



25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

COB-2019-1972

MODELLING OF WAX DEPOSITION AND REMOVAL BY ELECTRICAL HEATING IN SUB-SEA OIL PIPELINES

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Abstract. Wax deposition in oil production and transportation pipelines is one of the main flow assurance problems in the offshore petroleum industry. The flow of waxy crude oils through sub-sea pipelines surrounded by cold water causes some long-chain oil components to precipitate and deposit on the inner pipe wall. These deposits grow thicker over time, causing oil flow rate reduction, increased pumping power and several other costs associated with removal and prevention of wax deposits. In this article, the wax deposition rate is predicted through the calculation of a mass balance on the wax-oil interface after numerically solving the heat and mass transfer equations in the pipeline. Molecular diffusion is considered to be the only relevant deposition mechanism. The thickness is then updated and used to calculate the new pressure drop across the pipeline as well as the updated heat transfer coefficients. Electrical heating of the upstream oil is used to remove the wax deposit, which is assumed to change phase at a constant temperature. The purpose of this model is to be the basis of an optimization algorithm for minimizing the usage of overall electrical energy, which includes both pipe heating and oil pumping energies. It is known that pipe heating is not a definitive solution to the wax problem for very long lines due to the fact that the dissolved wax is reintroduced in the oil flow and may form a new deposit further ahead. However, this technique is a cost-effective way of keeping the flow rate at a desirable level while postponing the necessity of pigging, which is a considerably more expensive operation, since it requires a production halt.

Keywords: wax deposition, flow assurance, optimization

1. INTRODUCTION

During the past few decades, the oil and gas industry has turned more and more to the offshore fields. Nowadays, nearly half of the sedimentary basins that offer good prospects of finding petroleum are located offshore (Azevedo and Teixeira, 2003). With greater water depths, come the technological challenges. At depths greater than 1500m, seabed temperature will be always below 5°C. In most cases, oil production wells are located a few kilometers away from the floating unit. This means that there is a long path to be covered by the oil on seabed level before it starts to rise to the platform. In such cases, oil temperature will inevitably fall below cloud point or wax appearance temperature (WAT). When that happens, wax crystals start to precipitate in oil. This phenomenon has two undesired effects. One is that the presence of precipitated wax changes the behavior of the crude oil, usually resulting in higher effective viscosities. This can have a particularly high impact on pipeline restart (Oliveira *et al.*, 2010). The other effect is wax deposition. Once the wax crystals meet the inner pipe wall, they build up a solid wax deposit. This deposit grows in thickness over time, causing the oil flow rate to drop significantly and may even block the line completely.

An accurate prediction of the deposition rates along the pipeline is 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 oil flow at the desired rates (Misra *et al.*, 1995). One way to cope with the presence of wax deposits is to periodically remove them by heating the upstream oil. This technique is a low-cost intervention, since it does not require an interruption of the oil production. On the other hand, it should demand a considerable amount of electrical power, which can be a scarce resource for an offshore production unit.

The goal of this paper is model the processes of deposition and removal of wax on the inner walls of a pipe. This model contemplates a mechanism for wax deposition, which is a modified version of the Michigan Wax Predictor (Huang *et al.*, 2011), as well as a mechanism of wax removal by heating, which assumes that the phase change of wax occurs at a constant temperature. The melted wax is reintroduced in the oil flow and carried away by the velocity field.

2. DEPOSITION MODEL

Several deposition mechanisms have been suggested by Burger *et al.* (1981), including gravity settling, shear dispersion, molecular diffusion and Brownian diffusion. However, not all of them are relevant to the net deposition rate. In fact, as shown by Singh *et al.* (2000), all deposition mechanisms are negligible except for molecular diffusion (See Fig. 1). For this reason, it is the only deposition mechanism considered in this model.

Once a certain point in the oil domain reaches the wax appearance temperature (WAT), here referred to as T_{cloud} , the precipitation of solid wax crystals will occur if the local concentration of these particles is higher than the solubility limit. Precipitated particles in the bulk are carried away by the flow, while particles that precipitate on the wall will become a part of the deposit. The convective mass flux (A) is caused by the concentration gradient of dissolved wax, while the diffusive flux (B) exists due to the temperature gradient inside the deposit, since the oil trapped in it is saturated. The difference between fluxes (A) and (B) is responsible for increasing the deposit thickness, while flux (B) represents a counter diffusion process, where the oil trapped inside the structure of the deposit is replaced with more wax crystals, thus increasing the wax fraction of the deposit. This process is known as aging (Singh *et al.*, 2000).

