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Slug Flow Simulator: A Tool for the Teaching and Learning of Two-Phase Slug Flow Regime in Vertical Columns*

TIAGO SOTTO MAYOR, ALEXANDRA M. F. R. PINTO and JOÃO B. L. M. CAMPOS
Centro de Estudos de Fenómenos de Transporte, Departamento de Engenharia Química, Faculdade de Engenharia da Universidade do Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal.
E-mail: tsmayor@gmx.net

The learning-oriented approach, with its emphasis on student engagement, has been implemented in a course that utilizes a slug flow simulator (SFS), in the context of research assignments that complement traditional engineering lectures. The course is a Master's degree in Theoretical and Applied Fluid Mechanics, at the Engineering Faculty of Porto University (Portugal). The goal is to engage students proactively in the learning process, so as to enrich their learning experience and foster knowledge retention. The main features of the simulator are presented (main windows, input parameters and monitored variables) and the potential benefits of its use are discussed. A series of tasks of increasing complexity are proposed, covering both undergraduate and graduate levels.

Keywords: student engagement; visualization tool; slug flow simulator

NOMENCLATURE

D	column diameter	[m]
h_b	bubble length	[m]
h_s	liquid slug length	[m]
t	time	[s]
U_G	superficial gas velocity	[m/s]
U_L	superficial liquid velocity	[m/s]
z	vertical coordinate	[m]
Δt	time interval	[s]
Δz	column length interval	[m]

INTRODUCTION

SLUG FLOW, a complex and irregular two-phase flow, occurs in a variety of industrial and natural contexts. Some examples are pipeline transportation of hydrocarbons, chemical and nuclear reactors, geothermal power plants, membrane and crystallization processes, or even natural volcanic phenomena (such as the Stromboli volcano). Such a flow pattern is characterized by the intermittent and transient movement of elongated bullet-shaped gas bubbles (known as Taylor bubbles), separated by more or less aerated liquid plugs (known as slugs). The research on this topic already spans decades [1–8], but several points still remain open, fuelling the curiosity of the scientific community.

Several engineering courses at both undergraduate and graduate level encompass two-phase flows (in particular slug flow). Subjects like Fluid Mechanics or Heat Transfer, taught to every Civil, Chemical or Mechanical Engineering student, include the topic. It is, thus, an issue traversing the background education of any engineering student.

The shift from the teaching-oriented to the learning-oriented paradigm, a must for the future of engineering education as stressed by Melsa [9], advises teaching strategies that favour student involvement in the learning process. Student engagement promotes questioning, class attendance, good grades and lasting interest in subjects [10]. Hands-on activities are, undoubtedly, a potential promoter of student engagement. They enhance student participation in the learning process, along with augmenting the student's self-esteem. Kresta [11] reports a 30–80% increase in the attendance of fluid mechanics seminars after implementation of hands-on demonstrations. Such proactive activities favour peer-to-peer interaction, teamwork, and cooperative strategies, valuable assets in real work environments [9].

The advent of fast and robust computational platforms enabled the development of a variety of numerical and visualization tools (simulators) covering different topics. Computational fluid dynamics (CFD), for instance, is a field that profited greatly from the evolution of informatics systems. But even more confined approaches, regarding the simulation of specific phenomena/events, benefited from computational evolution. For instance, Higuchi [12] describes several web-based simulations on fluid mechanics and aerodynamics. Moreover, a number of other contributions covering different topics exist [13, 14].

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Besides the numerical information, all these approaches provide the means to visualize the evolution of phenomena/events, so as to build up mental image representations. According to Kolari and Savander-Ranne [15], visualization promotes students' apprehension and comprehension. It provides relevant representations of issues and helps students form visual interpretations of what concepts and abstractions mean. Simulators can therefore play a relevant role in lecture-like environments. While they bridge traditional lectures and hands-on real experiments, they also constitute a shift towards the learning-oriented approach. Moreover, they make it possible to overcome some of the economic and portability issues often accounted for in real experiments.

The use of a user-friendly slug flow simulator (SFS) in a context of research assignments complementing traditional lectures is discussed in this paper. Possible approaches and advantages of the use of such a tool are addressed. The simulator is currently used in the Master's course Theoretical and Applied Fluid Mechanics, at the Engineering Faculty of Porto University.

