Characterization of Restart Pressure in Production Pipeline for Waxy Crude Oil as A Result of Injection of Non-Reacting Gas

by

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CERTIFICATION OF APPROVAL

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Approved by,

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(Ir Dr Shaharin Anwar bin Sulaiman)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
January 2016

CERTIFICATION OF ORIGINALITY

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

BLYTHE KOLLIAS ANAK BIGA

ABSTRACT

Wax deposition within the walls of production pipeline of crude oil causes flow assurance issue due to reduction in flow rate. In the event of planned maintenance or an emergency shutdown due to bad weather condition, the crude oil will stop flowing in the pipeline, in which the temperature of the crude oil may drop below the Pour Point Temperature (PPT). As the crude oil is under a quiescent condition, wax crude oil may precipitate out of its liquid phase and becomes a wax-gel oil like substance, which may cause blockage in the pipeline. A high pumping pressure is needed in order to restart the pipeline and disintegrate the wax-oil gel. A recent study on gas voids in cured oil showed that the presence of gas voids within the pipeline could reduce the restart pressure needed to restart a crude oil production pipeline. It was anticipated that the volume of the gas voids could be increased through the injection of non-reacting gas in order to reduce the restart pressure needed. However, there was no previous attempt to study if the proposal would be practical in practice. The present study is aimed at studying the effects and effectiveness of gas bubbles intrusion through injection of external gas with respect to the restart pressure. A waxy crude oil flow loop was used in order to simulate the condition of a gelled waxy crude oil within the crude oil production line. A nitrogen gas injection system was attached to the test rig in order to inject the gas into the test section. The test section was injected with nitrogen gas just after the flow is stopped and is under static cooling at water bath temperatures of 15ºC, 20ºC and 25ºC. Once the crude oil temperature has dropped to the water bath's temperature, the pipeline is restarted with the aid of a 1.1 kW gear pump so as to disintegrate the wax within the pipeline. There were 2 ways in which the restart pressure is applied, namely the instantaneous restart and gradual restart approach. It was observed that the restart pressure under instantaneous and gradual start up approach decreases as compared to a restart pressure of a non-injected pipeline. A maximum restart pressure reduction of 11.48% and 17.44% was observed when the pressure is applied under instantaneous restart and gradual restart pressure approach. Through this study, it is shown that injection of nitrogen gas into the pipeline is able to reduce the restart pressure needed and thus allowing pipeline operators to reduce their capital and operational expenditure on acquiring additional pumps during pipeline restart operation.

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I would like to thank UTP for providing this course to final year students as it teaches students on how to apply their theoretical engineering knowledge into practice. As a final year student, it is imperative to apply all the knowledge that has been collected throughout five years of engineering study in UTP. Throughout this FYP course, I have equipped myself with both technical and soft skills through experimental works as well as presentations in which it is very much sought after in the industry.

I would like to take this opportunity to thank the Lab, Facilities and Services Department of UTP for consulting and guiding me throughout the FYP course. With their consultation, I managed to complete the gas injection system which is required in this study.

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TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

This chapter discusses about the background on the flow assurance issues due to presence of paraffin (wax) in waxy crude oil. This in turn will affect the pressure needed in order to restart the crude oil flow as the required pressure will be higher as compared to its operating pressure. The problem statement, objective and the scope of study are further discussed in detail within this chapter.

1.1 Background

Crude oil is currently the primary source of energy throughout the world. The global demand for this resource provides a challenge as we need to source for heavier, waxy crude oils and this leads to deeper water depth exploration within the oil producing region. Within the last decade, the exploration within the new oilfields has resulted a production of high quantities of waxy crude oil, in which it accounts for 20% of world petroleum reserves. It has been forecasted that the oil production from the deep sea water in 2017 will be three times greater at 8 million barrels a day as compared to the deep sea water production in 2002 (Venkatesan et al., 2002). Waxy crude oil is defined as a crude oil having a high pour point temperature (PPT) and low American Petroleum Institute (API) gravity and would contain paraffin wax (alkanes) (Bomba, 1986).

The current problem with waxy crude oil towards production is flow assurance issues due to paraffin (wax) deposition during the production and processing stage (Hamami et al., 1999). Paraffin wax deposition has cost billions of dollars to the oil and gas production industry as it reduces the production rate, increases the cost of chemical to mitigate pipeline blockage, choking of the flow line, equipment failure and an increase in horse power requirement. Due to this problem, based on the United States Department of Energy, the cost of remediation for pipeline blockage in water depths of around 400 meter can easily reach US $1 million/mile (Venkatesan et al., 2005).

According to Venkatesen (2005), under operating condition at reservoir temperature around 70ºC - 150ºC and pressures in the range of 8000-15000 psi, the wax molecules are soluble in crude oil and exhibits properties of Newtonian liquid. As the crude oil is transported within the pipeline, the crude oil temperature decreases, causing the temperature of it to drop below the Wax Appearance Temperature (WAT). WAT is a temperature region in which visible crystallization is observed. This is due to heat loss of crude oil to the surrounding, causing wax deposition along the pipeline. If the flow of the crude oil is stopped due to emergency situation such as during a bad weather or during a planned maintenance, the quiescent condition in the pipeline will cause the temperature and the solubility of the wax to decrease even further and the wax molecules will precipitate out of its liquid phase. If the crude oil is left trapped in the pipeline (depending on the rate of cooling), the temperature of the crude oil will drop below the Pour Point Temperature (PPT) and will become wax-oil gel due to the interlocking of solid wax crystals. At this conditions, the wax-oil gel will cause blockages within the pipeline (Lee et al., 2007).

Figure 1.1 shows cross-sectional view of a cut-away segment of a pipeline due to paraffin deposits along the pipe wall. The internal bore is significantly reduced and thus reducing the effective crude oil flow rate. The deposition of wax is largely dependent on flow rate of the crude oil, the temperature differential between the crude oil and the pipe surface, the cooling rate between the crude oil and the pipe surface and the pipeline surface properties (Misra, 1995).

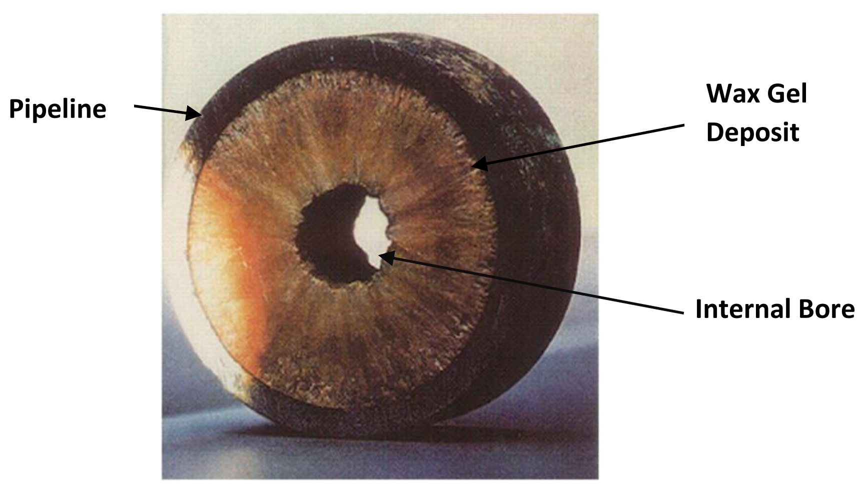


Figure 1.1: Cross-sectional view of paraffin deposits in pipeline (Venkatesan et al., 2005)

As a result of the blockage, the current operating pressure is not sufficient in order to displace the gelled oil. The pressure which must be applied needs to be more than the operating pressure in order to overcome the yield stress of the gelled oil and this will require the procurement pump with higher pumping capacity in order to restart the pipeline. A business will need to spend more on their capital expenditure (CAPEX) and operational expenditure (OPEX) in order to install additional pump in order to restart the pipeline.

In order to predict a restart pressure of a clogged pipeline, this conventional pressure difference is obtained through (Lee et al., 2007):

$$\Delta P = \frac{4\tau_{yL}}{D} \tag{1.1}$$

where Δp, L, D and τ_y are pressure difference applied to break the gel, length of the pipeline, internal diameter of the pipeline and yield stress of the gel respectively. The yield stress of the gel must be determined first before the pressure difference can be calculated.

Major heavy oil producing countries such as Venezuela, Mexico, Canada, Oman and California has flow assurance related issues such as wax deposition within its pipelines and flowlines (Mehta et al., 2004). According to Venkatesan et al (2005), Lasmo Oil Company (UK) had to abandon an off-shore oil platform due to wax plugging issue that keeps recurring and had cost them over 100 million dollars to remediate. The oil and gas fields in Malaysia suffers from the same problem as well, having wax deposition within its pipelines. The Puteri Field, located in Block PM 318 in Offshore Terengganu Peninsular Malaysia had wax deposition issues in which it stopped the oil production all together (Ragbir, 2014). The Puteri crude oil has a high cloud point of 69ºC and pour point temperature of 49ºC and provides flow assurance issues during operation. Due to a prolonged shutdown combined with the average water temperature of 24 degrees Celcius, it has caused a large wax plug in the Puteri Full Well Stream (FWS) pipeline, making the pipeline unserviceable. Figure 1.2 shows the Puteri Field which is located offshore of Terengganu, Peninsular Malaysia. The problems faced in Malaysia is not comparable to the other parts of the world as the composition of the crude oil, the operating water depth, seabed temperature and WAT and PPT of crude oil is different since it is dependent on geographical location.

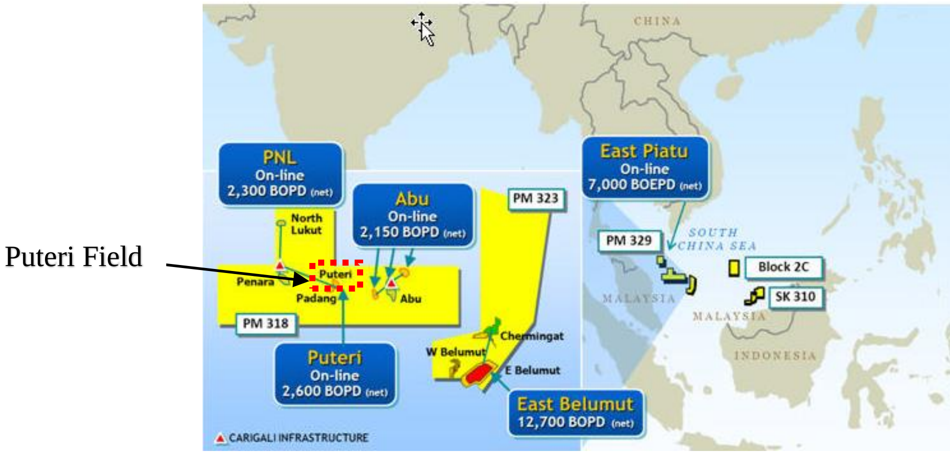


Figure 1.2: Puteri Field, Offshore Terengganu, Peninsular Malaysia (NFX, 2012)

1.2 Problem Statement

The presence of local gas voids that happens during thermal shrinkage due to decrease in the volume of waxy-crude gel during cooling was observed by previous researchers and it is believed to ease in restarting the pipeline. Previous studies on thermal shrinkage with relation to gas voids have concluded that gas voids along the waxy-oil gel structure is able to ease in restart pressure. Vinay et al (2007) observed that gas voids within the range of 4%-8% of the total length of the pipe were not unusual under shutdown conditions. The volume of the gas voids within the gel structure can be increased/manipulated through the injection of non-reacting gas into the pipeline. However, it is uncertain on how effective is the gas void in reducing the restart pressure. On top of that, the effectiveness of gas voids volume within the waxy-oil gelled structure in easing the restart pressure through the injection of external gas still remains unclear. Not only that, the ability of the gas to penetrate into the crude oil during flow and when the flow is completely stop flowing remains unclear as well. It was noted that air was used in the previous study conducted by Zakaria (2014). Since air might not be feasible for this study due to its combustion supportive nature, nitrogen gas which is a gas with inert/non-combustible properties will be used. Additional study using nitrogen gas may be required in order to understand its usage in restart pressure. An isolated test may need to be conducted in order to understand the effect of air on crude oil as opposed to nitrogen. Therefore, there is a need to study the restart pressure with relation to the volume of the artificial gas voids.

1.3 Objective and Scope of Study

The objective of this work is to study the effects of gas bubbles intrusion through injection of external gas in restart pumping. Through the injection of gas bubbles into the pipeline, it is anticipated that the restart pressure will be reduced as this affects the compressibility of the gelled crude within the pipeline as the gelled crude have more space to move when a pressure is applied. With the reduction in restart pressure, a business is able to reduce their OPEX and CAPEX as they might not have to spend more on additional pumps.

The scope of the study is the experimental works of intrusion of gas bubbles at the inlet of the test section of the test rig, under which the gas injection will be done after the pipeline has stop flowing and before the crude oil gelation occurs. The crude oil used under this study is taken from Sepat Field, Offshore Terengganu, Peninsular Malaysia. This crude oil is kept constant throughout the study as crude oil is known to have different wax appearance temperature, pour point temperature, density and viscosity parameters depending on its location. Under this study, the experiment is conducted on a waxy crude oil flow loop which is located in Universiti Teknologi PETRONAS (UTP).

CHAPTER 2

THEORY AND LITERATURE REVIEW

This chapter discusses in detail regarding previous works done by other researchers related to waxy crude oil and the restart pressure. Parameters which contributes to the ease in restart pressure is identified and discussed as well. The fundamentals and terminologies used are described in a more detailed manner as to give an overview to the readers about the current work.

2.1 Characteristics of Waxy Crude Oil

Waxy or highly paraffinic crude oil can cause severe damage to subsea pipelines, due the capability of the wax-oil gel to deposit within the pipeline. Waxes are mixtures which contains long chain hydrocarbons (n-paraffins) with carbon chain lengths with a range of C15 to C75+ (Hunt, 1996). Paraffin, the organic compound within the crude oil are classified possibly being in the deposit as (1) aliphatic hydrocarbons (both straight and branched chains), (2) aromatic hydrocarbons, (3) napthenes and (4) resins and asphaltenes (Shock et al., 1955). The gelled oil exhibits a complex time-dependent rheology with a yield stress and viscosity in which it depends on the time duration of shearing. It was noted that paraffin compounds which contains more than 20 carbon atoms are a potential threat to most of the oilfield operators. According to Hamami (1999), these waxes are crystalline in nature and will usually precipitate or crystallize out from the crude oil at temperature below its cloud point or "Wax Appearance Temperature (WAT)" point. Furthermore, according to Venkatesan et.al (2005), the deposition of paraffin takes place due to its solubility which is highly affected by temperature. He added that under reservoir temperatures at a range of 70-150ºC and with the pressure range of 8000-15000 psi, paraffin is soluble and behaves as a non-Newtonian fluid. As temperature of the crude oil decreases, the solubility of paraffin in the crude oil decreases drastically, in which it allows them to precipitate out and crystalize onto the pipeline wall. Waxy crude oils are considered to be thixotropic materials, apart than being a shear dependent, in which the rheological properties such as the viscosity and the yield stress depends on the thermal and mechanical history (Livescu, 2012 ; Tiwary et al., 2004). It was noted by Cazaux et al., (1998) that the key parameters in order to define the structure of the wax-oil gel structure would be through the shape of the crystal and the density of the wax crystals. Both size and shape of the wax crystal that is present in crude oil depends on the shear rate and the asphaltene fraction. Both of these parameters depends on the surrounding pipeline temperature as well as the cooling rate of the crude oil.