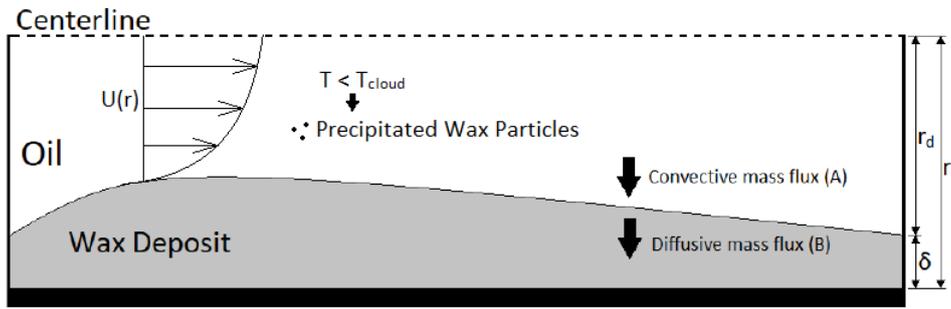


Figure 1: Schematics of the wax flux towards the wall and into the deposit

The flow of wax molecules from the bulk towards the wall can be calculated by Fick's law of diffusion, as

$$\frac{dm}{dt} = \rho_w D_{wo} A \frac{\partial C}{\partial r}, \quad (1)$$

where m is the mass of deposited wax, ρ_w is the specific mass of the solid wax, D_{wo} is the diffusion coefficient of wax in oil, A is the surface area on which the deposition occurs, C is the concentration of dissolved wax and r is the radial coordinate of the pipeline. From eq. 1, one can notice that in order to compute the mass flux towards the wall, the concentration field must be calculated. The details on how to do so are given in section 4.

Once the mass flux is obtained, one can proceed to calculate the growth and aging of the deposit over time. A mass balance at the oil-deposit interface yields the pair of coupled differential equations that describe the behavior of the deposit. Equation 2 is used to determine the deposition rates, while equation 3 gives the growth wax fraction, F_w , during the aging process. In these equations, D_{eff} is the effective diffusion coefficient of wax inside the deposit (Lee, 2008).

$$\frac{dr_d}{dt} = -\frac{1}{\rho_w F_w} \left(D_{wo} \frac{\partial C}{\partial r} \Big|_{interface,convective} - D_{eff} \frac{\partial C}{\partial r} \Big|_{interface,diffusive} \right), \quad (2)$$

$$\frac{dF_w}{dt} = \frac{2}{\rho_w (r_i^2 - r_d^2)} \left(-D_{eff} \frac{\partial C}{\partial r} \Big|_{interface,diffusive} \right). \quad (3)$$

Since the oil entrapped inside the deposit is always saturated, the concentration gradient from the diffusive side can be obtained with

$$\frac{dC}{dr} \Big|_{interface,convective} = \left(\frac{dC_{ws}}{dT} \right) \left(\frac{dT}{dr} \right), \quad (4)$$

where $C_{ws}(T)$ is the wax solubility in oil. From this equation it can be observed that the solubility curve of wax in oil has a direct influence on both deposition and aging rates.

3. REMOVAL MODEL

By the time this article was written, the only study found on the literature involving heating as a wax removal technique was published by Sarmiento *et al.* (2004). However, in their work, the heating was applied directly on the deposit area, as an attempt to clear a completely blocked pipe section. In the current work, a different approach is proposed, in which electrical heating is applied before the flow is interrupted. This allows the heat to propagate with the flow, extending the length of actuation several kilometers beyond the location of the heating coils.

