Proceedings of ENCIT 2010
13rd Brazilian Congress of Thermal Sciences and Engineering
December 05-10, 2010, Uberlandia, MG, Brazil

INFLUENCE OF THE INITIAL CONDITIONS FOR THE NUMERICAL SIMULATION OF TWO-PHASE SLUG FLOW

Alex A. Pachas Napa, alex.pachasn@gmail.com
Rigoberto E. M. Morales, rmorales@utfpr.edu.br
César D. Perea Medina, cesar.perea.medina@gmail.com
Cristiane Cozin, criscozin@yahoo.com.br
LACIT/PPGEM/UTFPR, Av Sete de Setembro 3165, CEP. 80230-901, Curitiba-PR-Brasil

Eugênio S. Rosa, erosa@fem.unicamp.br
Ricardo A. Mazza, mazza@fem.unicamp.br
2PFG/FEM/UNICAMP, Cidade Univesitária S/N, Campinas-SP

Abstract. *Multiphase flows in pipelines commonly show several patterns depending on the flow rate, geometry and physical properties of the phases. In oil production, the slug flow pattern is the most common among the others. This flow pattern is characterized by an intermittent succession in space and time of an aerated liquid slug and an elongated gas bubble with a liquid film. Slug flow is studied through the slug tracking model described as one-dimensional and lagrangian frame referenced. In the model, the mass and the momentum balance equations are applied in control volumes constituted by the gas bubble and the liquid slug. Initial conditions must be determined, which need to reproduce the intermittence of the flow pattern. These initial conditions are given by a sequence of flow properties for each unit cell. Properties of the unit cell in initial conditions should reflect the intermittence, for which they can be analyzed in statistical terms. Therefore, statistical distributions should be obtained for the slug flow variables. Distributions are complemented with the mass balance and the bubble design model. The objective of the present work is to obtain initial conditions for the slug tracking model that reproduce a better adjustment of the fluctuating properties for different pipe inclinations (horizontal, vertical or inclined). The numerical results are compared with experimental data obtained by 2PFG/FEM/UNICAMP for air-water flow at 0º, 45º and 90º and good agreement is observed.*

Keywords*: Slug flow, slug tracking, initial conditions, intermittence, distribution function.*

1. INTRODUCTION

Two phase slug flow is the most common flow pattern found in oil production in deep waters. This pattern is characterized by the intermittent succession of an aerated liquid slug and an elongated bubble with a liquid film. These regions compose a unit cell (Wallis, 1969) and each of them presents different characteristics along the pipe. The unit cell concept was used to develop many mathematical models for the prediction of the flow hydrodynamics in horizontal, vertical and inclined pipes. These models can be classifieds in two groups: stationary and unsteady.

Stationary models consider the flow as periodic; in other words, there is a constant sequence of the geometric and physical characteristics of the unit cell for the horizontal (Dukler and Hubbard, 1975) and the vertical (Fernandes *et al*, 1983) flow. Mean values of the important variables, are found, such as pressure drop and bubble velocity. However, the main characteristic of slug flow, its intermittence, is not captured.

Unsteady models were also developed, which attempted to simulate the transient phenomena occurring on the slug flow. The main methodologies are: two fluid model, drift flux model and slug tracking model. Among them, the slug tracking model is a lagrangian model which presents a lower computational cost, compared to the two-fluid model (Rodrigues, 2009). Due to the lagrangian characteristic, it can incorporate directly physical models for the propagation of the bubble-slug boundaries and it can lower the effects of numerical diffusion (Nydal and Banerjee, 1995). The slug tracking model is based on the integral form of the mass and momentum balance equations. As it uses mean values instead of local instantaneous values, it performs fewer operations at each time step, lowering the computing time. The slug tracking model calculates the flow parameters along the pipe, however, it can not reproduce the intermittency by itself. This intermittency is introduced by the initial conditions, which are a matter of concern to many authors.

One of the first works on intermittence of slug tracking was presented by Barnea and Taitel (1993). A model was developed for the slug length probability distribution highlighting the importance of the maximum slug length along the pipe. They also developed two types of slug length distributions at the entrance: a random and a uniform distribution. It was concluded that the slug length distribution at the entrance does not affect the following parameters: slug length evolution along the pipe, fully developed flow distribution, average, maximum and standard deviation of the slug length distribution.

Later, Cook and Benhia (2000) studied the Barnea and Taitel´s (1993) model with no-aerated slugs considering the film thickness in order to calculate the slug lengths in inclined pipes at +5º. Hout *et al.* (2001) developed a statistical analysis in a vertical pipe for different diameters considering the curve adjustment suggested by Moissis and Griffith

(1962). Hout *et al.* (2003) modified the empirical correlation of Moissis and Griffith (1962) to apply his model to inclined pipes at +10º, +30º and +60º.

Rodrigues (2009) studied the slug flow, using the slug tracking model and considering intermittent initial conditions at the pipe entrance implemented to the geometric and physical parameters of the flow. Distributions for the slug length, bubble length and the gas superficial velocities are found through the normal and log normal distributions, considering the volume fractions constant along the simulation. However, as the volume fractions are constant and the other parameters vary, problems with the mass balance can occur.

The geometric parameters and the main variables in each region show intermittence along the pipe. Therefore, it is not enough to know their average behavior, but also the distribution. For that reason, slug flow variables should be described in statistical terms (Barnea and Taitel, 1993). The flow intermittence can be reproduced by the use of the probability density function (PDF). In Figure 1, PDFs for the translational velocity, bubble and liquid slug length are shown. For the case of the slug length, it is observed that the maximum value is far from the average, which is an important fact to consider in the slug catchers design. In addition, bubble length distribution and translational velocity distributions are related to the coalescence as long bubbles with high velocities can overrun bubbles upstream.

