

EXPERIMENTAL ANALYSIS OF THE FLOW START-UP OF GELLED WAXY CRUDE OIL IN A PIPELINE PREVIOUSLY SUBMITTED TO DIFFERENT PRESSURIZATIONS

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Abstract. Energy and its production are major subjects of research and development, due to its importance to the economy. In this scenario, oil extraction and processing are some of the main ways of obtaining energy. In Brazil, oil is commonly extracted far away from the coast using oil platforms. Therefore, the fluid must be transported to land. One of the most used ways of doing it is through pipelines at the bottom of the sea, where the temperatures can be as low as 4°C. During this process, in eventual stops, gelation can occur to the oil, due to the waxy deposition that takes place at the low temperatures in which the seabed is. During the flow start-up, pressures larger than the usual steady state pressure are necessary to break the gel-like structure. If those high pressures are not taken into account when designing the oil transport system, the pipeline may be damaged and even broken. One important factor that influences the pressure development during restart is the pressure in which the pipeline is subjected prior to the start-up. The objective of this work is to evaluate the differences of pressure evolution in a start-up process where the pipeline was previously submitted to distinct pressurizations levels and then to a constant flow rate to break the gel. The tests were executed using an experimental apparatus, consisting of a pair of syringe pumps that injects oil with constant flow rate into a pipeline connected to a storage tank and a temperature control system. It was observed that for a higher internal pressure in the pipeline prior to the start-up the pressure overshoot was higher and occurred at shorter times.

Keywords: Waxy Crude Oil, Flow start-up, Offshore, Experimental Analysis, Pressurization

1. INTRODUCTION

Oil gelation is one of the major issues in waxy crude oil production and transportation. That occurs when the pipelines, which normally are settled over the seabed at temperatures as low as 4 °C, have their flow shut off for maintenance (Wardhaugh and Boger, 1987). In order to break the gel structure, pressures larger than the steady state pressure are necessary. Those high pressures must be taken into account when designing oil transport systems (Magda et al., 2013).

As stated in several works, the properties of the waxy crude oil are affected by the temperature and the cooling conditions to which the oil is submitted, such as test temperature (Davenport and Somper, 1971; El-Gamal and Gad, 1998; Hou and Zhang, 2010; Visintin et al., 2005; Wardhaugh and Boger, 1987), initial cooling temperature (Andrade et al., 2015; Jemmett et al., 2013; Marchesini et al., 2012; Rønningsen, 1992; Smith and Ramsden, 1978), shearing and cooling history (Chen et al., 2006; Cheng et al., 2000; Lee et al., 2008; Lin et al., 2011; Webber, 2001).

Some researches to investigate the behavior and the flow of oil at low temperatures in pipelines were realized using experimental apparatus. The oil shrinking during cooling and its impacts were addressed by Phillips et al. (2011). It was observed that for each 10 degrees lowered in the test temperature, the oil shrinks about 1% of its volume. The appearance of voids and the decrease of the pressure inside the pipeline were also noticed throughout the cooling of the sample. The cited paper also states that the bigger the cooling rate, the largest is the shrinking and gauge pressure decrease in the pipeline due to the volume reduction.

Jemmett et al. (2013) investigated the influence of homogeneous and heterogeneous gels in the start-up pressures. Heterogeneous gels are those that present wax crystals in its composition. In sum, the results show that heterogeneous gels require smaller start-up pressures than homogeneous at the same temperature and cooling rate.

In other study that utilized an experimental unity, it was noticed a pressure reduction when the temperature reaches the value defined as pour point. The researchers concluded that this behavior occurs due to contraction of oil during the cooling (Magda et al., 2013).

Deposition of wax on the inner surface of the tube can occur during the cooling of the pipeline. This deposition causes reduction in the diameter of the pipeline, becoming an obstacle for the oil flow and increasing the start-up pressure. In order to analyze how that deposition takes place, Guozhong and Gang (2010) utilized an experimental loop. With their experiments, they stated that when the temperature of the pipeline wall is reduced, the temperature of the oil located near the test section falls quickly, causing a rapid increase in the viscosity of the fluid viscosity. Due to a radial temperature difference in the test section, the differential pressure rises suddenly.

