EFFECT OF TEMPERATURE ON COMPRESSIBILITY OF GELLED CRUDE OIL TO RESTART THE FLOW OF WAXY CRUDE OIL AT LOW RISK

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Submitted to International Program
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ABSTRACT

Wax depositions issues which are impairing the flow of waxy crude oil production become major concern of the flow assurance to minimize the risk of its flow restart. Miss prediction of flow restart pressure of waxy crude oil may lead to high operating cost and high investment cost of the pump and piping system. The determination of restart pressure is too risky and it should be considered without wasting much energy and time. Compressibility of the waxy crude oil has significant influence in determining the restart pressure of the flow start-up or restart. Better understanding on compressibility of waxy crude oil in gel state is expected to be valuable information for determining the optimum restart pressure. This study is aimed at investigating the compressibility of gelled crude oil below its pour point and analyzing the effect of temperature and gas voids on its compressibility using experimental study on compression test so that the flow restart at low risk can be analyzed. Flow-loop rig had been used to perform cooling process and also restarting the test section, and then the test section will be compressed in compression device outside the rig. The result showed that compressibility of gelled crude oil showed different values according to its thermal history such as temperature and cooling process. In an instance, effect of thermal or temperature has significant influence on compressibility which can be used to predict the flow restart pressure of waxy crude oil more accurate. Therefore, it is very helpful for flow assurance engineer to restart the flow of waxy crude oil at low risk by considering this effect of temperature.

Keyword: Waxy crude oil, temperature, compressibility, compression test.

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CHAPTER I

INTRODUCTION

1.1. Background

Malaysia is one of the largest oil producers in South East Asia with more than 50% of the production is crude oil. Malaysia's production of crude oil and natural gas in the first quarter of 2016 has increased 2% compared to last year in same quarter. Although, the revenue for first quarter of this year has decreased 26% compared to the first quarter of 2015. The decreasing revenue is partially due to lower product sales and production costs (Petronas, 2016). This condition is a challenge for the oil production lines, such as upstream and downstream segment, to upgrade their performance.

Good performance of oil production lines can be achieved if the segment profit after tax is better compared to previous record. According to financial report of Petronas (2016), the operating segments, especially upstream segment was facing great decrease of profit in first quarter of 2016 than first quarter of previous year. This is mainly due to the declining of natural sources in upstream and high operating costs. In other hand, operational cost also a crucial challenge in order to get higher profit. Lower operational cost will result in higher segment profit.

Malaysia's upstream segment mostly is offshore oil field which extreme environment and high operational cost. One of the operational costs of offshore oil production is to provide high assurance for reservation and transportation of the oil. Mainly, oil transportation infrastructure in Malaysia's upstream is pipeline network.

The pipeline network of Malaysia is more than 3,300km in length which plays a vital role for oil transportation. In order to keep the productivity high, especially for deep-water pipeline which is affected by environment such as temperature of sea water, high assurance is necessary to ensure the flow of crude oil from shutdown. Considering the condition of Malaysia's oil production, the flow assurance plays an important role to minimize the risk and operational cost in such challenges.

Flow assurance of offshore oil production, especially in high paraffinic oil field, faces a huge challenge related with waxy crude oil transportation. Waxy crude oil will enter gelation phase below certain temperature called wax appearance temperature (WAT), the crude oil begins to crystallize and this results in impairing of the oil flow and even pipeline blockage due to wax deposition (Kelechukwu, 2011). This condition may yield in flow breakdown that be significant problem to restart the flow (Farayola, et al., 2010). Not only that, but the productivity will also be affected by the time loss when shutdown and it will influence the production cost.

The wax deposition issues in Malaysia's oil production are often occurred and it becomes big challenge for its flow assurance. The characteristic of crude oil in Malaysia is mostly high WAT and pour point that due to its carbon number distribution which has high probability for the crude oil to become gel even the temperature is above room temperature (Sharma, et al., 2016). One of feasible solution to restart the flow when shutdown is by pumping hot liquid, such as hot oil or water, so that the wax deposition can be removed and the production can be continued (Khandekar, 2015). This method of flow restarting has risk that can affect the operational cost. The risk is in the determination of pressure applied to restart the flow should be considered without wasting much energy and time.

In some cases the pressure needed to restart the flow is different from the predicted pressure (Wachs, et al., 2009). Longer restart time may be occurred when the pressure applied cannot overcome the gel's yield stress due to the properties of the wax is different from the prediction. In other case, the pressure predicted is exceeding the optimum pressure to overcome the gel and this result in too much energy wasted. So that miss prediction of restart pressure may result in high investment cost of pump and piping system.

In Malaysia's waxy crude oil cases, the behavior of the waxy crude oil is not only shear dependent, but also temperature dependent. These behaviors of crude oil will result in changing of the viscosity and yield stress of the waxy crude oil which have significant influence to restart pressure (Kaur, Jaafar, & Sariman, 2013). Regarding the extreme environment and characteristic of Malaysia's crude oil, the temperature of crude oil should be considered especially for restarting crude oil flow when the crude oil is in gel state where there are wax deposition issues.

Crude oil when in gel state is considered as incompressible fluid due to high yield stress (de Souza Mendes, et al., 2012). Meanwhile, formation of gas voids within the crude oil is appeared when it is entering gelation state due to thermal shrinkage which makes the gelled crude oil is compressible (Chala, et al., 2014). The compressibility of the crude oil is affecting the flow restart pressure, with higher compressibility of the fluid will result in faster to restart the flow of waxy crude oil (de Olivera, & Negrão, 2015). However, recent study on compressibility of waxy crude oil is mostly in liquid state and for gel state is slightly exposed.

1.2. Problem Statement

Compressibility of gelled crude oil has significant influence on determining the flow start-up or restart pressure which is crucial to oil productivity. Meanwhile, the understanding of compressibility of gelled crude oil is needed to be discovered further that due to mostly available literature concerned the compressibility of waxy crude oil in liquid condition. Considering the waxy crude oil has different properties influenced by temperature, such as below pour point, the compressibility of gelled crude oil may also be different. However, the effect of temperatures on compressibility of gelled crude oil was not well understood.

Therefore, experiment is required to study the effect of temperature on compressibility of gelled crude oil in order to restart the flow of waxy crude oil at low risk condition. The understanding of compressibility of gelled crude oil is not only significant to be considered in restarting the waxy crude oil flow at low risk for flow assurance of its production, but also can be a great contribution toward the development of flow start-up or restart model of waxy crude oil which requires the behavior knowledge of gelled crude oil influenced by temperature.

1.3. Research Objective

Based on problem statement, the objectives of present study are arranged as follow:

a. To investigate the compressibility of gelled crude oil in different temperatures below its pour point.
b. To identify the effect of temperature below pour point on the compressibility of gelled crude oil.
c. To investigate the effect of gas voids on compressibility of gelled crude oil.

d. To describe the possibility of flow restart of waxy crude oil at low risk based on the compressibility influenced by temperature.

1.4. Scope of the Research

Regarding the objectives, study on compressibility of gelled crude oil is conducted by experimental study which has scope as follow:

a. The crude oil used is Malaysia’s waxy crude oil.
b. The waxy crude oil is statically and dynamically cooled in flow-loop rig system below pour point in order to perform gelation state and restart the sample in the test section.
c. The compressibility study is done by experimenting on isothermal state which a test section consists of 10 samples in compression tools.
d. The samples used are in same temperature and assumed with same gas voids formation within the gel.

1.5. Research Benefit

Compressibility study of waxy crude oil is significant to be understood. The output of this compressibility study has great impact on studying of flow start-up or restart challenges of waxy crude oil, especially on the compressibility of gelation state oil. This experimental study and analysis on compressibility of gelled oil contributes as understanding and reference that can be used in developing flow start-up or restart model of waxy crude oil.

1.6. Systematic Writing

In this thesis, systematic writing applied is as follows:

CHAPTER I PRELIMINARY

This chapter contains the background study of the problem, formulation of the problem, problem definition, research objectives and benefits of the research.

CHAPTER II LITERATURE REVIEW

This chapter contains the analysis on the result of studies that have been done previously that has connection with the research undertaken. It also contains basic concepts and principles needed to solve the research problems, the basic theoretical basis to support the study to be conducted

CHAPTER III RESEARCH METHODS

This chapter contains the object of the study, required data regarding the study, experiment setup and tools, the research flow chart and Gantt chart.

CHAPTER IV DATA COLLECTION AND PROCESSING

This chapter describes the data collected during the experiments and processing of such data by a predetermined method of analysis results.

CHAPTER V DISCUSSION

This chapter discusses the results of research in the form of graphs concerning quantitative and statistical results of the experiment to answer the research objectives.

CHAPTER VI CONCLUSSION AND SUGESTION

This chapter contains a brief and precise statements derived from the results of the research and discussion to answer the problem. Advice were made based on author's experience and consideration, addressed to researchers in similar fields, who want to continue and develop the conducted research.

CHAPTER II

LITERATURE REVIEW

2.1. Inductive Study

Flow restart of waxy crude oil at low risk has been a challenge for flow assurance of its production regarding the wax deposition issues. Many studies of waxy crude oil flow restart have been conducted by researchers in order to minimize the risk to restart the flow. Considering the behavior of waxy crude oil, the studies of waxy crude oil flow restart was improving significantly for past two decades. The contradiction of some researches derived better studies to expose the possibility of flow restart at low risk.

Chang et al. (1999) simulated a flow start-up of waxy crude oil where the oil is in gelled condition and it is displaced with other fluid which is warmer such as hot water or hot oil. The simulation was using a model with assumption that the fluids are in isothermal and incompressible where the rheological properties are same across the pipe, but it is not valid when the compressibility and thermal shrinkage history of the waxy crude oil is significant. Based on the simulated model, the start-up of the flow was identified until the transient of yield stress which is time dependent has been overcome with pressure generated from $\Delta P=4\tau y$ L/D equation where τ_y is the yield stress of the crude oil. This model was continued by Davidson et al. (2004) with considering the fluid is compressible and it showed that the compressibility of the fluids influence the time to start the flow.

Vinay et al. (2006, 2007) examined the model of isothermal transient flows for fluids that weakly compressible viscoplastic/thixotropic. The study confirmed that compressibility influences the time for the flow to start or restart which high compressibility makes faster to restart the flow. So that the model generated high pressure drop at first stage in order to get high compressibility. In other model of flow start-up of waxy crude oil, Frigaard et al. (2007) developed a displacement model where weakly compressible waxy crude oil is displaced by lower viscosity fluid in a long pipeline. The model showed that compressibility has effect on the drainage time of waxy crude oil fluid from the pipeline linearly, which means high compressibility will result in shorter drainage time.

Wachs et al. (2009) combined the effect of compressibility and thixotropic behavior of waxy crude oil on flow start-up and restart model to examine the possibility of restart pressure which is lower than the predicted pressure through $\Delta P > 4\tau y\ L/D$ equation by assuming that the plastic viscosity of the waxy crude oil is constant. The model known as 1.5D numerical model which showed that there are some possible situations where pressure is lower than the minimum pressure from theoretical equation. Vinay et al. (2009) explained the model through analytical relation to predict the pressure and stated that the lower pressure situations is due to not only viscoplastic/thixotropic effect, but compressibility of waxy crude oil also effect on the restart pressure model.

Compressibility has significant impact on flow start-up or restart process of waxy crude oil. Some studies assumed that waxy crude oil when in gel state as incompressible fluid. de Souza Mendes et al (2012) focused on thixotropic behavior study which considering plastic viscosity of waxy crude oil without considering the compressibility effect and thermal shrinkage. The study argued that applying pressure on gelled crude oil below its critical pressure in a long period would not start the flow. It is due to the yield stress of gelled crude oil is time dependent. Meanwhile, Another analysis had been done by Ahmadpour et al. (2014) through developing a model of flow start-up of crude oil with consideration that variable of plastic viscosity is included in the analysis. The model generated that the variable of plastic viscosity showed effect on the successful of the model to simulate the start-up or restart flow of waxy crude oil, but the time to restart is longer than when the plastic viscosity variable is constant.

de Oliveira & Negrão (2015) developed model of flow start-up and restart of gelled crude oil with new approach where the time to restart the flow depends on the both time dependent behavior and fluid compressibility. The result described that compressibility of the fluid is affecting the time for restarting the flow which means the gelled crude oil is compressible. Regarding the time to restart the flow of waxy crude oil, another study had been done numerically also by Kumar et al. (2015) which summarized that thermal effect in the gel may accelerate the restart process. The thermal effect such as thermal shrinkage will result in appearance of gas voids space when the crude oil is began to crystallize.

Study of compressibility of waxy crude oil is mostly based on the liquid state and through numerical study, while the understanding of compressibility when the oil is in gel is slightly studied. An experimental study of waxy crude oil compressibility has been done by Gang et al. (2014) in compression chamber where there are hot oil and gelled oil compressed at once after the gelled oil is cooled at set point in same cooling rate. The study assumed that the experiment with gelled crude oil and hot crude oil can be considered as the compression of gelled crude oil only. Although, the properties of crude oil, such as viscosity; yield stress; and gas voids, are different depend on temperature and cooling rate which has a significant impact on the compressibility of waxy crude oil (Chala, et al,. 2015).

Therefore, further experimental studies of compressibility of gelled crude oil will contribute on estimation of optimum pressure regarding the flow start-up or restart of waxy crude oil at low risk by providing more information and understanding of crude oil compressibility when it is gelled even below its pour point. It is also a great impact on development of model start-up or restart for waxy crude oil issues by providing experimental data which is useful for analytical model.

2.2. Deductive Study

2.2.1. Behavior of Waxy Crude Oil

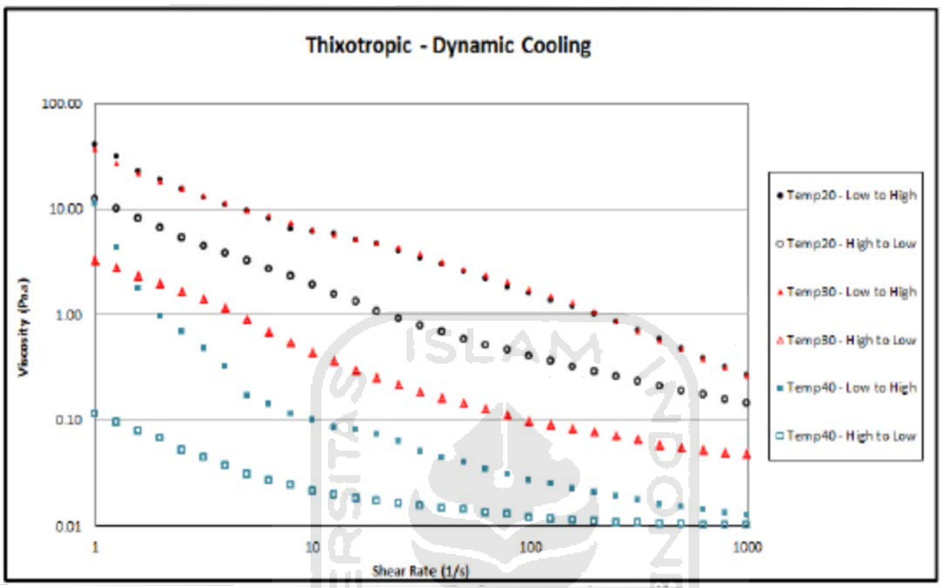
The definition of waxy crude oil is derived from the presence of paraffin deposition in crude oil where at some conditions the crude oil experiences changing of its properties and result in appearance of waxes (Chen, et al., 1997). Waxes in paraffinic crude oil is due to the mixing of heavy and high viscosity hydrocarbons with other hydrocarbon components during some processes cycle related with the changes of temperature (Chauduri, 2011). Based on the studies of property, waxy crude oil has different form influenced by temperature. The point of distinguishing is known as Wax Appearance Temperature (WAT); the crude oil becomes gel below WAT.

Waxy crude oil is behaving as Newtonian fluid above its WAT and as non-Newtonian fluid when it has lower temperature due to the viscosity temperature dependent. As concluded by Al-Zahrani & Al-Fariss (1998) in a developed viscosity model, waxy crude oil is experiencing viscosity change due to the temperature which can be used to describe yield stress of the waxy crude oil. Such behaviors can be explained by the changes of crude oil viscosity which it becomes high viscosity when the wax has appeared. High viscosity of the crude oil results in higher adhesion in the pipe wall and become wax deposition. Higher adhesion means that the shear rate of the fluid is small and it can be used to understanding the yield stress of the fluid (Munson, et al., 2013).

