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ON THE INFLUENCE OF THE INLET SLUG LENGTH DISTRIBUTION – A SLUG FLOW SIMULATOR

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ABSTRACT

A slug flow simulator was developed considering: (i) an overtaking mechanism based on air-water co-current continuous experimental data [1]; (ii) expansion of the gas phase and its consequences in bubble length and velocity and (iii) several types of slug length and gas flow rate distributions, at column inlet. The simulator allows the monitoring of various flow characteristics, namely (i) the evolution of the distributions of several variables along the column; (ii) the definition of column zones, with different coalescence and (iii) the evaluation of the flow stability height (flow developing length), for certain flow conditions.

The simulator was used to study the influence of the inlet slug length distribution over the stabilized slug flow pattern. Four similar simulations were prepared with inlet slug lengths normally distributed around averages of 0.075, 0.1, 0.15 and 0.2 m, and equal initial number of bubbles, inlet gas flow rate, and liquid flow rate. The output results showed to be independent of the inlet distributions, indicating that the bubble overtaking mechanism has dominant influence over the overall slug flow pattern development.

1 INTRODUCTION

Slug flow is a highly complex, intermittent and irregular gas-liquid flow pattern. It can be found in numerous applications, namely: pipeline transportation of hydrocarbons, steam production in geothermal power plants, gas-liquid heat and mass transfer in air-lift reactors, enhancement of membrane and crystallization processes.

Slug flow pattern is characterized by the occurrence of elongated bullet-shape gas bubbles, denominated as Taylor bubbles, separated by liquid slugs. These bubbles occupy most of the pipe cross section area, forcing the liquid to flow around, in a very thin film, between the bubbles' surface and the pipe wall.

The wakes of Taylor bubbles, formed by the liquid coming out of the annular film surrounding the bubbles, induce changes in the liquid flow pattern between bubbles. These disturbances are known to play an important role in the bubble interaction mechanism, by which one bubble, flowing in a train of bubbles, can accelerate towards the precedent one and eventually merge with it [1-6]. This dynamic behaviour of the slug flow pattern poses some difficulties in developing prediction methodologies, capable of furnish information concerning bubble and slug length distributions, average and maximum values for those parameters, all crucial data for design optimisation of slug flow applications.

Several researchers studied the motion of individual bubbles in stagnant liquid [7-10], usually in its asymptotic regimes: inertial flow, viscous flow and capillary flow.

For inertial controlled regime (ranges reported by White and Beardmore [10]), an expression was suggested for the bubble rising velocity in a stagnant liquid, U_∞, in vertical columns of internal diameter D [8]:

$$U_\infty = 0.35\sqrt{gD} \qquad (1)$$

Experimental studies on the velocity of individual bubbles rising in flowing liquid, reported by Nicklin et al. [11], led to the following expression:

$$U_B = C\,U_L + U_\infty \qquad (2)$$

where U_L is the superficial liquid velocity and C an empirical coefficient depending on the liquid flow regime ahead of the bubble. Values of 1.2 and 2 were suggested by several authors [11-13] for turbulent and laminar regime, respectively.

For continuous co-current gas-liquid flow, the liquid velocity is increased by the entrance of the gas phase. Thus, the expression for the velocity of an undisturbed bubble, Eq. (2), must be transformed to account for this increment, yielding:

$$U_B = C\,(U_L + U_G) + U_\infty \qquad (3)$$

where U_G is the superficial gas velocity.

Several experimental studies on vertical slug flow indicate that the minimum stable liquid slug length, i.e. the liquid slug length above which no more bubble-to-bubble interactions occur, ranges from 8 to 25 column diameters [2, 14-16]. Pinto et al. [5] reported a study on the coalescence of two bubbles, rising in a co-current flowing liquid, in vertical tubes, for turbulent flow pattern inside the bubble wakes. Different types of bubble-to-bubble interaction are reported according to the liquid flow pattern ahead of the bubbles. The study was afterwards widened to trains of bubbles rising in co-current turbulent and laminar liquid flows [1].

