Model of pressure losses in pipes during the transport of heavy oil with 11 API gravity

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Abstract**—**During the transport of heavy oils by pipes, there are difficulties related to their high viscosity with non-Newtonian behavior, directly affecting the performance of the transport facilities, because of the inaccuracies of the calculation methodologies. In the present work it obtain a mathematical model that describes the pressure variations for non-Newtonian oil flow in pipes; obtained from the limitations of methodologies and correlations, that allows the evaluation of the simultaneous effects of the viscous force and of mixing in the laminar and turbulent regime during the transport of heavy oils by pipes. Equation 15 is the generalized theoretical model for the calculation of pressure variations in the transport of heavy crude oil by pipeline. It takes into account the variation of temperature during transport, the effects of viscous friction, and the effects of mixing between flow layers. The values of the flow index for the transport of heavy oil of 11ºAPI by pipes oscillates between 0,917 and 0,929 in function of the temperature values that vary between 29 ^{o}C and 69.8 ^{o}C. The consistency index varies between 13.55 Pa.s and 1.46 Pa.s for the same temperature range.

Keywords**–**Heavy oil, rheological behavior, pressure gradient.

I. INTRODUCTION

The heavy oil transport facilities are considered as high consumers of energy, they represent an important index in the parameters of industrial efficiency [1]. The increase of the performance of the different equipment and the rational use of the available resources, have a considerable impact on the reduction of production costs, due to high viscosity and operational problems such as high pumping costs [2]. The methods for the estimation of pressure losses in pipelines are based entirely on studies and correlation of experimental data, due to the non-Newtonian behavior of the fluid;

which shows different behavior between the results of computational simulations and experimental values [3]-[4]. Hassanean analyze the effect of a commercially type of drag reducing agent on the crude oil production flow lines located in the Egyptian western desert [5]. The results showed that this drag reducing agent has great effects on the pressure drop and fanning factor.

In the selection and operational optimization of the transportation systems of these fuels, assumes a constant viscosity and does not have account for its rheological model, behavior of oil viscosity with relation to the gradient velocity variables and the temperature, which are significant on the viscosity of non-Newtonian fluids treated by heating [6].

Related to the models for the estimation of load losses in pipes, other researchers developed a theoretical-experimental equation take in consideration the flowed and dense phases. With the employment of the pattern it is simulated the dependence of the pressure losses, the solid flow and the concentration of the mixture in function of the gas flow of the lateritic mineral pneumatic transport systems. The authors predict the areas of lower energy consumption and make the correct selection of the systems [7]-[8].

Among the investigations related to the transport of heavy oils by pipes, the work carried out by [9]-[10] stands out. The pressure-driven displacement of a non-Newtonian fluid by a Newtonian fluid in a two-dimensional channel is investigated via a multiphase lattice Boltzmann method using a non-ideal gas equation of state well-suited for two incompressible fluids. The code has been validated by comparing the results obtained using different regularized models, proposed in the literature, to model the viscoplasticity of the displaced material [10].

Frigaard and Taghavi [11]-[12], propose the displacement models by pipe of a crude oil; they are applicable to different flow rates (transition, laminar and turbulent), considering different pipe diameters. Three distinct flow types belonging to this central displacement are identified namely corrugated, wavy and smooth depending on the level of the residual layer variation along the pipe. The transition between the flow regimes is found to be a function of the Reynolds number defined as the ratio of the inertial stress to the characteristic viscous stress of the viscoplastic fluid.

Other investigations present the results of a primarily experimental study of buoyant miscible displacement flows of a yield stress fluid by a higher density Newtonian fluid along an inclined pipe. The miscible displacement flows are always associated with molecular diffusion [13]-[14].

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Ubora's work is analyzed two phase fluid flow characteristics consisting of crude oil and natural gas, in straight pipes of the same internal diameter, using homogenous model [15]. Flow values were obtained from a Niger Delta flow station and predetermined experimental flow equations were used to determine the pressure drop in order to comprehend the flow characteristics in the pipeline. These results may be used as a baseline and guide to compare realistic measurements in similar flows.