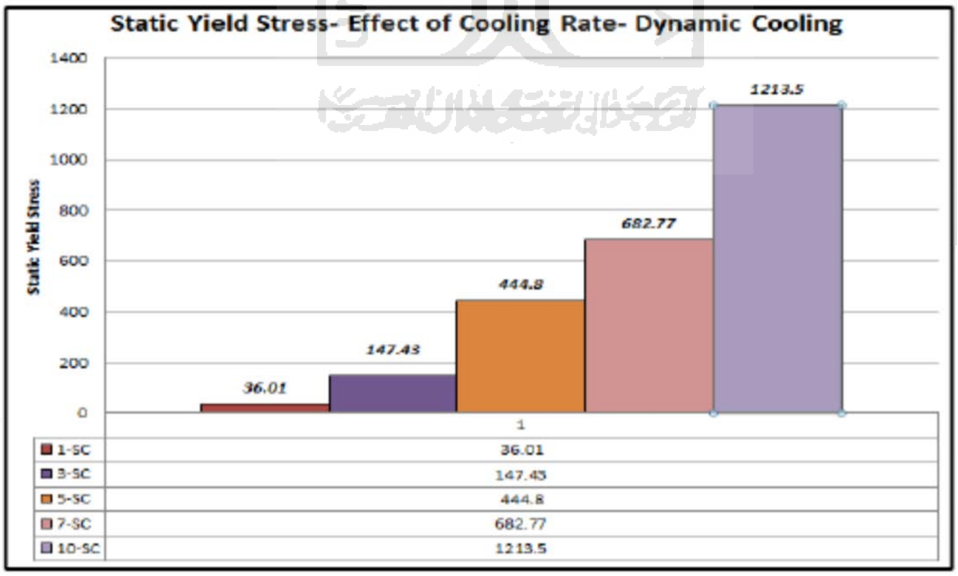
Vinay et al. (2005) developed a rheological model of waxy crude oil flows in transient non-isothermal viscoplastic Bingham flow which concluded that the viscosity and yield stress of the waxy crude oil is temperature dependent. Experimental study related with viscosity and yield stress measurement had been done by Kaur et al. (2013) which the result showed that the viscosity and yield stress of waxy crude oil is not only temperature dependent, but also shear dependent. This behavior of waxy crude oil is mentioned as thixotropic which has significant on determining flow start-up or restart pressure of waxy crude oil.

2.2.2. Characteristic of Malaysia's Waxy Crude oil

Wax content of waxy crude oil is differenced based on the characteristic of the oil. Waxy crude oil is high paraffinic oil that has high viscosity so that when entering its WAT, the wax deposition is appeared. According to Keluchukwu (2011), Malaysia's crude oil is highly possible having wax deposition problems. In his study about wax prediction of Malaysia's waxy crude oil, the result summarized that five samples of various waxy crude oil in Malaysia are high viscosity and high potential of waxing problem. Kaur et al. (2013) also measured the viscosity and yield stress of Malaysia's waxy crude oil experimentally which the result showed high viscosity and high yield stress when the crude oil at temperature below WAT. Fig. 2.1. showed the thixotropic behavior of Malaysia's waxy crude oil which influences the viscosity and yield stress.



(a)



(b)

Figure 2.1. Viscosity (a) and yield stress (b) of Malysia crude oil when cooled dynamically (Kaur, et al., 2013).

Based on the Figure 2.1, when the waxy crude oil is cooled dynamically, the viscosity is higher and the shear rate is lower as shown in Figure 2.1(a). Meanwhile, the yield stress of the waxy crude oil when it is cooled dynamically shown static result as shown in Figure 2.1(b).

Japper-Jaafar et al. (2015) measured some waxy crude oils within South East Asia as samples for yield measurement. The oils were measured using CPM, ASTM 5985-96, and ASTM D1250 for characterization and it showed that the characteristic of the tested oil had high WAT and pour point as shown in Table 2.1. Sharma, Samsodin, & Shahruddin (2016) characterized the Malaysian waxy crude oil through experiment in order to understand the properties so that can be contributed in formulating the solution for wax deposition issues. The study concluded that the wax content in crude oil was not directly influenced by temperature but due to the distribution of its carbon number. The result showed that Malaysian waxy crude oil mostly high WAT and high pour point as shown in Figure 2.2.

Table 2.1. Properties of South East Asia waxy crude oil (Japper-Jaafar, et al., 2015).

Properties	Crude A (Se)	Crude B (An)	Crude C (Pe)
WAT (°C)	41.2	41.1	68.2
Pour point	39	33	60
API gravity (at 15 °C)	33.76	36.86	25.15

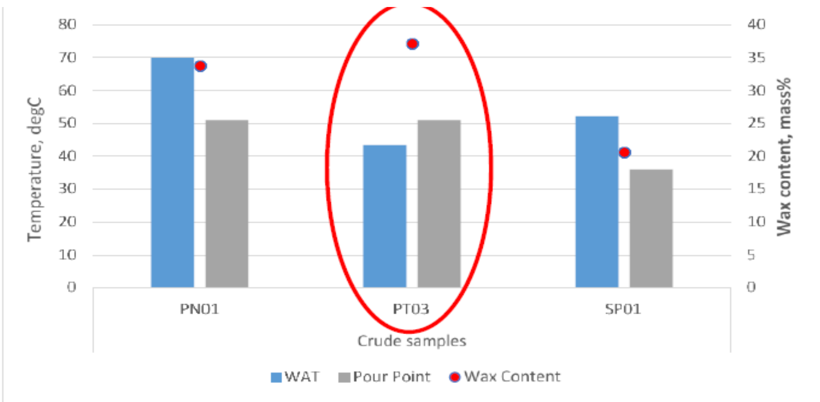


Figure 2.2. WAT and pour point of Malaysian waxy crude oil (Sharma, et al., 2016).

2.3. Gas Voids within Gelled Crude Oil

Waxy crude oil when it is entering gelation phase below WAT will experience shrinkage due to thermal loss which result in wax crystallization and appearance of gas voids that may create spaces within the gel and this makes the compressibility of gelled crude oil (Vinay, et al., 2006). A study related with gas voids formation within the gel has been done by Chala et al. (2014) which concluded that the gas voids has effect on yield strength and compressibility of gelled crude oil. In the study, the formation and the total volume of gas voids in gelled crude oil is observed by dynamic cooling with end temperature of cooled crude oil is 10^{o}C. The cooling rate is varied as 0.62^{o}C/min and 0.45^{o}C/min. The result of the study is described in Figure 2.3.

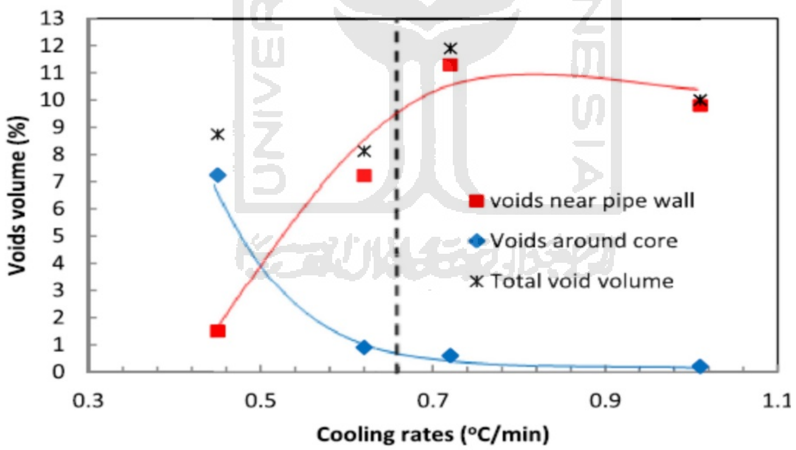


Figure 2.3. Total volume of gas voids in dynamic cooling (Chala, et al., 2014).

According to above figure, the gas voids presence within gelled crude oil showed that the total volume of gas voids is higher when the cooling rate is smaller. Even though the increasing of gas voids volume of gelled crude oil is less than 1%, but it may result in different compressibility value.

CHAPTER III

RESEARCH METHODOLOGY

3.1. Research Object

The object of this research is waxy crude oil that in gel state where the temperature is below pour point. The waxy crude oil that used in this research is Malaysia's waxy crude oil which typically high WAT and high pour point. The research is taken place at Flow Assurance of Oil Production under Laboratory of Mechanical Engineering, Universiti Teknologi Petronas, Malaysia. The detail of research object is shown at Figure 3.1.

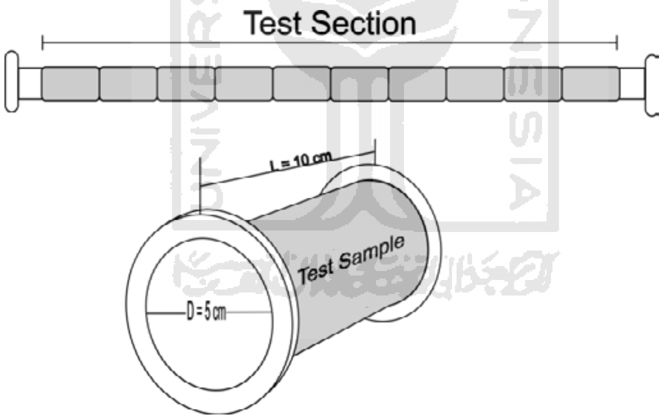


Figure 3.1. Sample of the research object.

Considering the waxy crude oil is shear dependent, in this research the material of the pipe that used is similar which the shear rate assumed to be the same. A test section pipe of Malaysia's waxy crude oil which detachable and consists of 10 cylindrical test samples made of stainless steel. The dimension of each test sample is 10cm in length and 5cm in diameter.

3.2. Data Requirement

According to problem statement and research objectives, the research is done by experiment. The kind of data that required in this research is defined as follows:

1. Primary Data

   The primary data of this research are the measurement data from the experiment and described as follow:

   a. Cooling rate profile of the cooling process in the experiment.

   b. Temperature of the test samples.

   c. Pressure drop of the sample for compression test.

   d. Displacement of piston in order to investigate the compressibility.

2. Secondary Data

   The secondary data of this research are derived from literature study related to problem solving of the research. The literature sources mostly are previous studies on waxy crude oil behavior, flow start-up and restart of waxy crude oil, and compressibility of waxy crude oil. The information related with waxy crude oil especially the information of total volume of gas voids that is influenced by the cooling rate, are used in this study to investigate its effect on the compressibility of gelled crude oil.

3.3. Experiment Setup

The experimental study of compressibility of gelled crude oil is the main objective of this research. In order to fulfill the research objectives, some setup of the experiment are prepared start from cooling process and restarting of waxy crude oil until the compression test. In this study, waxy crude oil is cooled not only to perform gelation phase, but also to set the thermal shrinkage history of the object so that gas voids effect can be investigated. The setup of cooling process is divided into two processes which are static cooling and dynamic cooling.

3.3.1. Static cooling setup.

The static cooling process is performed in order to investigate the compressibility of gelled crude oil in different temperature. Not only that, but static cooling is also applied in order to identified the effect of temperature on the compressibility while the crude oil is cooled in same cooling rate. The detail setup in this cooling process is shown in Table 3.1.

Table 3.1. Detail of experiment's temperature setup of static cooling.

Initial Temperature (^oC)	Initial Sea Bath Temperature (^oC)	End Temperature (^oC)	Cooling Time (min)
70	22	15	72
70	22	20	49
70	22	25	36
70	22	30	26

Table 3.1 is describing the gelled crude oils observed are at 15^{o}C, 20^{o}C, 25^{o}C, and 30^{o}C with statically cooled with same cooling load and cooling rate. The initial surrounding temperature is set in the same condition; in this system is the sea bath temperature, which makes the cooling process is in same cooling rate. The profiles of cooling rate in this static cooling are shown in Figure 3.2.

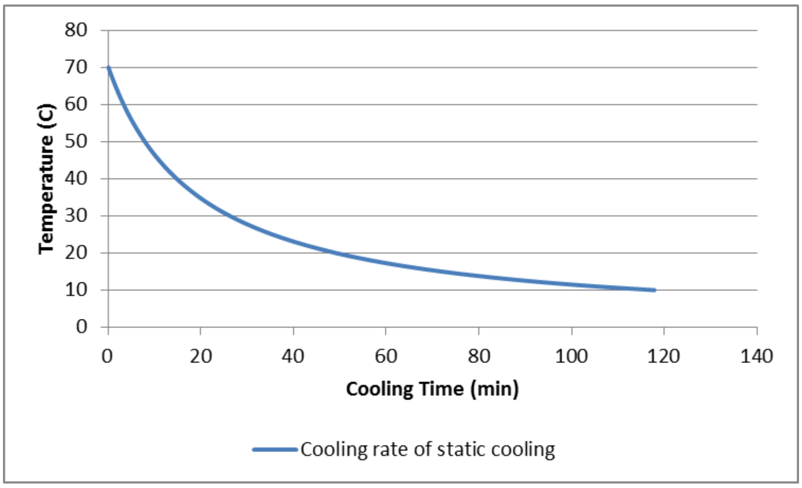


Figure 3.2. Cooling rate profiles of static cooling

The profiles of cooling rate, as shown in above graph, described the thermal shrinkage of the observed gelled crude oil. With same thermal shrinkage history, the gas voids volume within the observed gelled crude oil can be assumed the same. With similar gas voids volume, the compressibility of each observed temperature can be investigated and the effect of temperature on the compressibility of gelled crude oil also can be identified.

3.3.2. Dynamic cooling setup.

Dynamic cooling is used to perform the thermal shrinkage of cooled waxy crude oil in order to get different gas voids volume within the crude oil. In this cooling process, the observed gelled crude oil is set in same end temperature at 20°C with different cooling rate as described in table 3.2.

Table 3.2. Detail of experiment's temperature setup of dynamic cooling.

Initial Temperature (°C)	Initial Sea Bath Temperature (°C)	End Temperature (°C)	Temperature Range (°C)	Cooling Time (min)	Cooling Rate (°C/min)
70	25	20	50	61	0.8
70	22	20	50	49	1.0

In above table, the setup of cooling process is in same end temperature but different in initial sea bath temperature which result in different cooling time. The observed gelled crude oil is in 20°C temperature with different cooling rate. The profiles of cooling rate are shown in Figure 3.3.

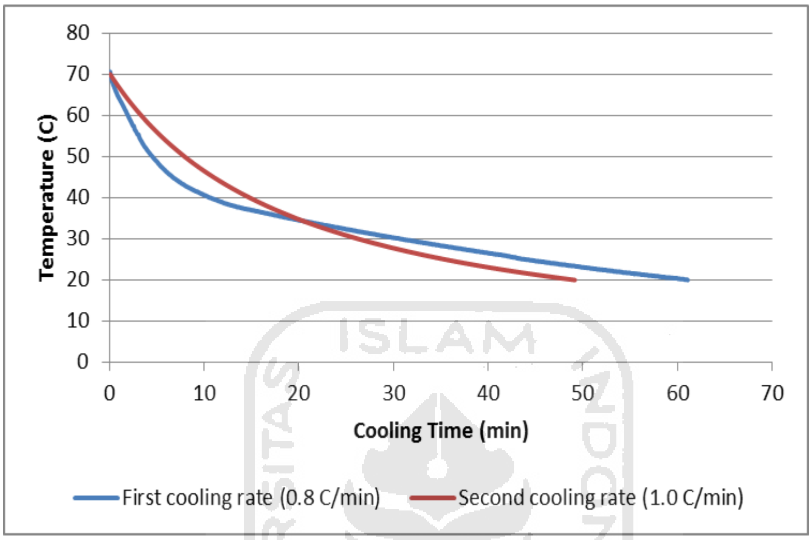


Figure 3.3. Cooling rate profiles of dynamic cooling.

Above figure showed the thermal shrinkage history of the observed gelled crude oils. Due to the differences of thermal history between the observed gelled crude oils, the gas voids formation and total volume in each gelled crude oil is also different. In dynamic cooling, the lower the cooling rate, the higher the total volume of the gas voids within the gel (Chala, et al., 2014). This cooling process setup is suit for investigating the effect of gas voids on the compressibility of the gelled crude oil.

3.3.3. Compression test setup

For the compression test setup will be conducted in isothermal which means the temperature of the test sample can be considered the same. In this experiment, a set of temperature range for test sample that can be considered the same if the test sample temperature is in range of end temperature -0.5°C < end temperature < end temperature + 0.5^{o}C. In compression test, the sample is compressed rapidly by one-push compressing set-up in high pressure. The pressure set-up for compressing is conducted in 1 – 5 bar or 100 – 500 kPa recorded from pressure gauge of air compressor. Considering the compression area is on circle area of the test sample, changing of crude oil volume due to compression can be represented by the displacement of the piston.

3.4. Experiment Technique

Experiment technique of this research is set as follows:

1. The test section pipe is statically cooled and restarted in flow-loop rig to perform gelation phase and set the temperature of sample compressed. First, the rig will be heated up and started to flow until the temperature of the outlet temperature showed the starting temperature as described in experiment setup. Then the rig will be set for cooling process until the outlet temperature showed the end temperature as described in experiment set-up.
2. After cooling, the test section pipe will be detached from flow-loop rig and then proceed to compression test.
3. In compression test, the test section pipe will be disassembled and then the test sample will be compressed one by one in compression device.
4. Before the compression test, the temperature of test sample is taken according to the setup.
5. In compression test, the sample will be compressed rapidly by one-push compressing setup in high pressure.

6. After the compression test is finished, the test samples are assembled and then it will be restarted in flow-rig to perform another set of experiment's object.