Several attempts have been made to simulate the slug flow pattern, by defining input relations, able to predict the rising bubble velocities, as a function of the length of the liquid slugs ahead of the bubbles. Barnea and Taitel [17] suggested a model requiring the definition of a minimum stable liquid slug length to establish an interaction mechanism accounting for the bubble coalescence events. The model considered an inlet slug length distribution and predicted the evolution of the slug length distribution along the column. Hasanein [3] used a similar strategy, although using a different expression for the bubble interaction mechanism, based on air-kerosene experimental data. However, the suggested models discard the gas phase expansion and furnish no information regarding bubble length distributions and average values along the column. Moreover, no inlet gas flow rate distribution is considered, an issue whose importance may become relevant for increasing gas flow rates.

Some doubts still exist concerning the prevailing mechanism in the development of the slug flow pattern: do the entrance distributions dominate the slug flow development or, alternatively, the overtaking mechanism by which bubbles eventually merge strongly influences the output of slug flow experiments [18]? Although some simulation results [17] indicate that the inlet slug length distributions have reduced influence over the outlet distributions of a slug flow experiment this remains as an open question requiring, therefore, some attention.

The main goal of the present work is to provide answers to the questions described above. A simulation algorithm was prepared based on experimental data gathered in co-current continuous gas-liquid flow [1] and special care was devoted to simulate, as accurately as possible, the slug flow pattern characteristics (including gas phase expansion and gas flow rate distributions to account for eventual fluctuations in the gas supply).

2 SIMULATOR CHARACTERISTICS

2.1 The upward bubble velocity as a function of the length of the liquid slug ahead of it - an input relation

Figure 1 represents schematically the slug flow pattern. As referred above, the velocity of a bubble, in a train of Taylor bubbles, is related to the length of the liquid slug ahead of it, and to the undisturbed upward bubble velocity, as defined by Eq. (1).

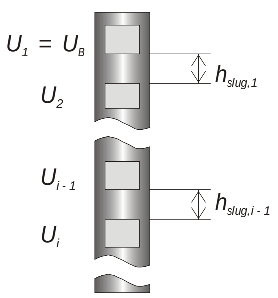


Figure 1. Representation of Slug flow pattern

The curve of the experimental data, reported by [1], regarding turbulent regime in liquid and in the bubble wake shows, when plotted against de dimensionless liquid slug length, a decreasing exponential behaviour well fitted by Eq. (4).

$$U_i = U_B\left(2 - e^{\frac{-1000}{\left(\frac{h_{slug,i-1}}{D}\right)^5}}\right) \tag{4}$$

where U_i is the upward velocity of the bubble i, and $h_{slug,i\text{-}1}$ is the length of the liquid slug ahead of it. The above relation is used as input in the developed simulator in order to account for the overtaking mechanism by which bubbles eventually merge, along their upward movement in the column.

2.2 Distributed parameters: slug length and gas flow rate

The simulation algorithm considers two independent variable distributions: slug length distributions and gas flow rate distributions. Several types of slug length distributions are implemented (Normal Random, Uniform Random, Constant and User defined distribution). The gas flow rate is distributed normally around an average value. This distribution serves to account for any eventual oscillation in the gas supply.

2.3 Bubble length as a function of slug length and gas flow rate

Figure 2 represents a train of Taylor bubbles flowing in co-current vertical slug flow. In the figure (a), $h_{bubble,i}$ is the length of a gas bubble i flowing in the column; U_L is the average liquid flow rate, and the several parameters of the form $U_{G,i}$ are the elements of the gas flow rate distribution (bubble$_i$ + slug$_i$ cell averages).