As presented before, the slug tracking model strongly depends on the initial conditions. This is the reason why the present work concentrates in the development of a methodology to generate these initial conditions, which need to reproduce the intermittence and other physical phenomena occurring in the flow. It must be understood as physical phenomena the quantity of bubbles in the liquid slug, the wake effect, the geometric shape of the bubble and others to be presented along the development of the work. Initial conditions are generated from averaged data by using stationary models and probability distributions. As a result, a sequence of unit cell generated data is obtained, which constitutes the input for the slug tracking model. The output obtained from the slug tracking model presents similar behavior compared with the data reported by Rosa and Altemani (2006) for several points along the pipe.

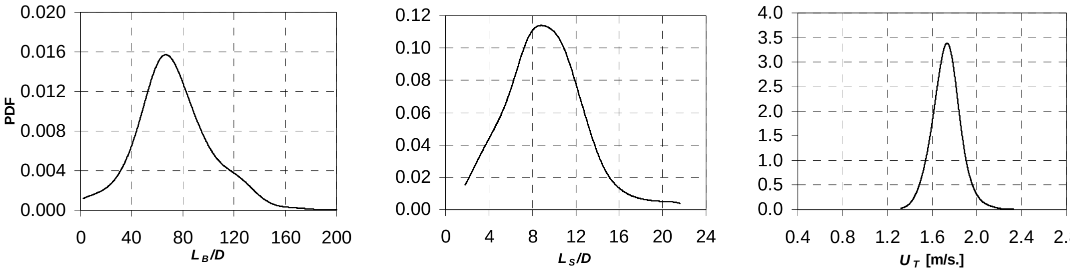

Figure 1. Representation of experimental distributions for j_L = 0.3 m/s e j_G = 1.2 m/s

2. SLUG TRACKING MODEL

Slug tracking model considers the bubble and liquid slug regions as separated elements that propagates along the pipe. In this section, the mathematical and numerical models are described. The result of the model is an equation system function of the main flow parameters: the liquid slug velocity and the gas bubble pressure.

The mathematical model, based on Rodrigues (2009), consists on an integral analysis of the mass and momentum balance equations in the one-dimensional form, applied to each component of the unit cell. Those control volumes are deformable and use the slug tracking method. Figure 2., presents the j^{th} unit cell, with coordinates X_j e Y_j that represent the front of the slug and the bubble, respectively. The mass and momentum balance determine the terms of the pressure drop, P_{GBj}-P_{GBj+1}, and the mean velocity on the liquid slug, U_{LSj}. Also, Figure 2. shows the bubble and liquid slug length. L_{Bj} and L_{Sj}, the mean liquid velocity in the film U_{LBj} , the mean dispersed bubble velocity in the slug U_{GSj} and the bubble translational velocity U_{Tj}.

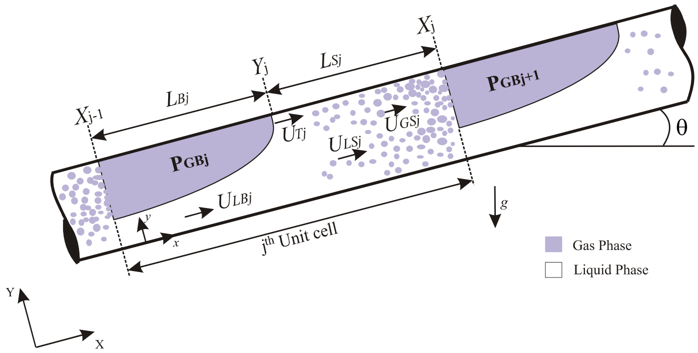

Figure 2. Slug flow unit cell

The mass and momentum balance equations are applied to the control volume considering the following hypothesis: incompressible liquid, ideal gas, constant temperature, negligible forces in the gas bubble, no axial variation of the pressure inside each bubble, liquid holdup in the slug R_{LS} and void fraction in the film R_{LB} variable with time.

Mass balance for the overall unit cell, is presented by Rodrigues (2009), as:

$$U_{LSj-1}-U_{LSj}=\frac{dH_{GBj}}{dt}\left[L_{Bj}\frac{\left(1-R_{LBj}\right)}{H_{GBj}}+\frac{L_{Sj}}{2}\frac{\left(1-R_{LSj}\right)}{H_{GBj}}+\frac{L_{Sj-1}}{2}\frac{\left(1-R_{LSj-1}\right)}{H_{GBj-1}}\right]+\left(\frac{1-R_{LSj}}{R_{LSj}}\right)U_{DSj}-\left(\frac{1-R_{LSj-1}}{R_{LSj-1}}\right)U_{DSj-1} \tag{1}$$

where, H_{GBj} is: $H_{GBj}=P_{GBj}/\rho_{GBj}$. Equation(1), represents the overall mass balance of the j^{th} unit cell.

In Eq. (1) the difference between the slug velocities in two adjacent unit cells (j and j-1) is related to the expansion occurring on the j^{th} bubble and the mass fluxes crossing the control surfaces X_{j-1} and Y_j. This expansion occurs due to the variation of the geometric characteristics on the unit cell along the space and the pressure variation along the time. The second and third terms at the right of Eq. (1) represent the mass fluxes.

Momentum balance is performed in the liquid slug. The pressures obtained from this balance are evaluated on the slug surfaces. However, Rodrigues (2009) expresses them as a function of the bubble pressures by applying balance equations in the positions Y_j and X_j. At position Y_j, fluxes are neglected due to the smooth shape of the bubble front and at X_j, fluxes are neglected due to the wake phenomenon occurring in this region. Considering the conditions above, the momentum balance in the liquid slug is:

$$\begin{aligned}H_j-H_{j+1}&=\frac{\left(\tau_{LBj+1}\bar{S}_{LBj+1}L_{Bj+1}+\tau_{Sj}\pi DL_{Sj}\right)}{\rho_L A}+\left(R_{LSj}L_{Sj}+\bar{R}_{LBj+1}L_{Bj+1}\right)g\,\mathrm{sen}\,\theta\\&+\left\{L_{Sj}R_{LSj}+L_{Sj}\frac{dR_{LSj}}{dU_{LSj}}\left[\frac{1}{2}\left(\frac{dX_j}{dt}+\frac{dY_j}{dt}\right)-U_{LSj}\right]\right\}\frac{dU_{LSj}}{dt}\end{aligned} \tag{2}$$

where τ_{LBj+1} is the shear stress of the liquid film, S_{LBj+1} is the liquid wetted perimeter in the film and A is the area of cross-section of the pipe.

