ALGEBRAIC MODEL FOR SLUG TRACKING IN VERTICAL GAS-LIQUID SLUG FLOW

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Abstract. *The intermittent gas-liquid flow, or slug flow, occurs over a wide range of gas and liquid flow rates. Thus, it is frequently encountered on the gas and oil industry. Predicting the properties of this flow is important to well design pumps, risers and other components involved. The current work presents a model to predict the evolution of fluid flow in vertical gas-liquid slug flow with: i) aerated liquid slug, ii) no bubble interaction, iii) periodic flow in the entrance of the tube and iv) the entrance or exit of bubbles and slugs do not cause pressure disturbances. This approach uses the bubble shape model presented by Taitel and Barnea (1990) to obtain the properties in the inlet of the tube. Once calculated, the model predicts the properties throughout the tube. The motivation of this model is its simplicity, easiness of application and low computational cost. It is a useful tool of reference data generation in order to check the consistency of numerical slug tracking models. The numerical results are compared with experimental data. The potential of the model is demonstrated comparing the gas bubbles and liquid slug size and pressure drop for gas-liquid slug flow.*

Keywords*: Vertical slug flow, gas-liquid, algebraic model.*

1. INTRODUCTION

The intermittent gas-liquid flow, or slug flow, occurs over a wide range of gas and liquid flow rates. This flow pattern is characterized by an intermittent sequence of liquid slugs and elongated bubbles distributed irregularly on time and space. The liquid slug may contain disperse bubbles and the elongated bubble flows underneath or inside a thin liquid film. The prediction of the gas-liquid properties (lengths, frequency and velocity as well as the pressure drop) is necessary to design facilities operating with slug flow pattern.

The unit-cell concept was introduced by Wallis (1969) to model the slug flow. The main idea of this concept is to consider a periodic flow in time and space. This simplification reduces the pipe flow modeling to a single repetition unit called by unit-cell, composed by an elongated bubble followed by a liquid slug as shown in Fig. 1. The lengths of the liquid slug and elongated bubble are L_S and L_B. U_T is the bubble's nose translational velocity, U_{LB} and U_{GB} are the liquid and gas velocities in the bubble zone; U_{LS} and U_{GS} are the liquid and gas velocities in the slug zone; R_{LS} is the liquid holdup within the slug zone and R_{GB} is the void fraction in the bubble zone. P is the gas pressure inside the bubble and γ is the pipe angle (90° for vertical flow).

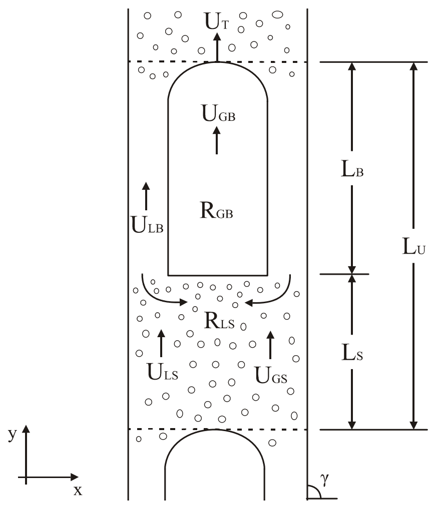

Figure 1. Vertical slug flow unit.

There are a number of slug flow models based on the unit-cell concept. Fernandes et al. (1983) proposed one hydrodynamic model to predict the flow properties of a gas-liquid slug flow in vertical tubes, Taitel and Barnea (1990a) reported one general model for horizontal, inclined and vertical flows and more recently Abdul-Mejeed and Al-Mashat (2000) developed one mechanistic model to predict the flow behavior for upward vertical and inclined two-phase slug flow.

