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THEORETICAL STUDY OF MIXTURE FRICTION FACTOR AND APPARENT VISCOSITY MODELS FOR HORIZONTAL OIL-WATER DISPERSED FLOW PATTERN

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Abstract. *Multiphase flows are present in many industrial processes, its understanding is essential to improve such processes. As mature oil fields are being developed the amount of water produced together with the oil increases and so increases the interest in understanding liquid-liquid flows. Going straight this reality, the equipment's dimension is intrinsically connected to multiphase flows characteristics correct being predicted, so allowing maximizing the productivities and reducing the operational costs. Within the horizontal liquid-liquid flow patterns, the dispersed flow patterns are of interest as they can be observed in several locations of the production line, such as valves, pumps and others. So, the correct prediction of dispersion characteristics such as apparent viscosity is necessary. This study proposes a theoretical work on comparison of experimental data for viscous oil-water flows from literature and models for apparent viscosity. This will be performed in two ways, comparing data of pressure gradient obtained in laboratories with the theoretical calculations as a function of the mixture friction factor and the apparent viscosity models.*

Keywords: *Liquid-liquid flows, dispersed flows, mixture friction factor, apparent viscosity, pressure gradient*

1. INTRODUCTION

Since the Industrial Age interest in multiphase flows has become important and expressive for the new equipment and technologies´ development. Studies began to be directed according to the different demands of the industries. However, in the last decades, the petroleum industry has become one of the main sponsors of this research, and its main motivation is the reduction of costs. Generally during oil exploration, the flow in the pipes occurs as an immiscible mixture (oil, water, sand and gas) assuming different flow patterns. With the increasing demand for oil associated with increasing distances in off-shore operations, there is the need to guarantee the flow of the multiphase mixture in an economical way.

Concerned with high investments, one of the greatest challenges in oil production is to minimize the amount of energy needed to perform this flow and for this it is fundamental to know the behavior of the multiphase flows. Among the several difficulties, one front study is associated with horizontal two-phase flows (liquid-liquid), more directly dispersed oil-water flow, which is the main objective of our study.

Currently, there are many articles about multiphase flows' behavior, but the most of them is directed to gas-liquid flows. One of the solutions was to apply the knowledge acquired in the gas-liquid flow to the liquid-liquid flow, but it was observed that this correlation was wrong to estimate the characteristics of such flows, as the pressure gradient and the volumetric fraction (holdup).

Generally, the formation of dispersed and emulsion flow patterns is associated with the supply of external energy to the water and oil system such as a hydraulic pump, centrifugal pumps or even flow through constraints such as valves. Water-in-oil dispersions (Dw/o) are not desired by the petroleum industry because they have a high viscosity and consequently a high pressure gradient, making the operation impracticable. Now, the oil-in-water dispersion (Do/w) is interesting because it has a real reduction in the apparent viscosity. Regardless of the flow pattern, it becomes necessary to understand the behavior and identify which physical properties can be considered to develop a mathematical model that represents the reality of the system.

For the calculation of the oil and water dispersion pressure gradient, many authors consider the homogeneous model adequate to equate the mathematical model (Trallero, 1995). In this line, using the properties of each water or oil phase, it is possible to simulate the pressure gradient of this mixture and compare it with the data obtained in the laboratory.

However, a number of distortions were observed, leading to further research to identify the true reasons for these differences. For pressure gradient calculations, there are two ways of conducting mathematical simulations through apparent viscosity and through mixture friction factor for both laminar and turbulent flow (Vielma, 2006). The essence in these experiments is to analyze the two-phase flow with different water cut and velocity conditions and then through pressure transmitters the data are collected. Many authors have proposed correlations for apparent viscosity for dispersed flows since 1906 with Albert Einstein. Currently there are many correlations presented by several authors. When it is observed that the apparent viscosity varies significantly from single-phase viscosities, it is understood that the fluid may exhibit Newtonian and non-Newtonian behavior (Vielma, 2006). Generally, for low fractions of the dispersed phase, the mixture behaves as a Newtonian fluid, and for high fractions of the dispersed phase, they behave as non-Newtonian.

