

COB-2023-0170
**STUDY OF COMMERCIAL COATING OF PIPES TO IMPROVE THE
FLOW OF WATER-OIL EMULSIONS**

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Abstract. *In offshore heavy oil production systems, crude oil and produced water flow from wells to the platform, experiencing shear and turbulence in pipes and equipment. These conditions lead to the formation of emulsions, where one phase disperses into the other. Water-in-oil (W/O) emulsions, at low to intermediate water content, reduce production efficiency due to higher viscosity compared to single-phase oil. Coating the interior of pipes and surfaces is a strategy that can mitigate this issue by altering the physicochemical properties of the surface and reducing friction at the pipe-wall fluid interface. The aim of this work is to analyze whether a commercial coated pipe improves emulsion flow. The affinity between two samples of the same steel surface, one coated (CS) and one uncoated (US), and different fluids (wettability) was evaluated by measuring the contact angle (θ) between the fluid and the solid surface. The fluids used in the study were crude oil, produced water, and W/O emulsions, made from mineral oil and distilled water. Experiments were conducted at temperatures ranging from 25 to 45°C. In addition, dynamic tests in a flow loop were also performed with tubes made of the same material as the surfaces. Based on the contact angle measurements, it was observed that crude oil had a higher affinity for the US compared to the CS. With emulsions, the results indicated a lower affinity for the CS, possibly reducing fluid-wall friction and improving flow under dynamic conditions. However, flow loop tests with oil and oil/n-pentanol mixture showed no significant reductions in pressure drop when comparing both pipes. Flow loop tests with the same W/O emulsion are being conducted to confirm or refute assumptions based on wettability results.*

Keywords: *Water-Oil emulsions, Coating, Wettability.*

1. INTRODUCTION

In crude oil reservoirs, water can originate from the formation itself as well as from advanced recovery techniques, such as water injection. In the reservoir water and oil are, usually, in separate phases, due to the difference in density and immiscibility between the phases (Kunert et al., 2007). Equipment of production systems such as pumps and valves may cause intense turbulence and shearing to which both oil and water phases are subjected along the lifting process, providing enough energy for the formation of emulsions to occur (Umar et al., 2018). In oil production, it is common to find water-in-oil (W/O) or oil-in-water (O/W) emulsions, however, the first one is the main responsible for production problems due to the increased viscosity in comparison to both water and oil phases (Kokal & Aramco, 2005).

Besides the fluids viscosity, the friction of the fluid on the pipe wall may play an important role on the system pressure drop and, consequently, on the flow rate, impacting the production. Thus, the reduction of the friction of the fluid on the pipe wall may be promising to improve the production without the injection of chemical additives on the flow stream and/or installation of expensive equipment to the production system (Santos et al., 2017). There are some strategies to reduce the friction of the fluid on pipe wall such as the core-flow and coating. The first technique demands specific elements in the pipelines to produce an annular flow of water with the crude flowing in the centre of the pipe, being usually more effective for flows in vertical pipelines. On the other side, some recent studies propose the use of a *coating* on the inner

wall of the pipe, which may act by modifying the chemical characteristics of the surface and, consequently, the wettability of the fluids by the pipe wall (Jiaqiang et al., 2017; Qi et al., 2019).

This work aims to determine whether the application of a commercial coating on the inner wall of the pipe can reduce the pressure drop in a flow. To achieve this objective, contact angle measurements will be performed on two steel plates, one coated (CS) and one uncoated (US), in order to determine the wettability of both surfaces by emulsions with different formulations. Furthermore, dynamic experiments in a flow loop are being carried out to study the effect of coating on pressure drop for the same emulsion systems.

2. LITERATURE REVIEW

In this section the basic concepts necessary for the development of this work will be presented. The review will start with fundamentals about emulsions, followed by a review about the application of coatings as flow improvers.