Equations (1) and (2) constitute the coupled system of the slug flow model formed by two differential equations. In order to solve numerically, the system is discretized through the finite differences method using the semi-implicit Crank-Nicholson scheme (Patankar, 1980). A couple of two equations is written for each j unit cell ($1 \le j \le n$). If n is the number of unit cells inside the pipe, there would be $2n$ equations. That way, there is an equation system in terms of the mean velocity in the liquid slug region U_{LSj} and the pressure inside the j^{th} bubble P_{GBj}. The set of units cells produce a linear system which can be written as $A.Ø = B$, where A, is a tridiagonal matrix, $Ø$ is the unknown vector and B the source term vector. One system is solved in each time step.

Finally, the TDMA method is used to solve the equation system. For the application of this method, some boundary conditions must be known for the first and last cells. In the first cell (j = 1), it is used the value U_{LS0}, which represents the instantaneous velocity of the liquid in the first slug. In the last cell (j = n), it is used the value H_{GBn+1}, which represents the pressure at the exit. Commonly, the atmospheric pressure written as $H_{GBn+1}=P_{atm}/\rho_L$, is used at the exit.

In order to initialize the simulation, conditions at $t=0$ must be established. In the present work, it is considered that the pipe is full of liquid with initial velocity U_{LS0} and the first bubble is positioned in $x=0$. However, whenever a cell needs to be inserted at the pipe entrance, the bubble and slug lengths and the superficial velocities must be known. These parameters will be calculated in section three.

3. INITIAL CONDITIONS

In the slug tracking method, the unit cells set as initial conditions are propagated along the pipe. Thus, coherent initial conditions determine an accurate simulation of the slug flow. For the initialization of the slug tracking, physical and geometric parameters of the pipe and the unit cells are needed. In order to determine the characteristics of the unit cells used as initial condition, it is necessary to know the variables listed on Table 1.

Each of the mean values and standard deviations will be used to generate a sequence of distributed values. In the case of L_B and j_G, normal distributions are applied. In the case of L_S a log-normal distribution is used (Rosa, 2006). In the case of j_L, it is not necessary to build a distribution as it is assumed constant along the simulation. Also, the slug liquid holdup R_{LS} and void fraction of the elongated bubble R_{GB} are calculated through the bubble design model presented in section 3.2.

Table 1 - Input data for the generation of initial conditions

Parameters	**Description**	**Parameters**	**Description**
$\overline{j_G}$	Mean gas superficial velocity	σ_{L_B}	Bubble length standard deviation
$\overline{j_L}$	Liquid superficial velocity	σ_{L_S}	Liquid slug length standard deviation
$\overline{L_B}$	Mean bubble length	σ_{U_T}	Bubble translational velocity standard deviation
$\overline{L_S}$	Mean liquid slug length	f	Frequency

3.1 Distribution functions for the unit cell

For the reproduction of L_S, using the log-normal distribution, the following parameters need to be calculated:

$$\begin{aligned}\Psi &= \sqrt{Ln\left[\left(\sigma_{L_S}\right)^2+1\right]}\\ \Gamma &= \overline{L_S}\cdot\exp\left[-\left(\Psi\right)^2/2\right]\end{aligned} \tag{3}$$

where, Ψ and Γ are statistical distribution parameters.

In order to obtain the distributed values sequence, the transformation proposed by Box and Muller (1958) is used. In this transformation, a sequence of random data with normal distribution can be generated through two lists of independent random (λ^1 and λ^2) values with a uniform distribution (between 0 and 1). If sequences data generated by the Box Muller (1958) function, is used, a third sequence of random data is calculated by:

$$\begin{aligned}\Omega_i &= \sqrt{-2Ln\left(\lambda_i^1\right)}\cos\left(2\pi\lambda_i^2\right)\\ \Omega_{i+1} &= \sqrt{-2Ln\left(\lambda_{i+1}^1\right)}\mathrm{sen}\left(2\pi\lambda_{i+1}^2\right)\end{aligned} \tag{4}$$

where λ_i^1 and λ_i^2 are independent random variables that are uniformly distributed in the interval < 0,1 >, Ω_i is an independent random variable. These random variables constitute a set of results close to the principal mean and with standard deviation equals to 1.

Then, the data set with normal distribution is used to obtain the slug flow parameters. In other words, it is obtained sequences with normal distribution for the gas superficial velocity (j_{Gi}) and bubble length (L_{Bi}) and sequences with log-normal distribution for the slug length. These sequences are function of the mean values and standard deviation, calculated through the following equations:

$$j_{Gi} = \overline{j_G} + \Omega_i\left(\sigma_{U_T}\right)\left[\overline{j_L}+\overline{j_G}+V_D/C_0\right] \tag{5}$$

$$L_{Bi} = \overline{L_B}\left[1+\Omega_i\left(\sigma_{L_B}\right)\right] \tag{6}$$

$$L_{Si} = \exp\left[\Omega_i\Psi + Ln\left(\Gamma\right)\right] \tag{7}$$

where V_D is the drift velocity and C_0 is the flow distribution coefficient related to the translational bubble velocity U_T. Calculation of these parameters is presented in section 3.2.

3.2 Bubble design model

When the parameters j_{Gi}, L_{Bi} and L_{Si} are known, the volume fractions R_{LSi} and R_{GBi} can be calculated using the bubble design model presented by Taitel and Barnea (1990):

$$\frac{\partial h_{LB}}{\partial x} = \frac{\dfrac{\tau_L S_L}{A_L} - \dfrac{\tau_G S_G}{A_G} - \tau_i S_i\left(\dfrac{1}{A_G}+\dfrac{1}{A_L}\right) + \left(\rho_L-\rho_G\right)g\,sen\theta}{\left(\rho_L-\rho_G\right)g\cos\theta - \dfrac{\rho_L V_{LB}^2}{R_{LB}}\dfrac{dR_{LB}}{dh_{LB}} - \dfrac{\rho_{GB}V_{GB}^2}{\left(1-R_{LB}\right)}\dfrac{dR_{LB}}{dh_{LB}}} \tag{8}$$

where the numerator of the Eq.(8) shows the shear stresses in the elongated bubble and the liquid film. The denominator has the inertial terms and the hydrostatic force in each point of the bubble profile.

