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APPLICATION OF A PHENOMENOLOGICAL MODEL FOR THE PREDICTION OF THE THICKNESS AND POSITION OF PARAFFIN DEPOSITS OF LIGHT CRUDE OIL IN PRODUCTION PIPE

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ABSTRACT

Wax deposition is an important problem in the petroleum industry because it may cause obstruction in well bores, production facilities and transportation pipelines during production. To control or avoid this problem it is necessary to predict the formation of these deposits under different operational conditions. In this work is presented an implementation of a deposition model proposed by Singh *et al.*, (2000) and applied to a highly paraffinic Colombian crude. Solution was carried out using a CFD code and the analysis considers the behavior of operational variables like: flow rate, wall temperature and time of deposition.

INTRODUCTION

Wax deposition over the internal surface of pipelines is common during oil transportation under the sea, where temperatures are around 4°C. In this case, wax deposition is caused by low temperatures that lead the decreasing of the solubility of the paraffin in the crude mixture. However, it has also seen that some crude oil with high paraffinic content undergoes a decrease on the solubility under less severe conditions of temperature. However, in order to reduce or control the deposition phenomenon, it is necessary to predict the effect of operational variables and the physical and chemical properties of oil over the paraffin deposition.

This study will use the model proposed by Singh *et al.,* (2000) which has been validated experimentally and cited recently by Huang *et al.,* (2011) and Lu *et al.,* (2012) In their model, they consider mass diffusion as the only transport mechanism for paraffin and, therefore responsible in the formation of deposits in the pipes for a laminar flow regime. Herein, this model was applied for a particular case using a sample of highly paraffinic oil from an oil field in Colombia with API gravity between 30 and 42.

The model solution is based on mass and energy balances of the fluid and wax deposit phases. These balances are coupled through with the interfacial mass balance, which takes into account the movement of the interface generated by the deposition of wax. The application of this model requires the characterization of crude oil in study in order to obtain both the physical properties and the curve of solubility of paraffinic in oil as a function of temperature, which are fundamental parameters in the model.

The aim of this work was to study the wax deposition process and the influence of parameters such as the flow rate and wall temperature of the pipe over the deposit thickness for light crude oil with high paraffinic content by implementing the model of Singh *et al.,* (2000). Pseudo steady conditions in the fluid phase are assumed during the analysis. The Finite Differences method was applied to solve the differential equation system and the solution was implemented numerically using the language programming C++. The model was validated with the experimental results reported by Singh *et al.,* 2000 and posteriorly used to simulate the growth of the deposit as a function of flow rate. The results of this study confirm the importance of this last parameter in the paraffinic deposition under assumptions made in this model.

NOMENCLATURE

C	[kg/m^3]	Wax concentration
C_b	[kg/m^3]	Bulk concentration of wax
C_p	[J/kg °C]	Allowable volumetric heat generation density increase
C_{wall}	[kg/m^3]	Wax concentration
D_{eff}	[m^2/s]	Effective diffusivity

D_{wo}	[m^2/s]	Molecular diffusivity of wax in oil
F_w	[-]	Wax fraction in the deposit
k	[W/m °C]	Thermal conductivity
k_M	[m/s]	Convective mass transfer coefficient
L	[m]	Pipe length
R	[m]	Radius of pipe
r	[m]	Radial coordinate
r_i	[m]	Effective radius of a pipe
T	[°C]	Temperature
v_z	[m/s]	Axial velocity
α_T	[m^2/s]	Thermal diffusivity
ρ	[kg/m^3]	Density of oil
ρ_{gel}	[kg/m^3]	Density of wax deposit

PHENOMENOLOGICAL DESCRIPTION OF THE MODEL

DEPOSITION MECHANISM

As before mentioned, the mechanism described below was proposed by Singh et al., (2000) and has been accepted by different authors and experimentally validated. In this, it is assumed that when a mixture of paraffinic crude contacts a surface with lower temperature than the crude, the layer nearest to the wall lose heat and the temperature decreases rapidly reaching the limit of solubility of the mixture and form a incipient gel layer over the cool surface.

When geometry is cylindrical, as in the production pipes, the temperature difference between the fluid and the wall generates a temperature gradient in radial direction. This results in a concentration gradient in the same direction due to the dependence of the wax solubility with the temperature, which allows mass transport through the fluid-gel interface.

Once paraffin is transported to the interface, it continues a diffusion process trough the gel layer, increasing the wax concentration in the deposit. Nevertheless, paraffin is not completely transported to the deposit, part of this is accumulated over the interface, allowing the growth of the deposit, as is shown in Figure 1.

