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EXPERIMENTAL ANALYSIS OF WATER/OIL EMULSION EFFECTIVE VISCOSITY IN PIPELINE

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Abstract. *This paper examines the experimental results of effective viscosity for water/oil emulsions and compares them with such literature models as Einstein (1906, 1911), Furuse (1972), Taylor (1932), Brinkman (1952) and Roscoe (1952). The experiment was carried out in a 10m long horizontal pipe line with 82.8mm i.d. In the experiment, researchers used two oil viscosities, 52 mPa.s and 313 mPa.s. Experimental effective viscosity was obtained by differential pressure measurements. The water/oil emulsions were produced by an 8-stage (in line) centrifugal pump (Electrical Submersible Pump - ESP) and a choke valve. The phase inversion phenomenon was detected by the sharp decline of the pressure drop in the emulsion line. For water-in-oil emulsion (oil as the continuous phase) with the 313 mPa.s viscosity oil, the experimental data fairly agreed with Einstein's (1906, 1911) model. In the case of water-in-oil emulsions with the 52 mPa.s viscosity oil, better agreement was observed with Brinkman (1952) and Roscoe (1952) models. For the oil-in-water emulsions (water as the continuous phase), the comparison between experimental data and all tested models presented satisfactory results.*
Keywords: *effective viscosity, water/oil emulsion, phase inversion, electrical submersible pump, pressure drop.*

1. INTRODUCTION

One element of many industrial and natural processes are liquid-liquid mixtures. The mixtures can be arranged in various geometric configurations; these are the flow patterns. An oil-water flow with the two liquids mixed well is known as an emulsion. Emulsions have greater viscosity than pure oil. An emulsion is composed of a dispersed phase and a continuous phase. This emulsion may be oil-in-water, where the oil is the dispersed phase. Or the emulsion may be water-in-oil, where the water is the dispersed phase. The emulsion's properties depend on which phase is dispersed. The boundary that separates the two types of dispersion (oil-in-water and water-in-oil) is called the phase inversion point. A physical property directly affected by the continuous phase in emulsion is the apparent viscosity. The apparent viscosity of an emulsion can be influenced by other factors such as oil and water viscosities, water content, temperature, droplet size distribution and shear rate (Kokal, 2005).

Several researchers have investigated the oil-water flow in pipes that usually occurs in the petroleum industry. Arirachakaran et al. (1989) studied oil/water flows in horizontal pipes via various experiments using a wide range of oil viscosity. They proposed a correlation to predict the phase inversion point. They also observed that the main factor that influences the inversion point is the oil viscosity; the water cut required to invert the dispersed phase increases with decreasing oil viscosity. Arirachakaran and colleagues also observed a sudden drop in pressure gradient due to friction when the continuous phase changed from oil to water. Their correlation for the phase inversion point of an oil-water system was applied in various experimental data of the literature and provided satisfactory results.

Ioannou et al. (2004) analyzed the phase inversion phenomenon in oil-water flow and its effects on pressure gradient in pipelines of different materials (steel and organic glass) and two pipe diameters (60 and 32mm i.d.). The authors observed that the mixture velocity and initial conditions (water in-oil or oil-in-water emulsion) modified the phase inversion point (hysteresis effect). The effect on pressure gradient was the same as that observed by Arirachakaran et al. (1989), i.e., a drop in the pressure gradient with phase inversion.

Another methodology to predict phase inversion in pipelines was proposed by Ngan et al. (2009). This method consists of comparing the apparent viscosity when oil or water is the continuous phase. The phase inversion point is determined when these apparent viscosities are equal. The method also uses various correlations presented in the literature to predict the mixture viscosity. Brinkman's (1952), Roscoe's (1952), Furuse's (1972) and Pal's (2001) correlations predicted the inversion within the experimental phase inversion range. This methodology was also compared with critical phase fraction models from the literature. A satisfactory result for apparent viscosity was obtained between models by Yeh et al. (1964) and Ngan et al. (2009) as well as for experimental data for a range of oil viscosities.