The most influential parameter in the bubble design model is the translational velocity U_{Tj} (Rodrigues, 2009) because it determines the distribution of the unit cell components. Its expression is given by an empirical correlation:

$$U_T = \left(C_o J + V_D\right)(1+\hbar) \tag{9}$$

where $V_D = C_\infty \sqrt{gD}$ is the drift velocity of the elongated bubble, J is the mixture velocity, $\hbar$ is the factor of the wake behind the bubble, and C_∞ is a coefficient related to the slope pipe. The coefficients C_∞ and C_o are calculated by Bendiksen´s correlations, as a function of the Reynolds number Re_M, Froude number Fr_M and Eötvös number E_o. For an inclined pipe the C_0 coefficient will depend on the angle (Bendiksen, 1983).

The wake factor in Eq. (9) is calculated as $\hbar = a_W \exp\left(-b_w \frac{L_S}{D}\right)$ (Moissis and Griffith, 1962), where the coefficient a_W and b_W modify the wake according to the inclination. The present work considers the coefficients $a_W = 0.4$ and $b_W = 1.0$ for horizontal pipe and $a_W = 8.0$ and $b_W = 1.06$ for vertical and inclined pipes (Rodrigues, 2009).

In order to integrate equation 11, some considerations must be taken. For horizontal and inclined pipes, it is necessary to determine an initial film height, which is defined as a fraction of the diameter: $h_f = K{\cdot}D$. The initial film height, must satisfy the condition $\left(dh_{LB}/dx\right) < 0$, where the slope evaluated in the initial height is negative (Yoshisawa, 2005). For vertical pipes, the initial height is considered as a function of the initial volumetric fraction R_{LB}. Once calculated the slope and the conditions initials in the film, closure relationships for the bubble design equations are needed.

Eq. (8) is integrated numerically from $x = 0$ to $x = L_{Bi}$ to obtain the bubble geometry. Then, the mean void fraction in the bubble R_{GBi} is calculated through the height distribution along the bubble length. The liquid holdup in the slug R_{LSi} is calculated through the mass balance applied in the unit cell (Taitel and Barnea, 1990). In Table 2 the equation for the liquid holdup for horizontal and vertical pipes is presented. For horizontal pipes, it depends on the mean liquid velocity in the film region; and for vertical pipes it depends on the mean dispersed bubble velocity in the liquid region. These equations are used as closure relationships for the bubble design model. β is the intermittency factor defined as $\beta = L_{Bi}/(L_{Bi}+L_{Si})$.

Table 2 –Slug liquid holdup R_{LS} according to the inclination of the pipe

Horizontal and inclined pipes	Vertical pipe
$R_{LS} = \dfrac{j_L + U_T \overline{R}_{LB}\left(1-\beta\right) - \overline{R}_{LB}\overline{U}_{LB}}{U_T\left(1-\beta\right)}$	$R_{LS} = 1 - \dfrac{j_G - \overline{R}_{GB} U_T\, L_B/L_U}{U_{GS} - U_T\, L_B/L_U}$; $L_U = L_B + L_S$
$R_{GB} = \dfrac{j_G}{U_T\beta} - \left(1-R_{LS}\right)\dfrac{\left(U_{GS} - U_T\beta\right)}{U_T\beta}$	

3.3 Algorithm

To sum up, it is presented the calculation algorithm, used to generate the initial conditions for the slug tracking model. The input data required to apply this method is shown in Table 1. This procedure is organized in six steps:
Generation of the data sequence

1) Generate as many random values as unit cells required through Eq. (4).
2) Apply Eqs. (3), (5), (6) and (7) to each generated value to calculate j_{Gi}, L_{Bi} and L_{Si}.
3) Assume a value for R_{LS}. Use the bubble design equation and the procedures described in Section 3.2 to calculate R_{GBi}.
4) Calculate R_{LS} and R_{GB} through the equations in Table 2.
5) Compare R_{LS} and R_{GB} from 4) with the assumed R_{LS} in 3) and R_{GB} from the bubble design. The convergence criteria are: 0.01% for R_{LS} and 0.1% for R_{GB}.
6) If the values in 5) don't converge, steps 3) and 4) are repeated using the R_{LS} found in 5).

In this section, the methodology to produce initial conditions was presented. These initial conditions reproduce the intermittence through distributions obtained as function of statistical variables and random values. Generated slug and bubble length are evaluated using the liquid mass balance in order to calculate the volume fraction. Thus, all the generated cells satisfy the mass balance.

4. METHODOLOGY

In the previous sections, it was presented the slug tracking model and the initial conditions for its initialization. In this section, the methodology for the solution of the slug flow is detailed. The lagrangian slug tracking model presented in section two is implemented in an object-oriented computational program written in FORTRAN language. In this approach, bubbles and slugs are discrete objects which are propagated along the pipe through the balance equations of mass and momentum. The software Intel Visual Fortran has been used as compiler.

Initial conditions must be introduced in the model, for which a procedure for its entrance should be explained. Once the data sequence is generated, they are saved in a file. This file will be read line by line by the program slug when the simulation starts.

When the simulation starts (at $t=0$), two unit cell are required from the generated sequence data. The first has its bubble nose at $X = 0$ and the second is behind the first one still outside the pipe. One time step later, the parameters of the first unit cell is updated through the solution of the tridiagonal system. Time steps are increased and tridiagonal systems are calculated until the first bubble is completely inside the pipe. In that moment, the second bubble starts entering the pipe and a third unit cell from the generated data is required. This third unit cell is positioned behind the second. This procedure is repeated for every single unit cell entering the pipe. Simulation finishes when a number of unit cells specified by the user leaves the pipe. In the next section, some results are presented, which are compared with experimental data obtained by 2PFG/FEM/UNICAMP.