The influence of compressibility and shrinkage of the oil was analyzed with the use of an experimental apparatus (Geest et al., 2015). The study concluded that the influence of these factors can be as significant as rheology or even more influential. They evaluated the start-up pressure after cooling and aging the crude oil under different pressures. The results did not show significant changes in the start-up pressure for tests at different pressures.

Out of the cited works that used an experimental apparatus, the research of Magda et al. (2013) also applied pressure on the oil while cooling. A compressed nitrogen gas cylinder was used to subject the model oil to a known pressure that was not time dependent. This procedure was adopted to bring the void formation, which takes place due to thermal contraction (Phillips et al., 2011), to a minimum. The other studies did not have the gauge pressure of the pipeline as a controlled variable.

In this context, this work has the emphasis of utilizing an experimental apparatus to evaluate the differences between tests realized at different pressures during cooling. The experimental unity operates in conditions that represent the adversities faced by the oil transportation in underwater pipelines, which are subjected to low temperature and that can be stopped for maintenance purposes. As the pipelines operate at the bottom of the sea, there is hydrostatic pressure during a shutdown, so the pressurized test adds another variable that may influence in a full scale oil transport operation. The variables to be evaluated are the start-up pressure of the gelled waxy crude oil, as well as the time required to break the structured gel and the development of the pressure curve. The study also aims to relate characteristics of the gelled oil, such as shrinkage, the formation of voids and the increase in the compressibility of the system, to the behavior of the pressure evolution in the flow restart.

2. EXPERIMENTAL APPARATUS DESCRIPTION

The experimental unity was built in the Research Center for Non-Newtonian Fluids (CERNN – UTFPR) and it is composed by a hydraulic circuit, a measuring and control system and a refrigeration and heating system. Figure 1 represents the experimental apparatus with its components and illustrates de operation loop.