Guet et al. (2006) proposed a model to obtain the superficial velocities in horizontal and slightly inclined oil-water pipe flow conditions using pressure gradient and mixture density data. To determine the inversion point for dispersion of oil-in-water or water-in-oil pipe flow, Arirachakaran et al. (1989) model was suggested. This model was used to develop a hybrid model for the dispersion effective viscosity. Its experimental validation was done in an 82.8-mm i.d. and 15-m length pipeline at various inclinations. The new hybrid viscosity model was based on drop break-up and coalescence effects and reasonably described the experimental data. The authors suggested a more detailed study of the effective viscosity with droplet size distribution by means of local measurements. A reasonable agreement between the proposed model to determinate the superficial velocities and the experimental data was found.

Using six different crude oils (viscosities ranging from 4.8 to 23.5 mPa.s), Plasencia et al. (2013) carried out a water-in-crude oil emulsions pipe flow comparative study in a small flow loop. They calculated the effective viscosity by pressure drop measurement. The phase inversion point and the in-situ droplet size distribution were measured using a Focused Beam Reflectance Measurement (FBRM) technique. Plasencia et al. (2013) observed a similar increase of emulsion viscosity with the six crude oils up to 30% water cut, and then its viscosities differences increased. They noticed the formation of smaller droplets with the increase of shear rates caused by mixture velocity. With the increase of water cut and with the phase inversion point approach, larger droplets showed up.

This study aims to compare the experimental water/oil emulsion effective viscosities with the Einstein (1906, 1911), Furuse (1972), Taylor (1932), Brinkman (1952), and Roscoe (1952) models for two oil viscosities (52 and 313 mPa.s).

2. EXPERIMENTAL PROCEDURE

2.1 Experimental facility

An experimental flow loop was designed to reproduce oil/water emulsion flow (Figure 1). The fluids were mixed at the intersection between the oil and water line prior to the ESP inlet. This mixture passed through an 8-stage ESP and then entered the return line that connected it with the oil/water separator tank. The temperature of the emulsion line (Ti) was controlled using a heat exchanger and a heat pump installed at the oil line. The oil viscosity was estimated by temperature (Ti).

The oil was injected by using a progressive cavity pump and the water by using a centrifugal pump. Before the oil and water mixing process, the water fraction contained in oil flow is verified using the water cut meter present in the oil line. Afterwards, the water was added until it reached the desired water cut. For each data acquisition point it was necessary to wait for the total flow rate and the temperature stabilization.