2.2 Wax Appearance Temperature (WAT) and Pour Point Temperature (PPT)

The temperature of the crude oil decreases as it moves along the pipeline due heat loss to the seabed in which it has a temperature range of 2ºC - 25ºC. Wax will start to precipitate out from the crude oil when the crude oil temperature reaches below the ‘cloud point’ or the “Wax Appearance Temperature (WAT)” point (Venkatesan et al., 2005). WAT is the temperature region in which visible crystallization occurs. As the temperature of the crude reaches WAT, the energy of the molecular motion becomes hindered and moves closer together to form a cluster of adjacently aligned chains. At temperature below the WAT, the crude oil will exhibit non-Newtonian fluid properties. The quality of the wax as well as the structure of the wax crystals being deposited along the walls of the pipeline will influence the crude oil flow. The process of nucleation begins when these paraffin molecules continues to attach to one another and reaches its critical size. Clusters of this molecule is called nuclei (Hamami, 1999). Thermodynamic WAT and experimentally-measured WAT were defined differently, according to Karan et al., (2000). There are currently different methods in which the WAT and cloud point temperature can be measured. Due to this, the true definition of WAT largely depends on the measurement principles of the equipment and the techniques as well as the procedures used during measurement. A thermodynamic WAT is defined as a true solid-liquid phase temperature boundary whereby the solid and liquid phases exist in an equilibrium at a fixed pressure. An experimentally-measured WAT is obtained experimentally at a fixed pressure in which it is usually lower than the thermodynamic WAT. The difference in thermodynamic WAT and experimentally-measured WAT is largely due to the sensitivity of the measuring equipment used. The experimentally-measured WAT depends largely on the sensitivity of the equipment since the temperature obtained represents the point in which the first crystal is first visibly detected.

There are several experimental technique that are currently being used in the laboratory in order to determine the WAT such as American Society for Testing and Materials (ASTM) D2500-88 or IP 219/82 methods, cold finger (CF), light transmittance (LT), cross polar microscopy (CPM), differential scanning calorimetry (DSC), filter plugging (FP) , Fourier Transform (FT-IR) spectroscopy (Hamami et al., 2004), Fourier Transform Infrared (FTIR) light scattering, differential scanning calorimetry (DSC) ultrasonic (Karan et al., 2000) and many more (Hammami et al., 2004)

Pour Point Temperature (PPT) defined as temperature in which the crude oil solidifies, producing wax-oil gels along the pipeline. This causes the amount of precipitated wax to increase significantly. The PPT is a rheological property of a waxy crude oil and is generally being used to define the 'waxiness' of the crude oil (Karan et al., 2000). PPT is usually tested/measured by using the ASTM D97 procedure. A new testing standard which is the ASTM D 5853-93, is used specifically to measure a crude oil's PPT. According to Ahmad (2012), the range of PPT for crude oil Malaysia is in between 18ºC - 36ºC.

Table 2.1 shows the terminology alongside with its definition and Table 2.2 shows the crude oil regions and its conditions.

Table 2.1: Terminology and its definitions (Karan et al., 2000)

Terminology	**Definition**
Wax Appearance Temperature (WAT)	The temperature at which the first crystals are detected
Pour Point Temperature (PPT)	The temperature in which crude oil solidifies during a temperature drop, causing an increase in the amount of precipitated wax
Boiling Point	The temperature at which the vapour pressure of the liquids equals the pressure surrounding the liquid and changes into vapour
Melting Point	The temperature at which it changes state from solid to liquid

Table 2.2: Waxy crude oil temperature regions and its condition (Karan et al., 2000)

Region	Condition
Above WAT	The fluid acts as a Newtonian fluid and no occurrence of wax deposition
Between WAT and PPT	The crude oil exhibits mild non-Newtonian fluid properties
Below PPT	The crude oil has tendency to become gel under non-flowing condition

2.3 Restart Pressure of Pipeline

In order to restart a pipeline after a shutdown period due to maintenance or bad weather, an applied pressure higher than the normal operating pressure is usually required in order to displace and overcome the yield strength of the gelled crude oil. The pressure difference, ΔP is calculated through Equation (1.1). ($\Delta P = \frac{4\tau_{yL}}{D}$). When the restart pressure is applied and the oil begins to flow, it will subject further shear within the pipeline and causes a breakdown through the waxy structure. This causes the oil viscosity to decrease and the oil flow to increase over time (Ronningsen, 1991). The amount of time needed to restart the pipeline depends on the pressure being applied and the rate of change of viscosity under shear stress as well as the compressibility of the oil. Theoretically, the gelled oil and the displacing liquid is assumed to be incompressible but that is not the case in practice. This has caused overestimation in the restart pressure of a gelled pipeline. Under practical conditions, both the gelled oil and the displacing liquid is compressible and the oil is not homogenous within the pipeline.

2.4 Yield Stress of Wax

The problem of paraffin deposition within the pipeline walls is not new during the production and transportation phase of crude oil. The cooled wax-oil gel within the pipeline has a very high yield stress, in some cases far exceeds the maximum allowable pressure that the particular pipeline may handle (Davidson et al., 2004 ; Lee et al., 2007 ; Shafquet et al., 2013). A gel strength can be measured in terms of its yield stress and therefore it is necessary to estimate the gel's strength in order to restart a blocked pipeline. In many years, there have many researches on how to overcome the restart problem of waxy crude oil in pipeline. Fossen et al (2013) noted that several techniques such as small pipe diameter restart experiments, the usage of rheometer and studies of the physics of the gel during the formation and breaking using an applied external shear force can be performed in order to assess the magnitude of the yield stress. Obtained yield stress will determine the required pumping pressure in order to initiate the flow during restart operations (Fossen et al., 2013). There are multiple factors that affects the investigation of restart pressure as observed by Phillips et al., (2011) and (2012). These factors include the rate of fluid cooling and shear forces acting on the fluid during cooling.

Wardhaugh and Boger (1991) in their paper has described qualitatively the yielding of waxy crude oils in detailed manner. The three mechanism for yielding of waxy crude oil are: (a) elastic response (b) creep and (c) sudden and dramatic failure. Figure 2.1 shows the transition from the elastic response to creep corresponds to the elastic limit yield stress (τ_e). At the starting point of the fracture (point B), the stress corresponds to static yield stress (τ_s) while the dynamic yield stress (τ_d), can be calculated after the complete fracture of the structure (at point C). Based on this experiment, it is observed that the elastic limit and the static yield stress are dependent upon the strength of the interlocking network of wax crystal before it was disturbed. The dynamic yield stress is highly dependent on the concentration and the size of the wax particles within the oil after the structure is completely disintegrated (Chang et al.,1998).

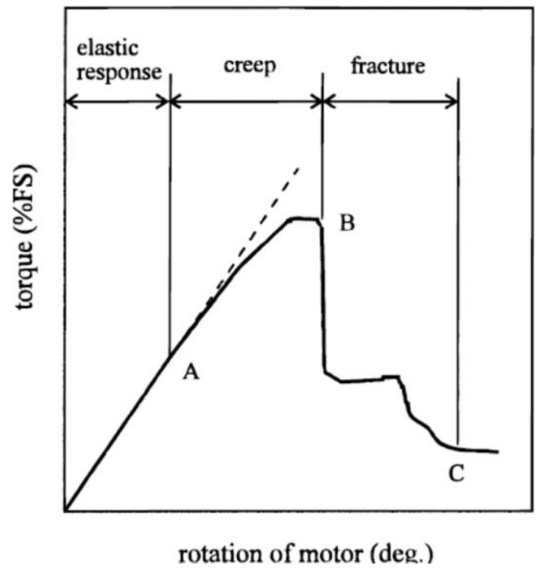


Figure 2.1: Yielding process of a waxy crude oil (Chang et al., 1998)

2.5 Effects of Cooling Rate on Crude Oil

There were several researches done on effect of cooling rates on a strength of a gelled wax. In an experiment conducted by Venkatesen et al (2005), a Cambridge Optical Shearing System (CSS 450) was used in order to observe the crystal structure of a wax that was formed under shear which was subjected to different cooling rates. It was found that the wax particle formed under a lower cooling rate of 1.8ºF/min were larger in size than the ones that was been formed under a high cooling rate of 10.8ºF/min. The maximum length of wax crystals formed was about 37 µm and 17 µm respectively for low and high cooling rate respectively. Within the study, it was noted that there were higher number of wax crystals being formed under a high cooling rate as compared to the lower cooling rate. This happens due to the decrement in crystal size and an increment in crystal number density as the cooling rate increases, leading to a higher number of wax crystals being formed. Figure 2.2 shows the effect of cooling rate on the size and number of wax crystals subjected to low cooling rate and high cooling rate of 1.8ºF/min and 10.8ºF/min respectively.

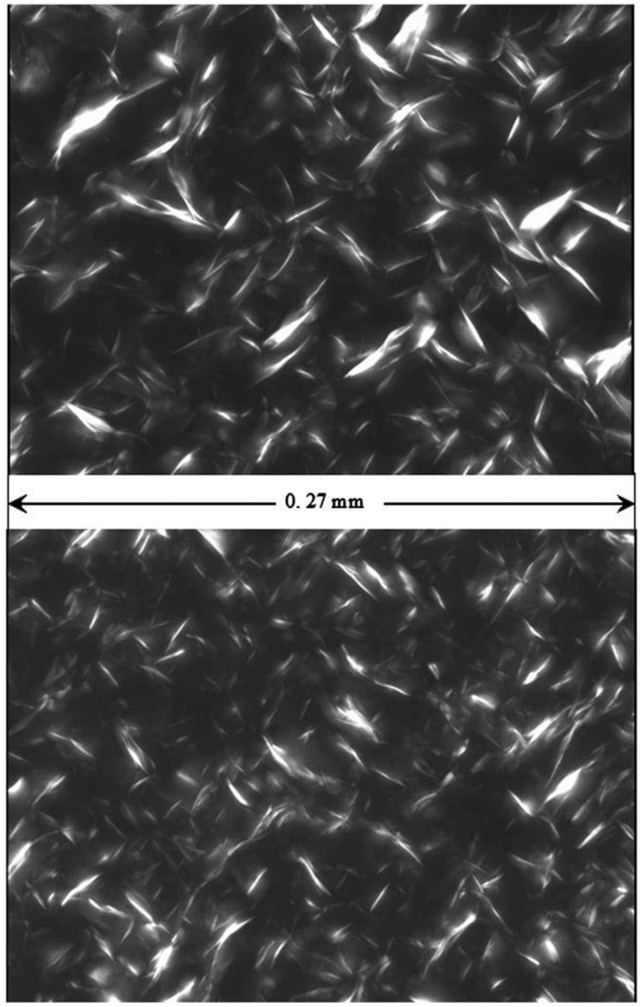


Figure 2.2: Size and number of wax crystals formed under low and high cooling rate (Top: 1.8ºF/min; Bottom: 10.8ºF/min) (Venkatesen et al. 2005)

Based on an experiment conducted by Lee et al (2007), in which a wax-oil mixture which was composed of 15% food grade paraffin (Gulf Wax), 33% kerosene and 52% mineral oil by weight was used in order to study the cohesive failure and adhesive failure of the wax subjected to low and high cooling rates of 3.5ºC/hr and 20ºC/hr respectively. The strength and the restart pressure of the wax-oil gel is dependent on the cooling rate under quiescent condition. Figure 2.3 shows the gel stress strength against rate of cooling. As shown in Figure 2.3, it was found that the gel failure strength increases with increasing cooling rates at low cooling rates and decreases at high cooling rate and there exists a delineation point between them.

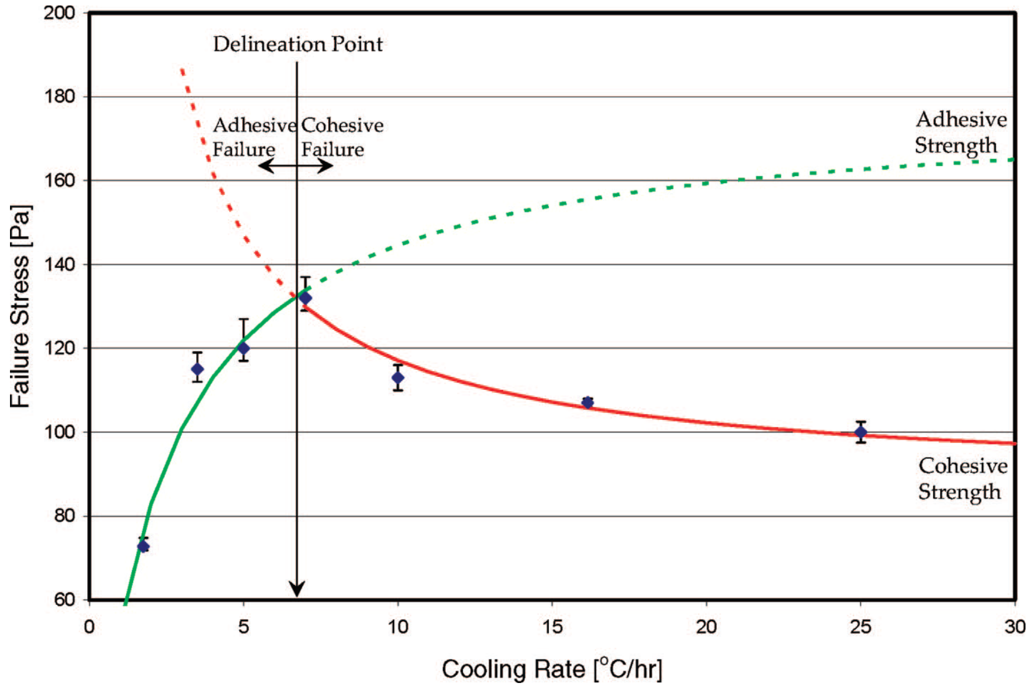
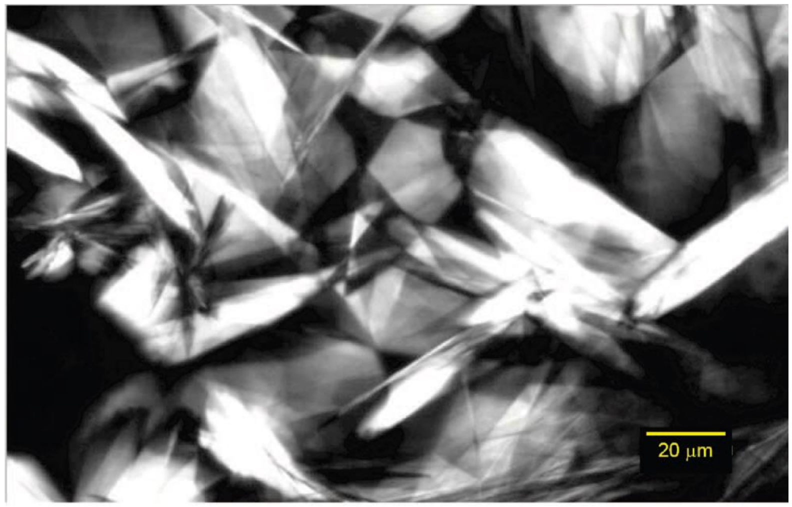


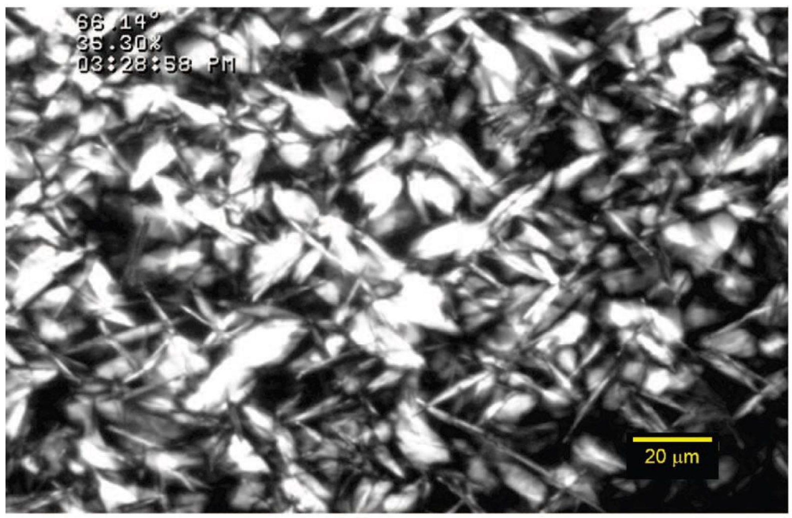
Figure 2.3: Gel failure stress vs cooling rate (Lee et al., 2007)

Based on Figure 2.3, when the cooling rate is below the delineation point of 7ºC/hr, the cohesive strength of the wax-oil gel is higher as compared to the adhesive strength and thus the gel will suffer from adhesive failure. In this case, the gel breaks away adhesively at the interface of the pipe metal surface. At a higher cooling rate beyond the delineation point, the gel will have a high adhesive strength as compared to the cohesive strength and thus will fail cohesively. By this, the gel will break within the gel structure itself cohesively.