In this article several models for apparent viscosity and the mixture friction factor approach are compared with experimental data of viscous oil-water flows in dispersed flow pattern from literature.

2. PRESSURE GRADIENT

For the pressure gradient calculation, two forms (apparent viscosity x mixture friction factor) are widely studied. In order to identify which model is more accurate comparison to experimental data are performed. In the mixture friction factor approach, it is governed by the shear equation and is more applied to an unstable turbulent regime. The apparent viscosity approach is based on correlations based on the viscosities and volumetric fraction of each phase. It is best suited for laminar and stable turbulent regimes (Vielma, 2006). For dispersed flows, the calculations will follow the homogeneous model, as defended by several authors (Trallero, 1995, Guet et al., 2006). We are presuming that there is no slippage between the water-oil phases and the properties follow as a Newtonian fluid.

Due the flows are horizontal with incompressible fluids, the gradient pressure associated with gravity and acceleration was disregarded. Thus, the pressure gradient is only the friction part as described in Eq. (1):

$$\frac{\delta p}{\delta L} = -\frac{f_m * \rho_m * U_{ms}^2}{2 * D} \tag{1}$$

where f_m is the mixture friction factor, ρ_m is the mixture density, U_{ms} is the mixture velocity and D is the pipe internal diameter. The friction factor is calculated based on the Reynolds number and the apparent viscosity. The mixture density is calculated through the phases' densities and volumetric fraction (homogeneous model).

2.1 Pressure gradient by apparent viscosity

The mixture observed in dispersed two-phase flows can present a Newtonian or non-Newtonian behavior according to the fractions of water. The behavior of the mixture is directly connected to the dispersed phase. It is observed that the dispersed phase influences the apparent viscosity, for this reason the stable or unstable term of the dispersed phase may be the key in understanding the behavior of this fluid as to its coalescence ability.

Due the two-phase flow has a different viscosity from the one of each phase, it is important to correlate these viscosities with an apparent viscosity model. Several authors developed correlation for such apparent viscosity, and we will apply them to find the best match. To build the table 1 all information was taken from Vielma (2006) and Bulgarelli (2018).

Table 1. Apparent Viscosity Models

Einstein (1906)	$\mu_e = (1 + 2.5 * \lambda_{dispersa}) * \mu_c$
Taylor (1932)	$\mu_e = (1 + 2.5 * A * \lambda_{dispersa}) * \mu_c$
Richardson (1933)	$\mu_e = [EXP(k * \lambda_{disperso})] * \mu_c$ k – empirical constant
Levinton & Leighton (1936)	$\mu_e = \{EXP[2.5 * A * (\lambda_{dispersa} + \lambda_{dispersa}^{5/3} + \lambda_{dispersa}^{11/3})]\} * \mu_c$ $A = (\mu_c + 2.5 * \mu_d) / (2.5 * \mu_c + 2.5 * \mu_d)$
Guth & Simha (1936)	$\mu_e = (1 + 2.5 * \lambda_{dispersa} + 14.1 * \lambda_{dispersa}^2) * \mu_c$
Broughton & Squires (1938)	$\mu_e = k_1 * [EXP(k_2 * \lambda_{dispersa})] * \mu_c$ k1, k2 – empirical constants
Van (1948)	$\mu_e = [EXP(2.5 * \lambda_{dispersa}) / (1 - 0.609 * \lambda_{dispersa})] * \mu_c$
Mooney (1951)	$\mu_e = [EXP(2.5 * \lambda_{dispersa}) / (1 - k_1 * \lambda_{dispersa})] * \mu_c$