2.1 Contact Angle and Wettability

Wettability is a thermodynamic parameter which allows to evaluate the fluid/ surface interactions, a phenomenon controlled by the balance of cohesive and adhesive interactions of the system. Based on the contact angle (θ), a surface can be classified as wettable ($\theta < 90^\circ$), non-wettable ($\theta > 90^\circ$) or neutral ($\theta = 90^\circ$), as can be seen in Figure 1.

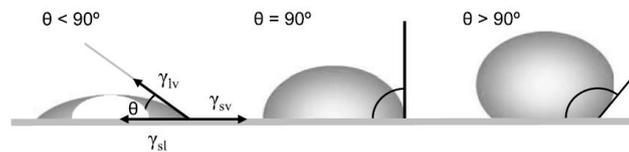


Figure 1. Contact angle measured on a flat surface: wettable ($\theta < 90^\circ$), non-wettable ($\theta > 90^\circ$) or neutral ($\theta = 90^\circ$) (Adapted from Bracco & Holst, 2013).

This measurement can be performed using the Sessile Drop technique, which consists of measuring the contact angle between the drop and the surface, through the tangent formed by the profile of the drop at the point of contact with the surface. The contact angle is a result of attractive forces which act around the perimeter of the drop, being represented by interfacial tensions. Based on the Young's equation, for water/ oil/ surface systems the relationship between θ and the interfacial tension values can be represented by the Eq. (1).

$$\gamma_{ow} \cos \theta = \gamma_{sw} - \gamma_{os} \quad (1)$$

Where γ_{os} , γ_{sw} and γ_{ow} are, respectively, the oil/surface, surface/water and oil/water interfacial tensions.

2.2 Emulsions

Emulsions are defined as dispersion of two immiscible liquids in which one phase is dispersed into the other. These systems can be classified as simple, water-in-oil (W/O) or oil-in-water (O/W), or multiple, W/O/W and O/W/O (Figure 2). To produce an emulsion, there must be immiscibility between the phases, energy application and the presence of surfactants (Akbari & Nour, 2018).

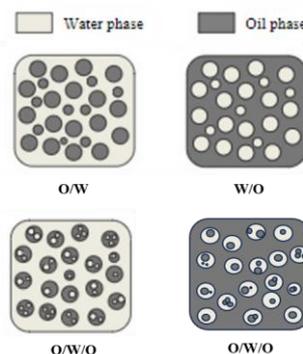


Figure 2. Representation of the emulsion types (adapted from Akbari & Nour, 2018).

The emulsion morphology basically depends on four types of variables: the physical-chemical, composition, mixing conditions and the physical properties of the components. The physical-chemical refers to the chemical characteristics of the components, at a certain pressure and temperature. These characteristics can be represented by a thermodynamic parameter known as HLD (Hydrophilic-Lipophilic Deviation), which consider the type of oil, salinity of the aqueous phase, surfactant and alcohol. This allows the HLD to be calculated with a high degree of freedom, since it is possible to adjust the formulation, changing only the variables of interest or performing several changes at once (Salager et al., 2003), according to Eq. (2).

$$HLD = b(S) - K \cdot EACN - f(A) + a_T \cdot \Delta T + C_c \quad (2)$$

In the HLD equation, the term (S) represents the salinity of the aqueous phase of the nonionic surfactant, the EACN denotes the hydrophobicity of the oil phase, reflecting the lipophilic interactions between the surfactant tail and oil molecules, ΔT refers to the temperature difference relative to 298 K, $f(A)$ is the type and concentration (%wt) of the alcohol and C_c represents the characteristic curvature that indicates the hydrophilic-lipophilic nature of the surfactant. The coefficients b , K and a_T are constants dependent on the surfactant.

The HLD value allows the prediction of the emulsion type that will form in a specific formulation, i.e., for $HLD < 0$, the surfactant is more soluble in the aqueous phase, resulting in oil-in-water (O/W) emulsions. On the other side, for $HLD > 0$, the surfactant has higher affinity for the oil phase, leading to water-in-oil (W/O) emulsions, according to Bancroft rule. Systems with $HLD = 0$, for ideal cases, the surfactant has the same affinity for both the oil and water phases, resulting in an ideal formulation where a triphasic behavior can be observed (Salager et al., 2010).

