

ENC-2022-0710

EXPERIMENTAL ANALYSIS OF THE START-UP FLOW OF MODEL WAXY OIL IN PIPELINE

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Abstract.

During exploration in ultra-deep water, crude oil is transported from reservoirs to the seashore as it loses heat to the ocean floor. The temperature difference induces the cooling of the oil causing the precipitation of paraffin crystals, which may lead to oil gelation during an eventual line shutdown. The gelled crude oil has several non-Newtonian behaviors, such as viscoplasticity, elasticity, time dependence, thermal and shear dependence. Understanding the influence of these variables on restart pressures is a difficult task due to the oil complexity. To restart the flow of the gelled oil it is usually necessary to impose pressures higher than the usual ones. If not controlled, high pressures may damage the pipeline causing environmental problems and financial losses. Therefore, the objective of this paper is to investigate how thermal dependence affects the pressures and restart time. To do so, flow start-up tests under different temperature and operation conditions were performed. The fluid used was a model waxy oil (5% wt.), which was studied on a laboratory-scale flow loop with thermal control. The results showed that the pressures and the restart times were influenced by temperature, cooling rate and pressurization during cooling.

Keywords: oil gelation, non-Newtonian fluid, model waxy oil, restart pressure, laboratory-scale flow loop.

1. INTRODUCTION

The search for new oil reserves has led to the exploration in ultra-deep waters, and increased the production of paraffinic oil (Li et al., 2015). During production and transportation of these waxy crude oils there is a flow assurance problem as a consequence of its chemical composition with high molecular weight paraffins such as n-paraffin of straight chain and iso-paraffin of branched-chain (de Souza Mendes and Thompson, 2012). Due to the high content of paraffin in its composition, the transport of waxy crude oil through the seabed is a challenging and costly task.

Commonly the oil in the reservoir has Newtonian behavior with soluble wax molecules as a consequence of the high temperature (approximately 80 °C) and pressure conditions. However, when the oil is transported, its temperature may decrease below the wax appearance temperature (WAT) due to the heat loss to the seabed (average temperature of 4 °C). When the oil temperature is below WAT, it behaves as a Non-Newtonian fluid as the wax precipitates and deposits along the pipeline. In case of any stoppage due to a planned maintenance or an emergency situation for a period of time, the oil may build up a gelled structure and even block the pipeline (Davidson et al., 2004). This gelled oil cannot flow with the normal operating pressure (Thomason, 2000) and requires a higher pressure imposition to break the gelled structure and then restart the flow (Wardhaugh and Boger, 1987). Besides of that, it is known that the overestimation of the imposed pressure could lead to oversized pipeline projects, which are unviable for application (Fossen et al., 2013).

The main non-Newtonian characteristics of waxy crude oils are viscoplasticity, elasticity, time dependence and dependence of thermal and shear histories (Tharcha et al., 2015). These characteristics added to different thermal operating conditions influence the complexity of the material behavior during the flow restart.

Therefore, in order to understand all these characteristics acting at the same time during the oil transportation it is interesting to evaluate the influence of these variables individually. Therefore, this paper discusses the influence of the thermal effect in the model waxy oil behavior which has similar characteristics to waxy crude oil. To do so an experimental apparatus placed in an insulated chamber was used to conduct flow start-up tests.

2. MATERIALS AND METHODS

The tests were performed with a model waxy oil in a laboratory-scale flow loop.

2.1 Working Fluid

A model waxy oil was used to perform the tests since it has a similar behavior to a gelled waxy crude oil below the crystallization temperature (Andrade et al., 2017). The oil was formulated by adding 5 wt% of a wax paraffin (Sigma Aldrich) in 11 L of mineral oil (Sigma Aldrich). To dissolve the paraffin, it was necessary to stir the mineral oil for 90 min at a temperature of approximately 80°C.

2.2 Experimental Apparatus

The flow loop consists of two syringe pumps, a long helical pipeline, a fluid reservoir, six pneumatic valves and four pressure transducers. Figure 1 shows a schematic diagram of the experimental apparatus. The main test section is the helical pipeline where is placed two pneumatic valves (V6 – entrance and V7 - exit), four pressure transducers (P1 to P4) and ten uniformly distributed thermocouples (T). The flow loop is placed inside a thermally insulated chamber to ensure that the temperature along the entire pipeline is the same.

