WAX DEPOSITION IN LAMINAR CHANNEL FLOW

Andrea Teixeira Leiroz
Departamento de Engenharia Mecânica, PUC-RIO, 22453-900, RJ
andrea@mec.puc-rio.br

Mao Illich Romero
Departamento de Engenharia Mecânica, PUC-RIO, 22453-900, RJ
mao@mec.puc-rio.br

Angela Ourivio Nieckele
Departamento de Engenharia Mecânica, PUC-RIO, 22453-900, RJ
nieckele@mec.puc-rio.br

Luis Fernando Alzuguir Azevedo
Departamento de Engenharia Mecânica, PUC-RIO, 22453-900, RJ
lfaa@mec.puc-rio.br

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. The accurate prediction of wax deposition rates and deposited wax spatial distribution would be invaluable information for the design of subsea lines. A critical review of the literature conducted lead to the conclusion that there is not enough experimental evidence to determine which are the relevant mechanisms responsible for wax deposition. Based on the conclusions of the literature search, a research program was initiated with the aim of identifying the relative importance of the suggested wax deposition mechanisms namely, molecular diffusion, Brownian diffusion, shear dispersion and gravity settling. To this end, simple basic experiments were designed and complemented by numerical simulations. In these experiments, visualization of the deposition process was sought for a laminar channel flow, submitted to a transverse temperature gradient. Detailed data of temporal and spatial distributions of the wax deposited were obtained. Numerical simulations of the experiments conducted were developed employing molecular diffusion as the only deposition mechanism, as it is done in the vast majority of the deposition models available in the literature. The results obtained presented significant differences between experiments and computation, indicating that molecular diffusion might not be the only relevant mechanism responsible for wax deposition.*

Keywords*: wax deposition, pipeline, laminar flow, molecular diffusion*

1. Introduction

Wax deposition in production and transportation pipelines continues to be a relevant problem for the industry, particularly in offshore operations. The crude oil flows out of the reservoir at, typically, 60 ^{o}C into the production pipelines. These lines carry the oil to the platforms and from the platforms to shore. At large water depths, the ocean temperature at the bottom is of the order of 5 ^{o}C. The solubility of wax in the oil is a decreasing function of temperature. As the oil flows, it loses 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. The accumulation of the deposited material may lead to increased pumping power, decreased flow rate or even to the total blockage of the line with loss of production and capital investment.

A significant research effort has been devoted to the understanding and modeling of the wax deposition problem (Burger et al., 1981, Brown et al., 1993, Creek et al., 1999 and Svendsen, 1993). This is a complex problem that involves several disciplines such as thermodynamics, heat transfer, mass transfer, crystal growth and fluid dynamics. An accurate prediction of the temporal and spatial distributions of the deposited wax along the pipeline would be invaluable information that would help in the design stages of the field, as well as in the scheduling of interventions in the pipeline, in order to assure the flow of oil at the desired rates.

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 included in the vast 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 deposition mechanism. Indeed, in a recent paper (Fusi, 2003) presents a mathematical model for wax deposition that considers both molecular diffusion and shear dispersion as the relevant mechanisms.

An observation of the deposition models available in the literature shows that they all make use of adjusting constants to fit the model predictions to field or laboratory data. In our view this practice, totally justified for yielding good predications for particular lines, difficults the task of assessing the relative importance of each deposition mechanism.

The present paper presents results of an ongoing research effort aimed at identifying the relative importance of the deposition mechanisms. To this end, small-scale, laboratory tests were conducted employing simple oil-wax mixtures with known properties. The test section constructed was simple, having well-defined boundary and initial conditions. The experimental tests were complemented by numerical simulations that allowed the testing of different deposition models. In the simulations, the measured properties of the test fluids were employed. No constants were adjusted to fit the predicted results to the measured data. It is believed that the comparison between the experimental and predicted results for these simple configurations would allow a better assessment of the relative importance of the deposition mechanisms. In the results presented here, only the molecular diffusion-based mechanisms will be studied.

As will be described next, the tests were conducted for wax deposition under laminar flow within a rectangular channel submitted to a transverse temperature gradient. The experiment was designed so as to allow the visualization of the deposition process. The test section employed is now described in details.