2.3 Coating

According to Jiaqiang et al. (2017), Qi et al. (2018) and Zhang et al. (2002) it has been observed that reducing friction in water/oil flows may be related to surface wettability, which is influenced by the properties of the material surface. As a result, the authors proposed modifying the surface to achieve increased hydrophilicity, allowing the water phase to form a layer on the pipe wall. This modification aims to reduce friction in the flow.

The studies conducted in a flow loop by Qi et al. (2018) suggested a relationship between surface wettability and friction reduction, i.e., an increase in the contact angle between a liquid droplet and the surface resulted in an increase in sliding velocity. This effect was attributed to the reduced fluid/ surface affinity.

Later, Qi et al. (2020) performed some tests under laminar flow, comparing non-metallic tubes (glass, acrylic and polypropylene) with stainless steel tubes. Three fluids (tap water, ethylene glycol and white oil) were used to measure contact angles by the sessile drop method. The results corroborate the conclusions of the previous study (Qi et al. (2018), i.e., flow improvement with increasing contact angle, with maximum friction reduction observed at $\theta = 39.9^\circ$).

Jiaqiang et al. (2017) also observed the same phenomenon in tests conducted with tap water and five tubes made of glass, stainless-steel, plexiglass, polypropylene and polytetrafluoroethylene. Additionally, tests were conducted with a PTFE tube and four different types of fluids: diesel, a mixture of white oil and diesel, a mixture of glycerine and tap water and a mixture of ethylene glycol and tap water. To minimize experimental errors, all tubes had the same diameter of 14 mm and length of 5 m. Furthermore, the tests with tap water and the four fluids were conducted under turbulent flow conditions and at the same Reynolds number. The experiments demonstrated that the wettability of the surfaces influenced the friction coefficient, where a higher contact angle (low wettability) resulted in a lower friction coefficient.

Furthermore, the industry has adopted another technique, known as core-flow, to reduce friction during flow. In this regard, Silva et al. (2006) chemically and mechanically modified surfaces to obtain a hydrophilic surface that favours the reduction of pressure drop in the flow. It was observed that surface roughness can also contribute to the reduction of pressure drop in the transportation of heavy oils using the core-flow method.

Additionally, coatings have been studied as a strategy to mitigate wax deposition. (Zhang et al., 2002) investigated coated surfaces to drag reduction and prevent wax deposition. Surfaces characterized by low free energy have the ability to affect surface wettability, which subsequently impacts both paraffin deposition and shear force. The authors observed that the drag reduction and paraffin deposition related to the wettability of the coating, which is influenced by the characteristics of the material. The authors concluded that surface coatings can be effective in reducing friction and preventing paraffin deposition during oil transportation.

The literature provides a consistent evidence of a pressure drop and surface wettability relationship. However, most of the studies available have focused on static tests and prevention of wax deposition. Based on the correlation between contact angle and pressure drop, this work focuses on studying the effect of coatings on pressure drop in W/O emulsion flow. The dynamic tests are currently being conducted in a flow loop to evaluate the effectiveness of a commercial coating under different flow conditions, in addition to the wettability tests.

3. MATERIALS AND METHODS

3.1 Materials

The fluids, surfaces and equipment used in the contact angle measurements are being described in Table 1. The CS surface features a layer of paint that acts as a coating, whereas the US surface consists solely of steel without any modifications to its surface.

Table 1. Materials used in contact angle measurements.