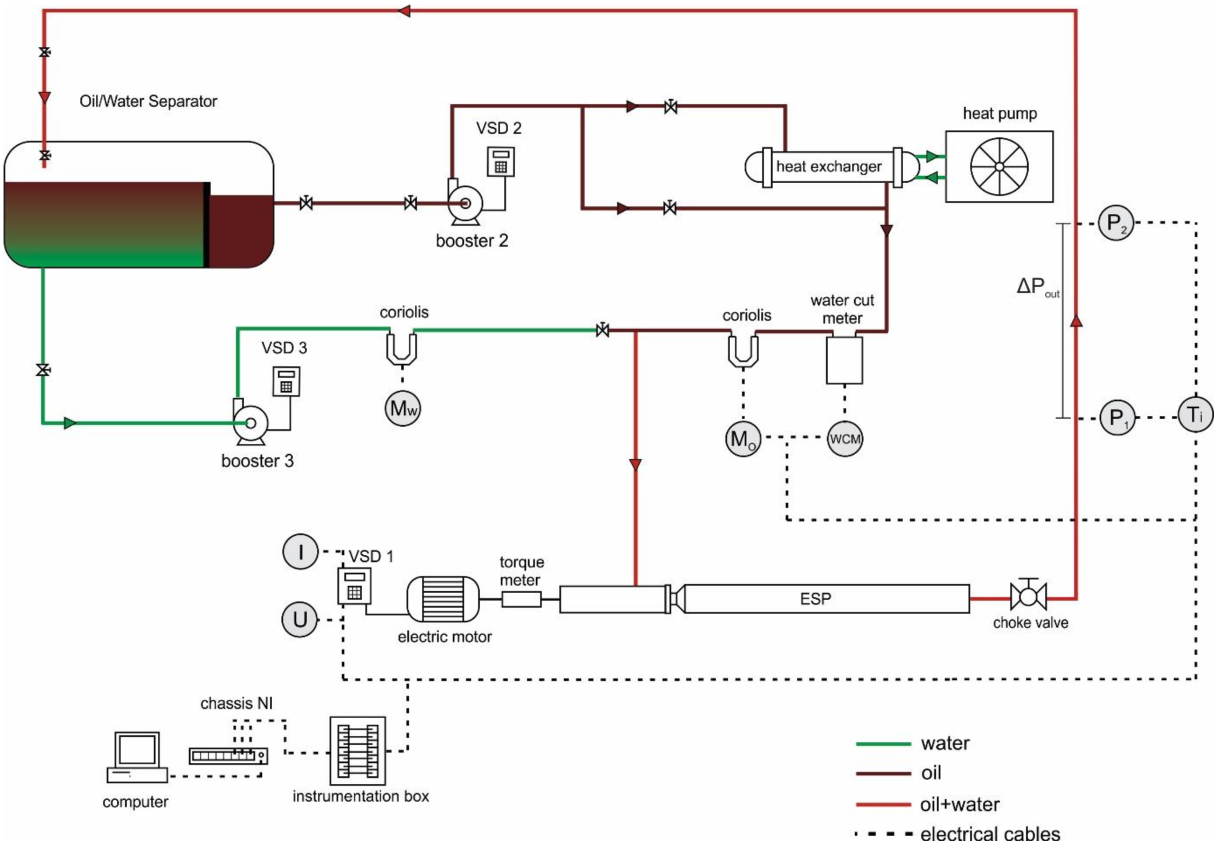

Figure 1: Experimental flow loop.

The test parameters are shown in Table (1). During each test, the total flow rate, temperature, and ESP rotating speed were kept constant.

Table 1. Test conditions.

Temperature [°C] (±0.25)	Oil viscosity [mPa.s] (±1)	Total flow rate [m³/h] (±0.05)	ESP rotating speed [rad/s] (±0.2)
50.15	52	25.72	188.5
20.31	313	40.42	251.3

Besides the turbulent energy caused by the oil-water flow, the ESP and choke valve—due to their shear effects—cooperated with the emulsion formation.

2.2 Emulsion effective viscosity

Frictional pressure gradient of emulsion was obtained through differential pressure transducers installed in the horizontal pipeline section at exit (oil/water pipeline) of the ESP. These data make it possible to determinate the effective friction factors and Reynolds number for the mixture.

The effective friction factors are obtainable through Eq. (1):

$$f = \frac{2d\Delta P}{\rho_e U_m^2 L} \tag{1}$$

where d is internal diameter, ΔP is the differential pressure, ρ_e is emulsion specific mass, U_m is mixture velocity, and L is the distance between the differential pressure taps.

Whereas ρ_e was calculated from homogeneous model, Eq. (2).

$$\rho_e = \phi\, \rho_w + (1-\phi)\, \rho_o \tag{2}$$

where ρ_w is the water specific mass, ρ_o is the oil specific mass, and ϕ is the water volumetric fraction (water cut).

From the effective friction factors (Eq.1), the Reynolds number of the mixture (Re_m) can be calculated via Eq. (3) for laminar flow and Eqs. (4) and (5) for turbulent flow. In the case of turbulent flow, the Haaland (1983) and Swamee-Jain (1976) correlations for friction factor, Eq. (4) and Eq. (5), respectively, were used. The correlation that best represented the system was used to determine the turbulent friction factor.

$$f = \frac{64}{Re_m} \tag{3}$$

$$f = \left[-1.8 log_{10} \left(\frac{6.9}{Re_m} + \left(\frac{e}{3.7d} \right)^{1.11} \right) \right]^{-2} \tag{4}$$

$$f = 0.25 \left[log_{10} \left(\frac{5.74}{{Re_m}^{0.9}} + \frac{e}{3.7d} \right) \right]^{-2} \tag{5}$$

where e is the pipe roughness.