2. Experiments with deposition under laminar flow

The experiments on wax deposition under laminar channel flow were conducted employing the test section that will now be described. Figures 1 and 2 show schematic views of the test section.
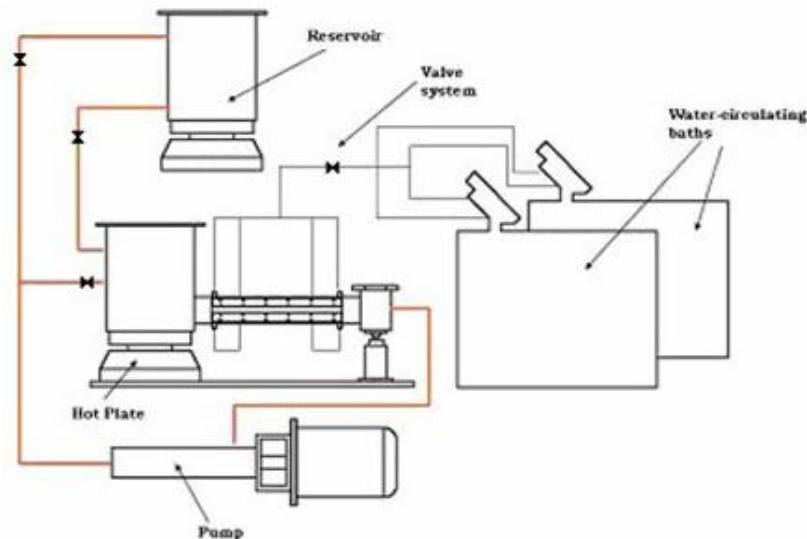

Figure 1. Schematic view of the test section for wax deposition studies in channel flow.

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 2 mm-thick glass plates. The upper and lower walls were made of copper and were soldered to hollow copper blocks. Water from a temperature controlling and water circulating unit was pumped through each of the copper blocks. Fine gauge thermocouples were installed in the copper walls to monitor its temperature. Each end of the rectangular channel was connected to a stainless steel tank. The larger upstream tank contained the solution to be tested. In order to control the solution temperature, the upstream tank was equipped with a coil-tube heat exchanger connected to a water circulating and thermostatic unit. The smaller downstream tank was equipped with an electric heater that was used to avoid the deposition of the wax in the tank. A progressive cavity pump was used to return the solution from the downstream tank to the upstream tank, thereby allowing for a continuous operation of the test section.

A 640 x 480 digital camera equipped with an 18–108 mm zoom lens was used to register de evolution of the wax deposition process inside the channel. The camera was mounted on a X-Y coordinate table, in such a way that the camera was positioned with its axis orthogonal 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. The temperature of the solution, as well as the temperature of water circulating inside the copper
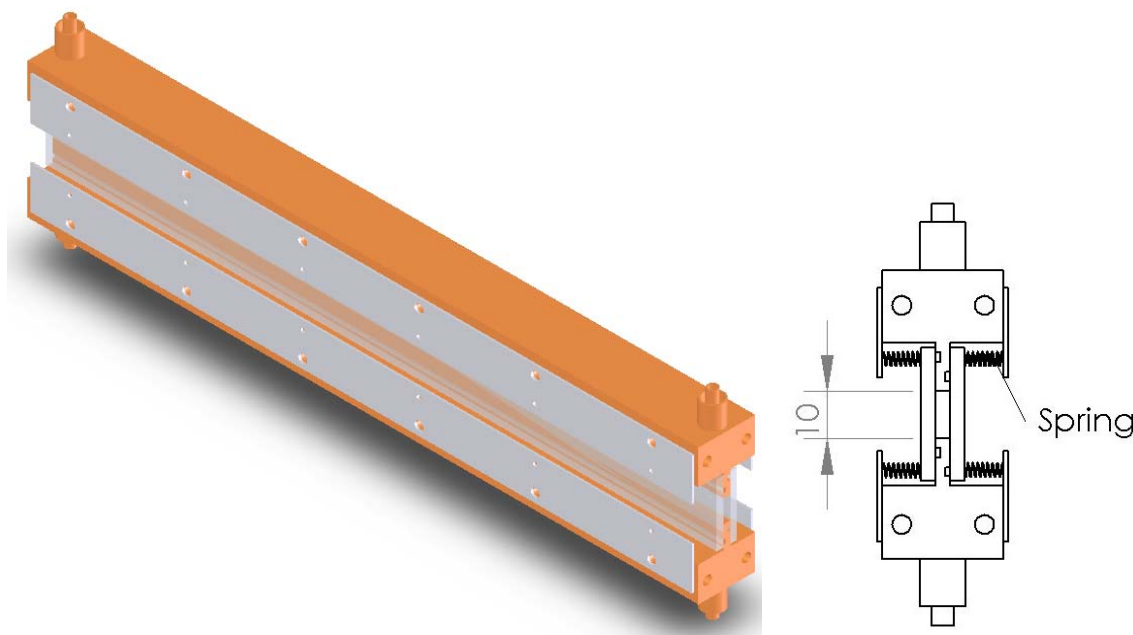
Figure 2. Pictorial view and detail of the rectangular channel test section.