Other studies were focused on experimental and numerical studies. Experimental measurements in a 50.8 mm diameter pipe were made by Mao (1989) and the results were compared with the model presented by Fernandes et al (1983). Kawaji (1997) developed and conducted numerical simulations using a Volume-of-Fluid approach to predict both the shape of the Taylor Bubble and the velocity profiles in the liquid phase. A description of the bubble propagation in both stagnant and flowing liquids was obtained using CFD by Taha Taha (2006) and an image analysis technique for the study of continuous co-current gas–liquid slug flow, in vertical columns, is reported by Mayor et al. (2007).

Although these models are popular and quite often used on pipe flow design, their predictions are applied just to the unit-cell length, but not to the whole pipe extension. They also do not predict gas expansion due to the pressure drop. The algebraic model extends the concept of unit-cell in a sense that its solution encompasses the whole pipe extension and includes the gas compressibility effects.

The main idea behind this model is to propagate a unit-cell along the pipe allowing the gas expansion. The model has as input the frequency at the pipe entrance, the gas and liquid superficial velocities at the exit, as well as the exit pressure. The unit-cells structures are propagated along the pipe using an algebraic model to calculate flow properties.

2. ALGEBRAIC MODEL

The development of the algebraic model is based on the same assumptions of the unit-cell models which are: (i) aerated liquid slug; (ii) the flow is periodic in time and space; (iii) there is no interaction between neighboring bubbles and (iv) the flow at the pipe entrance or pipe exit do not disturb neither the pressure nor the velocities inside the pipe. The present algebraic model also assumes an isothermal flow.

The conservation of volume of gas inside at any pipe cross section may be expressed as the product of the gas superficial velocity and the bubble's pressure if one uses the ideal gas law:

$$J_G(z)P(z) = J_{GS}P_{atm}\,, \tag{1}$$

where z is the coordinate along the flow direction and J_{GS} and P_{atm} represent the gas velocity and the pressure at the pipe exit. Equation (2) shows that the gas superficial velocity at any position of the pipe is determined once the pressure at this point is known. As the liquid is incompressible, its average superficial velocity, J_L, is constant along the pipe therefore the mixture average superficial velocity, J, at any position z takes the form:

$$J(z) = J_L + \frac{J_{GS}P_{atm}}{P(z)}\,. \tag{2}$$

2.1. Conservative Equations

Consider the flow of a slug unit, shown in Fig. 1. A mass balance of the liquid slug can be performed giving the following relation for the velocity of the liquid phase in the slug:

$$U_{LS} = (J - U_{GS})\frac{(1 - R_{LS})}{R_{LS}} \tag{3}$$

The Taylor bubble nose travels at a translational velocity, U_T, greater than the liquid and gas in the slug. Thus, two relationships can be developed for the liquid and gas velocities in the slug relative to the nose of the Taylor bubble. Fernandes (1983) proposed the following equations for the liquid and gas phases:

$$U_{GB} = U_T + (1 - R_{LS})\frac{(U_{GS} - U_T)}{(1 - R_{LB})} \tag{4}$$

$$U_{LB} = U_T + R_{LS}\frac{(U_{LS} - U_T)}{R_{LB}} \tag{5}$$

where U_{LS} is the liquid velocity in the slug, U_{GB} and U_{LB} are the gas and liquid velocities in the bubble length, R_{LS} is the liquid fraction in the slug and R_{LB} is the liquid fraction in the bubble.

Referring to Figure (1), momentum equations for the liquid film and the gas were obtained by Taitel and Barnea (1990), given by:

$$\rho_L V_{LB}\frac{dV_{LB}}{dz}=-\frac{dP}{dz}+\frac{\tau_{LB}S_{LB}}{A_{LB}}-\frac{\tau_i S_i}{A_{LB}}+\rho_L g\sin\gamma-\rho_L g\cos\gamma\frac{dH_{LB}}{dz} \tag{6}$$

$$\rho_G V_{GB}\frac{dV_{GB}}{dz}=-\frac{dP}{dz}+\frac{\tau_{GB}S_{GB}}{A_{GB}}+\frac{\tau_i S_i}{A_{GB}}+\rho_G g\sin\gamma-\rho_G g\cos\gamma\frac{dH_{LB}}{dz} \tag{7}$$