A mathematical description of the transport process of crude oil and sand in a horizontal pipe is presented in another paper [16]. Difference formulae were generated having applied diffusion Fick's equation to the mass conservation equations since diffusion is one of the transport mechanisms.

The flow of polymers in pipes is analyzed by Japper et al [17]; for the case under study, the relationship of the friction factor was determined through the experimentation of the pressure gradient, for Newtonian and non-Newtonian mixtures of the pseudo plastic type. The correlations obtained were expressed as a function of the Reynolds number, showing certain deviations from the traditional model in the case of the laminar regime, attributed to the effect of shear forces perpendicular to the fluid velocity in the pipeline; effects manifested in high viscosity liquids.

As inferred from the literature review, the problems related to the transport of heavy oils have not been sufficiently addressed in scientific-technical publications. In most of the previous investigations the phenomenology of non-Newtonian fluids is treated, which, although they serve as the basis for the investigation, do not describe the phenomenon of fluid transport with thermal exchange and the irregularities of flow in a laminar regime.

Taking into account the above criteria, **the objective of the article** is to obtain the model for the estimation of pressure losses in pipes during the transport of heavy oils.

II. METHOD DEVELOPMENT

A. *Procedures for determining the pressure gradient in pipes*

For the design of piping systems is required to know the relationship between the pressure gradients (dp/dx) to achieve volumetric flows (Q) in a range of different diameters (D) of the pipe, at different operating temperatures and different physical properties of fluids.

The model for the transport of petroleum in pipes is obtained from the simultaneous use of mass, momentum and energy equations, considering the effects of the mixing efforts between layers of the fluid [7]. For the analysis of the forces involved in the transport process, an inclined pipe section was considered, with movement of the fluid upwards and an angle (θ) from the horizontal (Figure 1).

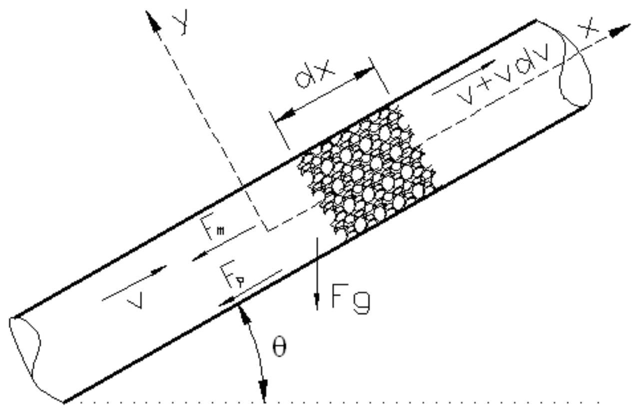

Figure 1. Structural diagram used to obtain the model

To the homogeneous flow model was added the pressure gradient caused by the mixing of fluid layers in the pipeline, the basic momentum conservation equation of the homogeneous model for flow in pipes, with the above-mentioned modification is expressed as:

$$\rho \cdot \frac{dv}{dt} = \frac{dp}{dx} - \frac{P \cdot \tau_p}{A} - F_m - \rho \cdot g \cdot sen\theta \qquad (1)$$

The stress (F_m) is caused by the effect of mixing between layers of fluid, increasing in the turbulent regime and in pipes of relatively large diameters (increase in the radial path of the particles in the pipe). When this effect is not taken into account, the pressure drop is simulated with errors higher than 25% [8].

When developing the left side of equation 1, the total derivatives also called material derivatives are:

$$\frac{dv}{dt} = \frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} \qquad (2)$$

When working with a permanent flow, the partial derivative with respect to time is canceled, resulting in:

$$\frac{dv}{dt} = v\frac{\partial v}{\partial x} \qquad (3)$$

Substituting equation 3 in 1 and presenting it as an explicit equation in terms of the pressure gradient, we have to:

$$\frac{dp}{dx} = \frac{P \cdot \tau_p}{A} + F_m + \rho \cdot v \cdot \frac{dv}{dx} + \rho \cdot g \cdot sen\theta \qquad (4)$$

In equation 4, the total longitudinal pressure gradient in the pipeline is divided into four components.

$$\frac{dp}{dx} = \left(\frac{dp}{dx}\right)_V + \left(\frac{dp}{dx}\right)_m + \left(\frac{dp}{dx}\right)_a + \left(\frac{dp}{dx}\right)_G \qquad (5)$$

