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Laminar pipeline flow of heavy oil–in–water emulsions produced by continuous in-line emulsification

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ABSTRACT

Oil-in-water emulsions have been proposed as an emergent technology to transport viscous heavy crude oils. In this work, pipeline flow properties of heavy oil–in–water emulsions and their feasibility to reduce the elevated pressure drop related to the viscous oil flow in pipelines are assessed. Rheological behavior and frictional energy loss were evaluated in a horizontal pipeline device in laminar flow. The experimental set-up consisted of a pilot-scale apparatus fitted with a ¾ in ID pipe. The flow behavior description for emulsions was obtained from flow rate and differential pressure measurements. Under pumping, emulsion apparent viscosity was found to be approximately 100 times lower than the heavy oil viscosity and the pressure drop achieved in the emulsion flow was 20 times lower than that for the flow of pure oil. Results also showed good correlations between the experimental data and the expected value of the Fanning frictional factor for disperse phase concentrations above 50 vol.%. In addition, a correlation between pumping power (related to pressure drop) and flow rate showed that significant pumping energy savings can be achieved and crude oil transportation can be enhanced using an optimal combination of internal oil content and flow rate. Overall, these results indicate that in-line emulsification is a feasible and viable method to move heavy and viscous crude oil in pipes.

1. Introduction

Heavy oil, extra-heavy oil and bitumen constitute a large amount of the fuel fossil reserves worldwide. Recent studies estimate that unconventional oil reserves, including heavy oils, extra-heavy oils and bitumen exceed 6 trillion barrels (Santos et al., 2014a,b). These oils generally display very high viscosity, which turns the utilization of conventional methods for their transportation unfeasible. Exploitation of the large heavy oil reserves may be useful for supporting the global demand of energy, fuels and other petroleum derivatives. However, the inclusion of these supplementary resources to convention reserves depend on if suitable technology is available to move high viscosity oils. The decrease of light oil reserves and the high cost of heating have reduced the potential for use of both heating and dilution for transportation of these viscous oils. In addition, the use of diluents, such as kerosene, to achieve the suitable viscosity for pumping operations is generally an expensive choice because of the high amount of these diluents required – it can reach up to the equivalent to 20% in relation to the heavy oil volume (for bitumen this amount can reach 50%). Besides, dilution is a low-efficiency method and it usually requires an additional heating to attain the pumping conditions (Yaghi and Al-Bemani, 2002). Even when the viscosity is reduced to required values, the bulk polarity of the resulting mixture increases (Gateau et al., 2004) and compatibility tests between the oils and diluent to avoid the solid formation will probably be necessary to prevent pipeline blockages (Sanière et al., 2004). Lubricated pipeline methods, which encompass techniques such as oil in water emulsion and core annular flow, stand out for the reduction of the maintenance and cleaning costs, for the increase in flow rate and for energy savings promoted by decreasing the flow friction losses. (Santos et al., 2014a).

Crude oil-in-water emulsions have been proposed as an effective way to move viscous crude oils and several studies have investigated different aspects of the production and characterization of these emulsions during the last three decades (Stockwell et al., 1988; Zhang et al., 1991; Salager et al., 2001; Langevin et al., 2004; Santos et al., 2011). In addition, it has been shown that technologies involving emulsions can enhance the oil recovery, leading to an increase in the recovery factor of heavy oil reservoir and mature fields (Bertero et al., 1994; Giuggioli and De Ghetto,

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1995; Lissant, 1997). Typically, oil-in-water emulsions present a complex composition due the presence of commercial emulsifying agents and of the natural amphiphilic compounds from crude oil. These sophisticated compositions may give rise to a complex rheological behavior under flow conditions.

While heating, dilution and partial upgrading are all methods applied to reduce the oil viscosity by modifying the oil microstructure, the flow of o/w emulsions produces a reduction of the energy frictional loss due to wall effects, or lubricated pipeline (Nuñez et al., 1998; Joseph, 1997; Bannwart, 2001; Salager et al., 2001). Crude oil-in-water emulsions are dispersions of the crude oil as small droplets into an aqueous continuous phase, avoiding the contact between oil and pipe wall during the flow (Rimmer et al., 1992; Santos et al., 2014a,b). The viscosity of the aqueous continuous phase controls the energy dissipation during flow, improving productivity by means of the increase of the flow rate and reduction of the maintenance and cleaning costs. The viscosity of the emulsion is much lower than the oil viscosity, especially for the heavy oils (Ahmed et al., 1999; Yaghi and Al-Bemani, 2002; Langevin et al., 2004; Santos et al., 2011).

Although the crude oil in water emulsions have proven positive aspects on the energy saving, some unfavorable features of the implementation of emulsions as a lubricating method need even to be fully addressed. In this way, environmental and economic issues should be highlighted. This issues include: (i) the formation of multiple emulsions (O/W/O or W/O/W), which are difficult to break; (ii) the cost of the emulsion production, which must count the high cost surfactants in the emulsion formulation and the power for mixture requirements; (iii) the emulsion breaking to recovery the crude oil in suitable conditions to application of traditional desalination and desalting methods before oil refining, and (iv) the pipe corrosion associated with presence of water. In fact, surfactant price has the major impact on the emulsion formulation cost.

