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Waxy crude oil transportation in Gulf-sirt offshore field.

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الملخص :

يُذكَر في هذه الورقة نقل النفط الخام في خطوط الانابيب التي تربط المنصات في مشروع خليج سرت البحري. حيث يؤدي ترسب الشمع (وهو في حالته الصلبة) في جدار الأنبوب الى حدوث خلل في الضغط والذي بدوره يسبب انسدادا اصطناعيا يؤدي الى انخفاض او انقطاع في الانتاج.

حيث يمكن ان يترسب الشمع وهو في الحالة الصلبة على جدار الأنبوب عندما تنخفض درجة حرارته إلى درجة اقل ،فيما يعرف (WAT) .

يهدف هذا العمل الى دراسة عملية ترسيب الشمع على السطح الداخلي لأنابيب إنتاج النفط وتأثيره على معاملات مثل معدل التدفق ، درجة حرارة جدار الأنبوب ، خط الأنابيب المعزول ، وتأثير تكوين النفط الخام ودرجات حرارة مياه البحر على سماكة الرواسب .

تم إجراء التحليل على افتراض وجود محاكاة على طور المائع وتم تنفيذ ذلك عدديا باستخدام برمجة MATLAB.

أظهرت النتائج ان زيادة معدلات التدفق تقلل من سماكة الرواسب القصوى ، ومنع العزل المزيد من الترسبات الصلبة ،كما أظهرت (WAT) أعلى سماكة أكثر للرواسب وانخفاض كمية المواد الصلبة المترسبة مع زيادة في درجة حرارة الزيت الخام او درجة حرارة مياه البحر حيث ينتشر على مسافة اطول في الانبوب معتبرين ان درجة حرارة الجدار ثابتة او تدرج حراري محوري مع ميل موجب ، ويلاحظ التأثير المعاكس عند النظر الى التدرج الحراري المحوري ذي المنحدر السالب .

Abstract:

Crude oil transportation in the pipe lines connecting platforms at projected offshore Gulf-Sirt project is assumed in this paper. The precipitation of the solid phase of wax in the pipe wall creates pressure abnormalities and causing an artificial blockages leading to a reduction or interruption in the production. Wax can precipitate as a solid phase on the pipe wall when its temperature drops below the appearance temperature (WAT).

This work is aimed to study the wax deposition process on the internal surface of oil production pipelines and the influence of parameters such as flow rate, pipe wall temperature, Insulated Pipeline, Effect of Crude-Oil Composition (or WAT), Effect of Crude-Oil and Seawater Temperatures on the deposit thickness.

The analysis was conducted assuming pseudo steady conditions on the fluid phase, the solution was implemented numerically using the MATLAB PROGRAMMING. The results showed that increased flow rates reduce the maximum deposit thickness, insulation preventing further solids deposition, The higher WAT gave a larger deposit thickness, reduction in the amount of deposited solids with an increase in either the crude-oil temperature or the seawater temperature, as it spreads on a longer distance in the pipe when considering a constant wall temperature or the axial thermal gradient with a positive slope, and the opposite effect is observed when considering the axial thermal gradient with a negative slope.

Key words : Waxy crude oil, MATLAB PROGRAMMING, wax deposition, crude oil transportation .

Introduction:

When a liquid flowing through a pipeline is exposed to a cold environment that is below its freezing-point temperature (or solubility temperature), solids deposition on the pipe wall is likely to occur. This phenomenon takes place frequently during the transportation of “waxy” crude oils that contain high-molecular-weight alkanes or paraffin waxes. Paraffin waxes have a reduced solubility in crude oils at lower temperatures, causing their crystallization and deposition on cooler surfaces.

The adverse effects of wax deposition are encountered in all sectors of the petroleum industry, ranging from oil reservoir formations to blockage of pipelines and process equipment. The deposited wax impedes the flow of oil through the pipeline, causing an increase in the pumping power. If not controlled adequately, the deposited solids may block the pipeline, resulting in high costs for its cleaning. Remediation can be carried out using mechanical cleaning methods, chemical cleaning methods, or by heating to melt the deposit.

