24th COBEM - 2017

ABCM Associação Brasileira de Engenharia e Ciências Mecânicas

24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-2004
DEVELOPMENT OF AN APPARATUS FOR PRODUCING WAX DEPOSITION IN PIPE SECTIONS FOR PIGGING TESTS

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Abstract. *This paper presents the development of an experimental apparatus for producing wax deposition in the inner pipe wall for pigging tests. It works through positioning an oil pipe section in a horizontal position under a mechanical structure, the pipe turns with controlled speed with heated oil inserted within. It is equipped with a cooling system in order to maintain the pipe cool. This will generate the temperature differential between the oil and the pipe wall, which is the main factor of causing wax deposition. The equipment counts on a data acquisition system and temperature sensors for monitoring the oil and pipe wall temperatures. According to the temperature values it was possible to observe the gradient temperature between the oil and the pipe wall and the instant which the oil was totally deposited in the inner pipe wall. It was also possible to investigate the temperature gradient influence in the deposition thickness. The apparatus can produce uniform deposits with different thickness and it represents a new tool for producing wax deposition in pipe sections used to test the pipeline cleaning devices mainly the PIGs ones.*

Keywords: *Wax deposition, PIG, Pipeline.*

1. INTRODUCTION

One of the biggest challenges of the oil industry has been the wax deposition in pipelines. It is caused due to the oil paraffin components that start to solidify and form crystals when a temperature known as wax appearance temperature (WAT) is reached (Mustaffa, 2010). In the reservoir the crude oil is melted and the paraffin components are dissolved, as the oil is transported it loses heat to the pipe wall and the paraffin crystals appears, agglomerates and may deposit in the inner pipe wall. The higher the temperature gradient between the oil and the pipe wall higher the deposition rate (Creek, 1999). The wax deposition is a porous structure composed of a crystal network with oil prisoned within and gradually this deposition thickens. The wax deposits can cause partial and sometimes total pipeline blockage, decreasing production in flow, there is increase in energy required for maintain the oil flowing and in the worst case the production halts bringing loss of money to the oil companies.

Wax deposition is a complex phenomenon involving several parameters, for example, pressure, flow regime, oil composition and the most important, temperature. As long as the oil temperature is maintained above the WAT, the paraffin components will be dissolved, no crystals will rise and then no deposition occurs.

There are many studies about the wax deposition phenomena, for example, mathematical models for prediction of the probable location in the pipeline where the deposition will occur and the experimental apparatus for simulating the deposition under controlled conditions (AIYEJINA et al, 2011). The flow-loop apparatus is widely used, its operation is very similar to the oil transportation in the field, its disadvantage is the high cost to build and operate and it requires a relative large volume of oil depending on the apparatus size.

Several efforts have been made to deal with the wax deposition problem, there are several methods of prevention and remediation, they can be thermal, chemical and mechanical. Among these, the mechanical method using PIGs are well stablished and very used, the PIG device is composed of a metal body called *mandrel* and polyurethane discs, they move with the flow, scraping the inner pipe wall removing any deposition. The Figure 1 shows an illustration of a PIG scraping a deposition.

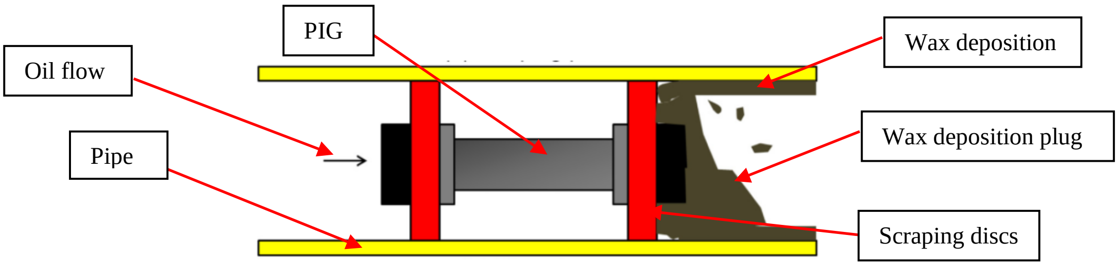

Figure 1. Diagram of pigging operation removing wax deposition in a pipeline (Wang, 2015).

