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STUDY OF DIFFERENT METHODOLOGIES FOR INITIATION OF SLUG FLOW USING A LAGRANGIAN SLUG TRACKING MODEL

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Abstract. Present in several industrial processes, slug flow is characterized by the intermittent repetition of liquid slugs followed by elongated gas bubbles. The slug tracking model describes this flow pattern and requires the following parameters for flow initiation: superficial velocities of the phases, elongated bubble and liquid slug lengths, as well as the gas void fractions in both the liquid slug and the elongated bubble regions. In this article, five methodologies for flow initialization in a simulator with slug tracking modeling are evaluated. The first methodology consists in data insertion obtained experimentally. The second is a list of distributed values around the standard deviations and mean values of experimental data. The third and the fourth methodologies use data from previous simulations for calculating the new superficial velocities, and the bubble and slug length values, respectively, acquiring the remaining data with the second methodology. The fifth uses bubble and slug lengths, the liquid superficial velocity and the gas void fraction in the slug region, obtained at the point of flow development, and recalculates the gas superficial velocity and the gas void fraction in the elongated bubble region. As the most independent one in terms of experimental data, methodology 5 is chosen for generating the lists' initial conditions.

Keywords: slug flow, gas-liquid slug flow, slug tracking, methodologies for the initialization of the slug tracking model

NOMENCLATURE

List of Symbols

A Pipe cross-sectional area

C_0 Drift flux parameter

D Diameter

g Gravity acceleration

h_f Liquid film thickness

j Cell number

J_G Gas superficial velocity

J_L Liquid superficial velocity

L Pipe length

n Number of bubbles inside the tube

P Pressure

R_L Liquid holdup

U Absolute velocity

x Liquid slug front

y Bubble nose front

Greek Symbols

ρ Density

τ Wall shear stress

Subscripts

B Elongated bubble region

D Slippage

G Gas phase

L Liquid phase

S Liquid slug region

T Translating the elongated bubble

1. INTRODUCTION

Multiphase flows are characterized by the simultaneous flow of more than one phase through the same conduit. Those phases may be different gases, liquids or solids. This kind of flow occurs in natural environments, e.g. sediment transport in rivers, and in industrial areas such as the petroleum equipment industry. During the oil production and transportation, gases, liquids and even solid particles can be found. These flows are usually modeled as two-phase liquid and gas flows due to their complexity. The biphasic mixture can assume several distributions in the pipe, called flow patterns. The most common biphasic flow pattern in oil production is slug flow.

The slug flow pattern is characterized by the intermittent repetition of long liquid plugs, or liquid slugs, which may or may not contain dispersed gas bubbles, followed by a gas bubble occupying most of the pipeline cross section. Wallis (1969) published one of the earliest slug flow studies, where he introduced the concept of the *unit cell* as being a structure formed by a liquid slug followed by an elongated bubble. Figure 1 shows a unit cell representation.

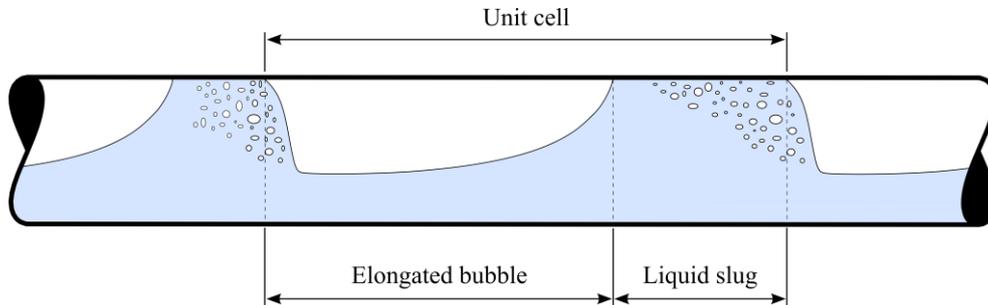


Figure 1. Slug flow unit cell.