Figure 2.4 shows the cross polar microscope photo of wax-oil gel under low and high cooling rate of 3.5ºC/hr and 20ºC/hr respectively.



(a) Cooling rate = 3.5°C/hr



(b) Cooling rate = 20°C/hr

Figure 2.4: Cross-polarized microscope photo of wax-oil gel for (a) Cooling rate of 3.5ºC/hr and (b) Cooling rate of 20ºC/hr (Lee et al., 2007)

As shown in Figure 2.4, the wax crystals formed under low cooling rate has a larger crystals and has a sheet like shape with an average surface area of 20 μm x 50 μm whereas the wax crystals formed under a high cooling rate is smaller and has the shape of a needlelike crystals and has an average surface area of 1μm x 20 μm. It was noted that the wax crystals subjected to high cooling rate has higher density as compared to the wax crystal subjected to low cooling rate. With this observation, it explains why there is a decrement in cohesive strength and an increment in adhesive strength as the cooling rate increases.

2.6 Effect of Pipe Diameter

Several researches have been conducted in order to study the dependency of yield stress of the wax on pipe diameter. A study by Davenport and Boger (1991) was conducted, in which pipes with diameter of 6-75 mm were used and they found that the yield values increases with decreasing pipe diameter. Another recent experiment conducted by Philips et al., (2011), in which small pipe sizes of 5.9 mm and 12.7 mm inner diameter were used. Through their experiments and numerical simulations, they have suggested several model predictions in which it is related to fluid volume shrinkage, shrinkage flow and void formation during a gel formation. It has been noted that the calculated restart pressures based on a small diameter pipe experiments would be too conservative, in which this would lead an overestimate of the restart pressure. An overestimate in the restart pressure would lead to an over design of the pump. A recent study by Fossen et al., (2013) in which an experiment was conducted on a larger diameter pipes, in order to study the effect of the pipe diameter on the yield stress. In the experiment, 3 carbon steel pipes with diameters of 28 mm, 55 mm and 82 mm at the length of 5.8 m were used and mounted horizontally and levelled. It was found during the experiment that the predicted restart pressure obtained based on the yield stress found on a 4.3 mm diameter pipe deviated by 140% in comparison to that of an 82 mm diameter pipe. Through this study, it was found that restart pressure could be over predicted if the calculation was made from yield stress values taken from a small diameter pipe experiment.

2.7 Thermal Shrinkage

As the crude oil undergoes gelation process, a phenomenon called “thermal shrinkage” takes place. As mentioned by Shafquet et al., (2013), gas voids appear during thermal shrinkage process in which it results in compressible nature. These gas voids affect the compressibility of the gelled structure since they have space for it to move due to applied pressure from a liquid and this significantly reduces the restart pressure required to break the wax-oil gel. Figure 2.5 shows the gas voids formed within gelled waxy crude oil. Experiments conducted by Wasch et al (2007), in which 1.5D numerical model was used in order to demonstrate that the flow could be restarted with a pumping pressure well below the value predicted by Equation 1.1 due to the presence of gas voids along the pipeline.

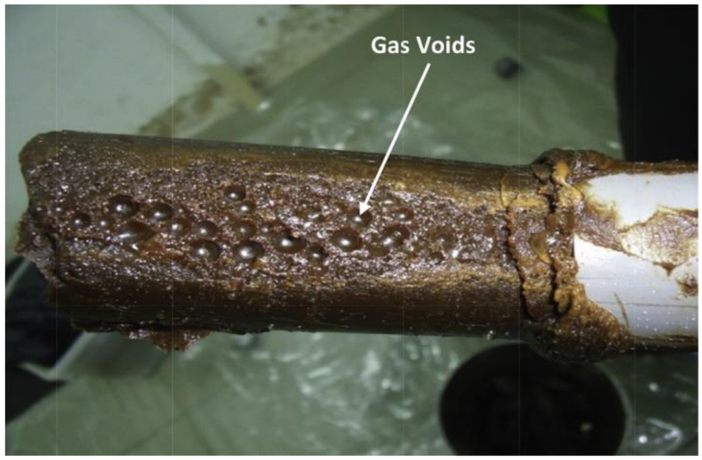


Figure 2.5: Gas voids formation on waxy crude oil (Chala et al., 2014)

The location and volume of gas voids strongly depends on the cooling rate of the crude oil and temperature as observed by Henaut et al (1999). As mentioned by Lee et al., (2007), there are many factors that contribute to the wax-oil gel properties since not all wax-oil gel formed within the pipeline is homogenous due to thermal and shear history within its axial and radial locations inside the pipeline. Due to this, the size and the shape of the wax crystals that is near the pipe wall might be different than those found at the center of the pipeline. Another research by Chala et al (2014) was done in order to observe and quantify the gas voids within the gelled crude oil due to thermal shrinkage, in which it was proven that gas voids formation depends not only on temperature of the crude oil but also on the cooling rate. A high cooling rate of 1.01ºC/min was observed to have large gas voids area near the wall of the pipe. Figure 2.6 shows the effect of cooling rates on gas voids distribution near the pipe wall. Along the center of the pipe, it was noted that low cooling rate of 0.45ºC/min has a large gas voids area as compared to high cooling rate of 1.01ºC/min along the center of the pipe. Figure 2.7 shows the effect of cooling rates on gas voids distribution around the center of the pipe. This shows that gas voids within the cooled gel has a profound effect on the restart pressure of pipeline.

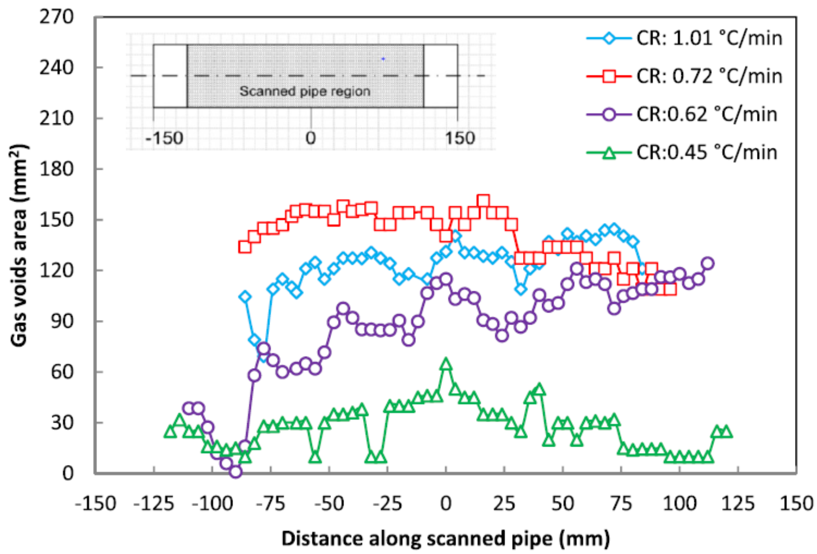


Figure 2.6: Effect of cooling rates on gas voids distribution near the pipe wall (Chala et al., 2014)

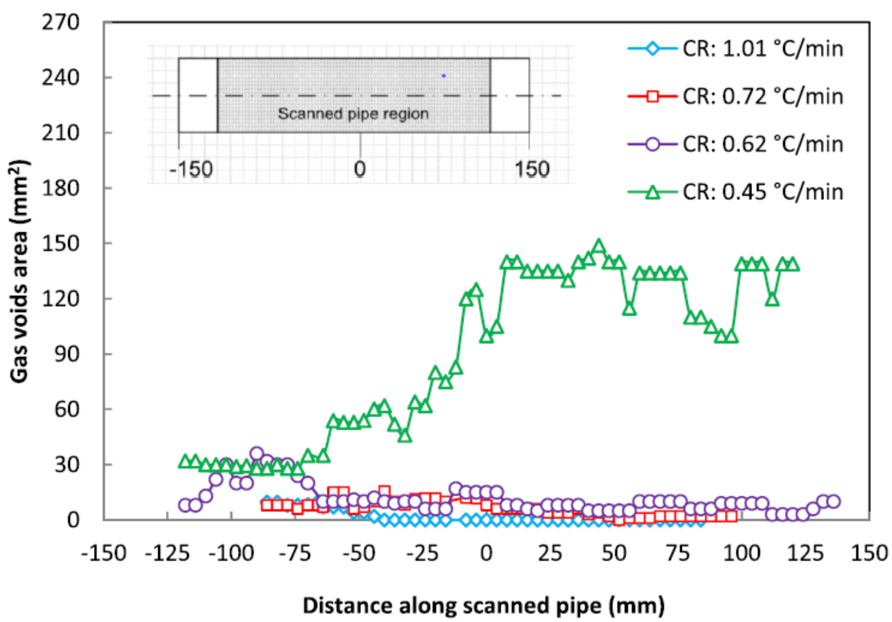


Figure 2.7: Effect of cooling rates on gas void distribution around the center of the pipe (Chala et al., 2014)

2.8 Intrusion of Gas into Waxy Crude Oil Pipeline

As observed by Shafquet et al., (2013), gas voids appear during thermal shrinkage process in which it results in compressible nature. This has contributed to a decrease in the restart pressure required in order to restart a pipeline. Due to the presence of a naturally occurring gas voids within the gel, a study was done by Zakaria (2014), in which gas was injected into a production pipeline of a waxy crude oil. This allows for more creation of voids as the gas is injected into the pipeline prior to shut down in order to further reduce the restart pressure. The experiment was conducted on a waxy crude oil flow loop test rig, in which the seabed temperature of 15ºC, 20ºC and 25ºC was simulated. It was found that there was a significant difference in restart pressure with and without the gas intrusion using a gradual flow start up method and instantaneous flow start up method. Under the gradual flow start up method, the pressure difference ranges between 0.2 to 0.51 bar and it was further noted that the differences in restart pressure increases as the water temperature decreases. It was noted that the effect of gas intrusion is more significant with water at lower temperature. Figure 2.7 (a) shows the restart pressure of waxy crude oil at different water temperature using gradual pressure approach. Under the instantaneous flow start up method, the pressure reduction within the range of 0.25 bar to 0.56 bar was noted, in which the highest pressure reduction was found when the water temperature is around 20ºC. Figure 2.7 (b) shows the restart pressure of waxy crude oil at different water temperature using instantaneous pressure approach. Although the study was done, it was not known quantitatively on how much volume of gas was injected within the test section.

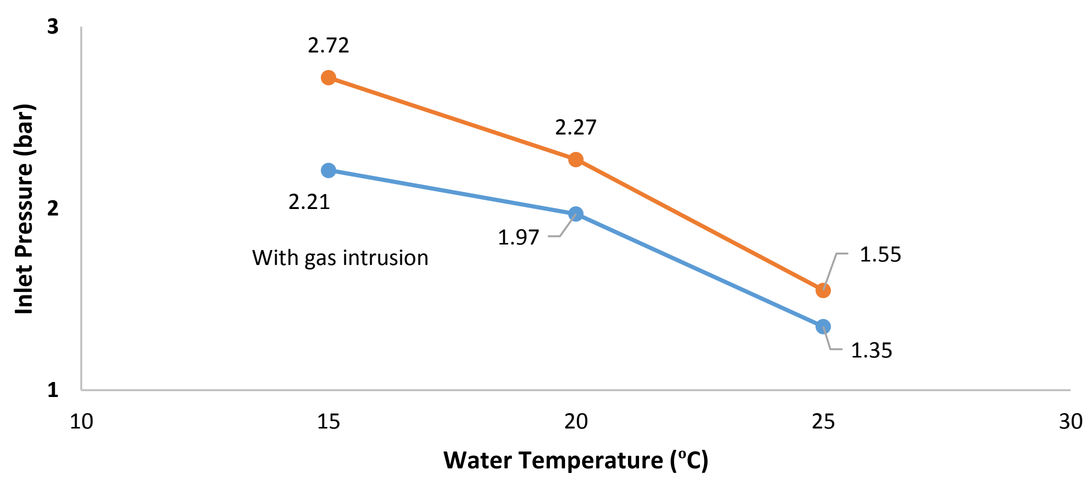


Figure 2.7 (a): Restart pressure of waxy crude oil at different water temperature using gradual pressure approach (Zakaria, 2014)

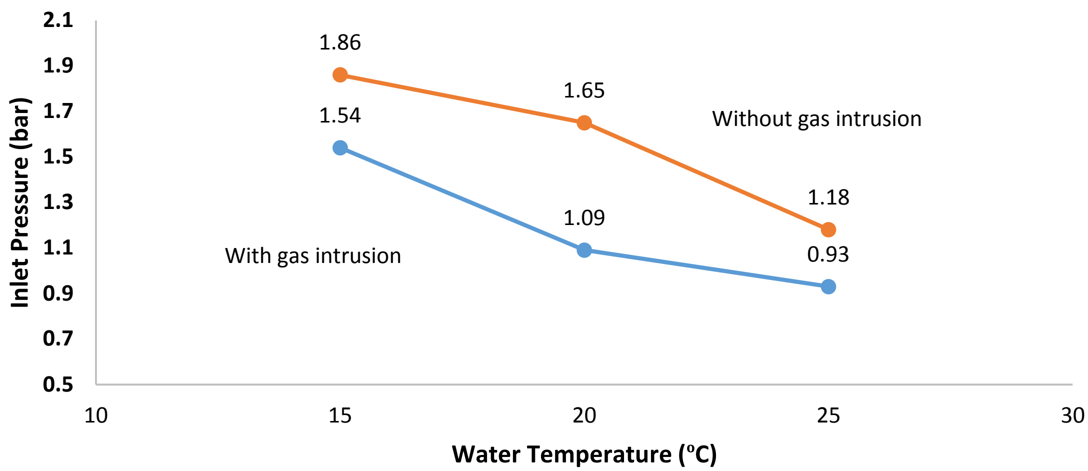


Figure 2.7 (b): Restart pressure of waxy crude oil at different water temperature using instantaneous pressure approach (Zakaria, 2014)

2.9 Usage of Nitrogen Gas in Oil and Gas Industry

Nitrogen, is a chemical element with a symbol N and has an atomic number 7. Under its standard condition and at a room temperature, nitrogen gas has an odorless, colorless, tasteless, non-irritating and inert capabilities. In an atmosphere, nitrogen gas makes up around 78% while the remaining balance is primarily oxygen gas, which stands at 21%. The chemical properties of nitrogen are shown in Appendix 1. Nitrogen gas is often used to keep materials free of contaminants such as oxygen, in which it is able to corrode an equipment or present a fire and explosion hazard when it comes into contact with a flammable liquid. Since nitrogen gas exhibits inert capabilities such as not able to support combustion, it is widely used within the oil and gas industries. The usage of nitrogen gas within industry is primarily used for inert gas lift, well clean outs, underbalance drilling (UBD), purging of instrument panels, pipeline purging or pigging, marine riser tensioner for offshore drilling, heave compensation for offshore lifting and drilling operations, fracking, enhanced oil recovery (EOR), dry gas compressor sealing, dry bulk transfer and air pressure vessel's (APV) for floating offshore platforms (NOXERIOR). Pipeline purging with the usage of nitrogen gas is usually done after a pigging operation has been completed. A dry nitrogen gas is being run through the pipeline in order to dry up any remaining water that still exist in the pipeline.

CHAPTER 3

METHODOLOGY

This chapter covers the experiment planning and the project schedule of the current studies, in which it is presented in the form of process flow chart and Gantt chart. The components used within the experiment is discussed here as well.

3.1 Research Overview

Figure 3.1 shows the detailed flow chart for methodology used in this study. The background study regarding the restart pressure of waxy crude oil flow is first conducted. In this phase, the problems and challenges faced during production and transportation of waxy crude oil is outlined and identified. This presents the magnitude of the problem currently being faced by the industry as it affects the pipeline integrity and the overall CAPEX and OPEX of the facilities. Once the background study has been conducted, the literature review phase is then conducted. During this stage, previous studies and researches regarding restart pressure of waxy crude oil are gathered and discuss. The findings at this stage is significant as it presents the data that has been captured in the researcher's previous experiments. At this stage, the parameters and conditions that attributes to the ease of restart is identified. After the literature review phase is done, the waxy crude oil flow loop experiment planning and consultation is conducted. At this stage, a discussion session was conducted with the lab technician and graduate assistant in order to find out more regarding the test rig that is available in Block 18, Mechanical Engineering Department, Universiti Teknologi PETRONAS. At this stage as well, the duration of the experiment can be estimated in order to efficiently utilize the machine. Next, the familiarization process with the test rig was conducted. As the test loop is an expensive and sophisticated machine, it is at upmost importance to learn on how to operate and know all the health, safety and environment (HSE) rules when operating the test loop. This ensures the reliability as well as the integrity of the machine when conducting the experiment later on. The familiarization process was conducted by the graduate assistant as he is very familiar with waxy crude flow loop test rig.

