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Full Length Research Paper

Effect of inertia in the study of two-phase oil-gas flow in horizontal pipelines

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The flow of oil and gas in the production pipelines is a crucial step for the oil industry, which always seeks to maximize the production of these valuable hydrocarbons. The modeling of the flow patterns allows a better analysis of the behavior of the mixture. In this work, the mechanical energy balance is applied to represent the multiphase oil-gas flow being evaluated; the contribution of the terms of kinetic energy and friction pressure drop along the pipe. The simulation results of pressure drop profiles showed that the kinetic effects due to the inertia of the gas are equivalent to those from compressible flow by gas expansion. The friction can also be significant to the overall result of the pressure drop that will depend on the flow pattern and contact conditions of the gas phase with the pipe wall.

Key words: Oil-gas flow, horizontal flow, kinetic effect, friction effect.

INTRODUCTION

The analysis and study of flow patterns are of paramount importance for the understanding and prediction of the kind of mixture of oil seeping into pipes. There are many scientific studies to better understand the mechanisms that determine the patterns of multiphase flow in oil pipelines (Hapanowicz, 2008; Ruder and Hanratty, 1990; Hewitt et al., 1990; Guang-yao et al., 2007) since they are fundamental in calculating a series of engineering properties related to the oil-gas flow from the production areas to the refining units. Currently, there is interest in the directional/horizontal drilling for achieving higher recovery factors in horizontal reservoirs due to the larger contact area with the production well (Pinto et al., 2003; Mohiuddin et al., 2007). Thus, the study of the behavior of oil and their mixtures through the horizontal multiphase flow in pipelines is necessary in the quest for better routines for calculating the properties concerned.

In multiphase flow of oil, we can find different phase configurations in which the oil-gas is a typical flow pattern in pipelines. In the literature, different configurations of phase were studied each one with its own purpose (Spedding et al., 2005; Guang-Yao, 2007; Jepson and Taylor, 1993). It was observed that the greater the number of phases present, the greater the complexity in the analysis and consequently the modeling. The modeling of multiphase flow in horizontal pipelines has been a constant in the search for models and mechanisms that lead to better understanding of the phenomena related to the dominant flow patterns. In the study of Guang-Yao et al. (2007), both the experimental and modeling study was performed in the horizontal flow of two phase oil-gas. The authors found a critical surface velocity of the liquid phase in the transition from stratified to the slug pattern. Numerical simulations were also performed on the basis of experimental data with the application of the volume of fluid technique (VOF). In this technique, a set of equations is applied to represent the two phases being utilized as an average of properties instead of using separate conservation equations for both phases. Garcia et al. (2007) developed correlations for calculating friction factor in two phase horizontal flow, taking into account the effect of relative velocity of

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phases. These models were based on data from 2560 experiments of gas-liquid flow in horizontal pipelines.

In this work the horizontal two-phase oil-gas flow is modeled by a mechanical energy balance that assumes independent contributions of the terms of oil and gas phase acceleration in the global balance of energy. The contribution of kinetic and friction terms is analyzed by profiles of pressure drop in wells subject to compressible and uncompressible flows.

MODELING

The modeling of the horizontal flow is assumed as one-dimensional variation of the properties along the length L with the gravitational term neglected. Equation 1 shows the balance of mechanical energy used in which the first term represents the variation of pressure (P) with the length (L) of the pipe. The second and the third terms represent respectively the friction loss, which is related to the friction factor (*f*), fluid density (ρ), velocity (*v*) and the pipe diameter (*D*); and the acceleration, which is related to the fluid velocity and density and the variation of velocity with the pipe length.

$$\frac{dP}{dL} = -f\frac{\rho v^2}{2D} + \rho v\frac{dv}{dL} \tag{1}$$

It is assumed that the gas can increase your speed linearly along the pile length through a type expression.

$$v = v_0 + a.L \tag{2}$$

Where v_o and *a* correspond to the initial velocity and the angular parameter, respectively. Thus, the increase in speed means that we have an increase in the holdup of the liquid (H_L) due to reduction of velocity of the liquid phase with the consequent increase in sectional area of tube occupied by liquid. In the calculations it is considered a constant volumetric flow of oil and gas along the pipe length.

In calculating the friction factor the model of Drew et al. (1930) is considered.