Dukler and Hubbard (1975) proposed a hydrodynamic model for the unit cell in horizontal flow. Taitel and Barnea (1990) presented a general model for pipes at any inclination. Those models are stationary, thus not capturing the intrinsic intermittent nature of the slug flow, considering that both the liquid slug and the bubble repeat in space and time.

Transient models can capture some important flow effects, such as the interaction between bubbles. Three widely used methodologies are known: the separated model, the drift flux and the slug tracking. The first two use the Eulerian approach for the most part. Ishii (1975) published one of the first studies on the separated model, where a one-dimensional model treating the two phases separately was developed. The OLGA[®] software (Bendiksen et al., 1991) was one of the first transient codes developed and is based on the separated model. The drift flux model, developed later, considers the two phases as a mixture and allows a constant slippage between them.

The slug tracking modeling uses the Lagrangean approach, where the mesh moves along with the control volumes and their boundaries vary in time and space. This modeling is unique to slug flow, tracking the unit cells along the pipe.

Barnea and Taitel (1993) published one of the first studies using the slug tracking model. Those researchers developed a simplified model considering a non-aerated slug with constant velocity, whereas the bubble's velocity varies according to system interactions. Franklin and Rosa (2004) conducted a study based on the Grenier (1997) work, in which gas is considered compressible and ideal. This study served later as the basis for the model proposed by Rosa et al. (2015).

In Rosa et al. (2015), the main variables are the velocities of the liquid slug and the pressures inside the bubbles. Control volumes are used to obtain mass and momentum conservation equations for each cell in integral form. The slug and the liquid film holdup are considered variables in time and both bubbles and slugs are introduced into the pipe by a list created from experimental data. This list includes the values of the superficial velocities of the two phases, bubble and slug lengths, and gas void fractions in the elongated bubble region and the liquid holdup in the liquid slug region. Naidek et al. (2017b) developed four methodologies to obtain these initial conditions; these methodologies were based on results obtained for long pipelines by Naidek et al. (2017a).

Smith e Nydal (2016) presented a slug tracking model for multiphase slug flow. Simulations performed with the model were compared with experiments for severe slugs. Influences of boundary conditions and insertion of a droplet field on the flow were analyzed.

This work aims at developing a fifth methodology to obtain the initial conditions necessary for the Rosa et al. (2015) model, as well as evaluating the four methodologies of Naidek et al. (2017b) to obtain the initial values list. Aiming at obtaining an independent methodology of experimental data for the Rosa's et al. (2015) model, numerical tests were performed with the five methodologies and compared with experimental data for an experimental circuit of 34.77 m (~1337 D), with a 26-mm pipe ID.

2. MATHEMATICAL MODEL

The mathematical model is one-dimensional and based on mass and momentum conservation equations in integral form. The balances are applied to movable and deformable control volumes, which surround the liquid slug, elongated bubble and liquid film regions.

The hypotheses used in the model are unidimensional flow, incompressible liquid, ideal gas, isothermal flow without phase change, negligible momentum associated with the gas and with the region of the liquid film, the gas pressure does not vary axially within an elongated bubble, and the gas bubble concentration in each slug does not change axially.

Rose et al. (2015) applies the mass conservation balance for the two phases in both the elongated bubble and the liquid slug. When joined, these equations result in a mass balance for the unit cell.

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

where U_{DSj} and U_{DSj-1} are the dispersed bubbles' drift velocities in slug j e $j-1$, respectively.

The left side of the equation represents the difference in the liquid velocities in adjacent slugs, which is due to the gas bubble expansion between the slugs (first term on the right hand side) and the differential velocity of the dispersed bubbles in the slug (second and third terms on the right hand side).