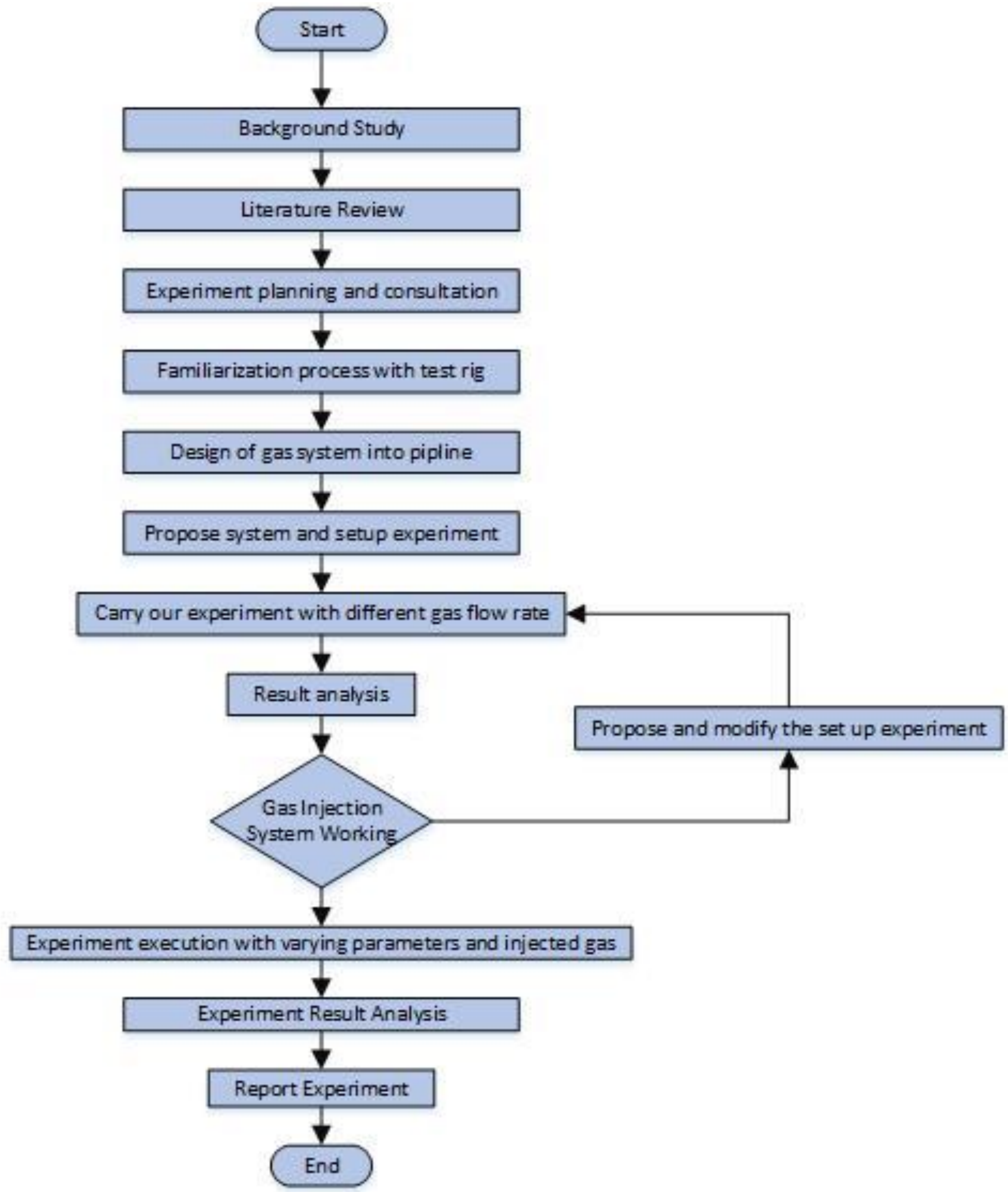


Figure 3.1: Flow chart of research methodology

The design of the gas system into the pipeline was then commenced. At this stage, a system was implemented in order to inject the gas into the test section of the test rig. Once the gas injection system is planned, the proposed system is then implemented and the setup of the experiment can begin. The was done as to ensure that there is no mishap that could happen during the later part of the experiment. An experiment was then carried out with different gas flow rate in order to verify on its function. The result from this experiment was analysed to see if the system needs any modification.

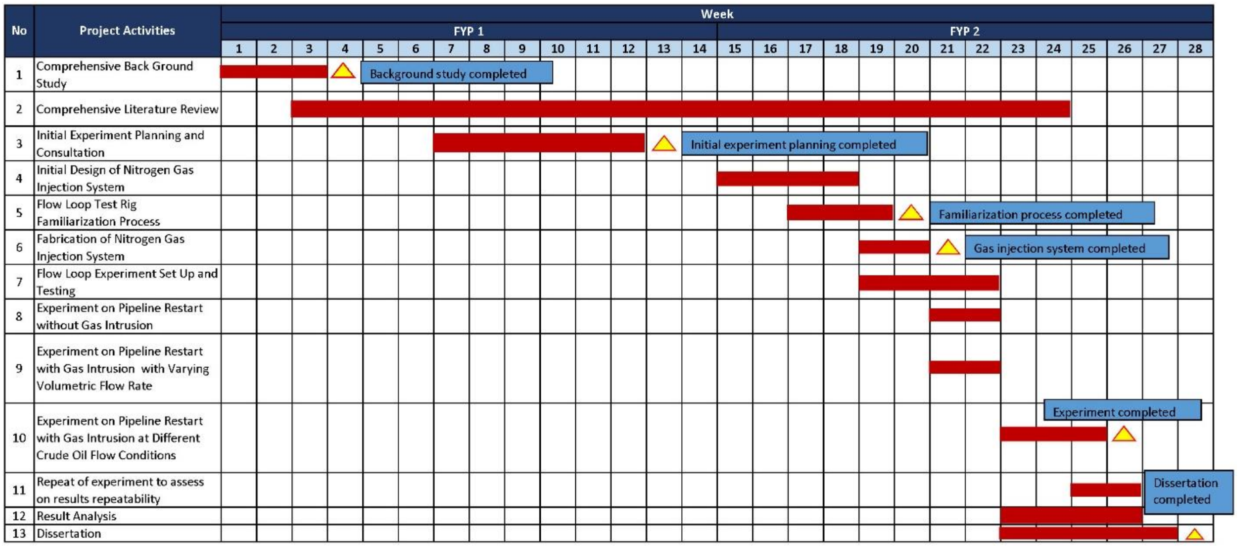
Once the system is verified and no more modification is done towards the test rig, the experiment regarding restart pressure with respect to different oil cooling rates and the temperature with the injected gas was commenced. All the data gathered were discussed once the experiment was done. The findings and discussion were then compiled into a report.

3.2 Gantt Chart / Project Planning

The project planning for Final Year Project 1 (FYP 1) is outlined and showed below under Figure 3.2. The duration given in order to complete the activities was 15 weeks starting from 21st September 2015 (Week 1) up to 21st December 2015 (Week 14). A comprehensive back ground study on problems with respect to restart pressure of waxy crude oil in which it was conducted on Week 1 up to Week 4. Concurrently, a comprehensive literature review was done on Week 3 in FYP 1 up to Week 24 in FYP 2. This long period is needed in order to continuously study on the parameters that affect the restart pressure of the waxy crude oil in a pipeline. The initial experiment planning and consultation was done on Week 7 up to Week 12. At this phase, a few introductory sessions with regards to lab facilities as well as the equipment was conducted with the lab assistant and the graduate assistant at Block 18, Mechanical Engineering Department, Universiti Teknologi PETRONAS. This concludes all the activities in FYP 1.

The initial design of the nitrogen gas injection system was outlined in Week 15 and Week 18 in FYP 2 and it includes all the necessary procurement of all the related components needed for the gas injection system. A familiarization process with the flow loop test rig was conducted on Week 17 up to Week 20 in which the graduate assistant showed how to operate the test rig safely and in a proper manner. At this phase, all Health, Safety and Environment (HSE) with respect to operate the test rig is shown, as well as the proper way to operate the machine so that it does not break down during the experiment phase. This particular process was followed by the fabrication of nitrogen gas injection system in which it was done in the same period of Week 19 and Week 22. After nitrogen gas injection system was in place, the whole test rig was set up and a small experiment was conducted in order to ensure that all components work perfectly. The first experiment on restart pressure without any gas intrusion was conducted in Week 21 up to Week 22. On top of that, another experiment on restart pressure with gas intrusion with varying volumetric flow rate was conducted on Week 22. Once that is done, another experiment on pipeline restart with gas intrusion at different crude oil flow conditions was conducted in Week 23 up to Week 26. In Week 23 to Week 26, one of the completed experiment was repeated in order to assess the data's repeatability. Once the experiment phase is done, the results are then analysed in Week 23 up to Week 26. At this phase, all the results regarding the experiment conducted earlier were discussed and presented in a proper manner.

There are 4 project milestones for this study, which are (1) background study completion, (2) initial experiment planning completion, (3) completion of waxy crude oil flow loop familiarization process, (4) completion of gas injection system, (5) completion of experiment and (6) completion of dissertation.



△ = key milestone

Figure 3.2: Gantt chart for FYP 1 and FYP 2

3.3 Test Rig Set Up

The Waxy Crude Oil Flow Loop (test rig) as shown in Figure 3.3, which is currently located in Block 18, Mechanical Engineering Department, Universiti Teknologi PETRONAS, was used in order to carry out the experiment on restart pressure of pipeline. This particular test rig comes with several key components in which it enables the researchers to study more on the properties of the wax as well as the restart pressure needed in order to restart a waxy crude oil pipeline. A detailed component specification is provided in Appendix 2 An acrylic test section of 1.2 m long with a diameter of 30 mm is immersed in a water bath in which it was used in order to observe any physical changes within the crude oil when it is subjected to low temperature environment. An evaporative coil is placed within the water bath section in order to cool down the water. This is done as to mimic the seabed temperature condition. The evaporative coil is then connected to a chiller system and the temperature can be adjusted on the control panel. A temperature and pressure sensor is placed at the upstream and downstream of the test section, in which it is able to monitor any changes. The readings from both the temperature and pressure sensor is then displayed on the control panel. As the acrylic test piece within the flow loop is detachable and can be taken out from the water bath, the effects of thermal shrinkage can be studied. A crude oil flow meter is used in order to measure the flow rate of the crude oil flowing inside the pipeline. It is connected upstream part of the pipeline and is a 1” corrollis flowmeter and was manufactured by Micron Motion Transmitter with model number 1700I12ABZEZZZ. A temperature sensor is placed within the storage tank in order monitor the temperature of the crude oil during the stirring process.

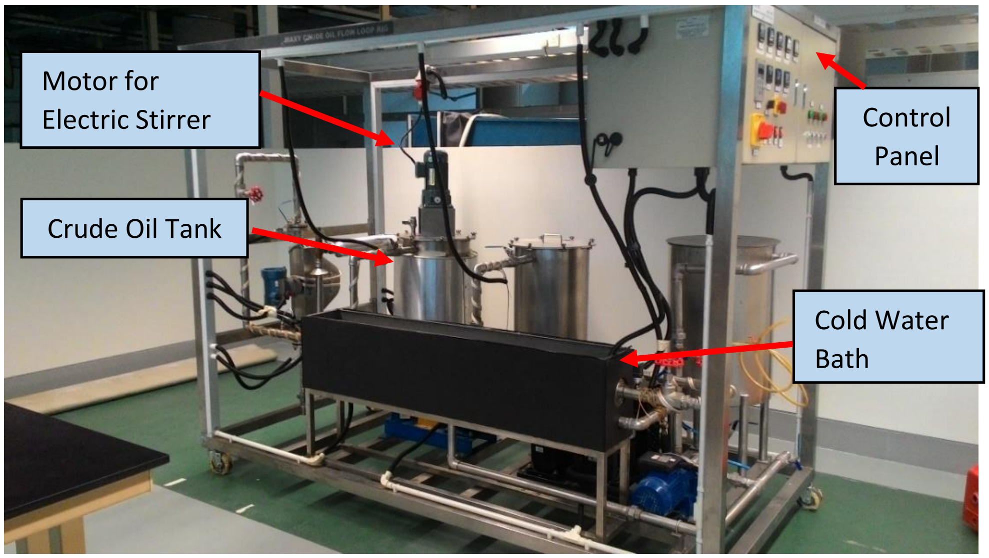


Figure 3.3: Major components of way crude oil flow loop

Based on the schematic in Figure 3.4, the whole rig acts as a closed loop system in which the waxy crude oil is circulated throughout the whole system in one complete cycle. The waxy crude oil is placed within the storage tank and heated to its operating condition (70ºC), in which it is stirred continuously to remove its past thermal behaviour and enhance the flow of the crude oil in the closed loop. During at any point in time whereby the test rig is not being used, the wax starts to solidify within the whole system, making it quit difficult in order to restart it. Therefore, the crude oil within the storage tank needs to be heated first, including the pipes within the system through the usage of trace heaters/heat tape. At this temperature, the crude oil behaves as Newtonian fluid and flows normally within the test piece. The pippings within the systems are rolled with trace heaters/heat tape all the way except for the test section piece within the water bath. Both the trace heaters along the pipe and heater within the storage tank is switched on at the same time. Once crude oil is heated up to a temperature of 70ºC, a gear pump manufactured by Marelli Motori from Italy with the model number MOT 3-MAA 90L6-B3 which is located upstream (after the storage tank), is then operated in order to build enough pressure in order to disintegrate the gelled crude oil in the acrylic test section. The crude oil starts flowing and then returns to the crude oil storage tank to be reheated and maintained at a temperature range of 60º-90ºC. The experiment can then be commenced by shutting off the gear pump that operates the crude oil and allow the water bath to cool down the crude oil through the usage of chiller system. The wax in the crude oil slowly solidify due to the low temperature within the water bath.

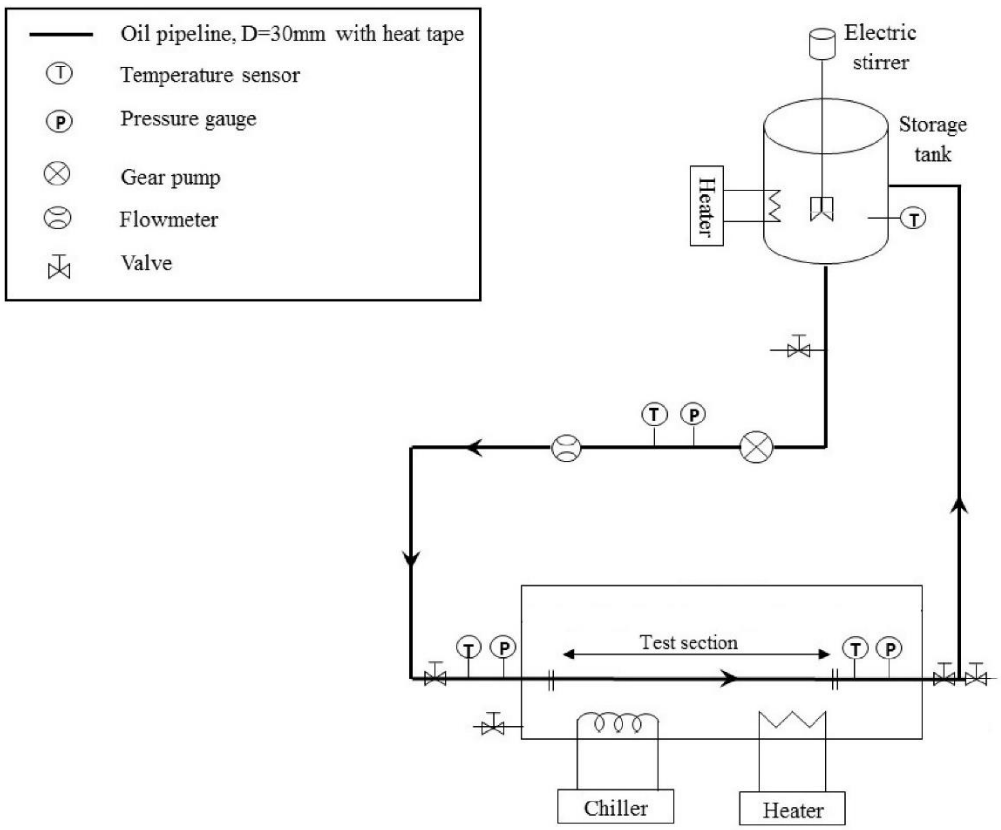


Figure 3.4: Schematic of the waxy crude oil flow loop

3.4 Mechanism for Intrusion of Nitrogen

A nitrogen gas injection system was built and implemented to the current waxy crude oil flow loop test rig. A nitrogen gas cylinder is first connected to the gas flow meter through a ¼ inch stainless steel reinforced Teflon hose with the length of 1.5 m. From the gas flow meter, it is then connected to a ball valve via ¼ inch stainless steel reinforced Teflon hose with a length of 1 m. The diameter of the hose is ¼ inch or 6.35 mm. The nitrogen gas will supply at a rate of 1 L/min through the 6.35 mm hose. The pressure of which the nitrogen gas will leave the gas cylinder will be set at 3.5 bar via the nitrogen gas regulator. The ball valve will be connected to the test rig through the opening along the oil pipeline which is covered with a heat tracer.

