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The Effect of Shear Stress on Wax Deposit Thickness with and without Spiral Flow

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Abstract

The main objective of this research is to estimate and discuss the effect of shear stress on wax deposition in the hydrocarbon pipeline. Two sets of experimental data were used to analyse the effect of shear stress on wax deposition with and without spiral flow at different inlet coolant temperatures and different flow rates. A new mathematical model was developed during this study to estimate the shear stress, because of the spiral flow, on wax deposition. The concept of this model was based on the forces that influence on the crude oil flow in the pipe, with and without inserting the twisted plate to create spiral flow, depending on the pressure drop along the pipe. The results are presented that, increasing the shear stress, because of the effect of the spiral flow, leads to decrease the wax deposit thickness with increasing the pressure drop while the shear stress decreased in the case of crude oil flow without spiral flow leading to increasing the wax deposit thickness. On the other hand, increasing the inlet coolant temperature leads to decrease the shear stress and wax thickness because of decreasing the value of the crude oil viscosity. This developed model can be considered as a base model for similar studies to calculate the shear stress in the fluid flow pipelines using the twisted plate to create spiral flow.

Keywords: Wax deposit thickness; Shear stress; Spiral flow; Pressure drop

Nomenclature: F1=Inlet force (N); F2=Outlet force (N); F3=Shear stress force (N); τ=Shear stress (Pa); *P* =Inlet pressure (Pa); Δ*P*= Pressure drop along the pipe (Pa); A_X = The cross-section area of the pipe (m²); *r* =The radius of the pipe (m); *L* =The length of the pipe (m); *Q* =The volumetric flow rate of the fluid (m³/s); $\underline{U}$ =The fluid velocity (m/s); A_{Xpipe} =The cross-section area of the pipe (m²); A_{Xplate} =The cross-section area of the twisted plate (m²)

Introduction

There appears to be a trend to a reduction in wax deposition tendency on the pipe wall at the higher rates of shear, due to increase pipe wall shear stress. An increase in shear rate should encourage more wax particles to disperse towards the pipe wall; the corresponding increase in wall shear stress may cause the more loosely held deposits to be stripped from the pipe wall [1].

It is generally accepted that shear stress is mainly responsible for shearing away of wax molecules and crystals. The shear stress and Reynold's Number depend on the systems flow characteristics and they have a direct effect on the diffusion of wax molecules to the wall [2].

Dwivedi [3] showed that there is a general decreasing trend in the deposit thickness by increasing the shear stress and decreasing thermal driving force. Venkatesan [4] concluded that, at a fixed cooling rate, the gelation temperature decreases as the shear stress applied on the sample is increased. The gelation temperature is an appropriate measure of the onset of gelation under flowing conditions. This reduction in gelation temperature leads to a decrease in paraffin deposition because of the prevention of deposit formation instead of removal. This study, describes mathematically the steps to develop the shear stress correlation, because of the spiral flow, on wax deposition on the hydrocarbon pipe wall. Also, present the estimated shear stress inside the pipe, using the new correlation, and compare the values of shear stress with and without using the spiral flow.

Methodology

Experimental data

The experimental data of Theyab and Diaz [5,6], Tables 1 and 2 were used during this work to estimate the shear stress inside the crude oil pipeline, using the developed model, with and without spiral flow.

Type of Flow	Temperature (ºC)	Pressure Drop (Pa)	Wax Thickness (mm)	Resource
Not Spiral	14	1200	1.82	[5]
Spiral		4000	1.03	[6]
Not Spiral	24	1000	1.5	[5]
Spiral		3400	0.85	[6]
Not Spiral	33	900	0.7	[5]
Spiral		2500	0.36	[6]
Not Spiral	40	600	0	[5]
Spiral		1700	0	[6]

Table 1: The deposit wax thickness at different pressure drops, and different inlet coolant temperatures at flow rate 2.7 L/min with and without the spiral flow [5,6].