Despite PIGs being widely used, there are few studies about the pigging operations and even though precautions are taken, depending on the deposition hardness and the agglomerate formed in the front of the PIG (plug), it may stall in the pipeline causing production interruption which is costly to remove it. Elaborating a pigging schedule is difficult due to the uncertainty of the wax deposit hardness, nowadays it is done only based on the experience in the field (Wang, 2015; Southgate, 2004). Wang (2008; 2015) reports some investigations about pigging removal dynamics, that is, the deposition hardness as function of its thickness, all the studies requires pipe sections with uniform wax deposition along with different thickness and hardness. These works show the importance of obtaining pipe sections with wax deposition, they are extremely important for analysis of its shape, composition, thermal behavior, thickness and hardness. This information may be used for validate theoretical models, understanding phenomena and determining best mitigation and prevention actions, and mainly, for pigging tests.

In this work an experimental apparatus is proposed for producing wax depositions in pipe sections for pigging tests and for observation of parameters that influence the wax deposition.

2. THE APPARATUS DEVELOPMENT

The apparatus developed is composed of mechanical, electronic and software components. The mechanical structures is made of aluminum profiles and has the function of supporting a pipe section under wheels in a horizontal positon, one of the wheels is connected to a motor that promotes the pipe rotation on its own axis. An electronic system was developed to control the pipe rotation speed. As the temperature gradient between the petroleum and the pipe wall is the main agent causing deposition, a cooling system composed of water jets was used to maintain the pipe wall cool, the Figure 2 shows a tridimensional design and an image of the apparatus developed.

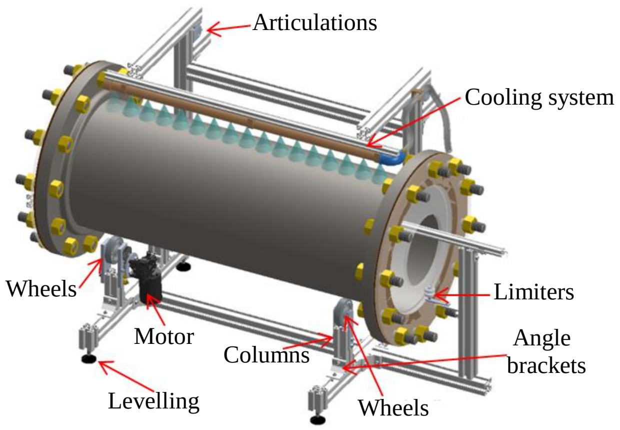

Figure 2. The tridimensional project and an image of the apparatus developed for the production of the wax deposition in pipe sections.

The wax deposition process using the apparatus occurs when a pipe section is positioned in the wheels and oil is inserted into the pipe through the hole in the acrylic flange. As the pipe turns the oil exchanges heat with the pipe, that is cooler, and gradually the oil will solidify and deposit forming layers in the inner pipe wall. Each complete pipe revolution determines the deposition layer, this occurs until no more liquid oil exists inside the pipe, the Figure 3 shows pictures of the pipe during a deposition cycle; in the beginning an oil puddle can be seen and it decreases gradually until the oil deposits completely in the inner pipe wall.

Figure 3. Images of the deposition process where it can be seen the heated oil gradually been deposited in the inner pipe wall.

The main factor of the wax deposition is the temperature gradient between the oil and the pipe wall; therefore, 5 digital temperature sensors were used to monitor some specific points in the oil and in the pipe section. Two in the pipe wall (T1, T3); to evaluate the cooling system effectiveness, one in the deposited layer (T2); for observing the thermal behavior of the wax. One in the heated oil puddle (T4), which together with the pipe wall sensors shows the gradient temperature and one for ambient temperature (T5), the Figure 4 illustrates the position of the sensors.