7. Statistical Analysis will be done to all measurement data in statistical analysis software. In this research, IBM SPSS are used for the statistical analysis in order to get the curve function fitting and estimation used for compressibility calculation.

3.5. Equipment and Tools

Some equipment and tools used in this experiment are mainly provided by Mechanical Engineering Laboratory of Universiti Teknologi Petronas which is described as follows:

1. Flow-Loop Rig

   Firstly, to perform cooling process and restarting the research object, Flow-loop Rig is used. The schematic of the Flow-loop rig is shown in Figure 3.4.

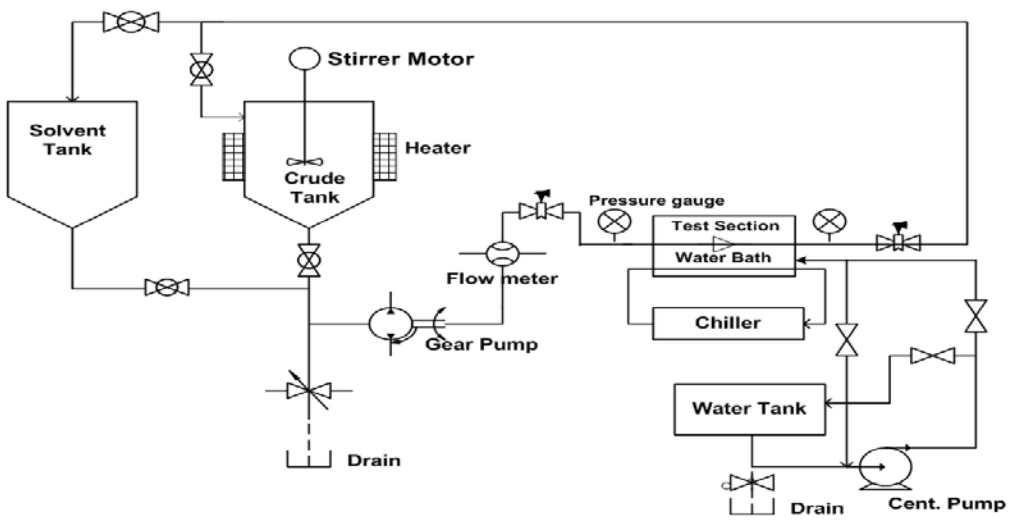


Figure 3.4. Cooling and restarting schematic of crude oil (Chala, et al., 2015).

The test section will be attached to the rig inside the water bath where the cooling process is taken placed as shown in above Figure. There are some transducers on the inlet and outlet of the test section pipe. These transducers are temperature and pressure and also water bath temperature. The Flow-loop rig is connected with computer where all transducers inside the loop can be observed and recorded into the computer. In this experiment, outlet temperature will be used as representative of the temperature set.

2. Compression Device

The schematic of compression device is shown in figure 3.3. In this device, there is a distance transducer for measuring the displacement of the piston. The displacement is measured by distance transducer connected to the computer with acquiring data every 0.001 second and accuracy 0.001 mm.

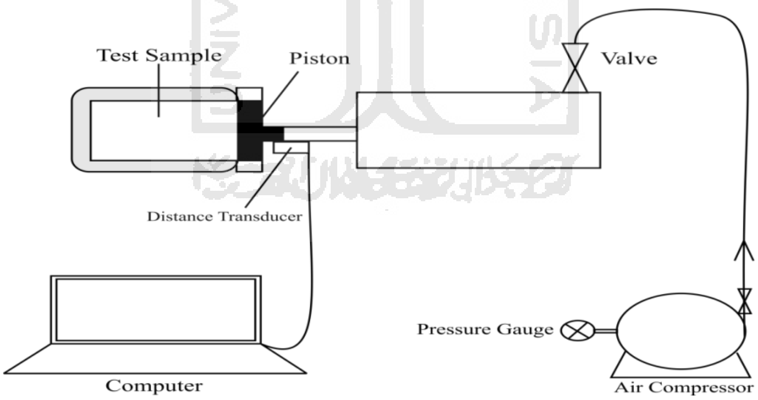


Figure 3.5. Schematic of compression test.

Above Figure described the compression test where the test sample is placed in-touch with the surface of the piston. The pressure is measured from the pressure gauge of the air compressor when the compression test is started. The valve is used to perform rapid one-push compression in same interval for all compression tests.

3. Assemble-Disassemble Tools and Thermocouple

Thermocouple is used in this experiment for measure the temperature of the test samples. The thermocouple used has accuracy $\pm 0.01^{o}C$. For attach-detach and assembling-dissembling of the test section pipe, assemble-disassemble tools are used.

3.6. Research Chart

The research has been done and followed by several schedules and methods as described in Gantt chart and flow chart below. The figure 3.6 is the Gant chart, and for flow chart is described in figure 3.7.

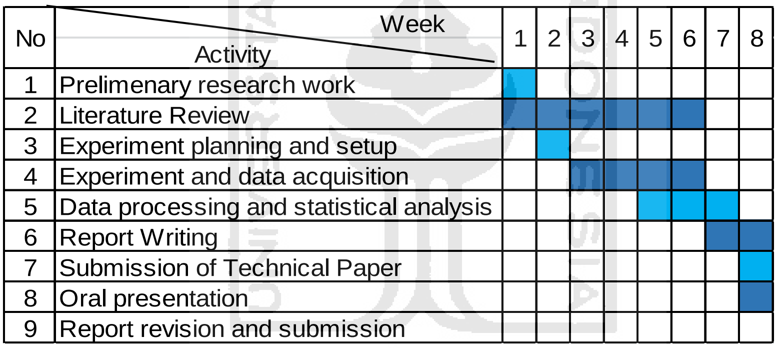
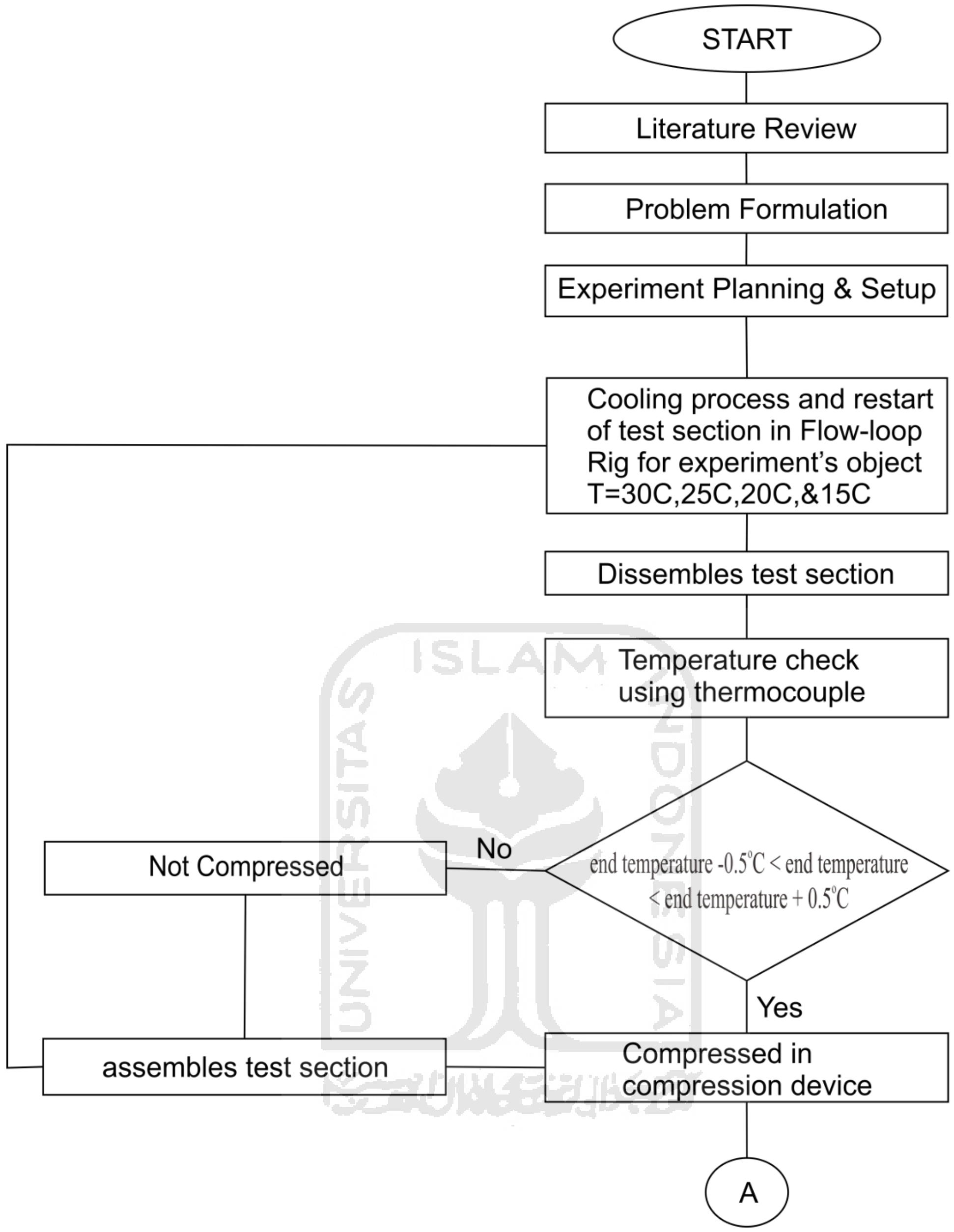


Figure 3.6. Gantt chart of the research.

The Gantt chart described the schedule that has been preceded during the research. According to the chart, the research had been performed in eight weeks with some activities that supported the research until it can be finished in such schedule. Meanwhile, the method of this research is schemed in a flow chart. The flow chart described the flow of the research from the start until the finish point of the research.


START
Literature Review
Problem Formulation
Experiment Planning & Setup
Cooling process and restart of test section in Flow-loop Rig for experiment's object T=30C,25C,20C,&15C
Dissembles test section
Temperature check using thermocouple
end temperature -0.5°C < end temperature < end temperature + 0.5°C
No
Not Compressed
Yes
Compressed in compression device
assembles test section
A

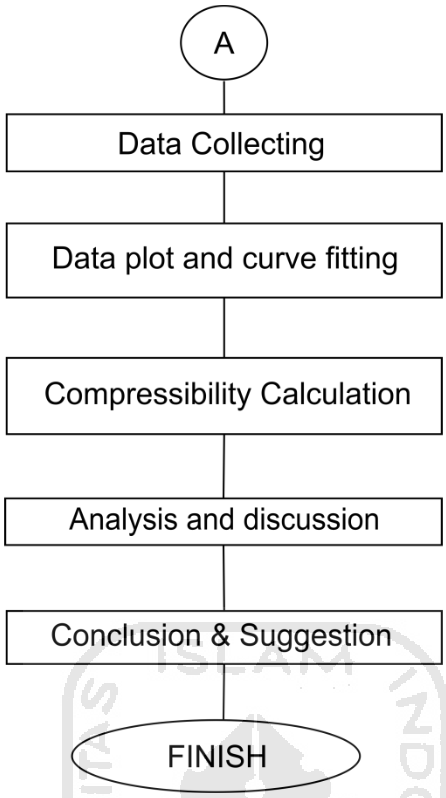


Figure 3.7. Flow Chart of the research.

CHAPTER IV

DATA COLLECTION AND PROCESSING

4.1. Data Collection

The data collected in this research has been through experimental study. The experiment conducted in laboratory was aiming to measure the compressibility of gelled crude oil with high precision and accuracy equipment and tools. The measurement data includes: the thermal history of cooling process for object's temperature that set to 15^{o}C, 20^{o}C, 25^{o}C, and 30^{o}C; piston displacement in each compression test with accuracy 0.001 in every 0.001 second; and pressure gauge of air compressor.

4.2. Compression Data Plot and Processing of Statically Cooled Crude Oil

The compression test has been applied to every object's temperature set. The sample's temperature was measured before the compression test, and the sample that accord with the setup will be processed. Compressibility definition based on the finite change of the state is the changing volume of the object due to the applied pressure and it is described as Eq. 4.1. (Davidson, et al., 2004). The compressibility calculation is based on Eq. 4.2. where the displacement data is representing the changing of volume and the compressibility is in kPa^{-1}; ΔL is changing of length and L is the initial length of the compressed samples in m; and ΔP is pressure applied in kPa. Figure 4.2. is the illustration of compressibility equation which is used in this research.

$$compressibility = -\frac{\Delta V}{V\,\Delta P} \qquad (4.1).$$

$$Compressibility = -\frac{2\pi r^2 (L_1 - L_0)}{2\pi r^2\, L\,\Delta P} = -\frac{\Delta L}{L\,\Delta P} \qquad (4.2).$$

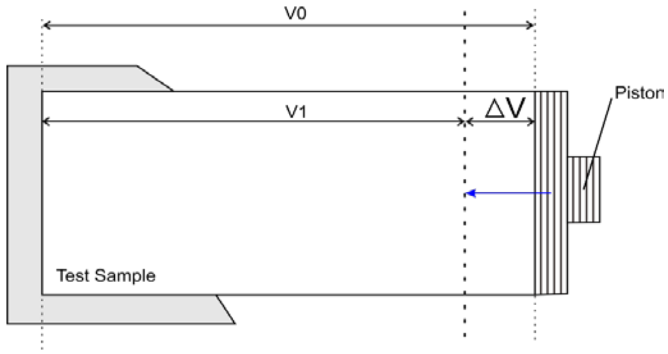


Figure 4.1. Illustration of compressibility equation.

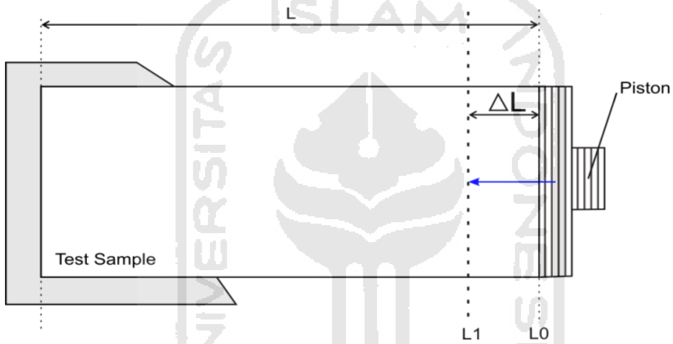


Figure 4.2. Illustration of compressibility equation using piston displacement.

The changing of length represented by the displacement of piston will be fit through curve fitting which result in a curve function. Based on this function, the changing of lengths are derived and used for compressibility calculation through the equation.

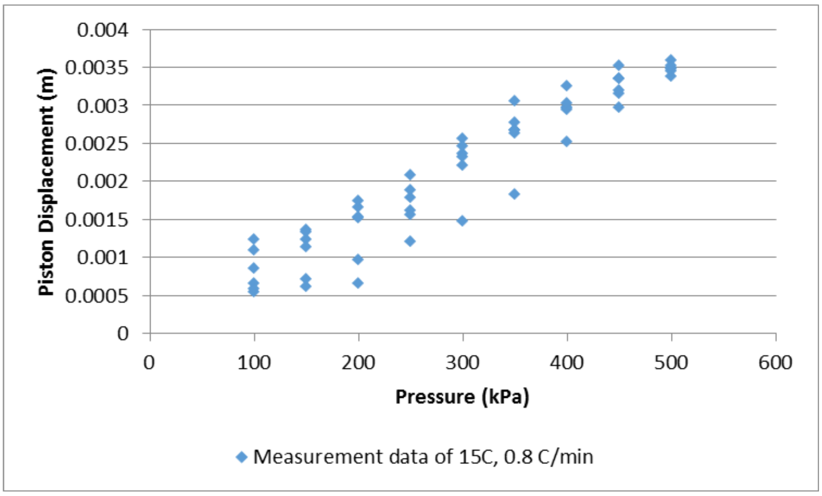
4.2.1. Compression data plot and processing of object's temperature 15^{o}C.

According to data acquisition of the experiment in compression test, the data for test sample with temperature 15^{0}C in static cooling are presented in Table 4.1. Based on that data, the compressibility can be calculated through substituting the changing of length derived from function which shown in Table 4.2 into the compressibility equation.

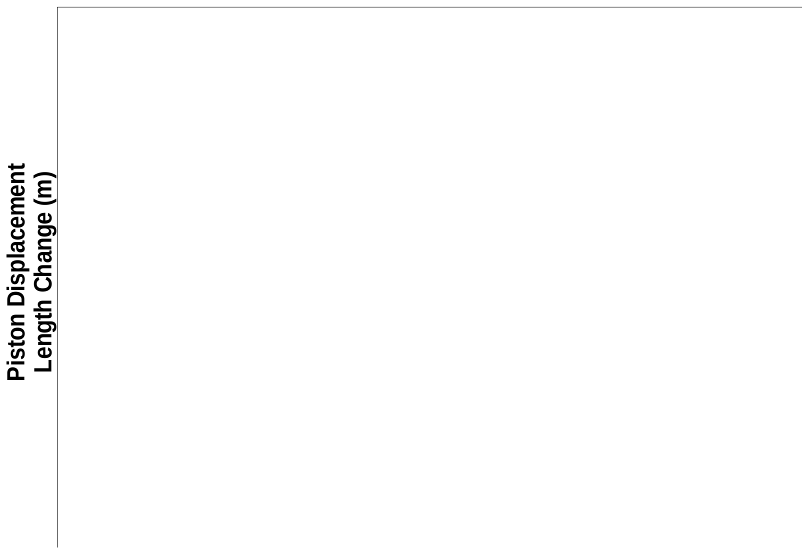
Table 4.1. Piston displacement of test sample 15°C..