where ρ_L and ρ_G are the liquid and gas densities, γ is the tube angle, g is the gravitational acceleration; τ_{LB}, τ_{GB} and τ_i are the local shear stresses of the liquid, gas and interface; A_{LB} and A_{GB} are the liquid and gas cross-section areas; S_{LB}, S_{GB} and S_i are the liquid, gas and interface surfaces and R_{LB} and R_{GB} are the liquid and gas fractions. The equations of these variables are presented in Table 1. The liquid and gas relative velocities are $V_{LB} = U_{LB} - U_T$ and $V_{GB} = U_{GB} - U_T$ and the gas and liquid cross sectional areas are given by $A_{LB} = AR_{LB}$ and $A_{GB} = A\,(1 - R_{LB})$.

Eliminating the pressure gradient, one can obtain a differential equation relating the bubble shape $H_{LB}(z)$ to the length z of the pipe, given by:

$$\frac{dH_{LB}}{dz}=\frac{\dfrac{\tau_{LB}S_{LB}}{A_{LB}}-\dfrac{\tau_{GB}S_{GB}}{A_{GB}}-\tau_i S_i\left(\dfrac{1}{A_{LB}}+\dfrac{1}{A_{GB}}\right)+\left(\rho_L-\rho_G\right)g\sin\gamma}{\left(\rho_L-\rho_G\right)g\cos\gamma-\rho_L\dfrac{V_{LB}^2}{R_{LB}}\dfrac{dR_{LB}}{dH_{LB}}-\rho_G\dfrac{V_{GB}^2}{R_{GB}}\dfrac{dR_{LB}}{dH_{LB}}} \tag{8}$$

The bubble length or a unit-cell can be obtained by the numerical integration of Eq. (8). For each step of length (dz), one can calculate an average value of H_{LB} and the average void fraction at the bubble, R_{GB}, given by:

$$R_{GB}=1-\frac{H_{LB}}{D} \tag{9}$$

To reach the correct value of the bubble length, one stop criterion must be used; otherwise this integration obtains one infinite result. One way is performing a mass balance of the liquid in the unit cell. The equation for this stop criterion suggested by Taitel and Barnea (1990) is given by:

$$\frac{L_U\left(U_{LS}R_{LS}-J_L\right)}{U_T}=R_{GB}L_B-L_B\left(1-R_{LS}\right) \tag{10}$$

This equation uses the bubble length, L_B, and the average void fraction, R_{GB}, obtained by Eq. (9), after the integration of Eq. (8). One can get the value of the bubble length when this mass balance is reached.

The unit cell length, L_U, is given by:

$$L_U=\frac{U_T}{freq} \tag{11}$$

where freq is the flow frequency at the entrance of the pipe. This paper will use an experimental value of the frequency obtained by Rosa (2006).

The liquid slug length can be easily obtained by:

$$L_S=L_U-L_B \tag{12}$$

The determination of the liquid, gas and interface perimeters is based on a cross section cut of the tube, shown on Fig 2.

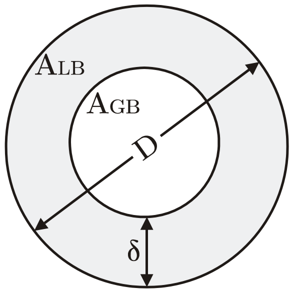

Figure 2. Schematic representation of plane interface.

where $\delta = H_{LB} / 2$. Using geometrical relations, one can easily obtain the following equations:

$$R_{LB} = 1 - \left(1 - \frac{H_{LB}}{D}\right)^2$$
$$S_{LB} = \pi D; \quad S_{GB} = 0; \quad S_i = \pi(D - H_{LB}) \tag{13}$$
$$\frac{dR_{LB}}{dH_{LB}} = \frac{2}{D} - \frac{2H_{LB}}{D^2}$$

2.3. Constitutive Equations

Three constitutive equations are used to calculate: the bubble velocity in the liquid slug, the bubble translational velocity and the liquid holdup in the slug.