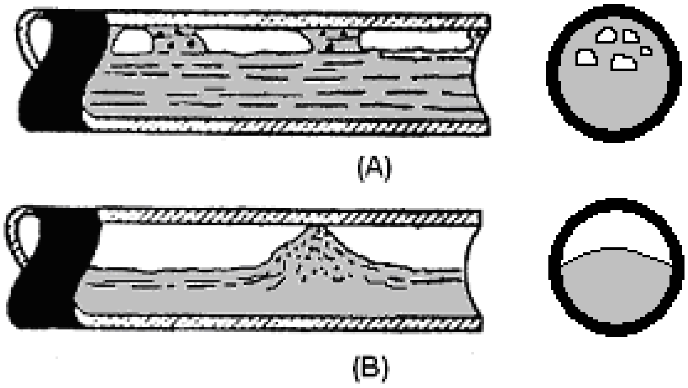

Figure 1. Examples of horizontal flow patterns: (A) bubbles dispersed (B) segregated.

$$f = 0.0056 + 0.5.\mathrm{Re}^{-0.32} \tag{3}$$

Where the Reynolds number is calculated through the density, velocity and viscosity of the mixture. The latter is calculated using the additive contributions of the liquid and gas holdup. In the acceleration term of the balance of mechanical energy (equation 1) there is the independent contribution of the gas and oil flow.

Figure 1 shows two examples of horizontal flow patterns. According to the type of pattern we can have different distributions of liquid and gas in contact with the pipe wall which leads to different values of energy loss from friction. In the case B the gas promotes a greater contact with the pipe wall than in the case A, since the gas is distributed over the net in the latter. The case A is more related to a pattern of bubbles dispersed in which an increase in the holdup of the liquid does not necessarily lead to an increase in liquid contact with the wall. The case B is be more related to a segregated pattern in which an increase of liquid holdup leads to an increase in liquid contact with the wall.

RESULTS AND DISCUSSION

In the calculations of pressure drop from mechanical energy balance (equation 1), a pipeline discretization of 10 (ten) control volumes along the total length is assumed. In the previous calculations, the speed variations of the gas and liquid phase were not considered. Figure 2 presents the results of pressure drop versus volumetric flow increasing the flow rate of gas-oil mixture. As expected, the increase of the gas-oil mixture flow leads to an increase in pressure drop, as can be seen from this result of available pressure curve. Also, Figure 2 shows that the lowest pressure drop corresponds to the case of larger fraction of the area occupied by gas (Case of lowest gas Holdup which is equal to 0.01). The case of intermediate holdup (H_L = 0.5) led to an intermediate pressure profile and that with higher fraction of liquid (H_L = 0.99) to a pressure drop which is equivalent to those typical experimental field results presented by Oliveira (2002). In the results of Figure 2, the following properties were used:

ρ_{gas} = 2 kg/m^3, ρ_{liq} = 900 kg/m^3, μ_{gas} = 0.02 cP, μ_{Liq} = 7 cP, *D* = 0.1 m and *L* = 1000 m

Figure 3 presents the results of the behavior of pressure drop with the pipe length. The simulation results in blue were compared to the experimental data of Oliveira (2002) in red showing that it is not necessary to increase the gas velocity to represent well the experimental points (no slip case). As can be seen, there is a good fit between the experimental data and the simulation showing a linear pressure profile which is equivalent to the data presented by Oliveira (2002). These results are expected as there is no change in the energy term of acceleration due to the constant holdup of liquid which keeps the friction loss of the mechanical energy balance constant. Therefore the pressure drop along the pipe is

