9°C above the expected pour point (estimated as a multiple of 3°C).

At each test thermometer reading that is a multiple of 3°C below the starting temperature remove the test jar from the jacket. Tilt the jar just enough to ascertain whether there is a movement of the specimen in the test jar. As soon as the specimen in the jar does not flow when tilted, hold the jar in a horizontal position for 5 s, as noted by an accurate timing device and observe carefully. If the specimen shows any movement, replace the test jar immediately in the jacket and repeat a test for flow at the next temperature, 3°C lower.

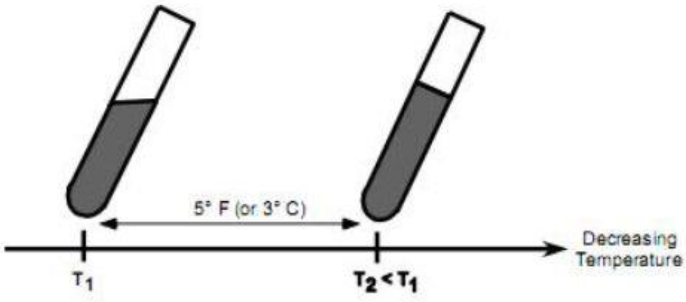

Figure 3.5: The flow test

Continue in this manner until a point is reached at which the specimen shows no movement when the test jar is held in a horizontal position for 5s. The observed reading of the test thermometer was recorded and used for the analysis of the study.