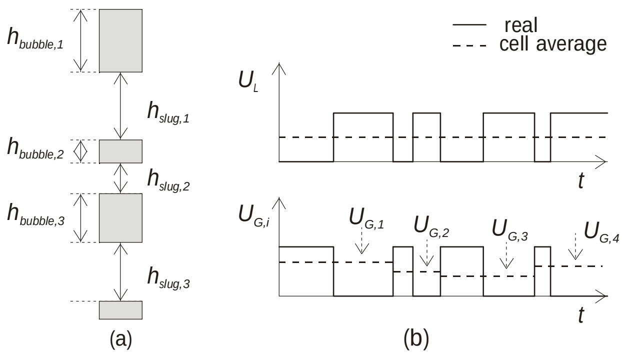


Figure 2. Representation of the slug flow intermittency

In order to assure, at the inlet of the column, constant gas and liquid flow rates (U_L and the several $U_{G,i}$; dashed lines in illustration (b)), a relation must exist between the length of the liquid slugs, the length of the gas bubbles and the mentioned flow rates (notice that in illustration (a), longer slugs follow longer bubbles). Eq. (5) represents that relation:

$$h_{bubble,i} = \frac{h_{slug,i}}{\frac{U_B\, S_{bubble}}{U_{G,i}\, S_{column}} - 1} \tag{5}$$

where S_{bubble} and S_{column} refer to the bubble and column cross sections areas, respectively. The above equation allows the determination of the adequate bubble length distribution to assure, at column inlet, the desired liquid flow rate, for given slug length and gas flow rate distributions.

2.4 Simulation start-up

The desired average inlet gas flow rate, U_G^{inlet}, must be introduced as input in the simulation algorithm. The evaluation of this parameter can be computed, at column inlet, by:

$$U_G^{inlet} = \frac{S_{bubble} \sum_{i=1}^{n} h_{bubble,i}}{S_{column} \sum_{i=1}^{n} \Delta t_i} \qquad (6)$$

where Δt_i is defined as the time intervals required for the entrance of the $bubble_i$ + $slug_i$ cells. Due to the non-linearity of this relation, the simulation start-up must be implemented in an iterative scheme. The following figure illustrates this strategy:

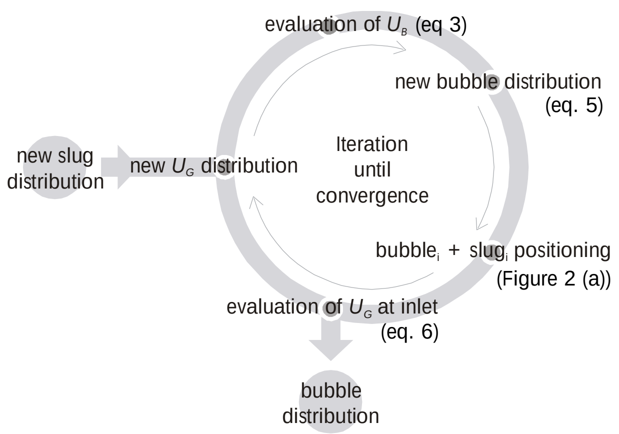


Figure 3. Representation of the iterative approach to the simulation start-up

The convergence of the described iterative procedure is achieved when U_G^{inlet}, evaluated by Eq. (6), becomes equal to the desired value (input parameter).

2.5 Gas phase expansion

The expansion of the gas phase along the column influences the development of the slug flow pattern. In order to simulate this phenomenon as accurately as possible, special care was devoted to the development of expansion routines, capable of adequately account for the hydrostatic pressure gradient existing in the column. The algorithm and its influence in the simulation results, albeit important, are outside the scope of the current work.

2.6 The movement of the gas bubbles along the column

Figure 4 represents two consecutive instants in the movement of a bubble *i*, flowing vertically in a column. In the figure, the position of the bubble nose and rear (bubble boundaries) is represented by $H_{bubble\ nose,i}$ and $H_{bubble,i}$ rear, respectively, in different instants (t_j and t_{j+1}).