Surfaces and Pipes	
Uncoated Steel plate test (US)	
Coated Steel plate test (CS)	
Uncoated Steel Pipe (US-Pipe, d= 21 mm)	
Coated Steel Pipe (CS-Pipe, d=20.8mm)	
Fluids	
Produced water	
Crude Oil diluted with 20 wt% diesel ($\mu = 4900$ mPa s, @ 55 °C)	
Distilled water	
n-pentanol (Neon, 99.9%)	
SPAN 80 Surfactant (Croda)	
Mineral oil (Lucheti, $\mu = 206$ (mPa s), @ 25 °C)	
Mineral oil + n-pentanol ($\mu = 119 \pm 0,44$ (mPa s), @ 25 °C)	
Equipment	
Tensiometer (PAT-1M, Sinterface)	
Thermostatic Bath (TC-502, Brookfield)	
Centrifugal Pump (Weg 22, EDRAL)	
Pressure Transmitter (2051CD, Rosemount)	
Mass Flow Sensor (CMFS050, Micro Motion)	
Cleaning of the surfaces	
Isopropanol (ACS Cientifica, 99.5%)	

3.2 Methods

3.2.1 Emulsion Preparation

Three different formulations of W/O emulsions were prepared, whose formulations were previously calculated based on the HLD equation (Eq. 2). The emulsions were prepared with distilled water, mineral oils, n-pentanol and SPAN 80. Three HLD values were obtained by varying the concentration of n-pentanol in the range of 4 and 6 wt%, according Table 2.

The procedure consists in mixing the n-pentanol and SPAN 80 with the oil phase and gently pour this mixture on the water phase, leaving the system to reach the surfactant partition equilibrium for 24 hours in a water bath at 25 °C. Afterwards, the emulsions were prepared using a mechanical disperser (Turrax T18, IKA) at a speed of 18000 rpm by 2.5 minutes. Distilled water was used to minimize oxidation on the uncoated surface (US).

Table 2. Formulation for emulsions with mineral oil.

Emulsion Type	Water cut (wt%)	n-pentanol (%)	Surfactant (SPAN80) (ppm)	HLD
W/O	5/30/60	4	500	1
		6		3

3.3 Contact Angle Measurement

The contact angle (θ) was measured by using a tensiometer adapted to work as a droplet goniometer by using the sessile drop method. The analysis was carried out by dropping a droplet of the fluid on the surface to be tested (drop/plate/air system). After settling on the surface, the contact angle remains constant, the data acquisition was started (Figure 3).

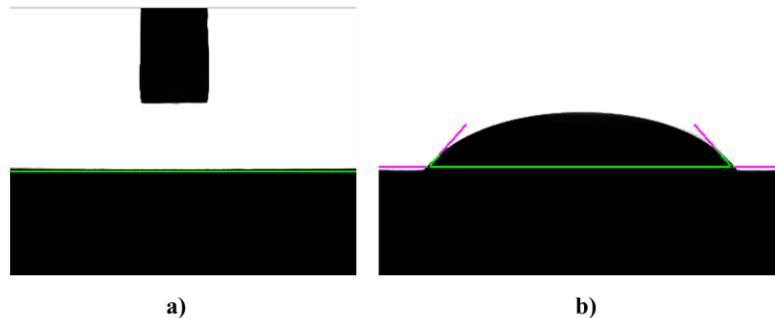


Figure 3. Procedure for measuring the contact angle. a) Needle for drop deposition; b) angle measurement from both sides of the drop image (PAT-1M Analysis Software).

Before each test, the surfaces were cleaned with isopropanol to prevent interference caused by contamination from the previous tests. The contact angle between crude oil and formation water and the steel plates was measured at 25, 35, and 45 °C. The contact angle was acquired for 10 minutes, and all tests were conducted in triplicate. For the emulsion with mineral oil and distilled water, the angle was measured only at 25°C, and the time was fixed at 2 minutes due to the stability of the mixture. The fluids, surfaces, and equipment used in the tests are detailed in Table 1.

3.4 Test on Flow-Loop

Dynamic tests were conducted in a flow-loop system, utilizing mineral oil, water, and oil with 4% n-pentanol.

3.4.1 Experimental Setup

The experimental setup (Figure 4) consists of a tank equipped with an internal stirrer, pipelines, both centrifugal and gear pumps, instrumentation, acquisition system, and heat exchanger (chiller).