15°C		Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
		Piston displacement (m)					
Pressure (kPa)	100	0.001243	0.00055	0.000668	0.00059	0.000856	0.001105
	150	0.001364	0.000616	0.001245	0.000726	0.001143	0.001345
	200	0.001524	0.000666	0.001534	0.000974	0.001667	0.001756
	250	0.001628	0.001215	0.001567	0.001793	0.001897	0.002089
	300	0.002222	0.001481	0.002366	0.002332	0.002567	0.002465
	350	0.002646	0.001842	0.002685	0.002784	0.003069	0.002678
	400	0.002954	0.002525	0.002975	0.002976	0.003254	0.003032
	450	0.003163	0.002976	0.003201	0.003356	0.003534	0.003356
	500	0.003383	0.003482	0.003455	0.003502	0.003602	0.003523
Temperature (°C)		15.4	15.5	15	15.3	15.3	15.5

Table 4.1 shows the measurement data of piston displacements of the observed gelled crude oil 15°C in compression test. These data known as the changing of length or ΔL that will be used to calculated the compressibility of gelled crude oil at temperature 15°C. The plot of the piston displacement data of measured gelled crude oil is shown in Figure 4.3(a). Then, all of plotted data will be processed in statistical analysis by curve fitting and estimation in order to get the representative function of the measured data. The curve function fitting is shown in Figure 4.3(b).



(a)



(b)

Figure 4.3. Data plot of length change (a) and curve function fitting (b) of test sample 15^oC.

In above Figure, the plot of measured data showed increasing values influenced by the increasing of pressure drop applied. The function fitting of this plot showed quadratic function with level of confidence that above 90% which is represented by the R square value. The function fitting is summarized in Table 4.2.

Table 4.2. Function fitting summary of test sample 15^oC.

Temp.	Data Fitted	Equation	Model Summary					Parameter Estimates		
			R Square	F	df1	df2	Sig.	Constant	b1	b2
15^oC	Length Change	Quadratic	.913	271.327	2	52	.000	2.073E-06	7.396E-06	-4.852E-10

Based on the summary, the fitted function has R square value 0,913 and significant below 0,05 which means that the function is fit to be a representative of the data. The function of piston displacement which is representing the ΔL function of gelled crude oil at temperature 15^oC, has derived the function equation based on its parameter estimated which is shown in Eq. 4.3.

$$\Delta L_{(15^oC)} = 2.073 \times 10^{-6} + 7.396 \times 10^{-6} \Delta P - 4.852 \times 10^{-10} \Delta P^2 \qquad (4.3).$$

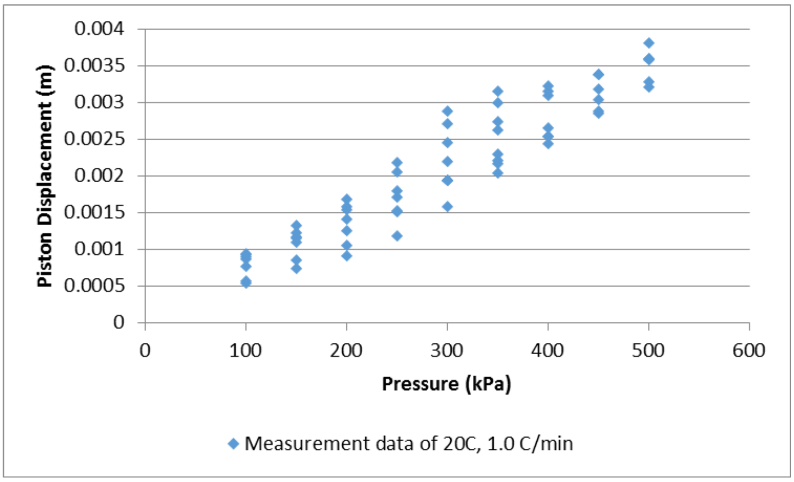
4.2.2. Compression data plot and processing of object's temperature 20^{o}C.

According to data acquisition of the experiment in compression test, the data for test sample with temperature 20^{o}C in static cooling are presented in Table 4.3. Based on that data, the compressibility can be calculated through substituting the changing of length derived from function which shown in Table 4.4 into the compressibility equation.

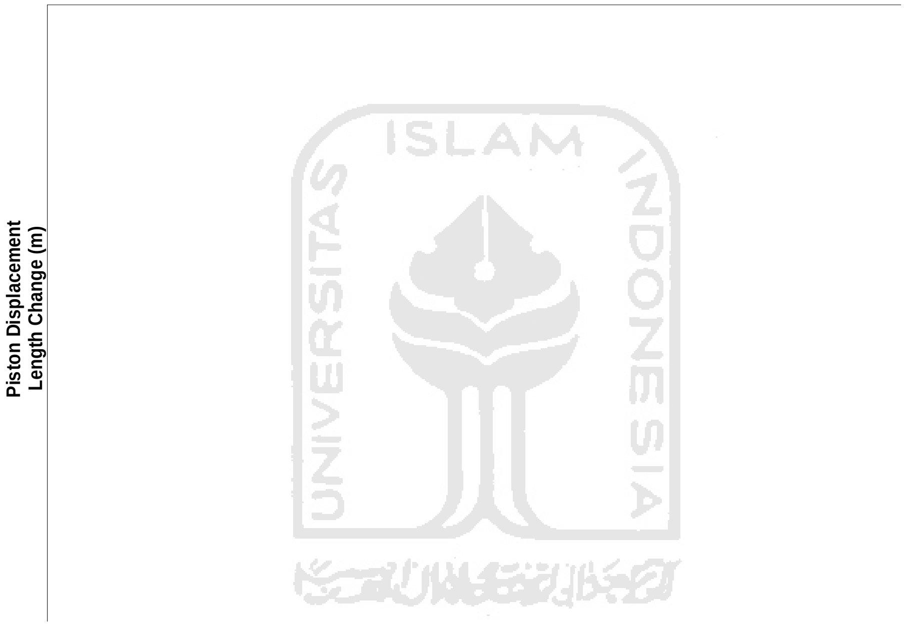
Table 4.3. Piston displacement of test sample 20^{o}C.

20^{o}C		Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8
		Piston displacement (m)							
Pressure (kPa)	100	0.000897	0.000875	0.001689	0.000935	0.00093	0.000567	0.000539	0.000776
	150	0.001161	0.001172	0.002475	0.001232	0.00132	0.001095	0.000743	0.000858
	200	0.001254	0.001419	0.002651	0.001546	0.001683	0.00159	0.000908	0.001062
	250	0.001513	0.001711	0.002761	0.001793	0.002052	0.002189	0.001183	0.001529
	300	0.001942	0.0022	0.002882	0.001947	0.002448	0.002717	0.00159	0.001947
	350	0.002294	0.002629	0.002998	0.002167	0.002734	0.003152	0.002041	0.002211
	400	0.002657	0.003229	0.003146	0.002536	0.003091	0.004147	0.002437	0.002541
	450	0.003179	0.00401	0.003377	0.003036	0.003388	0.004961	0.002855	0.002888
	500	0.003592	0.00484	0.003592	0.003586	0.003806	0.005676	0.003207	0.003284
Temperature (^{o}C)		20	20.2	20.2	20.2	20.2	20.5	20.5	20.5

Table 4.3 shows the measurement data of piston displacements of the gelled crude oil at 20^{o}C in compression test. These data of the changing of length or ΔL will be used to calculate the compressibility of the observed gelled crude oil. The plot of the piston displacement data of measured gelled crude oil is shown in Figure 4.4(a). Then, all of plotted data will be processed in statistical analysis by curve fitting and estimation in order to get the representative function of the measured data. The curve function fitting is shown in Figure 4.4(b).



(a)



(b)

Figure 4.4. Data plot of length change (a) and curve function fitting (b) of test sample 20^oC.

In Figure 4.4(a), the plot of measured data showed increasing values influenced by the increasing of pressure drop applied. The function fitting of this plot showed quadratic function as derived in Figure 4.4.(b). The fitted function has level of confidence 90% which is represented by the R square value. The function fitting is summarized in Table 4.4.

Table 4.4. Function fitting summary of test sample 20^oC.

Temp.	Data Fitted	Equation	Model Summary					Parameter Estimates		
			R Square	F	df1	df2	Sig.	Constant	b1	b2
20^oC	Length Change	Quadratic	.903	282.615	2	61	.000	3.311E-05	7.040E-06	-1.881E-10

Based on the summary, the fitted function has R square value 0,903 and significant below 0,05 which means that the function is fit to represent the data. The function of piston displacement which is representing the ΔL function of gelled crude oil at temperature 20^oC, has derived the function equation based on its parameter estimated which is shown in Eq. 4.4.

$$\Delta L_{(20^oC)} = 3.311 \times 10^{-5} + 7.040 \times 10^{-6}\Delta P - 1.881 \times 10^{-10}\Delta P^2 \qquad (4.4).$$

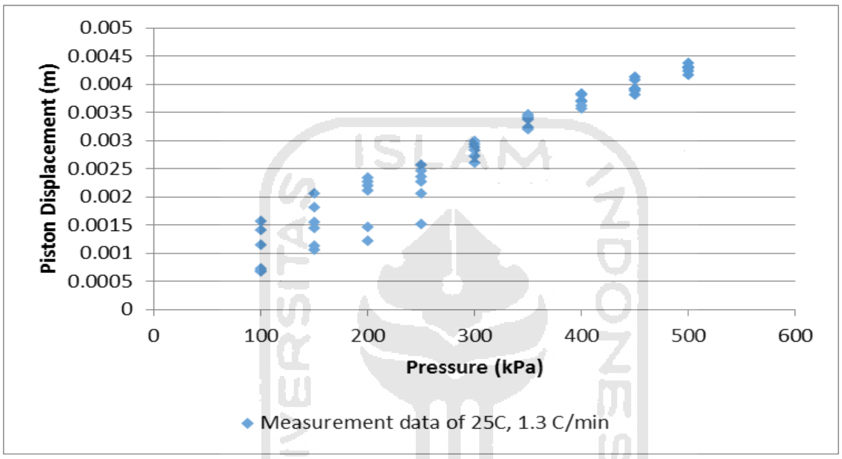
4.2.3. Compression data plot and processing of object's temperature 25^{o}C.

The acquired data of compression test of gelled crude oil with temperature 25^oC statically cooled are presented in Table 4.5. Based on that data, the compressibility can be calculated through substituting the changing of length derived from function which shown in Table 4.6 into the compressibility equation.

Table 4.5. Piston displacement of test sample 25^oC.

25 C		Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
		Piston displacement (m)					
Pressure (kPa)	100	0.001414	0.001573	0.001155	0.000726	0.000693	0.000671
	150	0.001826	0.002057	0.001551	0.001456	0.001067	0.001132
	200	0.002211	0.002338	0.002283	0.002115	0.001216	0.001469
	250	0.002276	0.002355	0.002567	0.002475	0.001524	0.002063
	300	0.002832	0.002933	0.002998	0.002727	0.002607	0.002882
	350	0.003378	0.003417	0.003461	0.003208	0.00324	0.003432
	400	0.003704	0.003835	0.003824	0.003617	0.003581	0.003718
	450	0.003929	0.004137	0.004089	0.003895	0.003823	0.003922
	500	0.004311	0.004384	0.004247	0.004306	0.004169	0.004296
Temperature (C)		24.7	24.6	24.6	24.6	24.5	24.5

Table 4.5 shows the measurement data of piston displacements of the gelled crude oil at 25^{o}C in compression test. These data of the changing of length or ΔL will be used to calculate the compressibility of the observed gelled crude oil. The plot of the piston displacement data of measured gelled crude oil is shown in Figure 4.5(a). Then, all of plotted data will be processed in statistical analysis by curve fitting and estimation in order to get the representative function of the measured data. The curve function fitting is shown in Figure 4.5(b).



(a)

(b)

Figure 4.5. Data plot of length change (a) and curve function fitting (b) of test sample 25^{o}C.

In Figure 4.5(a), the plot of measured data showed increasing values influenced by the increasing of pressure drop applied. The function fitting of this plot showed quadratic function as fitted in Figure 4.5.(b). The fitted function has level of confidence above 90% which is represented by the R square value. The function fitting is summarized in Table 4.6.

Table 4.6. Function fitting summary of test sample 25^oC.

Temp.	Data Fitted	Equation	Model Summary					Parameter Estimates		
			R Square	F	df1	df2	Sig.	Constant	b1	b2
25^{o}C	Length Change	Quadratic	.945	448.286	2	52	.000	-1.735E-05	1.061E-05	-3.779E-09

Based on the summary, the fitted function has R square value 0,945 and significant below 0,05 which means that the function is fit to represent the data. The function of piston displacement which is representing the ΔL function of gelled crude oil at temperature 25^{o}C, has derived the function equation based on its parameter estimated which is shown in Eq. 4.5.

$$\Delta L_{(25^oC)} = -1.735 \times 10^{-5} + 1.061 \times 10^{-6}\Delta P - 3.779 \times 10^{-9}\Delta P^2 \qquad (4.5).$$

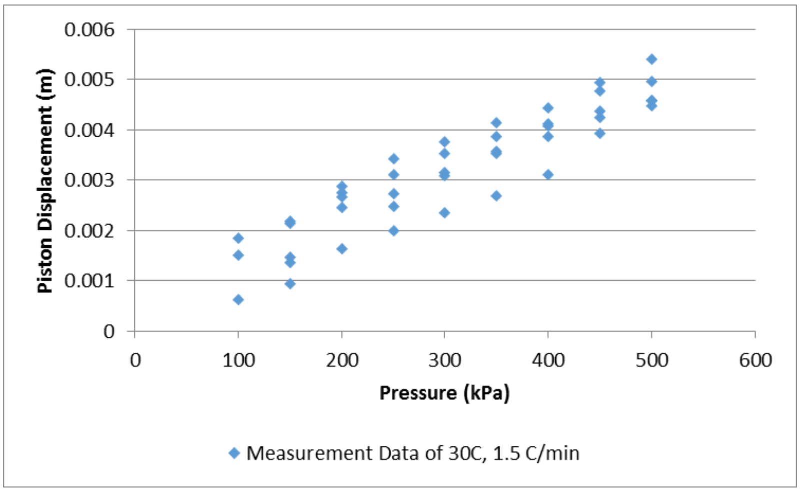
4.2.4. Compression data plot and processing of object's temperature 30^{o}C.

According to data acquisition of the experiment in compression test, the data for test sample with temperature 30^{o}C in static cooling are presented in Table 4.7. Based on that data, the compressibility can be calculated through substituting the changing of length derived from function which shown in Table 4.8 into the compressibility equation.

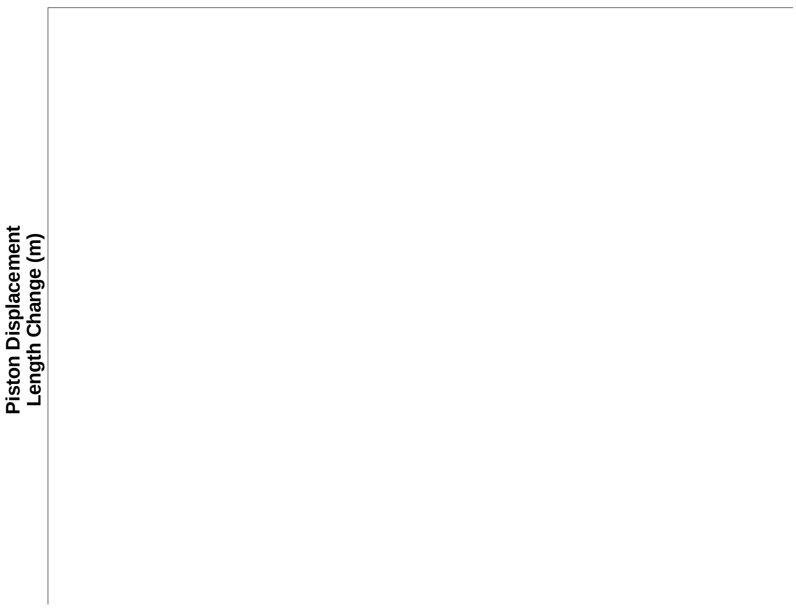
Table 4.7. Piston displacement of test sample 30°C.