Initially, the Reynolds number for the mixture (Re_m) was calculated assuming laminar flow. If the value obtained was greater than 2300, the friction factor was recalculated for turbulent flow. After that, the effective viscosity (μ_ϕ) was calculated using Eq. (6).

$$\mu_\phi = \frac{\rho_e U_m d}{Re_m} \tag{6}$$

2.3 Effective viscosity models

The models approached are based on the phases viscosity (dispersed and continuous phase) and water cut. These models do not address the effect of the droplet size. Einstein (1906, 1911) presented the first linear relationship between viscosity and the fraction of dispersed phase, Eq. (7), proposed for small solid spheres dispersed in an infinite fluid (continuous phase). Thus, it does not consider the interaction between the small rigid spheres. Einstein's model (Eq. 7) can provide good results for emulsions in cases where the droplets can be assumed to be rigid spheres in an infinite continuous phase, i.e., high interfacial tension, high viscosity of the dispersed phase, tiny droplets.

$$\mu_\phi = (1 + 2.5\phi)\, \mu_c \tag{7}$$

where μ_c is the viscosity of the continuous phase.

Einsten's model (1906, 1911) was improved by Taylor's equation (Eq. 8), which assumed the effect of the internal circulation caused by the tangential stresses on the particle surface on the drops. Thus, Taylor (1932) introduced in his equation a term with both phase viscosities, thus taking into account the deformation of the drops by the continuous phase. When the dispersed phase is more viscous than the continuous phase (droplets behaving like hard spheres), then Taylor's equation turns into Einstein's equation.

$$\mu_\phi = \left[1 + 2.5\phi \left(\frac{0.4 + \mu_d / \mu_c}{1 + \mu_d / \mu_c} \right) \right] \mu_c \tag{8}$$

where μ_d is the viscosity of the dispersed phase.

Furuse's model (1972) was based on Einstein's model. It considered the hydrodynamic effects' influence on the neighboring droplets in a concentrated solution, Eq. (9). Brinkman (1952) and Roscoe (1952) analyzed the increase of effective viscosity with the addition of one solute particle in a dispersion of known concentration, Eq. (10). Although the droplet size is not analyzed, this model considers a polydispersity system without interactions between the neighboring particles.

$$\mu_{\phi} = \frac{1+0.5\phi}{(1-\phi)^2}\mu_c \tag{9}$$

$$\mu_{\phi} = (1-\phi)^{-2.5}\mu_c \tag{10}$$

Used in the experiments, for comparison purposes, were two oil viscosities (52mPa.s and 313 mPa.s). In both experiments the emulsion flow was laminar before the phase inversion point (oil as a continuous phase) and turbulent after the inversion point (water as a continuous phase). The phase inversion point was determined by Arirachakaran et al. (1989) model, Eq. (11).

$$f_{w,INV} = 0.500 - 0.1108\log\left(\frac{\mu_o}{\mu_w}\right) \tag{11}$$

where μ_o is the oil viscosity and μ_w is the water viscosity.

3. RESULTS AND DISCUSSION

3.1 Friction factor analysis

This section compares the indirect measured effective viscosity with some correlations presented in Ngan et al. (2009) (Einstein, 1906, 1911; Taylor, 1932; Brinkman, 1952; Roscoe, 1952; Furuse, 1972). Before the comparison, researchers verified the friction factor correlation that best represented the system. Thus, a water singe-phase flow experiment was performed and, to determine the friction factor, the results were compared, as shown in Fig. (2), to the measured differential pressure at the emulsion line with the theoretical differential pressure calculated by Haaland (1983) (Eq. 4) and Swamee-Jain (1976) (Eq. 5) correlations.