Theoretical Formulation :

Consider a long pipeline carrying a “waxy” mixture that is completely immersed in water at a constant temperature (T_c). This is similar to the transportation of waxy crude oils through sub-sea pipelines from offshore wells. Heat transfer to the surrounding “colder” seawater would decrease the crude-oil temperature (T_h), which could lead to the precipitation and deposition of paraffin solids on the pipe wall. As mentioned above, wax crystals would form a deposit layer comprising a solid (wax) phase with immobile liquid oil trapped within it. With time, the deposit layer would grow in thickness until such time that its growth does not occur any more. At this point, the rates of heat transfer across the flowing oil, the wax deposit layer, and the pipe wall would be the same and remain constant with time. When this happens, the thickness of the deposit as well as the oil and wall temperature would each attain a constant value. Once the deposit layer achieves a constant layer thickness, the rate of heat transfer can be assumed to be under a thermal steady state because of the stable temperatures.

As shown schematically with radial temperature profiles in **Fig .1**, the transfer of thermal energy from the “hot” fluid (the flowing crude oil) to the “cold” fluid (the surrounding seawater) at steady state involves four thermal resistances in series: two convective resistances due to the flowing crude oil and the seawater and two conductive resistances offered by the pipe wall and the deposited layer.

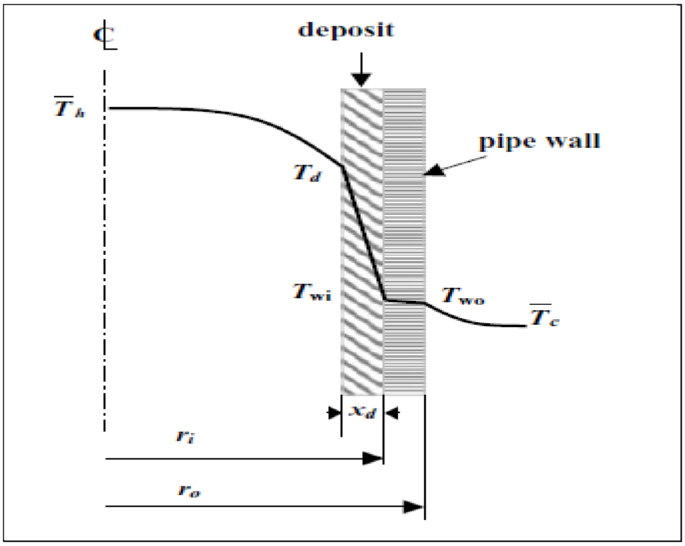

Figure 1. radial temperature profiles through the various thermal resistances.

Assuming one-dimensional heat transfer in the radial direction of the pipe, the rate of heat transfer could be equated to the rate of thermal energy lost by the hot waxy crude oil, the rate of thermal energy gained by the cold seawater, and the rate of heat exchange between hot and cold fluids, as follows:

$$q = \dot{m}_h C_h (T_{h\ in} - T_{h\ out}) = \dot{m}_c C_c (T_{c\ out} - T_{c\ in}) = U_i A_i (\overline{T_h} - \overline{T}_c) \quad (1)$$

Where: q = rate of heat transfer.

$\dot{m}_h, \dot{m}_c$ = mass flow rates of “hot” and “cold” streams.

C_h, C_c = average specific-heat capacities of “hot” and “cold” streams.

$T_{h\ in}, T_{h\ out}$ = inlet and outlet “hot” stream temperatures.

$T_{c\ in}, T_{c\ out}$ = outlet and inlet “cold” stream temperatures.

U_i = overall heat-transfer coefficient based on inside pipe surface area (A_i).

$\overline{T_h}, \overline{T_c}$ = average temperatures of “hot” and “cold” streams, respectively.

The rate of heat transfer can also be equated to the heat flow across the two convective thermal resistances, as follows:

$$\mathbf{q = h_c A_c (T_{wo} - \overline{T_c}) = h_h A_h (\overline{T_h} - T_d)} \qquad (2)$$

Where: h_c, h_h = convective heat-transfer coefficients on outside and inside of the
pipe, respectively .
A_c = pipe outside surface area in contact with cold stream.
A_h = inside surface area at deposit-oil interface.
T_d = temperature at this interface.

Note that, for a clean pipe with no deposit, A_h would be replaced by (A_i) and (T_d) would become equal to(T_{wi}).