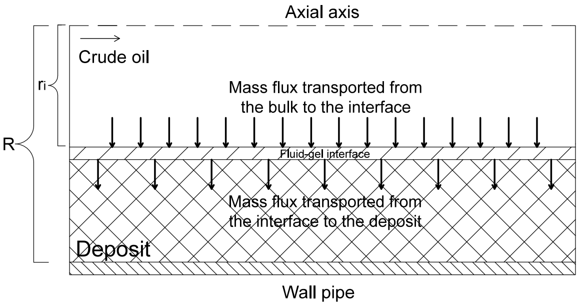

Figure 1 Deposition mechanism proposed by Singh *et al.* (2000) In this R is the inner radius of the pipe, r is the radial coordinate.

DEPOSITION MODEL

The phenomenological formulation of paraffin deposition in pipes must take into account the thermodynamic nature of the problem and the moving boundary established between the gel layer and the crude. In order to solve this problem is necessary to propose a mass and energy balances in the fluid and deposit. In case of fluid, has been proposed the energy (Eq. 1) and mass (Eq. 2) balances, assuming diffusion in radial coordinate and convection in axial direction.

$$v_z\frac{\partial T}{\partial z} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\alpha_T\frac{\partial T}{\partial r}\right) \tag{1}$$

$$v_z\frac{\partial C}{\partial z} = \frac{1}{r}\frac{\partial}{\partial r}\left(rD_{wo}\frac{\partial C}{\partial r}\right) \tag{2}$$

Where α_T is the thermal diffusivity and D_{wo} is the diffusivity of wax in the oil.

Boundary conditions for Eqs. 1 and 2 are shown as follows:

$$T(r, z = 0) = T_{in}, \tag{3}$$

$$\left.\frac{\partial T}{\partial r}\right|_{r=0} = 0, \tag{4}$$

$$T(r = R, z) = T_{wall}, \tag{5}$$

$$C(r, z = 0) = C_{in}, \tag{6}$$

$$\left.\frac{\partial C}{\partial r}\right|_{r=0} = 0, \tag{7}$$

$$C = C_{ws}(T); \qquad r_i \le r \le R. \tag{8}$$

Analysis of the paraffin deposit takes molecular diffusion as the dominant mechanism of diffusion of the wax within this; therefore, the mass transport within the deposit contributes to the increase of the wax fraction and the increase of the deposit thickness.

On the other hand, the radial temperature gradient in the pipe, results in a concentration gradient of paraffin in the oil mixture due to the dependence of the solubility of the wax with temperature. This makes that paraffin concentration in the center of the pipe greater than on the wall and generates a flux of paraffin molecules in radial direction transported to the wall. This flux is determined by assuming that in the deposit the convective transport is negligible and that the diffusive transport of wax can be approximated by the diffusive transport of wax in the fluid phase evaluated on the interface (Eq. 9).

$$\pi\rho_{gel}\left(R^2 - r_i^2\right)L\frac{dF_w}{dt} = 2\pi r_i L\left(-D_e\left.\frac{dC_{ws}}{dr}\right|_{r_i}\right). \tag{9}$$

In Eq. (9), R is the inner radius of the pipe, r is the radial coordinate, r_i is the deposit thickness, F_w the mass fraction of the gel, L is the length of the pipe, ρ_{gel} is the wax density, C_{ws} is the paraffin solubility in the oil and D_e is the effective diffusivity in the deposit as given by Cussler *et al*. (Eq. 10)

$$D_e = \frac{D_{wo}}{1 + \alpha^2{F_w}^2/(1 - F_w)}, \tag{10}$$

where α is the aspect ratio of the wax crystals in the deposit, D_{wo} is the molecular diffusivity of wax in oil and was given by Hayduk and Minhas (1982)

$$D_{wo} = 13.3\times10^{-8}\left(\frac{T^{1.47}\mu^{\gamma}}{V_A^{\,0.71}}\right) \tag{11}$$

$$\gamma = \frac{10.2}{V_A} - 0.791 \tag{12}$$

Where T is absolute temperature, μ is solvent viscosity, V_A is the molar volume of the wax, and V_A is a function of V_A. The calculation was reported by Lee (2007)

Regarding the interface, Singh et al., obtained an interfacial balance of wax, which is showed in the following equation

$$2\pi r_i F_w(t)\rho_{gel}\frac{dr_i}{dt} = 2\pi r_i k_l[C_{wb} - C_{ws}(T_i)] - 2\pi r_i\left(-D_e\frac{dC_{ws}}{dr}\bigg|_{r_i}\right) \tag{13}$$

In before equation, k_l is the convective mass transfer coefficient and C_{wb} is the bulk concentration of wax molecules. Eq. 13, implies that the growth speed of the deposit is determined by the difference between the wax flux normal to the interface in the deposit and the fluid phase, evaluated at the interface.