The description of the rheological behavior and the assessment of the pressure drop produced during the emulsion pipeline flow can be widely applied to design and evaluate new processes and pumping systems. Crude oil-in-water emulsions generally exhibit non-Newtonian rheological behavior and they are usually pumped under laminar conditions through pipelines. In addition, it is important to assess the magnitude of the energy loss due to the frictional flow. Recently, Zhang and Xu (2016) investigated the rheological behavior of oil in water emulsions using both a rheometer and a flow loop. The authors found that the phase inversion points obtained from pipe tests are closer to those measured at high shear rheometric flow.

This work aims at investigating the rheological behavior and frictional energy losses during the laminar flow of crude oil-in-water emulsions in horizontal pipelines. The experiments were performed in a pilot-scale apparatus fitted with an inline mixer and a ¾ inch ID horizontal pipe, where emulsions were produced and evaluated under continuous operation at steady state conditions. The rheological behavior and the frictional factor were estimated from the flow rate and differential pressure measurements. Proper correlations between the experimental data and the expected values obtained from Fanning friction factor were compared for oil-in-water emulsions containing disperse phase concentration above 50 vol %. In addition, data of pumping power as a function of crude oil flow rate were computed from the pressure drop and mean velocity data, showing that significant energy savings can be achieved, when using oil-in-water emulsions, in comparison with that of oil monophasic flow, and crude oil transportation can be optimized using a smart combination of internal oil content and flow rate.

2. Material and methods

2.1. Materials

This study used samples of a Brazilian heavy oil (BHO), free of dissolved gas. BHO was treated by a dehydration process to reduce the original water content from 29.2 wt% to 0.4 wt% before the emulsifying tests were performed. The hydration process consisted in heating slightly the crude oil under controlled vacuum. The system was properly stirred to produce thin layers of oil and then allow a water vaporization. Crude oil density was 960 kg/m^3 at 25 °C, which corresponds to 17^{o}API. This oil sample has a surface tension of 31.5 mN/m at 25 °C, and interfacial tension against water of 21.6 mN/m at 25 °C. Asphaltene content was 9.0 wt% for C5I and 3.0 wt% for C7I (as determined previously by Santos et al., 2011). The emulsifying agent was a mixture of an ethoxylated nonylphenol (Renex R150, 15 EO groups) and an ethoxylated amine (TA50, 5 EO groups), both obtained as a kind gift from Oxiteno (São Paulo, Brazil) and used as received. Other chemicals used were sodium chloride (from Merck, 99.5% purity) and 1-butanol (p.a., from Nuclear). Deionized and doubly distilled water was used throughout.

2.2. Experimental set-up and procedure

2.2.1. Emulsion formulation

Crude oil-in-water emulsions were formulated using the composition shown in Table 1. This formulation was extensively tested in batch tests, and selected for its stability and suitable properties for heavy oil transportation (Santos et al., 2011, 2014a,b).

2.2.2. Emulsification and evaluation systems

An experimental apparatus was built to produce oil-in-water emulsions and evaluate their properties under continuous flow conditions. The equipment consists of an emulsification system, for producing oil-in-water emulsions, and an evaluation system, where rheological properties were assessed (see Fig. 2). The oil-in-water emulsions were confirmed by dilution tests. The apparatus is composed by (i) storage system (50 L oil tank, 50 L aqueous phase tank and 100 L emulsion tank); (ii) pumping system (two centrifuge pumps were used to move independently emulsion and aqueous phase and a gear pump was used to move the oil); (iii) emulsification system (composed by static mixers and in-line Ultraturrax T-25 mixer); and (iv) evaluation system (composed by a pipeline built with 3 m length and ¾ in ID schedule 80, pressure differential transducer and thermocouples, besides flow meters and others facilities). Performance of the apparatus was checked using a glycerin aqueous solution and tap water under different flow rates.

2.2.3. Operational procedure of the pilot unit

Crude oil and aqueous phase were stored in 50 L tanks. Liquid phases were transferred to the emulsifying system by a gear-type positive displacement pump (for the oil) and a centrifugal pump (for aqueous phase). The flow rate was controlled through a by-pass valve (for the centrifugal pump) and by a frequency inverter (for the gear pump), keeping the oil/water ratio constant. An oil/aqueous phase pre-mixture was formed inside the pipeline because of the mixing generated by turbulence. The pre-mixture flowed through the static mixer (SM1). SM1 is a 16.51 cm long device, built in ¾ inch carbon steel pipe containing 7 helicoidal elements, which was connected to the pipe system by means threaded ends). Then the oil/water mixture flowed through the dynamic mixer (DM1). The dynamic mixer was an Ultra-Turrax disperser, UTL 25 model (Ika, Germany). DM1 worked at 17,500 rpm under a motor rating input/output of 500/300 W for producing the final emulsion. Since the

Table 1
Aqueous phase composition for BHO emulsion.

Component	Quantity
Emulsifier agent	1 wt%[a]
Emulsifier composition	40 wt% TA05 + 60 wt% R150[b]
n-Butanol	1 wt%.
NaCl	1.5 wt%

[a] Weight percentage is based on the aqueous phase mass.

[b] TA05 = ethoxylated amine and R150 = Renex 150, ethoxylated nonylphenol (see Fig. 1).