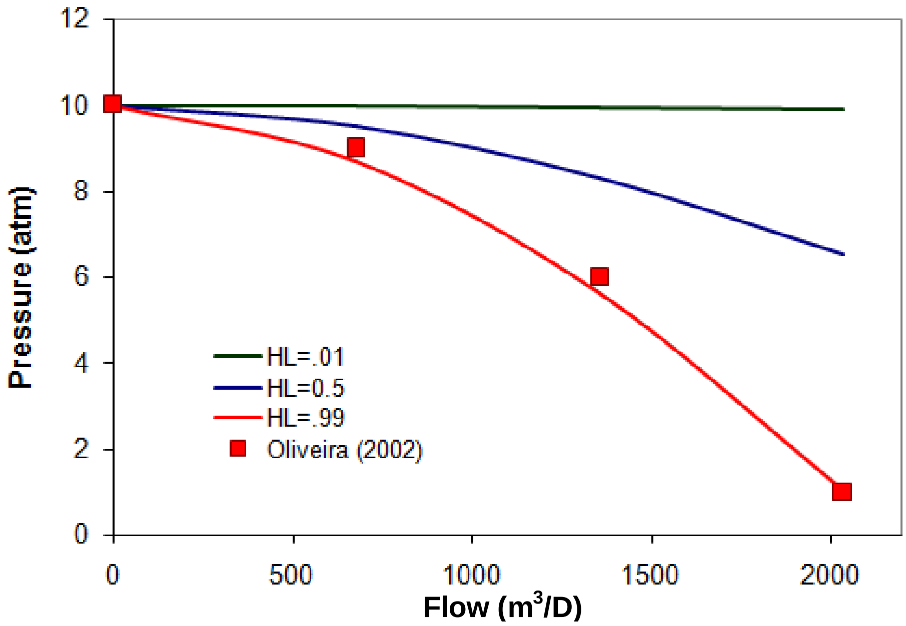

Figure 2. Comparison with field experimental data of available pressure from Oliveira (2002).

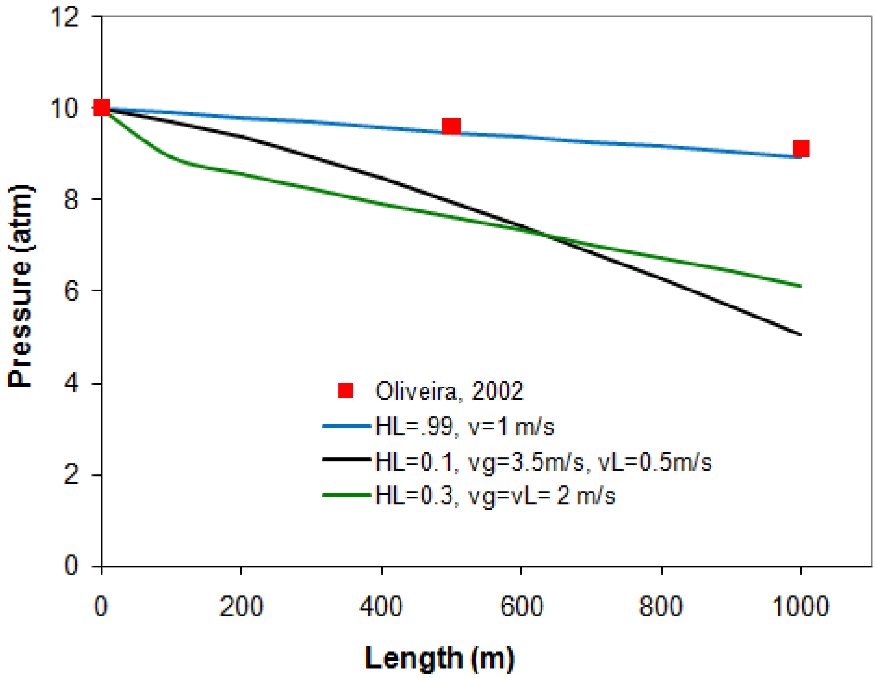

Figure 3. Comparison with experimental data of pressure drop with length from Oliveira (2002).

linear. In such simulation results, the following properties were utilized:

ρ_{gas} = 2 kg/m^3, ρ_{liq} = 900 kg/m^3, μ_{gas} = 0.01 cP, μ_{Liq} = 3 cP,

D = 0.1 m and L = 1000 m

According to Oliveira (2002), the black curve corresponds to a typical profile of pressure drop in compressible and