blocks, was above the WAT for the solution. 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 water in the copper blocks was lowered to a value below the WAT. The deposition of the wax along the lower and upper copper walls was registered by a tape recorder connected to 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. 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. Wax deposit growth at both upper and lower walls could be registered simultaneously in the same image fields. 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 moved to a new axial station, adjacent to the previous one. After attainment of steady state condition, the temperature of the copper walls was lowered 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 while 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 test experiments was conducted prior to the data runs. In this 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.

3. Numerical model for deposition in laminar channel flow

As already mentioned in the introduction, the numerical simulation of the wax deposition is an important part of the present research. The role of the numerical solution developed in the present work was to help identify the relative importance of the wax deposition mechanisms proposed in the literature. The idea was to develop a simple model that incorporated one deposition mechanism at a time and compare the predictions obtained with the simple experiments conducted. In the present paper, only a model for deposition by molecular diffusion was implemented, since this is the most widely accepted mechanism.

The numerical model developed for simulating wax deposition under laminar channel flow conditions followed the models normally described in the literature (e.g., Ribeiro et al., 1997).

In these models the flow is treated as one-dimensional, with the axial velocity varying with the axial coordinate due to the decrease in channel cross sectional area caused by the wax accumulation. A local varying friction factor for fully

developed flow was employed. The energy equation was solved to yield the axial variation of the bulk fluid temperature. Heat losses through the transverse channel direction were computed taking into account the convective thermal resistance within the channel and the conductive resistance in the deposited layer and channel metallic wall. Heat losses through the glass lateral walls were also considered.

The geometry of the problem modeled is presented schematically in Figure 3. The oil enters the domain, which has a rectangular cross section (height a and width W), with a uniform temperature T_{in} and a constant flow rate $\dot{m}$. The channel length is L. The oil loses energy to the ambient at temperature T_∞ through the side glass walls with an overall heat transfer coefficient U_{side}. Cold water with constant temperature T_{H2O} flows through channels connected to the upper and lower copper walls. The working fluid was considered as a binary homogeneous solution of oil, the solvent, and wax, the solute. The wax deposition begins when the oil interface temperature T_{int} is lower than the wax appearance temperature, T_{WAT}. The wax deposition thickness is δ.

To estimate the wax deposition, a one-dimensional model was considered. The oil temperature distribution was obtained through an energy balance, and the wax deposition was determined by a diffusion-based model. Further, the latent heat of the wax was taken into consideration at the wax/oil interface. The flow was considered laminar with a uniform velocity profile. Axial diffusion was neglected. The energy equation for the oil applied to the control volume of Figure 3 is,

$$\frac{\partial\, m\ cp\ T}{\partial\, t} + \frac{\partial\, \dot{m}\ cp\ T}{\partial\, x}\, dx + q_{int} + q_{lat} = 0 \ ; \ q_{int} = h_i\, 2\,W(T - T_{int})\, dx \ ; \ q_{lat} = U_{side}\, 2(a\text{-}2\delta)\, (T\text{-}T_\infty)\, dx \quad (1)$$