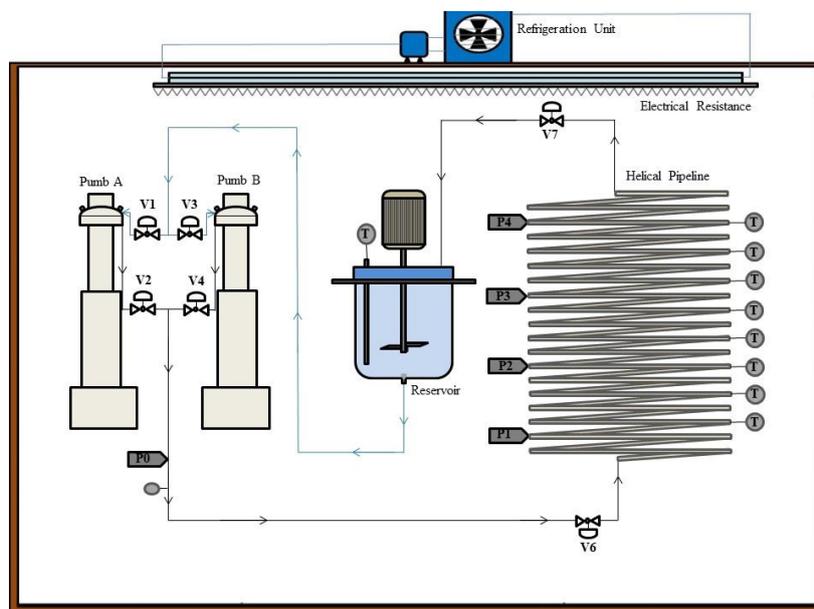


Figure 1. Schematic diagram of the experimental apparatus and its components.

To improve the fluid temperature control, an external tank was installed in the reservoir to maintain the temperature of the fluid at the initial temperature of the test (40 °C). It was also installed a thermal bath connected to the pumps to maintain the temperature of the fluid at the same temperature of the test (40, 25 and 15 °C).

The experimental flow loop operates with the two pumps with constant flow rate or pressure imposition. The pumps can work simultaneously or individually. For the tests, the normal condition was to use it in the individual mode, i.e., while one of the pumps is filling with fluid, the other one is pumping. After flowing through the helical pipe, the fluid returned to the reservoir where it was stored. The flow direction along the circuit is represented by the arrows in Fig. 1.

Both syringe pumps (model 500D) were manufactured by Teledyne ISCO™. The set of pumps works within a flow rate ranging from 0.001 to 204 ml/min, and accuracy of ± 0.5 %. The desired flow rate or pressure is set up by the user

through an external controller which allows pneumatic actuation of the ball valves V1, V2, V3 and V4 to fill or empty the pumps.

There were two models of absolute pressure transducers, all of which are manufactured by HBMTM. The P0 transducer is a P3 Top Class model with a maximum pressure of 100 bar and an accuracy of 0.13 bar. The other transducers (P1 to P4) are P3 Industrial Class model with a maximum pressure of 50 bar and an accuracy of 0.03 bar. These transducers have an internal resistance thermometer (RTD), which were used as a reference to the fluid temperature control.

The helical pipeline has an inner diameter of 10 mm and a total length of 50.53 meters. The distance of P1 regarding to P2, P3 and P4 were 11.03, 22.06 and 33.16 m, respectively. P4 was 8.63 meters from the pipe outlet.

The LabVIEW 2016TM software was used for data acquisition. Furthermore, the software drove a PID controller to achieve and maintain the desired average temperature for the experiments, by using a set of electrical resistances and a refrigeration unit. The average temperature was calculated by the average temperatures measured with nine thermocouples (T) along the pipe surface and the RTD (PT100) which was assembled inside the reservoir.