For safety issues, the test line is limited to operate up to 3 bar. The commissioning tests were conducted with single-phase water and also with the mixture of mineral oil and n-pentanol. The fluid circulated the loop by a centrifugal pump located near the tank outlet, and measurements are performed using 2051CD pressure transmitters.

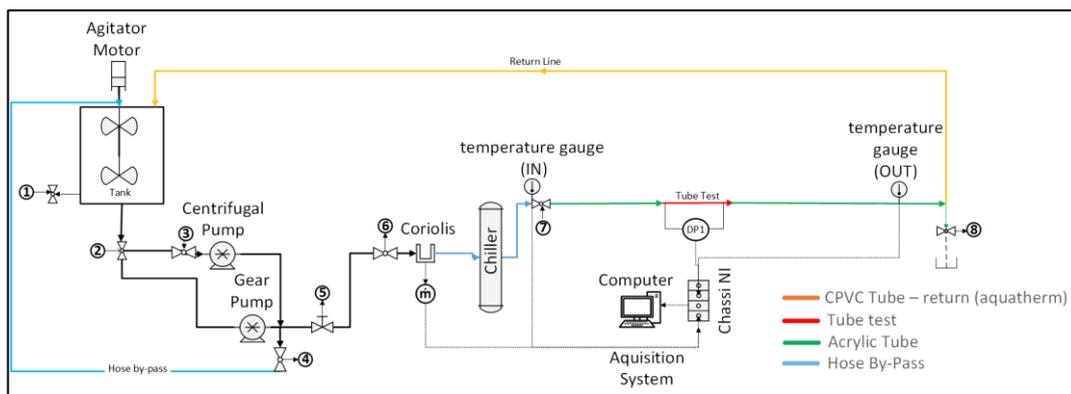


Figure 4 - Setup flow-loop for Dynamic Tests.

Head loss curves obtained for water played a crucial role in understanding whether the system is working properly. For the water tests, it was installed a single Rosemount 2051CD differential pressure transmitter with a range of 0 to 62 mbar. To validate the pressure transmitter functionality and the accuracy of theoretical calculations, the transmitter was initially placed within a 1 m section. In these theoretical calculations, the acrylic tube was considered a smooth pipe section.

After conducting measurements and verifications, also gathered measurements using the Rosemount 2051CD differential transmitter for both coated and uncoated steel pipes, with 20,8 and 21 mm of internal diameter respectively, and each having a length of 0.9 m. The effective friction was estimated based on experimentally obtained pressure differentials. To achieve this, it was first calculated the effective friction factor (Eq. (3)) and subsequently determined the Reynolds (Eq.(4)).

$$f = \frac{2D\Delta P}{\rho v^2 dL} \quad (3)$$

$$Re = \frac{64}{f} \quad (4)$$

4. RESULTS

In this section, the results will be presented and discussed based on the expected impact of the wettability of the coated and uncoated surfaces on the emulsion flow.

4.1 Emulsions

The contact angle results for W/O emulsions produced with mineral oil are shown in Figure 5. For the studies, it was chosen W/O emulsion type because this kind of emulsion are more usual in field production systems and, also, because the impact of W/O emulsions to the production process is far more serious. The tests were conducted at 25°C.