By heating a pipe section located upstream from the deposit location, the thermal energy is convected with the flow to the deposit region, where the wax-oil interface is heated until the surface temperature reaches T_{cloud} . Since there is no solid wax above this temperature (Villazon and Civan, 2009), a phase changing process is initiated, during which the temperature at the interface remains constant and the difference between the heat flux from the oil to the deposit and the heat flux from the deposit to the external environment is computed as a latent heat of fusion and associated with a wax melting rate as follows:

$$\frac{dr_d}{dt} = \frac{-1}{F_w \rho_w} \left(\frac{k_w}{L_w} \frac{\partial T}{\partial r} \Big|_{interface,convective} - \frac{h_0}{L_w} (T_\infty - T_{cloud}) + D_{eff} \frac{\partial C}{\partial r} \Big|_{interface,diffusive} \right), \quad (5)$$

where h_0 is the overall heat transfer coefficient from the wax-oil interface to the external environment, which accounts for the thermal resistance of the wax deposit, the insulation material and the external natural convection and T_∞ is the undisturbed sea water temperature. Equation 5 derives from the heat and mass balances at the wax-oil interface gives the rate of change in the deposit radius during the change of phase of the deposit back into liquid wax. During this process, the wax fraction inside the deposit is assumed constant, as the time scale of removal does not allow for the counter diffusion process to make significant changes.

In order to respect the principle of mass conservation, the flux of wax resulting from the melting at the interface has to be accounted for in the mass transfer equation. These wax molecules reintroduced in the oil flow are driven away from the pipe wall by the same molecular diffusion mechanism that led them towards it. They are then carried away by the velocity field and may eventually form a deposit further ahead, if conditions are appropriate.

4. TRANSPORT EQUATIONS

Computing both temperature and concentration fields inside the pipeline poses a two-dimensional axisymmetric problem that consists of solving equations 6 and 7, derived from energy and mass balances in an annular control volume of infinitesimal thickness (dr) and length (dz). For the wax deposition process, the time derivatives on the left side of these equations are considered null, as the increase of deposit thickness happens very slowly. The last term in equation 7 accounts for the precipitation kinetics, with k_r as the precipitation rate, calculated with the correlation given by Huang *et al.* (2011).

$$\frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(r \alpha \frac{\partial T}{\partial r} \right) - U(r) \frac{\partial T}{\partial z}, \quad (6)$$

$$\frac{\partial C}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(r D_{wo} \frac{\partial C}{\partial r} \right) - U(r) \frac{\partial C}{\partial z} - k_r (C - C_{ws}(T)). \quad (7)$$

These transport equations are solved numerically using a Crank Nicholson scheme for time discretization. The boundary conditions for the deposition process are described in equations 8 and 9, where k_w is the wax thermal conductivity and T_∞ is the undisturbed sea water temperature. At $r = 0$, the derivative with respect to the radius is null due to geometrical symmetry. For the temperature equation, there is a condition of heat exchange with the external environment at $r = r_d$, which is the radius of the wax-oil interface. For the concentration equation, two different conditions may apply depending on whether a wax deposit is present or not. For the locations where there is no solid wax deposited on the pipe wall, a condition of impenetrability is applied, thus resulting in a null radial derivative. On the other hand, when a deposit of wax is present, the concentration at the interface is equal to the solubility limit of wax in oil at the local temperature, because of the assumption that precipitation occurs instantly at the wall (Huang *et al.*, 2011).

$$\begin{cases} T = T_{inlet} & \text{at } z = 0 \\ \frac{\partial T}{\partial r} = 0 & \text{at } r = 0 \\ \frac{\partial T}{\partial r} = \frac{h_0}{k_w} (T_\infty - T_{interface}) & \text{at } r = r_d \end{cases}, \quad (8)$$

$$\begin{cases} C = C_{inlet} & \text{at } z = 0 \\ \frac{\partial C}{\partial r} = 0 & \text{at } r = 0 \\ C = C_{ws}(T) & \text{at } r = r_d \\ \frac{\partial C}{\partial r} = 0 & \text{at } r = r_i \text{ (no wax)} \end{cases} \quad (9)$$

For the removal process, the boundary conditions are modified as shown in equations 10 and 11. The imposed temperature at the wall is due to the fusion of wax at a constant temperature, while the imposed wax flux at this same coordinate makes sure that the liquefied wax goes back into the bulk and mixes with the oil. For the heated section of the pipe, the heat flux at the wall is equal to that supplied by the heat source, $\dot{q} = \frac{\dot{Q}}{A}$

$$\begin{cases} T = T_{inlet} & \text{at } z = 0 \\ \frac{\partial T}{\partial r} = 0 & \text{at } r = 0 \\ \frac{\partial T}{\partial r} = \frac{h_0}{k_w}(T_\infty - T_{interface}) & \text{at } r = r_d \text{ (no melting)} \\ T = T_{cloud} & \text{at } r = r_d \text{ (melting wax)} \\ \frac{\partial T}{\partial r} = \frac{\dot{q}}{k_w} & \text{at } r = r_i \text{ (heating)} \end{cases} \quad (10)$$