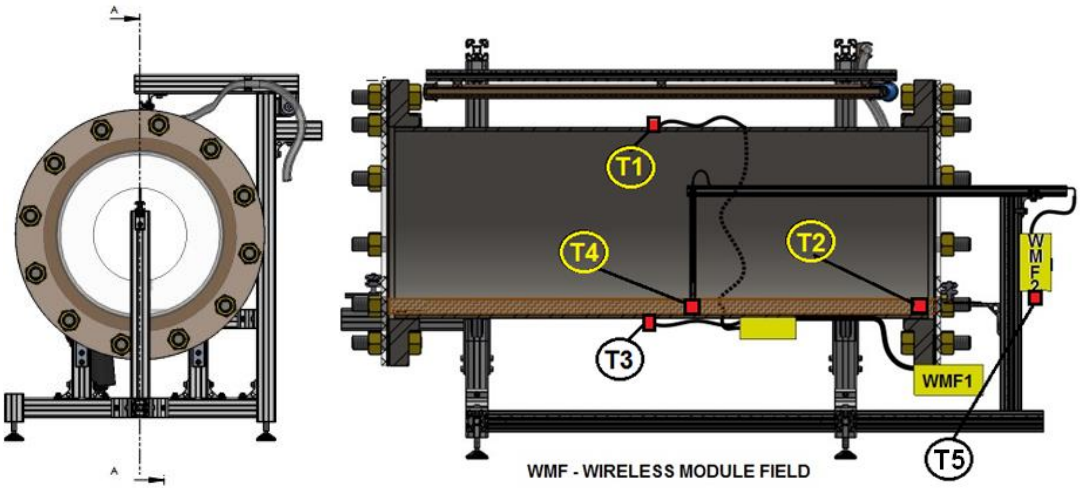

Figure 4. Ilustration of the sensors position.

In the literature the thickness evaluation is carried out by a weighing method where the pipe section is weighed before and after the deposition process. In this work this method is not viable because the pipe section is 14 inch, schedule 10, 1-meter length and then approximately 150 Kg weight. Thus, in order to evaluate the deposition thickness and uniformity in the pipe section, 20 mechanical test pieces using steel plates with 80 mm in length, 32 mm wide and 1.2 mm thickness were built. They were cut and shaped in order to be fixed in the pipe wall and to be easily inserted and removed, the deposition occurs in the inner pipe wall and on the test piece surface. Two magnets were inserted at its ends in order to be positioned in the pipe wall, the Figure 5 shows the test pieces that can be seen with the magnets at its extremities.

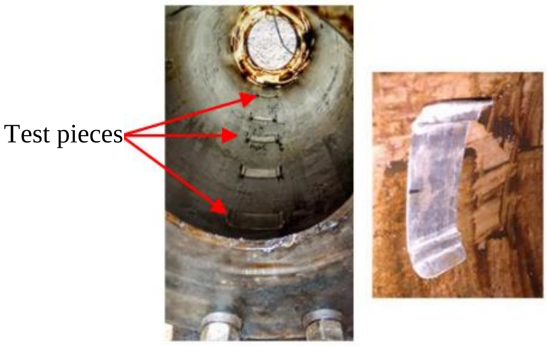

Figure 5. Images of the test pieces dimensions and its positioning in the inner pipe wall.

3. THE EXPERIMENTS

The experiments were conducted firstly by positioning a pipe section in the apparatus using an electrical winch and then the inner pipe wall was scraped in order to clean it. Two acrylic flanges were positioned at the ends of the pipe, its function being to keep the oil confined inside the pipe. The electronic system was positioned in the flange and the data acquisition software initialized. The crude oil kindly provided by Petrobras was melted by using a heating system and then inserted inside the pipe section and this way the deposition process took place, the Figure 6 shows an image of the apparatus in operation.