The momentum of the gas phase and liquid film was neglected, and the momentum conservation equation was only applied to the liquid phase in the volume control defined by the liquid slug.

$$P_{GBj} - P_{GBj+1} = \frac{\tau_{LBj+1} S_{LBj+1} L_{Bj+1} + \tau_{LSj} \pi D L_{Sj}}{A} + (R_{LSj} L_{Sj} + R_{LBj+1} L_{Bj+1}) \rho_L g \sin \theta + \rho_L L_{Sj} R_{LSj} \frac{dU_{LSj}}{dt} + \rho_L L_{Sj} \frac{dR_{LSj}}{dt} \left[\frac{1}{2} \left(\frac{dx_j}{dt} + \frac{dy_j}{dt} \right) - U_{LSj} \right] \quad (2)$$

where τ_{LBj+1} and τ_{LSj} are the wall shear stress in the liquid film and in the slug, respectively, and S_{LBj+1} is the wetted perimeter of the film.

It is observed that the difference between the gas pressures in two consecutive bubbles (left hand side of the equation) is due to: the friction forces acting on the liquid film and the wall of the slug (first and second terms); the gravitational force in the slug and in the liquid film (third term); the liquid momentum variation inside the slug, also called slug inertia (fourth term) and the momentum variation in the liquid slug due to the temporal variation of the liquid holdup in the said slug (last term).

The two equations form a coupled system of equations with two unknown parameters, U_{LSj} e P_{GBj} . Such system is solved numerically for each unit cell throughout the flow at every time step. The system solution requires the use of auxiliary equations.

The bubble translational velocity is the boundary displacement, y_j , which can be calculated by the empirical correlation:

$$\frac{dy_j}{dt} = U_{Tj} = (C_0 U_{LSj} + C_1 \sqrt{gD})(1 + h_j) \quad (3)$$

where C_0 , C_1 and h_j are constants. The constant C_0 represents the slug velocity term, with $C_0 \sim 1,2$ for turbulent flows and $C_0 \sim 2$ for laminar flows. The constant C_1 is related to the velocity a bubble would have were the liquid ahead stagnant. The constant h_j quantifies the wake effect that arises from the rear of the bubble due to the mass of liquid scooped from the liquid slug right ahead. This is calculated by Moissis and Griffith (1962):

$$h_j = a_w \exp\left(-b_w \frac{L_{Sj}}{D}\right) \quad (4)$$

being a_w and b_w constants adjusted experimentally.

For the calculation of the liquid film velocity mass conservation is applied to a fixed volume that moves with the velocity equal to bubble translational velocity.

$$U_{LBj} = U_{Tj} + \frac{R_{LSj}}{R_{LB}} (U_{LSj} - U_{Tj}) \quad (5)$$

3. NUMERICAL MODEL

The resulting equations from mass and momentum conservation balances form a linear system, which was discretized in relation to time using the semi-implicit Crank-Nicholson scheme, yielding the following equations:

$$\begin{aligned}
 & -U_{LSj-1}^N + H_{GBj}^N \left(\frac{2L_{Bj}R_{GBj}}{H_{GBj}^O \Delta t} + \frac{L_{Sj}R_{GSj}}{H_{GBj}^O \Delta t} + \frac{L_{Sj-1}R_{GSj-1}}{H_{GBj-1}^O \Delta t} \right) + U_{LSj}^N = U_{LSj-1}^O - U_{LSj}^O + \\
 & + \left(\frac{2L_{Bj}R_{GBj}}{\Delta t} + \frac{L_{Sj}R_{GSj}}{\Delta t} + \frac{L_{Sj-1}R_{GSj-1}}{\Delta t} \frac{H_{GBj}^O}{H_{GBj-1}^O} \right) - 2\Delta U_{Dj}
 \end{aligned} \tag{6}$$

$$\begin{aligned}
 & -H_{GBj}^N + U_{LSj}^N \left(\frac{2R_{LSj}L_{Sj}}{\Delta t} + 4C_{LSj} \frac{L_{Sj}}{D} U_{LSj}^O \right) + H_{GBj+1}^N = H_{GBj}^O - H_{GBj+1}^O + \\
 & + \frac{2R_{LSj}L_{Sj}U_{LSj}^O}{\Delta t} - \frac{2}{\rho_L} (\Delta P_{Sj+1} + \Delta P_{Gj} + \Delta I_j)
 \end{aligned} \tag{7}$$

These equations can be represented as a linear system solvable by the TDMA (Tridiagonal Matrix Algorithm) method at every step of time, resulting in U_{LS}^N e P_{GB}^N values for all the unit cells in the computational domain. The system can be represented in the $\mathbf{AX} = \mathbf{B}$ form, where \mathbf{A} is the coefficient matrix, \mathbf{X} the unknown parameter vector and \mathbf{B} is the solution vector.