2.3 Experimental Procedure

Before any test, it is necessary to perform the pre-test in order to clear the thermal history and also homogenize the model waxy oil. The pre-test consists in heating the entire flow loop to 40 °C, and then pumping the fluid for 30 minutes at the maximum flow rate of 193.2 ml/min. For the next step the flow loop was cooled to the final test temperature with a cooling rate of approximately 0.8 °C/min. Independently of the cooling process, the fluid inside both the reservoir and the pumps were maintained in the desired test temperature - a different temperature of the final test temperature. After reaching the final test temperature, all the valves (V1 to V4) are opened, so the pipeline achieves the same pressure distribution.

For the flow restart test, after the pre-test, the desired flow rate is set up in the pumps controller. Then, the start-up can be initiated while the pressure profile is recorded. The selected flow rate used in the tests is 64.4 ml/min for comparison purposes.

3. RESULTS AND DISCUSSION

This section presents the results of the flow start-up for the model waxy oil with different final test temperature (40, 25 and 15 °C) to assess the influence of the temperature over the material behavior. The analysis focus will be mainly in the transient regime of the pressure evolution with the material in the gelled state.

Figure 2 shows the start-up flow tests for the model waxy oil at the final test temperature of 15 °C. It can be seen that at 10 s the pump initiates and the pressure at the first transducer (P1) starts to increase, after 5 s it is followed by the P2, after more 3 s by P3 and then after more 3 s by P4. It was necessary 12 s until all transducers reached the last overshoot pressure in approximately 22 s, which is the moment where the flow restarted. During the transient regime, there are smaller overshoots pressure as a consequence of the voids formed during the gelation process. The physical explanation for these overshoots is that as the gelled material was pumped, it was filling the voids formed in the helical pipeline before the flow restart occurred.

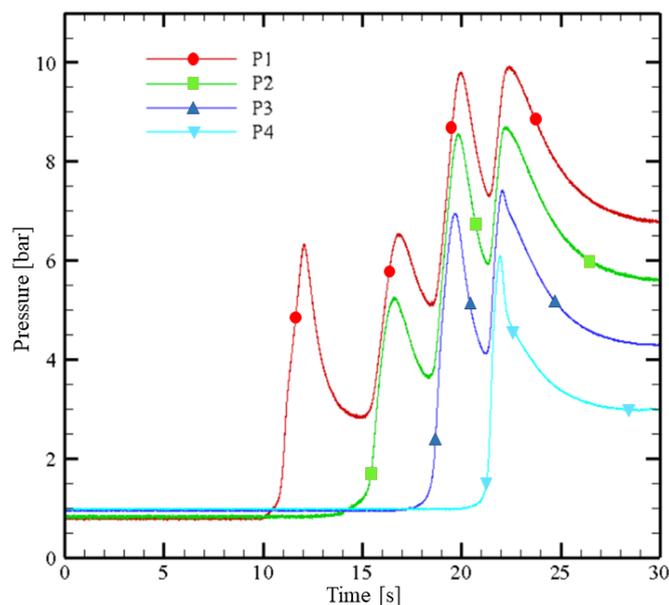


Figure 2. Flow restart of model waxy oil with a flow rate of 64.4 ml/min at a temperature of 15 °C

Considering that the rheological behavior of the model waxy oil depends on the temperature, it was carried out a flow restart test with different final temperature of 40 and 25 °C. The results for these tests are shown in Fig. 3a and b, respectively. Through Fig. 3a, it is observed that the pressure restart curve is similar to a Newtonian fluid, while in Fig. 3b, the material has an overshoot pressure indicating the thixotropic characteristic, as Laponite RD solution. It is interesting to note that the overshoot pressure observed in Fig. 3b is because the model waxy oil started to build the gelled structure, since the Wax Appearance Temperature (WAT) of the material is 27.11 °C, which was determined by the differential scanning calorimetry test. Therefore, below the WAT the wax starts to precipitate in the solution and so the gelation process.