THE SIMULATOR

The learning-oriented approach, with its emphasis on student engagement, has been implemented in the Master's course Theoretical and Applied Fluid Mechanics, at the Engineering Faculty of Porto University. The traditional theoretical and laboratory lectures are complemented by several small research assignments based on the use of various simulation tools. One such assignment, on the slug flow pattern, is based on the use of a slug flow simulator (SFS) developed by Sotto Mayor et al. [1] for vertical columns. The following sections outline the main features of the SFS. The aim is to give a general idea of the approach pursued for the development of a simulation tool on the slug flow pattern. Other phenomena (two-phase flow or others) could be addressed in a similar way.

"Windows" to the phenomena

In order to study the evolution of the slug flow pattern along the column, a set of "windows" to the phenomenon was developed. They are basically a set of horizontal and vertical "watchers" allowing a quantitative description of the flow pattern. Horizontal "watchers" compile two types of data: instantaneous and global. Instantaneous data (Fig. 1b) captures the characteristics of the bubbles inside the column, in a specific instant of time; it freezes the bubble motion and enables a detailed analysis of every bubble parameter (length, velocity and distance). Global data gathers information on the bubbles crossing a certain column vertical coordinate during a slug flow experiment/simulation (Fig. 1a); it promotes a global assessment of the flow characteristics in a specific time interval.

The slug flow simulator allows numerous horizontal watchers (global type) to be established at any column vertical coordinate, with two different reference boundaries: bubble nose and bubble rear. The latter is relevant when studying long bubbles.

Vertical "watchers" focus on the coalescence inside the column. By counting the coalescence events occurring below, vertical "watchers" compile data describing the coalescence along the vertical column coordinate. An example of the output of this analysis is shown in Fig. 2. Several coalescence zones can be defined, featuring different occurrences of coalescence events (intense, average, rare and very rare). Direct analysis of this type of chart enables determination of the "flow stability height" parameter, the vertical column coordinate above which almost no coalescence is observed.

Main windows

The various windows of the slug flow simulator include the input of data (Fig. 3), the customization of the simulator (Fig. 4), the output of a slug flow simulation (Fig. 5), the input of simulations for comparison (Fig. 6) and the output of simulations for comparison (Fig. 7). Several parameters can be defined or controlled in each of these windows. The following sections describe this in more detail.

Input Data window

The main parameters regarding the simulation are defined in the Input Data window. Some examples are: column characteristics (height, diameter, and exit configuration), superficial gas and liquid velocities (U_G and U_L), fluid properties, number of slug units (sets of bubble + liquid slug)

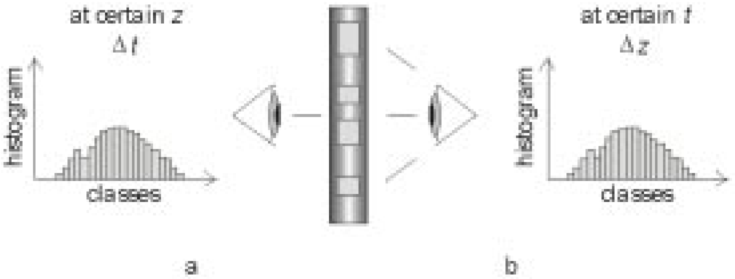


Fig. 1. Example of the data compiled by horizontal "watchers": (a) global column analysis; (b) instantaneous column analysis.