During the experiment, the nitrogen gas will be injected into the system during the gelling process of the crude oil after the crude oil has stopped flowing. A ball valve was placed at the inlet of the injection site in order to control the nitrogen gas flow. In this study, nitrogen gas with the volume of 50 mL was injected into the test section by opening the ball valve for a specific period of time. The period of time needed to open the ball valve in order to allow a known volume of gas to intrude the test section was calculated by using the following equation:

$$t_v = \frac{V}{Q} \tag{3.1}$$

where t_v, V and Q are the period of time needed to open the ball valve (s), the known gas volume that needs to be injected (mL) and the volumetric flow rate of the gas (LPM) respectively.

The components used in order to set up the gas injection system is shown in Appendix 2 and the schematic of the gas injection system is shown in Figure 3.5. The completed nitrogen gas injection is shown in Figure 3.6.

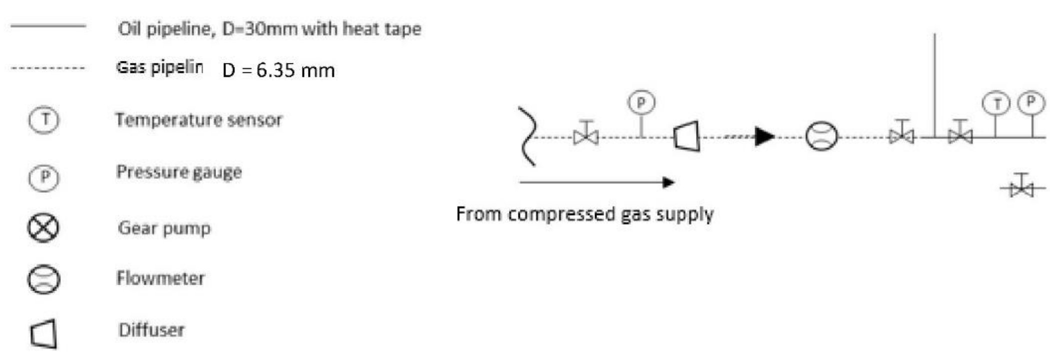


Figure 3.5 Schematic drawing of gas injection system

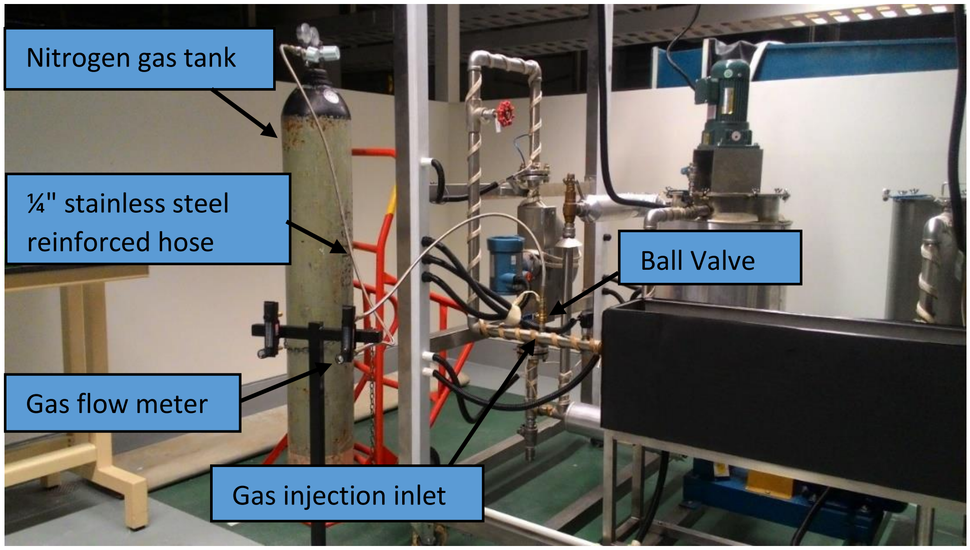


Figure 3.6: Completed nitrogen gas injection system set up

Figure 3.7 shows the gas voids that was formed through the injection of 50 mL of nitrogen gas into the test section.

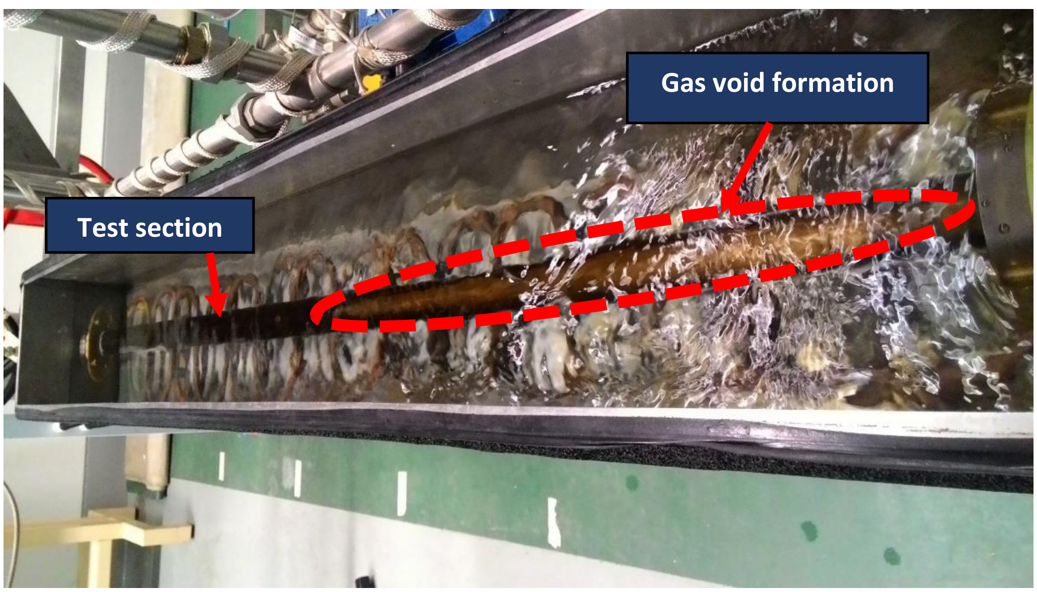


Figure 3.7: Formation of gas voids into the test section

3.5 Crude Oil Properties

For this experiment, the type of waxy crude oil to be used is identified. As different oil fields will have a different physical and chemical composition, it is important to know the characteristics of the crude oil being used in this particular experiment. The properties of the crude oil will have an effect on the gelation of the wax in the crude oil during the cooling period, and thus will result in different restart pressure depending on the type of the crude oil being used. In this present study, only one type of crude oil, namely the Sepat-7 was used in order to ensure the comparison between data obtained later on in the experiment is relevant. The crude oil has been supplied by PETRONAS CARIGALI Sdn Bhd and was taken from the Sepat field, offshore Terengganu. The properties of Sepat-7 crude oil are shown in Table 3.1. The density of the crude oil was determined from the Coriolis flow meter at temperature above 38.5ºC, the specific gravity was through a calculation, the dynamic viscosity was determined through viscometer, the WAT was determined through the ASTM D3117 method and the PPT was determined through ASTM D97 method.

Table 3.2 : Properties of Sepat-7 crude oil (Chala et al., 2014)

Crude Name	Sepat-7
Origin	Sepat Field, Offshore Terengganu , Peninsular Malaysia
Pour Point Temperature (PPT)	36ºC
Wax Appearance Temperature (WAT)	38.5ºC
Density	850 kg/m^3
Viscosity	0.002 Pa
Specific Gravity	0.85

CHAPTER 4

RESULTS AND DISCUSSION

This chapter discusses the data which was obtained through the experiment. All the results obtained from the experiment will be tabled and discussed in a detailed manner. In the Section 4.1, the result from the nitrogen gas injection system is shown and for the subsequent sections, the results of restart pressure with varying cooling rates that was subjected under two different start up conditions is presented and discussed.

4.1 Restart Pressure of Pipeline

The waxy crude oil test rig was equipped with a 1.1 kW gear pump in which it was placed further upstream from the test section, right after the crude oil tank. The pump was used to provide pumping pressure / restart pressure needed to disintegrate the gelled wax within the test section. All the pipping system that connects to and after the test section were equipped with a trace heater and it was set at 70ºC so as to liquefy any remaining gelled wax. The initial / inlet temperature at the test section was set at 70ºC so as to simulate temperature from the wellhead. Under this experiment, there were two ways in which a restart pressure was applied, namely instantaneous restart and gradual restart. In an instantaneous restart, maximum allowable pressure up to 2 bar was applied instantaneously on the gelled wax within the test section. In a gradual restart, a maximum allowable pressure of up to 2 bar is applied in a gradual manner / incremental manner up to a point the gelled wax begins to disintegrate. The pressure at which the gelled wax starts to disintegrate in both instantaneous and gradual restart is captured by a data logger. Within this study, the water bath temperature was set at 20ºC, 25ºC and 30ºC so as to simulate the seabed temperature. Under both approaches, nitrogen gas was injected in order to study the effects of gas injection with respect to its restart pressure. The pipeline is restarted under both cases when the temperature of the gelled wax reaches the water bath temperature. With the experiment data obtained, the restart pressure for both injected and non-injected pipeline were studied and compared.

4.1.1 Instantaneous Restart Pressure

As mentioned in Section 4.1, a maximum allowable pressure of up to 2 bar was instantaneously applied on to the gelled wax within the test section. Pressure builds up instantaneously at the point the after pump was switched on, which was placed at the upstream part of the test section and once the pressure is high enough, the gelled wax starts to disintegrate and the pipeline will resume flowing condition. Table 4.1 shows the summary results of instantaneous restart on the gelled wax pipeline with and without the gas injection. The restart time refers to the time taken for the gel to disintegrate at the moment the gear pump is switched on and the restart pressure refers to the pressure at the moment the gelled wax disintegrates.

Table 4.1: Restart pressure and restart time comparison using instantaneous pressure

Instantaneous Restart					
Initial Temperature, T_i (ºC)	**Water Bath Temperature, T_w, (ºC)**	**Restart Pressure, P_r (Bar)**		**Restart Time, T_r (s)**	
		Without Injection	**With Injection**	**Without Injection**	**With Injection**
70	30	1.415	1.368	16	18
70	25	1.563	1.465	10	26
70	20	1.785	1.58	9	21

In Table 4.1, the initial temperature is kept constant at 70ºC and the water bath temperature varies from 20ºC, 25ºC and 30ºC. It is noted that the restart pressure of the waxy crude oil pipeline is higher when the nitrogen gas not injected as compared to the restart pressure of a pipeline that has been injected with a nitrogen gas. Restart pressure of 1.785 bar, 1.563 bar and 1.415 bar was observed for water temperature of 20ºC, 25ºC and 30ºC respectively when it was not injected with gas. A lower restart pressure of 1.58 bar, 1.465 bar and 1.368 bar was observed for water temperature of 20ºC, 25ºC and 30ºC respectively when the test section is injected with nitrogen gas. The presence of gas voids allows for a lower restart pressure since the gelled wax has a lot of space to move when pressure was applied (Lee et al., 2008). This therefore reduces the amount of restart pressure needed as compared to the restart pressure of a non-injected pipeline. As the water temperature bath decreases, the restart pressure of the pipeline for both with and without nitrogen gas injection increases. This is largely due to a high cooling rate between the crude oil and the water bath temperature. A mentioned by Lee et al (2007), a slower cooling rate would yield a large, sheet like wax crystals in which it has low density as compared to the wax crystals that was formed under a high cooling rate. Wax crystals formed under high cooling rate was observed to be small in size and as result, the network wax-crystal structure loses its interconnectivity. Under a high cooling rate, the increased density and number of wax crystals increase the adhesive strength as the needle like crystal allows larger effective surface area at the interface between the wall (Greiner et al., 2007). This explains why a higher restart pressure was observed as the cooling rate is increased. The average cooling rate, C_{avg}, was calculated by using the following equation:

$$C_{avg} = \frac{\Delta T}{S} \tag{4.1}$$

whereby ΔT, s and C_{avg} is the temperate difference between the crude oil at the inlet and the water bath temperature (initial temperature – final temperature), time taken in minute for the crude oil to reach the final temperature and the average cooling rate in minute respectively. All static cooling period was kept constant at 60 minutes and the cooling rate for 20ºC, 25ºC and 30ºC are 0.666ºC/min, 0.75ºC/min and 0.833ºC/min respectively.

Table 4.2 shows the difference in restart pressure between a gas injected pipeline and a non-injected pipeline which was subjected to instantaneous restart. Figure 4.1 shows a graphical representation of the restart pressure difference between a gas injected pipeline and non-injected pipeline. Figure 4.2 shows the instantaneous restart pressure profile of gas injected at test section and Figure 4.3 shows the instantaneous restart pressure profile of pipeline without gas injection.

Table 4.2: Pressure difference between an injected pipeline and non-injected pipeline

Initial Temperature, T_i (ºC)	**Water Bath Temperature, T_w, (ºC)**	**Restart Pressure, P_r (Bar)**		**Pressure Difference, ΔP_r**	**Percentage Difference, %**
		Without Injection	**With Injection**		
70	30	1.415	1.368	0.047	3.32
70	25	1.563	1.465	0.098	6.27
70	20	1.785	1.58	0.205	11.48

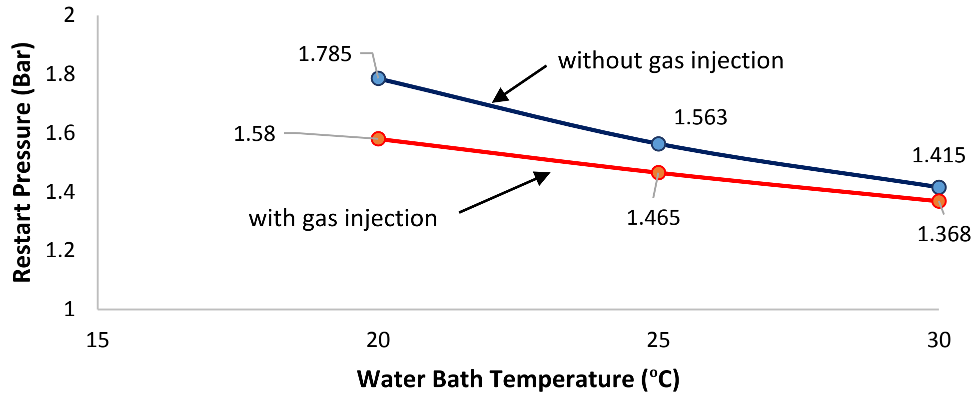


Figure 4.1: Pressure difference between a gas injected pipeline and non-injected pipeline subjected to instantaneous restart pressure approach

The percentage difference between the restart pressure of a non-injected pipeline and injected pipeline is calculated by using the following equation:

$$\%_{Pr} = \left[\frac{(P_{rwo} - P_{rw})}{P_{rwo}}\right] X\ 100\% \tag{4.2}$$

whereby P_{rwo}, P_{rw} and $\%_{Pr}$ are restart pressure of pipeline without gas injection (bar), restart pressure of pipeline with gas injection (bar) and percentage difference of restart pressure respectively. As shown in Table 4.2, the biggest difference in restart pressure when compared between a gas injected test section and a non-injected gas section is 11.48% when the water temperature is at 20ºC, followed by 6.27% when the water temperature is at 25ºC and 3.32% when the water temperature is at 30ºC.