Next, the overall or combined thermal resistance is expressed as the sum of four individual thermal resistances:

$$\mathbf{\frac{1}{U_i A_i} = \frac{1}{h_h A_h} + \frac{\ln\left(\frac{r_o}{r_i}\right)}{2\pi k_m L} + \frac{\ln\left(\frac{r_i}{(r_i - x_d)}\right)}{2\pi k_d L} + \frac{1}{h_c A_c}} \qquad \textbf{(3)}$$

At steady state, the heat flux (i.e., the rate of heat transfer per unit inside pipe wall area) through each of the four thermal resistances included in Ui is as follows:

$$\mathbf{\frac{q}{A_i} = \frac{h_h(\overline{T_h} - T_d)}{\frac{r_i}{(r_i - x_d)}} = \frac{k_d(T_d - T_{wi})}{r_i \ln\left(\frac{r_i}{(r_i - x_d)}\right)} = \frac{k_m(T_{wi} - T_{wo})}{r_i \ln\left(\frac{r_o}{r_i}\right)} = \frac{h_c(T_{wo} - \overline{T_c})}{\frac{r_i}{r_o}}} \qquad \textbf{(4)}$$

Where x_d = deposit thickness (assumed to be uniform along pipe length).
T_{wi}, T_{wo} = average inside and outside pipe wall temperatures.

k_d, k_m = thermal conductivities of deposit layer and pipe wall, respectively.

When dealing with the solidification or melting of a pure substance, the liquid-deposit interface temperature (T_d) would be the melting or freezing temperature; however, it would be the liquids or saturation temperature for a multicomponent mixture. From a modeling study, Singh et al. **[1]** estimated (T_d) to approach the (WAT) of waxy mixtures when the deposit layer thickness stops growing, while Bidmus and Mehrotra **[2]** verified experimentally that (T_d) and WAT are the same temperature at pseudo-steady-state conditions. The mathematical relationships for heat transfer and energy balance presented above can be utilized for calculations dealing with solids deposition in a pipeline.

Determination of Deposit Thickness(x_d) at different Crude-oil flow rate:

"waxy" crude oil is produced and transported via a pipeline from an offshore oil production platform to an onshore refinery for processing. The crude oil has a (WAT) of 26°C. At the beginning of the operation, about 100000, 150000 and 200000 barrels of oil per day (bopd) at a temperature of 40°C leaves the offshore platform into the pipeline. After a few months of pipeline operation, it is observed that the pressure drop across the pipeline has increased considerably and that the crude oil arrives at the refinery at a temperature of 28°C, which has been found to be more or less constant for several days. The engineer managing the operation believes that the increased pressure drop is a result of solids deposition, and the deposit thickness needs to be estimated before deciding on a suitable remedial action. It can be assumed that the seawater at an average temperature of 10°C flows across (or normal to) the pipeline at an average velocity of 0.1 m/s. How could the deposit thickness be estimated from heat-transfer considerations Pertinent pipeline data as well as average crude-oil and seawater properties are listed in **Table 1**.

Table 1 Data and Average Properties Used in Calculations.

Property	Value
Crude oil:	
Flow rate(F)	100000, 200000 and 300000 bopd
Specific-heat capacity(C_h)	2400 J/kg K
Thermal conductivity(k_h)	0.15 W/m K
Viscosity(μ_h)	0.0514082 pa s
Density (ρ_h)	898.4 kg/m^3
Seawater:	
Specific-heat capacity (C_c)	4200 J/kg K
Thermal conductivity (k_c)	0.65 W/m K
Viscosity(μ_c)	0.001 pa s
Density(ρ_c)	1020 kg/m^3
Deposit:	
Thermal conductivity(k_d)	0.24 W/m K
Pipeline:	
Wall thermal conductivity (k_m)	24 W/m K
Inside diameter (D_i)	0.254 m
Wall thickness ($r_o - r_i$)	0.0159 m
Outside diameter (D_o)	0.286 m

