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ANALYSIS OF SLUG FLOW IN HORIZONTAL PIPES

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Abstract. *Two-phase slug flow is present in several industrial processes, and even more so in the oil industry, during the production and transportation of oil and gas. Slug flow is characterized by the intermittent succession of liquid slugs possessing a large momentum, followed by elongated bubbles of compressible gas. A handful of mathematical models for this complex flow can be found in the literature. Among those, one might mention the Eulerian two-fluid and drift flux and the Lagrangian slug tracking models. Slug tracking modeling requires that some parameters, such as the gas and the liquid superficial velocities, the liquid slug and bubble lengths, and gas and liquid fractions are supplied as input/initial data for simulations. In this work, four methodologies for slug flow initialization in a simulator running the slug tracking modeling are evaluated. The first methodology consists of the insertion of data obtained experimentally. The second is a list of values distributed around the standard deviations and mean values of the experimental data. The third methodology is the application of data obtained in previous simulations for the calculation of the new superficial velocities, by using the correlation of Bendiksen (1984) to predict the translational velocity of the bubble. The fourth and last methodology uses the bubble and slug lengths obtained in previous simulations and the second methodology to supply the rest of the data necessary for the program initialization. By analyzing the outcomes of the simulations using the four methodologies, it is possible to observe that their results are in good agreement with the experimental data.*

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

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 flow of more than one phase through a conduit or porous medium, be those phases different gases, liquids or solids. This type of flow is common in natural processes such as sediment transportation in rivers, and in industrial scenarios, such as the oil and gas industry. During the production and transportation of petroleum gas, liquid and even solid particles such as sand are carried through pipes and other pieces of equipment. Owing to the complexity of the phenomenon, multiphase flows are usually modeled as two-phase flows of liquid and gas. Along the flow path, the liquid and the gas phases may assume different spatial configurations inside the duct, and those configurations are usually called *flow patterns*. One of the standards often found in industrial applications is liquid-gas two-phase slug flow in pipes. This pattern occurs over a wide range of liquid and gas flow rates (Taitel et al., 1980).

Slug flow is characterized by the intermittent repetition of large chunks of liquid – the liquid slugs – which may contain dispersed gas bubbles in their interior. Those slugs are followed by a large gas bubble filling much of a pipeline's cross sectional area. Wallis (1969) published one of the earliest studies on slug flow, where he introduced the concept of a *unit cell* as being a structure formed by a liquid slug followed by an elongated bubble. Figure 1 shows a representation of a unit cell.

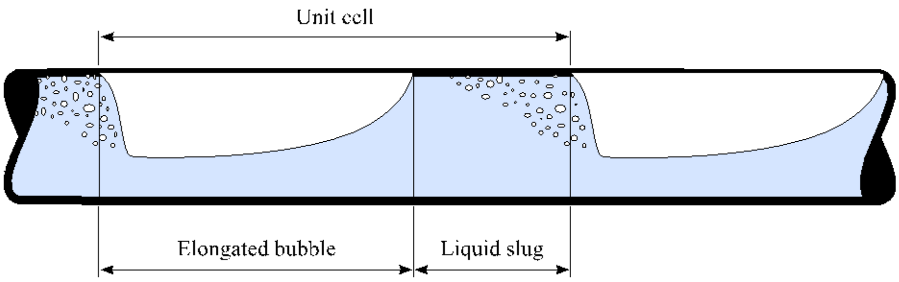

Figure 1. Unit cell of slug flow

Stationary models based on the unit cell concept were proposed in the early slug modeling days. Dukler and Hubbard (1975) proposed a hydrodynamic model for the unit cell in horizontal flow. Those authors introduced slug flow concepts that are accepted to this day, as the pressure drop due to the acceleration of the liquid that is scooped from the film by the slug following it. Taitel and Barnea (1990) presented a general model for pipes at any inclination. In this work, the authors took the shape of the elongated bubble into account, a feature that had not been considered in previous works. These models are stationary, as they do not capture the intrinsic, intermittent slug flow nature, considering those flows as a mere repetition, in space and time, of unit cells.