Table 1. Physical properties and operational conditions

Parameter	Value
Inner pipe radius	0.036[m]
Pipe length	665 [m]
Inlet temperature	41.2 [°C]
Wall temperature	15 [°C]
WAT	24 [°C]
Average flow velocity	0.0017 [m/s]
Heat capacity of oil	2300 [J/kg K]
Density of wax	787 [kg/m^3]
Density of oil	787 [kg/m^3]
Thermal conductivity of oil	0.1 [W/m K]
Thermal conductivity of wax	0.25 [W/m K]
Time step	60 [s]

ASUMPTIONS

The fluid is assumed to be Newtonian and incompressible while density of wax is assumed to be equal to the oil. This model applies for pipelines where there is no thermal energy generation in the fluid.

The maximum amount of wax dissolved in solution is determined by the WAT and the solubility function. Above the WAT the flow is single-phase and below it is a two-phase mixture of liquid oil and solid wax. No water content and no gas rate in the pipeline are assumed. The surrounding temperature is assumed to hold constant and the solid wax content in the deposit is assumed to increase with time.

PARAMETERS

Physical properties of a crude oil mixture used in this paper and operational conditions are shown in Table 1. Figure 2 shows the solubility curve of paraffin in the crude as function of temperature obtained by DSC technique according to the ASTM D 4419-90 (2010)

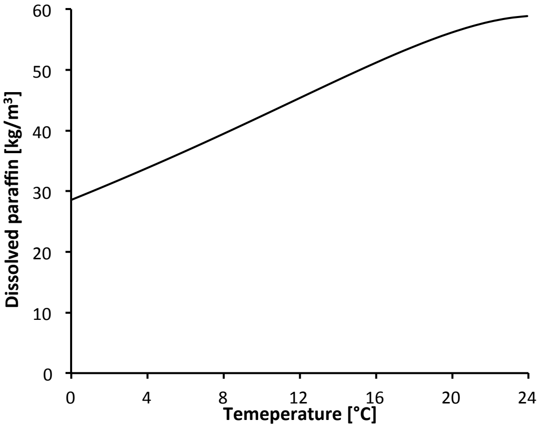

Figure 2 Solubility curve used in this study

NUMERICAL SOLUTION

In order to obtain the temperature and concentration distribution in the fluid phase, was implemented the finite volume method to solve Eqs. 1 and 2, while Eqs. 9 and 13 were integrated in time. A computer code in C++ language was developed, and the program flow chart is shown in Figure 3. The following algorithm was used to solve the wax deposition model:

1. Solve Eqs. 1 and 2 to get temperature and concentration profiles.
2. Calculate Sherwood number in order to obtain the convective mass transfer coefficient on each element in the dominium.
3. Integrate equations 9 and 13 to get new deposit thickness and wax fraction.
4. Repeat 1 to 3 until time reaches the final time.

RESULTS AND DISCUSSION

In order to show the behavior of deposit thickness and wax fraction is presented the figure4. There is seen how is reduced the effective radius (r_i/R) and incremented the wax fraction in to the deposit during deposition. Both starts whit a high rate and tend to keep constant with time. The case of study shows that after 20 days of deposition the inner radius of pipe has been saturated almost 2.5% (r_i/R = 0.95) while, the wax mass fraction reaches 0.21 of paraffin inside the deposit.

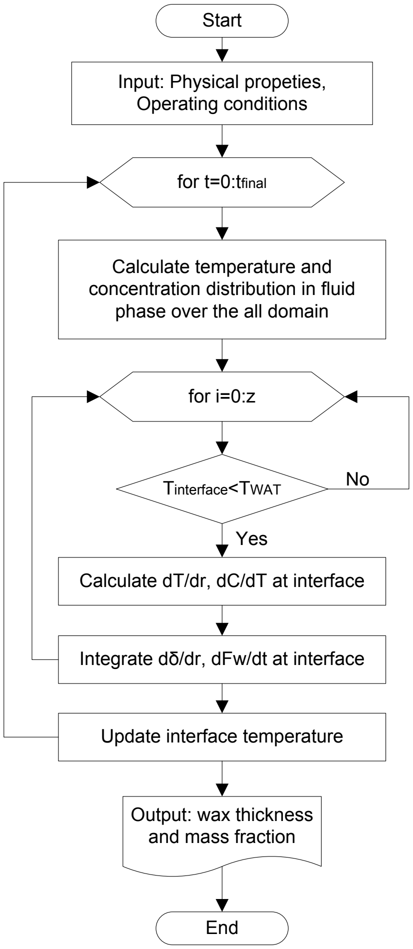

Figure 3. Program flow chart used to calculate the wax thickness and mass fraction.