	k1 – empirical constant
Brinkman (1952)	$\mu_e = [(1-\lambda_{dispersa})^{-2.5}] * \mu_c$
Maron-Pierce (1956)	$\mu_e = [(1-\lambda_{dispersa} / \lambda_{\max})^{-2}] * \mu_c$
Dougherty & Krieger (1959)	$\mu_e = [(1-\lambda_{dispersa} / \lambda_{\max})^{-\mu_i * \lambda_{\max}}] * \mu_c$
Eiler (1962)	$\mu_e = [1+2.5 * \lambda_{dispersa} * (1-a_e * \lambda_{dispersa})^{-1}]^2 * \mu_c$
Thomas (1965)	$\mu_e = [1+2.5 * \lambda_{dispersa} + 10.05 * \lambda_{dispersa}^2 + 0.00273 * EXP(16.6 * \lambda_{dispersa})] * \mu_c$
Chong et al. (1971)	$\mu_e = [1+0.75 * (\lambda_{dispersa} / \lambda_{\max}) * (1-\lambda_{dispersa} / \lambda_{\max})^{-1}]^2 * \mu_c$
Furuse (1972)	$\mu_e = [(1+0.5 * \lambda_{dispersa}) / (1-\lambda_{dispersa})^2] * \mu_c$
Barnea & Mizrahi (1973)	$\mu_e = \{EXP[(k1 * \lambda_{dispersa}) / (1-k2 * \lambda_{\max})]\} * \mu_c$
Barnea & Mizrahi (1975)	$\mu_e = B * \{[(2 * B/3) + (\mu_d / \mu_c)] / [B + \mu_d / \mu_c]\} * \mu_c$ $A = (\mu_c + 2.5 * \mu_d) / (2.5 * \mu_c + 2.5 * \mu_d)$ $B = \{EXP(5 * A * \lambda_{dispersa}) / [3 * (1-\lambda_{dispersa})]\}$
Pal & Rhodes (1989)	$\mu_e = [1+(\lambda_{dispersa} / k) / (1.1884 - \lambda_{dispersa} / k)] * \mu_c$ k – empirical constant
Polynomial 1	$\mu_e = (1 + k_1 * \lambda_{dispersa} + k_2 * \lambda_{dispersa}^2) * \mu_c$ k1, k2 – empirical constant
Polynomial 2	$\mu_e = (1 + k_1 * \lambda_{dispersa} + k_2 * \lambda_{dispersa}^2 + k_3 * \lambda_{dispersa}^3) * \mu_c$ k1, k2, k3 – empirical constants
Polynomial 3	$\mu_e = [(1 + k1 * \lambda_{dispersa} + k2 * \lambda^2{}_{dispersa} + k3 * \lambda_{dispersa}^3) / (1 + k3 * \lambda_{dispersa})^{k4}] * \mu_c$ k1, k2, k3, k4 – empirical constants

Different authors consider some constants (k, k1, k2….) in their equations. Even these constants being obtained experimentally, these authors provide the empirical constant values as a function of the dispersed (Do/w or Dw/o) flow. The table 2 presents the empirical constants for several models (Vielma, 2006).

Table 2. Empirical constants for apparent viscosity correlation.

Correlation Author	**Water in oil dispersion**	**Oil in water dispersion**
Richardson (1933)	k=2.37	k=3.44
Broughton & Squires (1938)	k1=2.22; k2=-0.90	k1=0.04; k2=8.53
Mooney (1952)	k=-0.37	k=0.50
Barnea & Mizrahi (1973)	k1=1.97; k2=0.60	k1=1.38; k2=0.94
Pal & Rhodes (1959)	k=1.02	k=0.89
Polynomial 1 – (Barnea & Mizrahi, 1973)	k1=-4.89; k2=12.42	k1=-5.55; k2=11.65
Polynomial 2 – (Barnea & Mizrahi, 1973)	k1=-1.39 k3=60.66 k2=-17.83	k1= -9.0 k3=-9.56 k2=23.27
Polynomial 3 – (Salager)	k1=-4.96 k3=8652.15 k2=10.31 k4=-0.18	k1=-4.11 k3=4.65 k2=4.65 k4=-2.61