where $m = \rho\, A_t\, dx$ is the mass of oil per unit length, ρ is the oil density, $A_t = 2\,W\,(a\text{-}2\delta)$ is the cross section area. The interface and lateral heat flux are q_{int} and q_{lat}, respectively. The heat transfer coefficient h_i was obtained from a Nusselt number correlation corresponding to a thermal developing condition (Incropera and DeWitt, 1990).
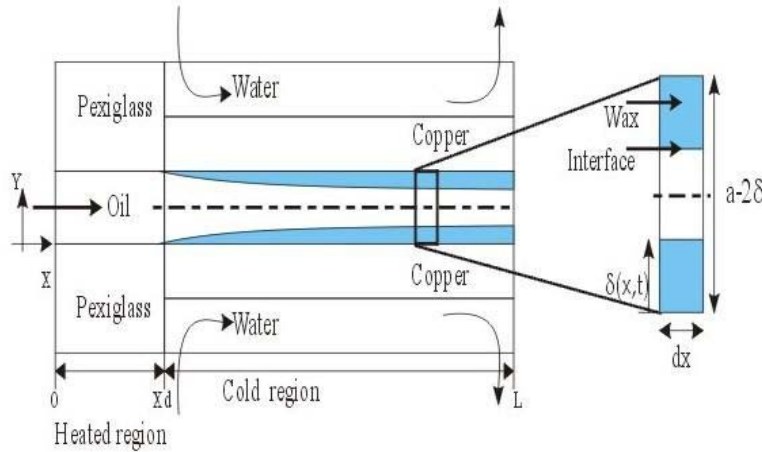

Figure 3. Schematic view of the computation domain.

The overall side wall heat transfer coefficient is formed by the oil forced convection resistance at the inner wall, the conduction resistance of the glass with thickness e_{glass} and thermal conductivity k_{glass}, and the natural-convection-based outer wall resistance $1/h_{side}$

$$Nu_i = \frac{h_i\, D_h}{k} \ ; \ D_h = \frac{4 A_t}{2\,(W + a - 2\delta)} \ ; \quad \frac{1}{U_{lat}} = \frac{1}{h_i} + \frac{e_{glass}}{k_{glass}} + \frac{1}{h_{side}} \quad (2)$$

The interface temperature T_{int} was determined by an energy balance at the wax/oil interface, i.e., the difference in heat fluxes from each side of the interface is proportional to the wax latent heat λ and rate of mass deposited, as

$$q_{int} - q_{wax} = \frac{d\, m_{wax}}{dt}\, \lambda \quad ; \quad m_{wax} = \rho_{wax}\, 2\,W\, \delta\, (1 - \phi) dx \quad ; \quad \rho_{wax} = \rho(T_{int}) \quad (3)$$

$$q_{wax} = U_{wax}\, 2\,W\,(T_{int} - T_{H2O})\, dx \quad ; \quad \frac{1}{U_{wax}} = \frac{\delta}{k_{wax}} + \frac{e_c}{k_c} + \frac{1}{h_{H2O}} \quad (4)$$

where the density of the wax is considered equal to the oil density at the interface temperature, $\phi = m/(m + m_{wax})$ is the porosity of the oil-filled wax deposit, where m_{wax} is the deposited wax mass, U_{wax} is the overall heat transfer coefficient at the wax side, formed by the conduction resistance of the copper walls and the wax, that have, respectively, thicknesses e_c and e_{wax}, and thermal conductivities k_c and k_{wax}, and $1/h_{H2O}$, the forced-convection based resistance of the cold water that flows in the duct that cools the copper walls. The interface temperature can then be determined by

$$T_{int} = \frac{h_i T + U_{wax} T_{H2O} - \rho_{wax}\, \lambda\, (d\delta/dt)}{h_i + U_{wax}} \tag{5}$$

Note that, at the beginning of the process, both δ and $d\delta/dt$ are zero, therefore, the interface temperature is equal to the copper wall temperature. The growth of the deposited layer was accounted for by a molecular diffusion mechanism, as suggested by Burger et al. (1981). In this model, the deposition occurs when $T_{int} < T_{WAT}$ and the diffusion flux of wax toward the cold wall is estimated by Fick's law of diffusion,

$$\frac{d\,m_{wax}}{d\,t} = -\rho_{wax}\ \mathcal{D}_{wax}\ 2\,W\,dx \left.\frac{d\,C}{d\,y}\right|_{int} \quad ; \quad \left.\frac{d\,C}{d\,y}\right|_{int} = \left.\frac{d\,C}{d\,T}\frac{d\,T}{d\,y}\right|_{int} = -\frac{d\,C}{d\,T}\frac{q_{int}}{2\,W\,dx\,k} = -\frac{d\,C}{d\,T}\frac{h_i\,(T - T_{int})}{k} \tag{6}$$