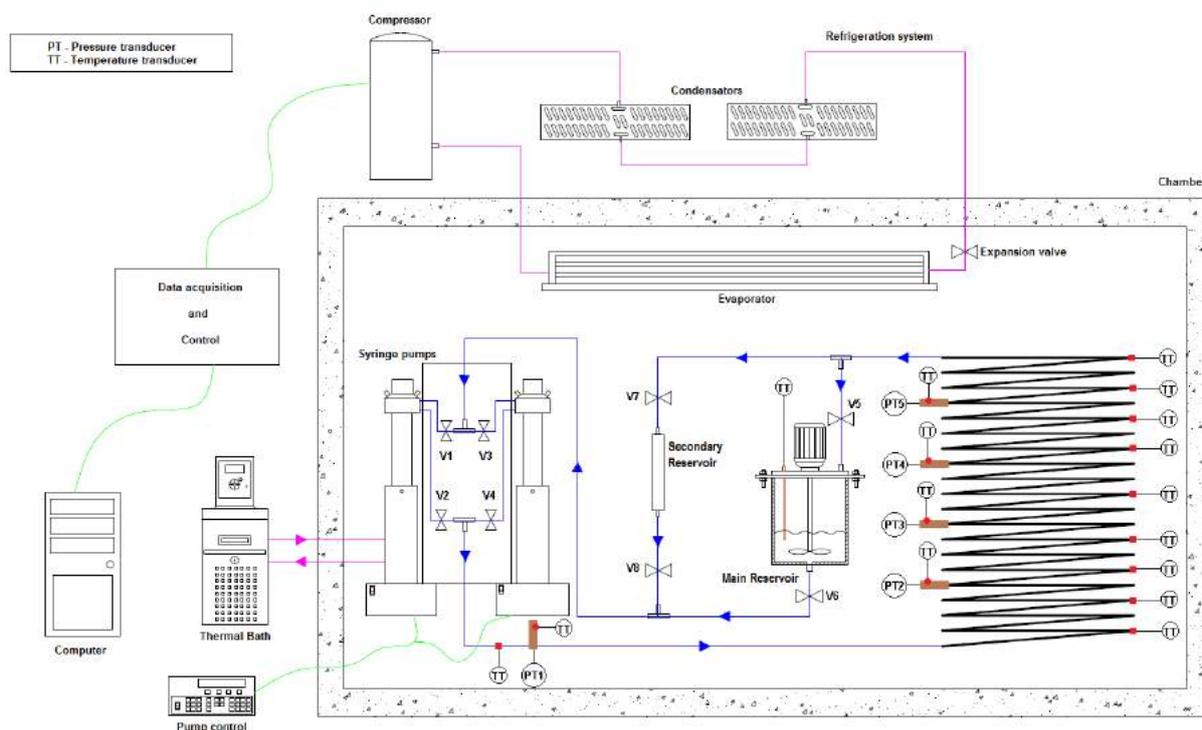


Figure 1 – Schematic representation of the experimental apparatus, adapted from (Rosso, 2014).

The hydraulic circuit is composed by two syringe pumps Teledyne ISCO, model 500D, which grants the flow of oil with a precision of $\pm 0.5\%$ for pressure and flow rate. The pumps work in an intermittent regime, which provides a constant flow rate. Valves were utilized to control the supply of the pumps and of the test section that is composed of stainless steel pipeline with internal diameter of 10.3 mm, external diameter of 13.3 mm, length of 56.6 m and internal volume of 4.3 L. This pipe stands as the main test section and was built in a helical shape of 750 mm in diameter and 752 mm in height. The main oil reservoir keeps the fluid at a constant temperature by means of a PT100 that measures the temperature and sends data to a control panel. This panel activates a secondary temperature control system and thermal resistances that control the temperature of the water jacket that involves the main reservoir. The main reservoir

is connected to a mechanical stirrer that agitates the oil to keep the composition homogeneous. A thermal bath keeps the pumps and the connection between the main reservoir and the pumps at a constant temperature. All those components were assembled in a chamber that can keep a constant temperature in its interior. The chamber has 2.34 m of length, 1.42 m of width and 1.38 m of height, with walls made of polystyrene plates of 100 mm. The measuring and control system has ten thermocouples and four thermo resistors PT100, that were installed within the pressure transducers. Three transducers with an operation range from 0 to 100 bar and an exactitude of 0.15% of the full scale were installed for the acquisition of pressure data: PT1, PT2 and PT4. The data was acquired by a National Instruments system and monitored by a LabVIEW based software. The first transducer was positioned on the exit of the pumps, while PT2 was installed 11.8 m away from PT1 and PT4 was set 21.8 m before the serpentine exit.

The system to control the temperature is composed by an evaporator, an expansion valve and a condensation module, as well as electrical resistances. This system can vary the temperature from -10 to 80 °C and maintain a constant temperature by means of a variable frequency drive which is controlled by the LabVIEW software.

The oil sample utilized in the experimental unity was provided by Petrobras. With a composition of 28% of aromatic compounds and 72% of waxy compounds, the crude oil have a pour point of 11 °C. A qualitative test described in (Rosso, 2014), indicated a shrinkage of 4% in volume for the same oil varying the temperature from 60 to 4 °C.

3. EXPERIMENTAL PROCEDURE

Two different procedures were used during the tests: Procedure 1 and Procedure 2. All tests started with a pre-treatment phase, the chamber temperature was elevated to 25 °C and when this temperature was reached, the oil was circulated through the serpentine at a constant flow rate of 150 ml/min. The circulation was maintained for 30 minutes. This phase has the objective to attribute the same temperature, shear and cooling history to the oil before the start of each test.

The second step (heating) initiates by stopping the flow and then elevating the temperature of the unity to the initial cooling temperature (30 °C in our experiments). The third part of the procedure (cooling) is when the fluid is cooled to the final temperature (4 °C in our experiments). The two types of tests differentiate when the fluid reaches the initial cooling temperature, as it is shown in Figure 2:

Procedure 1: the temperature of the test reached 30 °C and after aging for one hour at the initial temperature, the chamber temperature was set to 4 °C and the cooling occurred at a rate of 1.2 °C/min without any shear rate being applied to the oil – static cooling. The pipeline, which was under the pressure only of the atmosphere and the hydrostatic pressure of the fluid, did not receive additional volumes of crude oil during this process. The pipeline suffered a slight gauge pressure loss, due to the thermal shrinking and compressibility of the oil.