With the apparent viscosity calculated, we are ready to find the mixture Reynolds number and determine which friction factor will be considered for friction pressure gradient calculus. For friction factor, it is considered the table below:

Table 3. Friction factor models based on Reynolds number.

a	n	Flow	Re
16	1	Laminar	Re<2000
0.079	0.25	Turbulent	Re$<10^5$
0.046	0.2	Turbulent	Re$>10^5$

$$f_m = a * \mathrm{Re}_m^{-n} \quad (2)$$

2.2 Pressure gradient by mixture friction factor

The friction factor is a dimensionless value which relates shear stress and kinetic energy. For single-phase flows and Newtonian fluids, the friction factor is very well established, depending exclusively on the Reynolds number and the roughness of the pipe. Both the Fanning equation and the Moody diagram can be used for a good approximation of the friction factor in laminar flows. Turbulence occurs when viscous forces are not able to counteract the disturbances generated by the roughness of the tube walls. Thus, the calculation for the friction factor follows Table (2) for smooth walls.

Another way to estimate the friction factor is to use the law of the wall, Prandtl developed it and consists of integrating the velocity profile into the wall layer of the tube. It serves both single-phase and dispersed two-phase flows.

$$\frac{1}{\sqrt{f}} = 4*\log(\mathrm{Re}*\sqrt{f}) - 0,4 \tag{3}$$

For rough pipes, the roughness index (ε) should be added to the equation as below:

$$\frac{1}{\sqrt{f}} = 4*\log\left(\frac{\mathrm{Re}*\sqrt{f}}{1+0,2*\frac{\varepsilon}{d}*\mathrm{Re}*\sqrt{f}}\right) - 0,4 \tag{4}$$

3. COMPARISON WITH EXPERIMENTAL DATA

For our theoretical study, the database used was from Castro (2013). Only the data related to the dispersed flow were considered for the calculations. This database considers water fraction above 64%. Using the superficial velocities of the oil and water, the water fraction was obtained. The pressure gradient information was used to calculate both the friction factor and the apparent viscosity from the experimental data.

In figure 1, it is possible to compare the behavior of the apparent viscosity models as a function of the water fraction. Comparing the models of the different authors with experimental data, we observed that the precision of these models increases for high fractions of water as the viscosity approximates water viscosity, but we do not observe a good approximation for fractions of water below 90% for none of the models.

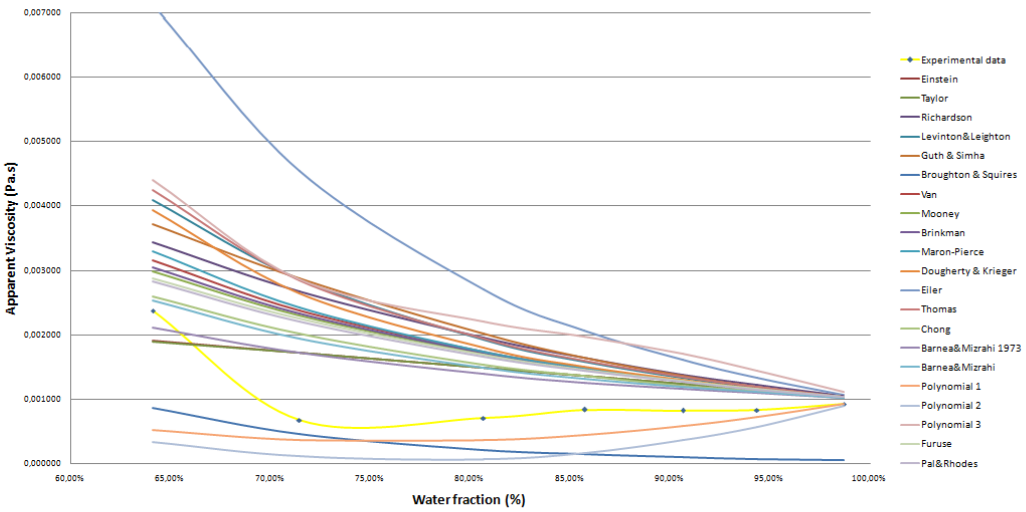

Figure 1. Apparent Viscosity x Water Fraction

Figure 2 presents comparison of the friction factor calculated directly and by apparent viscosity model. When analyzing these curves, all of curves have the similar tendency, but only two curves are approximate the experimental data.