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

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 unit cells along the pipeline. Barnea and Taitel (1993) published one of the first studies using the slug tracking model, where a simplified model was developed. In this work, the liquid slug is considered to be non-aerated and travels at a constant speed, and the velocity of the elongated bubble varies according to the interactions within the system. Franklin and Rosa (2004) conducted a study based on the work of Grenier (1997), considering gas as compressible and ideal. This work served as the foundation for the model proposed by Rosa et al. (2015).

In Rosa et al. (2015) equations are obtained from control volumes defined spatially by the liquid slugs and elongated gas bubbles. Those control volumes are tracked down and monitored throughout the simulation. The solution of the slug tracking model requires the geometric characteristics of the unit cells entering the pipeline as input data. The characterization of the unit cell for a given flow can be performed through an experimental study of the slug flow. In this case, the superficial velocities of the two phases, the bubble and slug lengths, and the gas fractions in the elongate bubble region and the liquid fraction in the liquid slug region must be measured. Those will be the data used as initial conditions for the model under scrutiny.

In the present work, four methodologies for obtaining the initial conditions are proposed. Those methodologies aim at obtaining a generalized procedure for the characterization of the unit cells. Such procedure will be in the center of the two-phase slug flow simulation.

2. MATHEMATICAL MODEL

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

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

Rosa et al. (2015) applies the mass conservation balance to the two phases in the elongated bubble region and to the liquid phase in the liquid slug. When coupled, those equations result in a mass balance for the unit cell:

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

where U_{DSj} and U_{DSj-1} are the slip velocities of the bubbles dispersed in the slugs j and $j-1$, respectively.

The left side of the equation represents the difference in liquid velocities in two adjacent slugs due to the expansion of the gas bubble between the slugs (first RHS term) and the velocity difference of the dispersed bubbles in the slugs (last two terms in the RHS).

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

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

being τ_{LBj+1} and τ_{LSj} the shear stresses on the walls wet by the liquid film and by the slug, respectively, and S_{LBj+1} is the average wetted perimeter in the film.

The difference between the gas pressures inside two consecutive bubbles (LHS of the equation) is due to: the change in the amount of liquid movement inside the slug, also called the slug inertia (first term in the RHS); the frictional forces acting on the liquid slug and on the liquid film (second and third term); to the gravitational force on the liquid in both the liquid slug and the film (fourth term); and the change in the amount of movement in the slug due to the temporal variation of the liquid fraction in the slug (last term).

The two equations above form a coupled system with two unknowns, U_{LSj} and P_{GBj}, that shall be solved numerically for each unit cell in the entire flow at each time step. The solution of this coupled system requires the use of auxiliary equations, such as the translational velocities of the elongated bubble and of the liquid film.

The velocity of translation of the elongated bubble is the temporal variation of the boundary y_j, which can be calculated by the empirical correlation:

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

where C_0, C_1 and h_j are constants. The constant C_0 represents the influence of the velocity of the liquid slug, be the flow either turbulent or laminar. The constant C_1 is related to the velocity an elongated bubble would have were the liquid in front of it stagnant. The constant h_j quantifies the wake effect that occurs at the rear of the elongated bubble flowing ahead of the bubble under analysis, calculated by Moissis and Griffith (1962):

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

where a_w and b_w are constants adjusted experimentally.

The velocity of the liquid film is calculated by applying the conservation of mass in an indeformable volume that moves with the same translational velocity of the bubble.

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

3. NUMERICAL METHODOLOGY

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

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

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

These equations are solved by the TDMA (Tridiagonal Matrix Algorithm) method at each step of time, resulting in values U_{LS}^{N} and P_{GB}^{N} values for all unit cells in the computational domain. The system can be represented as ***AX* = *B***, where ***A*** is the coefficient matrix, ***X*** is the vector of unknowns and ***B*** is the result vector.