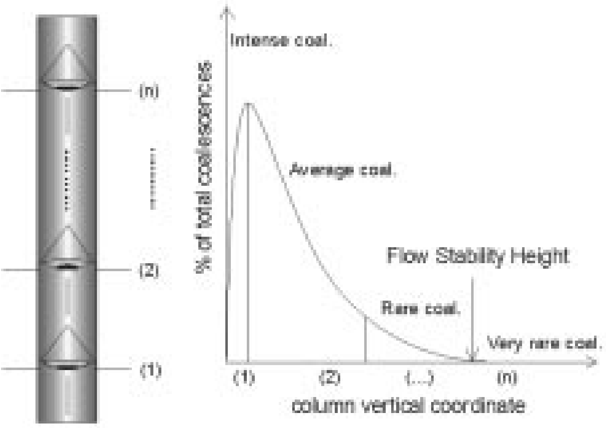
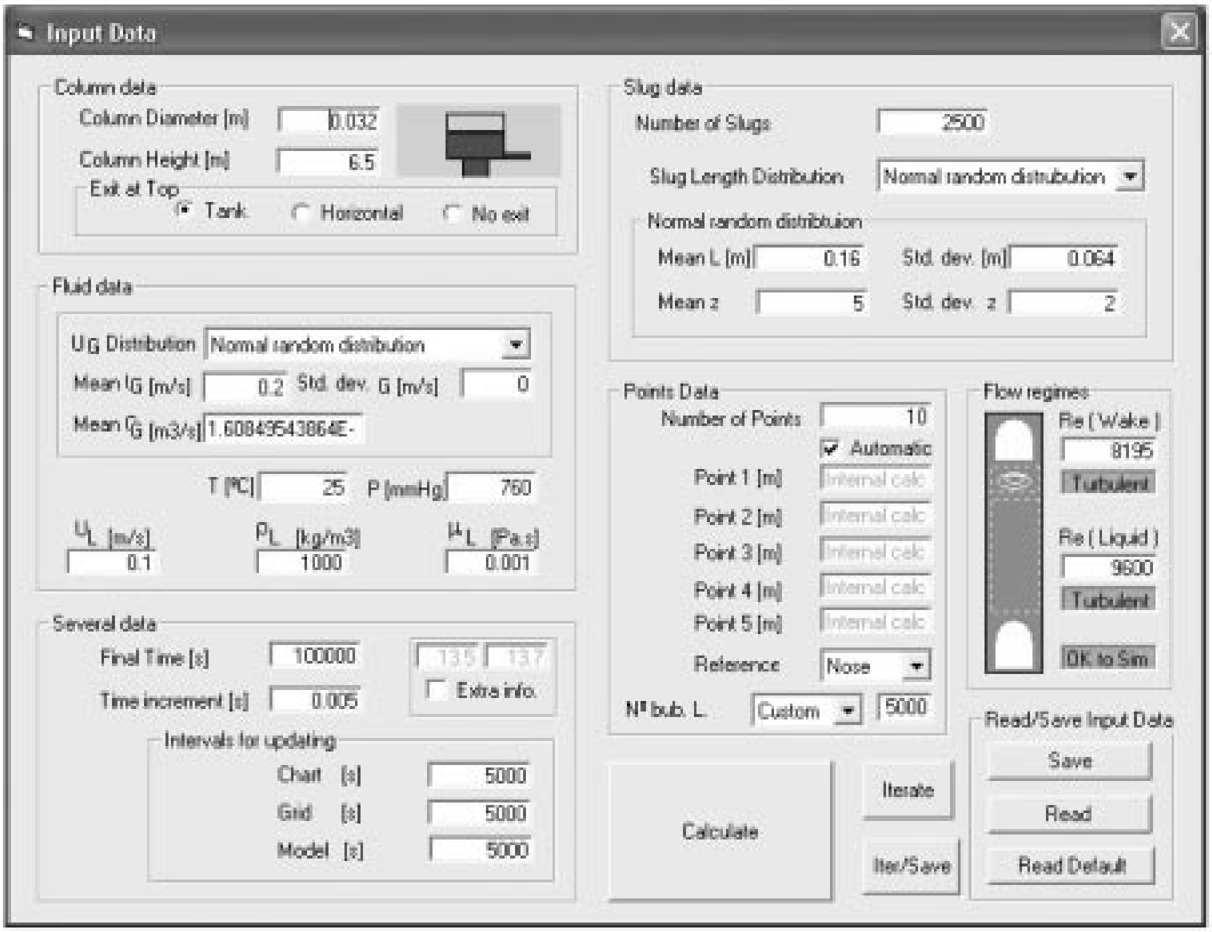


Fig. 2. Example of the data compiled by vertical "watchers".

and type of distributions at the column inlet (for liquid slug length and U_G). Some other parameters related to the numerical simulation and resulting data are also defined here. The time increment of the simulation, the number and positioning of the horizontal watchers, and the time intervals for updating charts, grids and the 2D flow picture are some examples. Note that by altering these time intervals the students can change the simulation rate. For instance, the simulation rate can be slowed down by setting the update of the 2D flow picture at very short time intervals.