30 C		Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
		Piston displacement (m)					
Pressure (kPa)	100	0.000347	0.000479	0.001848	0.000286	0.000616	0.001502
	150	0.000649	0.001353	0.002184	0.000935	0.001458	0.00214
	200	0.000875	0.001639	0.002464	0.002657	0.002877	0.002745
	250	0.002481	0.001986	0.002723	0.003416	0.003988	0.003119
	300	0.003152	0.002343	0.00308	0.003762	0.004549	0.003537
	350	0.003575	0.002684	0.003531	0.004131	0.004983	0.003861
	400	0.003867	0.003108	0.00407	0.004444	0.00517	0.00412
	450	0.004252	0.003933	0.004774	0.004934	0.005478	0.004378
	500	0.005577	0.004884	0.004956	0.005396	0.005891	0.004582
Temperature (C)		30	29.7	29.5	30	29.7	29.6

Table 4.7 shows the measurement data of piston displacements of the gelled crude oil at 30°C in compression test. These data of the changing of length or ΔL will be used to calculate the compressibility of the observed gelled crude oil. The plot of the piston displacement data of measured gelled crude oil is shown in Figure 4.6(a). Then, all of plotted data will be processed in statistical analysis by curve fitting and estimation in order to get the representative function of the measured data. The curve function fitting is shown in Figure 4.6(b).



(a)



(b)

Figure 4.6. Data plot of length change (a) and curve function fitting (b) of test sample 30^{o}C.

In above Figure, the plot of measured data showed increasing values influenced by the increasing of pressure drop applied. The function fitting of this plot showed quadratic function with level of confidence that approaching 90% which is represented by the R square value. The function fitting is summarized in Table 4.8.

Table 4.8. Function fitting summary of test sample 30^{o}C.

Temp.	Data Fitted	Equation	Model Summary					Parameter Estimates		
			R Square	F	df1	df2	Sig.	Constant	b1	b2
30^{o}C	Length Change	Quadratic	.867	133.760	2	41	.000	.000121	1.167E-05	-4.786E-09

Based on the summary, the fitted function has R square value 0,867 and significant below 0,05 which means that the function is fit to represent the data. The function of piston displacement which is representing the ΔL function of gelled crude oil at temperature 30^{o}C, has derived the function equation based on its parameter estimated which is shown in Eq. 4.6.

$$\Delta L_{(30^oC)} = 0.000121 + 1.167 \times 10^{-6}\Delta P - 4.786 \times 10^{-9}\Delta P^2 \qquad (4.6).$$

4.3. Compression Data Plot and Processing of Dynamically Cooled Crude Oil

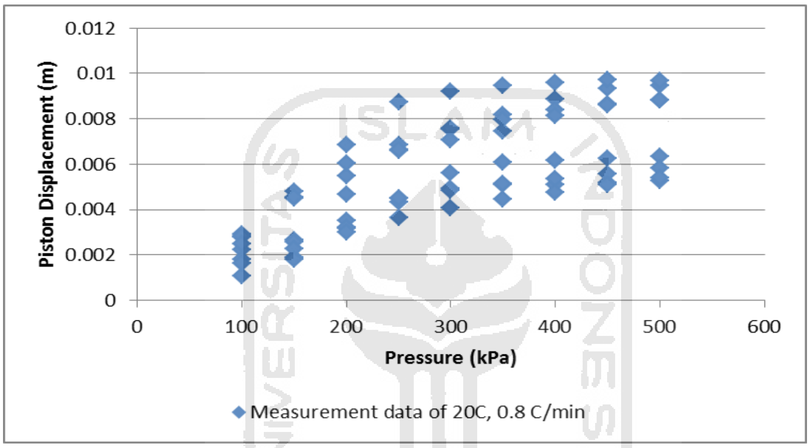
In this study, the dynamic cooling was performed as the experiment setup on two different conditions of observed crude oil. First observed crude oil is the gelled crude oil which is cooled until 20^{o}C with cooling rate 0.8^{o}C/min. The second observed crude oil is the gelled crude oil which is cooled also until 20^{o}C but with cooling rate 1.0^{o}C/min. The second observed crude oil is the gelled crude oil that observed in static cooling experiment and already described in sub-chapter of compression data plot and processing of statically cooled crude oil. So in this sub-chapter, the data plot and processing will be describing the gelled crude oil at 20^{o}C with cooling rate 0.8^{o}C/min only.

The data measured in compression test of first observed crude oil is represented by the piston displacement as described in Table 4.9. Based on that data, the compressibility can be calculated through substituting the changing of length derived from function which shown in Table 4.10 into the compressibility equation.

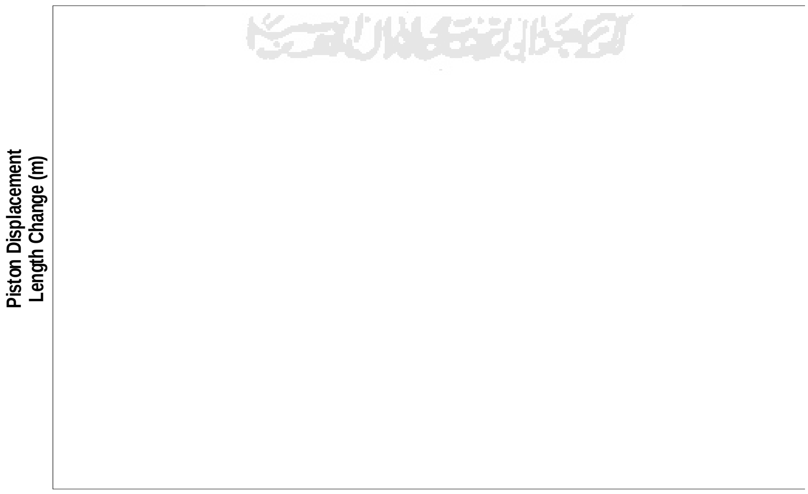
Table 4.9. Piston displacement of test sample 20^{o}C, 0.8 ^{o}C/min.

20^{o}C, 0.8^{o}C/min.		Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8
		Piston displacement (m)							
Pressure (kPa)	100	0.002904	0.002783	0.002838	0.001051	0.002233	0.002481	0.001793	0.001623
	150	0.004488	0.004796	0.004554	0.001881	0.002668	0.002547	0.002255	0.001793
	200	0.005495	0.006837	0.00605	0.003185	0.003498	0.004659	0.00319	0.002976
	250	0.0066	0.008734	0.006831	0.004307	0.00451	0.006628	0.004499	0.00363
	300	0.00753	0.009196	0.007574	0.004906	0.005627	0.007057	0.004857	0.004054
	350	0.008162	0.009444	0.007959	0.005082	0.006056	0.007442	0.005143	0.004439
	400	0.008872	0.00957	0.008377	0.005104	0.006149	0.008124	0.005357	0.00473
	450	0.009339	0.009735	0.008663	0.005165	0.006237	0.008586	0.005555	0.00511
	500	0.009438	0.009669	0.008811	0.005247	0.006325	0.008833	0.005808	0.005407
Temperature (^{o}C)		20	20.3	20.3	20.3	20.3	20.3	20.5	20.5

Table 4.9 shows the measurement data of piston displacements of the gelled crude oil at 20°C with cooling rate 0.8°C/min in compression test. These data of the changing of length or ΔL will be used to calculate the compressibility of the observed gelled crude oil. The plot of the piston displacement data of measured gelled crude oil is shown in Figure 4.7(a). Then, all of plotted data will be processed in statistical analysis by curve fitting and estimation in order to get the representative function of the measured data. The curve function fitting is shown in Figure 4.7(b).



(a)



(b)

Figure 4.7. Data plot of length change (a) and curve function fitting (b) of test sample 20°C, 0.8 °C/min.

In Figure 4.7(a), the plot of measured data showed increasing values influenced by the increasing of pressure drop applied. The function fitting of this plot showed quadratic function as fitted in Figure 4.7.(b). The fitted function is summarized in Table 4.10.

Table 4.10 Function fitting summary of test sample 20°C, 0.8 °C/min.

Temp.	Data Fitted	Equation	Model Summary					Parameter Estimates		
			R Square	F	df1	df2	Sig.	Constant	b1	b2
20°C	Length Change	Quadratic	.597	51.786	2	70	.000	-7.826E-04	3.340E-05	-3.403E-08

Based on the summary, the fitted function has R square value 0,597 and significant below 0,05 which means that the function is fit to represent the data. The function of piston displacement which is representing the ΔL function of gelled crude oil at temperature 20°C with cooling rate 0.8°C/min, has derived the function equation based on its parameter estimated which is shown in Eq. 4.7.

$$\Delta L_{(30^oC)} = -7.826 \times 10^{-4} + 3.340 \times 10^{-5}\Delta P - 3.403 \times 10^{-8}\Delta P^2 \qquad (4.7).$$

CHAPTER V

RESULTS AND DISCUSSION

5.1. Compressibility of Gelled Crude Oil below Pour Point Temperatures

In this research, the compressibility of gelled crude oil in different temperatures below its pour point is investigated through experiment. According to the data processing, the compressibility of gelled crude oil is calculated by substituting the changing of length of each observed setup on the compressibility equation. In this research the piston displacements are representing the changing of length or known as ΔL. The changing of length on each observed gelled crude oil is represented by the functions shown in Figure 5.1.

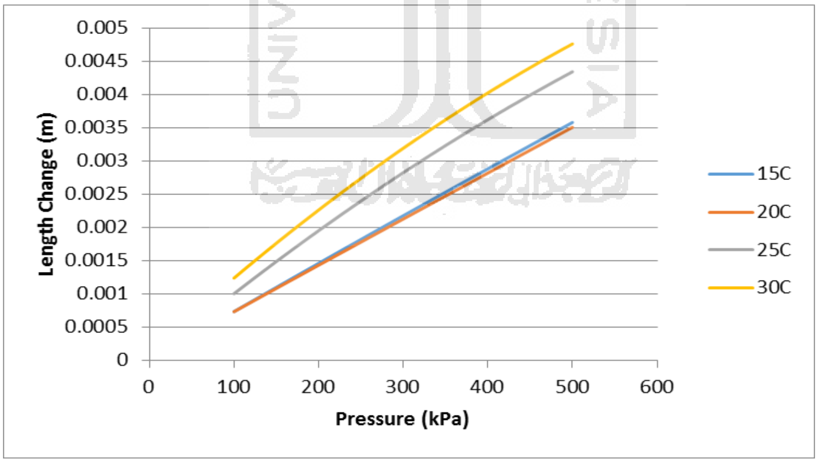


Figure 5.1. Functions of piston displacement of all experiment's object.

The measurement of piston displacement showed that the changing of length during compression test was varying based on different temperature of experiment's object. Through the curve fitting in Figure 5.1, the changing of length on different temperature of gelled crude oil showed different function. At the beginning of compression with 100 kPa of pressure gauge, Gelled crude oil with temperature 30^{o}C was almost reaching 1,5x10^{-3}m, while the gelled crude oil with lower temperatures was on 1x10^{-3}m and below. However, for gelled crude oil with temperature 20^{o}C and 15^{o}C have similarity on changing of length.

5.1.1. Compressibility of gelled crude oil at 15^{o}C.

According to the fitted function of changing of length in compression test of gelled crude oil at 15^{o}C, the compressibility of observed gelled crude oil is calculated and the profile of the compressibility shown in Figure 5.2. The detail calculation of the compressibility is shown in appendix.

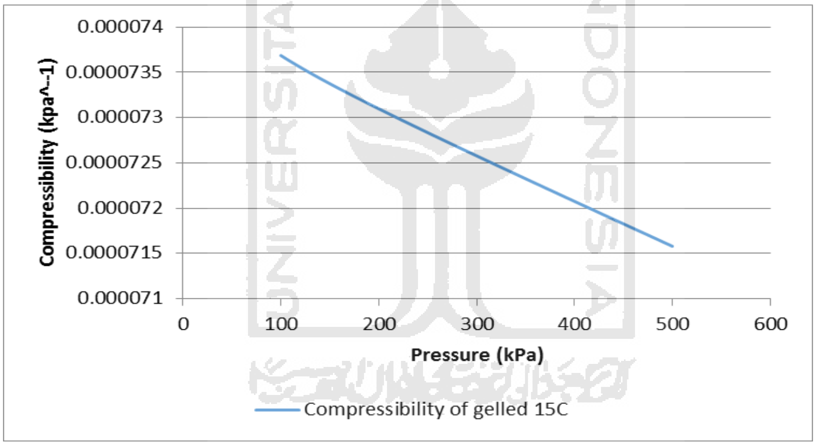


Figure 5.2. Compressibility profiles of gelled crude oil 15^{o}C.

Above graph of compressibility profile showed that the compressibility of gelled crude oil 15^{o}C is decreasing when higher pressure applied. At the beginning of compression with pressure applied at 100 kPa, the compressibility is $\pm$7.3 x 10^{-5} kPa^{-1}. Then, when higher pressure applied the compressibility is decreasing as shown that at 500 kPa the compressibility is $\pm$7.15 x 10^{-5} kPa^{-1}. This is due to the observed gelled crude oil is compacting when higher pressure applied.

5.1.2. Compressibility of gelled crude oil at 20°C.

The compressibility of gelled crude oil at 20°C is calculated based on the changing of length function of observed gelled crude oil. The detail of the compressibility calculation of gelled crude oil at 20°C is attached in appendix. Based on the calculation, the compressibility profile of the observed gelled crude oil is shown in Figure 5.3.

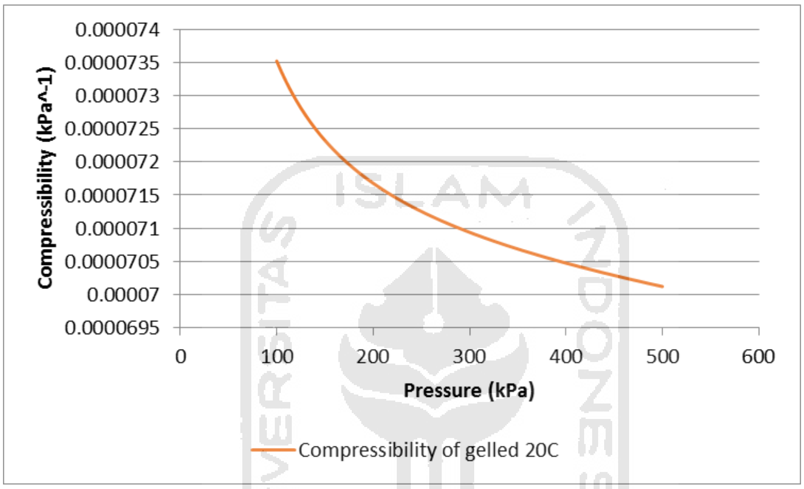


Figure 5.3. Compressibility profile of gelled crude oil at 20°C.

Above graph of compressibility profile showed that the compressibility of gelled crude oil 20°C is decreasing when higher pressure applied. This is due to the observed gelled crude oil is compacting when higher pressure applied. At the beginning of compression with pressure applied at 100 kPa, the compressibility is $\pm 7.3 \times 10^{-5}$ kPa^{-1}. Then, when higher pressure applied the compressibility is gradually decreasing as shown that at 500 kPa the compressibility is $\pm 7 \times 10^{-5}$ kPa^{-1}.

5.1.3. Compressibility of gelled crude oil at 25°C.

The compressibility of gelled crude oil at 25°C is calculated based on the changing of length function of observed gelled crude oil. The detail of the compressibility calculation of gelled crude oil at 25°C is also attached in appendix as another compressibility calculation. Based on the compressibility calculation, the compressibility profile of the observed gelled crude oil is shown in Figure 5.4.

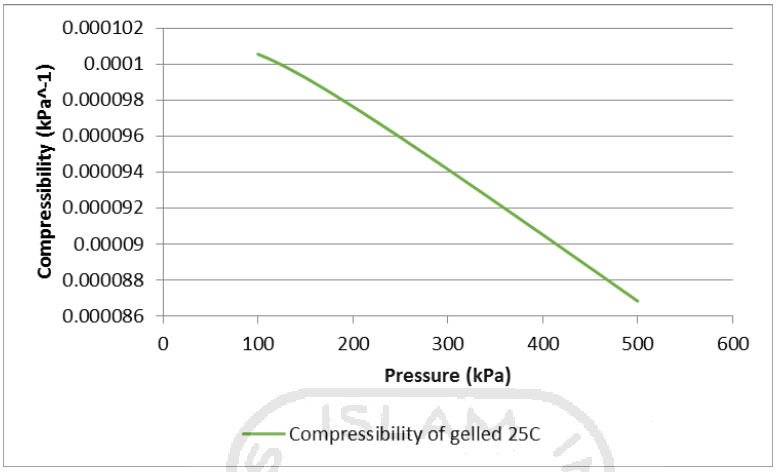


Figure 5.4. Compressibility profile of gelled crude oil at 25°C.

The graph of compressibility profile showed that the compressibility of gelled crude oil 25°C is decreasing when higher pressure applied. This is due to the observed gelled crude oil is compacting when higher pressure applied. At the beginning of compression with pressure applied at 100 kPa, the compressibility is $\pm 1 \times 10^{-4}$ kPa^{-1}. Then, when higher pressure applied the compressibility is lower as shown that at 500 kPa the compressibility is $\pm 8.7 \times 10^{-5}$ kPa^{-1}.