The bubble velocity in the liquid slug zone, U_{GS}, can be calculated using the relation proposed by Barnea (1990), given by:

$$U_{GS} = J + 1.54\left(\sigma g \frac{(\rho_L - \rho_G)}{\rho_L^2}\right)^{0.25} \sin(\gamma) \tag{14}$$

where σ is the surface tension.

The bubble translational velocity, U_T, is given by the kinematic relation proposed by Nicklin (1962), largely accepted and confirmed by many subsequent papers (Bendiksen, 1980; Cook and Behnia, 2001) as:

$$U_T = C_0 J + C_1, \tag{15}$$

where C_0 and C_1 are constants. The values of C_0 and C_1 are 1.0845 and 0.1696, respectively, obtained by Rosa (2006).

The liquid holdup in the slug can be calculated by different methods. This work will use the relation proposed by Andreussi et al. (1993) given by:

$$R_{LS} = \frac{F_0 + F_1}{Fr_M + F_1} \tag{16}$$

where the mixture Froude number is $Fr_M = J/\sqrt{gD}$ and the coefficients F_0 and F_1 are given by the following expressions:

$$F_0 = \max\left[0, 2.6\left(1 - 2\left(\frac{D_0}{D}\right)^2\right)\right] \quad \text{and} \quad F_1 = 2400\left(1 - \frac{\sin\gamma}{3}\right)Bo^{-3/4} \tag{17}$$

The Bond number is defined as $Bo = gD^2\Delta\rho_L/\sigma$ and the critical diameter value is D_0=2.5cm.

2.4. Pressure Gradient

The information of the pressure along the pipe is fundamental to close the algebraic model. It is calculated through the pressure gradient λ, given by:

$$\lambda = \frac{dP}{dz}, \tag{18}$$

Once λ is known, the pressure drop over the pipe yields:

$$P(z) - P_{atm} = -\int_z^L \lambda(z) \cdot dz, \tag{19}$$

where $0 \leq z \leq L$ and $z = L$ is the exit of the pipe. If λ is considered constant over the pipe, the pressure at any section z is obtained by the following linear relation:

$$P(z) = -\lambda(L - z) + P_{atm}. \tag{20}$$

It is not possible to determine the pressure drop over the entire pipe extent at once. However, one can calculate λ for a unit-cell. The pressure drop on a unit-cell is due to the pressure drop on the liquid slug, ΔP_{LS}, and on the liquid film along the bubble length, ΔP_{LB}. Therefore the pressure gradient for the unit-cell, λ_u turns to be:

$$\lambda_u = \frac{\Delta P_{LS} + \Delta P_{LB}}{L_S + L_B}. \tag{21}$$

The pressure drop on the liquid slug and on liquid film zones can be calculated by a momentum balance in a unit cell. Figure 3 presents gravitational forces and shear stresses acting in a unit cell. F_B and F_S are the gravitational forces in the bubble zone and in the liquid slug; τ_{LB} and τ_i are the average shear stresses of the liquid film and interface.

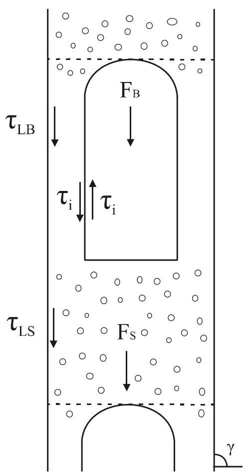

Figure 3. Gravitational forces and shear stresses in the unit cell.