where $\mathcal{D}_{wax}$ is the coefficient of molecular diffusion, and the gradient of the concentration C (or volume fraction of wax in the solution) at the interface was approximated by the product of the wax solubility coefficient dC/dT by the interface temperature gradient. Thus,

$$\frac{d\,\delta}{d\,t} = \beta\,(T - T_{int}) \quad ; \quad \beta = \frac{\mathcal{D}_{wax}}{1 - \phi}\frac{d\,C}{d\,T}\frac{h_i}{k} \tag{7}$$

The fluid properties such as density ρ (kg/m^3), absolute viscosity μ (kg/ms), wax coefficient of solubility dC/dT (1/^{o}C), were determined experimentally by Leiroz, 2004. The specific heat cp (cal/g ^{o}C) obtained from Leiroz, 2004, and the molecular diffusion coefficient $\mathcal{D}_{wax}$ (cm^2/s) obtained from Hayduk and Minhas et al, 1983, were both considered as temperature dependent. The thermal conductivity was taken as constant, $k = 0.281$ W/(mK) (Leiroz, 2004). These properties were obtained from the following correlations, with temperature in Celsius,

$$\rho = 863.345 - 0.61\,T - 4.545 \times 10^{-4}\,T^2 \quad ; \quad \mu = 1.03092\,T^{-1.29417} \quad ; \frac{d\,C}{d\,T} = 5.2408 \times 10^{-9}\,T^{4.133} \tag{8}$$

$$cp = \frac{0.425}{(\rho/\rho_{H2O,4C})^{0.5}} + 9 \times 10^{-4}(T - 15) \qquad D_{wax} = \frac{1.33 \times 10^{-7}}{(M_{wax}/\rho_{wax})^{0.71}}\,T^{1.47}\,\mu^{[(10.2\,\rho_{wax}/M_{wax}) - 0.791]}$$

The initial condition for the problem was a steady state solution, with water flowing at the entrance oil temperature, both hotter than the WAT for the solution.

The energy equation was discretized based on the finite volume method (Patankar, 1980), with the upwind scheme to treat the convection term. A totally implicit procedure was employed to handle the time integration of both Eq. (1) and (8). The set of algebraic equations were solved by the TDMA algorithm.

Mesh and time step independence tests were performed, until the solutions for different meshes and time steps agreed to better than 0.1%. The results presented in the present paper were obtained with 350 control volumes and a time step equal to 0.1 s.

4. Results and discussion

The results obtained in the present study will now be presented. The experimental methodology used in the present work allowed the determination of the spatial and temporal evolution of the wax deposits. Figures 4 and 5 show typical results obtained. In both figures the thickness of the deposited 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 walls. The symbols correspond to the experimental data, while the solid lines correspond to the numerical solutions. The time intervals range from 1 minute to 4 hours. At four hours, no more deposit growth was verified, indicating the attainment of a steady condition. In both cases presented in the figures, the fluid inlet and wall temperatures were 40 and 15°C respectively. The WAT for the test fluid was equal to 36°C. In the case of Fig. 4 the Reynolds number was 301, while in Fig. 5 it was 729.

The experimental data presented in Fig. 4 and Fig. 5 are, seemingly, the first published results that display the spatial and temporal variation of the wax deposited layer under flowing conditions.