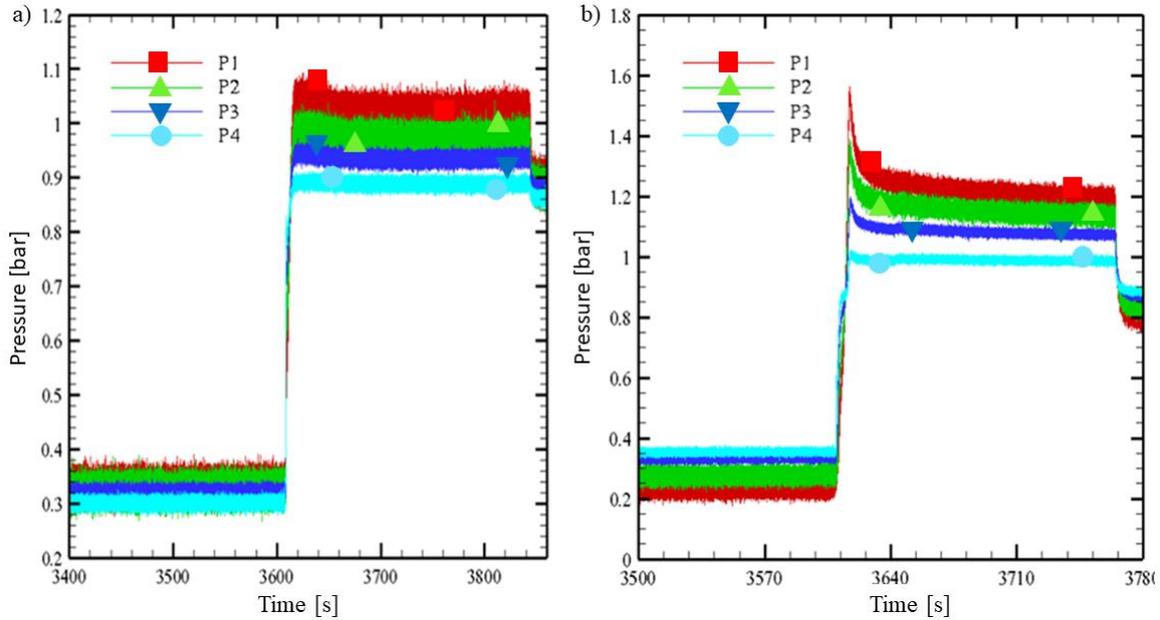


Figure 3. Flow restart of model waxy oil with a flow rate of 64.4 ml/min with a) Temperature of 40 °C and b) Temperature of 25 °C.

To visualize the material rheological behavior changing as the gelation process occurs, it was performed a cooling test in a sealed transparent beaker. The beaker was filled with approximately 81 ml of model waxy oil and it was inserted into the experimental apparatus to be evaluated under the same conditions as the tests. Figure 4 shows the temperature variation in the thermocouples distributed along the serpentine pipe. It is seen that the temperature varies from 40 to 15 °C with an average cooling rate of 0.8 °C/min.

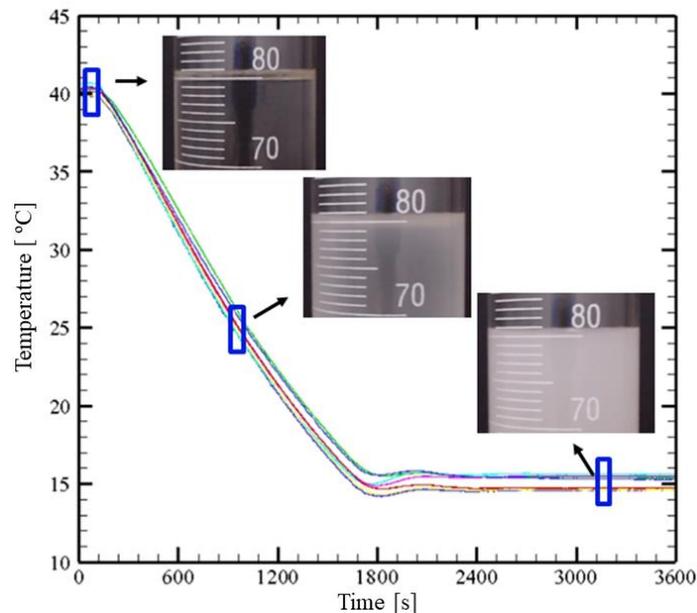


Figure 4. Temperature variation along the helical pipeline.

