

PARAFFIN DEPOSITION IN LAMINAR CHANNEL FLOW, IN THE PRESENCE OF SUSPENDED CRYSTALS

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Abstract. *Deposition of high molecular weight paraffins on the inner wall of subsea production and transportation pipelines continues to be a critical operational problem faced by the petroleum industry. Molecular diffusion, Brownian diffusion, shear dispersion and gravity settling are possible mechanisms responsible for wax deposition cited in the literature. Although molecular diffusion is employed in the vast majority of the deposition models available in the open literature, it is still not clear which one of them is the most relevant mechanism. In case the operational conditions are such that wax crystals are present in the bulk of the flowing solution, particle deposition mechanism may possibly play a more relevant role. In the present research, deposition experiments were conducted for laminar channel flow of a solution of wax and paraffin. The inlet temperature of the solution was set below the Wax Appearance Temperature – WAT, so that wax crystals were available for deposition. In the experiments, visualization of the particle migration and the deposition process were sought for three distinct heat flux conditions at the channel boundary: negative, zero and positive heat flux. The deposition of wax crystals was tracked by a video camera and detailed data of temporal and spatial distributions of the wax deposited were obtained. Three different flow rates were studied. It was verified that a negative temperature gradient (negative heat flux) is necessary to produce significant deposition. For all the experimental conditions tested, no deposition was verified under zero heat flux and positive heat flux conditions. In all cases studied the deposits measured were significantly thicker than those obtained for similar flow conditions and fluid-to-wall temperature differences, but for inlet temperatures above the WAT. The images have also shown that the removal of deposited wax by flow-induced shear is relevant at some operating conditions.*

***Keywords**: Wax deposition, pipeline, heat flux conditions, laminar flow, crystals in suspension.*

1. INTRODUCTION

Wax deposition in pipelines is one of the most critical problems faced by the petroleum industry in offshore operations. Significant losses of capital are caused by wax deposition problems, due to the high costs of prevention, loss of pipelines due to severe plugging, reduced production and increased pumping power. The ability to accurately predict wax deposition is an invaluable tool that would help during the pipeline design stages, as well as in the scheduling of interventions.

The crude oil flows out of the reservoir at, typically, 60^oC into the production pipelines. These lines carry the oil to the platforms and from the platforms to shore. At large ocean depths, the ocean temperature at the bottom is of the order of 5^oC. The solubility of wax in the oil is a decreasing function of temperature. As the oil flows, it looses heat to the surrounding water. If the crude oil temperature falls below the *Wax Appearance Temperature (WAT),* the wax may precipitate and deposit along the inner walls of the pipeline.

Modeling of wax deposition is a complex task that involves several disciplines, such as, thermodynamics, phase equilibrium, mass/heat transfer and fluid mechanics. A great number of studies have been dedicated to this field (e.g., Burger et al., 1981, Brown et al., Creek et al., 1999 and Svendsen, 1993). However, the analysis of the available literature has demonstrated that several basic issues remain to be better understood. A detailed critical review of the literature was prepared as part of a research project on wax deposition (Azevedo and Teixeira, 2003). One of the key works analyzed in this review was that of Burger et al., 1981, where the possible mechanisms responsible for wax deposition were identified. These mechanisms are molecular diffusion, Brownian diffusion, shear dispersion and gravitational settling. Molecular diffusion has been widely accepted as the dominant deposition mechanism, and has been employed in the majority of the models presented in the open literature (e.g., Ribeiro et al., 1997, Fusi, 2003). However, in the review article mentioned above, Azevedo and Teixeira, 2003, concluded that there was no experimental evidence to confirm that molecular diffusion is the dominant mechanism.

Molecular diffusion is the mechanism responsible for the transport of wax toward the cold pipe wall in the liquid phase. When the solution is below the *WAT* at a particular point in the flow, wax crystals may form and are available for deposition. The mechanisms responsible for the lateral transport of the wax crystals toward or away from the wall, and the possibility of deposition of those crystals, is still subject of current study (e.g. Todi, 2005). Brownian diffusion and shear dispersion have been cited as possible mechanisms, as described in Azevedo and Teixeira, 2003. In his recent work, Todi, 2005, also proposes thermophoresis as a possibility. Another subject of controversy in the case of crystal deposition is the role of the thermal boundary condition at the pipe wall. Cooling of the wall has been cited as being a necessary condition for deposition by some authors (e.g., Hamouda and Davidsen, 1995), while others have reported deposition under heating or insulated walls, where the heat flux is zero (e.g., Todi, 2005).