3.3 The rig and pipe design

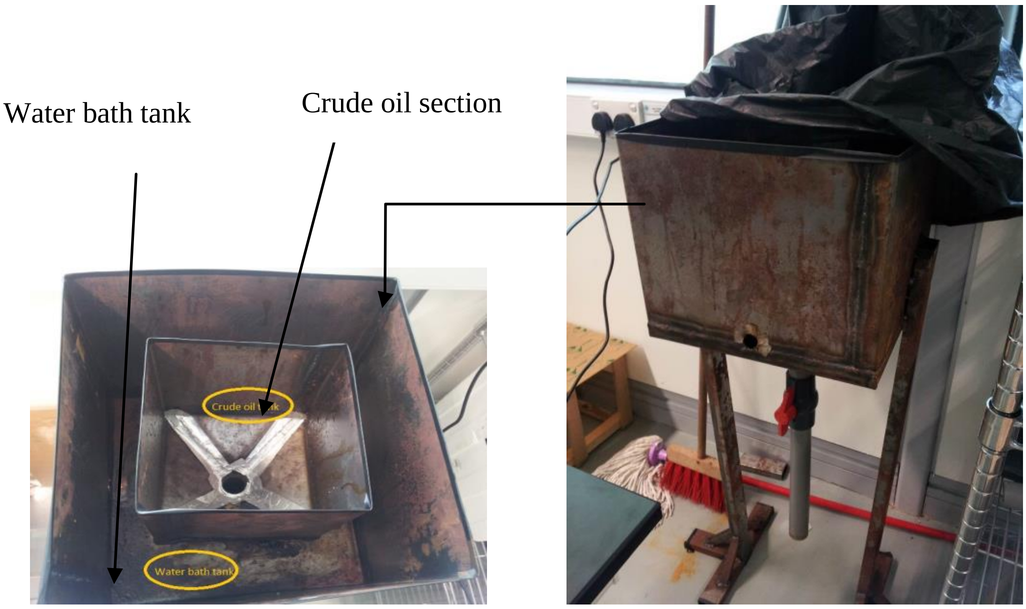

Figure 3.6: The old rig

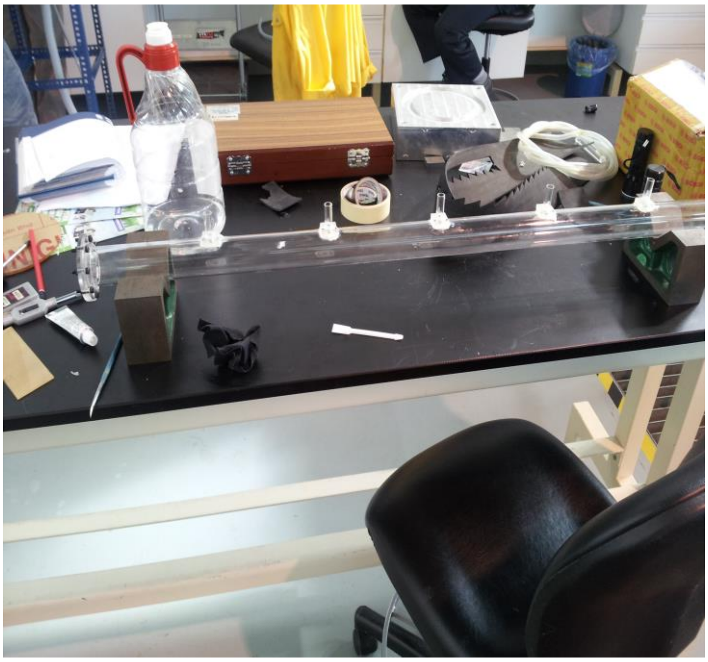

Figure 3.7: The acrylic pipe design

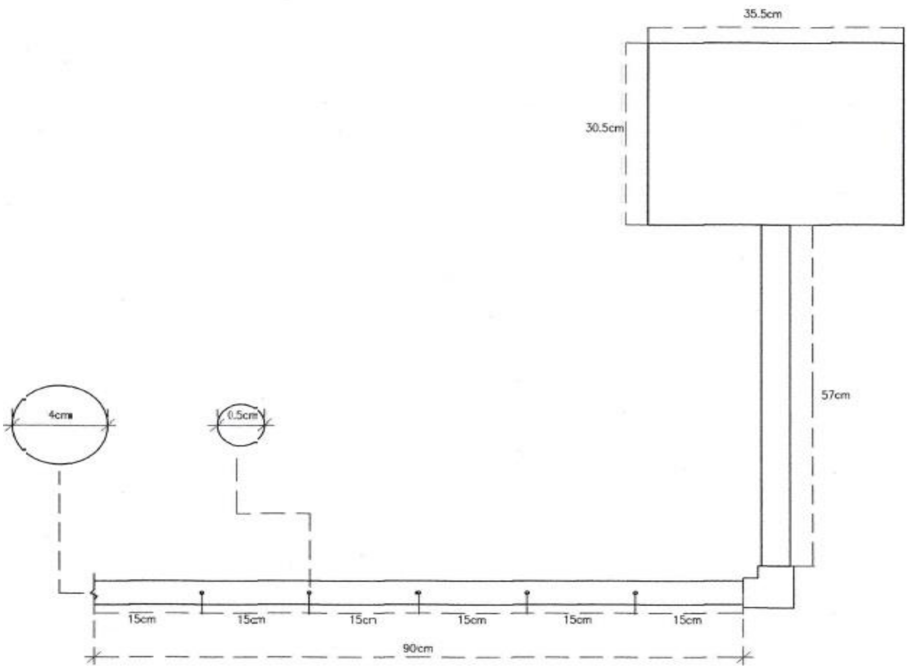

Figure 3.8: The AutoCAD drawing of the rig

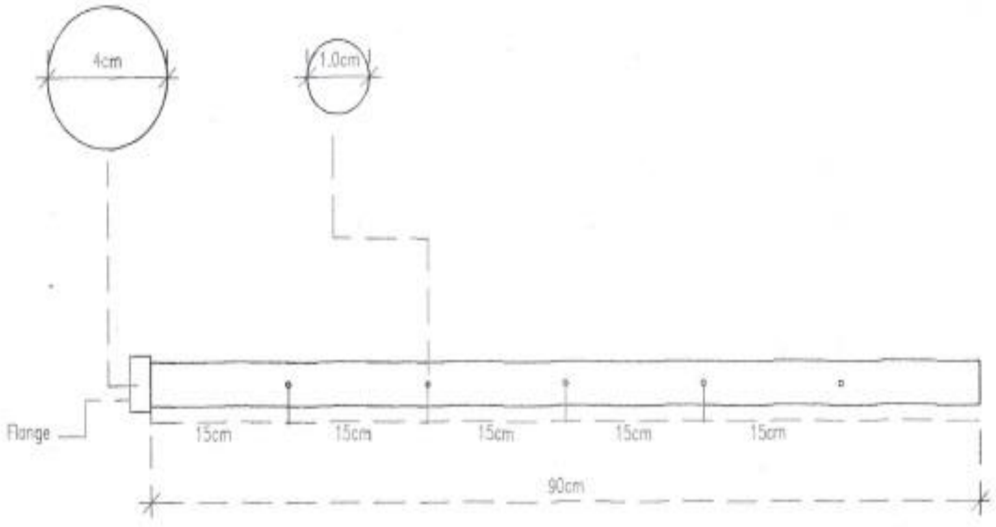

Figure 3.9: The drawing of the design arcylic pipe

The old rig as shown in Figures 3.6 and 3.7 used gravity as the main idea. When the valve is open, the oil will flow down through the pipe caused by the gravity. The crude oil will be left running in a constant heating and cooling condition until the crude oil in the test section gelled up. Thus, the old rig will be used to run down the crude oil. The experiment will be done with and without the air injection in order to compare the effect of voids appearance to the compressibility of the crude oil.

The arcylic pipe from Figures 3.8 and 3.9 were used to ease the observation and measurement of the length after the crude oil gelled up. The length of the pipe is 90 cm meanwhile the diameter is 40 cm. The pipe is design to have holes along the pipe for the air injection purpose. However, the hole must be close up using rubber or cork when the air is not use to avoid the oil from leaking out.

This old rig consists of several parts which are:

a) The oil tank

This was used to pour the heated oil before is let to flow to the pipeline.

b) The water bath

The water bath outside the oil tank was used to maintain the hot temperature of the oil like inside the reservoir.

c) The Valve

Valve was used to open or closed the pipe section when needed.

d) The ice box

For this rig, the ice is located in the box to maintain the cold temperature of the test section as like the seabed temperature.

e) The test section

The part where the crude oil undergoes temperature changes and gelled up.