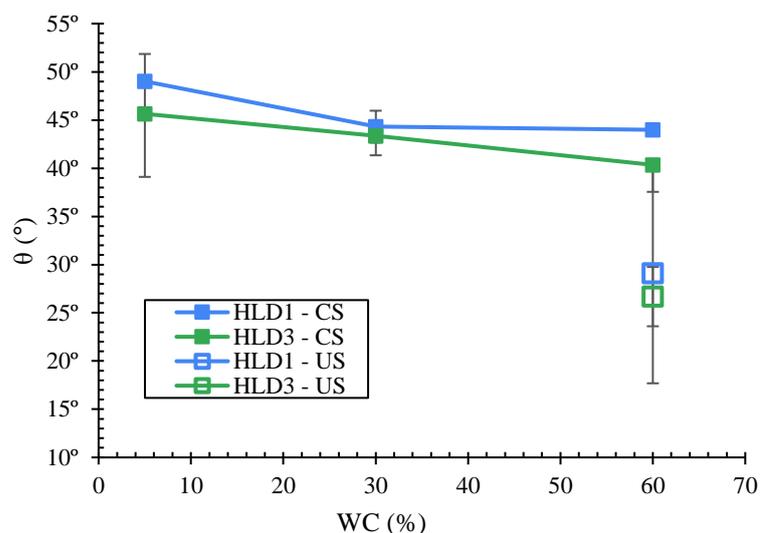


Figure 5. Contact angle (θ) as a function of WC at 25 °C. For WC 5 e 30% for US, the contact angles were less than 5° and not showed.

Due to technical constraints and limited availability of materials for the experiment, a low concentration of surfactant was used in the emulsion tests (500 ppm). As a result, the low kinetic stability of the emulsion leads the system to phase separation along the experiment time. Thus, to minimize the impacts of the phase separation in the contact angle, the measurement time was limited to 2 minutes.

It was observed a trend of decreasing contact angle for the CS as the HLD value increased, i.e. HLD 1 > HLD 3. This trend suggests that an increase in the HLD value results in greater wettability of the surface by the fluid. The CS with HLD 3 exhibited the lowest contact angle, indicating a higher affinity with the surface and also having the highest concentration of n-pentanol.

The results suggest that the increase in wettability is related to n-pentanol, which acts as a co-surfactant, reducing the surface tension of the system (SALAGER, 1980). However, it is important to note that an increase in affinity/wettability may not be desirable during flow, especially in emulsions, which tend to have higher resistance due to their high viscosity, leading to an increase in pressure drop.

Furthermore, the water concentration had an influence on the contact angle on both surfaces. It can be observed that there was an increase in the interaction between the fluid and CS as the water cut (WC) increased, in contrast to what is observed in the case of the US. This effect was more pronounced on the US at 5 and 30% WC, where the contact angle

was less than 5°, a value that is below the detection limit of the equipment, while at 60% WC, it was possible to perform the measurement, indicating a lower affinity.

Based on the results and the cited references, it is expected that the commercial coating (CS) will be more effective in reducing pressure drop during emulsion flow, due to its lower wettability compared to the US. The lower affinity results in weaker interactions between the fluid and the surface, which can lead to a reduction in the friction coefficient compared to the US.

4.2 Crude Oil and Produced Water

The influence of coated surface in wettability of real fluids as crude oil and produced water is evaluated by contact angle measurements in different temperatures (Figure 6).

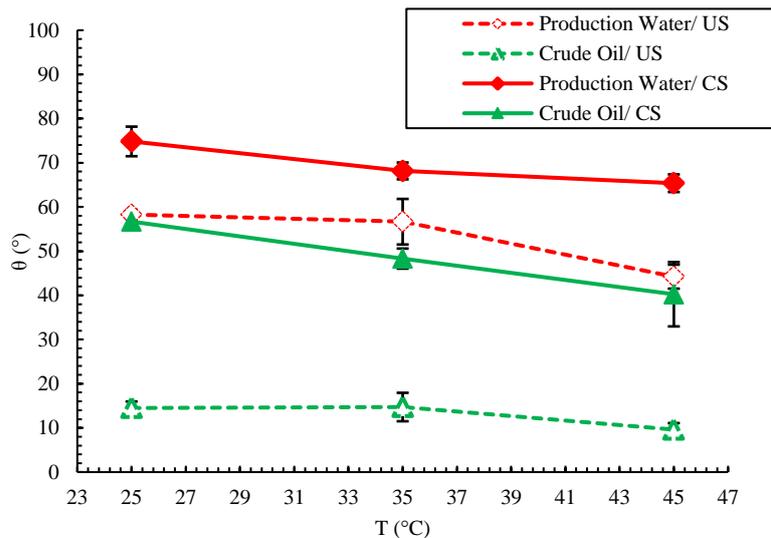


Figure 6. Contact angle (θ) at different temperatures (T) for crude oil and produced water on US and CS plate.