After reaching the final test temperature, the oil would rest for an hour in order to cool the totality of the sample and to continue the formation of gelled structures. The final step was to activate the pumps at a constant flow of 64.35 ml/min to break the gelled waxy crude oil, while the transducers monitored and recorded the pressure values in different extensions of the pipeline.

Procedure 2: when the initial cooling temperature was reached, a valve that closes the access of the pipeline to the main reservoir was manually activated, so the only source for the serpentine during cooling was the pumps. In the pump controller, the mode of operation was switched from constant flow to constant pressure and the pressure was set to 2 bar. In this operation mode, when the pump felt a pressure loss, more fluid was injected from the syringe so that the 2 bar pressure was kept constant. The oil was aged for one hour at initial cooling temperature, than the chamber temperature was set to the final test temperature.

When the final temperature of 4 °C was reached, after cooling at a rate of 1.2 °C/min, the sample rested at constant pressure for one hour. Then the valve that had been activated is deactivated and the mode of operation is switched back to constant flow. In order to break the gelled oil, a constant flow of 64.35 ml/min was given by the pumps, while the transducers acquired pressure data during the start-up.

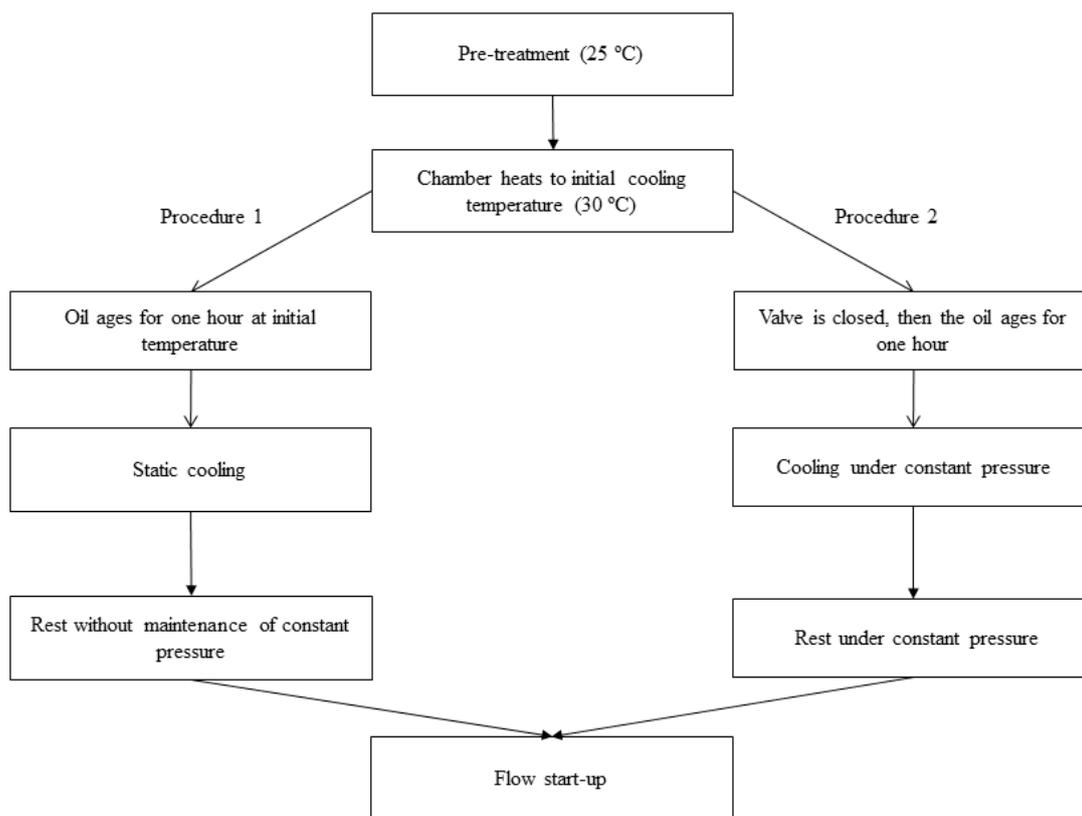


Figure 2 – Schematic representation of the experimental procedure.