$$\begin{cases} C = C_{inlet} & \text{at } z = 0 \\ \frac{\partial C}{\partial r} = 0 & \text{at } r = 0 \\ C = C_{ws}(T) & \text{at } r = r_d \text{ (no melting)} \\ \frac{\partial C}{\partial r} = \frac{\rho F_w}{D_{wo}} \frac{dr_d}{dt} & \text{at } r = r_d \text{ (melting wax)} \\ \frac{\partial C}{\partial r} = 0 & \text{at } r = r_i \text{ (no wax)} \end{cases} \quad (11)$$

The oil properties used in the simulations are listed in Tab. 1. The solubility curve used was empirically determined by Siljberg (2012) and is given in equation 12, where $C_{ws}(T)$ is the solubility limit of wax in oil given in wt-%.

$$C_{ws}(T) = 0.0007T^2 + 0.00989T + 1.7706 \quad (12)$$

Table 1: Oil properties used in simulation

Oil Property	Unit	Value
Cloud point temperature	$^{\circ}C$	40
Inlet temperature	$^{\circ}C$	50
External temperature	$^{\circ}C$	4
Overall heat transfer Coeficient	W/m^2K	3
Wax content	%	8.5
Viscosity at T_{cloud}	$mPa.s$	50
Specific mass	kg/m^3	750
Flow rate	m^3/s	3.65×10^{-2}
Specific heat	J/kgK	2300
Latent heat	J/kg	23000
Thermal conductivity	W/mK	0.1

5. RESULTS

5.1 Wax Deposition

In this section, results are shown for a two-thousand-meter long pipe with oil flow in laminar regime. Figure 2 shows a concentration gradient generated at the wall due to the change in boundary condition once T_{cloud} is reached. Physically,

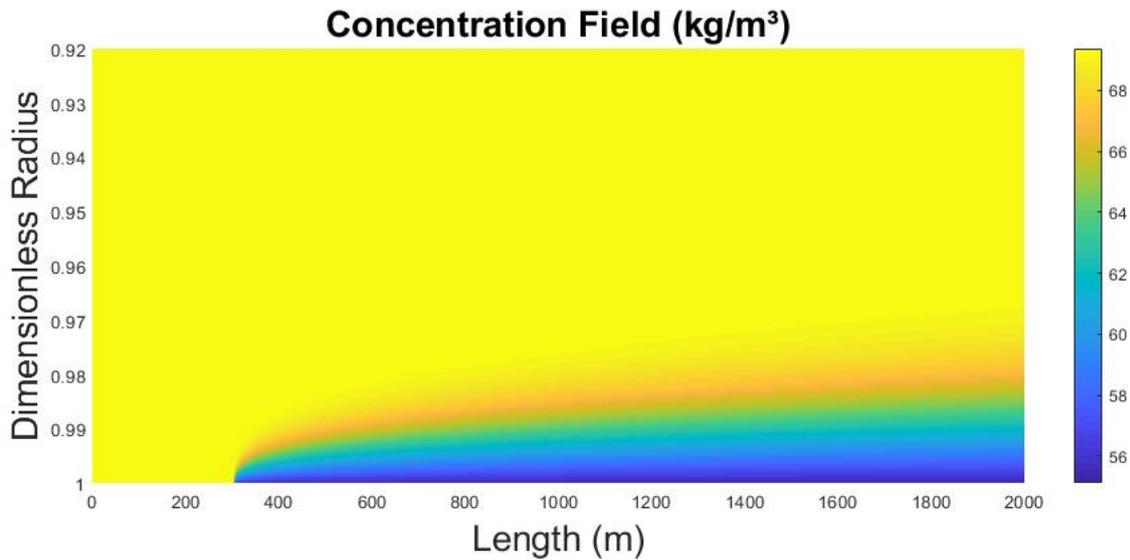


Figure 2: Concentration Field near the wall.

this change represents the precipitation of wax particles near the wall, driving the local concentration towards the solubility limit.

For model validation purposes, a comparison has been done between this work and the experimental results of Singh *et al.* (2000) and Huang *et al.* (2011). The results are shown in figure 3. The variables have been made dimensionless for comparison, since the experiments and the simulation involved have different input parameters. The τ parameter used in the time scale is the characteristic time of an exponential decay, calculated as the time necessary for the deposit thickness to reach 63.2% of its maximum value.