An observation of Fig. 4 reveals the rapid growth of the deposit layer. Indeed, the first 10 minutes of deposit accumulation are responsible for nearly 50% of the final, steady state thickness. A comparison of the results from Fig. 4 and Fig. 5 show that, as expected, the deposited layer is comparatively thinner for the higher flow rates represented by the higher value of the Reynolds number.
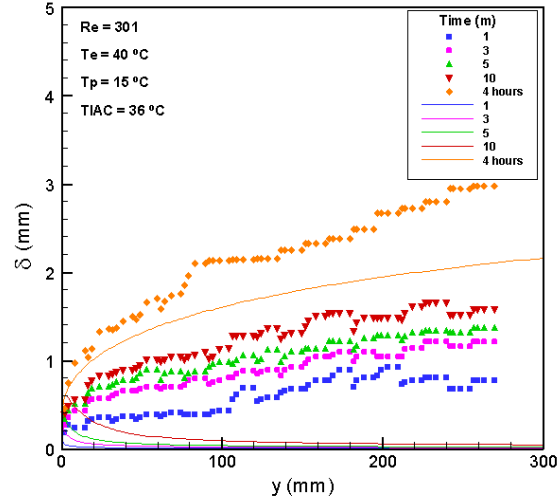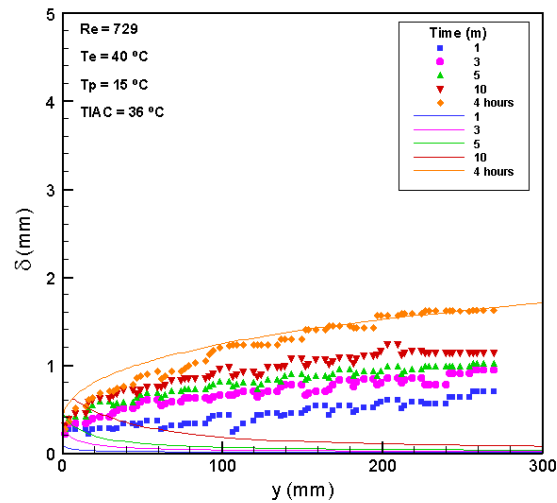

Figure 4 – Measured and predicted spatial and temporal evolution of deposited wax layer for channel flow. Inlet fluid temperature of 40 ^{o}C. Wall temperature of 15°C. Reynolds number equal to 301. WAT equal to 36°C.

Figure 5 - Measured and predicted spatial and temporal evolution of deposited wax layer for channel flow. Inlet fluid temperature of 40 ^{o}C. Wall temperature of 15°C. Reynolds number equal to 729. WAT equal to 36°C

We now turn our attention to the solid lines in Figure 4 and 5 that represent the predictions of the evolution of the deposited layer obtained with the numerical model developed as part of this study. The actual properties available for the test fluid employed in the experiments were used in the calculations. Note that the solid lines are the predictions from the model for the same times as those measured in the experiments. These lines are color-coded to the experimental data points.

A general observation of Fig. 4 and 5 shows the poor quality of the model predictions. Indeed, except for the steady state cases, the model was not able to even predict the correct trend of the spatial distribution of the deposited layer. While the experiments show an increase in deposition thickness with axial distance, the model predicts the opposite trend. At steady state, reasonable quantitative agreement and trends are obtained. This poor level of agreement is encountered in all models available in the literature. They all use molecular diffusion as the deposition mechanism. What is normally done in the literature is to adjust the numerical predictions to the experimental data via the

modification of the constant that incorporates the molecular diffusion coefficient, porosity, and other parameters. This procedure, in our view, is responsible for the popularity of the molecular-diffusion based models. Here, for the first time, we show that when actual properties are used, the molecular diffusion based mechanism as normally implemented in the literature is not capable of predicting the transient behavior of the deposition thickness even for this very simple configuration studied.

The reason for the discrepancy between measured and predicted results is no yet known. It is conceivable that deposition mechanisms other than molecular diffusion might be relevant. It is also plausible that a more elaborate model that solves the fully three dimensional momentum and energy equations coupled with conservation equations for the chemical species might yield better agreement with the experimental data. This line of research is presently being conducted.

5. Concluding Remarks

The present paper presents 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. In parallel with the experiments, numerical models of the deposition process were developed incorporating molecular diffusion as the only deposition mechanism. A comparison of the experimentally and numerically predicted results may help assess the validity of each deposition mechanism.

Experiments were conducted for the wax deposition in laminar channel flow and submitted to a transverse temperature gradient. 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. The diffusion-based model developed to simulate wax deposition under laminar flow displayed a poor predicting capability. Deposition thickness did not present even the correct trends, with the exception of the steady state configuration.

It is believed that the strategy adopted in the present research may contribute to a better understanding of the relative importance of the wax deposition mechanisms. The data generated is of good quality and was produced under well-defined conditions, being a good database for model testing. These data however are based on simple laboratory conditions and test fluids that are far from the actual field conditions.

6. Acknowledgements

7. References

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