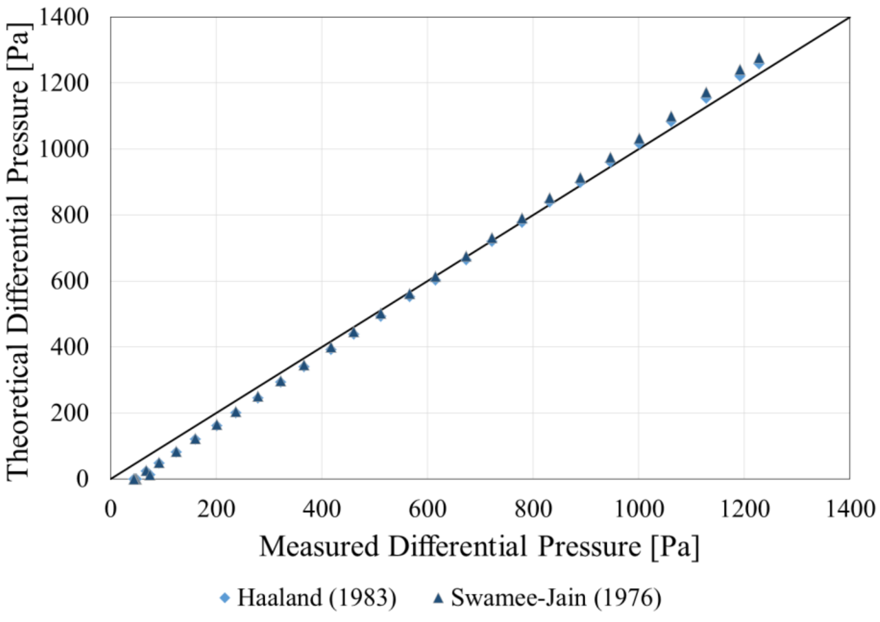

Figure 2. Comparison of experimental differential pressure with theoretical differential pressure using friction factor calculated by Halaand (1983) and Swamee-Jain (1976.)

Both correlations agreed with experimental data, but the Haaland (1983) presented the best results for high differential pressure. Hence, this was chosen to determinate the emulsion effective viscosity.

3.2 Effective viscosity comparison

Figure (3) presents the experimental data of effective viscosity as a function of the water cut and how it compares with the models from the literature (Einstein, 1906, 1911; Taylor, 1932; Brinkman, 1952 and Roscoe, 1952 and Furuse, 1972) for the oil viscosity of 52 mPa.s.

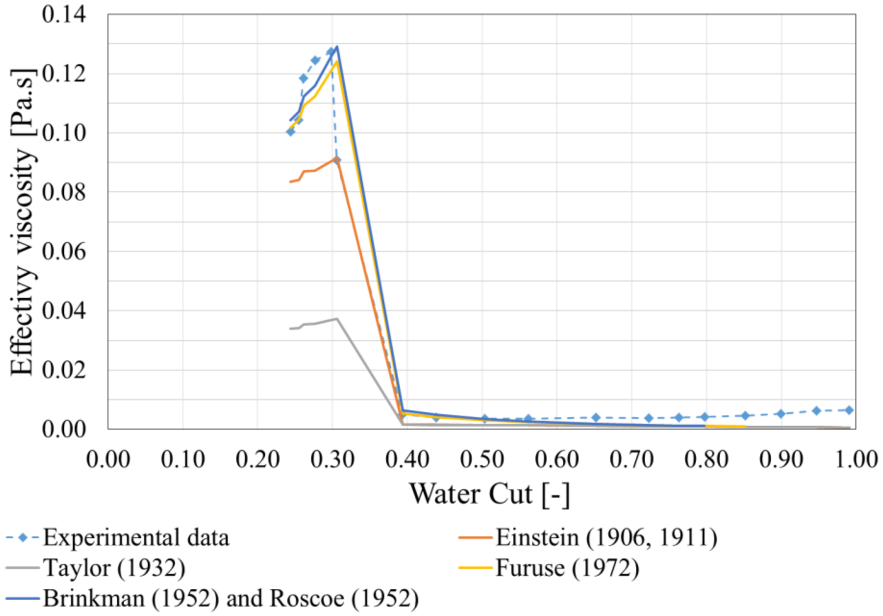

Figure 3. Comparison between experimental effective viscosity and the prediction models for 52 mPa.s oil viscosity.