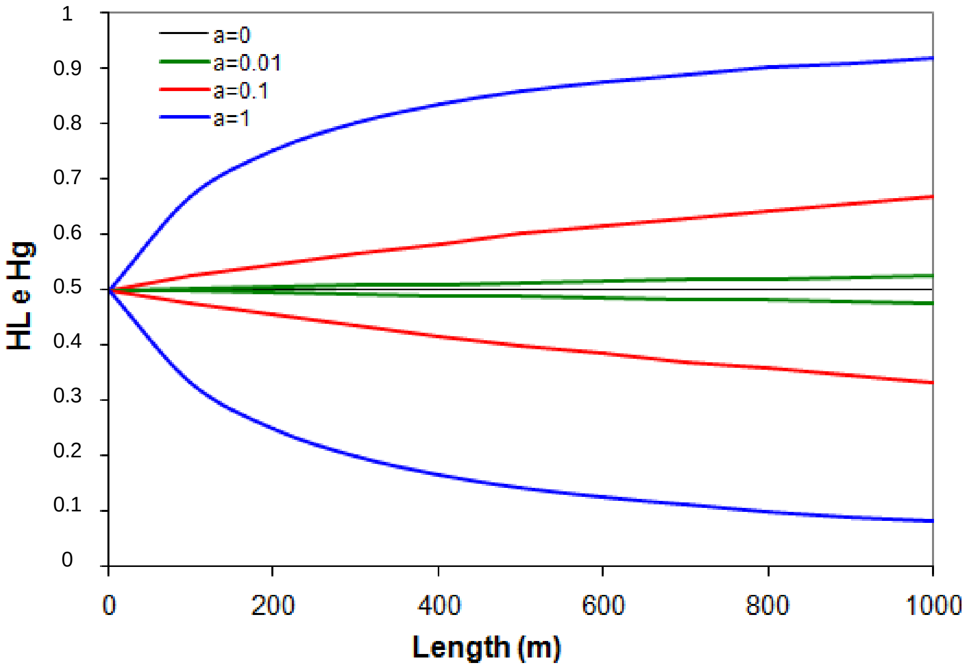

Figure 4. Holdup of liquid (H_L) and gas (H_g) in accordance with increasing gas velocity.

horizontal flow. This profile of pressure has a negative curvature in which the pressure drop increases by increasing the pipeline length. It should be noted that the pressure drop curve in question (black one) was obtained through simulations with lower liquid holdup and higher gas velocities (H_L = 0.1, v_g = 3.5 ms and v_L = 0.5 m/s) with an angular coefficient of gas velocity equal to one (= 1). Thus, such negative pressure drop profiles can be obtained in the conditions of increased acceleration of the gas phase. In the simulations represented here, the increase of the gas velocity is considered because the inertia effect is not responsible for its expansion (the flow of liquid and gas was kept constant with the alteration of the holdup of liquid and gas along the pipe). An exponential pressure profile (green curve) is obtained under no slip conditions (equal velocities) and with an intermediate value of liquid holdup.

In Figures 4, 5, 6 and 7, there is an analysis of sensitivity due to the contribution of the friction factor and the acceleration term in the expression of global balance of mechanical energy.

The conditions utilized are:

$$\rho_{gas} = 2\ \text{kg/m}^3,\ \rho_{liq} = 900\ \text{kg/m}^3,\ \mu_{gas} = 0.01\ \text{cP},$$

$$\mu_{Liq} = 3\ \text{cP},\ v_{og} = v_{oL} = 2\ \text{m/s},\ D = 0.1\ \text{m and}\ L = 1000\ \text{m}$$

Figure 4 shows the results of the holdup of the liquid (H_L, upper curves) and gas holdup (H_g, lower curves inversely equivalent to H_L) with the pipe length at different values of the angular coefficient of gas velocity (a = 0, 0.01, 0.1 and 1). Note that the holdup of liquid and gas is inversely equivalent. When there is no increase in the angular coefficient of the gas velocity, the gas and oil holdup does not change; it remains constant (black curve). For small increase in the angular coefficient, both holdup presents almost linear profile as in green and red curves. Already, a significant increase in gas velocity (as angular coefficient) leads to both asymptotic holdup profile which can significantly alter the energy loss by friction due to greater contact between the liquid phase with the tube wall.

The friction factors presented in Figure 5 are related to the simulation results from modeling approach implemented. This approach assumes that the increase of gas velocity changes the holdup of the liquid considering the properties of the mixture in the calculation of the friction factor. This is related to a more homogeneous pattern in which the gas bubbles are dispersed in the liquid phase.

It is observed from Figure 5 that, in case of no-slip flow (a = 0), there is no change in the holdup so the friction factor remains constant along the pipe length. For higher speed of the gas velocity, the friction factor tends to an exponential behavior with the length of the pipe. It should be noted that even with the increase of liquid holdup along the pipe, there is a more significant decrease in the friction factor which comes from the reduction in the velocity of the liquid flow.

The friction factors from segregated pattern (case B, Figure 1) were obtained in order to be compared to those from dispersed bubbles (case A, Figure 1). In the latter,