The first component $[(dp/dx)_V]$ is the pressure gradient due to the viscous effort of the fluid with the wall of the pipe, is customary to assume this as the total head loss of the pipe. The gradient for a non-Newtonian fluid in permanent flow, with a constant diameter, is obtained from an analysis of the distribution of shear forces in a pipeline. The equation that describes the pressure gradient due to the shear stress between the fluid and the wall of the pipe is represented by:

$$\left(\frac{dp}{dx}\right)_V = 2 \cdot K \cdot \left(\frac{3 \cdot n + 1}{n} \cdot \frac{4}{\pi \cdot D^2}\right)^n \cdot \left(\frac{2}{D}\right)^{n+1} \cdot Q^n \qquad (6)$$

The second component $[(dp/dx)_m]$ is the additional pressure gradient due to mixing effects of the fluid in the pipeline; it can be estimated by the Darcy-Weisbach equation.

$$\left(\frac{dp}{dx}\right)_m = \lambda * \cdot \frac{1}{D} \cdot \frac{v^2}{2} \cdot \rho \tag{7}$$

In this case, λ* represents the additional effects of the pressure gradient in laminar regime, manifested in large diameter pipes (effect of mixing of the flow that are not contemplated by equation 6) and is determined by experimentation, correlating it with the generalized Reynolds number, Re * (equation 8).

$$\lambda * = \frac{a}{\mathrm{Re}*^b} \tag{8}$$

Substituting the equation 8 in 7 and expressing it in function of the volumetric flow (Q), results:

$$\left(\frac{dp}{dx}\right)_m = \frac{a}{\mathrm{Re}*^b} \cdot \frac{8 \cdot \rho \cdot Q^2}{\pi^2 \cdot D^5} \tag{9}$$

The third component [(dp/dx) a] is the pressure gradient due to changes in density due to temperature variations in the fluid, the use is for change of mixing properties of fluids (equation 10).

$$\left(\frac{dp}{dx}\right)_a = \left(\frac{m}{A}\right)^2 \cdot \frac{d}{dx} \cdot \left(\frac{1}{\rho}\right) \tag{10}$$

Solving equation 10 and expressed in terms of mass flow, it obtain:

$$\left(\frac{dp}{dx}\right)_A = \frac{v^2}{L} \cdot \left(\rho_f - \rho_i\right) \tag{11}$$

Expressing equation 11 as a function of the volumetric flow, it obtains:

$$\left(\frac{dp}{dx}\right)_A = \frac{16 \cdot Q^2}{\pi^2 \cdot L \cdot D^4} \cdot \left(\rho_f - \rho_i\right) \tag{12}$$

Equation 12, is a function of the mixture density and must be taken into account for flow with non-stationary temperature, in the case that temperature variations are significant and small variations in density the term can be disregarded.

The fourth component $[(dp/dx)_G]$ is due to the changes in potential energy as a consequence of variations in the slope of the pipe. In the case of horizontal pipe this pressure gradient is canceled.

$$\left(\frac{dp}{dx}\right)_G = \rho \cdot g \cdot sen\theta \tag{13}$$

From the analysis performed and replacing equations 13, 12, 9 and 6 in equation 5; the expression of the pressure gradient for the transport of heavy oil by pipes is obtained. The model complies with the behavior of a pseudoplastic fluid, which is explicit as shown in equation 14:

$$\frac{dp}{dx} = \left[\begin{array}{l} 2K.\left(\frac{3 \cdot n+1}{n} \cdot \frac{4}{\pi \cdot D^2}\right)^n \cdot \left(\frac{2}{D}\right)^{n+1} \cdot Q^n + \frac{a}{\mathrm{Re}*^b} \cdot \frac{8 \cdot \rho \cdot Q^2}{\pi^2 \cdot D^5} + ... \\ + \frac{16 \cdot Q^2}{\pi^2 \cdot L \cdot D^4} \cdot \left(\rho_f - \rho_i\right) + \rho \cdot g \cdot sen\theta \end{array} \right] \quad 14$$