The simulations start with the tubing fully filled with liquid moving at a speed U_{LS0} and the first bubble is positioned at the pipe inlet. At the pipe outlet the pressure is assumed as atmospheric. In the next time step, the parameters of cell 1 are calculated by the linear system. After the bubble passes completely through the pipe inlet, another unit cell is inserted and the process starts over again. When a bubble reaches the pipe outlet, the entire unit cell is excluded from the simulation. At each new iteration the inflow, exit and coalescence of bubbles are verified. The simulation ends when a determined number of unit cells leave the tubing.

The system uses a list of initial conditions obtained with experimental data. In this list, the following characteristics of the unit cells are shown: 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 for the variables of interest are obtained from mean results and also from probability density functions, PDFs. The liquid slug and the elongated bubble lengths, the velocity of the elongated bubble front, the pressure drop, the number of bubbles coalescing inside the tubing and the inflow frequency of the bubbles are monitored.

4. SLUG FLOW INITIATION METHODOLOGIES

The slug tracking model is not designed to predict any flow pattern transitions. Therefore, it is necessary to guarantee that slug flow will be the existing flow pattern at both the pipe inlet and outlet. When a unit cell is inserted at the pipe entrance, some of its parameters must be known: slug length, L_{S0}, bubble length, L_{B0}, liquid fraction in the liquid slug, R_{LS0}, gas fraction in the slug, R_{GS0}, and the superficial velocities of the two phases, J_G and J_L. In this section, the four methodologies proposed to obtain these initial conditions of unit cells will be presented.

4.1 Methodology 1

When conducting experimental tests it is possible to obtain, after processing the raw data, information about all the unit cells that flowed through the pipeline. This information also includes the superficial velocities of the phases, the bubble and slug lengths, and the gas and liquid fractions as well. In some cases, it is not possible to obtain the values of the superficial velocities for each unit cell, thus the mean values of those velocities are used.

To initialize the simulations the parameters of the unit cell must be known, and the parameters obtained experimentally can be used for that purpose. Preferably, the experimental data obtained in the first section of pipe tests are inserted. Thus, in the simulations, virtual probes are placed at the same positions as the experimental test sections, in order to compare the numerical and experimental results.

4.2 Methodology 2

When evaluating the results of the experimental measurements, it was observed that the gas bubble and the liquid slug lengths and the bubble velocity showed a large distribution around the mean value. These distributions of the experimental results can be characterized by an average value and a standard deviation.

Thus, lists of values with L_{S0}, L_{B0} and J_{G0} were generated in such a way that the mean values and the standard deviation of these parameters are the same as those of the 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 velocity of the bubble front are easily obtained. However, due to the way it is obtained in the experiments, it becomes difficult to directly correlate those values with the superficial velocity of the gas, J_{G0}. Therefore, the superficial velocity of the gas is calculated with the Bendiksen (1984) bubble front velocity formulation. The superficial velocity of the liquid, J_{L0}, is assumed as constant, due to the incompressibility of the liquid.

By knowing experimentally the mean values and the coefficients of variation of L_{S0}, L_{B0} and 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. According to this transformation, a list of random data with normal distribution can be generated by the manipulation of two independent lists of random values with uniform distribution (between 0 and 1).

After obtaining the independent lists, whenever a new cell enters the pipeline, a value of each variable is retrieved from these lists and used as input data of the simulation.

4.3 Methodology 3

In pre-tests carried out for long pipelines, the use of a periodic list (a list with all parameters necessary for the initialization of the program) of average initialization values showed that the flow tends to stabilize after a few tens of meters. This stabilization distance varies with each superficial velocity pairs.

A growth trend is observed for the bubble length. The same trend is observed for the velocity of the bubble. The slug length and inflow bubble frequency tend to stabilize around a constant value. The Figure 2 shows those results.