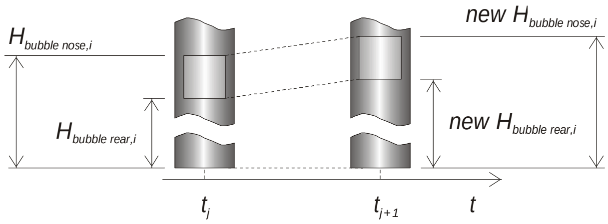


Figure 4. Representation of two consecutive instants in the upward movement of a Taylor bubble

If, at an instant t_j, the simulator holds the value for the velocity of the bubble under consideration, $U_i^{t_j}$, determined by Eq. (4), it is possible to increment the position of that bubble, by increments in the position of its boundaries:

$$H_{bubble\ rear,i}^{t_{j+1}} = H_{bubble\ rear,i}^{t_j} + U_i^{t_j}\ time_{increment} \qquad (7)$$

$$H_{bubble\ nose,i}^{t_{j+1}} = H_{bubble\ rear,i}^{t_{j+1}} + h_{bubble,i}^{t_{j+1}} \qquad (8)$$

where $time_{increment}$ is the time difference between t_{j+1} and t_j. Notice that the bubble velocity is considered constant in the time increment used in the simulation, an assumption whose correctness increases for decreasing time increment. Each bubble length and velocity is, then, corrected by expansion routines, to account for the change in the hydrostatic pressure acting on the bubble, in the updated position.

Considering now the boundaries of two consecutive bubbles, one can evaluate the length of the liquid slug, flowing between them, by:

$$h_{slug,i}^{t_{j+1}} = H_{bubble\ rear,i}^{t_{j+1}} - H_{bubble\ nose,i+1}^{t_{j+1}} \qquad (9)$$

This strategy is spanned to all the bubbles flowing in the column.

2.7 The merging of bubbles (coalescence)

When the length of a liquid slug, flowing between two consecutive bubbles, decreases due to the acceleration of the trailing bubble towards the leading one, a merging event occurs, in which the referred bubbles form a longer bubble. This phenomenon (coalescence) is illustrated in Figure 5.

Bubble indexation or identification, within the frame of the simulation algorithm, requires special care when considering coalescence phenomena: first, all bubbles flowing ahead (above) the two undergoing coalescence require no index correction; second, all bubbles flowing before (below) the referred two, require index correction by one unity; third, the new longer bubble and longer slug receive the index of the leading bubble. Notice that, each bubble index attaches several parameters describing the $bubble_i$ + $slug_i$ cell. Consequently, the referred index correction must migrate all parameters accordingly.

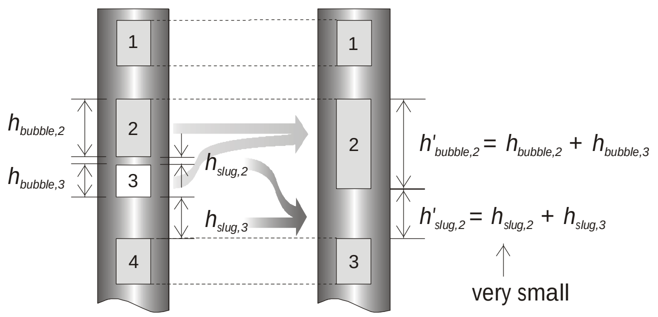


Figure 5. Representation of the merging of two consecutive bubbles (bubble index correction)

2.8 Open windows to the slug flow: horizontal and vertical “watchers”

In order to easily monitor the evolution of several flow characteristics along the column a set of horizontal and vertical “watchers” were implemented. These monitoring elements, placed strategically along the column, in user-defined positions, allow, for instance, the tracking of the evolution of the distributions of bubble and slug lengths (Figure 6), as they move upwards in the column, or the definition of column zones, with different coalescence (Figure 7).