From this test, it was possible to determine a 4% contraction of the sample during cooling, and extrapolating this value to the serpentine pipeline volume it would be equivalent to 160 ml, or even 2.04 m of contraction. The shrinkage of the material was determined by visualizing the cavity formed in the central part of the beaker, and it is not showed in this image. It is interesting to highlight that Rosso (2014) performed a similar test with crude oil and observed a 4% contraction when reducing the temperature from 60 to 4°C. Likewise, Van der Geest et al. (2015) calculated a 5% shrinkage for the oil through a PVT cell, varying the temperature from 70 to 5°C. It was also performed another test to visualize the contraction during cooling in the restart tests, to do so a 15 cm long transparent acrylic tube was installed before P0. From this test, it was visually verified that the material began to become opaque around the temperature of 27 °C, and afterwards the gelled oil shrunk towards the serpentine pipeline, resulting in an empty space in the tube.

Figure 5a shows the pressure descent level test for the flow rates of 193.2 - 128.8 - 64.4 - 6.44 - 0.644 ml/min and Fig. 5b highlights the transient regime of Fig. 5a. The main objective of this test is to validate the irreversible behavior of the model waxy oil. When the flow rate of 193.2 ml/min is imposed (Fig. 5b) there are some smaller pressure overshoots until the pressure reaches the final overshoot, then the pressure decreases towards an equilibrium value, which in this case is not reached due to the time imposed for this flow rate. For the following flow rates, there is a reduction in pressure level, followed by a gradual increase until the pressure reaches steady state. In this case, negative pressure overshoots are not observed as in Laponite (reversible material), as the model waxy oil has already been broken (irreversible) in the overshoot of 193.2 ml/min. So, the model waxy oil has an irreversible behavior.

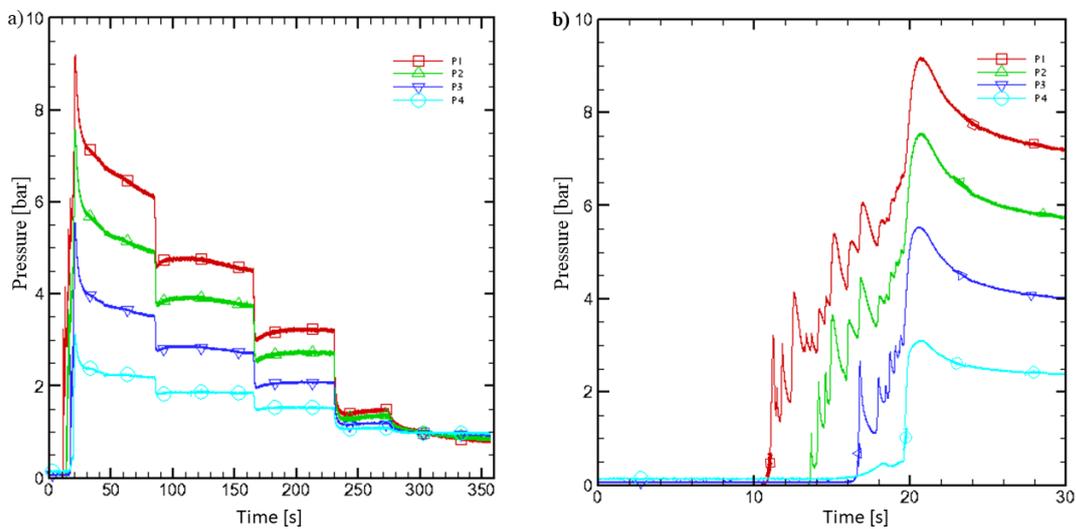


Figure 5. Imposition of descent level with the material in the final temperature of 15 °C. a) Flow rate of 193.2 - 128.8 - 64.4 - 6.44 - 0.644 ml/min; b) Transient regime.