5.1.4. Compressibility of gelled crude oil at 30°C.

According to the fitted function of changing of length in compression test of gelled crude oil at 30°C, the compressibility of observed gelled crude oil is calculated. The detail calculation of the compressibility is shown in appendix. Based on the compressibility calculation, the compressibility profile of the observed gelled crude oil is shown in Figure 5.5.

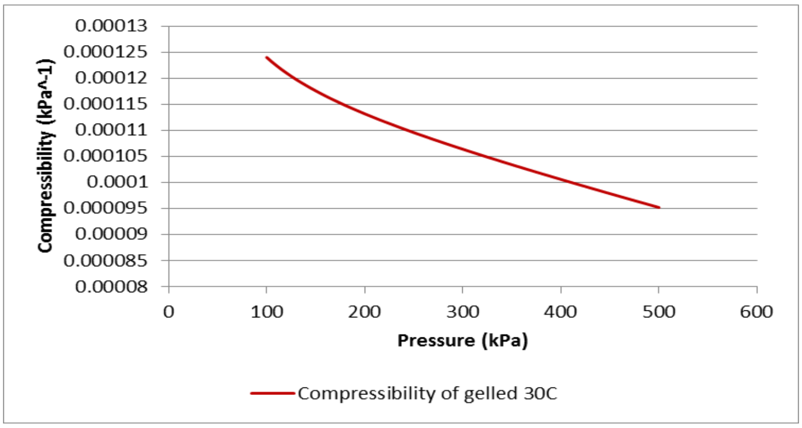


Figure 5.5. Compressibility profile of gelled crude oil at 30^{o}C.

According to the graph, the compressibility of gelled crude oil at 30^{o}C is also showing similarity with other observed gelled crude oil which is decreasing when higher pressure applied. The decreasing of compressibility is due to the observed gelled crude oil is compacting when higher pressure applied. At the beginning of compression with pressure applied at 100 kPa, the compressibility of observed gelled crude oil is reaching $\pm 1.25 \times 10^{-4}$ kPa^{-1}. Meanwhile, when higher pressure applied the compressibility is lower as shown that at 500 kPa the compressibility is $\pm 9.5 \times 10^{-5}$ kPa^{-1}.

5.2. Effect Of Temperature after Cooling Statically on Compressibility Of Gelled Crude Oil

As discussed in this study, the changing of length of gelled crude oil with different temperatures has different curves function. Based on this, the compressibility of each observed gelled crude oil is calculated and then the effect of temperature also can be analyzed. The analysis of temperature effect on compressibility can be done by comparing the beginning compression at 100 kPa on each experiment's object where the gelled crude oil is not compacted yet. The effect of temperature on compressibility of gelled crude oil is shown in Figure 5.6.

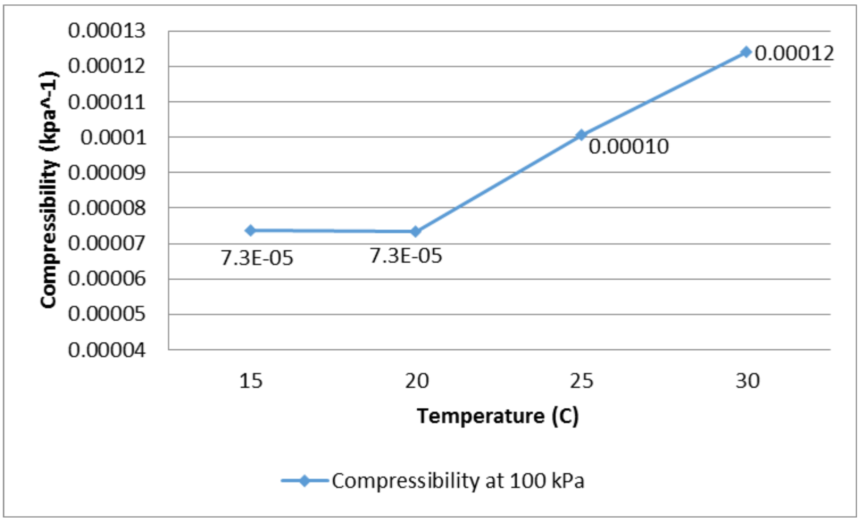


Figure 5.6. Compressibility at the beginning of compression.

Gelled crude oil below pour point temperature has different compressibility according how cold it is. The study showed that gelled crude oil with temperature 30^{o}C is more compressible than it is in lower temperature which the compressibility at 100 kPa is reaching 1,25 x 10^{-5} kPa.

According to above graph, the compressibility of gelled crude oil is influenced by the temperature which the colder the temperature, the compressibility is lower. However, at temperature below 20^{o}C, the compressibility is slightly the same. Compressibility of gelled crude oil at 15^{o}C is quite similar with gelled crude oil at 20^{o}C which is 7.3 x 10^{-5} kPa^{-1}. Then when the temperature is increasing, the compressibility is also increasing.

5.3. Effect of Gas Voids on Compressibility of Gelled Crude Oil

In this research, the investigation of gas voids effect on the compressibility of gelled crude oil has been done through comparison between two observed gelled crude oil at 20^{o}C with different cooling rate due to the dynamic cooling process. According to

Chala, et al. (2014), total volume of gas voids is influenced by the cooling process. The lower the cooling rate, the bigger the gas voids volume when it cooled dynamically. In this study, the comparison is shown in Figure 5.7.

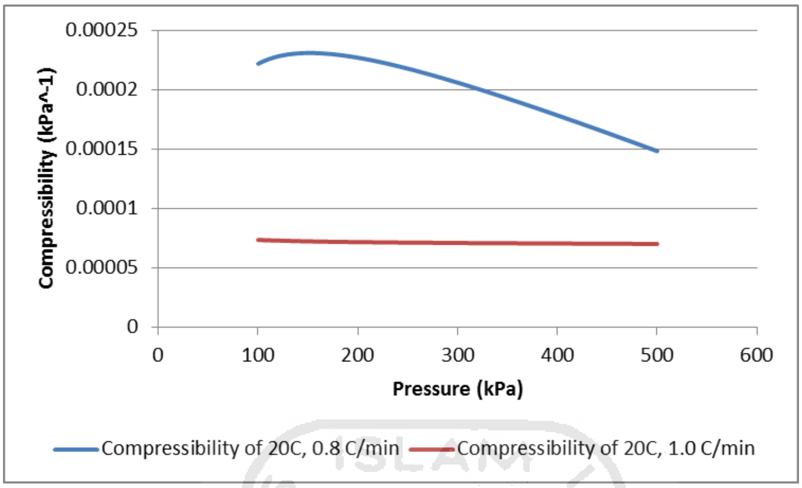


Figure 5.7. Comparison of compressibility profile of two observed gelled crude oil.

The comparison is about two compressibility profile of the observed gelled crude oil. According to above graph, the gelled crude oil with cooling rate 0.8^{o}C/min has higher compressibility profile compared to the gelled crude oil with cooling rate 1.0^{o}C/min. At the beginning of the compression with pressure applied 100 kPa, the gelled crude oil with cooling rate 1.0^{o}C/min showed compressibility at $\pm 7 \times 10^{-5}$ kPa^{-1}. Meanwhile, the gelled crude oil with cooling rate 0.8^{o}C/min has higher compressibility with a gap $\pm 1.5 \times 10^{-5}$ kPa^{-1}.

Based on the comparison of compressibility profile, the volume of gas voids within the gel is significantly influence the compressibility of gelled crude oil. Gelled crude oil with lower cooling rate will result in higher compressibility due to bigger total volume of gas voids. As shown in result that the compressibility of gelled crude oil with cooling rate 0.8^{o}C/min at 100 kPa is reaching 2.5×10^{-4} kPa^{-1}.

5.5. Possibility of Flow Restart of Waxy Crude Oil at Low Risk

Regarding the challenge of waxy crude oil flow due to the wax depositions issues, to restart the flow at low risk has been concerned in order to achieve low operating cost by applying optimum restart pressure. Optimum restart pressure means that the flow of waxy crude oil can be resumed by applying enough pressure to break the gel in few times, so that the compression of the invested pump is generating enough energy to restart the flow in short times. However, the behavior of waxy crude oil is dynamically changed due to the surrounding effects.

Thermal effects, such as heat treatment by reserving process at reservoir and thermal shrinkage by sea water temperature have significant influence on the properties change of waxy crude oil. According to this study, thermal shrinkage also has significant influence on the compressibility of waxy crude oil where the temperature and cooling process is affecting the gas voids volume within the gel which makes the waxy crude oil in gel state is compressible. Therefore, in determining the restart pressure of waxy crude oil flow, the thermal shrinkage history should be putted as the prior consideration.

According to the result of the experiment, this study identified that the waxy crude oil in gel state below its pour point is compressible which has different compressibility according to its thermal shrinkage history. When it is statically cooled, the compressibility of the waxy crude oil is also static depends on the how cold the temperature of the gelled crude oil. However, with different gas voids volume due to dynamic cooling, the gelled crude oil with same temperature showed different compressibility as shown in Figure 5.8.

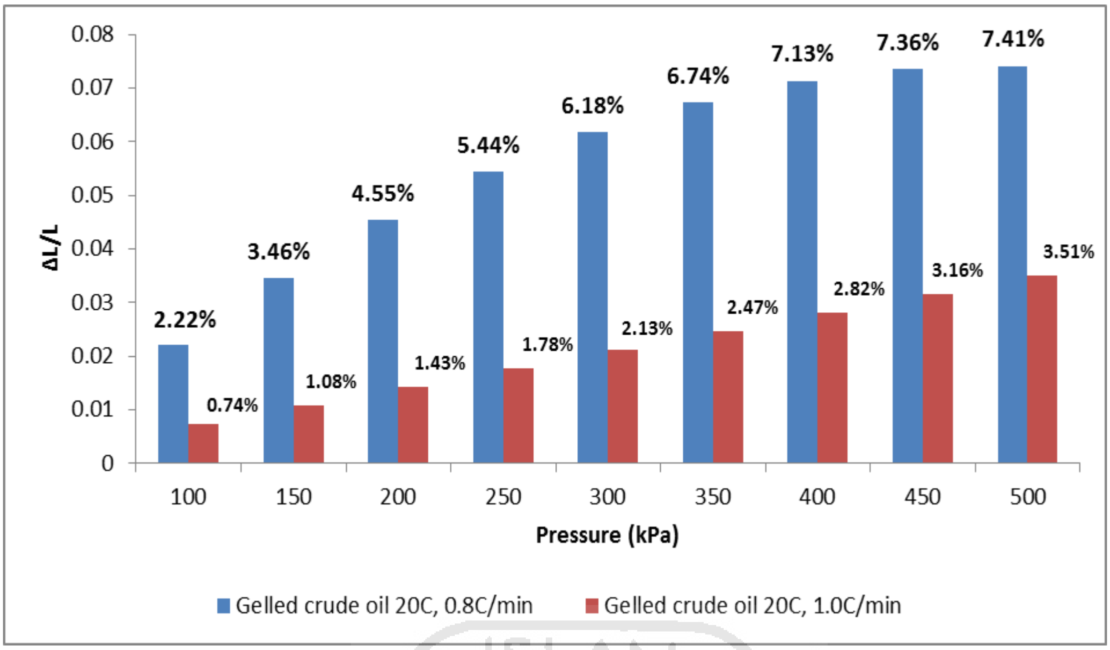


Figure 5.8. Compression percentage comparison of gelled crude oils dynamically cooled.

Above graph describes the comparison of compression percentage between gelled crude oils dynamically cooled. According to the graph, gelled crude oil with cooling rate 0.8^{o}C/min has higher percentage of compression than the crude oil with 1.0^{o}C/min. It is due to the effect of gas voids which result in higher compressibility if the total volume of the gas voids is bigger. The compression percentage of both gelled crude oil at 100 kPa already showed different value. The gelled crude oil with cooling rate 0.8^{o}C/min showed 2.22% at 100 kPa, while the gelled crude oil with cooling rate 1.0^{o}C/min showed 0.74% at the same applied pressure.

As confirmed by Wachs et al. (2009), the risk of restart pressure determination may lead in miss prediction of the restart pressure so that the investment cost of pump and piping system will be high. Considering the result of this study, the miss prediction of restart pressure can be explained by the graph on Figure 5.8.

If the prediction of restart pressure on gelled crude oil with temperature 20^{o}C has been done accordingly by assuming the thermal shrinkage is static as represented by the data of gelled crude oil with cooling rate 1.0^{o}C/min, while the actual thermal shrinkage on the real system shows different history as represented by the data of gelled crude oil with cooling rate 0.8^{o}C/min, the predicted restart pressure will be excessive. In an instance, to get percentage of compression 2.1% on gelled crude oil with temperature 20^{o}C, the prediction of pressure will refer to 300 kPa. However, actual pressure that is needed only 100 kPa.

To restart the flow of waxy crude oil at low risk can be achieved, if the thermal effect is considered accordingly. Considering in real system of waxy crude oil flow is naturally dynamic, flow assurance engineer should have enough information and experience regarding the thermal effect on the properties change of waxy crude oil, especially on its compressibility so that optimum pressure can be predicted accurately. Not only that, but in term of energy uses to provide pressure also can be reduced by understanding this effect. In this case, using the result shown in Figure 5.8, the energy uses to provide pressure from pump can be reduced up to 75%, from 300 kPa to 100 kPa which mean that the operation cost in the system also can be minimized.

CHAPTER VI

CONCLUSION AND SUGGESTION

6.1. Conclusion

Based on the result of the experiment, the conclusion of the research of compressibility of gelled crude oil can be made. This experimental study has fulfilled its objectives where the compressibility of gelled crude oil is investigated experimentally on waxy crude oil which has temperatures below its pour point. The waxy crude oil is cooled and restarted in flow-loop rig which simulates offshore oil production. Then the waxy crude oil was tested in compression device with high pressure in order to investigate its compressibility.

The compression test showed that the compressibility of gelled crude oil statically cooled has influenced by its temperature. At below its pour point temperature, the colder the gel the compressibility of gelled crude oil is smaller. The study showed that the compressibility of each observed gelled crude oil is different. However, gelled crude oil with temperature below 20^{o}C has slightly similar compressibility with it is on 20^{o}C. Meanwhile, gelled crude oil with above 20^{o}C has higher compressibility.

The study also identified that the gas voids volume showed significant impact on compressibility. In dynamic cooling, the compressibility had been observed by comparing two observed gelled crude oil at 20^{o}C with cooling rate 0.8^{o}C/min and 1.0^{o}C/min. The result showed that the gelled crude oil with cooling rate 0.8^{o}C/min which is higher volume of gas voids has higher compressibility.

By considering the thermal effect of surrounding, the flow of waxy crude oil can be restarted at low risk after shutdown. The study concluded that the effect of thermal or temperature has significant influence on compressibility of the gelled crude oil that can be used to predict restart pressure more accurately so that the energy uses to provide pressure can be reduced. Regarding the energy uses reduction to provide pressure from pump, the study also concluded that it can be reduced up to 75% by understanding this temperature effect.

6.2. Suggestion

The suggestions for further development regarding the compressibility study of gelled crude oil are listed as follows:

1. The result of this experimental study about compressibility of gelled crude oil is expected to be a great contribution toward the development of flow start-up or restart model.
2. The compressibility of gelled crude oil and another parameter such as gas voids within gel are influenced by temperature and cooling rate which could be important information for flow assurance engineer to predict the restart pressure of waxy crude oil flow accurately.
3. For future study, flow mechanism may be good consideration for creating gas voids formation inside the pipe to restart the flow smoothly.

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APPENDIX

A. Compressibility Computation

1. Compressibility computation of gelled crude oil at 15^{o}C based on the fitted function of piston displacement Eq. 4.3.

Table A.1. Compressibility computation of experiment's object 15^{o}C.