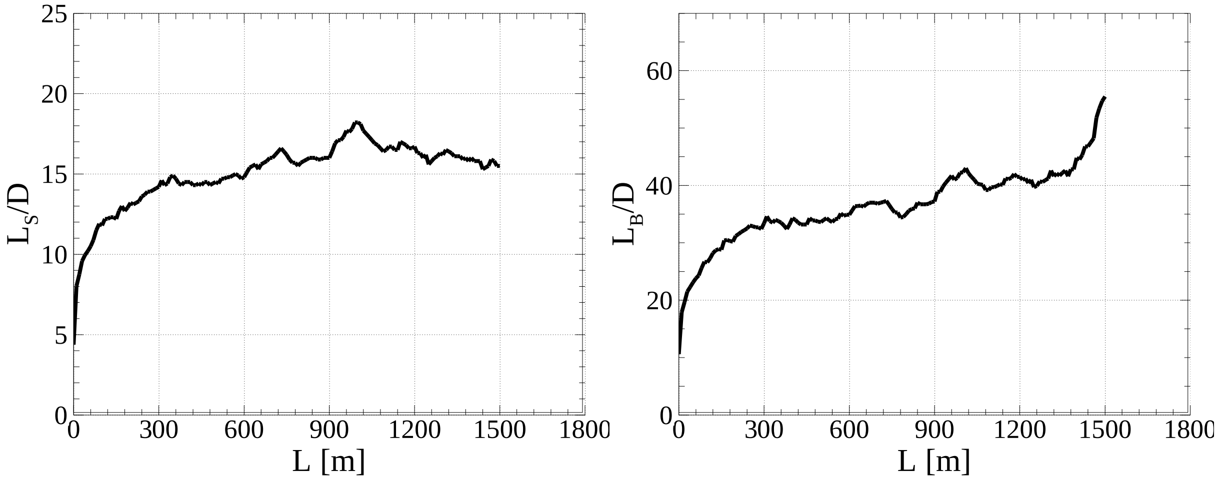

Figure 2. Mean results obtained for the length of the slug, L_S, and bubble length, L_B, in a 1500 m pipe, to the point A@W4

In view of these results, a method to generate the lists of initial conditions using the already stabilized flow data was used. Thus, the mean data values resulting from the simulations were used, namely the translational velocity of the bubble and the superficial velocity of the liquid. The Bendiksen (1984) formulation was used to calculate the new superficial gas velocity. The superficial velocity of the liquid is regarded as constant due to its incompressibility. The other values required to start the program were obtained by using Methodology 2.

4.4 Methodology 4

This methodology also makes use of the results obtained previously in the simulations for long pipes, using the simulated bubble and slug lengths. The other parameters required for the flow initialization are calculated following Methodology 2.

5. RESULTS AND DISCUSSION

, Results from simulations were compared with experimental data in order to evaluate the proposed methodologies. Water and air made the fluids used in the simulations. The pressure at the pipe outlet was set to 1 atm. The properties of the fluids and geometries used are presented in Tab. 1.

Table 1. Geometry and fluid properties.

Parameter	Value

Pipe length [m]	20.098
Diameter of the tube [m]	0.026
Tube inclination [°]	0
Liquid viscosity [Pa.s]	0.000855
Liquid density [kg/m³]	1000
Gas viscosity [Pa.s]	0.000017
Gas density [kg/m³]	1.2

Six experimental data points provided by FEM/UNICAMP were analyzed, and the results are obtained for points 1 and 4 are presented in Tab. 2.

Table 2. Properties of analyzed points.

Point	J_L (m/s)	J_G (m/s)	Freq. (Hz)	C_0
A@W1	0.33	0.64	2.89	1.12
A@W4	0.52	0.52		

The length of the simulated tubing is the distance between the first and the last sensor used during the experimental measurements. In order to compare the numerical and experimental results, the probes were positioned in the same positions as the sensors used in the experimental rig. These positions correspond to 0, 3.60, 9.56 and 16.91 [m].

Figure 3 shows a flowchart of the simulations. The Bendiksen (1984) formulation was used to calculate the bubble velocity, and the C_0 constant was set to 1.12, as suggested by previous studies. For the constants of the wake effect, the correlation proposed by Rodrigues (2008) was used.