4.1.2 Gradual Restart Pressure

As mentioned in Section 4.1, a maximum allowable pressure of up to 2 bar was gradually applied onto the gelled wax within the test section through the usage of a gear pump. Pressure builds up gradually within the upstream part of the test section the moment the pump is switched on and once the pressure is high enough, the gelled wax will start to disintegrate and the test section will resume flowing condition. Table 4.3 shows the summary result of restart pressure for gas injected test section and non-injected test section when subjected to gradual restart pressure.

Table 4.3: Restart pressure and restart time comparison using gradual restart pressure

Gradual Restart					
Initial Temperature, T_i (ºC)	**Water Bath Temperature, T_w, (ºC)**	**Restart Pressure, P_r (Bar)**		**Restart Time, T_r (s)**	
		Without Injection	**With Injection**	**Without Injection**	**With Injection**
70	30	1.49	1.351	86	76
70	25	1.812	1.496	177	85
70	20	2.077	1.858	136	115

Table 4.3 shows the restart pressure for a non-gas injected test section is higher as compared to the gas injected test section. It was shown that lowest restart pressure for a gas injected pipeline was found to be at 1.351 bar when the water bath temperature was at 30ºC as compared to the restart pressure of 1.49 bar when the test section was not injected with nitrogen gas. The highest restart pressure was found to be at 1.858 bar when the water bath temperature was at 20ºC as compared to the restart pressure of 2.077 bar when the test section was not injected with nitrogen gas. It can be observed that the restart time taken reduces when the test section is injected with nitrogen gas. As the displacing fluid, which in this case was a liquefied waxy crude oil moves and fills up the gas voids within the test section, it effectively reduces the time taken in order to restart the pipeline. Table 4.4 shows the difference of restart pressure between a gas injected test section and a non-injected test section when it is subjected to gradual restart pressure approach.

Table 4.4: Pressure difference between gas injected and non-injected pipeline

Initial Temperature, T_i (ºC)	**Water Bath Temperature, T_w, (ºC)**	**Restart Pressure, P_r (Bar)**		**Pressure Difference, ΔP_r**	**Percentage Difference, %**
		Without Injection	**With Injection**		
70	30	1.49	1.351	0.139	9.33
70	25	1.812	1.496	0.316	17.44
70	20	2.077	1.858	0.219	10.54

Table 4.4 shows the difference in restart pressure between a test section with and without gas injection at 0.139 bar, 0.316 bar and 0.219 bar for water bath temperature of 20ºC, 25ºC and 30ºC respectively. The biggest difference in restart pressure can be observed when the water bath temperature of 25ºC in which the percentage difference was 17.44 %, followed by 10.54% at water bath temperature of 20ºC and 9.33 % when the water bath temperature was at 30ºC. As expected, the restart pressure decreases when the pipeline has been injected with nitrogen gas due to the effect of compressibility that exist when pressure is applied. Figure 4.4 shows the graphical representation of difference in restart pressure for both gas injected and non-injected test section. Figure 4.5 and Figure 4.6 shows the gradual restart pressure profile of a gas injected pipeline and non-injected test respectively.

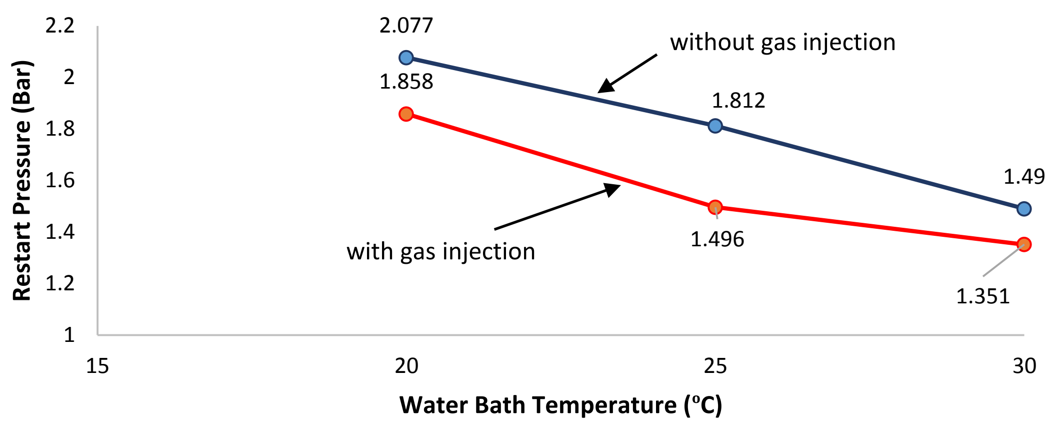


Figure 4.4: Restart pressure difference between gas injected pipeline and non-injected pipeline subjected to gradual restart pressure approach

4.2 Effect of Gas Oil Ratio (GOR) on Restart Pressure

In this study, the effects of gas volume that was injected to the pipeline after the pipeline has stop flowing and prior to static cooling process is studied. Within this study, four volumes at 0 mL, 50 mL, 100 mL and 150 mL of nitrogen gas was used in order to study its effect on the restart pressure of the pipeline. Both the initial temperature and the water bath temperature are kept constant at 70ºC and 25ºC respectively. The volume of injected nitrogen gas was adjusted by controlling the ball valve at the inlet of the gas injection system which was placed at the upstream part of the test section. Using the Equation 4.1, the duration or period in which the ball valve needs to be open at a volumetric flow rate of 1 LPM can be calculated as the nitrogen gas volume is known. The volume of the acrylic test section can be calculated through following equation:

$$V_t = \frac{\pi d^2 L}{4} \tag{4.3}$$

where V_t, d and L are volume of the test section (m^3), internal diameter of the test section and length of the test section respectively. The length and internal diameter of the test section is 1.2 m and 0.03 m respectively. From the calculation using Equation 4.3, the volume of the test section V_t, is 8.482 x 10^{-4} m^3 or 848 mL. In this study, the effects of varied nitrogen gas volume on the restart pressure needed was done by applying pressure instantaneously and gradually onto the gelled wax within the test section. The gas to oil volume ration was calculated using the following equation:

$$R_{GO} = \frac{V_g}{V_t} \tag{4.4}$$

where R_{GO}, V_g and V_t are gas to oil volume ratio, volume of nitrogen gas and volume of crude oil in test section respectively. Table 4.5 shows the summary of the restart pressure experiment with respect to different gas to oil volume ratio using the instantaneous restart pressure approach and Figure 4.7 shows graphical representation of restart pressure recorded. Figure 4.8 shows the instantaneous restart pressure profile with varying gas to oil ratio.

Table 4.5: Summary of restart pressure with varying gas to oil volume ratio using instantaneous restart pressure approach

Initial Temperature, T_i (°C)	**Water Bath Temperature, T_w, (°C)**	**Volume of Test Section, V_t (mL)**	**Volume of gas, V_g (mL)**	**Gas to Oil Ratio, R_{GO}**	**Restart Pressure, P_r (Bar)**
70	25	848	0	0	1.563
		848	50	0.05894	1.465
		848	100	0.11792	1.356
		848	150	0.17688	1.209

As shown in Table 4.5, as the volume of the injected nitrogen gas increases, the restart pressure needed to disintegrate the gelled wax decreases. At gas to oil volume ratio of 0, the restart pressure recorded was 1.563 bar and for the subsequent gas to oil volume ratio of 0.05894, 0.11792 and 0.17688, the restart pressure was recorded at 1.465 bar, 1.356 bar and 1.209 bar respectively. This shows a decrement in restart pressure as the gas to oil ratio (GOR) is increasing when it is subjected to instantaneous restart pressure. This result was expected due to the amount of volume in which the gelled wax is able to move as pressure is applied through a displacing fluid. An increment in injected gas volume leads to a high compressibility effect on the gelled wax.

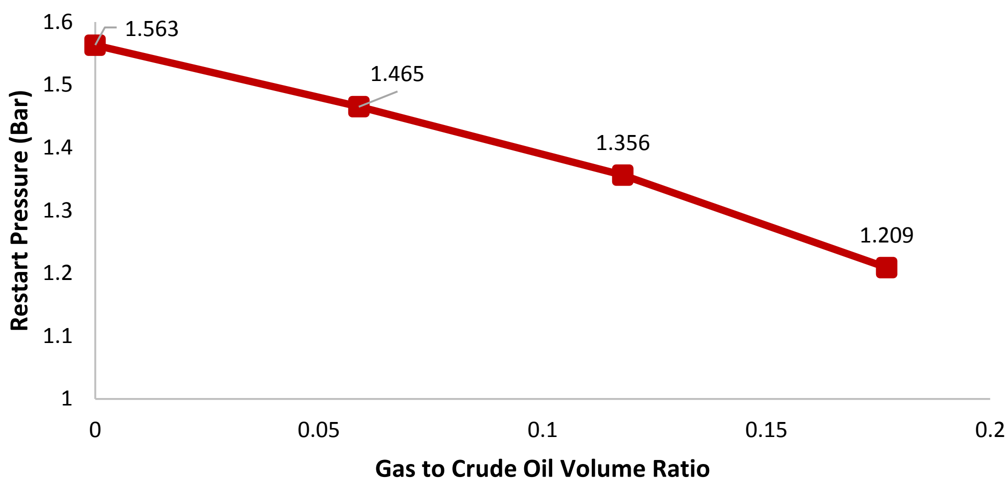


Figure 4.7: Restart pressure at gas to crude oil volume ratio using instantaneous restart pressure approach

A similar trend can also be observed when the pipeline is subjected to a gradual restart pressure approach. In this study, both the initial temperature and water bath temperature were kept constant at 70ºC and 25ºC respectively and the volume of the nitrogen gas injected is 0 mL, 50 mL, 100 mL and 150 mL. Table 4.6 shows the summary of restart pressure with varying gas to oil ratio using gradual restart pressure approach.

Table 4.6: Summary of restart pressure with varying gas to oil ratio using gradual restart pressure approach

Initial Temperature, T_i (°C)	**Water Bath Temperature, T_w, (°C)**	**Volume of Test Section, V_t (mL)**	**Volume of gas, V_g (mL)**	**Gas to Oil Ratio, R_{GO}**	**Restart Pressure, P_r (Bar)**
70	25	848	0	0	1.789
		848	50	0.05894	1.496
		848	100	0.11792	1.396
		848	150	0.17688	1.270

As shown in Table 4.6, at a gas to oil ratio of 0, the restart pressure was recorded at 1.789 bar and for the next subsequent of gas to oil ratio of 0.05894, 0.11792 and 0.17688, the restart pressure was recorded at 1.496 bar, 1.396 bar and 1.270 bar respectively. This shows that as the gas to oil ratio increases, the restart pressure needed in order to resume flowing condition within the pipeline decreases. Figure 4.9 shows the graphical representation of restart pressure recorded with varying gas to oil volume ratio using the gradual restart approach. Figure 4.10 shows the restart pressure profile with varying gas to oil ratio subjected to gradual restart pressure.

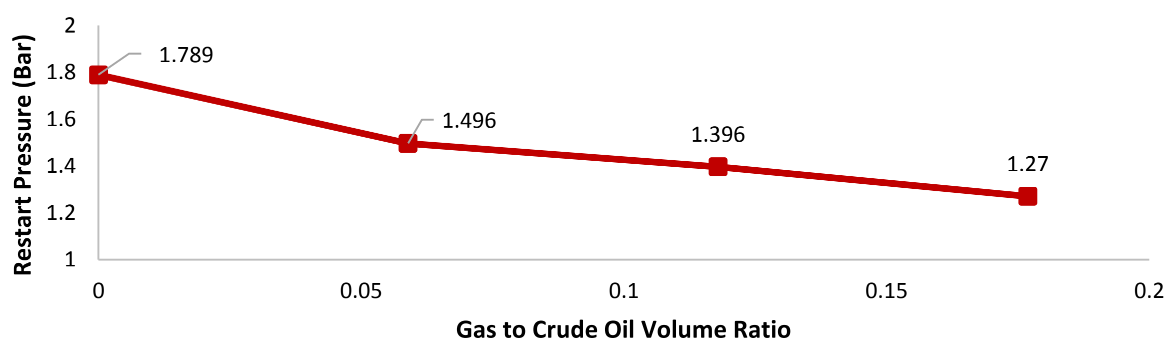


Figure 4.9: Restart pressure recorded with varying gas to oil volume ratio using the gradual restart approach

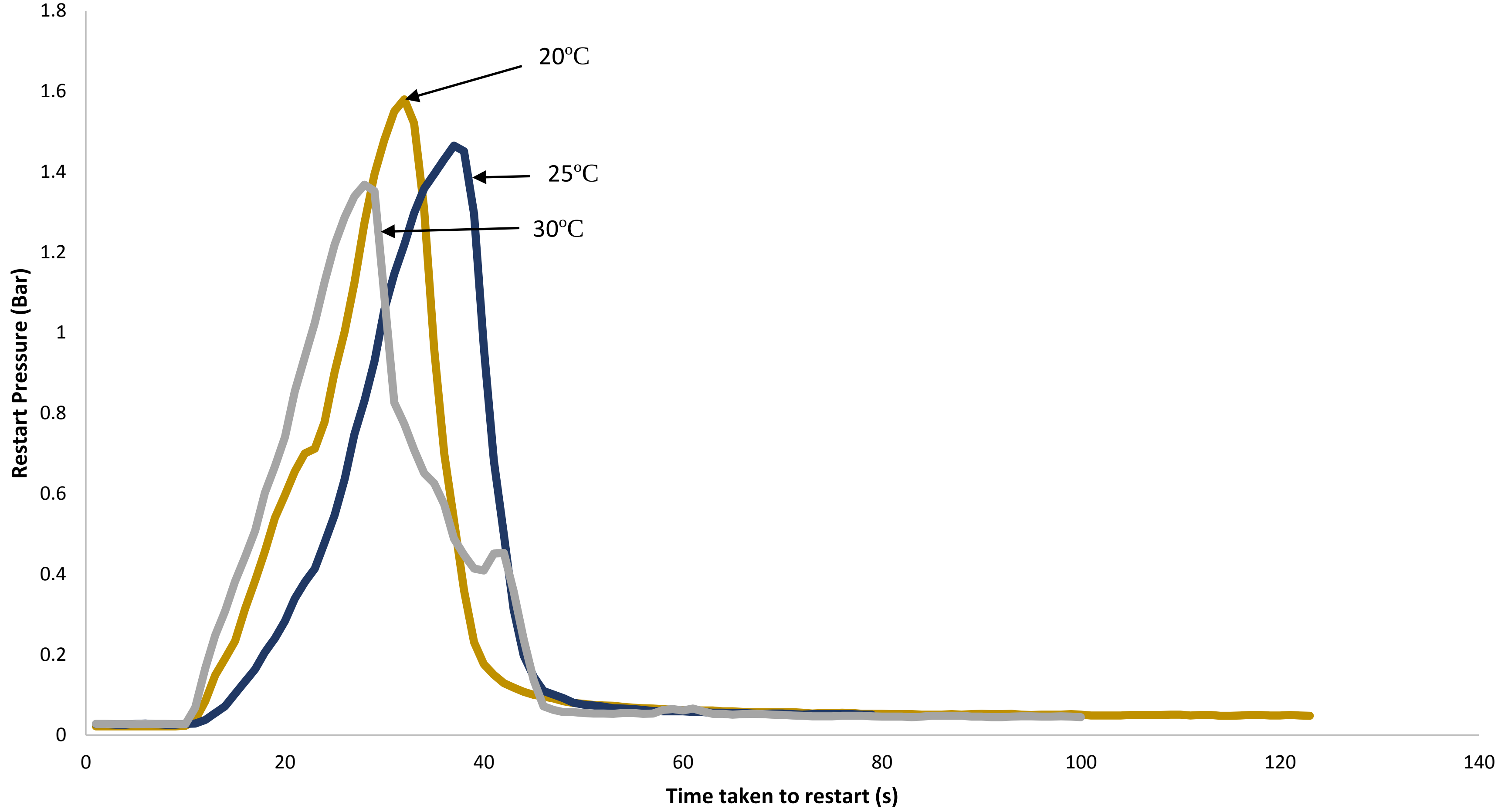


Figure 4.2: Instantaneous restart pressure profile with the injection of nitrogen gas