To evaluate the compressibility for the waxy model oil, two tests were performed, one pressurized at 2 bar and one without pressurization for the flow rates of 0.644, 6.44, 64.4 and 128.8 ml/min shown in Fig. 6a and 6b, respectively.

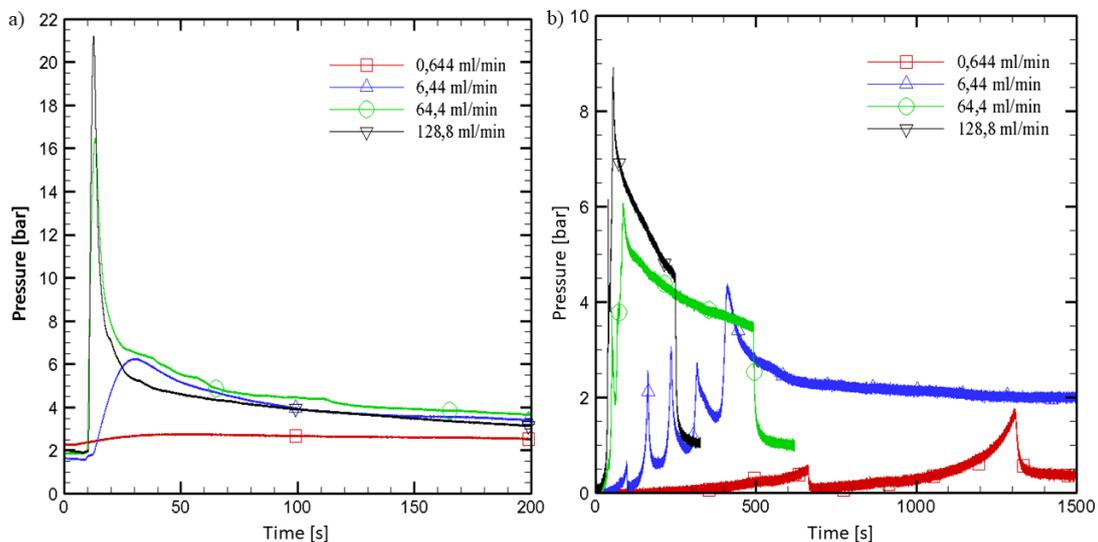


Figure 6. Comparison of the flow restart for different flow rates: a) Pressurized at 2 bar; b) Without pressurization.

In the Fig. 6a it is observed that for the flow rates greater than 64.4 ml/min, the required restart time was less than 12 s and for smaller flow rates it was greater than 30 s. While for the test without pressurization (Fig. 6b) the restart time increased considerably, for flow rates greater than 64.4 ml/min the restart time was less than 80 s, and for lower flow rates it was greater than 400 s. In both tests, the difference in the restart times and overshoots pressure are noticeable. This difference in restart time is a consequence of the voids formation in the test without pressurization, which does not occur in the same proportion in the pressurized one, since in this case there is compression of the material during the cooling process.

It can be seen in Fig. 6b that during the transient regime there are smaller overshoots pressure due to the gradual pressurization of the fluid in the pipeline, as the voids were formed and the material was compacted. It is expected that all curves reach the overshoot pressure and then reduce towards the steady state, however the flow rates of 128.8 and 64.4 ml/min do not reach the steady state due to the test time that is limited by the volume of the bomb reservoir.

Table 1 compares the restart times and overshoots pressure for both tests showed above. Note that the restart times for the tests without pressurization are considerably higher than for the pressurized ones due to the greater compressibility of the material. Besides that, the overshoot pressures for the pressurized tests are greater than the values for the unpressurized test.

Table 1. Comparison of the start-up time and pressure overshoot for pressurized and non-pressurized test.