Type of Flow	Temperature (ºC)	Pressure Drop (Pa)	Wax Thickness (mm)	Resource
Not Spiral	14	3000	1.5	[5]
Spiral		8000	0.78	[6]
Not Spiral	24	2700	1.36	[5]
Spiral		7000	0.61	[6]
Not Spiral	33	2100	0.63	[5]
Spiral		6100	0.39	[6]
Not Spiral	40	1200	0	[5]
Spiral		4500	0	[6]

Table 2: The deposit wax thickness at different pressure drops, and different inlet coolant temperatures at flow rate 4.8 L/min with and without the spiral flow [5,6].

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They used a flow loop system to recirculate the waxy crude oil with API about 35 and the wax content about 20.15 wt%, and to study the effect of the inlet coolant temperatures 14, 24, 33 and 40 °C, the effect of the flow rates 2.7 and 4.8 L/min, and the effect of the spiral flow on wax deposit thickness.

Derivation of shear stress model

This section describes mathematically the steps to develop the shear stress model, because of the spiral flow, on wax deposition on the hydrocarbon pipe wall. It shows the forces that influence on the crude oil flow in the pipe with and without inserting the twisted plate depending on the pressure drop along the pipe.

Fluid flow in a pipe

The concept of the spiral flow mechanism in this research is based on an elemental fluid flowing in the pipe. The initial conditions for the elemental fluid are taken in the way that; the high-pressure value is taken from the injection side and drives uniformly decreasing throughout the pipe. Shearing action is integrated from the elemental radius up to maximum flow channel radius. The forces acting on the system are quantitatively described below [7,8].

The driving force due to pressure (Force=pressure × area) can describe as shown in Figure 1 of this study.

Where:

Inlet force=Inlet pressure × cross-section area of the pipe ($F_1 = PA_X$).

Outlet force=outlet pressure × cross-section area of the pipe ($F_2 = (P - \Delta P) A_X$), Where, P is the inlet pressure (Pa), A_X is the pressure drop along the pipe (Pa), and A_X is the cross-section area of the pipe (m²).

Shear stress force=shear stress × surface area of the pipe ($F_3 = \tau 2\pi r L$).

Where, τ is the shear stress (Pa), r is the radius of the pipe (0.00675 m), and L is the length of the pipe (1.5 m).

The driving force due to pressure equals to:

$$F_3 = F_1 - F_2$$

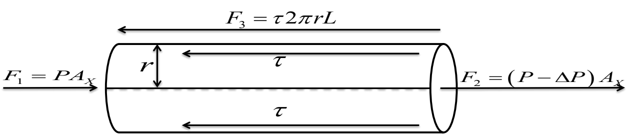

Figure 1: Forces affects on the element of fluid flow in a pipe.

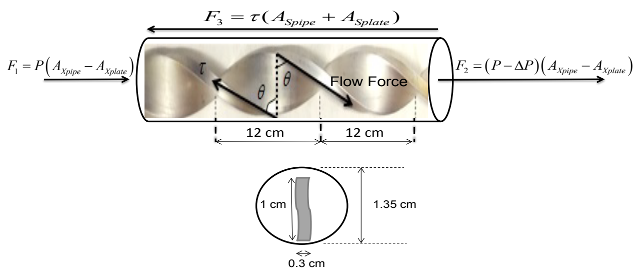

Figure 2: Forces affect on the element of fluid in a pipe with the effect of spiral flow created by inserting a twisted plate inside the pipe.

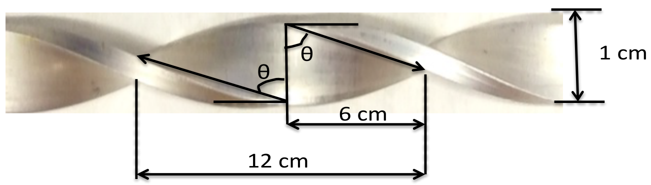

Figure 3: Estimate the angular flow of the twisted plate and equals to $\tan^{-1}(6/0.5) = 85°$.

$\tau 2\pi r L = P\pi r^2 - (P - \Delta P)\pi r^2$, simplify the equation results to $\tau 2\pi r L = \Delta P \pi r^2$, then shear stress equals to:

$$\tau = \frac{\Delta P r}{2L} \quad (1)$$

The velocity of the fluid inside the pipe can be calculated from divide the volumetric flow rate to the cross-section area of the pipe $Q = uA$

$$u = Q / \pi r^2 \quad (2)$$

Where, Q is the volumetric flow rate of the fluid (m³/s), u is the fluid velocity (m/s).