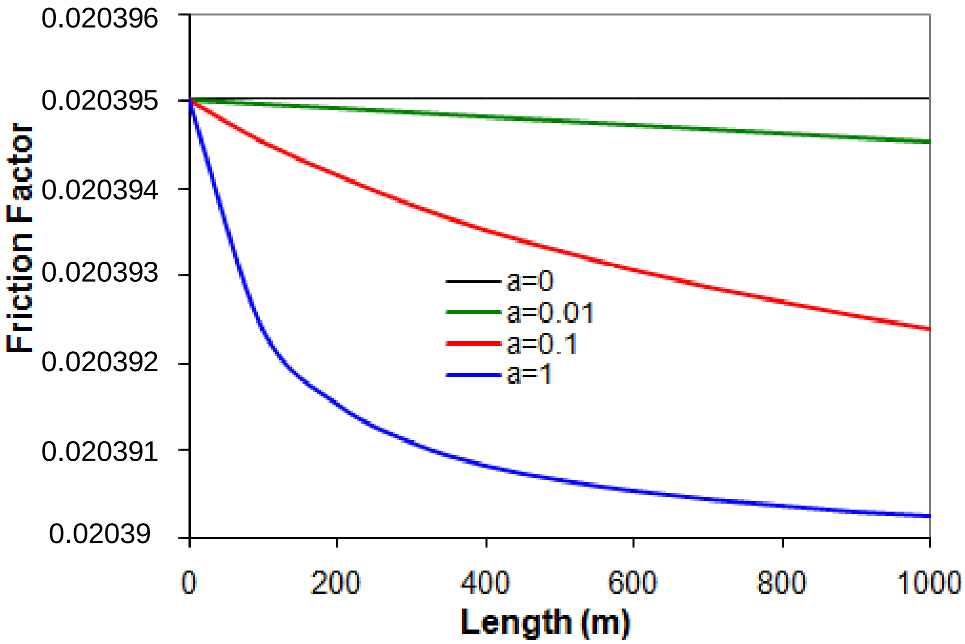

Figure 5. Values of friction factor from dispersed bubbles pattern.

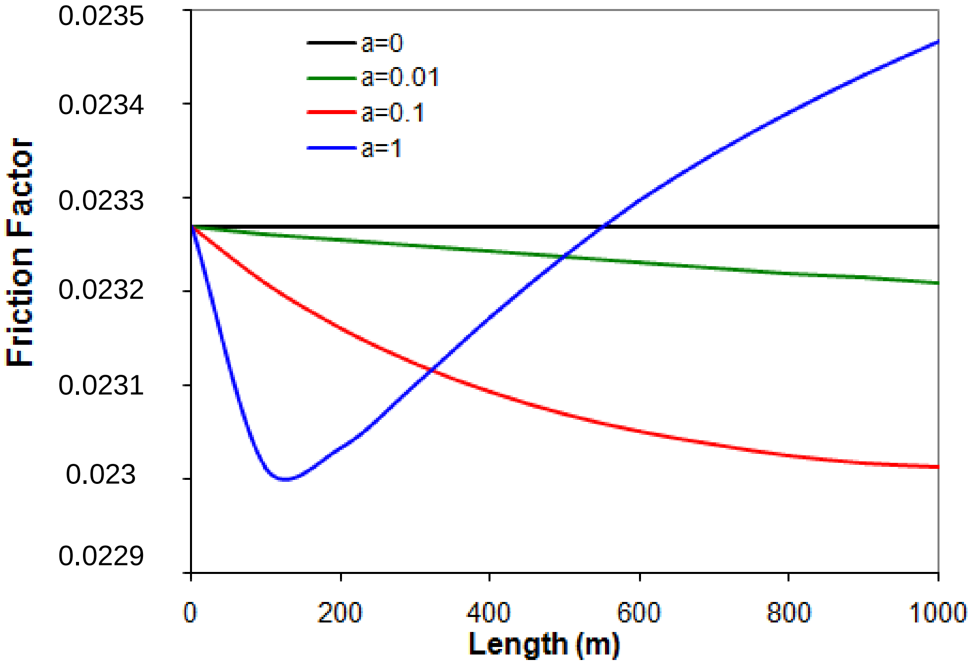

Figure 6. Values of friction factor from segregated pattern.

an increase in the holdup of the liquid leads to a further increase in liquid contact with the pipe wall. This approach assumes that the hydraulic diameter of the liquid and gas phases is proportional to the areas occupied respectively by each one.