The simulations begin with liquid-filled pipe and the first bubble is positioned at the pipe inlet. At the outlet, the pressure is considered atmospheric. In the next time step, the parameters of cell 1 are calculated by the TDMA algorithm. After the bubble goes through the pipe inlet, another unit cell is inserted and the process starts all over again. When the bubble reaches the pipe outlet, the whole unit cell is suppressed from the simulation. The simulation ends when a given number of unit cells leave the pipe.

The system uses an initial conditions' list, obtained with experimental data, containing bubble and liquid slug lengths, and superficial velocities of the two phases.

The results are recorded by virtual probes, which can be distributed along the pipe. The results are obtained through mean results and probability density functions, PDF. It contains values of liquid slug and elongated bubble lengths, bubble velocities, pressure drops, number of coalescing bubbles within the pipe and also input bubble frequency.

4. METHODOLOGIES FOR SLUG FLOW INITIATION

The slug tracking modeling is exclusive to the slug flow pattern and it is therefore not designed to predict any flow pattern transitions. Thus, it is necessary to make sure that slug flow is the existing flow regime at both the pipe inlet and outlet.

Upon the insertion of a unit cell at the pipe inlet, one needs to know the following geometric parameters: liquid slug length, L_{S0} , bubble length, L_{B0} , liquid slug holdup, R_{LS0} , gas void fraction in the liquid slug, R_{GS0} , and the superficial velocities of the phases, J_G e J_L . In this section five methodologies developed for obtaining initial unit cell conditions will be presented; the first four have already been put forth by Naidek et al. (2017b).

4.1 Methodology 1

Whenever performing experimental tests, information about each single unit cell that has traveled along the pipe is obtained by means of measured data processing. Among the information there are the mean superficial velocities of the phases, elongated bubble and liquid slug lengths, and gas void fraction and liquid holdup of the unit cells.

Methodology 1 makes direct use of data from the experiments, measured in the first section of the experimental loop, for the generation of initial conditions' lists.

4.2 Methodology 2

During the evaluation of the results from the experimental measurements, it was observed that the gas bubble and liquid slug lengths, and the bubble velocity show a large distribution around the mean value. These experimental result distributions can be characterized by a mean value and a standard deviation.

Therefore, values list for L_{S0} , L_{B0} e J_{G0} were generated so that the mean values and standard deviation of these parameters are equal to those experimental ones. The generated lists are independent of each other, following a normal distribution for L_{B0} and J_{G0} , and log-normal for L_{S0} .

The mean values and standard deviations for the bubble and slug lengths and for the translational velocity are easily obtained. However, due to the way they were obtained in the experiments, it is difficult to correlate these values directly to the gas superficial velocity, J_{G0} . Hence, the gas superficial velocity is calculated with the Bendiksen (1984)

translational velocity model for an elongated bubble. The liquid superficial velocity, J_{L0} , is considered constant, due to the liquid incompressibility.

Knowing the mean experimental values and standard deviation of L_{S0} , L_{B0} e J_{G0} , lists of distributed values of these variables are generated. To obtain these lists, the transformation proposed by Box and Muller (1958) was used, in which a random data list with normal distribution can be generated through the manipulation of two independent lists of random values with uniform distribution (between 0 and 1). After obtaining the independent lists, to each new cell entering the pipe a value for each variable is obtained from these lists and used as input data for the simulation.