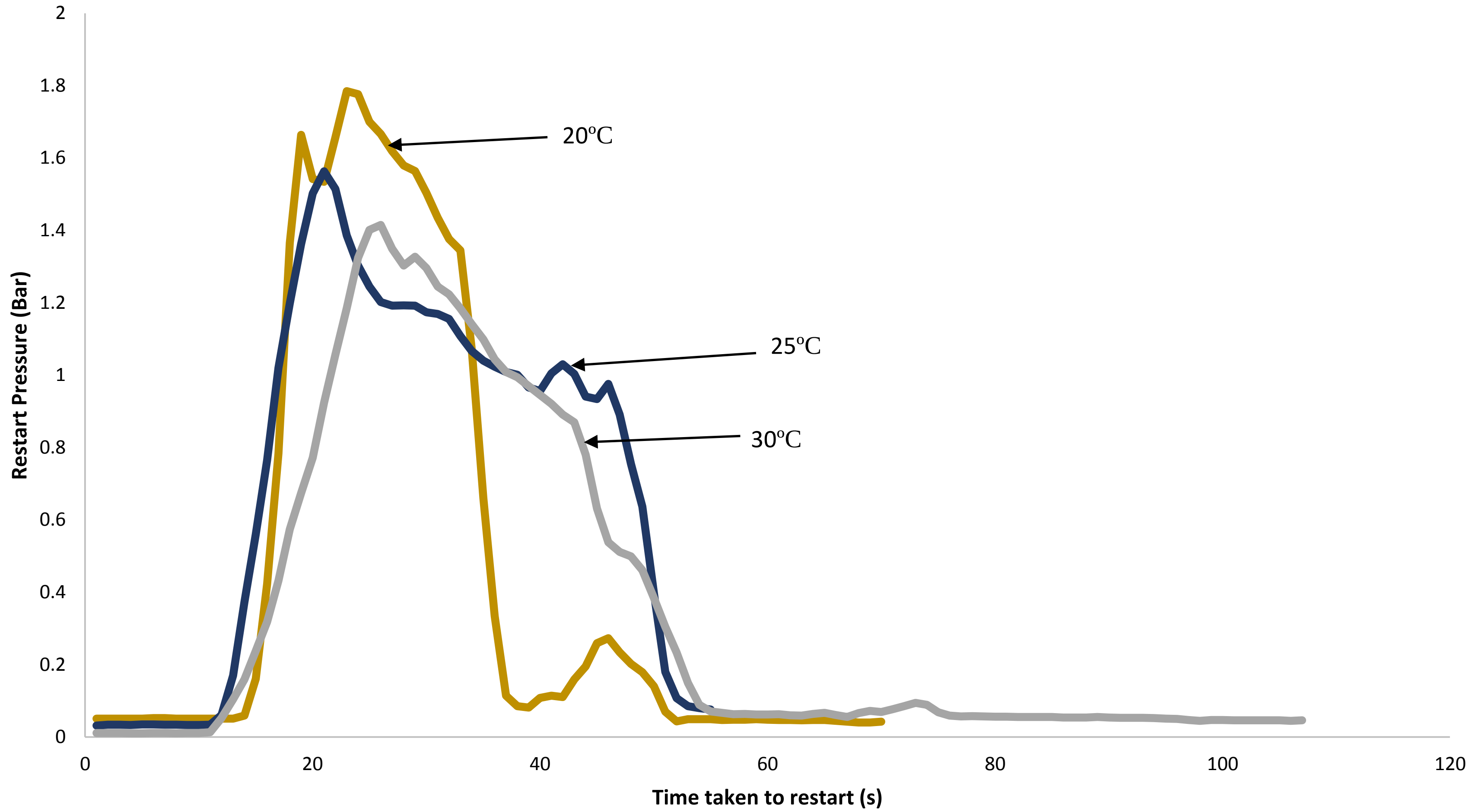


Figure 4.3: Instantaneous restart pressure profile without nitrogen gas injection

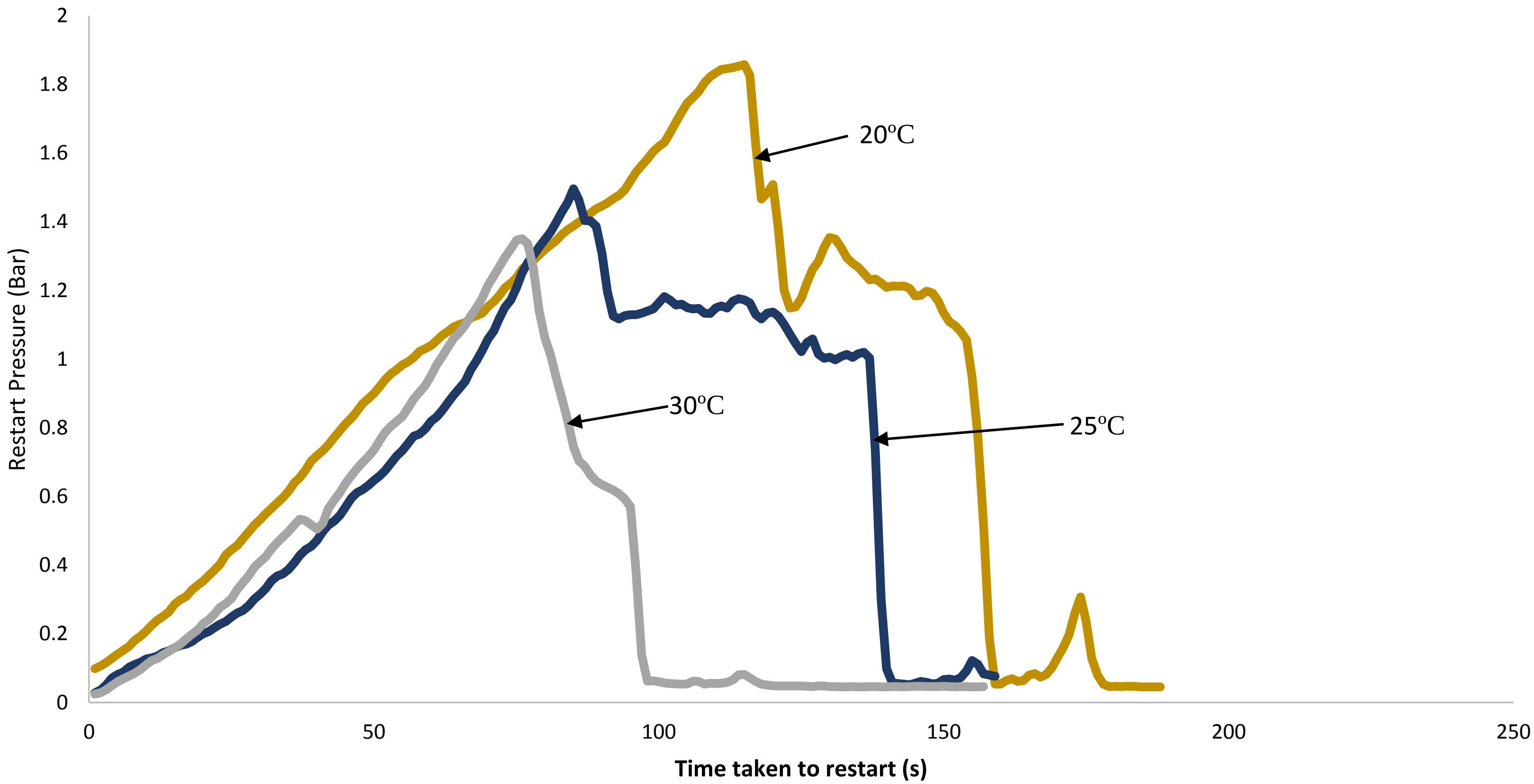


Figure 4.5: Gradual restart pressure profile with the injection of nitrogen gas

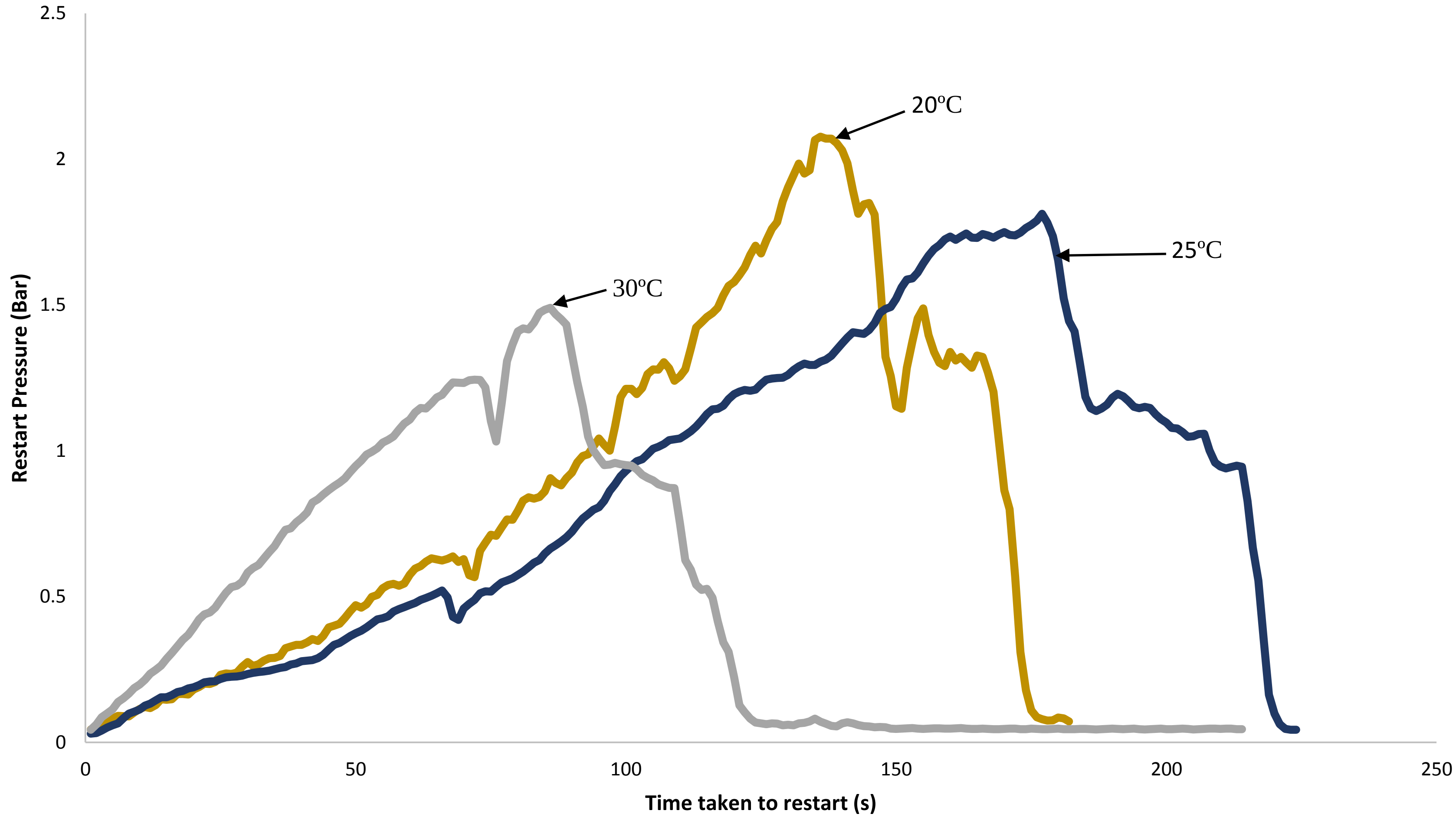


Figure 4.6: Gradual restart pressure profile without the injection of nitrogen gas

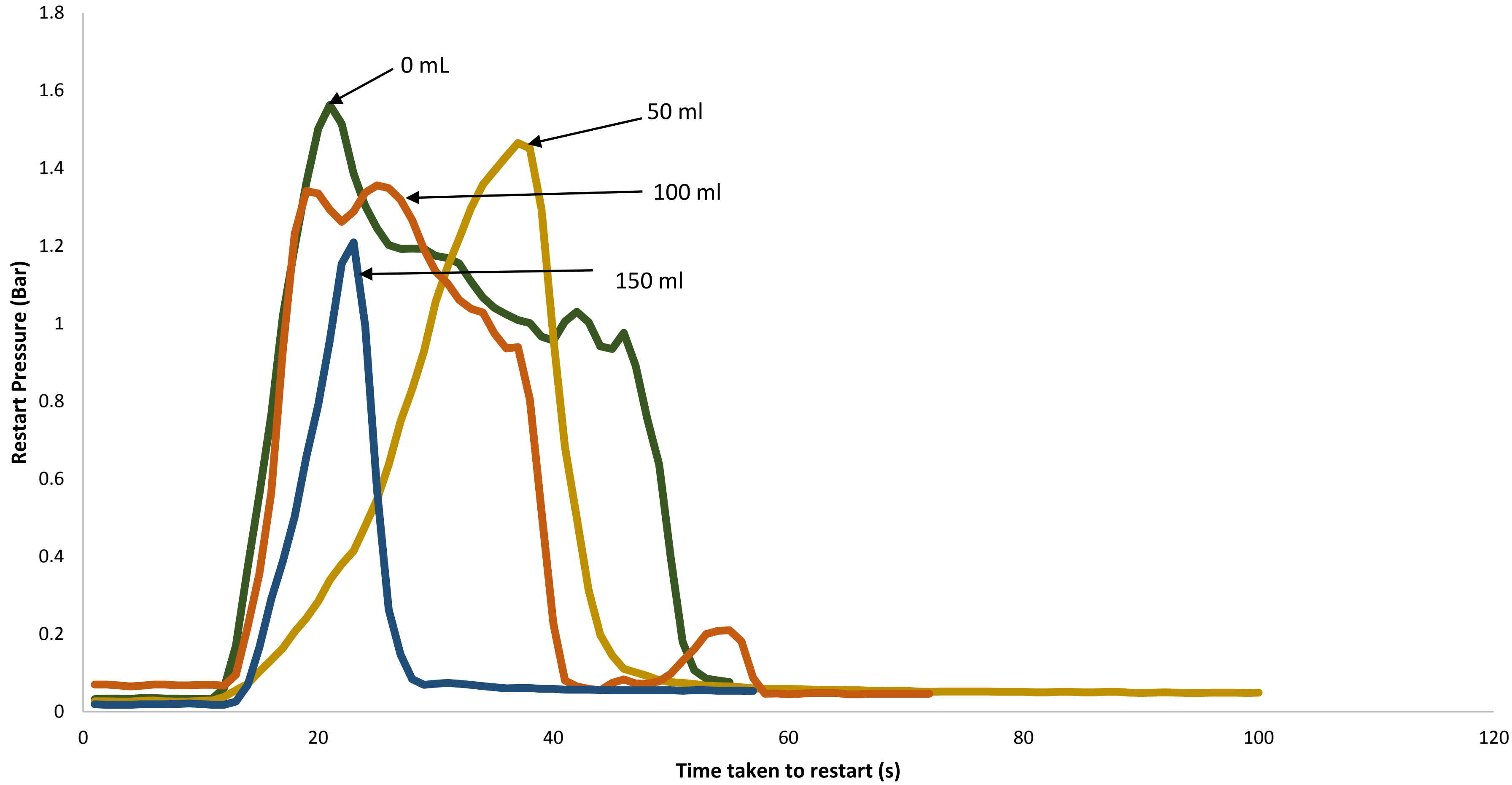


Figure 4.8: Instantaneous restart pressure profile with varying volume of injected nitrogen gas