$$\frac{\pi D_{HL,Hg}^{\ \ 2}}{4} = A_{L,g} \tag{4}$$

Thus, the Reynolds number is calculated for each phase

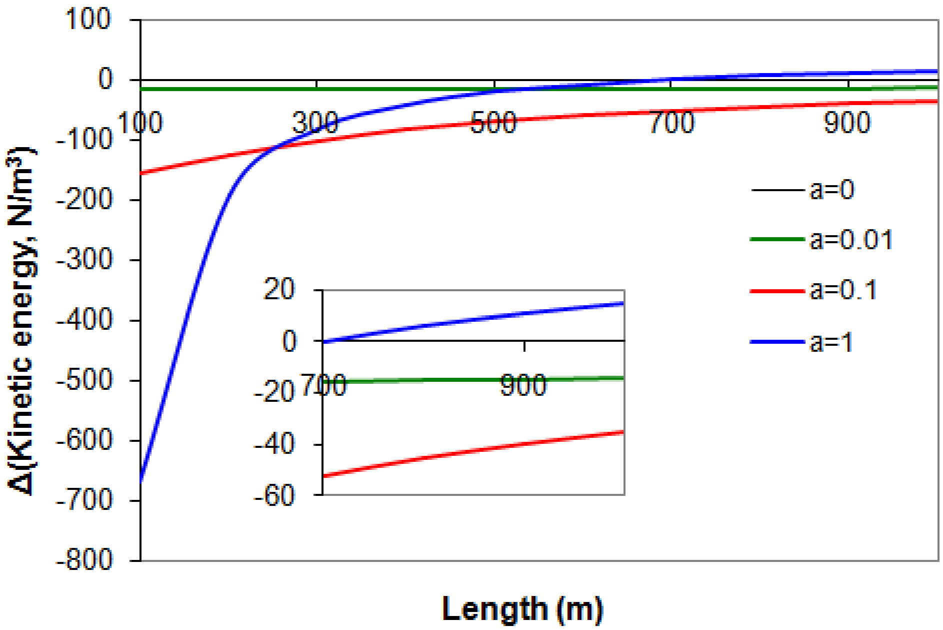

Figure 7. Effect of the kinetic energy term according to the pipe length.

according to the hydraulic diameter of each one. The friction factor was first calculated for each phase according to the respective Reynolds numbers and finally the global friction factor was obtained from the sum of the friction factor of each phase multiplied by each respective holdup. Figure 6 presents the simulation results of friction factor according to the segregated pattern. Note the behavior similar to the approach of bubbles dispersed in relation to small coefficient of gas phase velocity (up to 0.1). For higher values of gas velocity (a = 1) the friction factor shows a drop at the beginning of the pipe presenting a significant increase after this point. This increase is related to the increased contact of the liquid phase with the pipe wall under these conditions of speed.

Figure 7 shows the profiles of change of kinetic energy versus pipe length according to different velocities of gas phase (increasing the angular coefficient). As expected, there is no kinetic energy variation with no-slip between the phases (a = 0). Remember that the delta of kinetic energy is the sum of the portion of the gas and liquid phases. In most of the simulation cases presented in Figure 7, the contribution of kinetic energy term is negative in the balance of mechanical energy showing an increase along the length. In the simulation conditions of Figure 7, the delta of kinetic energy becomes positive after the position length of 700 m which corresponds to the highest value of gas phase velocity (a = 1). The positive variation of the term of kinetic energy is related to the increase of liquid holdup that has a greater share of contribution due to the higher density of the liquid compared to gas phase, despite the slow velocity of liquid phase.

Conclusion

The use of the overall balance of mechanical energy associated with expressions of speed related to the inertia of gas motion in oil-gas two-phase flow can be a good possibility of representation of these systems under such conditions. The modeling routine implemented showed simulation results which are very close to those observed experimentally in the work of Oliveira (2002).

The inertia of gas phase, under the conditions here studied, led to pressure drop along the pipe length which is similar to those observed for compressible flow. In the compressible flow, the pressure drop increases with the length of pipe in horizontal flow due to speed increase of gas associated with its own expansion (Oliveira, 2002). Thus, profiles of such pressure drop (increase with the length) can not exclusively be associated with compressible flow since the speed increase due to the inertia of the gas phase also led to similar results. A previous analysis of the pattern of two-phase flow is of paramount importance as the friction factor can change significantly by variations in the holdup that leads to different contacts of the liquid phase with the tube wall. In those situations of holdup variations due to gas inertia it was observed a positive change in the kinetic energy term that is strongly influenced by the increase in gas velocity.

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Nomenclature

P - Pressure (*atm*)

L - Length (*m*)

f - Friction factor

ρ - Density (*kg/m3*)

v - Velocity (*m/s*)

μ - Dynamical viscosity (*cP*)

v_0 - Initial velocity of gas phase (*m/s*)

a - Angular coefficient of the gas velocity expression

D - Pipeline diameter (*m*)

Re - Reynolds number

H_L - Liquid *Holdup*

D_{HL} - Liquid hydraulic diameter (*m*)

D_{Hg} - Gas hydraulic diameter (*m*).

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