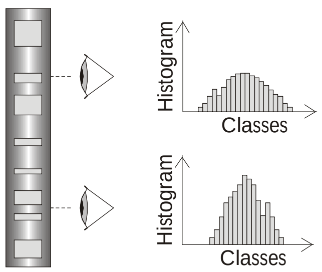


Figure 6. Representation of the data gathered by horizontal “watchers”

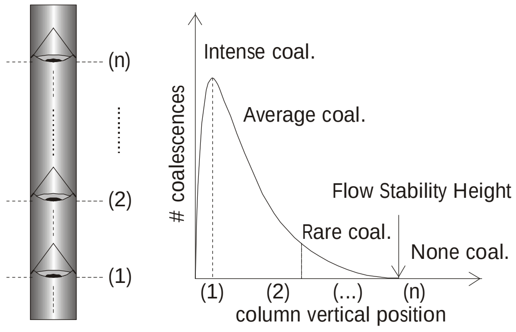


Figure 7. Representation of the data gathered by vertical “watchers”

3 RESULTS AND DISCUSSION

3.1 Simulation as a good representation of experimental data

Figure 8 shows a direct comparison between bubble and slug length experimental data (reported by Pinto et al. [1]) and simulation results, for similar conditions. The simulation’s results represent adequately the experimental data, validating therefore the implemented algorithm.

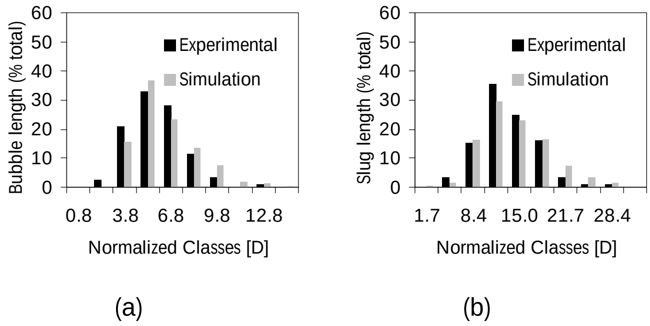


Figure 8. Experimental and simulation bubble lengths (a) and slug lengths (b) histograms, at column vertical position 5.5 m (U_G = 0.13 m/s, U_L = 0.08 m/s, D = 0.032 m, for column height of 6.5 m)

3.2 A detailed analysis: the influence of the average of the inlet slug length distribution

Four similar simulations were prepared with inlet slug lengths normally distributed around averages of 0.075, 0.1, 0.15 and 0.2 m. As comparison requirement, all four simulations had equal initial number of bubbles and inlet gas flow rate (as well as liquid flow rate). The simulations were compared systematically and a summary of the results is depicted in Figure 9 and Figure 10 (all data are normalized by the column diameter).

Figure 9 shows the average of several flow parameters at the inlet of the simulated columns. All parameters are, at that position, constant, except for the average inlet bubble length, which increases for increasing inlet average slug length. This variation is expected as both variables are related, at inlet, by Eq. (5).

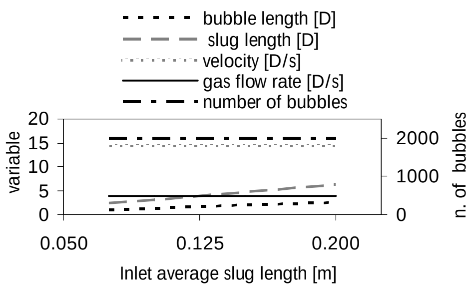


Figure 9. Average of main flow parameters vs. inlet average slug length, at column inlet (D as normalization variable)

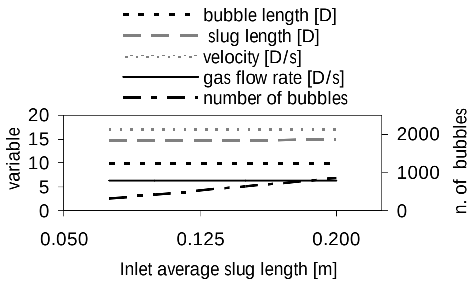


Figure 10. Average of main flow parameters vs. inlet average slug length, at column outlet (*D* as normalization variable)