For all tests the parameters kept constant were the initial cooling temperature, the final cooling temperature, the cooling rate, the aging time and the start-up flow rate. Different procedures were tested experimentally and those parameters were set as the values that granted the best repeatability, within the experimental apparatus limitations (Rosso, 2014).

4. RESULTS

The start-up can be divided in three phases. In the first phase, the pressure grows continually after the pump is activated, but the pressure variation does not occur at the same instant for the three transducers. The PT1, which is positioned near to the exit of the pump, is the first to detect a pressure increase, while the other transducers have a delayed response to the variation in pressure in comparison to the time of activation of the pump. This is shown in Figure 3, where the results of pressure evolution for transducers PT1, PT2 and PT4 are represented for Procedure 1. That behavior can be explained by the shrinkage of the material during cooling and the subsequent increase of the compressibility of the system due to the formation of void spaces, which causes dissipation of the pressure applied by the pumped fluid. As the system gets compressed, the pressure is transmitted to further regions of the pipeline.

In the second phase, all three transducers reach a maximum value (overshoot pressure). This value indicates that as the oil gets compressed and the gelled structures break, the material goes from a predominantly elastic behavior to a predominantly viscous behavior, and thus restarting the flow in the pipeline. The three overshoots occur practically at the same time, as presented in Figure 3, because after a certain amount of fluid is injected by the pumps for the start-up, the voids are minimized by the compression and the pressure is transmitted to the totality of the oil inside the serpentine. Although the last transducer responds later to the variation of pressure, the pressure increase happens more suddenly. Finally, in phase three the oil that initially was gelled gets expelled from the pipeline and the flow tends to operate in steady state.