5. RESULTS

Once the methodology is implemented in the program, the simulation through the slug tracking model can take place. Simulations are performed in a processor PC Intel ® Core™ 2 CPU 2.13 GHz with 2.00 GB RAM. For the generation of the data sequence, 3000 unit cells were generated in a period of 15 minutes. For the slug tracking model, the stop condition is the exit of 600 bubbles which take an average of 20 minutes. Tables 3, 4 and 5 represent the geometric and physical characteristics of the experiments performed by Rosa and Altemani (2006) who reported data for horizontal, vertical and inclined pipes. Data from the simulations are plotted with the experimental data in order to compare at specific locations on the pipe. Analyzed parameters at these locations are: the bubble translational velocity, the slug and the bubble length.

Table 3 – Geometric configurations of the horizontal flow

Pipe length, [m.]	20	Wake effect factor [a_w]	0.4
Diameter, [m.]	0.026	Wake effect factor [b_w]	1.0
Location of probe #1 [m.]	0.10	Liquid density [kg/m^3]	999
Location of probe #2 [m.]	3.64 (140D)	Liquid Viscosity [Pa.s]	0.000855
Location of probe #3 [m.]	9.54 (367D)	Superf liquid velocity [m/s]	0.33
Location of probe #4 [m.]	16.9 (650D)	Superf gas velocity [m/s]	0.595

Table 4– Geometric configurations of the vertical flow

Pipe length, [m.]	5.81	Wake effect factor [b_w]	1.06
Diameter, [m.]	0.026	Liquid density [kg/m^3]	999
Location of probe #1 [m.]	0.10	Liquid Viscosity [Pa.s]	0.000855
Location of probe #2 [m.]	4.693 (180.5D)	Superf liquid velocity [m/s]	0.33
Wake effect factor [a_w]	8.0	Superf gas velocity [m/s]	0.464

Table 5– Geometric configurations of the inclined pipe (+45º)

Pipe length, [m.]	5.81	Wake effect factor [b_w]	1.06
Diameter, [m.]	0.026	Liquid density [kg/m^3]	999
Location of probe #1 [m.]	0.10	Liquid Viscosity [Pa.s]	0.000855
Location of probe #2 [m.]	4.693 (180.5D)	Superf liquid velocity [m/s]	0.586
Wake effect factor [a_w]	8.0	Superf gas velocity [m/s]	0.420

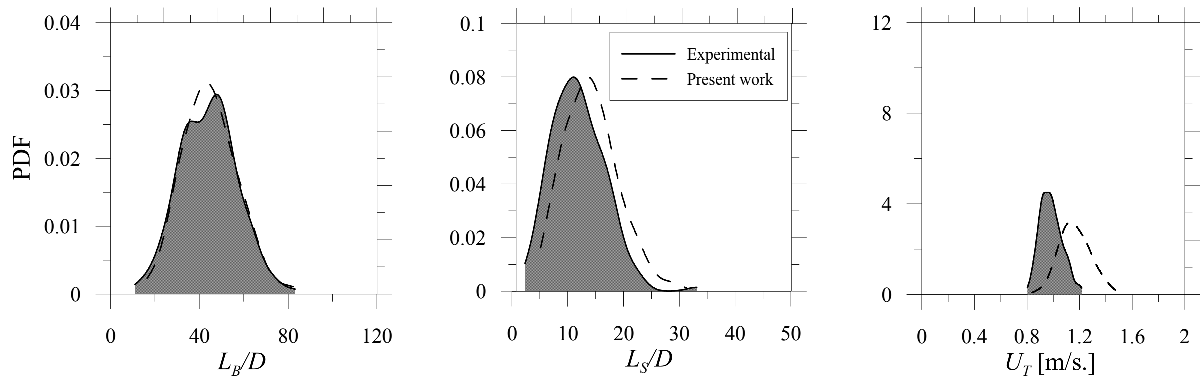

Figure 3 - Probability density function at the entrance for the horizontal pipe with j_L = 0.33 and j_G = 0.595 m/s.

Figure 3 and Figure 4, present the probability density functions for the horizontal pipes with mixture velocity less than 1 m/s. The liquid slug length, the bubble length and the bubble translational velocity showed similar distributions compared with the experimental data at each position (Probe). The obtained lengths in the unit cell coincide with the maximum values at each probe. However, the numerical distribution of the bubble translational velocity, is dislocated from the experimental distribution. Probably, the Bendiksen´s correlation tends to overestimate the value of the translational velocity for horizontal flow. The sequence data generated obtained values in a range from 4.5D to 30D for the slug length and from 20D to 80D for bubble length at the pipe entrance. As the wake factor directly affects the coalescence of the bubbles (Rodrigues, 2009), in the case of horizontal flow, a low coalescence rate is observed.