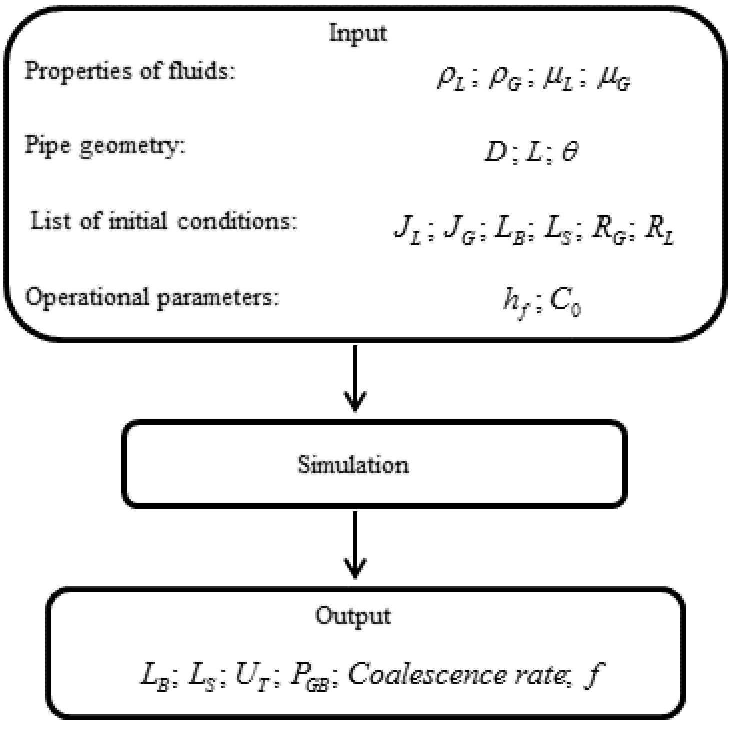

Figure 3. Simulation flowchart

Figures 4 and 5 present the average results obtained for the slug length, L_S, bubble length, L_B, bubble velocity, U_T, bubble pressure, P_{GB}, and bubble inlet frequency in the pipe, f, for points A@W1 and A@W4, respectively.

For the point A@W1, Methodology 2 agrees better with the experimental data for bubble length in the first and second probes; in the other two probes, the four methodologies do not present great discrepancy with the experimental results. For the bubble velocity and bubble inlet frequency, Methodologies 1, 2 and 3 presented results closer to the experimental ones.

For point A@W4, Methodologies 1, 2 and 3 represent the experimental results better when it comes to the bubble velocity and length and the frequency the bubbles entering the pipeline. Methodology 4 was the most suitable one to represent the slug length.

In general, any methodology produced satisfactory results. As the first methodology makes use of the experimental results for simulation initialization, it represents the experimental data a little better. The Methodologies 2 and 3 present very similar results, since the only difference between the two is the superficial velocity of the gas phase. Methodology 4 presents the largest data bubble lengths that had already been inserted in the program as results of previous simulations.