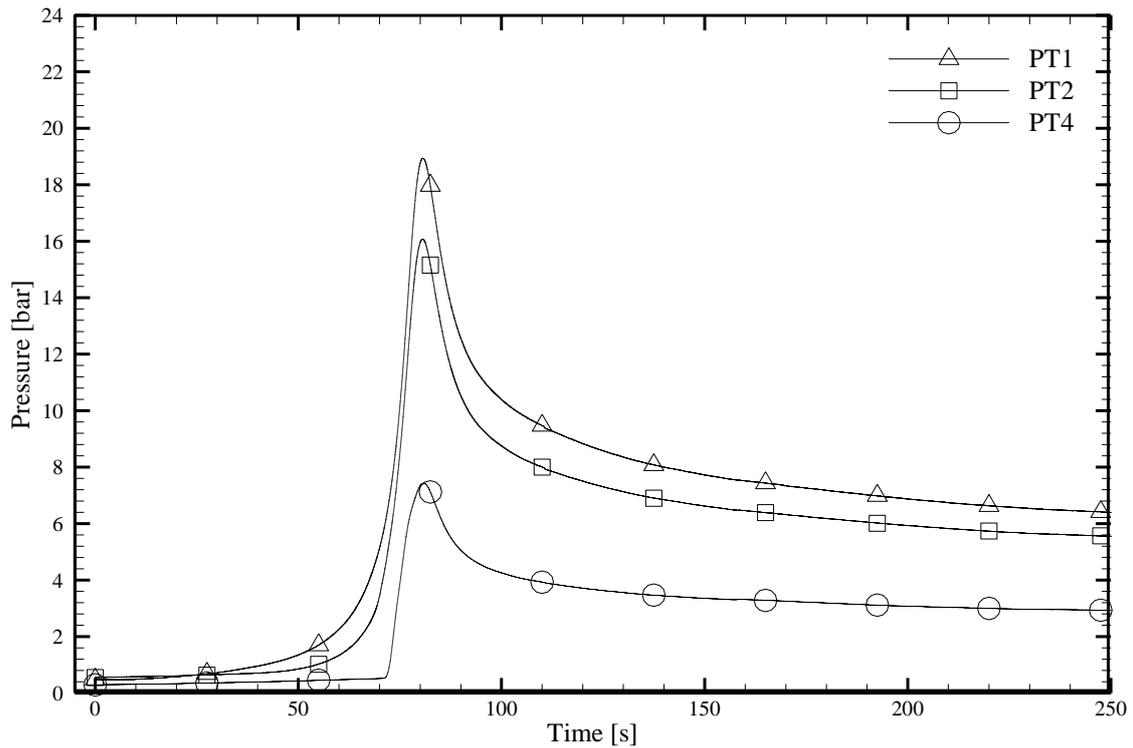


Figure 3 – Pressure evolution of a start-up test realized by using Procedure 1.

Figure 3 shows the pressure evolution of PT1, PT2 and PT3, for three different tests realized under Procedure 1. The overshoot pressure in PT1 for tests 1, 2 and 3 was, respectively, 22.60, 22.56 and 22.25 bar, which represents close values for the same conditions of start-up. Using Test 1 as reference, for PT1, Test 2 presented a difference of 0.18% for overshoot pressure value and Test 3 presented a difference of 1.55%. For PT2, the variations of pressure peak for tests 2 and 3 were, respectively, 0.58% and 1.74%. For PT4, the percentage difference of maximum pressure for Test 2 and Test 3 was, respectively, 0.41% and 2.03%. Those numbers represent a consistent repeatability for all three transducers in the tests realized utilizing Procedure 2.

Figure 4 presents the pressure evolution for tests realized under Procedure 2. The results for the pressurized tests were similar to the ones of the non-pressurized tests, but with a shorter time to break the gelled oil. The quicker increase of pressure is an evidence that the pressure waves are propagated with more velocity than in tests with Procedure 1, as the injection of more fluid to maintain the constant pressure disfavors the formation of voids.