The present work is part of an ongoing research program aimed at contributing to the identification of the relative importance of the mechanisms responsible for wax deposition. The strategy of the work is to conduct simple experiments with well defined boundary and initial conditions, employing simple fluids with known thermophysical properties. The detailed deposition data thus obtained is then compared to simulations employing a single deposition model. By this comparison, it is expected that the relative importance of the deposition mechanisms can be better assessed. The focus of the present paper is on experimental results for wax deposition under the presence of suspended crystals. This condition was obtained by running the experiments with the inlet wax solution below the *WAT*. The aforementioned issue related to the thermal boundary conditions at the wall was also explored in the experiments.

Results related to wax deposition under the presence of suspended crystals is first found in the literature in the work Jessen et al., 1958, as cited by Todi, 2005, where deposition of particles was proposed to explain higher deposition rates verified in steel pipes for conditions where the radial temperature gradient was low and, therefore, molecular diffusion was also expected to be low. Different conclusions were reached by Hunt, 1962, who conducted adhesion tests of wax deposits to different types of surfaces. In his work, no deposition was verified when the bulk fluid temperature was the same as the wall temperature (zero-heat flux condition), what led the author to conclude that molecular diffusion is the controlling deposition mechanism. Creek et al., 1999, verified that deposition rate increased almost linearly with the fluid-to-wall temperature difference, indicating that molecular diffusion is the prevailing mechanism, since this mechanism is also linearly proportional to this temperature difference. Hamouda and Davidsen, 1995, conducted experiments in a pipe section divided into three sectors. In the first sector the pipe wall was cooled, while in the second sector the wall was insulated. In the third sector the wall was again cooled. They observed deposition in the first sector, almost no deposition along the insulated pipe sector, and deposition again in the cooled third sector. They concluded that deposition mechanisms based on lateral motion of crystal, such as shear dispersion or Brownian motion, are not relevant.

Burger et al. 1981, investigated wax deposition at the Tran Alaska Pipeline, and conducted laboratory experiments under laminar flow which were made at conditions scaled based on the shear stress. Deposition rates were modeled as a sum of mass transfer by molecular diffusion of dissolved wax and by shear dispersion and Brownian diffusion of precipitated wax crystals. Molecular diffusion was modeled by Fick's law, while deposition by shear dispersion and Brownian diffusion were combined in a single term representing the rate of incorporation of solid particles at the solid – liquid interface, modeled as,

$$\frac{dm_i}{dt} = k^* C_w^* \gamma A$$

where, the rate of incorporation of solid particles is, dm_i/dt, C_w^* is the concentration of solid particles at the solid-liquid interface, γ , is the wall shear rate, k^* is a deposition rate constant, and A is the surface area available,

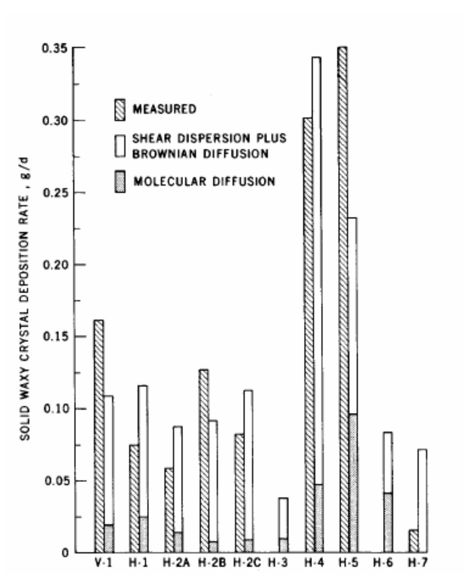

Figure 1. Comparison of laboratory-measured and predicted solid waxy crystals deposition rates (Burger et al., 1981).

The laboratory experimental results showed that deposition rates were too small to be determined quantitatively for those tests in which the shear rates were very low. Figure 1 shows a comparison between the measured and predicted wax crystal deposition rates. The results depicted in the figure clearly show that the molecular diffusion predictions underestimated the deposition rates measured. The most relevant information in Fig. 1, is that the experimental deposition rate measured was, in most cases, higher than that predicted by molecular diffusion. These results are an indication that deposition mechanisms other than molecular diffusion might be acting. In additional tests performed by Burger et al. (1981), deposition rates were measured under very high wall shear stress conditions. The results of these experiments suggested that deposits could be reduced, perhaps by a sloughing mechanism. In the tests conducted at zero heat flux condition, where molecular diffusion does not contribute, Burger et al. (1981) observed a deposit formation but not in a very significant amount. The deposition rate estimated from the experimental data was considerably lower than that predicted according to eq. (1). In Fig. 1, the series H-7 show this result. On the basis of these results, they conclude that it is probable that little or no accumulation occurs under zero heat flux condition.