Test	Pressurized at 2 bar		Without pressurization	
	Start-up time (s)	Overshoot Pressure (bar)	Start-up time (s)	Overshoot Pressure (bar)
0.644 ml/min	48 s	2.74 bar	2325.1 s	1.75 bar
6.44 ml/min	30.4 s	5.21 bar	409.9 s	4.24 bar
64.4 ml/min	16.5 s	16.45 bar	84.4 s	5.90 bar
128.8 ml/min	12.4 s	21.12 bar	52.5 s	8.79 bar

The cooling rate is another variable analyzed to verify how this parameter influences the restart time and overshoot pressure of the model waxy oil. In this test different cooling rates of 0.56, 0.68 and 0.83 °C/min were imposed in the material during the pre-test. Figure 7 shows the temperature variation inside the experimental unit during cooling, the pink curve indicates the cooling rate of 0.56 °C/min, the green curve of 0.68 °C/min and the black curve of 0.83 °C/min. The time to reach the steady state at the final temperature of 15 °C with the cooling rate of 0.56 °C was approximately 50 min, for the rate of 0.68 °C/min it was 45 min and for the rate of 0.83 °C/min it was of 35 min.

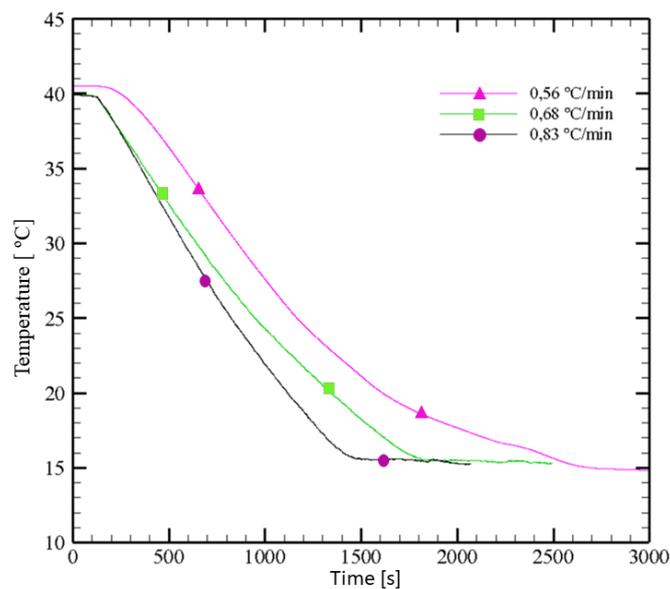


Figure 7. Tests with different cooling rates of 0.56, 0.68 and 0.83 °C/min.

For the cooling rate of 0.56 and 0.68 °C/min, the overshoot pressure and the restart time were similar reaching approximately 7.5 bar and 13 s, respectively, while the cooling rate of 0.83 °C/min reached 8 bar and 15 s, as illustrated in Fig. 8. In this test there is a preliminary indication that for the cooling rate range between 0.56 and 0.68 °C/min the influence on the overshoot pressure and the restart time is low, and for higher rates it may cause an increase in the

overshoot pressure and in the restart time. Although the cooling rates evaluated are close, a hypothesis for the difference in the behavior of the material may be due to the size of the crystals formed during cooling. Andrade (2017) observed that there may be variation in the characteristic size of the crystals formed when analyzing the rates of 0.5 and 1 K/min. It is important to note that these results are preliminary and to better understand the influence of this variable it is necessary to carry out more tests with a wider range of cooling rates in the experimental apparatus.

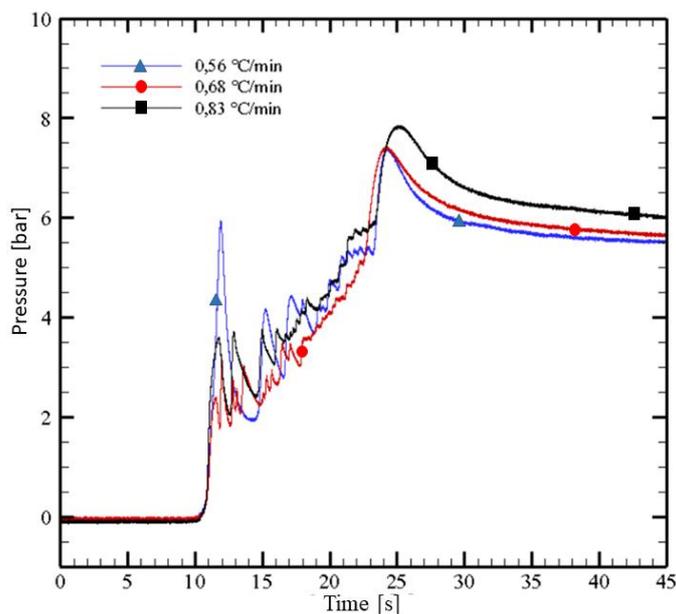


Figure 8. Influence of the cooling rate on the flow restart pressures imposed by flow rate.