Estimation of inside heat-transfer coefficient (h_h) : The average velocity of crude oil in the pipeline is:

$$\overline{u_h} = \frac{F}{A_i} = \frac{4F}{\pi {D_i}^2}$$

The Reynolds number of crude oil in the pipeline is:

$$R_e = \frac{\rho_h \overline{u_h} D_i}{\mu_h}$$

The Prandtl number is:

$$P_r = \frac{C_h \mu_h}{k_h}$$

Given that the flow is turbulent (Re > 4000) and assuming L/D_i to be large, the Holman correlation **[3]** can be used to estimate the average heat-transfer coefficient in the pipeline(h_h):

$$Nu = \frac{h_h D_i}{k_h} = 0.023\ Re^{0.8} Pr^{0.3}$$

Estimation of outside heat-transfer coefficient (h_c):

$$R_e = \frac{\rho_c \overline{u_c} D_o}{\mu_c}$$

$$P_r = \frac{C_c \mu_c}{k_c}$$

The Churchill-Bernstein equation **[4]** can be used to obtain the average heat-transfer coefficient for cross flow across a cylindrical surface:

$$Nu = \frac{h_c D_o}{k_c} = 0.3 + \frac{0.62 Re^{1/2} Pr^{1/3}}{\left[1 + \left(0.4/Pr\right)^{2/3}\right]^{1/4}} \left[1 + \left(\frac{Re}{282000}\right)^{5/8}\right]^{4/5}$$

Estimation of deposit thickness (x_d):

The average oil temperature is (T_h) = (40 + 28)/2 = 34°C. As already explained, the deposit-oil interface temperature (T_d) will be assumed to be equal to the (WAT) of 26°C. Therefore, using Eq. (4), we obtain:

$$\frac{h_h(\overline{T_h} - T_d)}{\frac{r_i}{(r_i - x_d)}} = \frac{k_d(T_d - T_{wi})}{r_i \ln\left(\frac{r_i}{(r_i - x_d)}\right)} = \frac{k_m(T_{wi} - T_{wo})}{r_i \ln\left(\frac{r_o}{r_i}\right)} = \frac{h_c(T_{wo} - \overline{T_c})}{\frac{r_i}{r_o}}$$

Solving these equalities simultaneously for (T_{wi}), Two, and (x_d).

The Case of Insulated Pipeline:

With an additional thermal resistance (due to insulation), Eq. (4) becomes:

$$\frac{h_h(\overline{T_h}-T_d)}{\frac{r_i}{(r_i-x_d)}}=\frac{k_d(T_d-T_{wi})}{r_i\ln\left(\frac{r_i}{(r_i-x_d)}\right)}=\frac{k_m(T_{wi}-T_{wo})}{r_i\ln\left(\frac{r_o}{r_i}\right)}=\frac{h_c(T_{ins}-\overline{T_c})}{\frac{r_i}{(r_i+x_{ins})}}=\frac{k_{ins}(T_{wo}-T_{ins})}{r_i\ln\left(\frac{r_o+x_{ins}}{(r_o)}\right)} \tag{5}$$

where (k_{ins}) and (x_{ins}) are the thermal conductivity and the thickness of the insulation material, respectively, and Tins is the temperature of the insulation material surface in contact with the seawater. Without any solids deposition (i.e., $x_d = 0$), $T_{wi} \geq T_d$. Equation (5),Azevedo , Teixeira**[5]**, therefore, becomes:

$$h_h(\overline{T_h}-T_{wi})=\frac{k_m(T_{wi}-T_{wo})}{r_i\ln\left(\frac{r_o}{r_i}\right)}=\frac{h_c(T_{ins}-\overline{T_c})}{\frac{r_i}{(r_i+x_{ins})}}=\frac{k_{ins}(T_{wo}-T_{ins})}{r_i\ln\left(\frac{r_o+x_{ins}}{(r_o)}\right)}$$

Effect of Crude-Oil Composition (WAT):

A change in the crude-oil composition will affect its (WAT). Basically, the waxier a crude oil is, the higher is its (WAT). The effect of wax composition will, therefore, be investigated by varying the (WAT).

Since crude-oil properties and other data (listed in Table1) as well as operating conditions are the same, the individual heat-transfer coefficients can be used. Equation (4) can be solved for (x_d) by substituting the given (WAT) values for the interface temperature (T_d).

Effect of Crude-Oil and Seawater Temperatures:

Using Eq. (4) with the same properties and heat-transfer coefficients, we get (x_d).