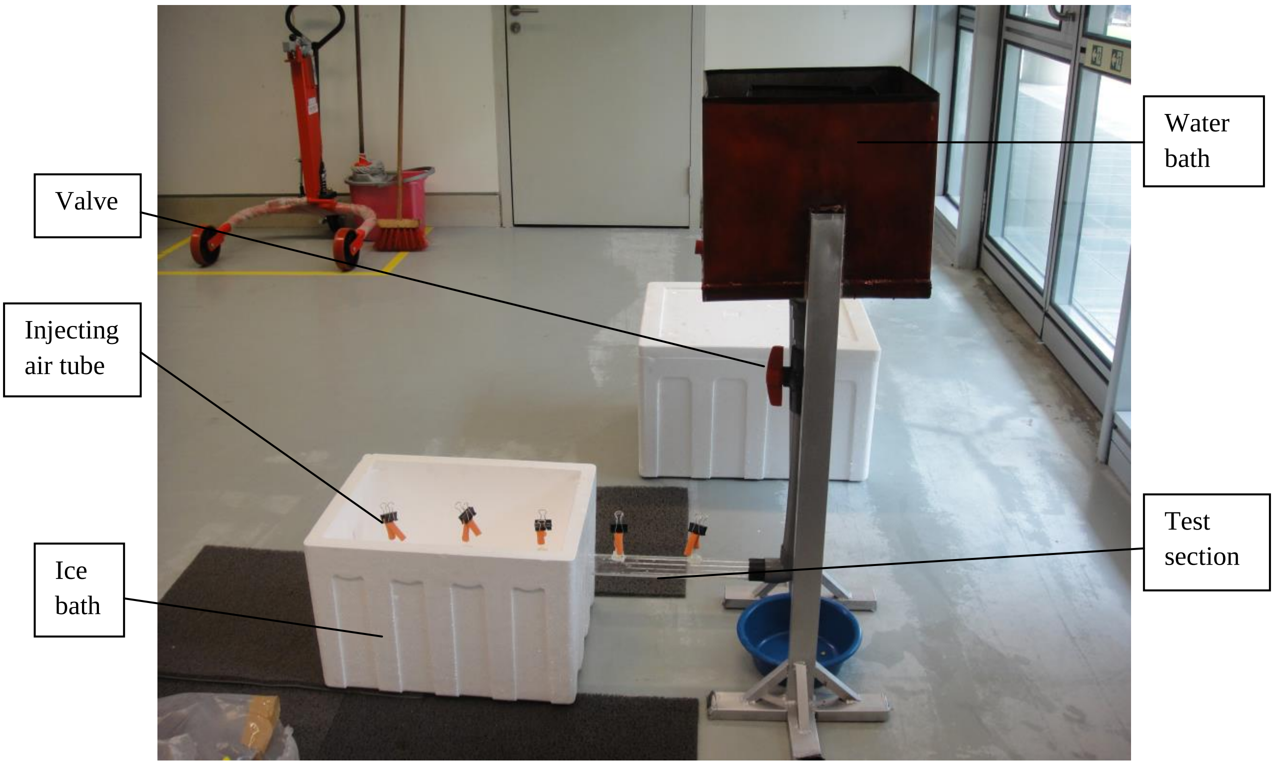

Figure 3.10: The flow loop for the experiment

Figure 3.10 shows the flow loop used for the study. Firstly, the crude oil was heat up until certain temperature and then will be left flow in the flow loop until the crude oil fill up in the test section. Then, the test section has been cooled until certain temperature using the ice bath to apply seabed condition. After sometimes when the crude oil gelled up, the formation of voids will be observed in the test section.

As only one test section is available, the experiment was repeated by injecting some air to the test section using the air line. The air was injected to 2 out of 5 tubes located on the test section pipe. The tubes were closed to avoid the air from escaped. The difference of the original and injecting air sample or gas voids formation is recorded. The time taken for the crude oil gelled up will roughly take about 1 hour to 1 hour and 30 minutes.

After each sample, the test section will be taken to test the compressibility. The compressibility test proposed in the project is by using bicycle pump and plunger like as shown in Figure 3.11. The bicycle pump is connected to pressure gauge and the end tube is connected to the pipe to push the pipe in order to compress the gelled crude oil. The pressure is applied manually but with constant value to each sample. The length of the compressible crude oil is recorded and compared between both samples.

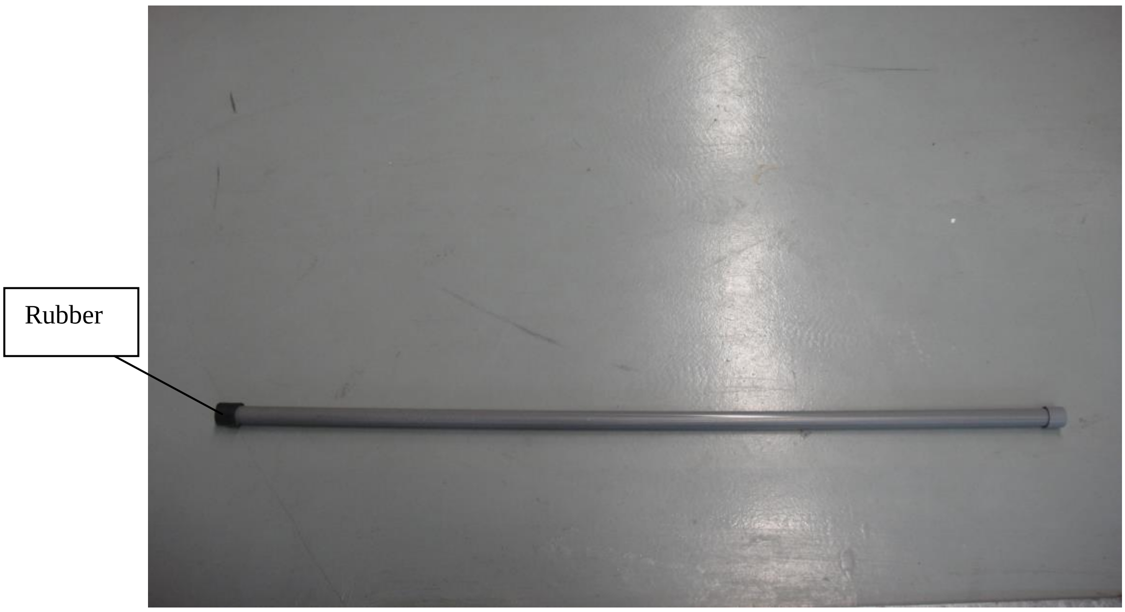

Figure 3.11: The plunger like type

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Wax Appearance Temperature (WAT) analysis

The Wax Appearance Temperature (WAT) shows the temperature at which wax structure started to forms meanwhile Pour Point Temperature (PPT) shows the temperature when wax crude oil turn gelled solid like. The gelled up crude oil was build-up from the network of waxy crystals. The WAT analysis depends on the wax content of the oil and wax particles size and number. Table 4.1 shows the result of wax appearance temperature and pour point temperature for Sepat 7 crude oil.

Table 4.1: The WAT experiment result

Temperature (°C)	55	52	49	46	43	40	37	34
2.5 ml of Crude	x	x	x	X	Wax starts to appear	Wax starts to appear	Cease to flow completely	Cease to flow completely
5.0 ml of Crude	x	x	x	x	Wax starts to appear	Wax starts to appear	Cease to flow completely	Cease to flow completely

From the results, it is shown that for Sepat 7 crude oil the wax started to appear in the crude sample at the temperature of 43^{o}C. At the temperature of 40^{o}C, the wax content is more visible and starts to cover most of the crude. Finally, at 37^{o}C, the crude ceases to flow completely. In this WAT experiment, the result of PPT also is recorded based on the phase changes of the crude oil. Therefore, based on the experiment, it is concluded that for Sepat-7 crude, the Wax Appearance Temperature (WAT) is 43^{o}C and the Pour Point is 37^{o}C. However, the confirmation of the temperature for the gelled was done via the Pour Point Temperature (PPT) experiment.