Expressing equation 14, in pressure difference and substituting, the resulting equation is:

$$\Delta p = \left[\begin{array}{l} 2 \cdot K \cdot L.\left(\frac{3 \cdot n+1}{n} \cdot \frac{4}{\pi \cdot D^2}\right)^n \cdot \left(\frac{2}{D}\right)^{n+1} \cdot Q^n + \frac{a}{\mathrm{Re}*^b} \cdot \frac{8 \cdot L \cdot \rho \cdot Q^2}{\pi^2 \cdot D^5} + ... \\ + \frac{16 \cdot Q^2}{\pi^2 \cdot D^4} \cdot \left(\rho_f - \rho_i\right) + \rho \cdot g \cdot \Delta Z \end{array} \right] \tag{15}$$

The model obtained (equation 15) once identified and validated, has great practical application in obtaining the pressure variation in pipes that transport fluids with pseudoplastic behavior. When calculating transport systems with the aforementioned model, scaling errors are minimized extrapolating experimental laboratory results. It takes into account the variation of temperature during transport, the effects of viscous friction, and the effects of mixing between flow layers.

B. Experiments design

The experiments were carried out with temperature variations of 63 to 65 ° C. The data for the validation of the temperature gradient model were obtained for diameters 0.2 m and 0.3 m, these being the most representative in industrial facilities. By obtaining the pressure gradients, the graph of the hydraulic slope (i = f (Q)) was prepared for the flow of the fuel during pipeline transport.

With the obtaining of the graph λ = f (Re), the correlation between the friction factor and the Reynolds number increase was established. The Reynolds number was determined depending on the rheological model of the fluid.

In the model identification is necessary to use an iterative procedure starting from the reference state, and the Runge - Kutta fourth order method that takes into account the behavior of the one derived in four points of each interval. This method, like part of the iterative process is used to solve the theoretical model and to find the values of the characteristic parameters in the heavy oil.

The number of experiments was determined from the application of a multifactorial design. In agreement with the determined levels of each variable, at least eight levels of the volumetric flow are established in two pipe diameters, for three replicates of the experiments. The variable temperature is taken according to its random behavior in the transport system.

The confirmation of the validity of the experimental results with the theoretical model is developed through the relative error, that is, the difference between the experimental value module "X_{exp}" of the pressure drop and the theoretical value "X_{teo}" obtained by the model for the same conditions of the experiment. The relative point error (E_P) is calculated by the following expression:

$$E_p = \left| \frac{X_{\exp} - X_{teo}}{X_{\exp}} \right| \cdot 100 \tag{16}$$

III. RESULTS AND DISCUSSION

Table 1, lists the values of the experimental data to the temperature of 69,8 ºC, which were obtained from the hydraulic slope and velocity relationship [i = f (v)] taking in consideration the piping diameter: 0,2 and 0,3 m. The friction factor and the Reynolds number were determined considering different temperature values and the experimental results obtained.

Table 1. Experimental results for the identification of the model (for the temperature of 69,8 ºC).

Nº	D (m)	Q (m^3/s)	i_{EXP} (Pa/m)	i_{THEO} (Pa/m)	Error	Δi (Pa/m)	Re
1	0,2	0,005	162,13	149,02	0,09	13,11	26,73
2		0,010	314,03	281,96	0,11	32,07	56,51
3		0,015	456,72	409,45	0,12	47,27	87,56
4		0,020	612,11	533,51	0,15	78,60	119,46
5		0,025	766,57	655,09	0,17	111,48	152,02
6		0,030	898,40	774,72	0,16	123,68	185,10

7		0,040	1189,06	1009,46	0,18	179,60	252,55
8		0,044	1297,15	1090,45	0,19	206,70	276,50
1	0,3	0,005	34,33	32,44	0,06	1,88	16,17
2		0,010	66,89	61,39	0,09	5,50	34,18
3		0,015	101,39	89,14	0,14	12,24	52,96
4		0,020	131,85	116,16	0,14	15,69	72,26
5		0,025	167,50	142,63	0,17	24,87	91,95
6		0,030	195,19	168,67	0,16	26,51	111,96
7		0,040	258,69	219,78	0,18	38,91	152,76
8		0,044	275,07	237,41	0,16	37,66	167,24

To make the adjustment of the model, the pressure drop is estimated during transport by pipes and the rheological parameters of the oil are selected for different temperatures, which are shown in Table 2.