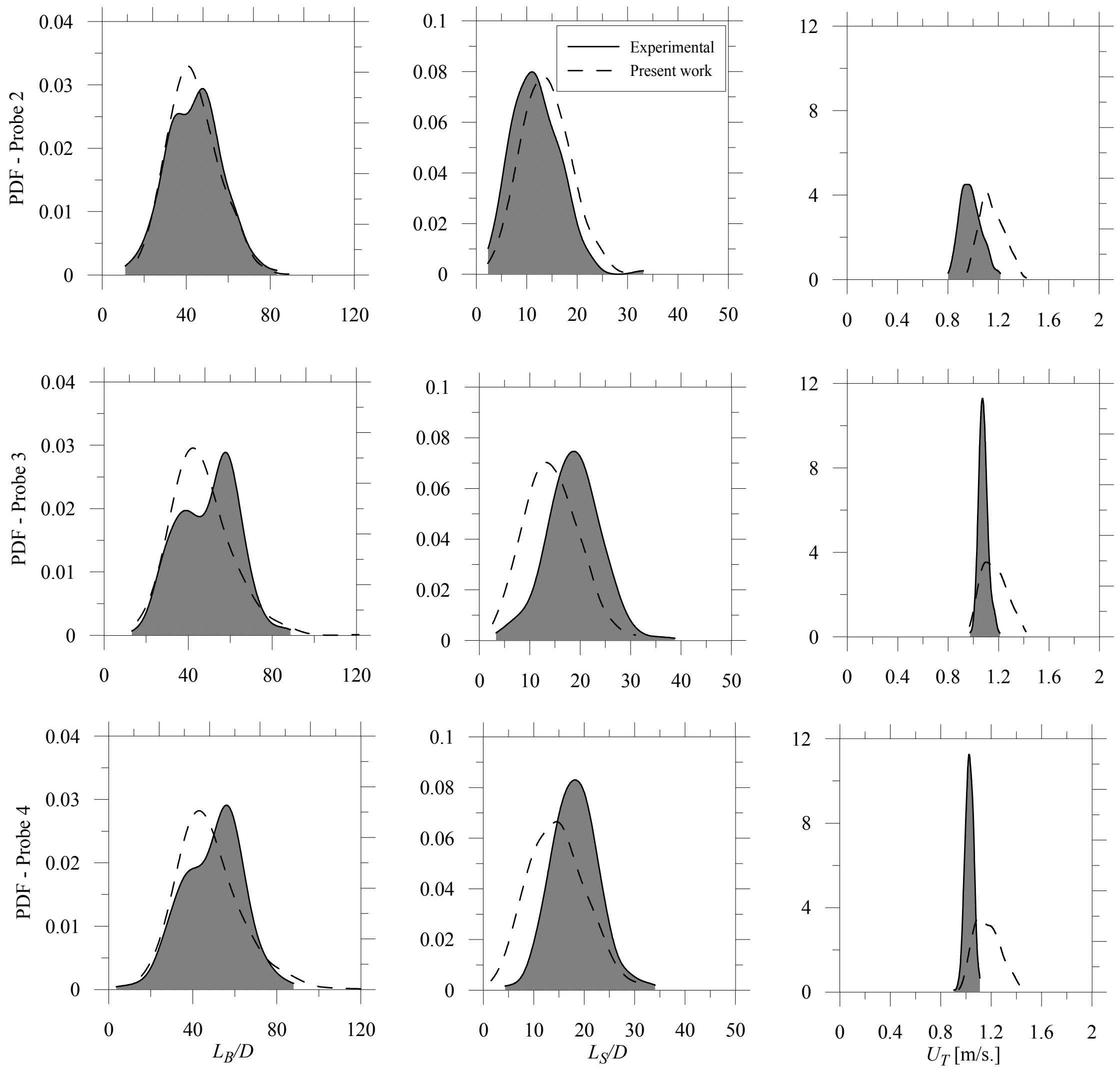

Figure 4 – Probability density function along the pipe for the horizontal pipe with j_L = 0.33 and j_G = 0.595 m/s.

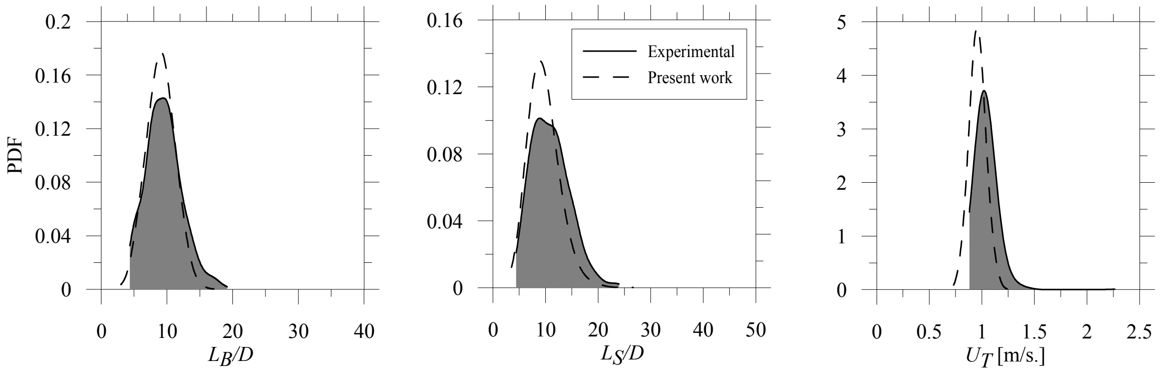

Figure 5 – Probability density function at the entrance for the vertical pipe with j_L = 0.33 and j_G = 0.464 m/s.

Figure 5 and Figure 6 present the probability density functions for the air–water vertical flow, where the mixture velocity is less than 1 m/s. The numerical mean values for the bubble and liquid slug length are similar with the experimental data. The bubble translational velocity is approximate at the entrance and at probe 2. There is a displacement of the mean in Probe 3 for the geometric and physical parameters. However, the maximum values adjusts to the experimental data. The bubble lengths are between 3D and 18.65D and for the liquid slug lengths are between 3D and 26D. Just as horizontal flow, a low coalescence rate is observed.