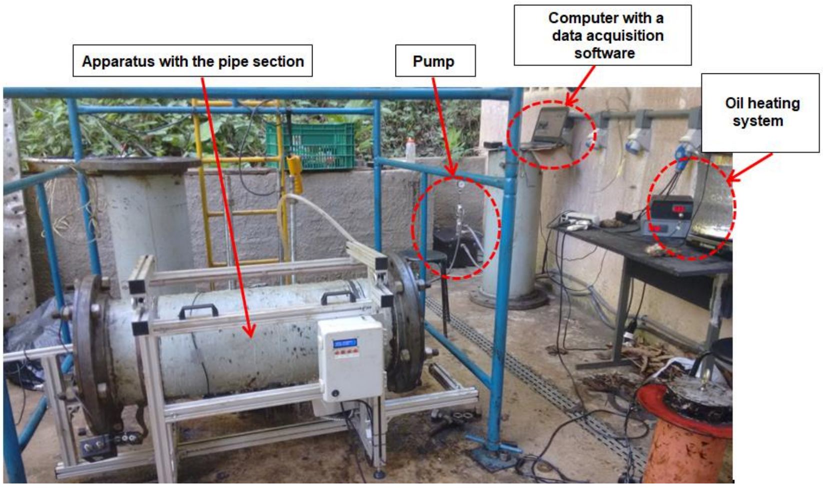

Figure 6. Image of the apparatus in operation.

The first experiment consists of observing the thermal behavior of the oil and the pipe wall, using a thermal camera and the sensors system. The second experiment consists of evaluating the uniformity of the wax deposition, where 9 test pieces were positioned in the inner pipe wall and two deposition cycles were made, one using 3 Kg of crude oil and the other one using 5 Kg of crude oil. The end of the deposition cycles were established when the liquid oil was completely deposited in the inner pipe wall, the test pieces were removed and the deposition thickness was measured with a thickness digital gage.

The third experiment was performed in order to observe the temperature gradient influence in the deposit thickness, then were used 3 Kg of oil and three deposition cycles were carried out. The oil temperature was maintained at 66 ºC, above the WAT which maintained in liquid state, and the water from the cooling system varied, in the first cycle was 26 ºC, the second 18 ºC and last one 10 ºC. Therefore, the temperature gradient between the oil and the pipe wall was 34 ºC, 42 ºC and 50 ºC.

4. THE RESULTS

The results were divided into thermal behavior, uniformity evaluation and temperature gradient. In the thermal behavior results a deposition test was performed and the pictures of the thermal camera were taken each every 10 seconds, during 24 minutes. The Figure 7 shows one of the pictures from the test, where the gradient of temperature between the hot oil puddle and the pipe wall can be seen, it were traced straight lines assigning these regions. Along the lines the average temperature data for different thermographic pictures were taken and used to plot the curve on Figure 8, it illustrates three curves compiling information from the pictures; it can be seen the inner pipe wall, the oil puddle temperatures and the gradient between these two curves. It is clearly seen that the oil temperature decreases while pipe wall temperature remains quite constant due to thermal isolator behavior of paraffin.

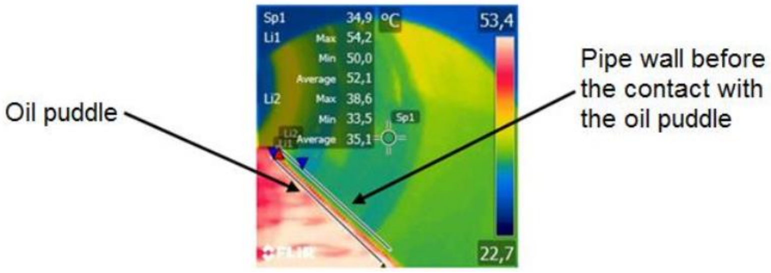

Figure 7. Thermal image from the inside of pipe section showing the lines used as temperature mesurements points.

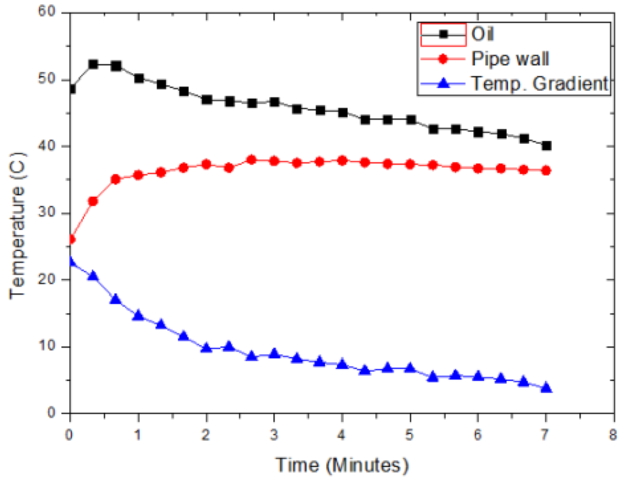

Figure 8. Curves of temperature as a function of time from the oil, pipe wall and the gradient temperatura between them.

