INVERSION POINT OF EMULSIONS AS A MECHANISM OF HEAD LOSS REDUCTION IN ONSHORE PIPELINE HEAVY OIL FLOW

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ABSTRACT
This work addresses the transportation of viscous crude oil as concentrated oil-in-water (O/W) emulsions flowing in a partially submerged onshore pipeline. The main goal of this study is to analyze the effects of inversion point of the water-in-oil emulsion in the pressure drop with the aid of Pipesim® software. Pressure drop is determined by applying the Dukler correlation (Taitel and Dukler, 1976) to represent dead oil viscosity as a function of temperature, and API density using the Hossain correlation (Hossain et al., 2005). The Brinkman model (Brinkman, 1952) is applied to calculate the viscosity of the emulsion, with the Brauner and Ullmann (2002) equation for the water cut off method (inversion point). The pipeline, of 3,600 m and 4 inches in diameter, transports the oil and consists of three sections. The first and third sections are above ground and are in contact with the external environment. The intermediate section is sitting on the river bed and is the critical part of the pipeline, once high heat losses are observed. The results of this 1D and non-isothermal problem show that water cuts of 5 and 6%, for low heat exchange and high heat exchange, respectively, make it possible to transport the oil, as an oil-in-water emulsion, through the entire extension of the pipeline. However, a water cut of 10% creates a high-pressure drop in the system, assuring the movement of the fluid in long sections without compromising the system operation. The use of isolation influences the temperature gradient but doesn’t have a high influence on pressure gradient compared to emulsions.

KEYWORDS
heavy oil; oil pipeline; heat exchange; head loss reduction; emulsion

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1. INTRODUCTION

Oil transportation has become a complex and highly technical operation. One of the major difficulties in pipeline transportation is due to the presence of high viscous fluids that require efficient and economical ways to transfer heavy crude (Hasan et al., 2010; Martínez-Palou et al., 2011; Jing et al., 2020; Santos et al., 2020). Also, heavy crude oils are not pumped easily through the pipelines because of the high concentrations of sulphur and several metals, particularly nickel and vanadium. Crude oils are complex fluids that can cause a variety of difficulties during the production, separation, transportation, and refining processes (Al-Besharah et al., 1987; Araujo & Romero, 2019; Pereira et al., 2017; Rigatto & Romero, 2018; Speight, 1998; Sousa & Romero, 2017; Martins et al., 2020).

The formulation of the emulsion presents another challenge to the petroleum industry. Crude oil is often produced with water, and, normally, both are immiscible under several conditions. This is the main characteristic of a dispersed mixture. As the oil-water mixture passes over chokes and valves, mechanical input leads to the formation of water-in-oil (W/O) emulsions (Mohammed et al., 1993; Sjoblom et al., 2001; Fingas & Fieldhouse, 2003; Mendes et al., 2019). The presence of emulsifying compounds in crude oil creates emulsion stability. This is a negative characteristic in the separation process.

Emulsion occurs when one immiscible liquid is dispersed in the form of droplets in another immiscible liquid (refer to Figure 1a for a graphical representation). These droplets are usually referred to as the dispersed or internal phase. The three major factors contributing to the formation of emulsions are i) the presence of two immiscible liquids, ii) the presence of emulsifying agents, which are surface-active agents, and iii) the involvement of sufficient mixing energy to disperse one liquid into another liquid phase as droplets (Sen, 2016).

Such emulsions are considered a ruthless problem within the petroleum industry because they lead to various costly problems in terms of production loss and transport difficulties.

Another issue is the paraffin precipitation and deposition in transport flowlines and pipelines, which is an increasing challenge for the development of deep-water subsea hydrocarbon reservoirs (Abdurahman et al., 2012). Deposits of paraffin wax cost the oil industry billions of dollars worldwide for both prevention and remediation efforts.