Table 2. Rheological parameters.

#	Parameters	Temperature				
		29 °C	38,6 °C	50,2 °C	57,4 °C	69,8 °C
1	n (dimensionless)	0,917	0,926	0,926	0,925	0,929
2	K (Pa.s)	13,55	6,89	3,1	2,22	1,46

The experimental results were compared with the theoretical results obtained by using equation 6, which estimates the pressure variation in a pipe when a pseudoplastic fluid is transported in a laminar regime; behaved according to the parameters ¨n¨ and ¨K¨ of the rheological model. In Figures 2 and 3, the results of the hydraulic slope (experimental and theoretical) for each pipe diameter analyzed are shown.

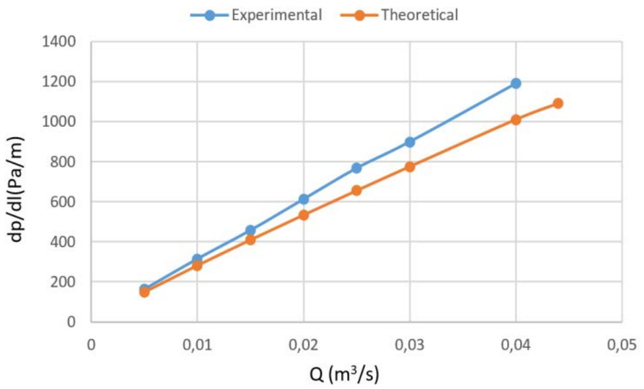

Figure 2. Experimental and theoretical specific pressure losses as a function of the volumetric flow of oil for the 0,2 m diameter pipe.

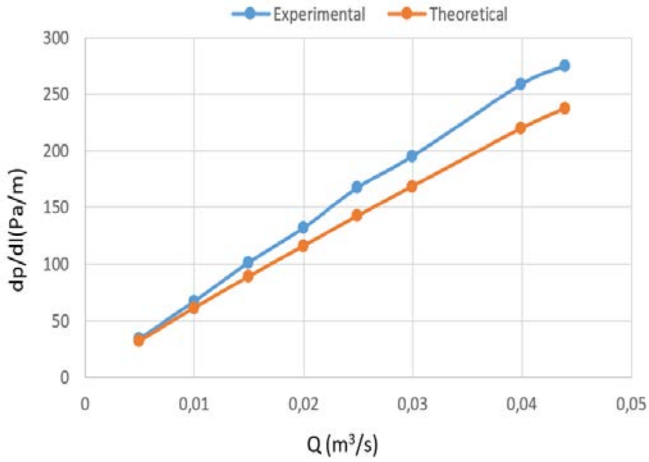

Figure 3. Experimental and theoretical specific pressure losses as a function of the volumetric flow of oil for the 0,3 m diameter pipe.

The results presented in figures 2 and 3 show the increase in specific pressure losses with the increase in volumetric flow, the significant values are related to the pipe diameter through which the heavy crude oil is transported. The specific pressure losses reach the values of 1200 Pa/m for a diameter of 0.2 m; decrease to 250 Pa/m when the diameter increases to 0.3 m. The effect is attributed to the mixing between layers that the heavy crude oil manifests as it flows through the pipe. The Behavior of the specific pressure losses depending on the Reynolds number for a diameter of 0.3 m are shown in figure 4.

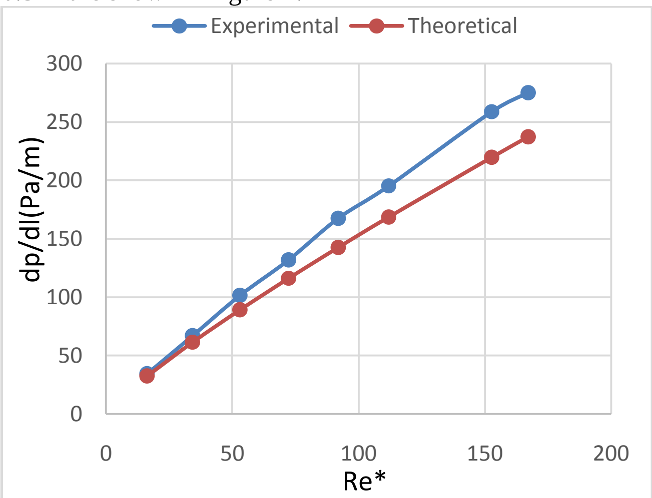

Figure 4. Experimental and theoretical specific pressure losses as a function of the Reynolds number for the 0,3 m diameter pipe.