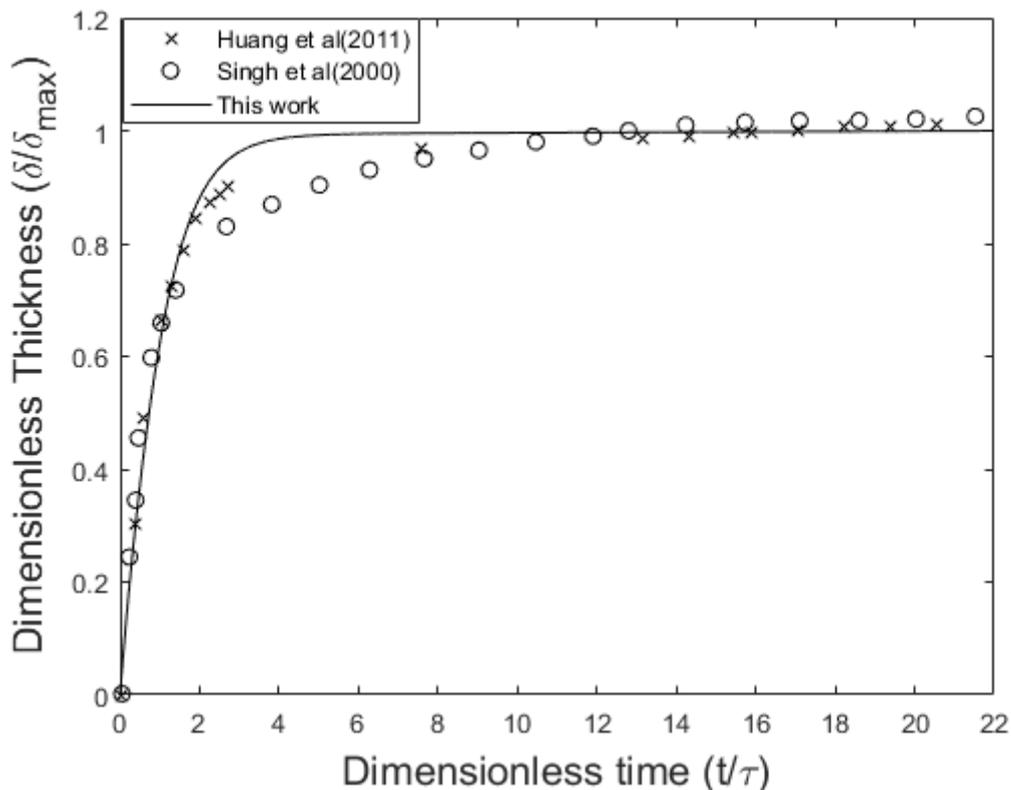


Figure 3: Deposit thickness as a function of time. Comparison with experimental data from studies of Huang *et al.* (2011) and Singh *et al.* (2000)

Figure 4(a) shows the thickness profiles of the deposit along the length of the pipe. After 47 days of growth, the deposit

reached it's maximum size. This occurs due to the fact that there can be no solid wax above the cloud point temperature. As the deposit grows, the interface temperature increases due to the increase of thermal insulation provided by the wax layer(see Fig. 4(b)). This temperature eventually reaches the cloud point, causing the deposition to cease.