The production of heavy crude oils is expected to increase significantly as low viscosity crudes are depleted (Plegue et al., 1989). Currently, there are three general approaches for transportation of heavy and extra heavy oil: i) viscosity reduction, ii) drag minimization, and iii) in-situ oil upgrading (Rafael et al., 2011; Justiniano & Romero, 2017; Sousa et al., 2017; Abdulredha et al., 2020). Several special nonconventional methods for the transport of heavy oil have been proposed, and they include preheating the crude oil with subsequent pipeline heating (Layrisse, 1998; Saniere et al., 2004; Santos et al., 2020), diluting it with lighter crude oils (Iona, 1978), and injecting water sheath around the viscous crude. Each of these methods has logistic, technical, or economic drawbacks.

Another promising technique is the transport of viscous crudes as concentrated oil-in-water (O/W) emulsions (Lappin & Saur, 1989; Gregoli et al., 2006; Plasencia et al., 2013; Mendes et al., 2019). With the aid of suitable surfactants, as the water amount continues to increase, the water-in-oil emulsions reach a phase inversion point, resulting in crude oil becoming the dispersed phase, while water will become the continuous phase, i.e. oil-in-water emulsions are formed (Feng et al., 2019) (Figure 1a). The formation of O/W emulsion causes a significant reduction in its effective viscosity (Figure 1b, 1c). Because of this reduction in viscosity, transportation costs and transport-assisted problems are also controlled.

The application of oil-in-water emulsions helps to resolve the challenges of transporting highly viscous crude, as the effective viscosity of the oil-in-water emulsions system is much lower than the single-phase viscosity of heavy crude.

The technical viability of this method was demonstrated in an Indonesian pipeline (Lamb & Simpson, 1963) and in a 20 km-long, 0.203 m-diameter pipeline in California.
The present work aims to study the influence of oil in water (O/W) and water in oil (W/O) emulsions on pressure and temperature drops when it flows in a horizontal pipeline partially submerged in a river.

2. MATERIALS AND METHODS

The present work is a continuation of a previous paper by Romero et al. (2016), which analyzed heat transfer of a fixed proportion of water, oil, and gas flowing in a pipeline, by using numerical tools. The geometry of the pipeline and operational conditions are similar in both works. For that reason, our emphasis in the present article is to show how the phase inversion point of a water-in-oil emulsion is important to allow the transport of heavy oils. We use a numerical approach to analyze, mainly, the influence of water content in the pressure profile along a horizontal pipeline.

2.1 Problem statement

The oil-water mixture flows at 21 m³/d in an onshore pipeline of 3,600 m length and 4 inches in diameter. As shown in Figure 2, oil enters at the left side of the three-section pipeline at $P_{in} = 5$ kg/cm² pressure and $T_{in} = 66.7 \, ^{°}C$ temperature, being pumped along the one-dimensional horizontal pipeline with dimensions and operational conditions described in Table 1. Table 2 details the main properties of water and oil.

The dispersed mixture transported is susceptible to heat loss because the external ambient is at a lower temperature. An intense heat loss rises the oil viscosity at levels where the pressure drop requires high-energy consumption to guarantee the fluid flow until the end of the pipeline. Higher pressure drop is proportional to higher pumping power requirement, or lower flow rate.
At some point, and without any enhancement, the fluid flow would be no longer possible due to technical challenges and high economic costs associated to the process. The proposal is to increase the water content of the mixture looking for the reduction of pressure drop. The pressure drop is determined by applying the Dukler correlation (Taitel & Dukler, 1976) which considers slippage between phases. Our choice to represent the dead oil viscosity as a function of temperature and API density is the Hossain correlation (Hossain et al., 2005).

![Dukler correlation](image)

**Figure 2.** Simplified representation of a horizontal 1D pipeline divided into three sections. In this domain, the flow of water-in-oil or oil-in-water emulsion is studied. $T_m(x)$ is the mixture average temperature inside the pipeline, $T_{\text{ext}}$ is the external temperature, and $q$ represents heat loss.