Weingarten and Euchner (1986), have conducted experiments in a test loop under controlled conditions. The tests measured the total deposition by the pressure differential method and it was compared with the expected contribution of molecular diffusion. For low shear rates, the deposition rate was greater than that predicted by molecular diffusion only, indicating that other deposition mechanisms could be present. This result verifies that waxes deposit by shear transport, as well as by diffusion. Figure 2 shows the results obtained for low values of the shear rate comparing with the deposit measured by molecular diffusion.

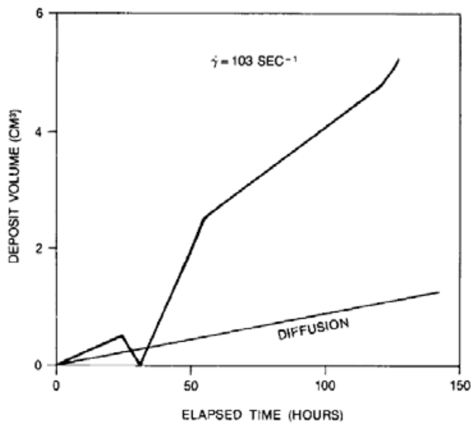

Figure 2. Deposition history for low shear rates (Weingarten and Euchner, 1986).

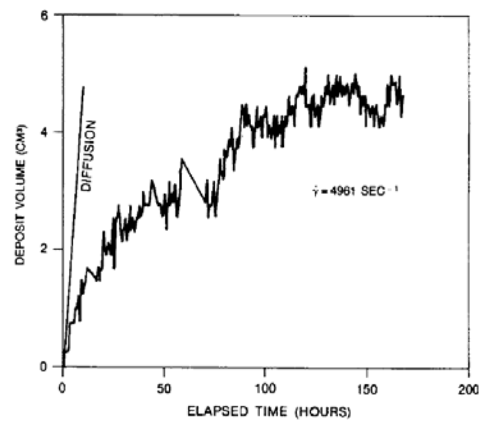

Figure 3. Deposition history for high shear rates (Weingarten and Euchner, 1986).

Figure 3 shows a typical deposition history for higher shear rates. Here, the deposit grew rapidly at first, approximating the expected diffusion rate, but then the rate began to decrease. At these flow rates, even in laminar conditions, waxes were sloughed when the wall shear stress exceeded the strength of the wax deposit.

Leiroz (2004) focused her work on fundamental studies trying to contribute with a better understanding of the basic mechanisms responsible for the wax deposition. Firstly, experiments were conducted for a stagnant layer of fluid sealed in a cavity and submitted to a transverse temperature gradient. Glass walls allowed visual access to the deposition process. Close up images of the deposition process were obtained with the help of a microscope. The images revealed that, besides the wax crystal formation at the cool wall, wax crystal are also formed at the vicinity of the wall and are freely moving before being trapped by the network formed in the later stages of the deposition process. The diffusion-based model developed to simulate wax deposition in the stagnant fluid was able to predict the correct trend of the evolution of the deposition front. However, the model significantly under-predicted the deposition thickness, indicating that other deposition mechanisms may be present.

Additionally, tests were conducted for wax deposition under laminar flow conditions within a rectangular channel. Glass walls allowed visual access of the deposition process. Close up images of the deposition process allowed, seemingly for the first time, the measurement of the spatial and temporal evolution of the deposited layer. Moreover, the author concluded that, due to the excellent symmetry presented by the deposits on both top and bottom walls, gravity settling is not a relevant deposition mechanism.

Recently, Todi, 2005, developed a numerical model based on wax deposition measurements performed in laminar flow conditions with the oil mixture injection temperature below the *WAT*, what produced suspend crystal in the solution. Particle image velocimetry and laser scattering techniques were used to obtain information, respectively, on the flow velocity profiles and crystals distribution profiles. The experiments revealed that the concentration of wax crystals at the channel cross section is determined by two competing mechanisms. While shear dispersion tend to concentrate the particles at preferred radial positions, Brownian diffusion works toward dispersing the particles evenly in the cross section. The author concludes that, since shear dispersion acts as to move the particles away from the wall, Brownian diffusion is the only possible mechanism responsible for particle deposition. Contrary to results that will be presented in the present paper, Todi, 2005, verified deposition for all three possible thermal boundary conditions, namely, cooling, heating and zero heat flux, as long as the wall temperature was below the *WAT.*

As can be verified by the brief literature review presented, there are still controversy regarding the relative importance of the proposed deposition mechanisms and the effect of shear rate and thermal heat transfer boundary condition. The present work is aimed at contributing to the clarification of some of those issues. In our experiments, visualization of the particle migration and the deposition process were sought for a laminar channel flow, submitted to three heat flux conditions: negative, zero and positive heat flux.