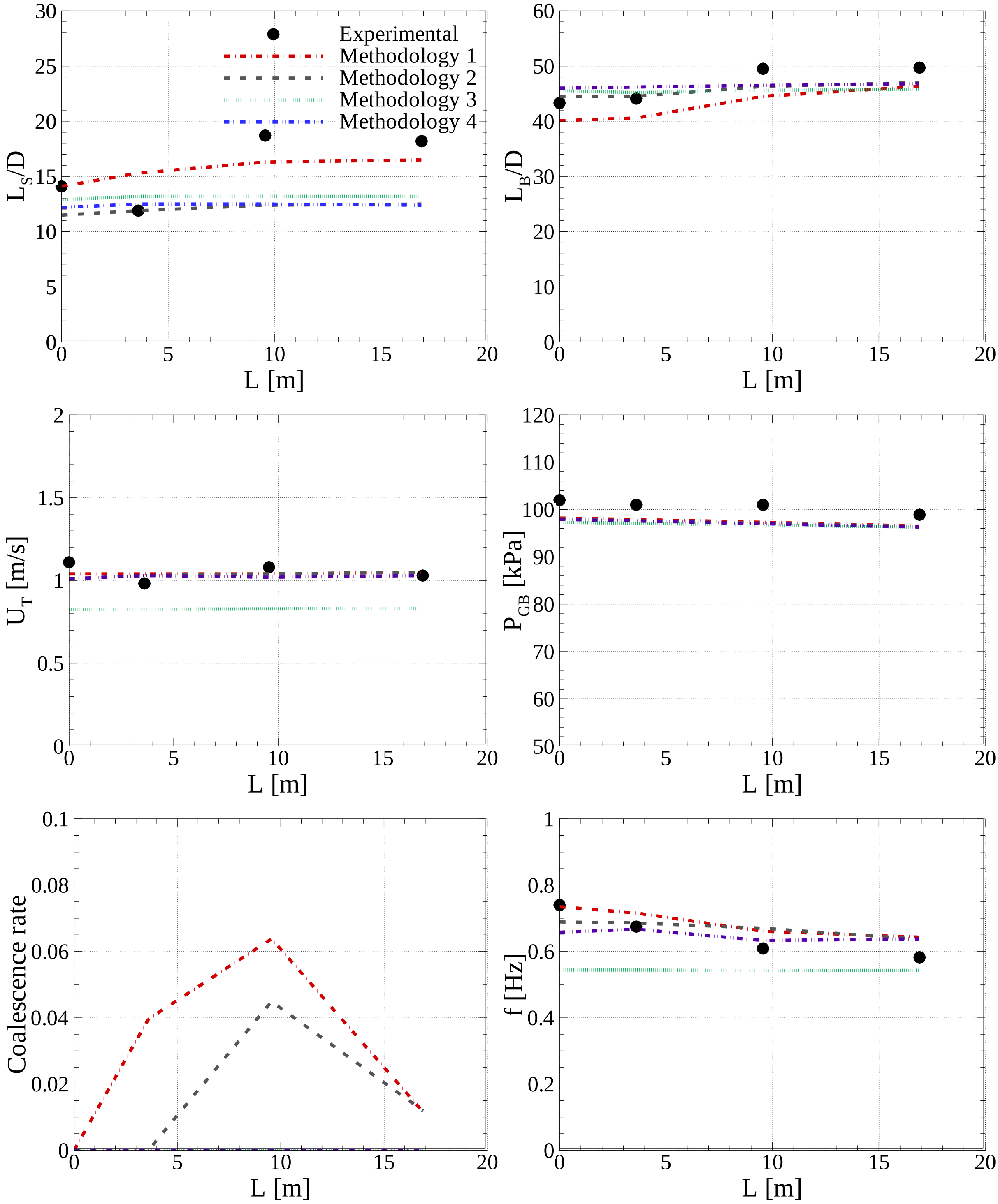

Figure 4. Average results obtained for the length of the slug, L_S, bubble length, L_B, bubble velocity, U_T, bubble pressure, P_{GB}, and bubble inlet frequency in the pipe, f, for the point A@W1