### Table 1. Dimensions and operational conditions of the onshore pipeline.

| Section | Length m | Diameter in (cm) | Thickness in (mm) | Roughness in (mm) | Conditions | Ambient temperature °C |
|---------|----------|------------------|-------------------|-------------------|------------|-------------------------|
| 1       | 802      | 4 (10.16)        | 0.251 (6.37)      | 0.001 (0.0254)    | Above ground | 26                      |
| 2       | 203      | 4 (10.16)        | 0.251 (6.37)      | 0.001 (0.0254)    | Through 6 m river, base asphalt insulation | 16                      |
| 3       | 2,595    | 4 (10.16)        | 0.251 (6.37)      | 0.001 (0.0254)    | Above ground | 26                      |

### Table 2. Fluid properties.

| Property                          | Value |
|----------------------------------|-------|
| Relative water density           | 1.02  |
| Oil density, °API                | 13.2  |
| Viscosity of dead oil at 93.3 °C, cP | 69.4  |
| Viscosity of dead oil at 15.5 °C, cP | 20,269 |
| $H_2S$, %                       | 0.06  |
The Brinkman model (Brinkman, 1952) is applied to calculate the viscosity of the emulsion, with Brauner and Ullmann’s (2002) equation for the water cut off method (inversion point). Only the mathematical models related to emulsions are presented in section §2.2. More details about equations employed are available in the article of Romero et al. (2016).

The 1D governing equations, with appropriate boundary conditions, are solved using the steady-state Pipesim® software.

2.2 Water-in-oil (W/O) and oil-in-water (O/W) emulsions

2.2.1 Correlation for emulsion viscosity

Brinkman (1952) derived from Einstein’s correlation (Einstein, 1911), an equation more suitable for the calculation of dispersion viscosity, Equation (1). This correlation is indicated for the calculation of emulsion viscosity ($\mu_e$), especially the ones with high asphaltene content (Rajagopal et al., 2007).

$$\mu_e = \mu_{cp}(1 - \varepsilon_{dp})^{-n}$$  \hspace{1cm} (1)

The subscript $cp$ denotes continuous phase, and subscript $dp$ denotes the dispersed phase, $\varepsilon_{dp}$ is the volumetric fraction of dispersed phase ($0 < \varepsilon_{dp} < 1$), and exponent $n$ is defined by Taylor (1932), in Equation (2), as

$$n = 2.5 \left( \frac{\mu_{dp} + 0.4\mu_{cp}}{\mu_{dp} + \mu_{cp}} \right)$$  \hspace{1cm} (2)

Before the inversion point, the dispersed phase is the water (w), and the continuous phase is the oil (o), which is a water-in-oil (W/O) emulsion. Then, Equations (1) and (2) are represented by $\mu_e = \mu_o(1 - \varepsilon_w)^{-n}$, $n = 2.5 \left( \frac{\mu_w + 0.4\mu_o}{\mu_w + \mu_o} \right)$.

2.2.2 Phase inversion model

With the aid of suitable surfactants, the oil phase becomes dispersed in the water phase and stable oil-in-water emulsions are formed (configuration presented in Figure 1a). As a result, a significant reduction in emulsion viscosity occurs at the inversion point of the emulsion (Figures 1b and 1c).

Brauner and Ullmann (2002), through the analysis of the system’s free energy, reached a correlation for determining the volumetric fraction of oil at the inversion point ($\varepsilon_o^i$), given by Equation (3)

$$\varepsilon_o^i = \frac{\rho_R^{0.6}\mu_R^{0.4}}{1 + \rho_R^{0.6}\mu_R^{0.4}}$$  \hspace{1cm} (3)

where $\rho_R$ is the density ratio between oil and gas, $\rho_R = \rho_o/\rho_w$, and $\mu_R$ is the dynamic viscosity ratio, $\mu_R = \mu_o/\mu_w$. The volumetric fraction of water at this point is $\varepsilon_w^i = 1 - \varepsilon_o^i$.

This correlation explains the observation made in many experimental studies, that is, the more viscous phase (oil) tends to form the dispersed phase. This observation can be represented as $\rho_R^{0.6}\mu_R^{0.4} > 1$, $\varepsilon_o^i > 0.5$, and $\varepsilon_o^i \rightarrow 1$ as $\rho_R^{0.6}\mu_R^{0.4} \gg 1$, where the larger is the oil viscosity, the wider is the range of the oil volumetric fraction ($0 \leq \varepsilon_o < \varepsilon_o^i$). The configuration of oil drops dispersed in water is associated with lower surface energy.