No.	ΔP (kPa)	ΔL	ΔL / L	Compressibility (ΔL / L / ΔP)
1	100	0.0007369	0.0073686	7.36862E-05
2	105	0.0007733	0.0077335	7.3652E-05
3	110	0.0008098	0.0080981	7.36188E-05
4	115	0.0008462	0.0084624	7.35863E-05
5	120	0.0008827	0.0088265	7.35546E-05
6	125	0.0009190	0.0091904	7.35234E-05
7	130	0.0009554	0.0095541	7.34928E-05
8	135	0.0009917	0.0099174	7.34626E-05
9	140	0.0010281	0.0102806	7.34328E-05
10	145	0.0010644	0.0106435	7.34035E-05
11	150	0.0011006	0.0110062	7.33744E-05
12	155	0.0011369	0.0113686	7.33457E-05
13	160	0.0011731	0.0117308	7.33173E-05
14	165	0.0012093	0.0120927	7.32891E-05
15	170	0.0012454	0.0124544	7.32611E-05
16	175	0.0012816	0.0128158	7.32334E-05
17	180	0.0013177	0.0131771	7.32058E-05
18	185	0.0013538	0.0135380	7.31785E-05
19	190	0.0013899	0.0138987	7.31513E-05
20	195	0.0014259	0.0142592	7.31242E-05
21	200	0.0014619	0.0146195	7.30973E-05
22	205	0.0014979	0.0149794	7.30705E-05
23	210	0.0015339	0.0153392	7.30438E-05
24	215	0.0015699	0.0156987	7.30173E-05
25	220	0.0016058	0.0160580	7.29908E-05
26	225	0.0016417	0.0164170	7.29644E-05
27	230	0.0016776	0.0167758	7.29382E-05

28	235	0.0017134	0.0171343	7.2912E-05
29	240	0.0017493	0.0174926	7.28859E-05
30	245	0.0017851	0.0178507	7.28599E-05
31	250	0.0018208	0.0182085	7.28339E-05
32	255	0.0018566	0.0185660	7.2808E-05
33	260	0.0018923	0.0189234	7.27822E-05
34	265	0.0019280	0.0192805	7.27564E-05
35	270	0.0019637	0.0196373	7.27307E-05
36	275	0.0019994	0.0199939	7.27051E-05
37	280	0.0020350	0.0203503	7.26795E-05
38	285	0.0020706	0.0207064	7.26539E-05
39	290	0.0021062	0.0210622	7.26284E-05
40	295	0.0021418	0.0214179	7.26029E-05
41	300	0.0021773	0.0217732	7.25775E-05
42	305	0.0022128	0.0221284	7.25521E-05
43	310	0.0022483	0.0224833	7.25267E-05
44	315	0.0022838	0.0228379	7.25014E-05
45	320	0.0023192	0.0231924	7.24761E-05
46	325	0.0023547	0.0235465	7.24509E-05
47	330	0.0023900	0.0239005	7.24256E-05
48	335	0.0024254	0.0242541	7.24004E-05
49	340	0.0024608	0.0246076	7.23753E-05
50	345	0.0024961	0.0249608	7.23501E-05
51	350	0.0025314	0.0253138	7.2325E-05
52	355	0.0025666	0.0256665	7.22999E-05
53	360	0.0026019	0.0260189	7.22748E-05
54	365	0.0026371	0.0263712	7.22498E-05
55	370	0.0026723	0.0267232	7.22248E-05
56	375	0.0027075	0.0270749	7.21997E-05
57	380	0.0027426	0.0274264	7.21748E-05
58	385	0.0027778	0.0277777	7.21498E-05
59	390	0.0028129	0.0281287	7.21248E-05
60	395	0.0028479	0.0284795	7.20999E-05
61	400	0.0028830	0.0288300	7.2075E-05
62	405	0.0029180	0.0291803	7.20501E-05
63	410	0.0029530	0.0295303	7.20252E-05
64	415	0.0029880	0.0298801	7.20003E-05

65	420	0.0030230	0.0302297	7.19755E-05
66	425	0.0030579	0.0305790	7.19506E-05
67	430	0.0030928	0.0309281	7.19258E-05
68	435	0.0031277	0.0312769	7.1901E-05
69	440	0.0031626	0.0316255	7.18762E-05
70	445	0.0031974	0.0319739	7.18514E-05
71	450	0.0032322	0.0323220	7.18266E-05
72	455	0.0032670	0.0326698	7.18018E-05
73	460	0.0033017	0.0330175	7.17771E-05
74	465	0.0033365	0.0333648	7.17523E-05
75	470	0.0033712	0.0337120	7.17276E-05
76	475	0.0034059	0.0340589	7.17029E-05
77	480	0.0034406	0.0344055	7.16782E-05
78	485	0.0034752	0.0347519	7.16535E-05
79	490	0.0035098	0.0350981	7.16288E-05
80	495	0.0035444	0.0354440	7.16041E-05
81	500	0.0035790	0.0357897	7.15794E-05

2. Compressibility computation of gelled crude oil at 20^{o}C based on the fitted function of piston displacement Eq. 4.4.

Table A.2. Compressibility computation of experiment's object 20^{o}C.

No.	ΔP (kPa)	ΔL	ΔL / L	Compressibility (ΔL / L / ΔP)
1	100	0.0007352	0.0073521	7.35209E-05
2	105	0.0007702	0.0077021	7.33538E-05
3	110	0.0008052	0.0080521	7.32011E-05
4	115	0.0008402	0.0084020	7.30608E-05
5	120	0.0008752	0.0087518	7.29314E-05
6	125	0.0009101	0.0091015	7.28117E-05
7	130	0.0009451	0.0094510	7.27004E-05
8	135	0.0009801	0.0098005	7.25967E-05
9	140	0.0010150	0.0101500	7.24997E-05
10	145	0.0010499	0.0104993	7.24087E-05
11	150	0.0010848	0.0108485	7.23232E-05
12	155	0.0011198	0.0111976	7.22426E-05
13	160	0.0011547	0.0115466	7.21664E-05
14	165	0.0011896	0.0118956	7.20943E-05

15	170	0.0012244	0.0122444	7.20259E-05
16	175	0.0012593	0.0125931	7.19608E-05
17	180	0.0012942	0.0129418	7.18989E-05
18	185	0.0013290	0.0132904	7.18398E-05
19	190	0.0013639	0.0136388	7.17833E-05
20	195	0.0013987	0.0139872	7.17292E-05
21	200	0.0014335	0.0143355	7.16773E-05
22	205	0.0014684	0.0146836	7.16275E-05
23	210	0.0015032	0.0150317	7.15797E-05
24	215	0.0015380	0.0153797	7.15336E-05
25	220	0.0015728	0.0157276	7.14892E-05
26	225	0.0016075	0.0160754	7.14464E-05
27	230	0.0016423	0.0164231	7.1405E-05
28	235	0.0016771	0.0167708	7.13649E-05
29	240	0.0017118	0.0171183	7.13262E-05
30	245	0.0017466	0.0174657	7.12886E-05
31	250	0.0017813	0.0178130	7.12522E-05
32	255	0.0018160	0.0181603	7.12168E-05
33	260	0.0018507	0.0185074	7.11824E-05
34	265	0.0018854	0.0188545	7.1149E-05
35	270	0.0019201	0.0192014	7.11165E-05
36	275	0.0019548	0.0195483	7.10848E-05
37	280	0.0019895	0.0198951	7.10539E-05
38	285	0.0020242	0.0202418	7.10237E-05
39	290	0.0020588	0.0205883	7.09943E-05
40	295	0.0020935	0.0209348	7.09655E-05
41	300	0.0021281	0.0212812	7.09374E-05
42	305	0.0021628	0.0216275	7.09099E-05
43	310	0.0021974	0.0219737	7.0883E-05
44	315	0.0022320	0.0223198	7.08566E-05
45	320	0.0022666	0.0226659	7.08308E-05
46	325	0.0023012	0.0230118	7.08055E-05
47	330	0.0023358	0.0233576	7.07806E-05
48	335	0.0023703	0.0237033	7.07563E-05
49	340	0.0024049	0.0240490	7.07323E-05
50	345	0.0024395	0.0243945	7.07088E-05
51	350	0.0024740	0.0247400	7.06857E-05

52	355	0.0025085	0.0250854	7.0663E-05
53	360	0.0025431	0.0254306	7.06406E-05
54	365	0.0025776	0.0257758	7.06186E-05
55	370	0.0026121	0.0261209	7.05969E-05
56	375	0.0026466	0.0264659	7.05756E-05
57	380	0.0026811	0.0268107	7.05546E-05
58	385	0.0027156	0.0271555	7.05339E-05
59	390	0.0027500	0.0275002	7.05134E-05
60	395	0.0027845	0.0278448	7.04933E-05
61	400	0.0028189	0.0281894	7.04734E-05
62	405	0.0028534	0.0285338	7.04538E-05
63	410	0.0028878	0.0288781	7.04344E-05
64	415	0.0029222	0.0292223	7.04153E-05
65	420	0.0029566	0.0295665	7.03964E-05
66	425	0.0029911	0.0299105	7.03777E-05
67	430	0.0030254	0.0302545	7.03592E-05
68	435	0.0030598	0.0305983	7.0341E-05
69	440	0.0030942	0.0309421	7.03229E-05
70	445	0.0031286	0.0312857	7.03051E-05
71	450	0.0031629	0.0316293	7.02874E-05
72	455	0.0031973	0.0319728	7.02699E-05
73	460	0.0032316	0.0323162	7.02526E-05
74	465	0.0032659	0.0326595	7.02354E-05
75	470	0.0033003	0.0330027	7.02185E-05
76	475	0.0033346	0.0333458	7.02016E-05
77	480	0.0033689	0.0336888	7.0185E-05
78	485	0.0034032	0.0340317	7.01685E-05
79	490	0.0034375	0.0343745	7.01521E-05
80	495	0.0034717	0.0347172	7.01358E-05
81	500	0.0035060	0.0350599	7.01198E-05

3. Compressibility computation of gelled crude oil at 25°C based on the fitted function of piston displacement Eq. 4.5.

Table A.3. Compressibility computation of experiment's object 25°C.

No.	ΔP (kPa)	ΔL	ΔL / L	Compressibility (ΔL / L / ΔP)
1	100	0.0010055	0.0100550	0.00010055
2	105	0.0010547	0.0105466	0.000100444
3	110	0.0011036	0.0110363	0.00010033
4	115	0.0011524	0.0115241	0.00010021
5	120	0.0012010	0.0120101	0.000100084
6	125	0.0012494	0.0124941	9.99526E-05
7	130	0.0012976	0.0129762	9.98171E-05
8	135	0.0013456	0.0134565	9.96776E-05
9	140	0.0013935	0.0139348	9.95345E-05
10	145	0.0014411	0.0144113	9.93883E-05
11	150	0.0014886	0.0148859	9.92392E-05
12	155	0.0015359	0.0153586	9.90876E-05
13	160	0.0015829	0.0158294	9.89336E-05
14	165	0.0016298	0.0162983	9.87775E-05
15	170	0.0016765	0.0167653	9.86195E-05
16	175	0.0017230	0.0172304	9.84597E-05
17	180	0.0017694	0.0176937	9.82983E-05
18	185	0.0018155	0.0181550	9.81354E-05
19	190	0.0018615	0.0186145	9.79711E-05
20	195	0.0019072	0.0190721	9.78056E-05
21	200	0.0019528	0.0195278	9.76389E-05
22	205	0.0019982	0.0199816	9.74711E-05
23	210	0.0020433	0.0204335	9.73023E-05
24	215	0.0020883	0.0208835	9.71325E-05
25	220	0.0021332	0.0213316	9.69619E-05
26	225	0.0021778	0.0217779	9.67905E-05
27	230	0.0022222	0.0222222	9.66183E-05
28	235	0.0022665	0.0226647	9.64454E-05
29	240	0.0023105	0.0231052	9.62718E-05
30	245	0.0023544	0.0235439	9.60976E-05
31	250	0.0023981	0.0239807	9.59228E-05
32	255	0.0024416	0.0244156	9.57474E-05

33	260	0.0024849	0.0248486	9.55716E-05
34	265	0.0025280	0.0252797	9.53952E-05
35	270	0.0025709	0.0257090	9.52184E-05
36	275	0.0026136	0.0261363	9.50411E-05
37	280	0.0026562	0.0265618	9.48634E-05
38	285	0.0026985	0.0269853	9.46853E-05
39	290	0.0027407	0.0274070	9.45068E-05
40	295	0.0027827	0.0278268	9.4328E-05
41	300	0.0028245	0.0282447	9.41489E-05
42	305	0.0028661	0.0286607	9.39694E-05
43	310	0.0029075	0.0290748	9.37896E-05
44	315	0.0029487	0.0294870	9.36095E-05
45	320	0.0029897	0.0298973	9.34292E-05
46	325	0.0030306	0.0303058	9.32486E-05
47	330	0.0030712	0.0307123	9.30677E-05
48	335	0.0031117	0.0311170	9.28866E-05
49	340	0.0031520	0.0315198	9.27052E-05
50	345	0.0031921	0.0319207	9.25237E-05
51	350	0.0032320	0.0323197	9.23419E-05
52	355	0.0032717	0.0327168	9.21599E-05
53	360	0.0033112	0.0331120	9.19777E-05
54	365	0.0033505	0.0335053	9.17954E-05
55	370	0.0033897	0.0338968	9.16128E-05
56	375	0.0034286	0.0342863	9.14301E-05
57	380	0.0034674	0.0346740	9.12473E-05
58	385	0.0035060	0.0350597	9.10642E-05
59	390	0.0035444	0.0354436	9.08811E-05
60	395	0.0035826	0.0358256	9.06977E-05
61	400	0.0036206	0.0362057	9.05143E-05
62	405	0.0036584	0.0365839	9.03307E-05
63	410	0.0036960	0.0369602	9.01469E-05
64	415	0.0037335	0.0373347	8.99631E-05
65	420	0.0037707	0.0377072	8.97791E-05
66	425	0.0038078	0.0380779	8.9595E-05
67	430	0.0038447	0.0384466	8.94108E-05
68	435	0.0038813	0.0388135	8.92264E-05
69	440	0.0039178	0.0391785	8.9042E-05

70	445	0.0039542	0.0395416	8.88575E-05
71	450	0.0039903	0.0399028	8.86728E-05
72	455	0.0040262	0.0402621	8.84881E-05
73	460	0.0040620	0.0406195	8.83033E-05
74	465	0.0040975	0.0409751	8.81184E-05
75	470	0.0041329	0.0413287	8.79334E-05
76	475	0.0041680	0.0416805	8.77483E-05
77	480	0.0042030	0.0420303	8.75632E-05
78	485	0.0042378	0.0423783	8.73779E-05
79	490	0.0042724	0.0427244	8.71926E-05
80	495	0.0043069	0.0430686	8.70072E-05
81	500	0.0043411	0.0434109	8.68218E-05

4. Compressibility computation of gelled crude oil at 30^{o}C based on the fitted function of piston displacement Eq. 4.6.

Table A.4. Compressibility computation of experiment's object 30^{o}C.

No.	ΔP (kPa)	ΔL	ΔL / L	Compressibility (ΔL / L / ΔP)
1	100	0.0012399	0.0123988	0.000123988
2	105	0.0012933	0.0129332	0.000123174
3	110	0.0013465	0.0134653	0.000122412
4	115	0.0013995	0.0139950	0.000121695
5	120	0.0014522	0.0145223	0.000121019
6	125	0.0015047	0.0150471	0.000120377
7	130	0.0015570	0.0155696	0.000119766
8	135	0.0016090	0.0160897	0.000119183
9	140	0.0016607	0.0166074	0.000118625
10	145	0.0017123	0.0171228	0.000118088
11	150	0.0017636	0.0176357	0.000117571
12	155	0.0018146	0.0181462	0.000117072
13	160	0.0018654	0.0186543	0.00011659
14	165	0.0019160	0.0191601	0.000116122
15	170	0.0019663	0.0196634	0.000115667
16	175	0.0020164	0.0201644	0.000115225
17	180	0.0020663	0.0206629	0.000114794
18	185	0.0021159	0.0211591	0.000114374
19	190	0.0021653	0.0216529	0.000113963

20	195	0.0022144	0.0221443	0.00011356
21	200	0.0022633	0.0226333	0.000113166
22	205	0.0023120	0.0231199	0.00011278
23	210	0.0023604	0.0236041	0.0001124
24	215	0.0024086	0.0240859	0.000112027
25	220	0.0024565	0.0245653	0.00011166
26	225	0.0025042	0.0250423	0.000111299
27	230	0.0025517	0.0255169	0.000110943
28	235	0.0025989	0.0259892	0.000110592
29	240	0.0026459	0.0264590	0.000110246
30	245	0.0026926	0.0269265	0.000109904
31	250	0.0027392	0.0273915	0.000109566
32	255	0.0027854	0.0278542	0.000109232
33	260	0.0028314	0.0283145	0.000108902
34	265	0.0028772	0.0287723	0.000108575
35	270	0.0029228	0.0292278	0.000108251
36	275	0.0029681	0.0296809	0.000107931
37	280	0.0030132	0.0301316	0.000107613
38	285	0.0030580	0.0305799	0.000107298
39	290	0.0031026	0.0310258	0.000106986
40	295	0.0031469	0.0314694	0.000106676
41	300	0.0031910	0.0319105	0.000106368
42	305	0.0032349	0.0323492	0.000106063
43	310	0.0032786	0.0327856	0.00010576
44	315	0.0033220	0.0332195	0.000105459
45	320	0.0033651	0.0336511	0.00010516
46	325	0.0034080	0.0340802	0.000104862
47	330	0.0034507	0.0345070	0.000104567
48	335	0.0034931	0.0349314	0.000104273
49	340	0.0035353	0.0353534	0.00010398
50	345	0.0035773	0.0357729	0.00010369
51	350	0.0036190	0.0361901	0.0001034
52	355	0.0036605	0.0366049	0.000103113
53	360	0.0037017	0.0370174	0.000102826
54	365	0.0037427	0.0374274	0.000102541
55	370	0.0037835	0.0378350	0.000102257
56	375	0.0038240	0.0382402	0.000101974

57	380	0.0038643	0.0386431	0.000101692
58	385	0.0039044	0.0390435	0.000101412
59	390	0.0039442	0.0394416	0.000101132
60	395	0.0039837	0.0398372	0.000100854
61	400	0.0040230	0.0402305	0.000100576
62	405	0.0040621	0.0406214	0.0001003
63	410	0.0041010	0.0410098	0.000100024
64	415	0.0041396	0.0413959	9.97492E-05
65	420	0.0041780	0.0417796	9.94753E-05
66	425	0.0042161	0.0421609	9.92021E-05
67	430	0.0042540	0.0425398	9.89298E-05
68	435	0.0042916	0.0429163	9.86582E-05
69	440	0.0043290	0.0432905	9.83874E-05
70	445	0.0043662	0.0436622	9.81173E-05
71	450	0.0044032	0.0440315	9.78478E-05
72	455	0.0044398	0.0443985	9.7579E-05
73	460	0.0044763	0.0447630	9.73109E-05
74	465	0.0045125	0.0451252	9.70433E-05
75	470	0.0045485	0.0454849	9.67764E-05
76	475	0.0045842	0.0458423	9.65101E-05
77	480	0.0046197	0.0461973	9.62443E-05
78	485	0.0046550	0.0465498	9.59791E-05
79	490	0.0046900	0.0469000	9.57144E-05
80	495	0.0047248	0.0472478	9.54502E-05
81	500	0.0047593	0.0475932	9.51865E-05

5. Compressibility computation of gelled crude oil at 20^{o}C with cooling rate 0.8^{o}C/min based on the fitted function of piston displacement Eq. 4.7.