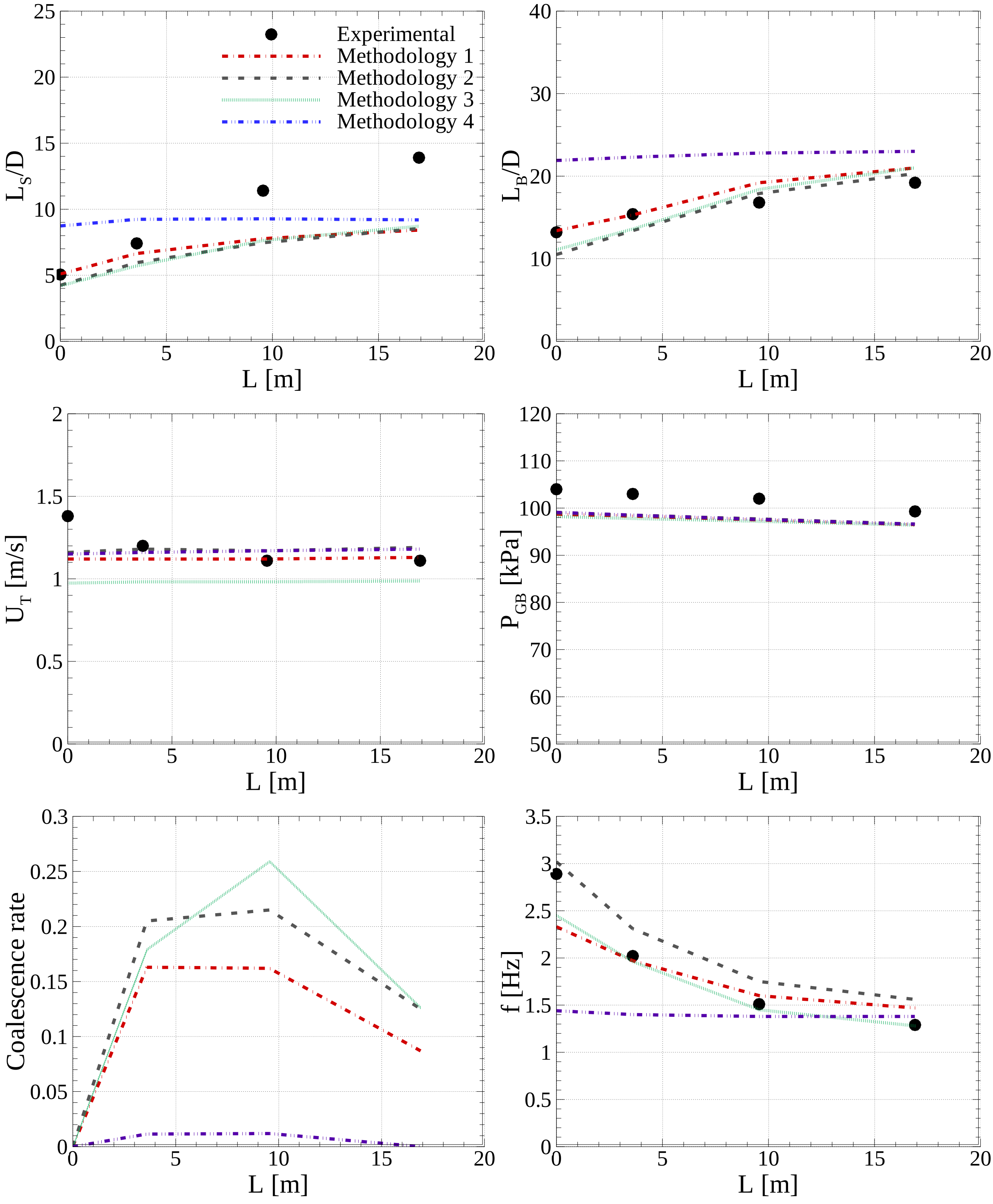

Figure 5. Mean results obtained for the length of the slug, L_S, bubble length, L_B, bubble velocity, U_T, bubble pressure, P_{GB}, and bubble inlet frequency in the pipe, f, for the point A@W4

6. CONCLUSIONS

The model of Rosa et al. (2015) uses the slug tracking model, where the inflow of bubbles and slugs is accomplished by a list created from experimental data. Four methodologies have been proposed for the creation of this list necessary for initiating the simulation.

The first methodology consists of the insertion of the data obtained experimentally. The second is a list of values distributed around the standard deviations and mean values of the experimental data. The third is the application of data obtained in previous simulations for the calculation of the new superficial velocities, using the correlation of Bendiksen

(1984) for the translational velocity of the bubble. The fourth uses the lengths of the bubble and slug obtained in previous simulations, with the rest of the data necessary for the initialization of the program obtained with the second methodology.

Based on the results obtained, the four methodologies presented good results. Methodology 1 is the best to represent the experimental results at flow initiation, since it uses the experimental data as the initial condition. However, Methodologies 2 and 3 present very similar results throughout the flow, since the only difference between the two is the superficial velocity of the gas phase. Methodology 4 presents the largest bubble length data that are already inserted in the program as results of previous simulations, such as developed lengths.

7. ACKNOWLEDGEMENTS

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