The range of 64% to 73% of the water fraction, the mixture friction factor model is more appropriated to calculate the friction factor. However, for larger volumetric fractions of water, the Polynomial 1 model is the curve that most closely approximates the behavior obtained in the laboratory.

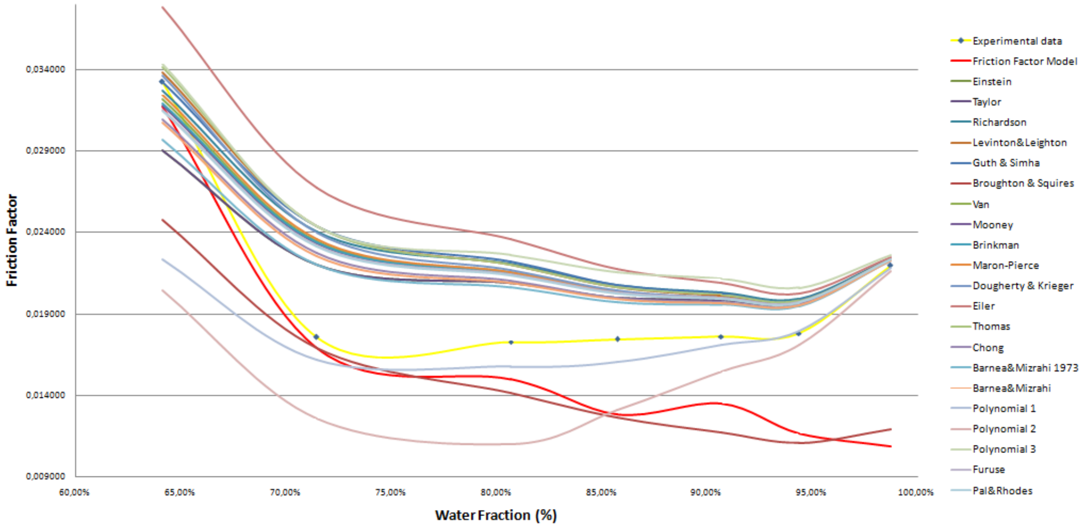

Figure 2. Friction Factor x Water Fraction

In Figure 3, we observe that the pressure gradient reaches its peak pressure in the region between 83% and 87%, decreasing when it exceeds this range. It is observed that the pressure gradient when calculated through the friction factor, obtains a better result in the range of 60% to 80%, but the apparent viscosity model "Polynomial 1" presents a better result after this range.