Fluid flow through spiral

In order to develop an equation for the pipe wall shear stress plus the shear stress of the twisted plate inside the pipe, the following steps will illustrate that in Figure 2.

Inlet force=inlet pressure × (cross-section area of the pipe - cross section area of the twisted plate).

$$F_1 = P\left(A_{Xpipe} - A_{Xplate}\right)$$

Where, A_{Xpipe} is the cross-section area of the pipe (m²), and A_{Xplate} is the cross section area of the twisted plate (m²).

$$F_1 = P\left(\pi r^2 - 3\times10^{-5}\right)$$

Outlet force=outlet pressure × (cross-section area of the pipe - cross section area of the twisted plate).

$$F_2 = (P - \Delta P)\left(A_{Xpipe} - A_{Xplate}\right)$$

$$F_2 = (P - \Delta P)\left(\pi r^2 - 3\times10^{-5}\right)$$

$$F_2 = P\pi r^2 - 3\times10^{-5} P - \Delta P \pi r^2 + 3\times10^{-5}\Delta P$$

In order, to calculate the shear stress force, it should be taken into account the shear stress of the pipe plus the shear stress results from the twisted plate inside the pipe.

The twisted plate divided to 12.5 sections; each section equal to 12 cm and height 1 cm. Therefore, to calculate the total shear stress results from the twisted plate, it should be calculated the shear stress results from each section of the twisted plate multiplied by 12.5. The surface area of each section of the twisted plate equals $3.12\times10^{-3} m^2$, and the angle of each section of the twisted plate estimates to be about 85°, (Figure 3), and it comes from $\tan^{-1}(6/0.5) = 85$.

Shear stress force=(shear stress × surface area of the pipe) + (shear stress × surface area of the twisted plate inside the pipe).

Shear stress force=(shear stress × surface area of the pipe) + shear stress (number of twisted plate sections × cosθ × surface area of the twisted plate section).

$$F_3 = \tau 2\pi rL + \tau(12.5\times\cos\theta\times 3.12\times 10^{-3})$$

$$F_3 = \tau 2\pi rL + \tau(12.5\times\cos 85\times 3.12\times 10^{-3})$$

$$F_3 = \tau 2\pi rL + 0.0034\tau$$

$$F_3 = \tau(2\pi rL + 0.0034)$$

In the case of the spiral flow, the driving force along the pipe due to pressure equals to:

$$F_3 = F_1 - F_2$$

$$\tau(2\pi rL + 0.0034) = P\left(\pi r^2 - 3\times 10^{-5}\right) - \left(P\pi r^2 - 3\times 10^{-5}P - \Delta P\pi r^2 + 3\times 10^{-5}\Delta P\right)$$

Simplify the equation,

$$\tau(2\pi rL + 0.0034) = P\pi r^2 - 3\times 10^{-5}P - P\pi r^2 + 3\times 10^{-5}P + \Delta P\pi r^2 - 3\times 10^{-5}\Delta P$$

$$\tau(2\pi rL + 0.0034) = \Delta P\pi r^2 - 3\times 10^{-5}\Delta P$$

$$\tau(2\pi rL + 0.0034) = \Delta P\left(\pi r^2 - 3\times 10^{-5}\right)$$

So, the total shear stress results from the pipe and the twisted plate can be calculated from the following equation:

$$\tau = \frac{\Delta P\left(\pi r^2 - 3\times 10^{-5}\right)}{(2\pi rL + 0.0034)} \quad (3)$$

The velocity can be calculated by dividing the volumetric flow rate to the (cross-section area of the pipe minus cross section area of the twisted plate).

$$u = \frac{Q}{\left(\pi r^2 - 3\times 10^{-5}\right)} \quad (4)$$

Results and Discussion

In the case of fluid flow in a pipe without spiral, for example, at flow rate 2.7 L/min and pressure drop 1200 Pa, the shear stress calculated from equation (1) above equals to:

$\tau = \frac{(1200\times 0.00675)}{(2\times 1.5)} = 2.7Pa$, and by increasing the flow rate to 4.8 L/min., the shear stress at pressure drop 3000 Pa results using equation (1) to: $4.5\times 10^{-5}m^3/s$

Equation (1) represents the shear stress inside the pipe without the twisted plate.