4.3 Methodology 3

In tests performed by Naidek et al. (2017a) using a periodic list of mean values for the slug program initialization, it was observed that the flow tends to stabilize after a few tens of meters. This stabilization distance varies with each superficial velocity pair.

Naidek et al. (2017a) presented results showing that the bubble length exhibits a tendency of growth. The same trend was observed for the bubble velocity. Slug lengths and bubble input frequencies tend to stabilize around a constant value, however.

In view of these results, a method to generate initial conditions using stabilized flow data was sought. Thus, the mean data resulting from the simulations were used, and those mean values were the bubble's translational velocity and the liquid superficial velocity, and, using Bendiksen (1984) formulation, a new gas superficial velocity was calculated. The liquid superficial velocity is considered constant due to its incompressibility. The other values required to run the program were obtained using Methodology 2.

4.4 Methodology 4

This methodology also uses results obtained by Naidek et al. (2017a) in simulations for long pipes, using simulated bubble and slug lengths.

The gas and liquid superficial velocities, and phase fractions are obtained with the methodology 2.

4.5 Methodology 5

Based on the results obtained by Naidek et al. (2017a) for long pipes, a methodology to generate initial conditions lists using data at the time that begins the flow development was developed.

This methodology uses values of bubble and slug lengths, liquid superficial velocities and gas void fraction in the liquid slug obtained from the starting point of the flow development. The gas superficial velocity is recalculated using the Bendiksen (1984) formulation and the bubble gas void fraction is then recalculated.

5. RESULTS AND DISCUSSION

The tests were carried out with air and water, with atmospheric pressure at the pipe outlet. The pipe geometry and the fluid properties used during the experiments are shown in Table 1.

Table 1. Geometry and fluid properties.

Variable	Value
Pipe length [m]	24.590
Diameter of the pipe [m]	0.026
Pipe inclination [°]	0
Liquid viscosity [Pa·s]	0.000855
Liquid density [kg/m ³]	1000
Gas viscosity [Pa·s]	0.000017
Gas density [kg/m ³]	1.2
Probe #1 [m]	~ 0
Probe #2 [m]	5.09
Probe #3 [m]	10.22
Probe #4 [m]	15.35
Probe #5 [m]	20.45

The actual, simulated pipe length is the distance between the first and the last sensors used during the experimental measurements. The probes were positioned at the same positions as the sensors used in the experimental rig, allowing the comparison between numerical and experimental results.

Eleven experimental points were analyzed, and the results obtained for points 01 and 10 are presented in Table 2.

Table 2. Properties of points analyzed.

Point	J_L (m/s)	J_G (m/s)	Freq. (Hz)	C_0	C_∞	a_w	b_w
P01	0.7	0.3	2.89	1.3036	-0.2183	0.2	0.5
P10	0.75	1.25					

The bubble velocity was calculated using the Bendiksen (1984) formulation, with the constants C_0 e C_∞ adjusted to the experimental points. The wake effect constants were adjusted to the experimental results used. Figure 2 shows a flowchart of the simulations.