From the tests with the thermographic camera was possible to visualize the temperature gradient between the heated oil inserted in the pipe and the inner pipe wall as well as the external wall temperature. With the curves generated from the data of the images was possible to see the point where there was no longer liquid oil in the pipe section, that is, all of it had solidified and deposited in the internal wall. The thermal insulating effect of the deposition was also observed due to the fact that it cools slowly. However, it was not possible to observe the temperature increase of the pipe wall due to the insertion of the heated oil. The thermal behavior of the whole paraffin deposition was not also observable, the temperature shown is only from the outer deposition layer.

A deposition cycle was performed, using the monitoring system developed, in the same conditions as those performed using the camera, the Figure 9 shows an image of the deposition process where the liquid oil puddle can be seen inside the pipe and the Sensor T4, responsible for the measurement of temperature. The temperature values of the 5 sensors were acquired every 3 seconds, Figure 10 shows the temperature curves as a function of time.

Figure 9. Image showing the oil puddle and the sensor T4 used to measure it.

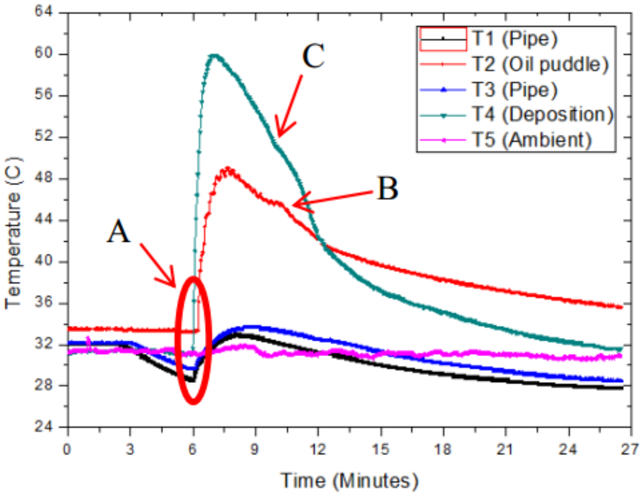

Figure 10. Temperature curve plotted from the data adquisition system.

From the curves of the Figure 10 is observed the moment when the heated oil is inserted into the pipe (A), T1, T2, T3 and T4 show increase of temperature. In about 10 minutes T2 (sensor of the deposition) changes behavior (B) as well as T4 (oil puddle sensor) (C), this is explained as being the moment when all liquid oil is solidified and deposited in the pipe wall, this was visually perceived during the test.

Regarding to the pipe wall, differently from the behavior observed with the thermal camera, T1 and T3 (duct sensors) clearly show the increase in the duct wall temperature, approximately 4 °C above the temperature before the oil is inserted. It was also possible to see that it takes approximately 13 minutes for the duct to return to the same temperature value of the moment prior to the insertion of the oil. The ambient temperature was monitored during the tests through T5, in the tests performed no changes in the thermal behavior of the measured regions were noticed.

From the tests with the sensors system, more information was acquired when compared with the thermal camera and was possible to confirm that the duct undergoes na increase in temperature. The data from the thermal camera was influenced by the cooling system jets, which caused the false impression that the duct temperature remained constant even with the insertion of the hot oil. It was possible to measure the temperature of the whole deposition area, since the T2 sensor was inserted in the wax deposition. More importantly, the temperature gradient between the duct wall (T1 and T3) and the oil (T4) can be monitored throughout the deposition cycle, this information is important for controling the depositions obtained for different temperature gradients, that will influence the thickness, hardness and composition, this from the point of view of the carbon distribution.