4. CONCLUSIONS

Oil exploration in ultra-deep waters is a challenging and costly task because of the non-Newtonian rheological. During the flow restart, the characterization of these properties are even more problematic due to the coexistence of such characteristics with different operational conditions. In order to understand the thermal influence in the oil behavior, this paper used an experimental apparatus to study the start-up flow of a model waxy oil (5 % wt.).

The main conclusions obtained in this paper were: a) the final temperature of the test influenced the behavior of the material, and consequently, the pressure overshoot; b) the transient regime of the flow restart for the model waxy oil has partial and gradual pressurization (smaller overshoots) due to the appearance of voids formed during the gel ation of the material; c) the model waxy oil had a shrinkage of 4% during cooling from 40 to 15 °C; d) the flow restart without pressurization is influenced in the transient regime by the voids formation during, while the pressurized test was not influenced the same proportion; e) the cooling rate influenced the overshoot pressure and the restart time. The higher the cooling rate, the longer the overshoot and restart time.

5. ACKNOWLEDGEMENTS

The authors acknowledge the financial support of PETROBRAS S/A and ANP (Brazilian National Oil Agency).

6. REFERENCES

- Andrade, D. E. V., Marcelino Neto, M. A., Negrão, C. O. R., 2017. "The importance of supersaturation on determining the solid-liquid equilibrium temperature of waxy oils". *Fuel* 206: 516–523.
- de Souza Mendes, P. R., Thompson, R. L., 2012. "A critical overview of elasto-viscoplastic thixotropic modeling". *J. Non Newtonian Fluid Mech.* 187–188: 8–15.
- Davidson, M. R., Nguyen, Q. D., Chang, C., Rønningsen, H. P., 2004. "A model for restart of a pipeline with compressible gelled waxy crude oil". *Journal of Non-Newtonian Fluid Mechanics* 123: 269–280.
- Fossen, Martin, Terje Øyangen, and Ole Jacob Velle., 2013. "Effect of the pipe diameter on the restart pressure of a gelled waxy crude Oil". *Energy and Fuels* 27: 3685–3691.
- Morais, J.M., 2013. "Petróleo em Águas Profundas". Instituto de Pesquisas Econômica Aplicada.

Duarte Jr, R. M., Marcon, L. E., Germer, E. M., Andrade, D., E. V., Negrão, C. O. R.
Experimental Analysis of the start-up Flow of Model Waxy Oil in Pipeline

Rosso, N., 2014. “Análise experimental do reinício do escoamento de petróleo parafínico em tubulações”. Dissertação de Mestrado, PPGEM, Universidade Tecnológica Federal do Paraná, Curitiba-PR, Brasil.

Van Der Geest, C., Bizotto Guersoni, V. C., Merino-Garcia D., Bannwart, A. C., 2015. “The influence of compressibility and shrinkage in the start-up of a flow of gelled waxy crudes in pipelines”. *Offshore Technology Conference*.

Li H., Zhang J., Song C, Sun G., 2015. “The influence of the heating temperature on the yield stress and pour point of waxy crude oils”. *J. Petrol. Sci. Eng.* 135:476–483.

Tarcha, B.A., Bárbara, B.P., Soares, E.J., Thompson, R.L., 2015. “Critical quantities on the yielding process of waxy crude oils”. *Rheol. Acta* 54:479–499.

Thomason, W. H. Proceedings 2000 *Offshore Technology Conference*, Houston, TX, 2000.

Wardhaugh, L. T., Boger, D. V., 1987. “Measurement of the unique flow properties of waxy crude oils”. *Chemical Engineering Research and Design* 65: 74–83.

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