Results:

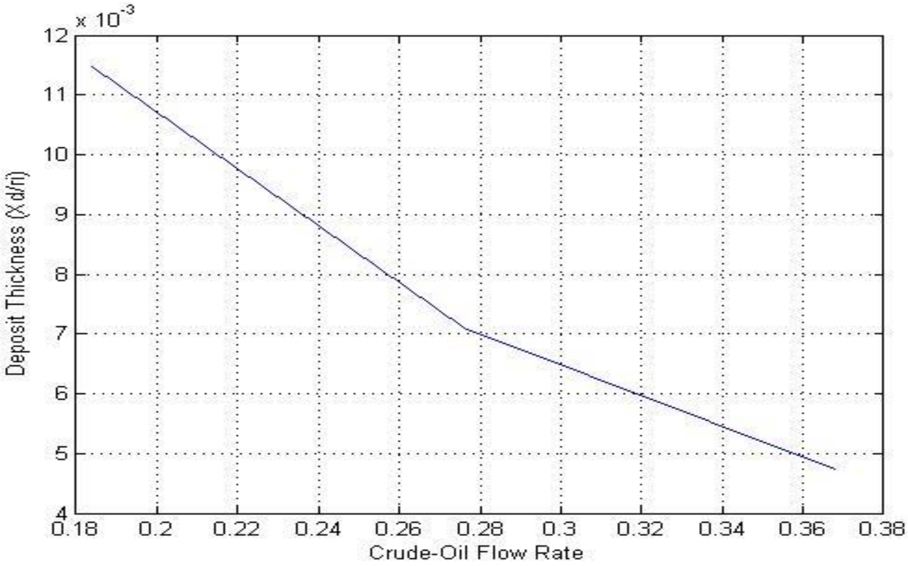

Figure 2. Effect of Crude-Oil Flow Rate on deposit thickness under similar operating conditions at 0.184 m^3/s.

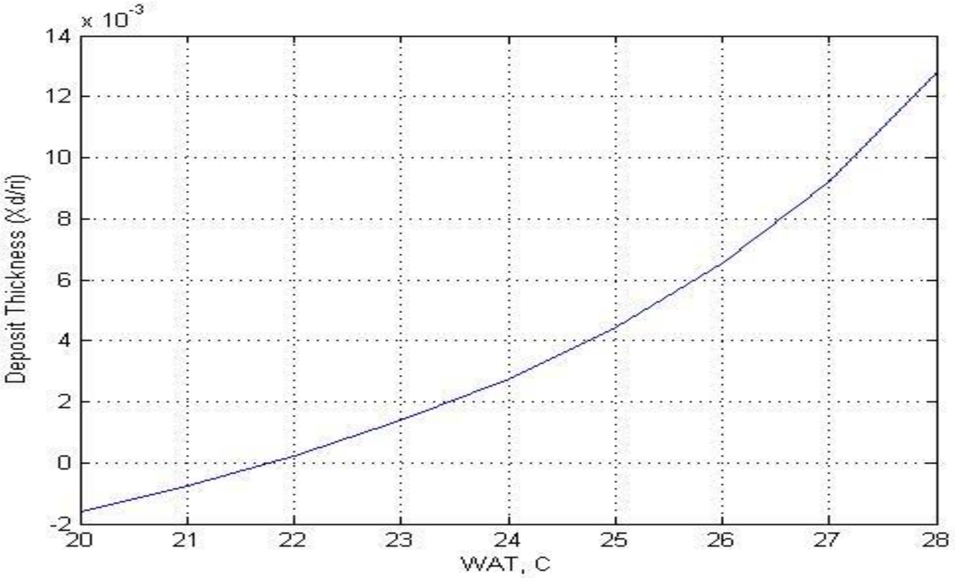

Figure 3. Effect of crude-oil WAT on deposit thickness under similar operating conditions at 0.184 m3/s.