Depending on the specification of the superficial gas velocity (in terms of pressure), two different simulations can be performed: a straightforward simulation (*calculate* button) if U_G is given at the column inlet pressure, or an iterative procedure (*iterate* button) if U_G is given at the atmospheric outlet pressure. In the latter, several simulations must run sequentially until the required U_G is



Column data
Column Diameter [m] 0.032
Column Height [m] 6.5
Exit at Top: ● Tank ○ Horizontal ○ No exit

Fluid data
UG Distribution: Normal random distribution
Mean UG [m/s] 0.2 Std. dev. G [m/s] 0
Mean QG [m3/s] 1.60849543864E-
T [ºC] 25 P [mmHg] 760
UL [m/s] 0.1
ρL [kg/m3] 1000
μL [Pa.s] 0.001

Several data
Final Time [s] 100000
Time increment [s] 0.005
135 137
☐ Extra info.
Intervals for updating
Chart [s] 5000
Grid [s] 5000
Model [s] 5000

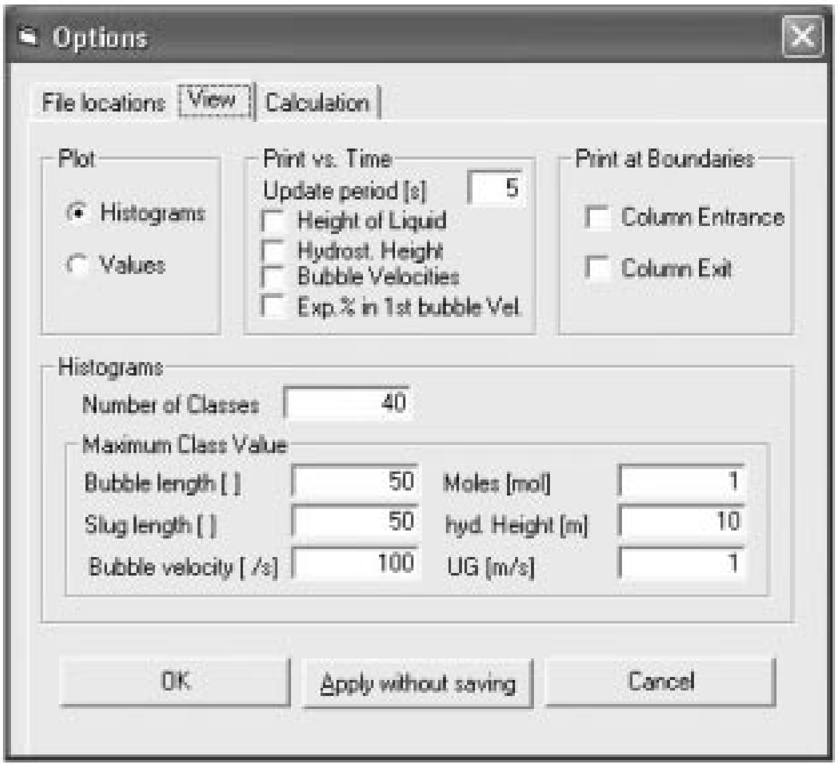
Slug data
Number of Slugs 2500
Slug Length Distribution: Normal random distrubution
Normal random distribtuion
Mean L [m] 0.16 Std. dev. [m] 0.064
Mean z 5 Std. dev. z 2

Points Data
Number of Points 10
☑ Automatic
Point 1 [m] Internal calc
Point 2 [m] Internal calc
Point 3 [m] Internal calc
Point 4 [m] Internal calc
Point 5 [m] Internal calc
Reference: Nose
Nº bub. L. Custom 5000

Flow regimes
Re (Wake) 8195 Turbulent
Re (Liquid) 9600 Turbulent

Read/Save Input Data

Fig. 3. Input Data window.



Plot
● Histograms
○ Values

Print vs. Time
Update period [s] 5
☐ Height of Liquid
☐ Hydrost. Height
☐ Bubble Velocities
☐ Exp.% in 1st bubble Vel.

Print at Boundaries
☐ Column Entrance
☐ Column Exit

Histograms
Number of Classes 40

Maximum Class Value

Bubble length [ ]	50	Moles [mol]	1
Slug length [ ]	50	hyd. Height [m]	10
Bubble velocity [/s]	100	UG [m/s]	1

Fig. 4. Options window (View Tab).

obtained at the outlet. More details on this subject can be found in Sotto Mayor *et al.* [1].

Options window

Several parameters concerning the numerical simulation and format of the output results are defined in the Options window. Some examples are: the phenomena acknowledged in the simulation (existence or absence of coalescence and gas expansion), the number of classes in the resulting histograms and the parameters whose variations along time are to be analysed in more detail.