4.2 Pour Point Temperature Analysis

The Pour point qualitatively indicates the limit temperature at which the crude oil will gels under statics condition. The gelling is a result of accumulation of the waxy crystals network. The network formation is depends on the wax content of the oil and wax particles size and number. Table 4.2 shows the result of pour point temperature for Sepat 7 crude oil.

Table 4.2: Pour point temperature recorded for Sepat 7 crude oil

Test no.	**Recorded pour point (°C)**	**Reported pour point (°C) (recorded +3°C)**
1	34	37
2	35	38
3	34	37
4	34	37

In Table 4.2, it is shown that the pour point temperature for Sepat 7 crude oil is 37°C which is the same data analysed from WAT experiment. The PPT temperature of 37°C is quite high. The small difference between WAT and PPT might be caused by the high wax content or large wax particle size. The one with large size wax crystals will require only a small quantity of wax in order for the crude oil to gel up. The high number of wax particles might be possibility of one of the causes. The high wax content crude oil will precipitate enough wax to form a network for the crude oil to turn gelled at high temperature.

With the result of high pour point value, it is expected that the crude oil was gelled up in the pipeline. With this type of crude oil, the decreasing seabed temperature was the main factor of the gelled up crude oil during the transportation as the seabed temperature is lower than the pour point. Thus, even there are slight changes of temperature in the pipeline the crude oil will gel up faster.

4.3 The data analysis of Effect of Gas Voids Formation in Gelled Crude Oil

Table 4.3: Sample 1(original) test data

Item	Water bath Temperature (°C)	Seabed Temperature (°C)	Time taken to fill the test section (sec)	Time taken to gel up (hour)
Test 1	94	12	65	1.33
Test 2	96	8	60	0.92
Test 3	95	10	63	1.15
Average	95	10	62.7	1.13

Table 4.4: Sample 2 (injecting air) test data

Item	Water bath Temperature (°C)	Seabed Temperature (°C)	Time taken to fill the test section (sec)	Time taken to gel up (hour)
Test 1	91	14	75	1.50
Test 2	93	10	68	1.33
Test 3	95	9	62	1.25
Average	93	11	68.3	1.36

The Tables 4.3 and 4.4 show the data recorded for the gas voids formation study using the flow loop. The Sample 1 is the original condition of the crude oil used in the study. Meanwhile, the Sample 2 is second condition where the air is injected into the crude oil to observe the differences in voids formation compared to Sample 1. The experiment is repeated three times for each sample and the average reading is taken for the recorded data. Based on the data in Table 4.3 and Table 4.4, a graph was constructed to identify the trend of the experiment. The air injected is 500 cm^3. The mass of the crude oil used is 980 g which is equal to 0.0012 m^3.

In Sample 1, no additional air is added but in Sample 2 the air is injected into the test section. The images in Figures 4.1 and 4.2 shows the differences between the two samples tested.