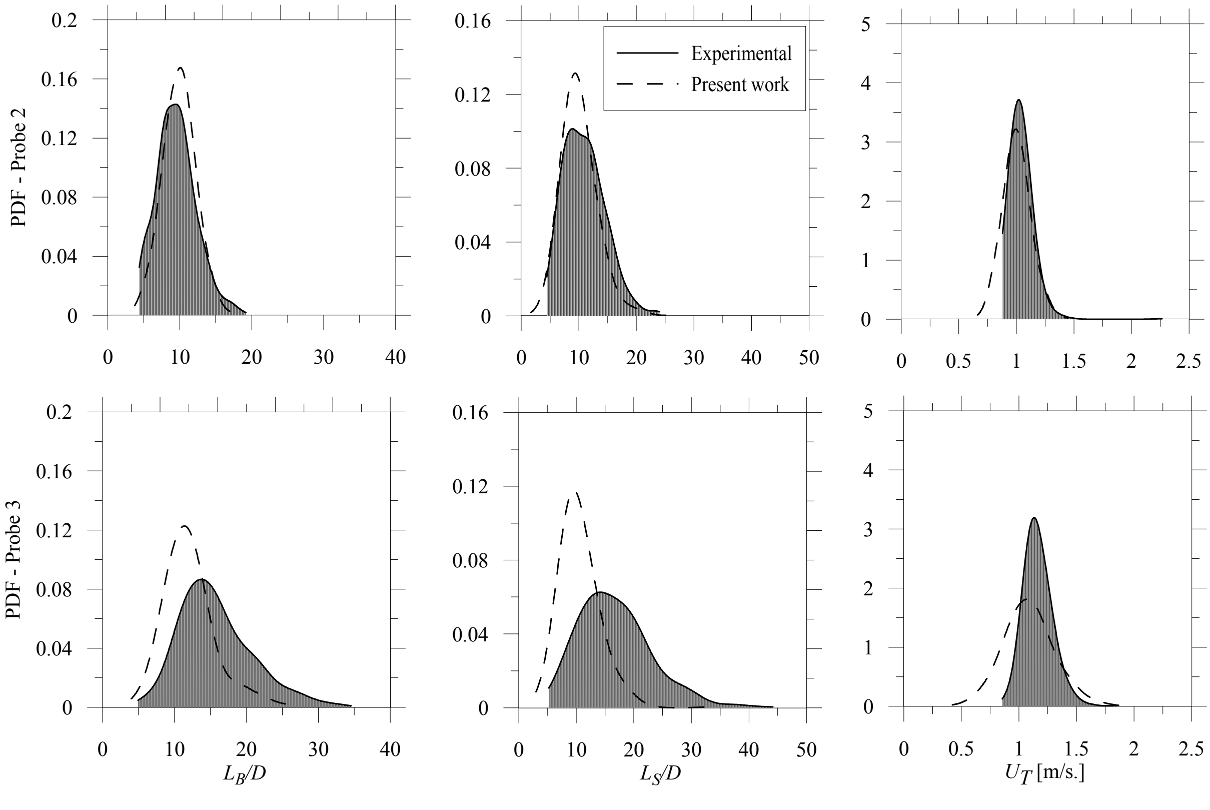

Figure 6 - Probability density function along the vertical pipe with j_L = 0.33 and j_G = 0.464 m/s.

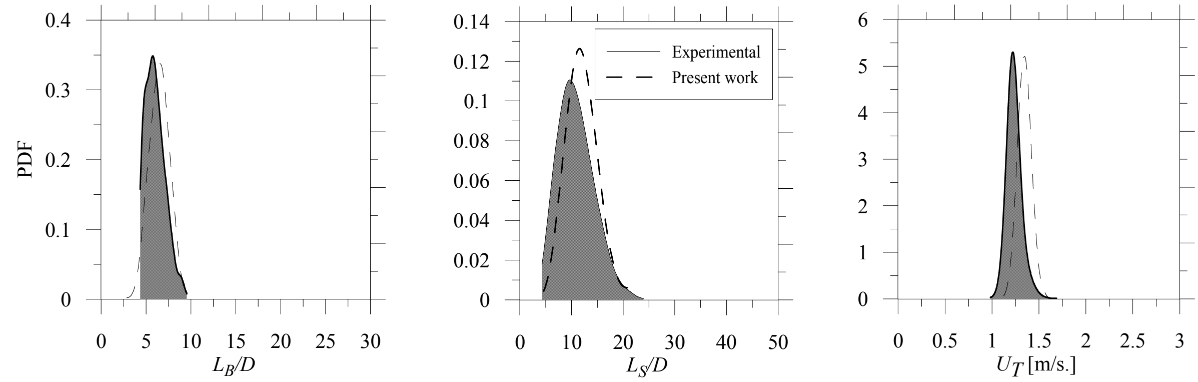

Figure 7 - Probability density function at the entrance for the inclined pipe with j_L = 0.586 and j_G = 0.420 m/s.

Figure 7 and Figure 8 present the probability density functions for the inclined flow (+45^o) of air-water, where the mixture velocity is 1 m/s The mean values are displaced compared with the experimental data at the entrance and at the Probe 2. However, at Probe 3 the geometric and physical distributions are similar, just as the maximum value for the bubble and liquid slug length. The bubble length is between the range of 2.5D to 10D and 5D to 24D for the liquid slug length.