3. EXPERIMENTS

The wax deposition experiments under laminar channel flow were conducted employing the test section that will be described now. Figures 4 and 5 show the schematic views of the test section constructed.

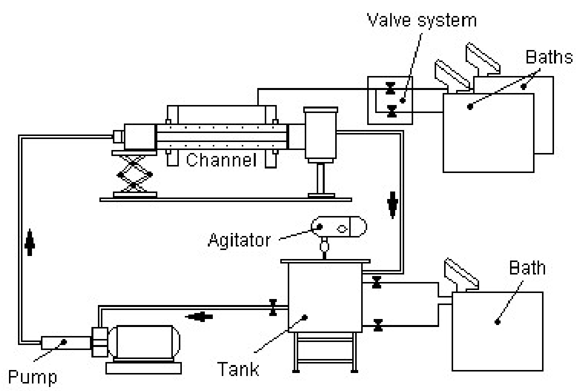

Figure 4. Schematic view of the flow loop.

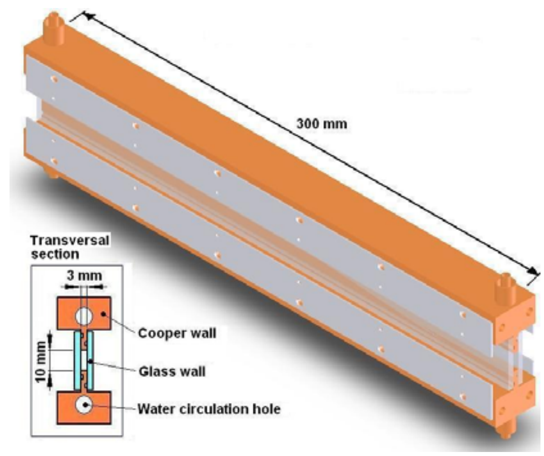

Figure 5. Pictorial view and details of the rectangular channel test section.

The oil and wax solution employed in the experiments was kept in a stainless steel tank equipped with an agitator and connected to a temperature controlling unit. With this storage system the solution could be maintained at temperatures below the *WAT.* The solution was pumped through the test section and back to the tank employing a progressive-cavity pump that was pre-calibrated to yield the volume flow rate as a function of the pump motor revolutions set a frequency controller.

The heart of the test section was a rectangular channel with internal dimensions of 3x 10 x 300 mm (width x height x length). The vertical walls of the channel were made of 3 mm-thick glass plates. The upper and lower walls were made of copper and were soldered to hollow copper blocks in order to control the temperature boundary conditions. Water from two temperature controlling baths was pumped through each of the copper blocks. Fine gauge thermocouples were installed in the copper walls to monitor their temperature. Since the experiments were to be conducted at temperature levels below the laboratory ambient temperature, deposition of wax was expected to happen at the inner surface of the glass lateral walls, thereby obstructing the visual access to the channel. To avoid this effect, a set of six air nozzles jets with controlled temperature and flow rate was positioned at each side of the glass walls, producing a controlled heating of the glass surface and avoiding the deposition. Fine-gauge thermocouples were installed in one of the glass walls, close to the surface that was exposed to the air jets. These thermocouples were used to monitor the temperature history of the glass surface. Figures 6 and 7 show schematic views of the air jets setup and the position of the thermocouples at the glass wall.

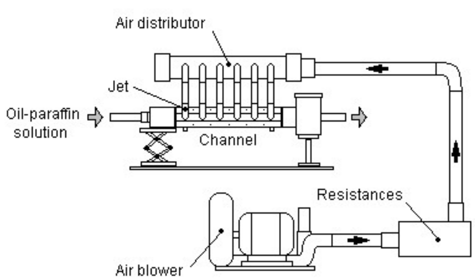

Figure 6. Schematic view of the jet system.

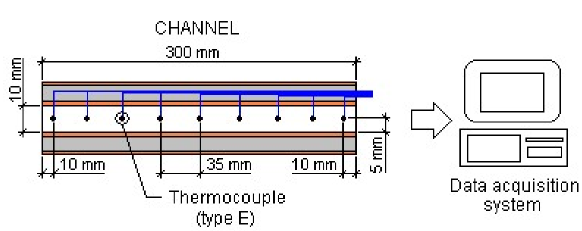

Figure 7. Details of the thermocouple position.