Before the uniformity evaluation experiments was carried out, the wax deposition thickness was calculated for 3 Kg and 5 Kg of crude oil by using the oil density and the pipe geometry, as can be expressed by the equation 1 (Hoffman, 2009). Where, p is the oil density, L is the pipe length and R is pipe radius, the theoretical thickness for 3 Kg was 2.96 mm and for 5 Kg was 5.1 mm.

$$H = R - \sqrt{R^2 - \frac{m}{\rho \pi L}} \quad (1)$$

In the uniformity evaluation test, at the end of the two deposition cycles, the test pieces were removed and the thickness measured, the Figure 11 shows the 6 measurements points in the test pieces, these 6 values were used to obtain an average thickness of the wax deposition. These measurements were performed in the 9 test pieces, the Table 1 shows the thickness values and the errors calculated considering the theoretical values.

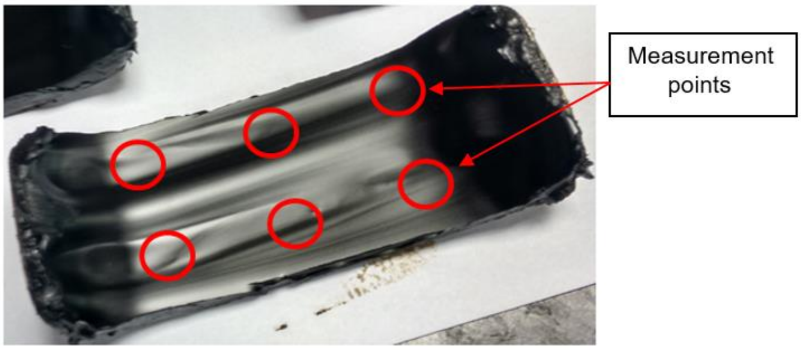

Figure 11. Image of one test piece with wax deposition showing the thickness measurement points.

Table 1. Thickness values from the test pieces used in the depositions with 3 Kg and 5 Kg of crude oil.

Test piece	Average thickness (mm)	Standard deviation (mm)	Error (%)
1	2,69	0,09	9,29
2	2,66	0,22	10,07
3	2,62	0,11	11,49
4	2,89	0,24	2,31
5	2,7	0,1	8,78
6	2,88	0,19	2,87
7	2,88	0,31	2,76
8	2,43	0,11	17,96
9	2,65	0,18	10,36
		Average error (%)	**8,43**

Test piece	Average thickness (mm)	Standard deviation (mm)	Error (%)
1	4,26	0,2	16,57
2	4,59	0,44	10,03
3	4,42	0,75	13,43
4	4,93	0,48	3,3
5	4,51	0,42	11,67
6	5,34	0,15	4,5
7	5,81	1,18	12,24
8	4,65	0,37	8,76
9	4,66	1,22	8,69
		Average error (%)	**9,91**

The Table 1 shows the average thickness values of the deposits from each test piece and the thickness considering all the test pieces, the deposition using 3 Kg of oil the thickness was 2.71 ±0,17 mm and the deposition using 5 Kg the thickness was 4.80 ±0.58 mm. The errors values were 8.43 % and 9.91 % for 3 Kg of oil and 5 Kg respectively, they are considered reasonable when taken into account that not all the oil was deposited along the 1 m length of the pipe. A portion of the oil was lost, part deposited in the recipient, in the acrylic flanges and in the weld interfaces between the pipe and in the steel flanges. Even though the oil in these cited regions has been removed and weighed there is still a small amount of oil that is lost, for example, in the support used to insert the oil inside the pipe. The pipe is not uniform and has a diameter deviation along its length; in addition, the flaps of the test pieces create turbulence in the liquid oil.

From the uniformity evaluation it is possible to see that the deposition with 3 kg of oil has more uniformity than with 5 kg, what can be observed from the values of standard deviation and error. This was expected since in the deposition with 5 kg was observed that the drip is higher due to the higher oil volume still in the liquid phase remaining for a longer period during the deposition cycle. The Figure 12 shows some test pieces used in the 3 kg and 5 kg with wax depositions, it is possible to see clearly that the deposition with 5 kg (Figure 12 (B)) is much less uniform and with some undulations and drip marks of the oil.

Figure 12. Image of test pieces with wax depsition obtained using 3 Kg (A) ang 5 Kg (B) of oil.