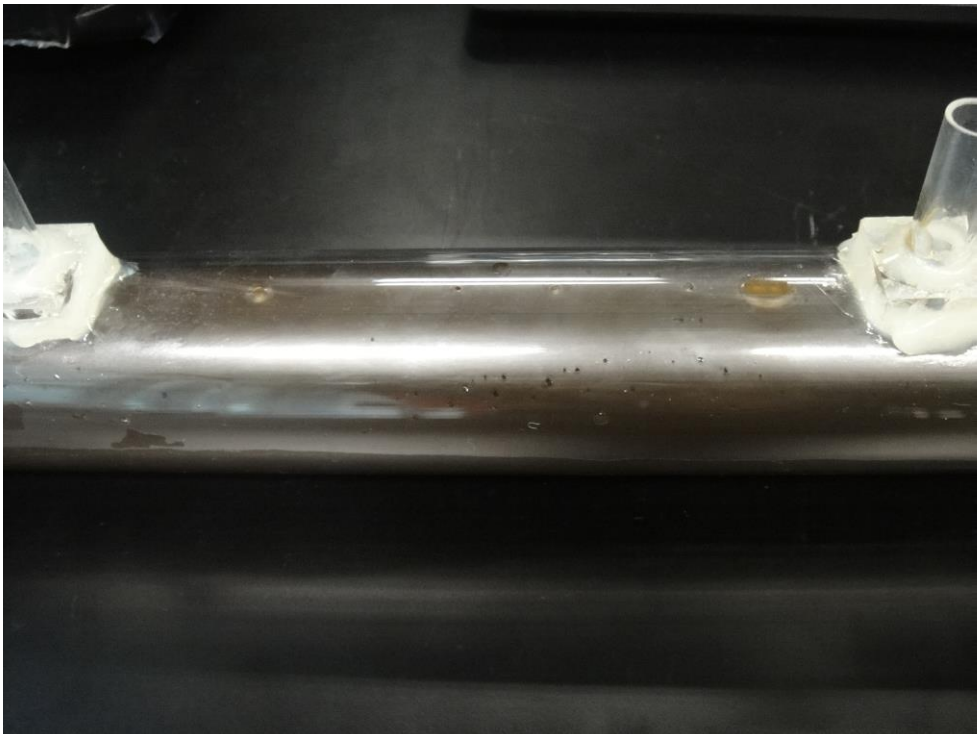

Figure 4.1: The image of voids formation before injecting air

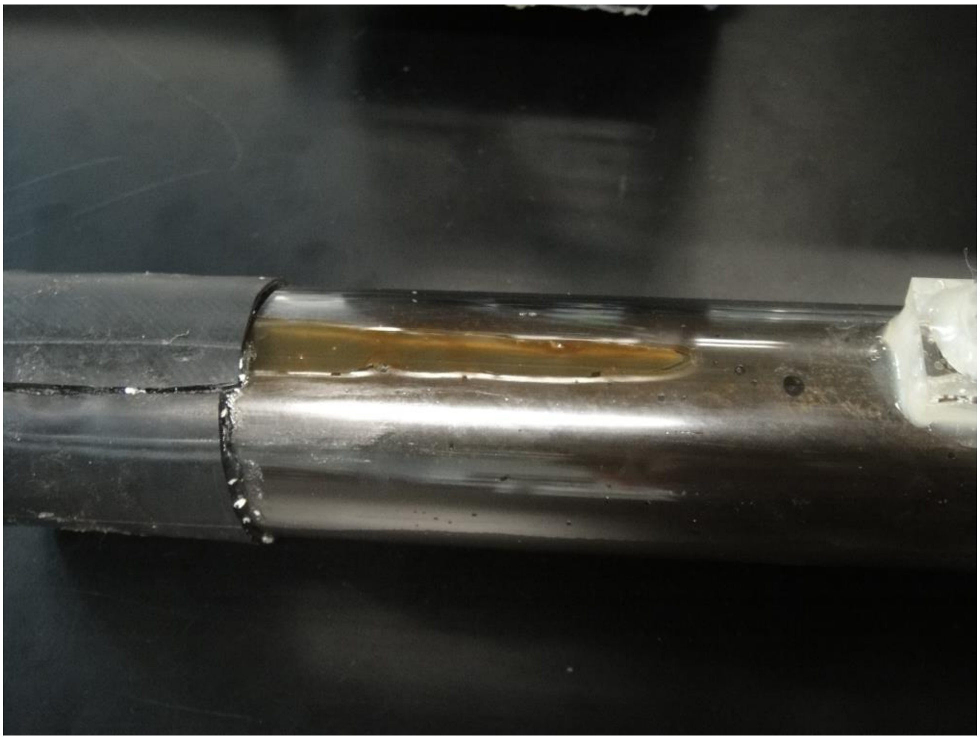

Figure 4.2: The images of voids formation after injecting air

4.4 The compressibility calculation

The constraints that need to be solved are the leaking of the piston system and the ways to apply and quantify the Force that is needed to apply to the crude oil. Based on the Figure 4.3, it shows that the force applied will affect the length of the crude oil. Thus, at the end of the experiment, in order to achieve the objective, the result must show how much the force affects the compressibility.

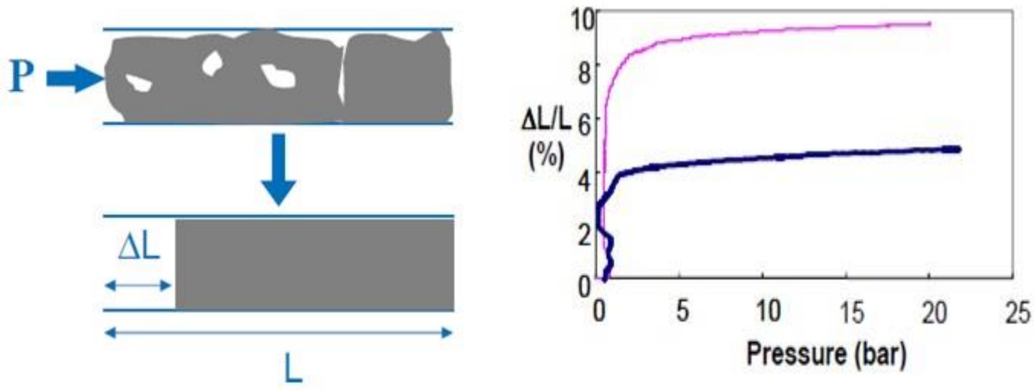

Figure 4.3: The relationship between pressure and length

The compressibility coefficient can be calculated using below equation:

$$c = \frac{-1}{V}\frac{\partial V}{\partial p} \qquad c = \frac{1}{\rho}\frac{\partial \rho}{\partial p} \qquad (4.1)$$

The components involved in Equation 4.1 are; c for the compressibility factor, V is the volume of the fluid, P is the pressure applied to the fluid, and p is the density of the fluid used.

Table 4.5: The Compressibility Test Data at 0.5 Bar

Item	Sample 1 (original)		Sample 2 (injecting air)	
	Original length (m)	**Compressible length(m)**	**Original length (m)**	**Compressible length (m)**
Test 1	0.85	0.85	0.84	0.82
Test 2	0.84	0.82	0.85	0.82
Test 3	0.79	0.78	0.81	0.79
Average	0.83	0.82	0.83	0.81

The constant variable that is used for the data in Table 4.5 are the volume of the fluid which is equal to 0.0012 m^3 , the pressure applied to the fluid is 0.5 bar that is equal to 50 kN/m and the density of the fluid is 847 kg/m^3. Thus, based on the formula in Equation 4.1 and the constant variable applied to the experiment, the compressibility factor for Sample 1 is 0.001 while the compressibility factor for Sample 2 is 0.003.

Table 4.6: The Compressibility Test Data at 1 Bar

Item	Sample 1 (original)		Sample 2 (injecting air)	
	Original length (m)	Compressible length(m)	Original length (m)	Compressible length (m)
Test 1	0.83	0.81	0.85	0.81
Test 2	0.78	0.75	0.78	0.72
Test 3	0.77	0.75	0.72	0.68
Average	0.79	0.77	0.78	0.72

The constant variable that is used for the data in Table 4.6 are the volume of the fluid which is equal to 0.0012 m^3 , the pressure applied to the fluid is 1 bar that is equal to 100 kN/m and the density of the fluid is 847 kg/m^3. Thus, based on the formula in Equation 4.1 and the constant variable applied to this experiment, the compressibility factor achieved for Sample 1 and Sample 2 are 0.002 and 0.006 respectively.