A 640 x 480 pixels digital camera was used to register de evolution of the wax deposition process inside the channel. Objective lenses with 6x, 11x and 45x magnification were used. The camera was mounted on a X-Y coordinate table, in such a way that its axis was positioned orthogonally to the glass wall of the channel. The camera could be moved along the axial and cross-stream directions of the channel. In the cross-stream direction a precision screw allowed the motion of the camera to within 1/100 mm. That was necessary to adjust the focus of the image. Back illumination through the opposite glass wall of the channel was employed.

A data run was initiated by circulating the oil-wax solution to be tested through the channel and back to the tank in a closed loop. For the tests presented in this paper a 10% in weight solution of commercial paraffin dissolved in spindle oil was used. The *WAT* for the utilized solution was measured to be 36.6^{o}C. The temperature of the solution, as well as the temperature of water circulating inside the copper blocks, was below the *WAT*. The mass flow rate desired for the particular experiment was set in the pump. After a steady state condition was achieved, the temperature of the circulating water in the copper blocks was set to the desired value to begin the experiment. With the new temperature conditions at the cooper walls it was possible to create the heat flux condition needed. Any wax deposition along the copper walls could be registered by the digital camera.

At any fixed axial position of the camera, the temporal evolution of the deposited wax could be obtained by the analysis of the recorded images. However, the field of view of the lenses employed only allowed the visualization of an area of approximately 15 x 15 mm^2. This area was sufficient for visualizing the whole 10-mm height of the channel, but the channel length of 300 mm could not be observed in such a small field of view. A special experimental procedure was devised to allow the visualization of the deposition along the whole length of the channel. Firstly, the camera was positioned at the entrance of the channel, imaging the first 15 mm of its length. The transient evolution of the deposited layer at this axial position was registered by the camera up to the attainment of a steady state condition for the deposited thickness. After attainment of the steady state condition for the particular mass flow rate being studied, the temperature of the copper walls was raised to a value above the *WAT*. With this operation, all the deposited wax was removed. The coordinate table was then used to move the camera to a new axial station, adjacent to the previous one. One more time, after the attainment of steady state condition, the temperature of the copper walls was lowered and set to the same values used in the experiments for the previous position of the camera. The transient evolution of the deposited wax layer was registered until a steady condition was reached. This procedure of forming and removing the wax deposit and moving the camera was repeated until the whole channel length was visited.

In order to estimate the accuracy of the measuring procedure just described, a series of preliminary test experiments was conducted prior to the data runs. In these test experiments, the camera was kept fixed in a particular axial position and registered the time evolution of the deposit. After steady state, the deposit was removed by increasing the wall temperature. The experiment was then repeated without, however, moving the camera. The results of several replications were compared. In all cases the deviations were within ± 5%, what was considered satisfactory.

5. RESULTS AND DISCUSSION

The results obtained in the present study will now be presented. The experimental methodology used allowed the determination of the spatial and temporal evolution of the wax deposits. The experiments were run for all three heat flux conditions and the effects of flow rate and temperature were also studied.

5.1. Deposition experiments

Positive and zero heat flux boundary conditions:

As already commented, the literature review revealed that there is some controversy in the interpretation of the results for conditions of zero and positive heat flux. A positive heat flux is defined as the configuration where the channel wall is warmer than the fluid. Hunt (1962), Brown et al. (1993), Hamouda et al. (1995), and Creek et al. (1999), conducted experiments for the zero heat flux condition, concluding that wax deposition is not present. However, Burger et al. (1981), and Todi (2005), conducted experiments for the same condition observing a very thin deposit layer after a few hours. These contradictions motivated the development of experiments to reproduce the zero heat flux conditions.

The first experiment under zero heat flux boundary condition was performed with the lowest Reynolds number allowed by the test section, namely, *Re*=151, which produces the lowest shear rate. The zero heat flux condition between the oil mixture and the copper walls was obtained with an oil mixture injection temperature of T_{inj}=34±0.3ºC and walls temperature of T_w=34.5±0.3ºC. The choice of an average temperature of the wall slightly higher than the bulk fluid temperature, was an imposition of the uncertainty of the temperature measurements that could, otherwise, allow for moments where negative heat fluxes existed, and that could lead to misleading deposition measurements. This uncertainty on the wall and bulk fluid temperatures is an important issue. Although the experiments are seeking for the zero heat flux boundary condition, in reality there could me an alternation among zero, positive and negative heat flux boundary conditions as the temperature of the wall fluctuates around the mean value. Indeed, caution should be taken to interpret the experiments of Todi, 2005, where deposition was observed for the zero heat flux condition. In his experiments the uncertainty on the temperature of the wall was reported to be of the order of ±1°C, what could, conceivably, have led to moments of negative heat fluxes. The choice of temperatures mentioned above for our experiments guarantees, at least, that there was no negative heat flux boundary condition.