To investigate the temperature gradient influence were used 5 test pieces in each every one of the three deposition cycles, they were inserted in the inner pipe wall as can be seen in the Figure 13. The apparatus was configured to perform 5 rotations of the pipe section, then at the end of the deposition cycle the test pieces were removed, weighed and its thickness measured, using these values a curve was plotted as can be seen in the Figure 14. The same behavior is observed as reported by Creek (1999) that the higher the gradient temperature the higher the depositions rate and in turn its thickness. The results shows quantitatively that the gradient temperature between the oil and the pipe wall influences in the deposition process.

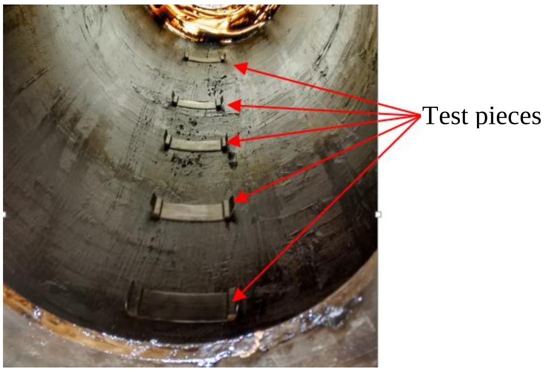

Figure 13. Image of the inner pipe wall with the test pieces positioned right before the wax deposition cycle.

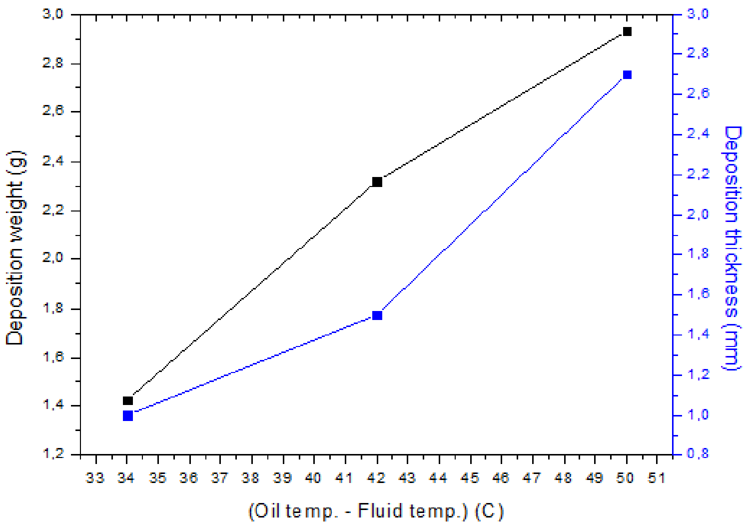

Figure 14. Curves of weight and thickness of the 5 test pieces used in the depositions obtained from different gradient temperature.

5. CONCLUSION

This paper presents part of an ongoing project that proposes an experimental apparatus for production of wax deposition in the oil pipe sections used for pigging tests. The mechanical structure was stable and supported a 150 Kg pipe section, the electronic system was also stable, and it was possible to acquire the temperature values from the oil and the pipe. The thermal behavior tests show the gradient temperature between the oil and the pipe wall through images furnished from the thermal camera and from the sensors system, this gradient is crucial in the wax deposition process.

The pigging tests for removal of deposits is performed by using different wax deposition thickness, the deposition uniformity tests show that using the apparatus it was possible to obtain uniform wax depositions with 2.71 mm and 4.8 mm thick with errors of 8.43 % and 9.91 % respectively. The last investigation was about the gradient temperature influence in the wax deposition where it was observed that the higher the gradient temperature between the oil and the pipe wall higher the wax deposition rate.

Further investigations are ongoing, using the apparatus developed, aiming to obtain wax deposition utilizing different crude oils with different thickness and hardness in order to be used for testing the performance of a *mandrel*

PIG. The apparatus developed represents a new tool for the wax deposition production and investigation of the wax deposition phenomena, the patent of the apparatus has already been deposited in the Brazil.

6. ACKNOWLEDGEMENTS

The authors wish to thank all the team from Optical Properties Laboratory – UFBA and Petrobras for the crude oil.

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