Figure 5 shows the behavior of the friction coefficient as a function of Reynolds number, this values satisfies the adjustment of equation 15 for the range of experimental data and allows to obtain a reliable value (with an average error of 4.5%) in the simulation of the heavy oil transport process of 11 °API. The results obtained are satisfactory for the calculation of pressure variation in industrial facilities where heavy crude oil is transported by pipeline, and are the starting point for validating the model and the subsequent simulations for other pipe diameters and other fluids with pseudoplastic behavior.

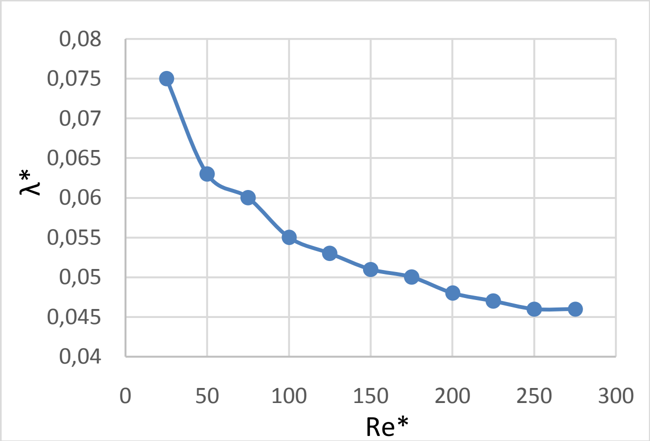

Figure 5. Behavior of the additional friction coefficient as a function of the Reynolds number for transport of the heavy oil with11 °API

IV. CONCLUSIONS

- Equation 15 is the generalized theoretical model for the calculation of pressure variations in the transport of heavy crude oil by pipeline. It takes into account the variation of temperature during transport, the effects of viscous friction, and the effects of mixing between flow layers.
- The values of the flow index for the transport of heavy oil of 11°API by pipes oscillates between 0,917 and 0,929 in function of the temperature values that vary between 29 °C and 69.8 °C. The consistency index varies between 13.55 Pa.s and 1.46 Pa.s for the same temperature range.
- The behavior of the friction factor for the transport of heavy crude oil by pipes as a function of the Reynolds number exposes maximum values of the friction coefficient when the Reynolds number is less than 50; the values of the coefficient converge when the Reynolds number is greater than 250. The results obtained are satisfactory for the calculation of the pressure variation in industrial facilities where heavy crude oil is transported.
- The specific pressure losses increase with the volumetric flow, the significant values are related to the pipe diameter through which the heavy crude oil is transported. The specific pressure losses reach the values of 1200 Pa/m for a diameter of 0.2 m; decrease to 250 Pa/m when the diameter increases to 0.3 m. The effect is attributed to the mixing between layers that the heavy crude oil manifests as it flows through the pipe.

Nomenclature:

A - Cross section area, m^2
P- Perimeter of the pipe, m
ρ - Fluid density, kg/m^3
θ - Pipe inclination, degrees
dp/dx - Pressure gradient in the flow direction, Pa/m
τ_p - Friction coefficient in the wall of the pipe, Pa
g - Gravity acceleration, m/s^2.
F_m- Additional pressure stress in the pipe, Pa/m
v - Fluid velocity; m/s.
Q: Volumetric flow, m^3/s
D: Pipe diameter, m
n - Flow index, dimensionless
K - The consistency index, Pa.s
λ^* - Additional friction coefficient, dimensionless
a and b - coefficients that depend on the fluid regime, dimensionless
Re*- Reynolds number, dimensionless
m - Mass flow, kg/s.
ρ_f and ρ_i - final and initial oil density, kg/m^3

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