The external temperature of the channel glass walls was measured by nine thermocouples distributed along the channel. This temperature was directly influenced by the air jet warming system with a temperature set at T_j=35±0.5ºC, controlled at the exit of each jet. This higher temperature uncertain (±0.5ºC) was caused by the laboratory air temperature fluctuations during the day.

The experiments under zero heat flux boundary condition conducted with the parameters mentioned above were repeated three times. After 4 hours of test duration, there was no deposition observed on the copper channel walls.

An additional experiment for the zero heat flux boundary condition was performed. This time we aimed at increasing the concentration of wax crystals in suspension. To this end, the oil mixture injection temperature was set at T_{inj}=32±0.3ºC (2ºC below the injection temperature of the previous experiment). In order to approximate the zero heat flux condition, the copper walls temperature were set at T_w=33±0.3ºC with an air jet temperature of T_j=33±0.5ºC. The reduction of the oil mixture injection temperature from T_{inj}=34ºC to T_{inj}=32ºC caused a significant increment of the oil mixture viscosity. In consequence, keeping the same volumetric flow, the Reynolds number dropped from 151 to 106. Despite the more favorable deposition conditions due to the higher concentration of suspended crystals, there was no deposition observed at the end of the test.

A new set of experiments was conducted for a higher value of the Reynolds number, namely, 249. The temperature settings for the fluid and the walls were the same as those described in the previous paragraph. At higher Reynolds numbers, higher levels of shear rate are imposed on the fluid. The presence of deposition would be an indication that shear-induced mechanisms could be relevant for deposition. After 4 hours of tests, no deposition was observed.

Experiments were also conducted for the positive heat flux boundary condition, a configuration where molecular diffusion does not contribute to wax deposition. The literature on paraffin deposition shows a small number of experimental works investigating this condition. For example, Hsu et al. (1994), affirm that zero and positive heat fluxes could generate wax deposition as long as the wall and oil injection temperature were below the *WAT*. Another experiment conducted by Todi (2005) for the positive heat flux condition resulted in an irregular thin layer of wax deposited at the end of the 3rd day of tests. Hence, based on these results, a set of experiments was conducted to investigate the positive heat flux boundary condition.

The test sequence was initiated by reducing the oil mixture injection temperature to the desire value. Then, the channel walls temperatures were set. One more time, the lowest Reynolds number was chosen for the tests, what offered the most favorable conditions for deposition. The positive heat flux condition was obtained by setting the oil injection temperature at T_{inj}=32±0.3ºC, the copper walls at T_w=35±0.3ºC and the air jet temperature at T_j=35±0.5ºC. Contrary to the results obtained by Todi (2005), after four hours, there was no deposited wax visualized for this heat flux condition.

Negative heat flux boundary condition:

In the case of the channel walls being cooler than the flowing solution, the negative heat flux boundary condition, larger amounts of wax deposits are expected. To avoid the possibility of plugging the channel, the experiments were conducted with only one wall being cooled. The other wall was maintained at a temperature approximately equal to the inlet temperature of the solution. The experiments were conducted for three different values of the Reynolds number, namely, 151, 213 and 354. In all the experiments the oil mixture inlet temperature was kept at T_{inj}=34ºC, while the top copper wall was kept at, T_{tw}=35ºC. For each flow rate, three different bottom copper wall temperatures were studied: T_{bw}=29, 19 e 9ºC.

Figures 8 and 9 show typical results obtained. In both figures the deposit thickness layer, given in millimeters, is presented as a function of the axial coordinate of the channel, given also in millimeters. Each curve represents a different time counted from the initiation of the cooling of the lower wall. The time intervals range from 1 minute to 80 minutes. In both cases presented in the figures, the bottom copper wall temperature was 9°C. The *WAT* for the test fluid was equal to 36.6°C. In the case of Fig. 8 the Reynolds number was 151, while in Fig. 9 it was 354.

The experimental data presented in Fig. 8 and Fig. 9 are, seemingly, the first published results that display the spatial and temporal variation of the wax deposited layer under flowing conditions with crystals in suspensions.