The simulation results at the column outlet, depicted in Figure 10, indicate that: (i) the number of coalescences occurring along the columns decreases for increasing inlet average slug length (as the number of bubbles, at outlet, increases), and (ii) the average of the represented parameters (bubble velocity, bubble length, slug length and gas flow rate) show no dependence over the inlet average slug length. This last observation is confirmed by the histograms of the bubble length and slug length distributions, at column outlet (Figure 12 (b) and Figure 13 (b), respectively). Indeed, although the inlet histograms of these parameters are centred on different classes (charts (a) of the referred figures), in agreement with the mentioned increasing averages, the outlet histograms are similar. This is an important result as it indicates that the stabilized slug flow pattern depends more on the overtaking mechanism (which influences the bubble coalescence), than it does on the type of bubble injector/nozzle (which changes the inlet distributions). Barnea and Taitel [17] arrived at a similar conclusion, although using a different overtaking model, and discarding the gas phase expansion.

It is interesting to consider again the simulation data regarding the average of the flow parameters at the column outlet (depicted in Figure 10), with a different normalization strategy. Instead of using the column diameter as the normalization variable, the correspondent inlet values are used. This strategy enables withdrawing the influence that the inlet trends might have over the outlet results (notice that, as mentioned, the slug and bubble length averages are different, in the four simulations under comparison). Figure 11 depicts this alternative normalization scheme.

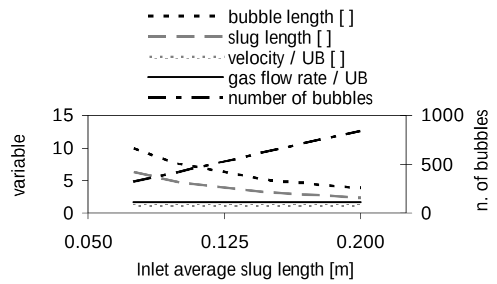
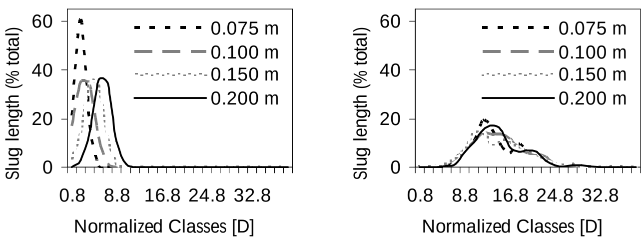


Figure 11. Average of main flow parameters vs. inlet average slug length at column outlet (inlet values as normalization variables)

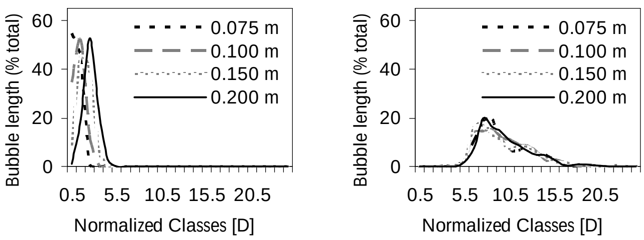
With the alternative normalization it becomes obvious that the average bubble length and slug length decrease asymptotically with increasing inlet average slug length. This variation is now coherent with the less frequent coalescence, taking place in simulations with higher inlet average slug length (coalescence increases both average bubble length and slug length).

In Figure 14 the number of coalescences is plotted against the column vertical position, for the four inlet average slug lengths considered. This plot shows that increasing the inlet average slug length shifts the coalescence curve to higher positions of the column. In order to observe this trend, the column position corresponding to 50% of the total coalescence is plotted, together with the column position of maximum coalescence, against the inlet average slug length. The resulting chart (Figure 15) depicts data corroborating the mentioned trend.