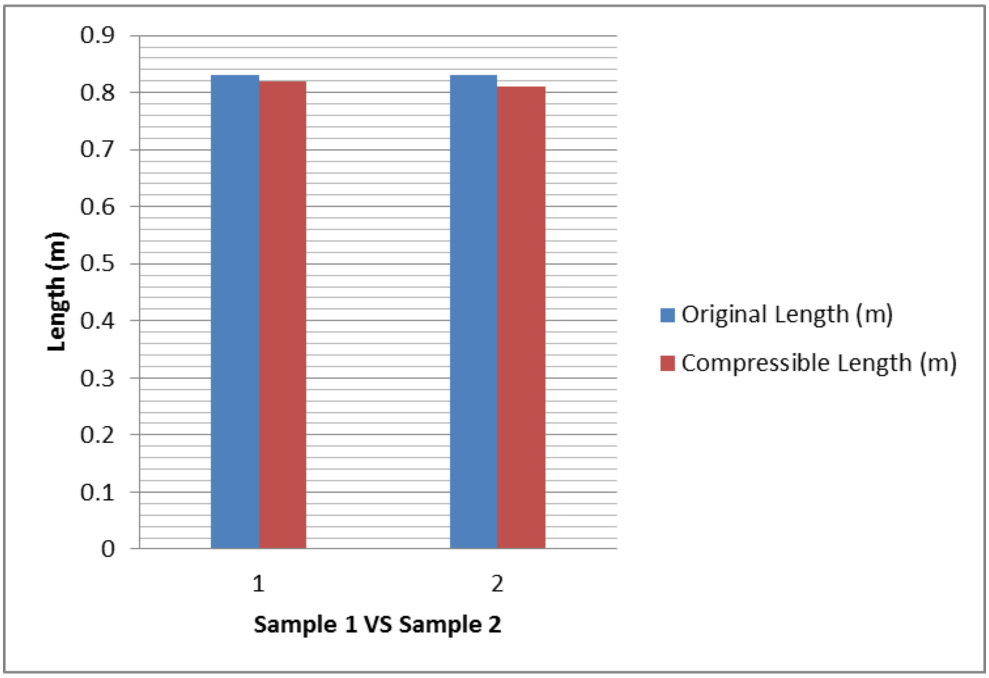

Figure 4.4: The Bar Chart at Pressure 0.5 Bar

Figure 4.4 shows the comparison of the Sample 1 with original comdition and Sample 2 when air is injected into the crude oil at pressure applied of 0.5 bar. From the figure above, there is only slightly changes in Sample 1 in the length about 0.01 m after it has been compressed. Meanwhile, in Sample 2, the changes of the length after it has been compressed is 0.02. The changes in Sample 2 is slightly larger compared to Sample 1. The pressure of 0.5 bar might not affect so much to the compressibility of gelled crude oil. However, as there is slight differences, the pressure and the condition of the sample still affect the comrpessibility. Based on calculation, the compressibility factor for sample 1 is 0.001 meanwhile for Sample 2 where the air is injected, the compressibility factor is 0.003.

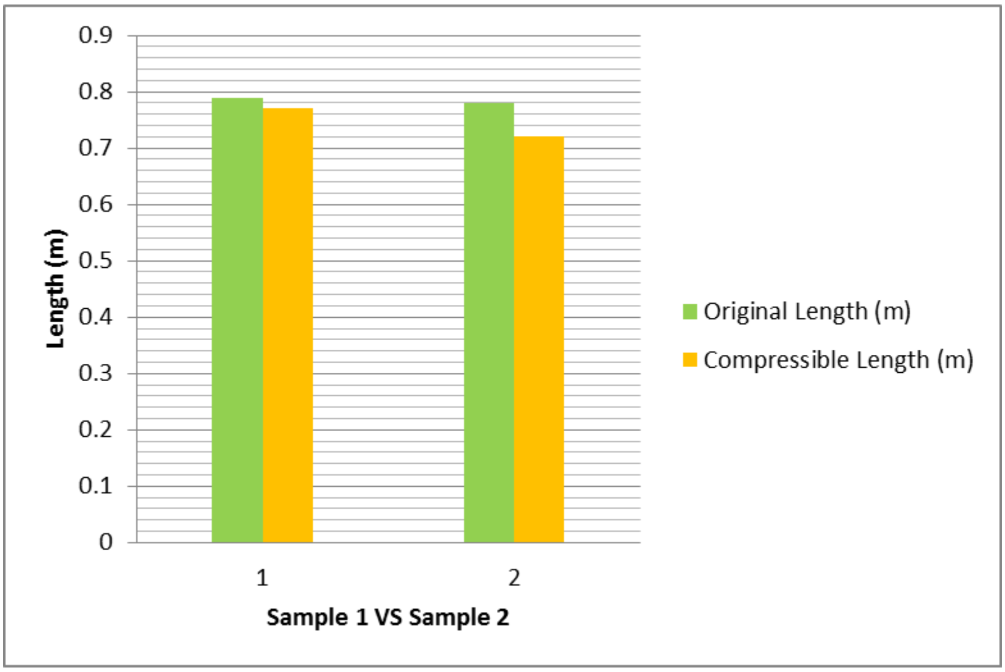

Figure 4.5: The Bar Chart at Pressure of 1 Bar

In Figure 4.5, the bar chart shows the the comparison of the Sample 1 with original comdition and Sample 2 when air is injected into the crude oil. However, for this part the pressure applied is at 1 bar. From the result, in Sample 1 the changes in length is about 0.02 m after compression. Meanwhile, in Sample 2, the compressible length is 0.06 m after it has been compressed. In this figure, the chnages are quiet significant compared to the one that only 0.5 bar is applied. This prove that when the air is added and more pressure is applied, the gelled crude oil can be compressed more. Based on calculation, the compressibility factor for sample 1 is 0.002 meanwhile for Sample 2 where the air is injected, the compressibility factor is 0.006. The compressibility factor increses two times when the pressure is doubled.