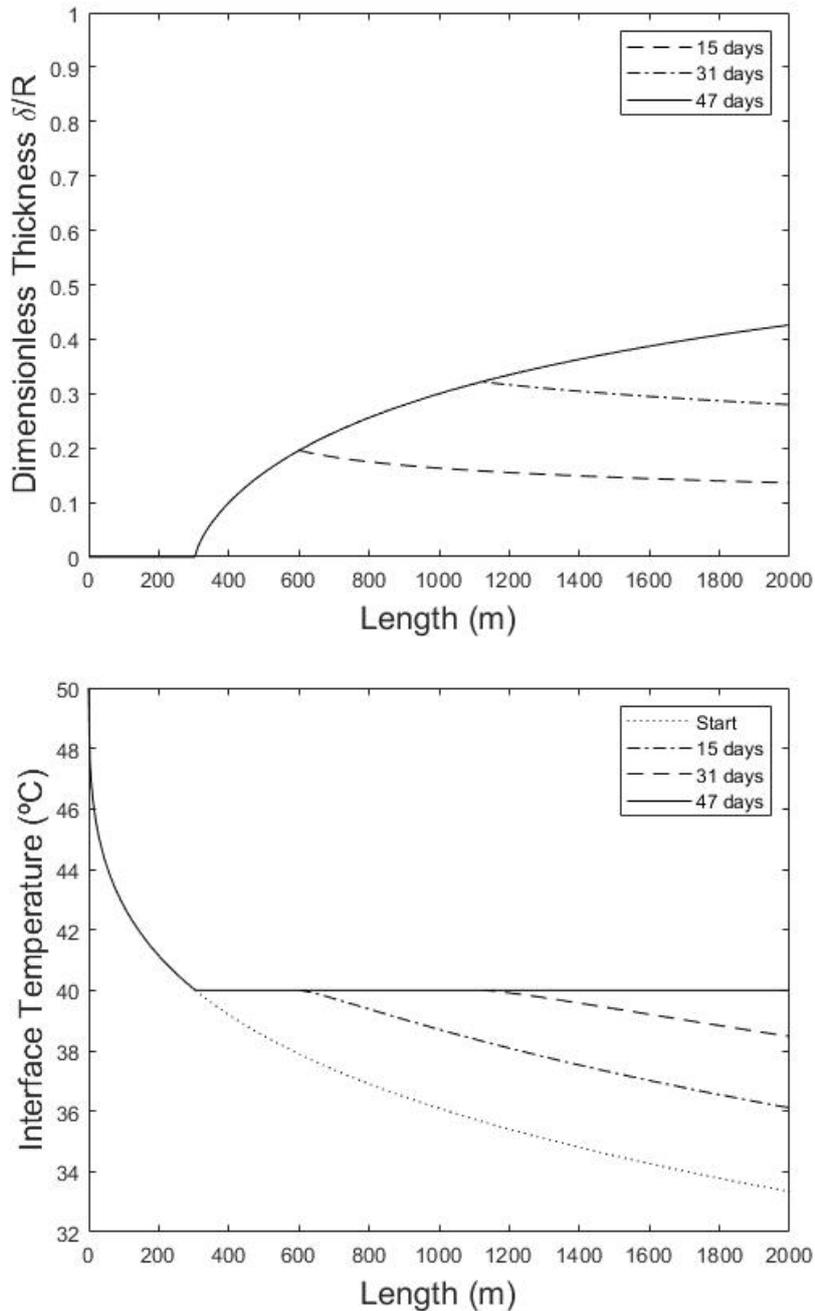


Figure 4: (a)Predictions of the wax deposit thickness profile in a pipeline for different periods of time, (b)Interface temperature versus pipe length for different periods of time

The aging process, on the other hand, goes on uninterrupted as it can be seen in Fig. 5. The wax fraction of the deposit is directly related to it's mechanical resistance and therefore is an important parameter for scheduling interventions, especially pigging. From Fig. 5 it can be noted that the closer to the inlet, the faster the deposit ages. This happens due to the fact that a smaller thickness will result in a quicker increase of the wax fraction, as it can be concluded from equation 3. The physical explanation for faster aging rates where the deposit is thinner is that there will be a smaller volume to absorb the wax incoming through the interface, and therefore the thinner the deposit section is, the bigger the impact on wax fraction caused by a given mass flux.