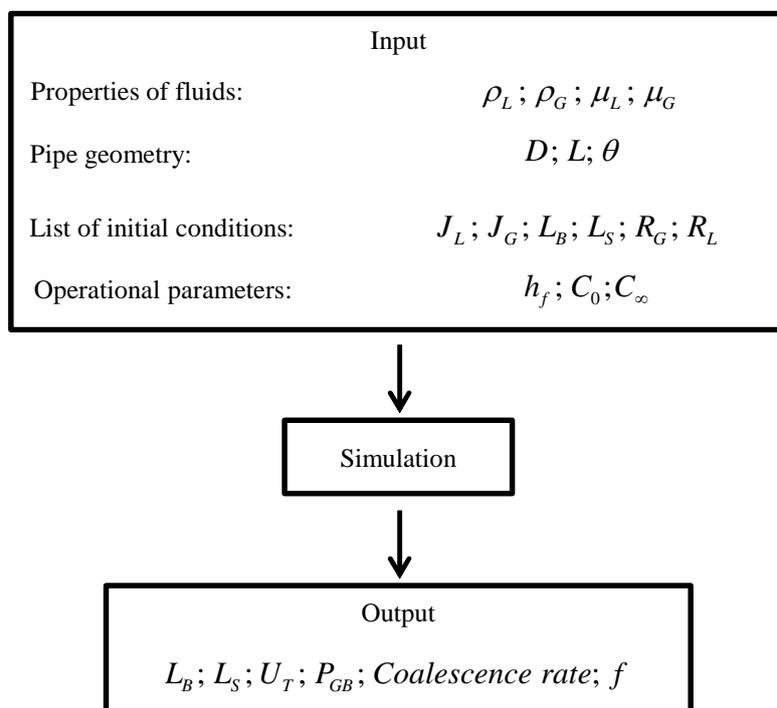


Figure 2. Simulation flowchart.

Figures 3 and 4 depict mean results for the elongated bubble length L_B , the liquid slug length L_S , the bubble velocity V_B , the coalescing rate, the bubble pressure and the input frequency of the unit cells, obtained from simulations at points P01 and P10, respectively.