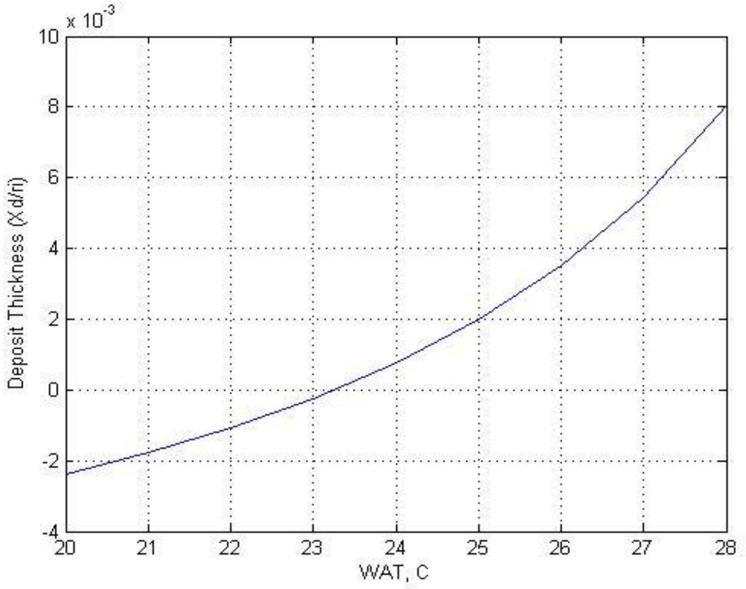

Figure 4. Effect of crude-oil WAT on deposit thickness under similar operating conditions at 0.276 m^3/s.

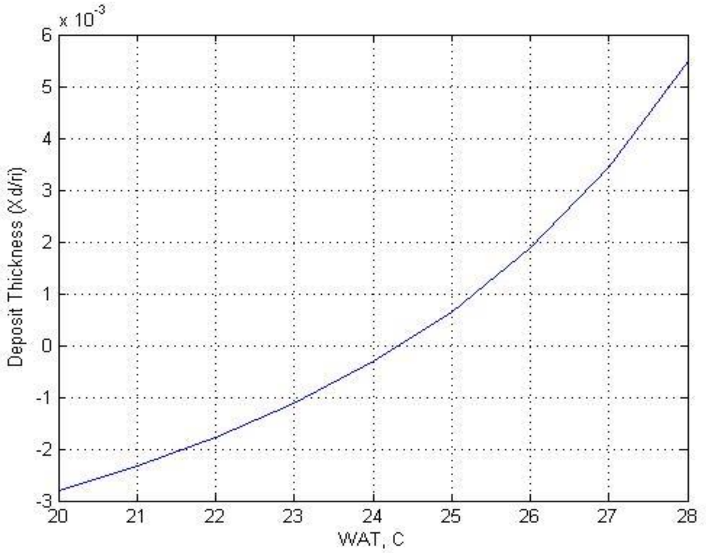

Figure 5. Effect of crude-oil WAT on deposit thickness under similar operating conditions at 0.368 m3/s.

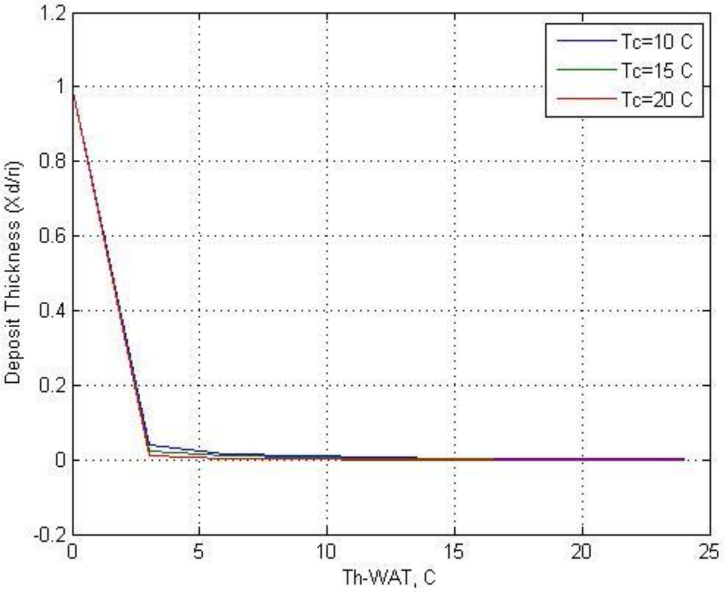

Figure 6. **Predicted variations in deposit thickness with crude-oil temperature at different seawater temperatures at 0.184 m^3/s.**