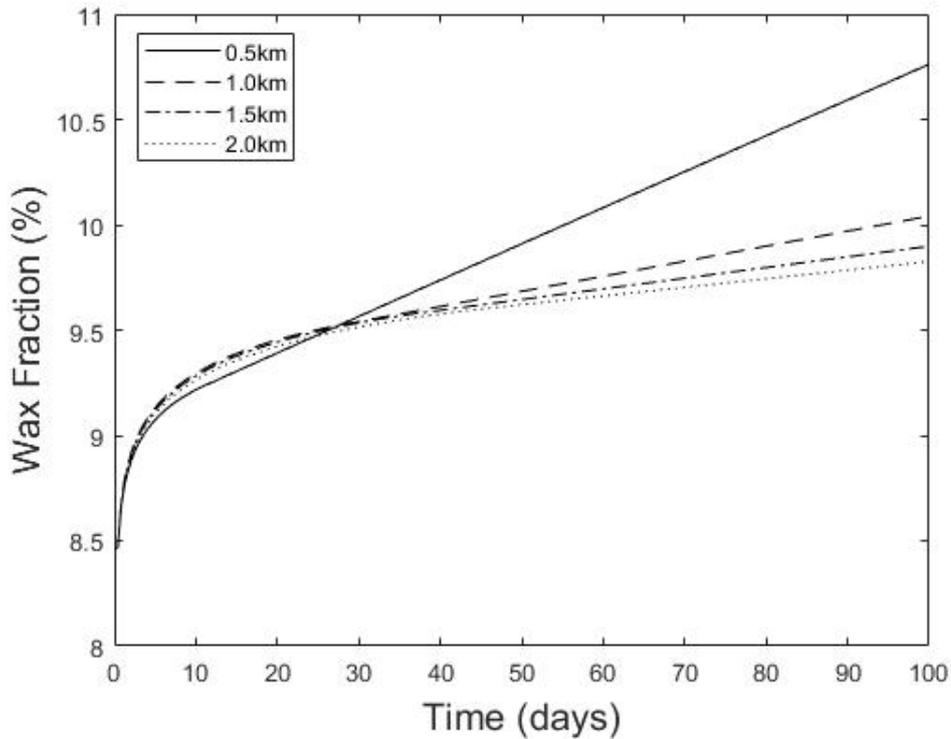


Figure 5: Predictions of the wax fraction of the deposit for different cross sections along the pipeline

5.2 Wax Removal Through Electrical Heating

After the deposit has reached its maximum size, electrical heating is turned on. The walls at the first 200 meters of pipeline are supplied with 300 kilowatts distributed evenly in length and around cross section. The result, as seen in Fig. 6, is an increase in the temperature along the entire pipe length, especially in the vicinities of the wax-oil interface.

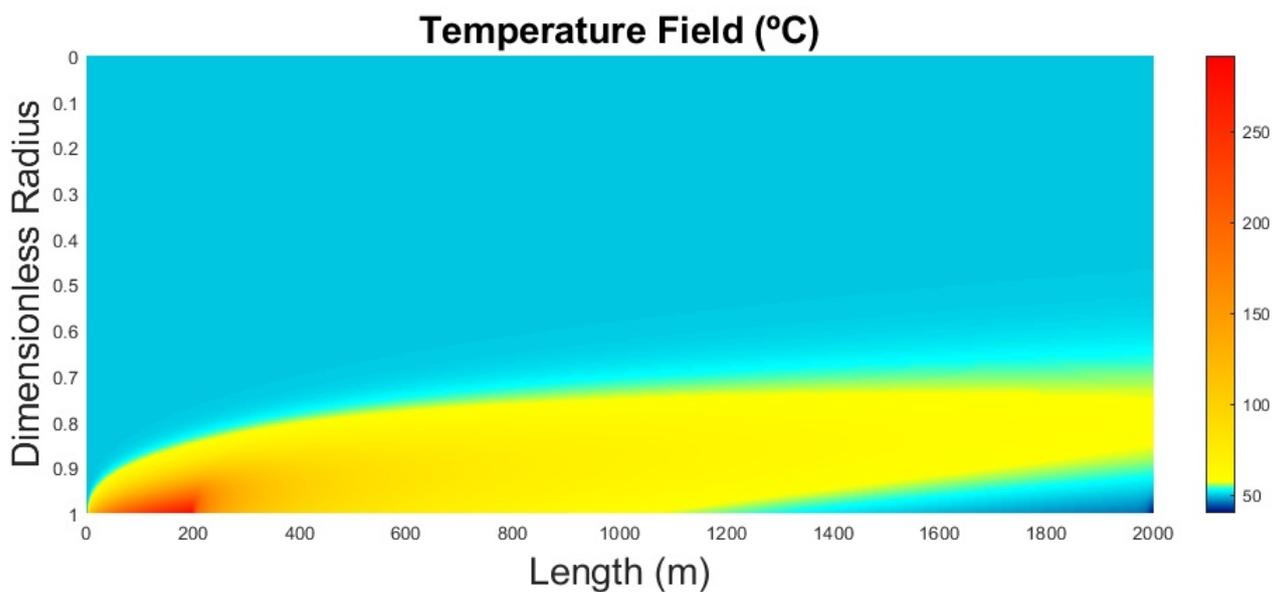


Figure 6: Temperature field during removal through electrical heating

Figure 7 shows the successive wax thickness profiles during the removal procedure through heating. The total removal time was of approximately two hours.