The pressure drop on the liquid slug, ΔP_{LS}, and on liquid film zone, ΔP_{LB}, are given by:

$$\Delta P_{LS} = \rho_S g \sin(\gamma) L_S + \bar{\tau}_{LS} \pi D \frac{L_S}{A} \quad \text{and} \quad \Delta P_{LB} = \rho_B g \sin(\gamma) L_B + \bar{\tau}_{LB} \bar{S}_{LB} \frac{L_B}{A} + \bar{\tau}_{GB} \bar{S}_{GB} \frac{L_B}{A} \tag{22}$$

where ρ_S and ρ_B are the average densities in the slug and bubble zones. It is important to note that the shear stresses used in this equation are the average values along the bubble and slug lengths.

Table 1 shows the equations for the shear stresses, the friction factors, the Reynolds number, the hydraulic diameters and slug and bubble zone average densities used in the bubble shape model and the pressure drop equations.

3. CALCULATION PROCEDURE

As seen in section 2 the sizes, velocities and pressure, at any pipe location, z, are calculated as a function of the local pressure, P(z). On the other hand, the local pressure, P(z) is a function of the flow properties. In order to obtain a solution to the flow properties including the pressure, an iterative procedure is developed to correct the pressure at any pipe location based on the calculated pressure drop in each iteration. Convergence is achieved considering a tolerance equal or less than 0.1%. The procedure consists of two parts.

Table 1. Shear stress, friction factors, Reynolds number and hydraulic diameters equations.

Shear Stresses	$\tau_{LB} = f_{LB}\left(\rho_L \lvert U_{LB}\rvert U_{LB}/2\right)$	(23)
	$\tau_{GB} = f_{GB}\left(\rho_G \lvert U_{GB}\rvert U_{GB}/2\right)$	(24)
	$\tau_i = f_i\left(\rho_G \lvert U_{GB}-U_{LB}\rvert (U_{GB}-U_{LB})/2\right)$	(25)
	$\tau_S = f_S \rho_G J^2/2$	(26)
Friction factors for phase k (k = LB, GB, S)	$f_k = \begin{cases} 64/Re_k & Re_k < 2300 \\ 0.3164/Re_k^{0.25} & Re_k \geq 2300 \end{cases}$	(27)
	$f_i = 0.014$	(28)
Reynolds Number	$Re_{LB} = \rho_L U_{LB} Dh_{LB}/\mu_L$ $Re_{GB} = \rho_G U_{GB} Dh_{GB}/\mu_G$ $Re_S = \rho_L JD/\mu_L$	(29)
Hydraulic diameter	$Dh_{LB} = 4A_{LB}/S_{LB}, \quad Dh_{GB} = 4A_{GB}/(S_{GB}+S_i)$	(30)
Slug and bubble zone average densities	$\rho_S = \rho_L R_{LS} + \rho_G(1-R_{LS}), \quad \rho_B = \rho_L(1-R_{GB}) + \rho_G R_{GB}$	(31)

PART 1 - Properties at the pipe entrance (z = 0).

a) Guess the pressure gradient through the pipe, λ_u.
b) Calculate the pressure at the pipe entrance, P(z = 0) [Eq. (20)].
c) Calculate the following flow properties at the pipe entrance: $J_G(0)$ [Eq. (1)], $J(0)$ [Eq. (2)], $U_T(0)$ [Eq. (15)], $R_{LS}(0)$ [Eq. (16)].
d) The bubble length is obtained by the numerical integration of Eq. (8) respecting the mass balance.
e) Calculate the liquid slug length, $L_S(0)$.
f) Calculate the liquid slug and film pressure drop, $\Delta P_{LS}(0)$ and $\Delta P_{LB}(0)$ [Eq. (22)].
g) Calculate the new pressure gradient, $\lambda_{unew}(0)$ [Eq. (21)].
h) Compare λ_{unew} to λ_u: If the error is grater than 0.1% repeat steps b) to g), else go to part 2.