In the range of oil volumetric fraction $0 \leq \varepsilon_o < \varepsilon_o^i$, the flow pattern will be oil-in-water dispersion, whereas water-in-oil emulsion will be obtained in the range of $\varepsilon_o^i \leq \varepsilon_o \leq 1$ (Brauner & Ullmann, 2002).

3. RESULTS AND DISCUSSION

The initial pipeline configuration is represented in software symbolic language (Figure 3). N1 and N2 are the node’s connectors between pipeline segments, sections 1, 2, and 3.

The calculated pressure gradient, at the initial condition (with mixture entering at the left side of the pipeline at $P_{in} = 5$ kg/cm² and $T_{in} = 66.7$ °C), is shown in Figure 4 at two levels of heat exchange. The fluid does not have sufficient energy to flow to the end of the 3,600 m pipeline length. It only runs through the first 2,626 m, 73% of the full length. Then, in these conditions, with $U_a = 1.135$ W/ (m² K), the production does not take place.

For the high heat exchange value, once the conditions become more unfavourable, a greater pressure drop occurs along the route, causing a smaller displacement of the fluid compared to the low heat exchange condition. More intense heat
exchange means that in sections 1 and 3, which are exposed to air, the value of the coefficient is equal to $U_a = 113.57 \text{ W/}(\text{m}^2 \text{ K})$, 100 times greater than the previous one; and in section 2, which is submerged in water, is $U_c = 1,135.7 \text{ W/}(\text{m}^2 \text{ K})$, even bigger than previous one.

In Figure 5, the oil enters the pipeline with a temperature of 66.7 °C, and decreases along the route until reaching a temperature of approximately 29.5 °C at 2,626 m, which is the maximum distance that the fluid is moved at a low heat exchange ($U_a$). As section 1 is 802 m long, section 2 is 203 m, and section 3 is 2,595 m, the oil tends to seek equilibrium with the external environment, which happens at a temperature of 26 °C, and, therefore, reaching the only part of section 3. At a high heat exchange ($U_b$), an abrupt and continuous decrease of the fluid temperature occurs until the equilibrium with the external medium, at 16 °C, can be reached. It allows the arrival of the fluid only at 863 m (part of section 2), 23.97% of the full length of the tube, with a temperature of 20 °C.
During operations, with the reduction of the oil temperature, the oil viscosity increases sharply, and paraffin eventually begins to precipitate in the inner wall of the pipeline. The appearance of paraffin deposits is manifested by the breaking of phase equilibrium, caused by the oil cooling and/or the release of the lighter fractions dissolved originally in oil. Paraffin, when exposed to a certain temperature, called WAT (wax appearance temperature), precipitates in crystal forms and is characterized by a solid phase. It deposits on the internal walls of the pipelines, obstructing the flow and promoting the increase of pressure drop in production lines.

The pressure behavior for water cut ($W_{\text{cut}}$ in the figure) varies from 0 to 90% and is shown in Figure 6. Looking at the graph, one can observe that the emulsion inversion occurs at the same value between the range $0\% < W_{\text{cut}} < 10\%$ because the pressure profile doesn't decrease drastically anymore. For $W_{\text{cut}}$ of 40, 50, 70, and 80% the pressure profiles along the pipe remained unchanged for the most part, concerning $W_{\text{cut}} = 90\%$, and, therefore, are not shown. These results assume a low heat exchange in the system.
To identify the point of inversion, water cuts varying from 0 to 10% in steps of 1% were plotted in Figure 7. The pressure profile began to change since $W_{cut} = 4\%$, representing the water cut at the inversion point. This observation can be better visualized in Figure 8, where emulsion viscosity is plotted to several values of water cut. These results also assume a low heat exchange in the system $U_a = 1.135 \text{ W/(m}^2 \text{ K)}$ in the three sections. Figure 7 shows that, with $W_{cut} = 5\%$, the oil flows through the entire extension (3,600 m) of the pipeline. However, the outlet pressure is approximately 0.41 kg/cm², which is considered a low pressure if compared to 4.1 kg/cm² reached when $W_{cut} = 10\%$.

The temperature profile, Figure 9, shows that an increase in pressure has a smaller temperature decrease reaching the final destination with approximately 27.76 °C ($W_{cut} = 5\%$) and 28 °C ($W_{cut} = 10\%$).