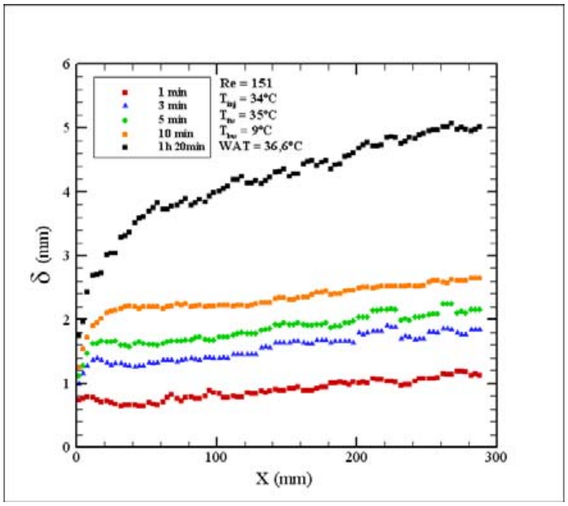

Figure 8. Measured spatial and temporal evolution of deposited wax layer for channel flow. (ΔT=25ºC). *Re*=151.

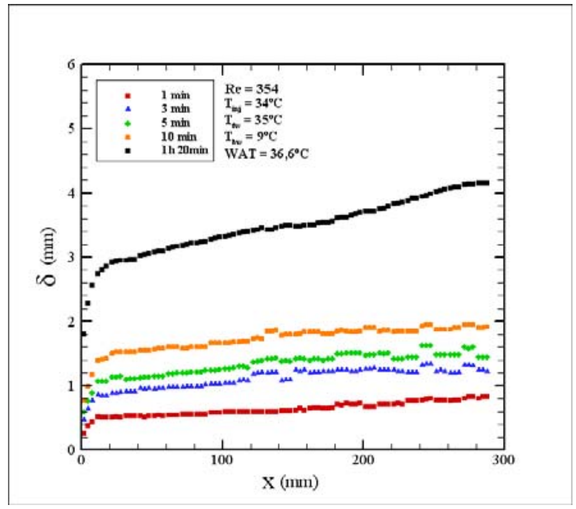

Figure 9. Measured spatial and temporal evolution of deposited wax layer for channel flow. (ΔT=25ºC). *Re*=354.

An observation of Fig. 8 reveals the rapid growth of the deposit layer. Indeed, the first 10 minutes of deposit accumulation are responsible for nearly 50% of the final thickness (1 hour and 20 minutes). A comparison of the results from Fig. 8 and Fig. 9 shows that, as expected, the deposited layer is comparatively thinner for the higher flow rates represented by the higher value of the Reynolds number. For the conditions tested here, the flow rate was always seen to reduce the deposit.

If deposition mechanisms based on shear dispersion were relevant, it would be expected that the experiments with higher values of the Reynolds number and, therefore, presenting higher shear rates, should display higher deposit thicknesses. This was not the case in the results observed, indicating that the shear dispersion does not seem to be a relevant factor in the deposition. It must be said, however, that the shear dispersion mechanism can be responsible for the formation of crystal concentration gradients in regions next to the wall, a necessary requirement for the activation of the Brownian diffusion deposition mechanism. It should be also mentioned that for the same temperature difference between the inlet solution and the cooled wall, and for the same Reynolds number, the deposits measured for the case where suspended crystals were present, were approximately two times thicker than those observed in the experiments conducted by Leiroz, 2004, where the inlet fluid temperature was above the *WAT*, and suspended crystals were not present. This comparison is a clear indication of the importance of deposition mechanisms based on the lateral transport of wax crystals.

5.2. Visualization experiments of wax crystal transport

During the negative heat flux experiments performed in the presence of suspended crystals (fluid injection temperature below the *WAT*), a region of high concentration of wax crystals flowing adjacent to the cold wall was observed. Additional experiments with higher magnification lenses (45x) were performed with the objective of trying to identify any possible crystals transport in the wall direction.

The high particle concentration region next to the copper wall appeared immediately after the beginning of the wall cooling. The shape of this region, thin at the entrance and thicker at the exit of the channel, resembled a thermal boundary layer developed at the cooled wall. At the same time, a thin layer of deposited wax was observed to grow on the cold wall, probably governed by molecular diffusion. As time passed, the wax deposited layer adjacent to the wall grew, and the high particle concentration region was seen to decrease in thickness and concentration as a consequence of the insulating effect of the wax deposited at the cooper wall. Two regions were selected for observation of the motion of the crystals: one at the entrance and the other at the exit section of the channel. Representative visualization results are presented in Fig. 10.