Table A.5. Compressibility computation of experiment's object 20^{o}C, 0.8^{o}C/min.

No.	ΔP (kPa)	ΔL	ΔL / L	Compressibility (ΔL / L / ΔP)
1	100	0.0022176	0.0221760	0.00022176
2	105	0.0023497	0.0234974	0.000223784
3	110	0.0024802	0.0248017	0.00022547
4	115	0.0026089	0.0260891	0.000226862
5	120	0.0027359	0.0273595	0.000227995
6	125	0.0028613	0.0286128	0.000228902
7	130	0.0029849	0.0298491	0.000229608
8	135	0.0031068	0.0310684	0.000230136
9	140	0.0032271	0.0322707	0.000230505
10	145	0.0033456	0.0334559	0.000230731
11	150	0.0034624	0.0346242	0.000230828
12	155	0.0035775	0.0357754	0.000230809
13	160	0.0036910	0.0369096	0.000230685
14	165	0.0038027	0.0380268	0.000230466
15	170	0.0039127	0.0391270	0.000230159
16	175	0.0040210	0.0402102	0.000229772
17	180	0.0041276	0.0412763	0.000229313
18	185	0.0042325	0.0423254	0.000228786
19	190	0.0043358	0.0433576	0.000228198
20	195	0.0044373	0.0443726	0.000227552
21	200	0.0045371	0.0453707	0.000226854
22	205	0.0046352	0.0463518	0.000226106
23	210	0.0047316	0.0473158	0.000225313
24	215	0.0048263	0.0482629	0.000224478
25	220	0.0049193	0.0491929	0.000223604
26	225	0.0050106	0.0501059	0.000222693
27	230	0.0051002	0.0510018	0.000221747
28	235	0.0051881	0.0518808	0.000220769
29	240	0.0052743	0.0527427	0.000219761
30	245	0.0053588	0.0535877	0.000218725
31	250	0.0054416	0.0544156	0.000217662
32	255	0.0055226	0.0552265	0.000216574

33	260	0.0056020	0.0560203	0.000215463
34	265	0.0056797	0.0567972	0.000214329
35	270	0.0057557	0.0575570	0.000213174
36	275	0.0058300	0.0582999	0.000212
37	280	0.0059026	0.0590257	0.000210806
38	285	0.0059734	0.0597345	0.000209595
39	290	0.0060426	0.0604262	0.000208366
40	295	0.0061101	0.0611010	0.000207122
41	300	0.0061759	0.0617587	0.000205862
42	305	0.0062399	0.0623995	0.000204588
43	310	0.0063023	0.0630232	0.000203301
44	315	0.0063630	0.0636299	0.000202
45	320	0.0064220	0.0642195	0.000200686
46	325	0.0064792	0.0647922	0.000199361
47	330	0.0065348	0.0653478	0.000198024
48	335	0.0065886	0.0658865	0.000196676
49	340	0.0066408	0.0664081	0.000195318
50	345	0.0066913	0.0669127	0.00019395
51	350	0.0067400	0.0674002	0.000192572
52	355	0.0067871	0.0678708	0.000191185
53	360	0.0068324	0.0683243	0.00018979
54	365	0.0068761	0.0687608	0.000188386
55	370	0.0069180	0.0691804	0.000186974
56	375	0.0069583	0.0695828	0.000185554
57	380	0.0069968	0.0699683	0.000184127
58	385	0.0070337	0.0703368	0.000182693
59	390	0.0070688	0.0706882	0.000181252
60	395	0.0071023	0.0710226	0.000179804
61	400	0.0071340	0.0713400	0.00017835
62	405	0.0071640	0.0716404	0.00017689
63	410	0.0071924	0.0719238	0.000175424
64	415	0.0072190	0.0721901	0.000173952
65	420	0.0072439	0.0724395	0.000172475
66	425	0.0072672	0.0726718	0.000170992
67	430	0.0072887	0.0728871	0.000169505
68	435	0.0073085	0.0730854	0.000168012
69	440	0.0073267	0.0732667	0.000166515

70	445	0.0073431	0.0734309	0.000165013
71	450	0.0073578	0.0735781	0.000163507
72	455	0.0073708	0.0737084	0.000161996
73	460	0.0073822	0.0738216	0.000160482
74	465	0.0073918	0.0739178	0.000158963
75	470	0.0073997	0.0739969	0.00015744
76	475	0.0074059	0.0740591	0.000155914
77	480	0.0074104	0.0741042	0.000154384
78	485	0.0074132	0.0741323	0.00015285
79	490	0.0074143	0.0741434	0.000151313
80	495	0.0074138	0.0741375	0.000149773
81	500	0.0074115	0.0741146	0.000148229

B. Documentation of the Experiment

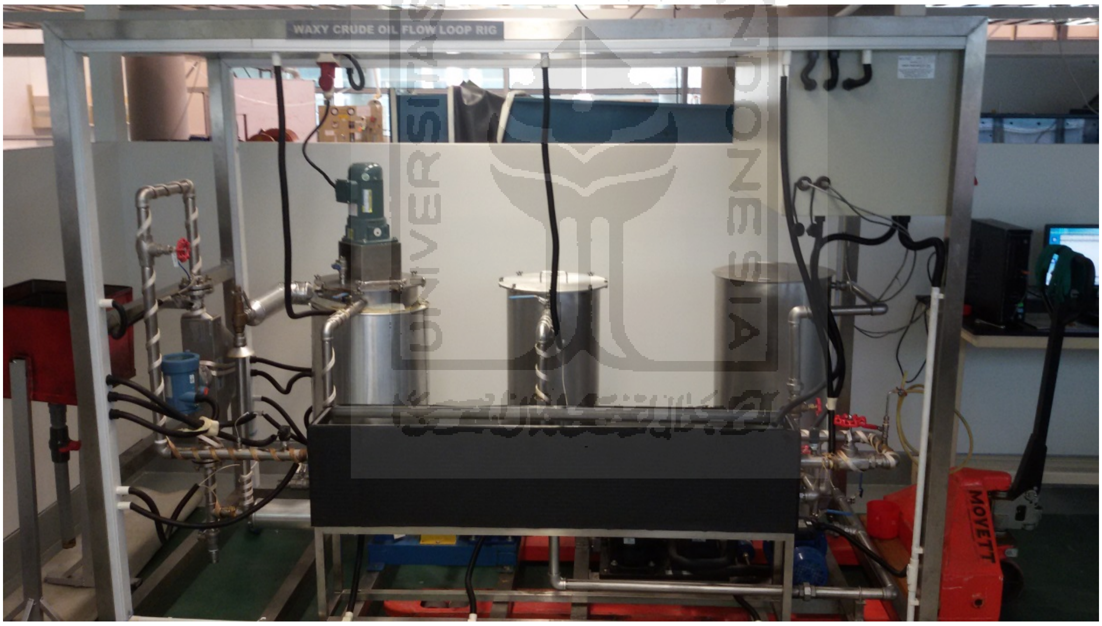

Figure B.1. Flow-loop rig of waxy crude oil.

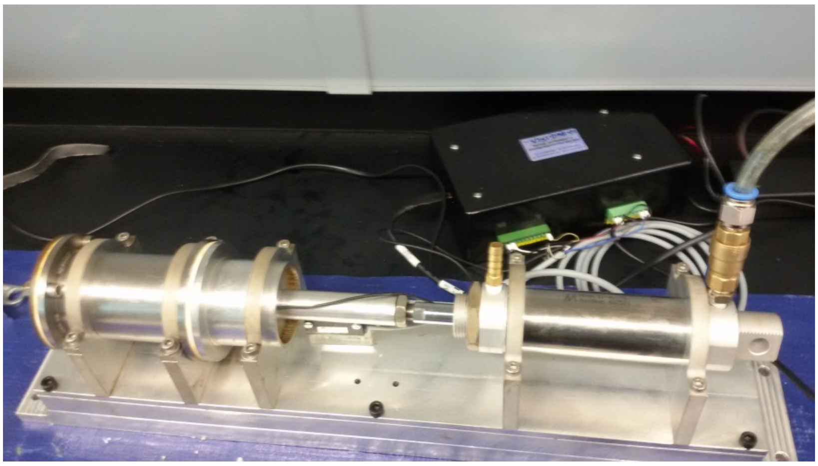

Figure B.2. Compression device.

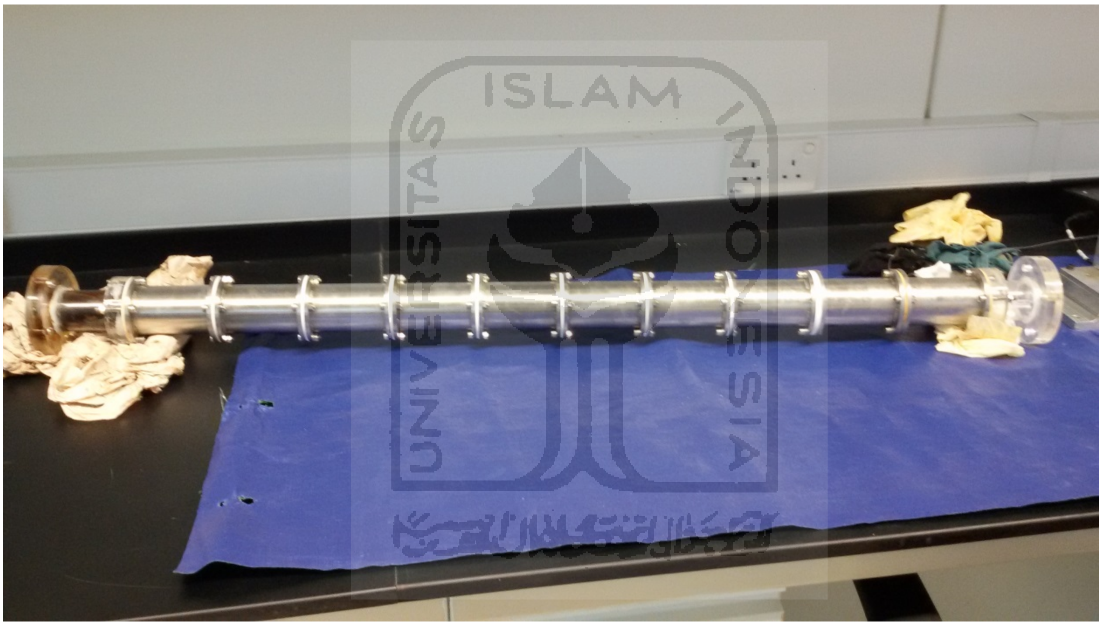

Figure B.3. Pipe of the test section.

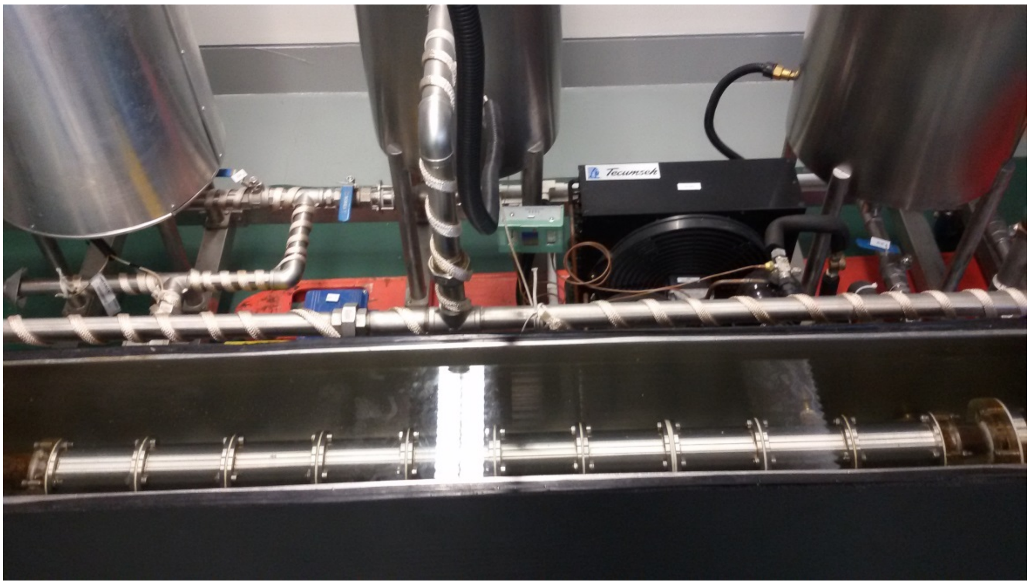

Figure B.2. Sea bath for cooling process.


Figure B.5. Fixing the test section in Flow-loop rig.

Figure B.6. Test sample of compression test.

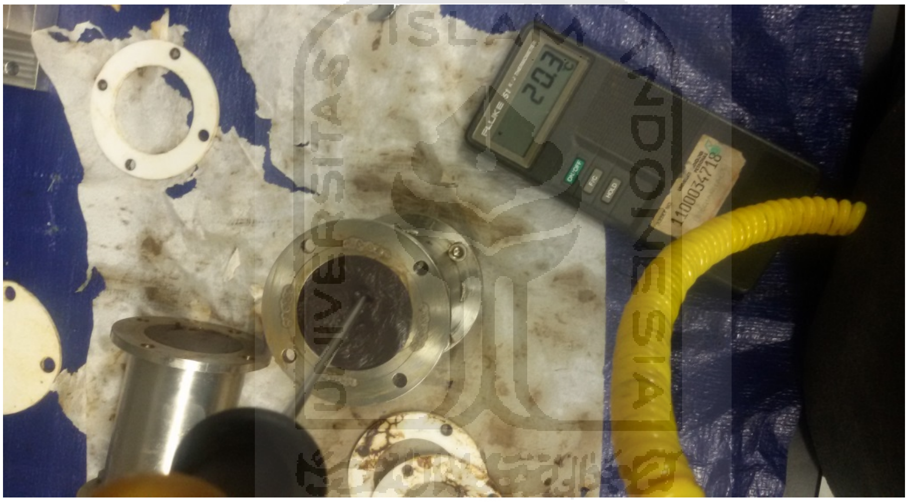

Figure B.7. Temperature reading of the test sample.

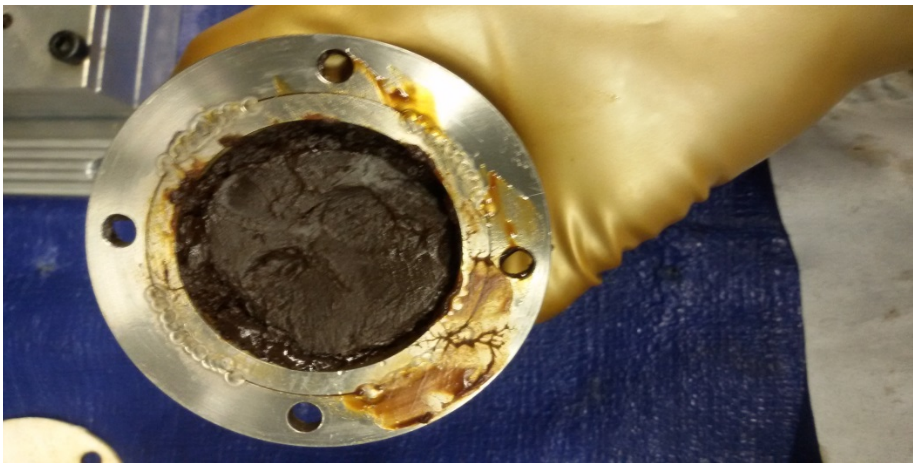

Figure B.8. Compressed test sample.

C. Profile of the Author

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