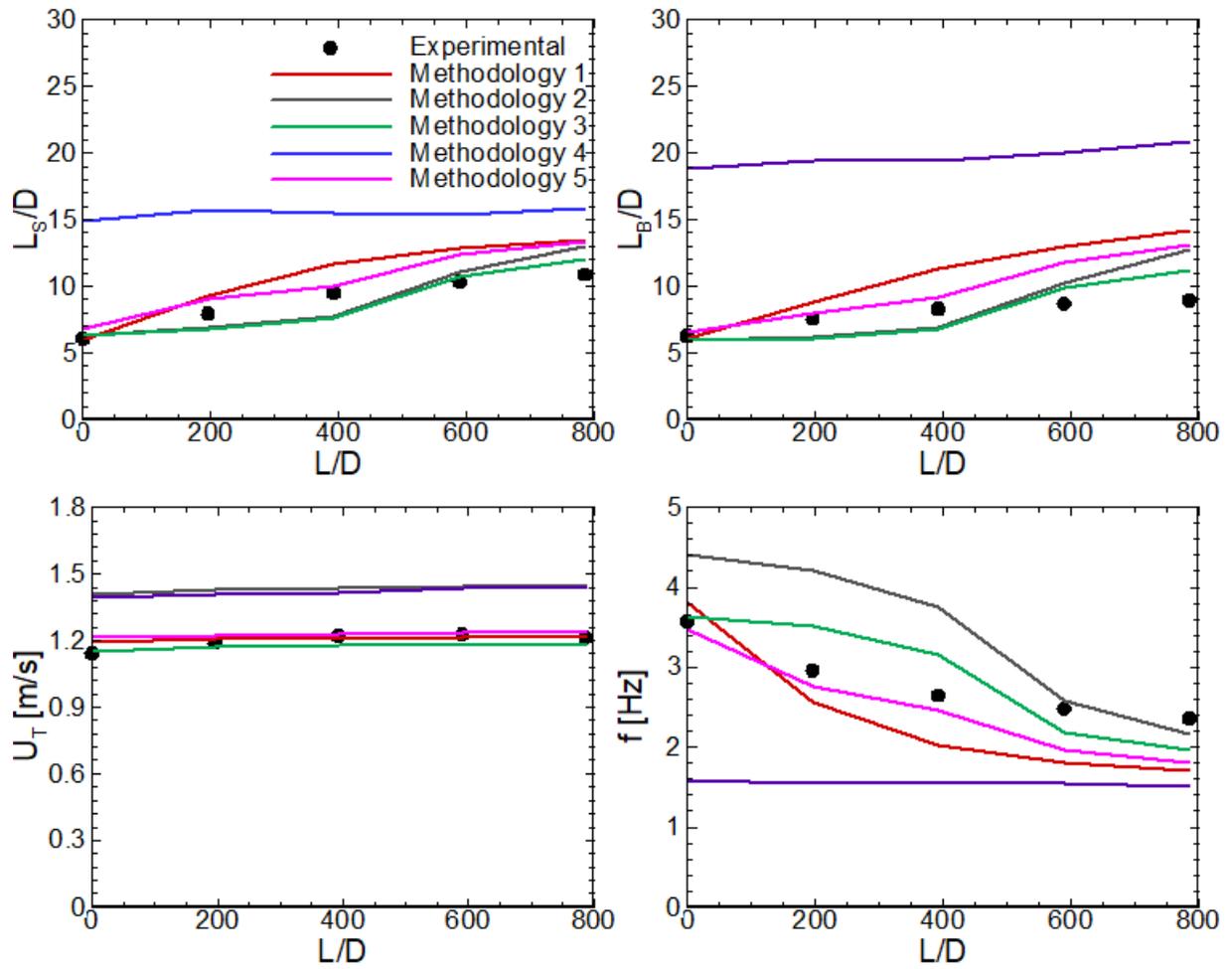


Figure 3. Mean results obtained for the elongated bubble length L_B , liquid slug length L_s , bubble velocity V_B , coalescing rate, bubble pressure and unit cell input frequencies in point P01.