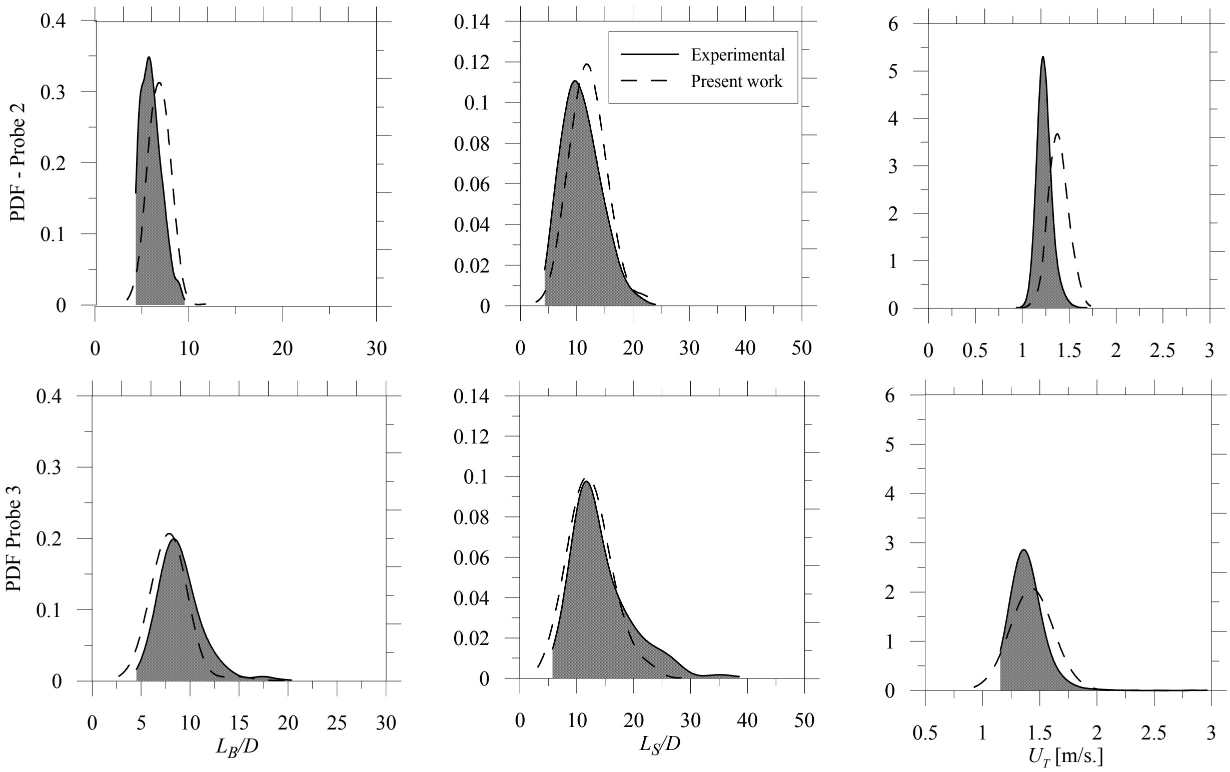

Figure 8 - Probability density function along the inclined pipe with j_L = 0.586 and j_G = 0.420 m/s.

6. CONCLUSIONS

A model for the simulation of slug flow was presented. Special focus was put on the development of randomly generated input data. The intermittence is implemented, considering the geometric and physical parameters in a random and controlled way. For the superficial gas velocity and bubble length, a normal distribution is used while for the liquid slug region, a log-normal distribution is used. Each parameter is characterized by its mean and its standard deviation obtained from experimental data. The liquid holdup R_{LS} and the void fraction R_{GB} were calculated through the bubble design model. They were included at the entrance in a variable form, showing a better adjustment to the experimental distributions along the pipe.

The numerical results were compared with experimental data for horizontal, vertical and inclined (+45^o) air-water flow, approximately capturing the intermittence of the unit cell length and the bubble translational velocity. Numerical results also approximate to the maximum liquid slug length for all inclinations.

The evolution of the mean values is approximated to the experimental data along the pipe. The results show the influence of the input data at the entrance and the wake factor in the distributions of each parameter along the pipe. A low coalescence rate is found for the three inclinations due to the selected wake factor. It was observed that the Bendiksen´s correlation works well for vertical and inclined pipes, but tends to overestimate its value for horizontal flow. Future works can be developed by changing the flow conditions, the type of fluids and the wake factor.

7. REFERENCES

Barnea and D., Taitel, Y., 1993 "A Model for Slug Length Distribution in Gas – Liquid Slug Flow", International Journal of Multiphase Flow, Vol. 19, No. 5, pp. 829-838.

Grenier, Philippe, 1997 "Evolution des longueurs de bouchons en écoulement intermittent horizontal". Toulouse: Institut de Mécanique des Fluides de Toulouse, Institut National Polytechnique de Toulouse, pp.193. Doctor thesis.

Dukler, A. E., Hubbard, M. G., 1975 "A Model for Gas-Liquid Slug Flow in Horizontal and Near Horizontal Tubes". Ind. Eng. Chem. Fundam., 14 (4), 337-347.

Cook, M., Benhia, M., 2000 "Slug Length Prediction in Near Horizontal Gas – Liquid Intermittent Flow". Chemical Engineering Science, Vol. 55, pp. 2009-2018.

Fernandes, R.C., Semiat, R., Dukler, 1983 "A. E. Hydrodynamic Model for Gas-Liquid Slug Flow in Vertical Tubes." AIChE Journal, Vol. 29, No. 6, pp. 981-989.

Kjell, H. Bendiksen 1983 "An Experimental Investigation of the Motion of Long Bubbles in Inclined Tubes". International Journal of Multiphase Flow, Vol. 10, No. 4, pp. 467-483.

Moissis, R., Griffith, P., 1962 "Entrance effects in a two – phase slug flow". Journal Heat Transfer, Vol. 85, pp. 29-39.

Nicklin, D.J., Wilkes, J.O., Davidson, J.F., 1962 "Two-phase flow in vertical tubes." Trans Inst. Chem. Eng., Vol. 40, pp. 61-68.

Nydal, O. J., Banerjee, S., 1995 "Dynamic Slug Tracking Simulations for Gas-Liquid Flow in Pipelines". University of California Santa Barbara, United States

Patankar, S.V., 1980, "Numerical Heat Transfer and Fluid Flow". Philadelphia: Taylor & Francis.

Rodrigues, H. T.,2009 "Simulação Numérica de Escoamento Bifásico gas-líquido no padrão de golfadas utilizando um modelo lagrangeano de seguimento de pistõesl". Universidade Tecnologica Federal do Paraná. Curitiba, Brasil, pp. 192 Master thesis.

Rosa, E. S and Altemani, C. A. C., 2006 "Análise de Escoamentos em Golfadas de Óleos Pesados e de Emulsões Óleo-água" Quarto Relatório de Atividades e Resultados alcançados, Projeto UNICAMP / CENPES – PETROBRAS, Campinas, SP.

Taitel, Y. and Barnea, D., 1990 "Two phase slug flow", Advances in Heat Transfer, Hartnett J.P. and Irvine Jr. T.F. ed., vol. 20, 83-132, Academic Press.

Van Hout, R., Barnea, D., Shemer, L., 2001 "Evolution of Statistical Parameters of Gas – Liquid Slug Flow Along Vertical Pipes". International Journal of Multiphase Flow, Vol. 27, pp. 1579-1602.

Van Hout, R., Shemer L., Barnea, D., 2003 "Evolution of Hydrodynamic and Statistical Parameters of Gas – Liquid Slug Flow Along Inclined Pipes". Chemical Engineering Science, Vol. 58, pp. 115-133.

Yoshisawa, C., 2005 "Estudos de Modelos para Formas das Bolhas em um Escoamento Intermitente Padrão Golfadas". Universidade Federal do Paraná. Curitiba, Brazil, pp. 113, Master thesis.