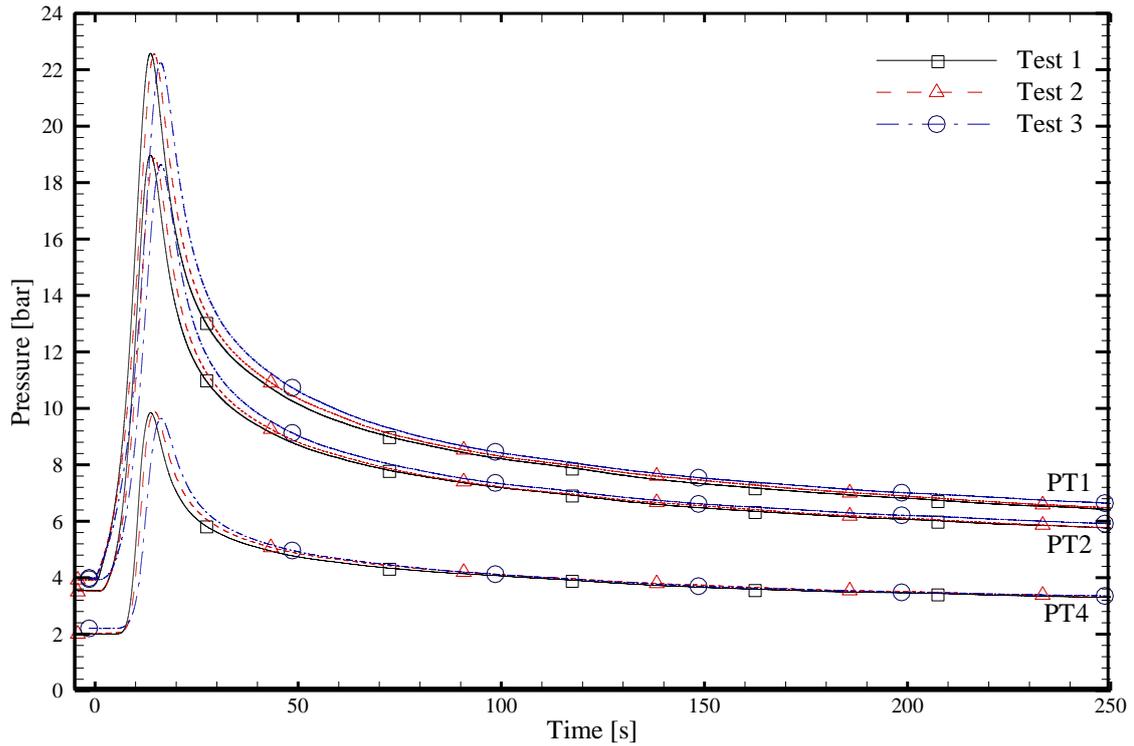


Figure 4 – Pressure evolution for pipeline pressurized at 2 bar (Procedure 2).

A comparison between the pressure data acquired with Procedure 1, where the fluid cooled without any additional oil injection to keep a given pressure, and Procedure 2, where the fluid cooled under a constant pressure is presented in Figure 5.

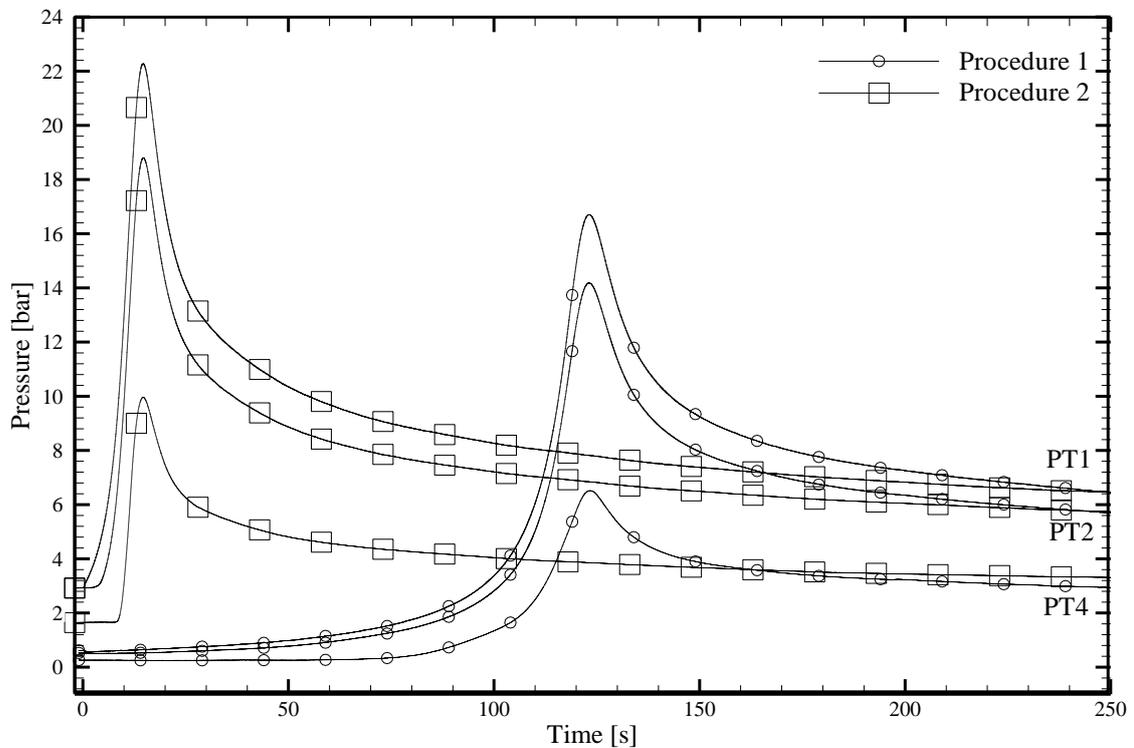


Figure 5 – Comparison between the pressure data obtained utilizing Procedure 1 and Procedure 2.