The experimental data, before phase inversion, is best represented by the Brinkman (1952), Roscoe (1952), and Furuse (1972) models. Thus, one can conclude that neighboring droplets (concentrated solution) wield hydrodynamic effects in this system due to the lower viscosity of the continuous phase (52 mPa.s). After the phase inversion point, all the models addressed in this study provided the same prediction for the oil-in-water emulsions and presented good agreement with the experimental data. The small deviation at the end of the experimental curve may be related to experimental uncertainties.

Fig. (4) shows a comparison between the experimental data and literature models for the oil viscosity of 313 mPa.s.

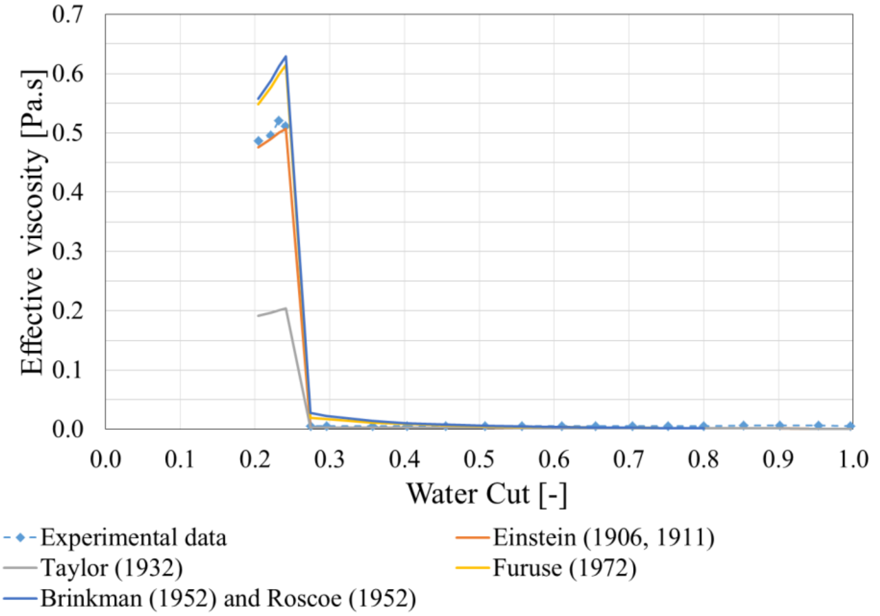

Figure 4. Comparison between experimental effective viscosity and the prediction models for 313 mPa.s oil viscosity.

For the 313 mPa.s oil viscosity, Einstein (1906, 1911) presented the best result for effective viscosity before phase inversion point. In this experiment, it may concluded that the droplets behave as small rigid spheres and there are no interactions between them. After the phase inversion point, all models tested showed good agreement with the experimental data.

4. CONCLUSIONS

The emulsion-effective viscosity was indirectly obtained through measurements of the differential pressure in an emulsion line (ESP exit). Four models of the dispersions' effective viscosity (Einstein, 1906, 1911; Taylor, 1932; Brinkman, 1952 and Roscoe, 1952 and Furuse, 1972) were compared with the experimental data for two oil viscosities, 52 and 313 mPa.s. After the inversion point, all models tested presented satisfactory agreement with measured effective viscosity for both oil viscosities. Before the phase inversion point, the Brinkman (1952) and Roscoe (1952) models showed good agreement with the experimental data for the 52 mPa.s oil viscosity (polydispersed system). For 313 mPa.s, Einstein (1906, 1911) presented the best effective viscosity prediction (smaller droplet sizes behaving like rigid spheres).

5. ACKNOWLEDGEMENTS

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