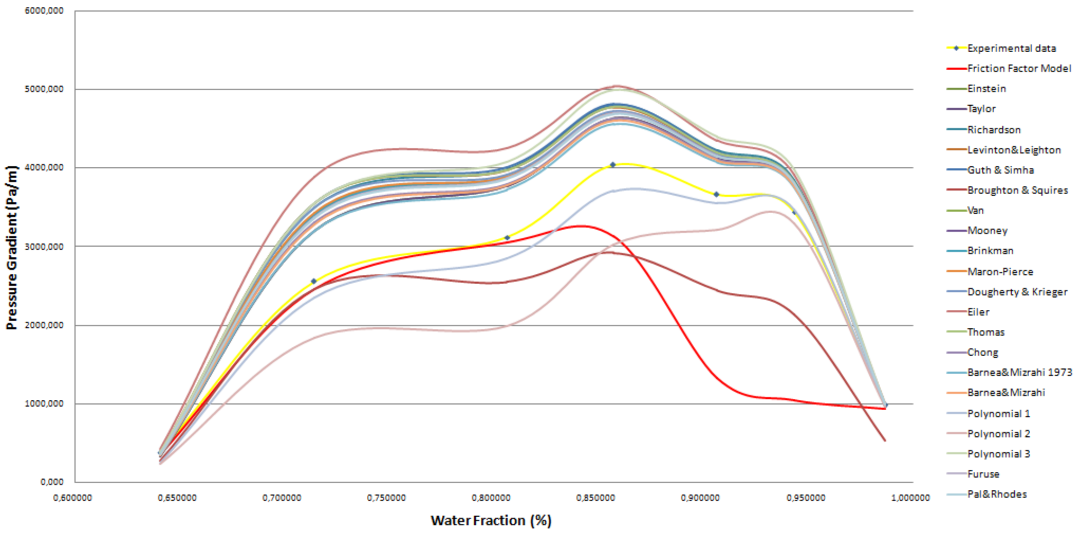

Figure 3. Pressure Gradient x Water Fraction.

In figure 4, it is possible to see the standard deviation of all models for apparent viscosity and mixture friction factor are analyzed for pressure gradient. It is observed that for the range of analysis the model Polynomial 1 is the best one, the standard deviation was 7,35%, and the mixture friction factor is the worse, more than 50%.

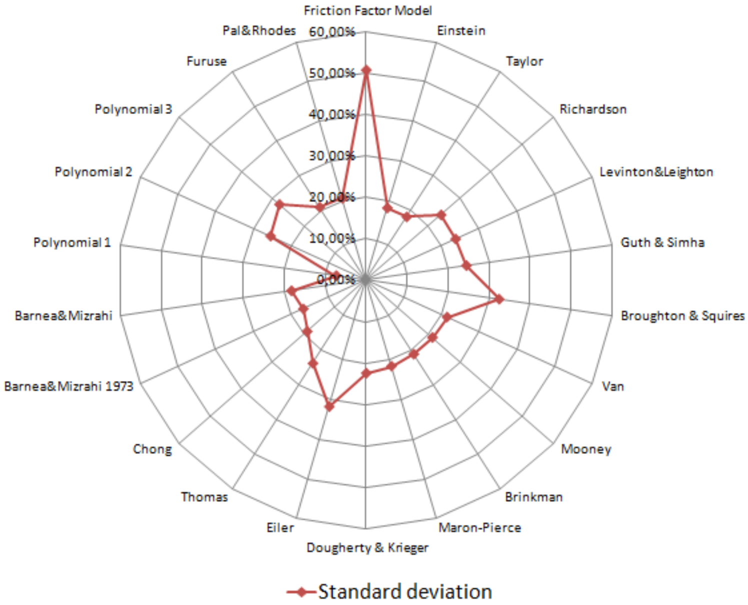

Figure 4. Pressure Gradient standard deviation

4. CONCLUSIONS

When we analyze the two-phase flow (liquid-liquid), we can project the value of the pressure loss in pipes from the apparent viscosity or the mixture friction factor models. For our theoretical study, the data analyzed took into account fractions of water over 60%,

When we compare the curves of apparent viscosity from different authors, we couldn´t find a good solution. All the curves represented error more than 50%. Only the high volumetric water, the accuracy is good enough (more than 95%).

For friction factor, it was compared values from apparent viscosity and mixture fraction factor. No one give us a good match, but several models from apparent viscosity offered better accuracy than mixture fraction factor.

Finally, when we observe the Fig. 3, two distinct regions are present, where the reference is 83% of water fraction. The first region, indices below this reference, we notice that the curve that approaches more closely is that of mixture friction factor. The second area, the best match equation is polynomial 1 apparent viscosity model.

In general, the apparent viscosity gives us the feeling of providing a more generalist results of the flow, perhaps without high accuracy.

Obviously for a more reliable conclusion, new data will be needed to compare the behaviors themselves and finally develop new equations that seek to approximate the real behaviors of these flows.

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