In this comparison, it is evident that the time to reach the overshoot pressure is dependent of the adopted procedure. The overshoot was reached after 120 s for Procedure 1 and after 20 s for Procedure 2. The difference between the values of the overshoot pressure was considerable as well. The maximum pressure reached with Procedure 1 was

16.72 bar. While with Procedure 2 the overshoot pressure was 22.29 bar. That represents an increase of 33.3%. On the other hand, after the pressure overshoot, the pressure evolution indicates that with both procedures the fluid tends to equilibrium with similar pressure values independent of the procedure. Steady state is not reached at the time scale represented in Figure 5, so the pressure values at 250 s were adopted as equilibrium pressure for comparison purposes. Those values in Procedure 1, for PT1, PT2 and PT4 were, respectively, 6.47, 5.70 and 2.94. For Procedure 2, the equilibrium pressure values for PT1, PT2 and PT4 were, respectively, 6.45, 5.74 and 3.31. Using Test 1 as reference, the percentage difference was 0.31% for PT1, 0.70% for PT2 and 12.58% for PT4.

Those variations in the tests are strongly related to the system compressibility. In tests realized under Procedure 1, the fluid shrank and therefore, voids probably appeared in the material. During the restart, those voids increased the system compressibility, therefore the pressure waves faced a barrier each time a void was in its way and the transmission of pressure occurred less effectively. This can be observed in Figure 5 by the larger delay in the time to detect a variation in pressure for all transducers. It was also observed that the pressure overshoot with Procedure 1 was smaller than with Procedure 2. This can be related to the compressibility as well. During the start-up, each time that the pumped oil encountered a void, the pressure was relieved, and the gel breakage occurred in a more gradual way, so the magnitude of the pressure overshoot was smaller.

In the test with Procedure 2, when the material started to shrink, the pump pressure controller felt a pressure decrease and then it pumped a given amount of oil to compensate that loss. This process minimizes the formation of voids and that is indicated by the smaller delay in the time in which the PT4 detected a pressure variation, in comparison to the test realized under Procedure 1. This behavior shows that the pressure wave was able to propagate in a faster way, finding less voids that difficult the transmission of pressure. The higher magnitude of the overshoot pressure denotes that there was less dissipation of the pressure throughout the oil and the break of the gelled structures occurred in a more sudden way. This behavior is related to the system compressibility, because both tests were subjected to the same cooling rate, initial and final temperatures and oil composition, so the variable that varied was the pressure to which the oil was subjected during cooling. The gelled structure of the oil was more rigid in the tests that were cooled under 2 bar. As the pressure was maintained by injecting oil from the pumps, a larger volume of gelled oil was present with considerably less voids. Those factors resulted in a more elastic behavior, requiring higher pressures to start-up the flow.

5. CONCLUSION

The utilization of experimental apparatus for the investigation of the behavior of gelled waxy crude oil in start-up operations is important. This approach permits to evaluate the variables in a condition that better represents the real conditions of operation. The presence of pipelines, pumps, and temperature control makes the analysis more loyal to the environments in which the oil transportation actually occurs.

The pressure that the pipeline is subjected during a shutdown has a significant influence on the start-up pressure and time to reach the pressure peak. In a test in which the pressure during cooling was kept constant by the injection of oil by the pump, the maximum pressure was more intense and the time taken to break the gelled structure was smaller, than in a test where there was not a previous pressurization in the pipeline.

The effects of shrinkage and formation of voids represent a considerable influence in the behavior of the oil during a start-up process as the system compressibility increases. The attenuation of the pressure by the compressibility of the gelled oil system can decrease the intensity of the pressure overshoot. The presence of voids, as well as the compressibility of the system, causes a more gradual break of the gel like structures, so the sections of the pipeline that are more distant from the pump, are subjected to the pressure with a delay from the moment of activation of the pumps during restart.

This work concludes that when projecting a system for transport of offshore waxy crude oil, not only is important to know the rheological properties of the oil that is going to be pumped, but also the conditions in which the transport will operate. For instance, if a transport system goes through a shutdown and the pumps keep pressurized, that causes the injection of oil to the pipeline and disfavors the creation of void spaces, so the project of the pipelines must anticipate a more intense pressure overshoot.

6. ACKNOWLEDGEMENTS

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