(a) (b)

Figure 12. Histograms of slug length distributions, at column inlet (a) and outlet (b), for different inlet average slug lengths



(a) (b)

Figure 13. Histograms of bubble length distributions, at column inlet (a) and outlet (b), for different inlet average slug lengths

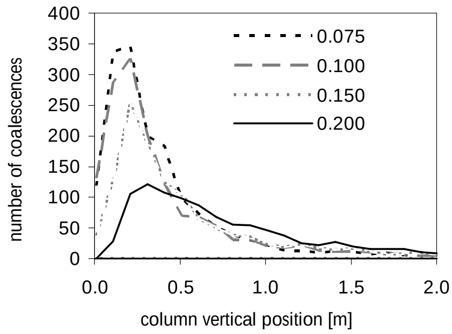


Figure 14. Coalescence events vs. column vertical position (intervals of 0.1 m), for different inlet average slug lengths

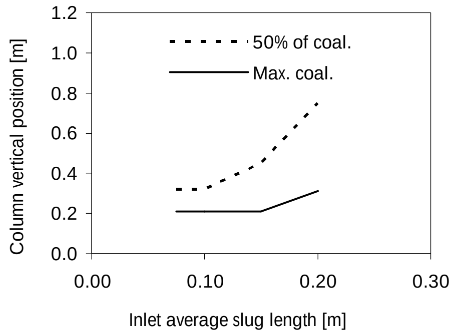


Figure 15. Column vertical position corresponding to maximum and 50 % of the total number of coalescences vs. inlet average slug length

The rising of the coalescence curve for increasing inlet average slug length was expected. It is, obviously, related to the fact that for higher inlet average slug length, the bubbles enter the column at higher distances from the previous ones.

4 SUMMARY AND CONCLUSION

A Slug Flow Simulator has been developed. A bubble overtaking mechanism based on air-water co-current continuous experimental data [1] is considered, and the expansion of the gas phase is taken into account. Several slug length distributions (Normal Random, Uniform Random, Constant and User defined) are allowed at column inlet. Normal distributions for gas flow rate parameter are implemented as well. The simulator allows the monitoring of several flow characteristics, namely (i) the evolution of distributions of several variables along the column; (ii) the definition of column zones, with different coalescence occurrence; (iii) the evaluation of the flow stability height, for certain flow conditions, etc.

The simulation algorithm produces outlet data describing adequately experimental data reported previously [1].

The simulator was used to investigate the influence of the inlet average slug length over the results of a slug flow experiment. These results showed to be independent of the inlet distributions, indicating, therefore, that the bubble overtaking mechanism has dominant influence over the overall slug flow pattern development.

Further studies regarding the influence of other parameters, over the development of slug flow pattern, are under preparation.

5 ACHKNOWLEDGEMENTS

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6 NOMENCLATURE

C	empirical coefficient	
D	column diameter	[m]
g	gravity acceleration	[m/s^2]
$H_{bubble\ nose,i}$	vertical coordinate of bubble i nose	[m]
$H_{bubble\ rear,i}$	vertical coordinate of bubble i rear	[m]
$h_{bubble,i}$	length of gas bubble i	[m]
$h_{slug,i}$	length of liquid slug i	[m]
S_{bubble}	bubble cross section area	[m^2]
S_{column}	column cross section area	[m^2]
$time_{increment}$	simulation time increment (t_{j+1}-t_j)	[s]
t_j	time instant	
t_{j+1}	time instant, after t_j	
U_B	bubble upward velocity	[m/s]
U_G	gas flow rate	[m/s]
$U_{G,i}$	ith element of a gas flow rate distribution	[m/s]
U_G^{inlet}	average gas flow rate at column inlet	[m/s]
U_i	bubble i upward velocity	[m/s]
$U_i^{t_j}$	bubble i upward velocity, at instant t_j	[m/s]
U_L	liquid flow rate	[m/s]
U_∞	bubble rising velocity in a stagnant liquid	[m/s]
Δt_i	time interval *i*, required for entrance of bubble$_i$ + slug$_i$ cell	[s]

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