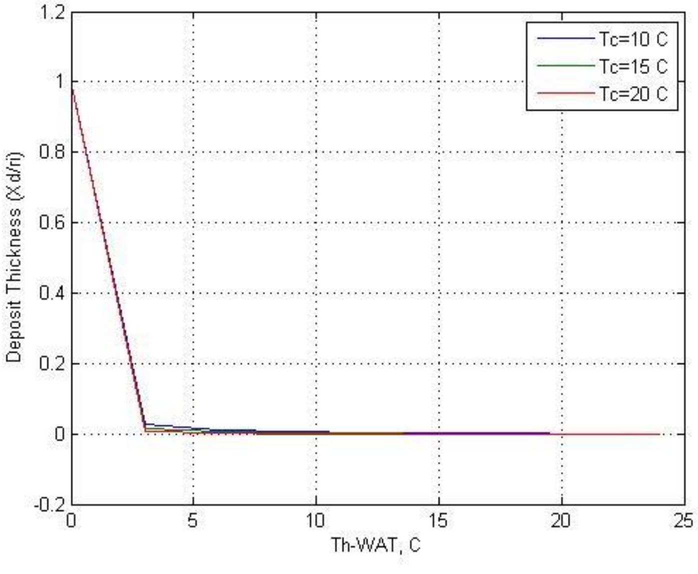

Figure 7. **Predicted variations in deposit thickness with crude-oil temperature at different seawater temperatures at 0.276 m^3/s.**

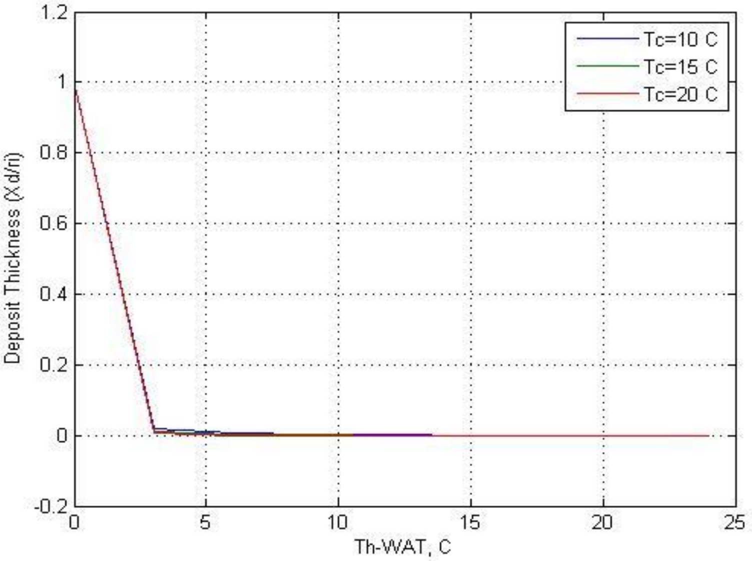

Figure 8. **Predicted variations in deposit thickness with crude-oil temperature at different seawater temperatures at 0.368 m^3/s.**

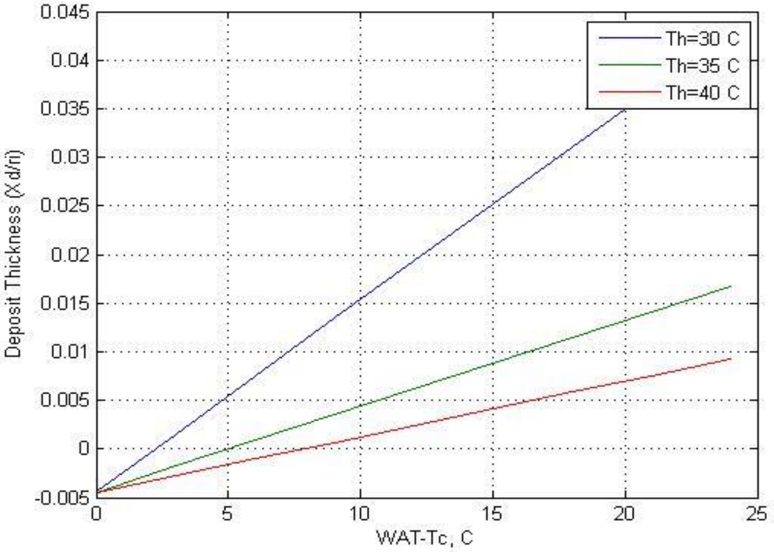

Figure 9. **Predicted variations in deposit thickness with seawater temperature at different crude-oil temperatures at 0.184 m^3/s.**