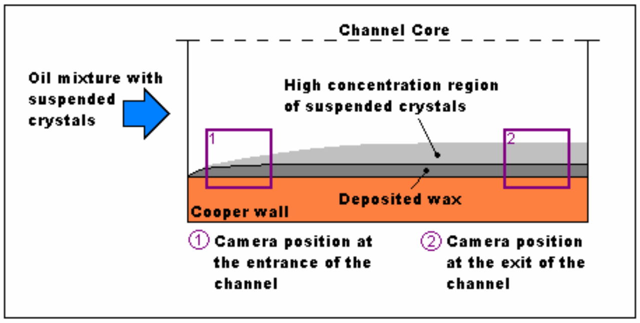

Figure 10. High concentration region of suspended crystals
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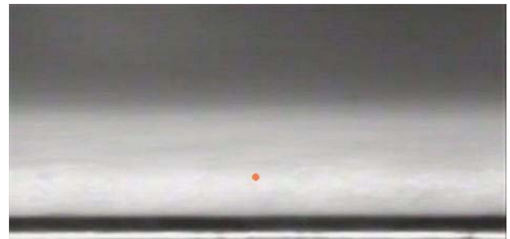

Figure 11. Typical image obtained in the visualization experiments (Viewing area: 1.2 x 2.5 mm²).

The first visualization experiment was performed at the lowest Reynolds number and with the lower wall cooled at the lowest temperature (Re=151 and T_{pi}=9ºC) in order to produce the most favorable deposition conditions allowed by the test section. With the camera positioned at the entrance of the channel (position 1 in Fig. 10) and with the wall cooling just initiated, an homogeneous growing of the wax deposit with a thin region of high concentration crystals flowing adjacent to the deposited wax was observed. At this channel position, the wax crystal deposition was not obvious, so it was reasoned that the wax deposit grew mainly due to the molecular diffusion mechanism.

At the second camera position, a few seconds after the initiation of the wall cooling, it was observed a tick region of high crystal concentration flowing next to the copper wall, while a very thin wax deposited layer was growing slowly, in similar conditions as in the first position, as shown in Fig. 11. The crystals flowing next the cold wall adhered to the existent thin wax deposited layer promoting a rapid increase in its thickness. With the thickness increment of the wax deposit, the high crystal concentration region was less evident due to a reduction of crystals concentration that might be caused by the thermal insulation effect of the deposited wax. This visualization made evident the existence of the wax crystals transport toward the cold wall induced by a mechanism that apparently acts in the presence of a high particle concentration conditions. Even with this visualization experiments it was difficult to define the mechanism or mechanisms responsible for the wax crystals deposition phenomenon. In Fig. 11, the copper wall of the channel is seen as a dark region in the lower part of the figure. An orange dot marks the interface between the deposited wax and the high particle concentration region. Above this region, a lower particle concentration region is seen in gray.

An additional visualization experiment was conducted for Reynolds number equal to 354. Although the general aspects of the visualization were similar to those described previously for the lower value of Re, it was observed that the region of flowing suspended crystals was thinner and presented a lower concentration of crystals. The total deposition thicknesses obtained were smaller than in the previous experiments. So, a higher shear rate led to smaller agglomeration of suspended crystals at the wall.

The visualization experiments evidenced the high complexity of the wax deposition phenomenon. Although the process by which suspended crystals were added to the wax deposited layer was visualized, it was not possible to identify the mechanism responsible for this particle transport. With the level of quality of images obtained it was not possible to confirm the action of a sloughing mechanism.

6. CONCLUSIONS

The present paper presented results of an ongoing research program aimed at studying the mechanisms responsible for wax deposition in petroleum pipelines. The strategy employed in the study was to conduct laboratory experiments in simple geometries with well-defined boundary and initial conditions employing fluids with known thermo-physical properties.

The literature research conducted revealed a lack of small scale fundamental laboratory tests aimed at identifying the relative importance of the deposition mechanisms, and revealed some discrepancies in the interpretation of deposition experiments. Therefore, the work was focused in obtaining experimental data that helped the understanding of the deposition phenomena and wax particle transport. In order to study the relevance of particle transport mechanisms (Brownian diffusion, shear dispersion and gravity settling), wax deposition experiments were performed in laminar flow conditions with the oil mixture injection temperature below the Wax Appearance Temperature, what led to the presence of suspended crystals in the solution.

The experiments have shown that it is necessary a negative heat flux at the channel wall to produce wax deposition. The thick wax deposited layers resulting from the negative heat flux experiments, allowed the measurement of temporal deposition profiles for different Reynolds and temperature conditions. These transient, spatial deposition profiles are original information that is useful for future comparisons with simulation models.

Visualization experiments performed for the negative heat flux boundary condition and with the solution entering the channel with temperature below the *WAT*, have shown regions of suspended crystal flowing close to the wall, and adhering to the deposited layer. The deposition of precipitated crystals at the cold wall was evident, although it was difficult to define the mechanism responsible for the deposition.

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