PART 2 - Properties at predetermined, z, positions along the pipe.

a) Calculate the pressure along the pipe, P(z) [Eq. (20)], using λ_u from part 1 (g).
b) Calculate the flow properties along the pipe: $J_G(z)$ [Eq. (1)], $J(z)$ [Eq. (2)], $U_T(z)$ [Eq. (15)], $R_{LS}(z)$ [Eq. (16)].
c) Calculate $L_B(z)$ along the pipe using the bubble shape model as shown in part 1 (d).
d) Calculate the liquid slug length, $L_S(z)$.
e) Calculate the liquid slug and film pressure drop, $\Delta P_{LS}(z)$ and $\Delta P_{LB}(z)$ [Eq. (22)].
f) Calculate the new pressure gradient in each position of the pipe, $\lambda_{unew}(z)$ [Eq. (21)].
g) Repeat steps b) to f) using $\lambda_{unew}(z)$.
h) If the difference of all properties using λ_u and $\lambda_{unew}(z)$ are less than 0.1%, the process is over; else, go to (b).

4. RESULTS

The algebraic model results are compared to experimental data obtained in vertical air-water flow. The experiments were done at the experimental facilities of the Energy Department of Unicamp, Brazil. Probes at two different positions along the pipe (z = 0 and z = 4.69m) were used to measure the local pressure, bubble velocity and bubble and liquid slug lengths. The fluid properties and flow configurations are presented in Table 2.

Four experiments were done using different liquid and gas exit superficial velocities. Table 3 presents these values, the exit pressure and inlet frequency measured in these cases.

Figures 4 and 5 present a comparison between the experimental and the algebraic model values. Figure 4 displays a comparison between slug and bubble dimensionless lengths. Near the pipe inlet, the model results for bubble and slug lengths present a good agreement with the experimental ones. This reflects the boundary condition at the inlet given by the frequency. As the cells are propagated through the pipe, it is expected an increase in the bubble length due to gas expansion and/or bubble coalescence. In this case, the slug length may decrease (if no coalescence is observed) or increase (when coalescence occurs). The experimental results present a great number of coalescences increasing the bubble and slug lengths. However, the algebraic model only takes into account the lengths variations due to gas expansion. For this reason, the comparison of the results downstream of the pipe is not so good.

Table 2. Fluid properties and pipe characteristics.

Fluids	Air and water
Pipe length, L (m)	5.8
Pipe diameter, D (m)	0.026
Liquid density, ρ_L (kg/m^3)	999
Gas density, ρ_G (kg/m^3)	1.21
Liquid viscosity, μ_L (cP)	0.855
Gas viscosity, μ_G (cP)	0.0181
Surface tension, σ (N/m)	0.0727

Table 3. Experiment data.

Experiment	1	2	3	4
Liquid superficial velocity, J_L (m/s)	0.330	0.300	0.610	0.880
Gas superficial velocity, J_{GS} (m/s)	0.603	1.691	1.083	0.828
Exit pressure, P_{atm} (Pa)	97883	98271	102202	105114
Inlet frequency (Hz)	1.930	1.909	3.192	4.424