For example at the fluid flow without spiral, to calculate the fluid velocity in the pipe at flow rate 2.7 L/min ($4.5\times 10^{-5}m^3/s$) using equation (2) above results:

$$u = 4.5\times 10^{-5}/\pi(0.00675)^2 = 0.31m/s$$

By increasing the flow rate to 4.8 L/min ($8\times 10^{-5}m^3/s$) lead to $u = 8\times 10^{-5}/\pi(0.00675)^2 = 0.56m/s$. The increase in the velocity means an increase in the shear stress that reduces wax deposit on the pipe wall.

In the case of fluid flow in a pipe with spiral, for example, at flow rate 2.7 L/min and pressure drop 4000 Pa, the shear stress calculated from equation (3) results:

$\tau = \frac{4000\left(\pi(0.00675)^2 - 3\times 10^{-5}\right)}{(2\pi\times 0.00675\times 1.5 + 0.0034)} = 6.75Pa$, and by increasing the flow rate to 4.8 L/min., the shear stress at 8000Pa results using equation (3) to: $\tau = 13.51Pa$

For example, to calculate the fluid velocity at flow rate 2.7 L/min using equation (4) in the case of using the twisted plate inside the pipe leads to:

$u = \frac{4.5\times 10^{-5}}{\left(\pi(0.00675)^2 - 3\times 10^{-5}\right)} = 0.4m/s$, and at flow rate 4.8 L/min. using the same equation leads to $u = 0.71m/s$.

The velocity of the fluid flow is increased by inserting a twisted plate inside the pipe, because of reducing cross-section area of the pipe with the constant flow rate.

From the above, it can be concluded that the twisted plate changed the fluid flow type from laminar or turbulent to spiral flow depending on the velocity and the angle of the fluid flow. This angle analyses the angular flow to two forces one vertically to the wax deposit and the second force horizontally, those forces work together to reduce wax deposition on the pipe. Tables 3 and 4 show the data of shear stress at the different wax thickness, different pressure drop, and different inlet coolant temperatures.

At the same inlet coolant temperature, it can be seen that increasing the shear stress, because of the effect of the spiral flow, leads to decrease the wax deposit thickness with increasing the pressure drop. On another hand, increasing the inlet coolant temperature leads to decrease the shear stress and wax thickness because of decreasing the value of the crude oil viscosity (Table 3).

Increasing the flow rate from 2.7 to 4.8 L/min, leads to increasing the shear stress and pressure at the same inlet coolant temperature because of reducing the cross-sectional area of the pipe that affects to increase the crude oil velocity. This high velocity minimises the wax deposit on the pipe wall because of converting the laminar or turbulent flow to the spiral flow (angular flow). The high temperatures of the pipe wall lead to low shear rates and low wax thickness because of increasing the solubility of wax in the crude oil that works to reduce the crude oil viscosity (Table 4).

If we assumed, that the flow rate increased to 6 L/min and by following the same procedure above it can be estimate the shear stress produced at different inlet coolant temperature and with and without spiral flow as shown in Table 5.

Figure 4 shows the effect of increasing the shear stress on wax deposit thickness, where at the same flow rate 2.7 L/min it can be seen that increasing the shear stress leads to reduce wax deposit thickness from 1.8 to 1 mm at inlet coolant temperature 14ºC. Increasing the flow

Type of Flow	Temperature (ºC)	Pressure Drop (Pa)	Shear Stress (using the new model) (Pa) at 2.7 L/min.	Wax Thickness (mm)
Not Spiral	14	1200	2.7	1.82
Spiral		4000	6.75	1.03
Not Spiral	24	1000	2.25	1.5
Spiral		3400	5.74	0.85
Not Spiral	33	900	2.03	0.7
Spiral		2500	4.22	0.36
Not Spiral	40	600	1.35	0
Spiral		1700	2.87	0

Table 3: Estimated shear stress and wax thickness at different pressure drops and different inlet coolant temperature at flow rate 2.7 L/min with and without the spiral flow.