For water cut in the range of $0\% \leq W_{cut} \leq 90\%$ and high heat transfer condition, i.e., sections 1 and 3 with $U_b = 113.57 \text{ W/(m}^2 \text{ K)}$ and section 2 with $U_c = 1,135.7 \text{ W/(m}^2 \text{ K)}$, the pressure profile is shown in Figure 10. For $W_{cut} = 40, 50, 70,$ and $80\%$, the pressure profiles along the pipe remained significantly unchanged concerning $W_{cut} = 90\%$ and, therefore, are not plotted in Figure 10. Again, it seems that the inversion point of W/O emulsion occurs at some value between $0\% < W_{cut} < 10\%$ but that, relying solely on this data, the value remains undetermined.

![Figure 8](image_url)

**Figure 8.** Emulsion inversion point obtained for $W_{cut}$ ranging between 0% to 90%.

![Figure 9](image_url)

**Figure 9.** a) Temperature variation over the pipeline length for $W_{cut} 0\%, 5\%$ and $10\%$ with low heat exchange $U_a = 1.135 \text{ W/(m}^2 \text{ K)}$ in all sections; b) detail of region in Figure 9a.
Complementary simulations increasing water cut from 0% to 10% in steps of 1% were developed to identify the value where the pressure begins to change. The results are shown in Figure 11, where it is possible to visualize the variation along the 3,600 m length in more detail. Of course, the reduction in pressure drop can be attributed solely to water cut.

In this figure, the pressure curve with $W_{cut} = 4\%$ is where the inversion point has already occurred, and the maximal distance achieved by the mixture is 1,700 m. A small increase in water cut, from 4% to 6%, reduced the pressure difference required, allowing the mixture flow all along the pipeline extension to be delivered at 1.17 kg/cm².

Unlike small temperature variations obtained with low heat exchange (Figure 9, with $W_{cut} 0\%, 5\% e 15\%$), at high heat exchange the temperature has an abrupt decrease, from 66.7 °C, at the input plane of pipe, to 26 °C, in the first 400 m (as seen in Figure 12), with $W_{cut} = 6\%$. Comparing both profiles in the initial 400 m, the temperature gradient changes from $-0,028 \, ^\circ C/m$ (low heat exchange) to $-0.1 \, ^\circ C/m$ (high heat exchange).
As the second section is submerged in the river, the oil temperature further decreases and finds an equilibrium point with an external ambient temperature of 16 °C at 903 m (Figure 12). At 1,005 m (section 3), oil exchanges heat with air at a temperature of 26 °C, comes into equilibrium (1,330 m), and maintains this temperature until the output plane at 3,600 m. For \( W_{cut} \) of 10\%, the temperature profile along the pipe showed little change concerning Figure 12, and, for this reason, that result is not shown.

In both situations (low and high heat exchange), a \( W_{cut} \) greater than 10\% seems to be unnecessary, since the objective is to transport oil with this water and the head loss reduction obtained is satisfactory.

4. CONCLUSION

The influence of temperature drop on the flow can provide great difficulties in flowing through the pipe, especially when dealing with heavy oils. The appearance of paraffin, hydrates and/or asphaltenes are examples of problems caused by this thermal unbalance.

a) There is a need for a water cut of 5\% and 6\% for low heat exchange and high heat exchange, respectively, to drive the fluid as an oil-in-water emulsion to the delivery location;

b) The use of isolation with W/O emulsion was proved unnecessary since the pressures that reached the outlet are similar in both cases (low and high heat exchange);

c) A satisfactory head loss reduction was reached with a \( W_{cut}=10\% \) for both cases, showing that a percentage of water greater than that is unnecessary. The purpose of the pipeline is to carry the largest volume of oil possible until the delivery.

Besides, a refinement of this research involves studying pipe corrosion and the initiation of growth of paraffin deposits at oil-in-water emulsion. Because water is the continuous phase, crude oil has no contact with the pipe's wall, reducing pipe corrosion for crudes with high sulfur contents and preventing the deposition of sediments in pipes, as is common for crudes with high asphaltene contents (Poynter & Tigrina, 1970).

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