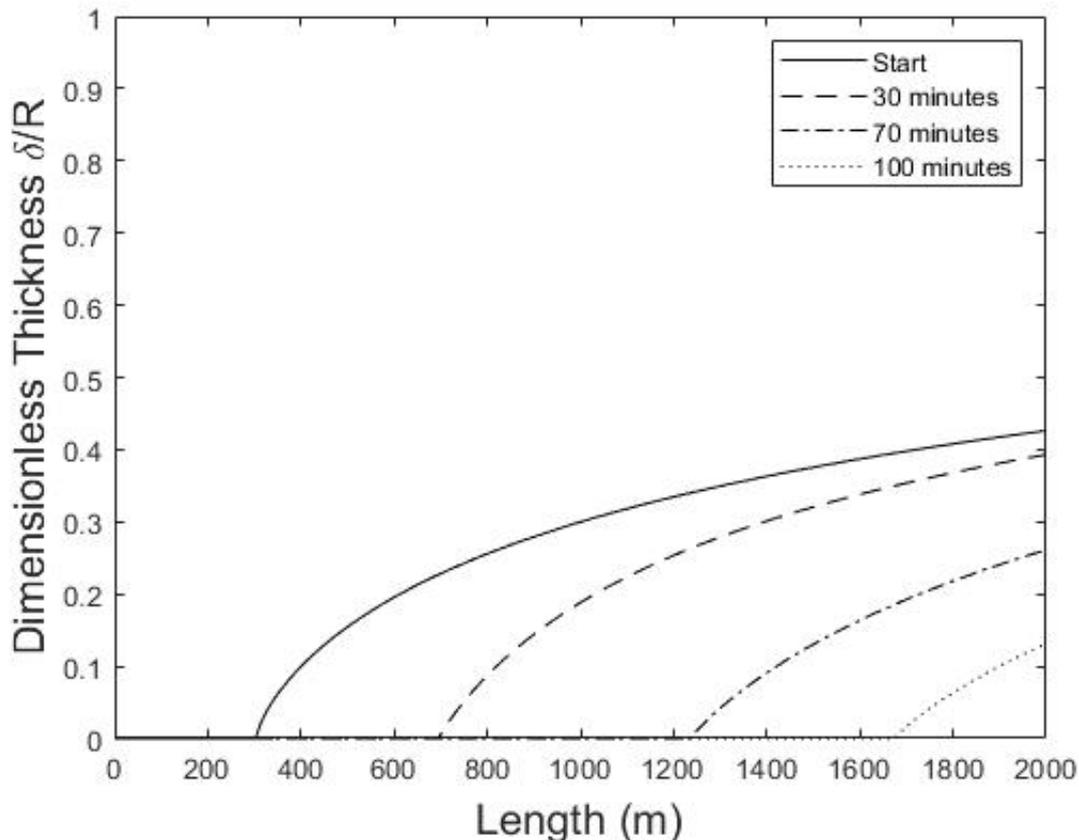


Figure 7: Time progression of the wax thickness profile during removal through electrical heating

6. CONCLUSION REMARKS

A wax deposition and removal model has been developed for laminar flow regime. For the deposition rates, the model has shown good qualitative agreement with experiments from other researches. Unfortunately, for the removal process, no experimental data was available for comparison.

Simulations suggest that it would be viable to remotely remove wax from short-distance oil pipelines without any aid from support vessels, divers or ROVs. A pressure down-pipe gauge (PDG) could be used to monitor the pressure drop across the line and make a closed-loop control system to determine the time and duration of heating. In the case of very long lines, this removal technique may be used to postpone pigging interventions, which are considerably more expensive, since they require the oil production to be interrupted.

This model was developed under the assumption of constant flow rate. In a real situation, this could be achieved through an actively controlled pumping system. If that would be the case, because of the large difference in time-scale between the deposition and removal stages, it is highly likely that the pumping energy would be the most relevant parameter for determining the periodicity and duration of heating cycles.

The present model may be used to determine the minimum necessary electrical power in order to guarantee the complete removal of wax layers, given the fluid characteristics, pipeline dimensions and heat exchange coefficients. In the case of flexible pipelines, which are composed of several polymeric layers, a viability study may be required to assure the integrity of all layers during the heating procedure.

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