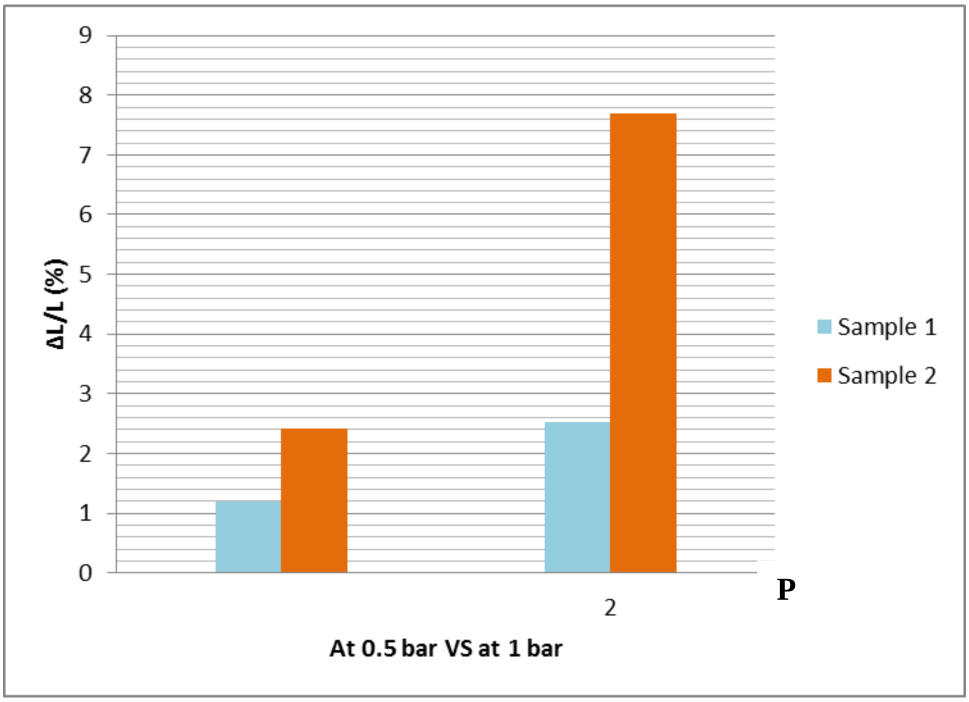

Figure 4.6: The percentage of the compressibility length at different pressure

Next, the Figure 4.6 shows the comparison between the percentages of the changes in length with difference pressure applied. From the figure above, it shows that at 0.5 bar, the percentage changes in Sample 1 is 1.2% meanwhile in Sample 2 is about 2.41%. However, at pressure of 1 bar, the percentage of length changes in Sample 1 is 2.53% whereas in Sample 2 it increases to 7.69%. At this point, the result shows that the gelled crude oil can be compressed with certain condition. However, the result might be inaccurate as there is lack during the experiment. For example, the bigger test section should be used for larger gas voids formation. The type of material that is used for the test section which is acrylic was not good to overcome the high pressure. Thus, the pressure applied is restricted to the condition of pipe to avoid the test section from break. The equipment used to compress might not be so consistent, to use automatic pneumatic system should be better but hard to design and construct.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The objective of this project to study the effect of gas voids gelled waxy crude and its effect on compressibility has been achieved. The transportation of highly waxy crude oil that turned into gelled like proves to cause many problems. From the experiment and previous research shown that the waxy crude oil that contains high value of carbon chain hydrocarbons can easily gelled up upon cooling when the temperature decreases. The restart pressure applied to move the gelled crude oil depends on the estimation of the lowest pressure needed to be applied at the pipe inlet to restart the flow. In order to that, the study of gas voids formation and the effect of compressibility can improve the calculation of the restart pressure.

This project used a flow loop to study the effects of voids towards the crude oil in the pipe with injected air condition. The studies and application on different temperature give better understanding on the behavior of waxy and gelled crude oil. The flow loop has been designed to apply the same conditions as at sea bed and the test section can be taken out to test the compressibility of the crude oil with the effect of voids formation.

As a conclusion, from the result obtained, the crude oil from Sepat 7 platform relatively has high pour point temperature which explains it's gelled up behavior in the room temperature. The objective of this project is to study the compressibility of waxy crude oil with the effect voids formation. The gas void of waxy crude oil that is formed changes when air is injected into the test section. The gas voids seems larger and more when air is injected in Sample 2 compared to the one form in Sample 1.

The result of compressibility factor based on the data which is at 0.5 bar, the compressibility factor for Sample 1 is 0.001 whereas in Sample 2 is 0.003. For the pressure at 1 bar, the compressibility factor in Sample 1 is 0.002 while in Sample 2 is 0.006. It is tested by applying different pressure to show how much a pressure can compress the gelled crude oil. The compressibility factor increases when the air is applied and the pressure is higher.

With this, the compressibility factor can then be introduced into the equation to calculate the restart pressure. This factor was the result of differences in gas voids and the thermal shrinkage formed by the gelled up crude oil. However, the constraint to conduct the compressibility factor and the design must be overcome and improved for better and significant result in future. The time limitation also has been a factor for the project to be completed.

5.2 Recommendations

For further study in future, there should be some improvement to be done. Firstly, the material used for the test section should be changes to glass compared to acrylic pipe as it cannot withstand high pressure. The low resistant to pressure of acrylic pipe might affect the compressibility result and the data for higher pressure cannot be taken.

A scanner should be used to identify better and calculate the area of the voids formation. With the information, better data can be recorded. Furthermore, better equipment to test the compressibility should be used as the one in this project using the bicycle pump is not automatic. Thus, the force applied might be not constant. Using an automatic pneumatic system is better. However, it is hard to construct and applied the system.

The crude oil from different fields should be considered to use as the comparison between the results will provide more information about the characteristics of waxy gelled crude oil. Other condition such as pressure and pipe coating should be consider in observing the formation of gas void since it will give better environment to emulate the condition of seabed.

Some other new methods to measure the pressure, volume and composition of the gas void should be used as it might provide better results. For better understanding and prove, introducing a compressibility factor into the equation which is used to calculate the restart pressure will be a great deal. This factor will take into account the gas voids and the thermal shrinkage formed by the gelled up crude oil.

REFERENCES

Ajienka, J. et al. (1991) The Effect of Temperature on the Rheology of Waxy Crude Oils. *SPE Journal*, (SPE 23605).

Al-Yaari, M. 2011. *Paraffin wax deposition: mitigation and removal technologies*.

Apkabio, M. 2013. *Cold Flow in Long-Distance Subsea Pipelines*. MASTERS DEGREE (M.Sc.) IN PETROLEUM ENGINEERING. Norwegian University of Science and Technology.

Bai, Y. and Bai, Q. (2005) *Subsea Pipelines and Risers*. Elsevier, p.387.

Benkreira, H. et al. (2011) "Rheology and Start-up Pipeline Resources of Waxy Crude OIl", paper presented at *8th Energy Conversion Congress and Exposition (ECCE)*, Berlin, Germany, 25-29 September 2011. University of Bradford,United Kingdom.

Borghi, G. et al. (2003) "Prediction and Scaleup of Waxy Oil Restart Behaviour", paper presented at *SPE International Symposium on Oilfiled Chemistry*, Houston, Texas, 5-8 February. Society of Petroleum Engineers.