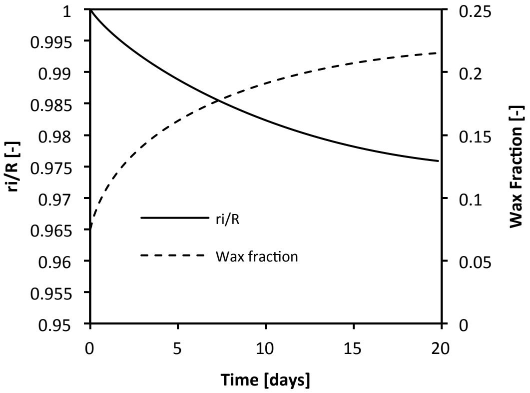

Figure 4. Wax deposit growth and wax fraction change at a fixed axial distance of the pipe.

Figure 5 compares the deposit thickness at different deposition times. Calculations were carried out during 4 different deposition times, 1, 5, 10 and 20 days keeping constant the rest of parameters. As was expected, if the time deposition is higher the deposit is bigger. In figure can be observed how the deposition starts form the entrance of the pipe because the wall temperature is lower that the wax appearance temperature (WAT) In addition, when the crude flows trough the pipe, the temperature decrease until reach the wall temperature, vanishing the thermal gradient and consequently the deposition stops in this region of the pipe.

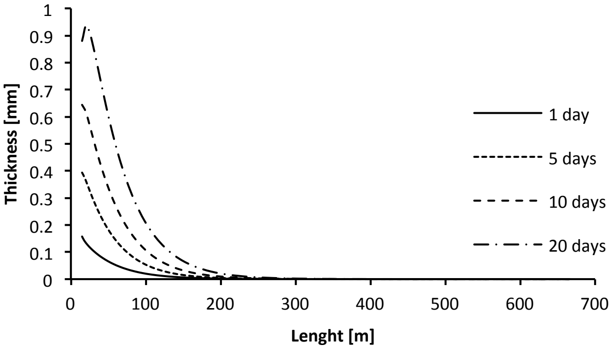

Figure 5. Axial thickness profiles at different deposition times.

Figure 6 shows the deposit thickness at different delta of temperature between the wall temperature and the inlet temperature keeping constant other parameters. In this case, when the thermal gradient in radial direction between the crude and wall temperature is higher the deposit thickness is bigger. In this case, when ΔT=31°C the deposit gets bigger rather than in other cases.

When the flow rate is increased, one and a half and two times the used in this study, the maximum deposit thickness decreases. However, it spreads in a major part of the pipe increasing the deposit as is shown in Figure 7. The flow rate has a direct influence over the bulk temperature and this at the same time on the heat transfer. Hence, if the flow rate is increased, the changes of temperature in the fluid are present in a longer distance in the pipe.

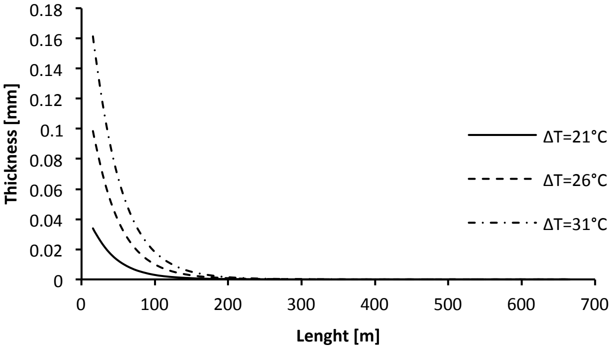

Figure 6. Axial thickness profiles at various wall temperatures.

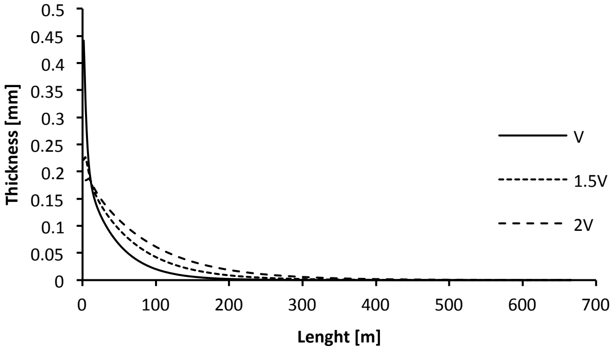

Figure 7. Axial thickness profiles at different flow rates.

CONCLUSIONS

In this work, has been implemented the wax deposition model proposed by Singh et al. (2000) and applied to a paraffinic Colombian crude. The effect of operational conditions such as flow rate; deposition time and wall temperature of the pipe was evaluated over the deposit thickness. The results showed that the increase of the flow rate reduce the deposit thickness but spread it over a longer distance in the pipe. Moreover if the wall temperature is increased the thickness is reduced as the thermal gradient does in the fluid. Finally is evident that if the deposition time is increased the deposit grows as was expected. Finally, implementation of the Singh *et al.* model, or others more complex, shows to be useful in the prediction of the paraffin deposition severity, as well as in the implementation of preventive techniques.

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