Type of Flow	Temperature (°C)	Pressure Drop (Pa)	Shear Stress (using the new model) (Pa) at 4.8 L/min.	Wax Thickness (mm)
Not Spiral	14	3000	6.75	1.5
Spiral		8000	13.51	0.78
Not Spiral	24	2700	6.08	1.36
Spiral		7000	11.82	0.61
Not Spiral	33	2100	4.73	0.63
Spiral		6100	10.3	0.39
Not Spiral	40	1200	2.7	0
Spiral		4500	7.6	0

Table 4: Estimated shear stress and wax thickness at different pressure drops and different inlet coolant temperature at flow rate 4.8 L/min with and without the spiral flow.

Type of Flow	Temperature (°C)	Pressure Drop (Pa)	Shear Stress (using the new model) (Pa) at 6 L/min.	Wax Thickness (mm)
Not Spiral	14	4000	9	1
Spiral		10000	16.15	0.6
Not Spiral	24	3000	6.75	0.8
Spiral		8000	12.92	0.5
Not Spiral	33	2500	5.63	0.4
Spiral		7000	11.3	0.3
Not Spiral	40	1500	3.38	0
Spiral		5000	8.1	0

Table 5: Estimated shear stress and wax thickness at different pressure drops and different inlet coolant temperature at flow rate 6 L/min with and without the spiral flow.

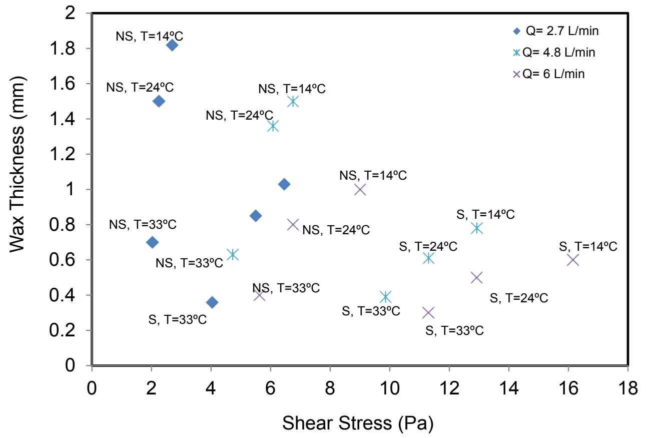

Figure 4: The effect of shear stress with spiral flow (S) and non-spiral flow (NS) on wax deposit thickness at different pressures and different inlet coolant temperatures.

rate to 4.8 L/min leads to increase the shear stress that works to reduce wax deposit thickness from 1.5 to 0.78 mm at the same temperature. While increasing the flow rate to 6 L/min results in increasing the shear stress that reduced the wax thickness from 1 to 0.6 mm.

Conclusion

The current work studied the effect of the shear stress on wax deposition inside the hydrocarbon pipeline. A series of experimental data of Theyab and Diaz [5,6] was used to estimate the shear stress value resulting from the pipe wall surface and the twisted plate that was inserted into the pipe to create spiral flow. This work presented a new correlation (model) to calculate the shear stress depending on the concept of, the forces that influence on the crude oil flow in the pipe with and without inserting the twisted plate depending on the pressure drop along the pipe. It was observed that the wax deposit thickness decreased with increasing the shear stress while the shear stress decreased, in case of crude oil flow without spiral flow leading to increasing the wax deposit thickness. However, an increase in flow rates results in a decrease in the wax deposition because of increasing the shear stress. Also, it was observed that increasing the inlet coolant temperature leads to decrease the shear stress and wax thickness because of increasing the solubility of the wax molecules in the bulk of the crude oil that leading to decreasing the value of the crude oil viscosity. This study presented the newly developed model as a base model for similar studies to calculate the shear stress in the fluid flow pipelines using the twisted plate to create spiral flow.

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