Figure 6 presents a comparison of the wettability of the US and CS with production fluids, crude oil, and produced water. The results show that the US has a high affinity for crude oil, while the CS is less wettable.

For both surfaces, wettability increases with temperature, indicating that the increase in temperature improves the fluid/ surface interaction, making the surface more wettable. This may have occurred because the increase in temperature can cause a reduction in surface and interfacial tension between solid-liquid-air (Shaw et al., 2003).

Another aspect to note, is that both surfaces exhibit a higher degree of wettability towards the oil phase in comparison to the water phase. The US, in particular, demonstrates significantly lower contact angles, indicating a stronger affinity for the oil phase when compared to the CS.

Based on these results, it is expected that the coated surface will be more effective in reducing pressure drop during flow, considering the wettability obtained in the static system. Previous studies, such as those by Jiaqiang et al. (2017) and Qi et al. (2020), have observed an inverse relationship between the contact angle and the friction coefficient, suggesting that a higher contact angle corresponds to a lower friction coefficient. This analysis is related to wettability, which reflects the interaction between the fluid and the surface.

Additionally, it was found that wettability is sensitive to temperature changes, being observed the lowest wettability of the surfaces to fluids at 25 °C. However, further evaluation through dynamic testing will be required to assess the effectiveness of the coating under flow conditions.

4.3 Flow loop tests

Figure 7 and Figure 8 displays a comparison between the friction factor and Reynolds number for both US and CS surfaces. It was tested two homogeneous fluids, a mineral oil and mixed of oil mineral with 4.0 wt% of n-pentanol. Due to the nature of viscous mixture, considering the pressure operating limit of the flow-loop, the tests were performed under laminar flow.

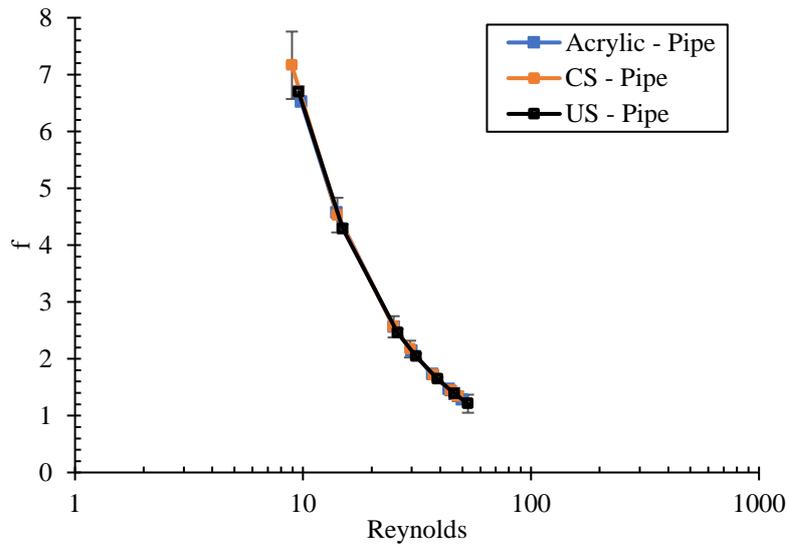


Figure 7 - Friction Factor as a function of Reynolds number. Comparison Between CS and US in a Flow-loop test with Mineral Oil at 25°C.