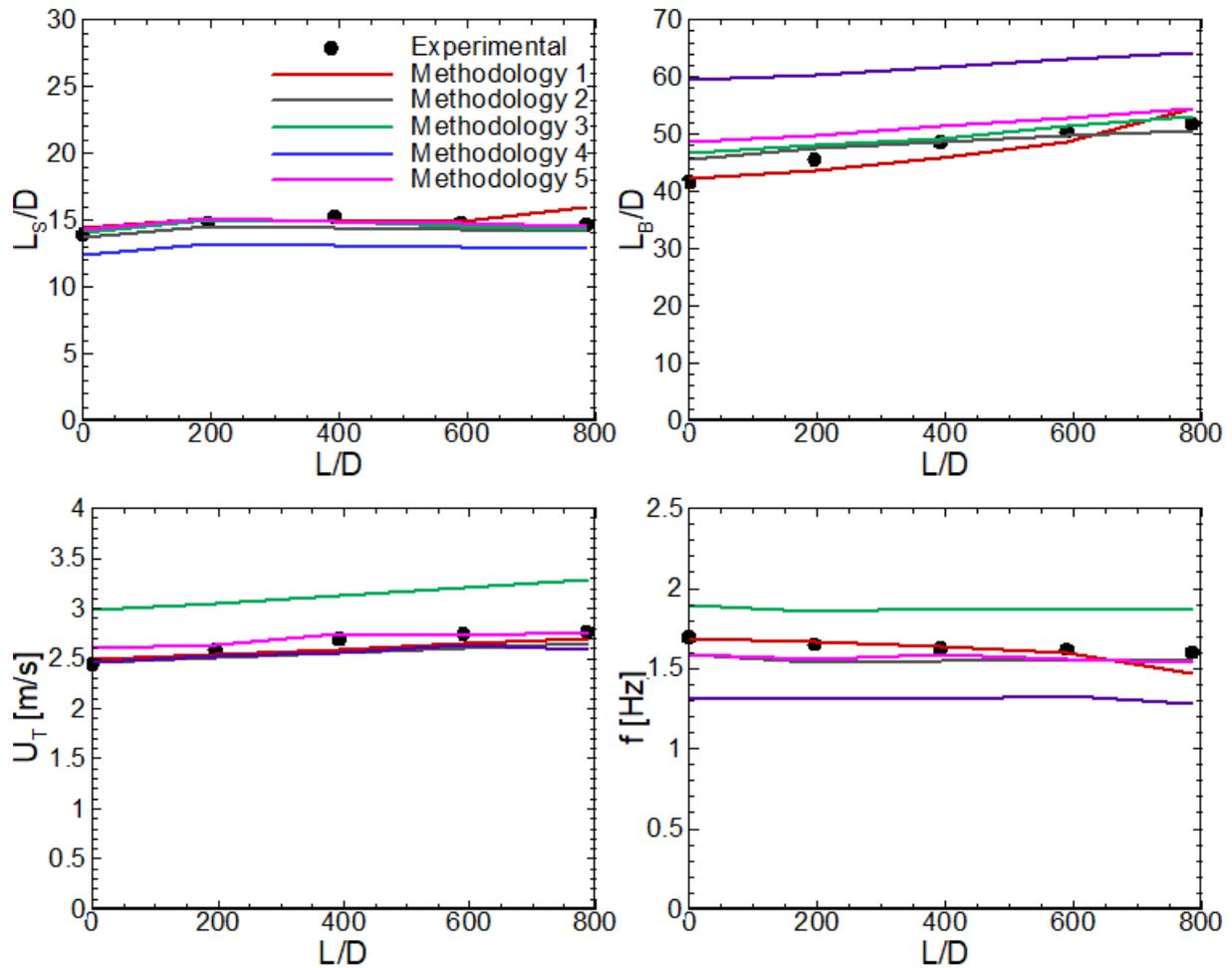


Figure 4. Mean results obtained to elongated bubble length L_B , liquid slug length L_S , bubble velocity V_B , coalescing rate, bubble pressure and unit cell input frequencies in point P10.

The variation in bubble and slug lengths is related to gas expansion, due to pressure drop along the pipe, and the interaction between bubbles (coalescence), related with intermittent flow. Note that the coalescence rate was not recorded in point P10. Because of this non-capture we obtained linear graphs for the bubble length, indicating that its growth is due to the gas expansion. The modeling of bubble interaction owes its complexity to its randomness, making it difficult to capture in the simulation.

When the coalescence rate is not recorded in the simulations, the slug length decreases since the liquid film increases with the bubble through the liquid transfer from the slugs. Conversely, coalescence produces longer slug lengths, since the liquid remaining after coalescence is distributed to other slugs.

As for pressure and frequency, the lists generated by all the methodologies presented results similar to the experimental data. As pressure drop values are highly dependent on fluid properties the variations between methodologies are small. Furthermore, the frequency is determined by the ratio between bubble velocity and unit cell length, whose data are obtained from the simulations performed with their respective lists, generating curves close to one another.

Analyses using the graphs and the errors have shown that, in general, methodology 1 fits the experimental data best, since experimental data are used for the generation of lists containing the initial conditions. Methodology 4 presented the largest discrepancies in relation to the experimental data for the elongated bubble and liquid slug lengths, since these lengths enter the pipe developed and larger, coming from a simulation performed with periodic lists. Moreover, in this methodology, as the frequency of passing bubbles is calculated from data resulting from the simulation itself, that is, the ratio between V_B and $L_S + L_B$, larger lengths result in smaller frequencies if compared with experimental.

The methodologies 2, 3 and 5 presented satisfactory results for all variables. Method 5 provided results closer to the experimental data for liquid slug length and frequency, while methodology 3 reached satisfactory values for the elongated bubble length. The methodologies 3 and 5 present results farther from the experimental ones for the elongated bubble velocity due to the nature of list generation: the liquid superficial velocity is recalculated to a developed flow

and in the imminence to develop, respectively, and, when performing the calculation, the bubble velocity is greater than that obtained experimentally. For the bubble velocity, methodology 2 presented better results.

6. CONCLUSIONS

Based on the data obtained, the five methodologies presented satisfactory results in relation to the experimental ones: the elongated bubble lengths and the bubble velocities tend to increase, while there is a drop in pressure, and the slug length and the unit cell input frequencies tend to remain constant.

In order to obtain a list of initial conditions most independent of experimental data, methodology 5 is indicated, which although it has not shown the smallest errors in relation to other methodologies, approaches the experimental results graphically, mainly of slug length and frequency parameters.

7. ACKNOWLEDGEMENTS

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