Civan, F. and L. Rasmussen, M. 2003. "Analysis and Interpretation of Gas Diffusion in Quiescent Reservoir, Drilling, and Completion Fluids: Equilibrium vs. Non-equilibrium Models", paper presented at *SPE Annual Technical Conference and Exhibition*, Denver, Colorado, 5-8 October. Society of Petroleum Engineers.

De Souza Mendes, P. et al. (2012) Startup Flow of Gelled Crudes in Pipeline. *Journal of Non-Newtonian Fluid*, p.179-180.

Ekweribe, C. et al. (2008) "Pressure Effect on Waxy Crude Pipeline-Restart Conditions Investigated by a Model System", paper presented at *SPE Annual Technical Conference and Exhibiton*, Denver, Colorado, 21-24 November. Society of Petroleum Engineers, (SPE 115672).

En.wikipedia.org (2008) *Petroleum - Wikipedia, the free encyclopedia*. [online] Available at: http://en.wikipedia.org/wiki/Petroleum [Accessed: 15 February 2013].

Golczynski, T. and Kempton, E. 2006. Understanding Wax Problems Leads to Deepwater Flow Assurance Solutions.*World Oil Magazine*, Iss.Vol 7,No 3.

Goodland, R. 2005. "Oil and Gas Pipelines Social and Environmental Impact Assessment: State of the Art", paper presented at *International Association of Impact Assessment*, Boston, USA, May 2005.

Gudmundsson, J. 2012. *Flow Assurance Solids in Oil and Gas Production*. [report] Department of Petroleum Engineering and Applied Geophysics, Norwegian University of Science and Technology, 7491 Trondheim, Draft Manuscript, September 2012.

Henaut, I. et al. (1999) "Waxy Crude Oil Restart:Mechanical Properties of Gelled Oil", paper presented at *SPE Annual Technical Conference and Exhibiton*, Houston, Texas, 3-6 October. Society of Petroleum Engineers.

Hoffmann, R. 2012. "Longer and Colder: Wax Control for Long Step-Out Distances", paper presented at *IEEE 2012 Services Workshop on Security and Privacy Engineering*, Honolulu, Hawaii, USA, 24-29 June 2012. Hawaii, USA: Statoil Presentation,SPE, pp. 4-10.

Ijogbemeye Oseghale, C., Akpabio, E. and Edebor, O. 2012. Mitigating Potential Risk of Paraffin Wax Deposition on Oil Pipelines in Niger Delta. *Journal of Engineering and Applied Sciences*, 7 (4), pp. 348-352.

Karan, K. et al. (2000) "Measurement of Waxy Crude Properties Using Novel Laboratory Techniques", paper presented at *2000 SPE Annual Technical Conference and Exhibition*, Dallas, Texas, 1-4 October 2000. Society of Petroleum Engineers, (SPE 62945).

Kullbotten, H. and Lervik, J. 2007. *Direct Electrical Heating System for Preventing Wax and Hydrates in Pipelines*. No-7465 Trondheim, Norway: SINTEF PROJECT MEMO,SINTEF Energy Research, pp. 3-8.

Lederson, J., Long, J., Sum, A., Christiansen, R. and Sloan, E. 1996. Effective Kinetic Inhibitors for Natural Gas Hydrates. *Chemical Engineering Science*, 51 (8), pp. 1221-1229.

Lee, H. (2008) *Computational and Rheological Study of Wax Deposition and Gellation in Subsea Pipelines*. Ph.D. Univesity of Michigan.

Lenes, A., Lervik, J., Kullbotten, H., Nysveen, A. and Bornes, A. 2005. "Hydrate Prevention on Long Pipelines by Direct Electrical Heating", paper presented at *Proceedings of the Eleventh International Offshore and Polar Engineering Conference*, Seoul, Korea, 19-24 June 2005. ISBN 1-880653-64-8.

Nguyen, Q. et al. (2000) Influence of Thermal History on the Waxy Structure of Statically Cooled Waxy Crude Oil. *SPE Journal*, Volume 5, No 2 p.148-156.

Paez, J., Blok, R., Vaziri, H. and Islam, M. 2001. "Problems in Gas Hydrates: Practical Guidelines for Field Remediation", paper presented at *Latin American and Caribbean Petroleum Engineering Conference*, Buenos Aires, Argentina., 25-28 March 2001. SPE, SPE Paper 69424.

Scott-Hagen, C. 2010. "Hydrate Inhibitors: Alternatives to Straight Methanol Injection", paper presented at *Northern Area Western Conference (NACE) International*, 1440 South Creek Drive, Houston, Texas 77084-4906, 15-18 February 2012. Publications Division.

Siljuberg, M. 2012. *Modeling of Paraffin Wax in Oil Pipelines*. Master’s Thesis. Norwegian University of Science and Technology.

Singh, A., Lee, H. and Sarica, P. 2011. "Flow Assurance: Validation of Wax Deposition Models Using Field Data from a Subsea Pipeline", paper presented at *Offshore Technology Conference*, Houston, Texas, USA, 2–5 May 2011. Houston, Texas, USA: p. OTC 21641, pp 1.

Singh, P., Venkatesan, R., Fogler, H. and Nagarajan, N. 2000. Formation and Aging of Incipient Thin Film Wax Oil Gels. *AIChE Journal*, 46 (5), pp. 1059-1074.

Tigger.uic.edu. 1993. *Parffin / Wax and Waxy Crude Oil*. [online] Available at: http://tigger.uic.edu/~mansoori/Wax.and.Waxy.Crude_html [Accessed: 3 Jul 2013].

Time, R. W. 2011. *Flow Assurance and Multiphase Flow (Part II)*. University of Stavanger, Department of Petroleum Engineering. Seminar Presented at Aker Solutions,Stavanger.

Wolden, M. 2008. *Cold Flow for Very Long Multiphase Transportation Pipelines*. Norway: SINTEF Petroleum Research. http://www.sintef.no/upload/Petroleumsforskning/dokumenter/SINTEFTechDay2008_Cold Flow_EH.pdf [Accessed: 12 August 2013].