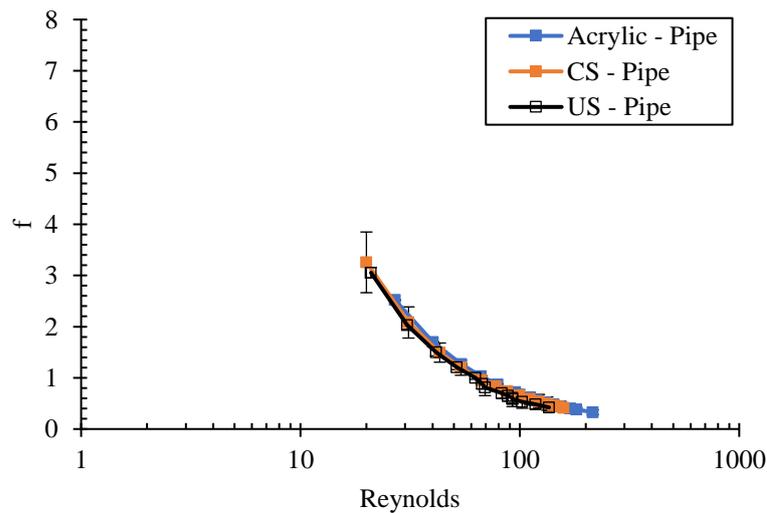


Figure 8 – Friction Factor as function of Reynolds number. Comparison Between CS and US in a Flow-loop test with Mineral Oil + 4% n-pentanol at 25°C.

No significant differences were observed between the US and CS pipes, in both cases, suggesting that the coating in study did not have any significant effect on reducing pressure drop.

It is understood that, due to the laminar flow nature, fluid viscosity is the primary factor that may have influenced the pressure drop. In the case of oil/n-pentanol mixture, it was observed a reduction in the friction factor by comparing the same Reynolds number. This is due to the decrease in oil viscosity by dilution effect when n-pentanol is added, compared to mineral oil, indicating a relationship between friction factor and viscosity. The viscosity decreased from 206 to 119 mPa s (Table 1).

On the other hand, in the operating range, the effect of internal pipe roughness was not considered, which can explain the overlap of the pressure drop curves, as evidenced in Figure 7 and Figure 8. It is possible that under turbulent flow conditions, different results can be observed.

5. CONCLUSIONS

The results indicated that the commercial coating applied on a stainless-steel plate (CS) was able to reduce the wettability between the W/O emulsion by the surface, in comparison to the uncoated plate (US). The lower wettability

means weaker interaction between the emulsion and the surface, what may able to reduce the friction at the pipe wall/ fluid interface, improving the flow of water-in-oil emulsion type.

The emulsion formulation showed to be an important parameter, being the wettability increased with increasing HLD values. If the dynamic experiments indicate that the wettability play an important role on the flow, changes in emulsion formulation in oilfield by injecting a surfactant could become a valuable strategy to improve the flow along the lifting/ transport lines. In the tests conducted with crude oil and production water, it was observed that the wettability of the surfaces is sensitive to temperature, increasing as the temperature rises. Furthermore, it was found that both surfaces are wettable to the oil phase. Tests will be performed with crude oil/ produced water emulsions in order to evaluate if the values and trends observed for the model system are representative of the crude oil emulsions.

In addition to the wettability test, dynamic tests are being conducted in a flow loop using pipe segments with and without the same commercial coating used for the contact angle measurements. For tests performed with mineral oil and mineral oil/n-pentanol mixture, no significant differences were observed, which may be a consequence of the operating range be limited to the laminar regime. Tests with emulsions in a range of water cuts will be conducted, which will provide sufficient information to consider the interaction between the surface and the fluid as a determining parameter that affects the flow of the emulsion along the pipelines. The emulsion results will be presented during the Congress.

6. ACKNOWLEDGEMENTS

We gratefully acknowledge the support of EPIC – Energy Production Innovation Center, hosted by the University of Campinas (UNICAMP) and sponsored by FAPESP – São Paulo Research Foundation (2017/15736-3 and 2021/14810-0). We acknowledge the support and funding from Equinor Brazil and the support of ANP (Brazil’s National Oil, Natural Gas and Biofuels Agency) through the R&D levy regulation. Acknowledgements are extended to the Center for Energy and Petroleum Studies (CEPETRO) and School of Mechanical Engineering (FEM).

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Study of Commercial Coating of Pipes To Improve The Flow of Water-Oil Emulsions

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8. RESPONSIBILITY NOTICE

The authors, Rafaela Ferreira, Carlos E. Perles, Vanessa C. B. Guersoni and Antonio C. Bannwart are responsible for the printed material included in this paper.