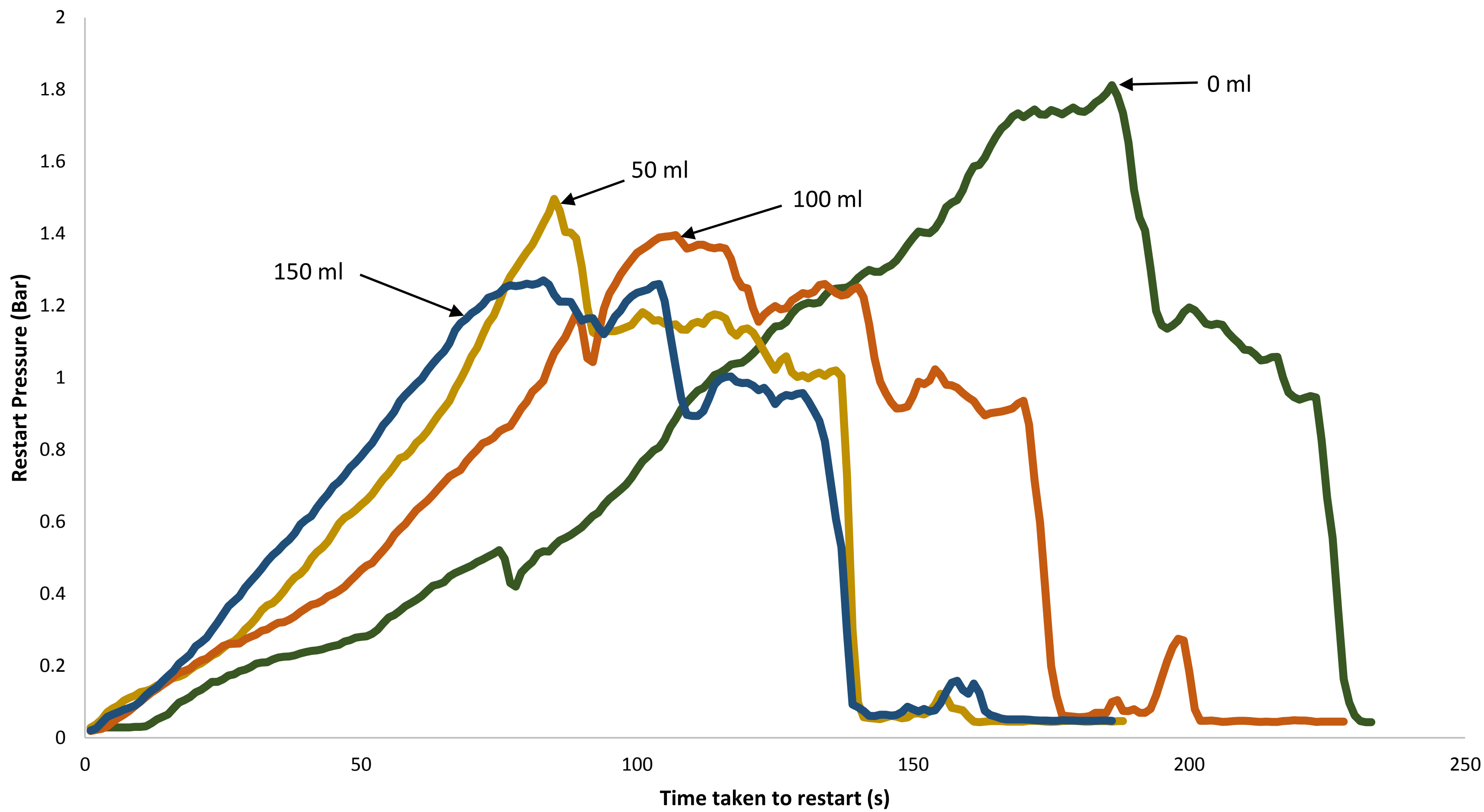


Figure 4.10: Gradual restart pressure profile with varying volume of injected nitrogen gas

CHAPTER 5

CONCLUSION AND RECOMMENDATION

In this chapter, the conclusion with respect to this study is presented in detailed manner. All the findings that was noted during the experiment is discussed as well. Future improvements related to the study for future expansion is listed out and discussed.

5.1 Conclusion

In this present study, the experiment for characterization of restart pressure in a production pipeline for waxy crude oil as a result of injection of non-reacting gas was successfully conducted. The objective of this work have been achieved, as implied by the reduction in restart pressure for every run conducted. The following were the findings observed throughout the experiment.

i) The formation of gas voids was found mainly at the downstream side of the test section. After the nitrogen gas was injected into the test section, right after the crude oil stopped flowing, most of the nitrogen gas moves downstream. As the crude oil cools down to the same temperature of the water bath, it was noted that the gas voids were growing larger due to the effects of thermal shrinkage.

ii) In both cases where by the restart pressure was applied instantaneously and gradually, it was found that the restart pressure needed in order to disintegrate the gelled wax was reduced at most by 11.48% at water temperature of 20ºC and 17.44% at water temperature of 25ºC respectively. This was largely due to the effects of compressibility of the gelled wax as there was space for the wax to move when a pressure was applied.

iii) The restart pressure needed in order to resume flowing condition through gradual restart pressure approach was found to be higher as compared to instantaneous pressure approach as the gradual pressure build up was needed in order to overcome the adhesive strength of the gelled wax.

iv) In both instantaneous and gradual restart pressure approach, it was found that restart pressure was reduced as the gas to oil volume ratio increases. This was due to the high volume of voids created by the nitrogen gas and causes the gelled wax to compress even more when pressure was applied through displacing fluid.

In essence, it was proven that the injection of nitrogen gas into the pipeline during static cooling, prior to gelation is able to reduce the restart pressure. This can be significant as oil and gas operators are able to save more cost on capital expenditure (CAPEX) and operating expenditure (OPEX) during the designing stage of the pipeline. Production pipeline that is currently in service would have a reduction in terms of its specific material yield stress (SMYS) and therefore would not be able to support high pressure due to corrosion and erosion activity that occurs during operation. If pressure applied is beyond the pipeline's SMYS, the chances that the pipeline would burst is significantly increased. Since it was proven through the study conducted that gas intrusion is able to reduce the restart pressure needed, it provides an assurance to pipeline operators that chances of pipeline will burst is reduced during a restart operation.

5.2 Recommendation

The study conducted can be carried out in the future with further expansions as the experiment conducted is only limited to water temperature of 20ºC, 25ºC and 30ºC. The following recommendations can be used in order to further expand this study in the future.

i) It was found during the experiment that if the water temperature is lower than 20ºC, the restart pressure needed is greater than 2 bar which is the maximum allowable pressure of the test section. During the experiment, it was noted that gas bubbles will start to leak out at the upstream part of the test section causing leakage of crude oil. It is proposed in further study that the material of the test section is substituted with aluminium as it is able to with stand higher pressure.

ii) The gas injection site was done at the upstream side, which is beyond the test section rather than on the test section itself. This causes problems as the nitrogen gas injected might not enter the test section completely and some of the gas might be trapped within the pipping. Due to this, there is an irregularity when trying to recorded the restart pressure that is needed in order to disintegrate the gelled wax within the test section. It is proposed in further studies that the gas injection site is done on the test section itself, and the gas being injected radially along the wall of the test section. This is to ensure that all of the injected gas will be confined to the test section.

iii) A gas bleeding system might need to be implemented within the test rig so as to remove any remaining gas that was injected in previous experiment run. There were difficulties in obtaining the restart pressure as previously injected gas was still present within the pipping and test section of the pipeline. This produces an inaccurate reading when all the experiment runs were repeated.

iv) For this particular study, the crude oil is subjected to static cooling under quiescent conditions. It is proposed in further study that crude oil can be cooled gradually, in which it will lead to a complete no flow condition.

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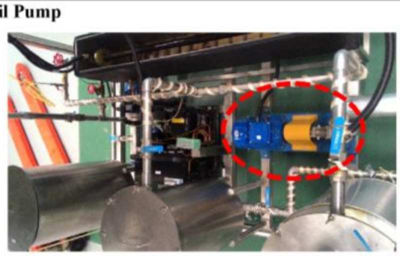
APPENDICES

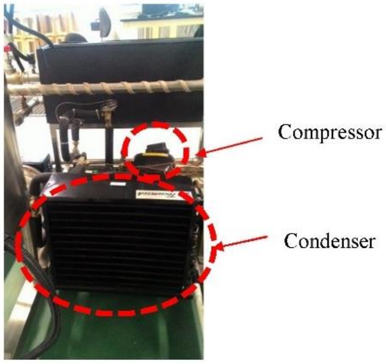
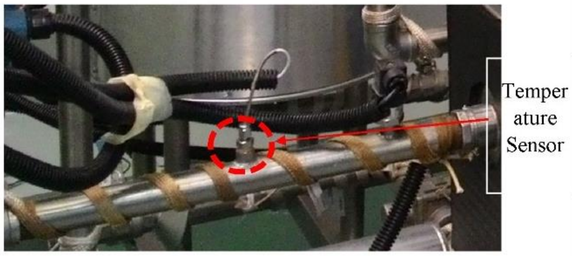
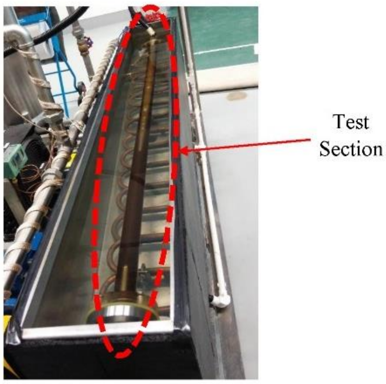
Appendix 1	Physical and Chemical Properties of Nitrogen
Appendix 2	Detailed Component Specifications of Waxy Crude Oil Flow Loop
Appendix 3	List of Components for Nitrogen Gas Injection System
Appendix 4	List of Calculations

Appendix 1: Physical and Chemical Properties of Nitrogen

Chemical Formula	N_2
Molecular Weight	28.01
Boiling Point @ 1 atm	-320.5
Freezing Point @ 1 atm	-346
Critical Temperature	-232.5
Critical Pressure	492.3 psia
Density, Gas @ 68 ºF (20ºC), 1 atm	0.0725 lb/scf
Specific Gravity, Gas @ 68 ºF (20ºC), 1 atm	0.97
Specific Volume Gas @ 68 ºF (20ºC), 1 atm	13.80 scf/lb
Latent Heat of Vaporization	2399 Btu/lb mole
Expansion Ratio, Liquid to Gas, Boiling Point to 68 ºF (20ºC)	1 to 694

Appendix 2: Detailed Component Specifications of Waxy Crude Oil Flow Loop

Components	Details / Specifications
Crude Oil Tank (T-101) Storage Tank 	Capacity : 50 Liter Material : Stainless Steel 304 The crude oil tank is equipped with a 12 kW heater A motor stirrer is mounted on top of the tank in order to mix the crude oil to a homogenous state
Solvent Tank (T-201) 	Capacity : 50 Liter Material : Stainless Steel 304 The solvent tank is equipped with isolation section in order to isolate the solvent and crude oil
Water Bath 	The water bath tank is made from stainless steel 304 and has the capacity to store 60 liters of water. The water bath is equipped with evaporators in which it is connected to a chiller for water cooling purposes.
Crude Oil Pump 	The crude oil pump has a power generation of 1.1kW and has 6 poles with 3 ph. The pump was made by Marelli Motori in Italy with the model number MOT.3-MAA 90L6-B3
Crude Oil Flow Meter 	The crude oil flow meter is used in order to measure the flow rate of the crude oil flowing inside the pipeline. It is connected to the upstream part of the pipeline and is a 1" corrollis flowmeter. The flowmeter was manufactured by Micro Motion Transmitter and the model number is 1700I12ABZEZZZ
Water Circulation Pump 	The pump shown is a centrifugal water circulation pump and it able to produce water flow rate at 40 liters per minute at operating pressure of 2 bar.

Components	Details / Specifications
Chiller 	The chiller is placed within the water bath and is used to cool down the water. The heat transfer between the chiller and the water in the water bath takes place within the evaporator and the chiller has the cooling capacity of 3kW at 15°C cooling capacity.
Temperature Sensor 	A thermocouple temperature sensor is placed at the upstream and downstream part of the test section. The temperature sensor has the capability to measure temperatures at the range of 0-100 degree Celcius
Acrylic Test Section 	The test section is made from acrylic in which it is 1.2 meters in length with a diameter of 30 mm. The acrylic test section will be fully immersed in the water bath as to simulate the conditions of the subsea floor.
Crude Oil Motor Stirrer 	The crude oil motor stirrer is made by TPG and is a 3-phase gear motor. The model number is GV-22-400-20S and it has a rating of 0.5 HP, 0.4KW, 4 poles, 2.0/1.15 A, frequency of 50/60 Hz and revolution per minute of 1450/1720.

Appendix 3: List of Components for Nitrogen Gas Injection System

Component	Function
Nitrogen Gas Cylinder 	Contains compressed nitrogen gas with maximum storage pressure of 200 bar.
Stainless Stell Reinforced Teflon Hose 	2 units of ¼ inch with the length of 1 m each were used. This hose will be used in order to transport the nitrogen gas from the gas cylinder into the opening before the test section.
Nitrogen Gas Regulator 	Will be used for regulating the pressure coming out from the gas cylinder. The regulator will be installed on top of the gas cylinder valve.
Ball Valve 	Acts a controlling mechanism for the nitrogen gas to enter the pipeline. It will be installed at the opening just before the test section.
Gas Flow Meter 	The gas flow meter will be installed in between 2 hoses so as to monitor the flow rate or control the flow rate of the gas coming in from the gas cylinder.

Appendix 4: List of Calculations

i) Calculation for period of valve opening time

a) For 50 mL

$t_v = \frac{50\ mL}{(\frac{1\ LPM\ x\ 1000}{60})}$

$\therefore t_v$ = 3 sec

b) For 100 mL

$t_v = \frac{100\ mL}{(\frac{1\ LPM\ x\ 1000}{60})}$

$\therefore t_v$ = 6 sec

c) For 150 mL

$t_v = \frac{150\ mL}{(\frac{1\ LPM\ x\ 1000}{60})}$

$\therefore t_v$ = 9 sec

ii) Calculation for cooling rate of crude oil

a) For 30 ºC

$$C_{avg} = \frac{40\ ºC}{60\ min}$$

$$\therefore C_{avg} = 0.667\ ºC/min$$

b) For 25 ºC

$$C_{avg} = \frac{45\ ºC}{60\ min}$$

$$\therefore C_{avg} = 0.75\ ºC/min$$

c) For 30 ºC

$$C_{avg} = \frac{40\ ºC}{60\ min}$$

$$\therefore C_{avg} = 0.8733\ ºC/min$$

iii) Calculation for % difference

a) Instantaneous Restart Approach

1) For 30 ºC

$$\%_{Pr} = \left[\frac{(0.047)}{1.415}\right] X\ 100\%$$

$\therefore \%_{\mathrm{Pr}} \quad = 3.32$ %\

2) For 25 ºC

$$\%_{Pr} = \left[\frac{(0.098)}{1.569}\right] X\ 100\%$$

$\therefore \%_{\mathrm{Pr}} \quad = 6.27$ %

3)For 20 ºC

$\%_{Pr} = \left[\frac{(0.205)}{1.785}\right] X\ 100\%$

$\therefore \%_{\mathrm{Pr}} \quad = 11.48\ \%$

b) Gradual Restart Approach

1) For 30 ºC

$\%_{Pr} = \left[\frac{(0.139)}{1.49}\right] X\ 100\%$

$\therefore \%_{pr} = 9.33\ \%$

2) For 25 ºC

$\%_{Pr} = \left[\frac{(0.316)}{1.92}\right] X\ 100\%$

$\therefore \%_{pr} = 17.44\ \%$

3)For 20 ºC

$\%_{Pr} = \left[\frac{(0.219)}{2.077}\right] X\ 100\%$

$\therefore \%_{pr} = 10.54\ \%$

iv) Calculation of test section volume

$$V_t = \frac{\pi 0.03^2 1.2}{4}$$

$\therefore V_t = 8.4823\ x\ 10^{-4}$ m^2 or 848 mL

v) Calculation of Gas to Oil Ratio

i) For 50 mL

$$R_{GO=}\frac{50\ mL}{848\ mL}$$

$\therefore R_{GO=}0.05894$

ii) For 100 mL

$$R_{GO=}\frac{100\ mL}{848\ mL}$$

$\therefore R_{GO=}0.11792$

iii) For 150 mL

$$R_{GO=}\frac{150\ mL}{848\ mL}$$

$\therefore R_{GO=}0.17688$