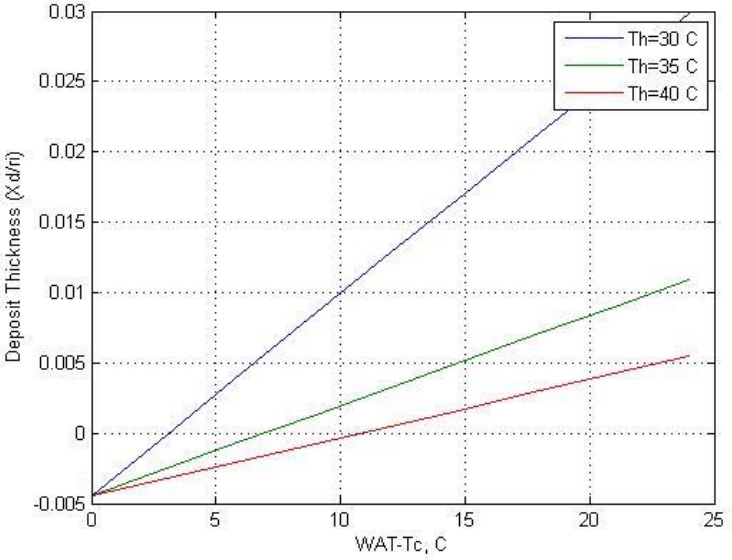

Figure 10. Predicted variations in deposit thickness with seawater temperature at different crude-oil temperatures at 0.276 m^3/s.

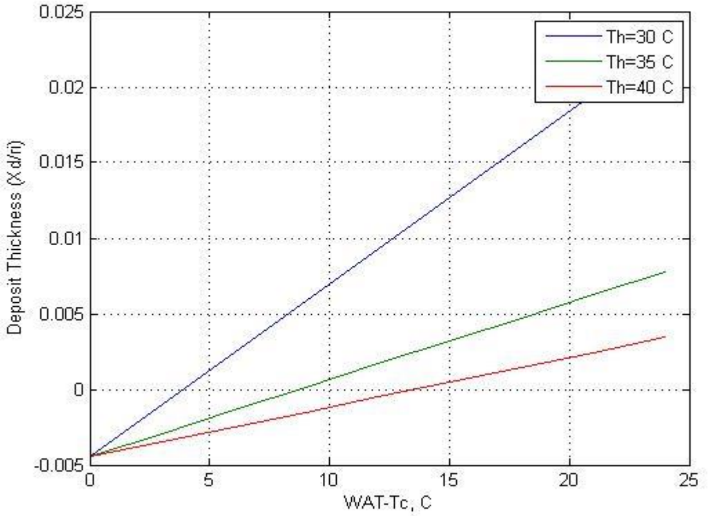

Figure 11. Predicted variations in deposit thickness with seawater temperature at different crude-oil temperatures at 0.368 m^3/s.

Conclusion:

- The deposit thickness is reduced as a result of an increase in the crude-oil flow rate. This is caused by the increased inside heat-transfer coefficient due to the increased flow rate. The resulting higher wall temperature then yields a reduction in the amount of deposition.
- The predictions are shown in **Figs.3** and **4**, which indicate that there is a reduction in the amount of deposited solids with an increase in either the crude-oil temperature or the seawater temperature. Conversely, a reduction in either the crude-oil or the seawater temperature would yield a larger amount of deposited solids. These predictions are in good agreement with experimental results reported by Mehrotra and Bidmus **[6]**, who had performed wax deposition experiments over a range of operating conditions using a concentric draft tube assembly with a “hot” wax-solvent mixture flowing in the inner tube and cold water flowing through the annular region.
- The higher WAT gave a larger deposit thickness and a lower WAT of gave a smaller deposit thickness of. These results imply that an increase in the crude-oil wax concentration would lead to an increase in the amount of deposit in the pipeline. This effect is further illustrated in **Fig.2**, where the deposit thickness has been obtained for WAT values ranging from 20 to 27°C. It should be noted that, in these calculations, it was assumed that all crude-oil properties remain constant even though the concentration of wax was varied. Properties such as the viscosity and density of the crude oil can be altered by an increase in wax concentration, which would alter the value of inside heat-transfer coefficient. However, even with such crude-oil property changes, an increase in wax concentration would lead to increased amount of deposit in the pipeline.
- During the solids deposition process, the deposit layer acts as an insulation to heat transfer, thereby preventing further solids deposition. The importance of the deposit thermal conductivity is illustrated in case study. Also note the much larger temperature difference across the insulation material.

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