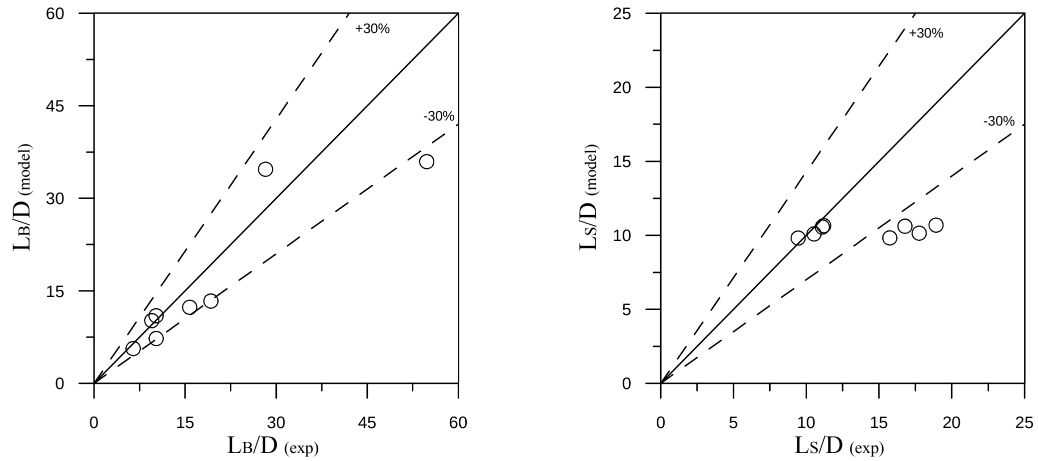

Figure 4. Bubble and slug dimensionless lengths.

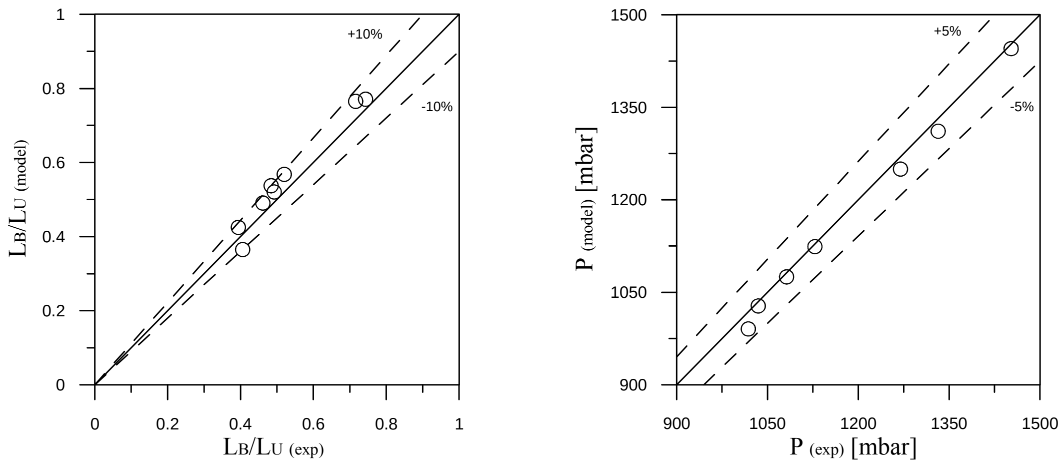

Figure 5. Intermittence factor and local pressure.

Figure 5 presents the comparison between the model and experimental results for the intermittence factor (L_B/L_U) and for the local pressure. Despite the errors obtained for the bubble and slug lengths presented in Fig. 4, the intermittence factor presents good agreement between the model and the experiments. This result shows that the intermittence factor is (at a first analysis) unaffected by the coalescences occurring along the pipe. In the local pressure results, the agreement is excellent. In the same manner as the intermittence factor, the pressure drop is not a strong function of the bubble and slug lengths, but depends on the combination of these variables. Furthermore, this result shows that the pressure drop calculations are consistent to the physical model.

5. CONCLUSIONS

The algebraic model embodies a bubble tracking model capable to represent the gas compressibility effects as the gas-liquid mixture travels along the pipe. The model extends the capabilities of a unit-cell model allowing the determination of the flow properties along the pipeline extent at once.

The advantage of this model is its simplicity, easiness of application and low computational cost, making it a useful tool of reference data generation in order to check the consistency of numerical slug tracking models. Its main disadvantage is similar to the unit-cell models: the periodicity of the gas-liquid structures. The model's output compares favorably to the experimental data. There are though some differences between the predicted and the measured slug and bubble lengths. These differences arise due bubble coalescence which is not modeled due the lack of bubble interaction on the model.

Future works should perform tests with different fluid properties and analyze the model's sensitivity to the variation of parameters such as the constants belonging to constitutive equations.

6. ACKNOWLEDGEMENTS

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8. RESPONSIBILITY NOTICE