Simulation Results window

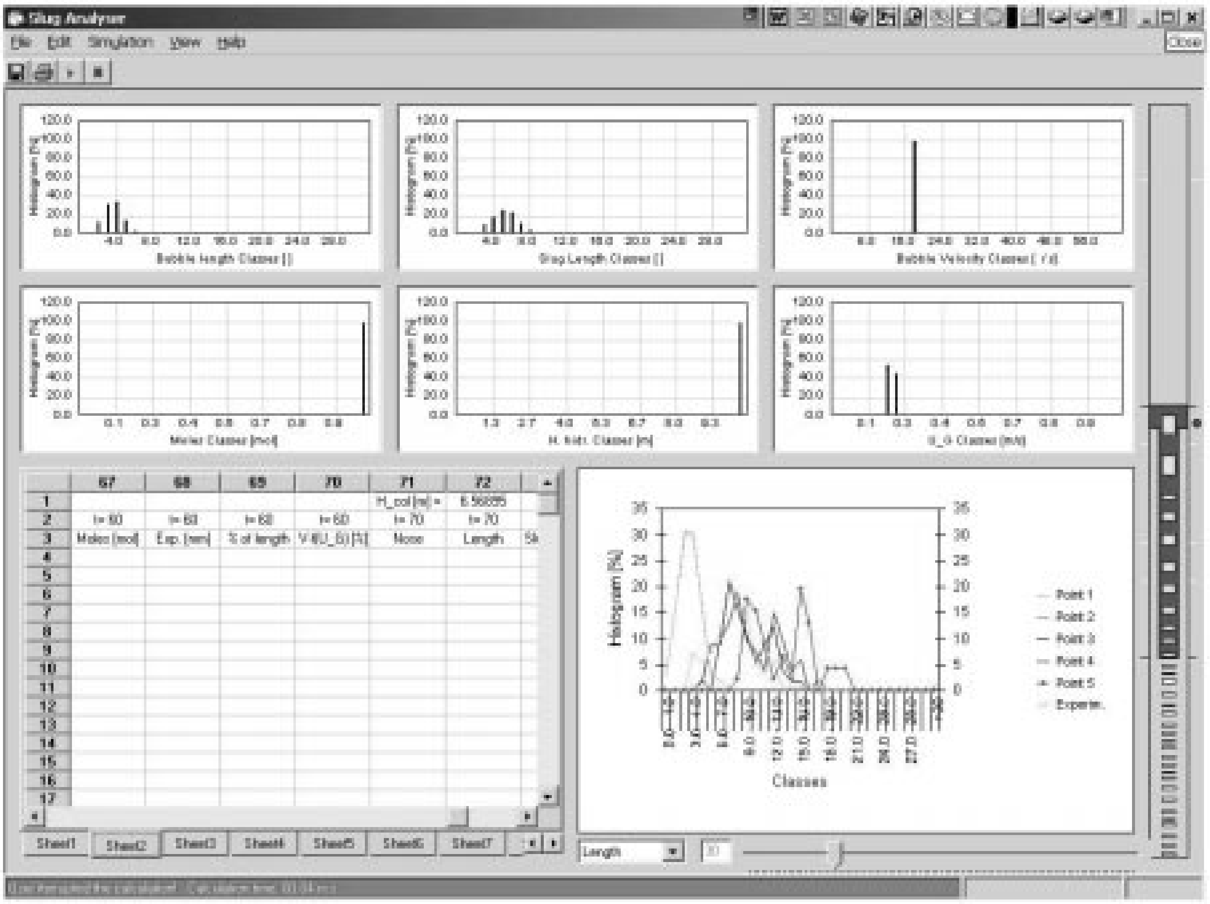
Two types of data visualization can be found in the Simulation Results window: a graphical representation of several parameters and a detailed numerical description of each parameter. The first type includes, for instance, charts and histograms of bubble velocity, bubble length and liquid slug length, or charts of coalescence plotted against the vertical coordinate of the column. Additionally, the 2D flow picture (on the lower right corner of Fig. 5), updated incrementally at the time interval defined in the Input Data window, enables a deeper and more realistic assessment of the development of the slug flow pattern. The second type of data visualization includes a set of eight sheets featuring several numerical data describing the bubbles inside the column (regarding, for instance, positioning, velocity and distance) and their motion over time. The content of these sheets is:

- Sheet 1—distribution at the inlet (characteristics of bubbles)
- Sheet 2—characteristics of bubbles inside the column at several points in time
- Sheet 3—characteristics of bubbles passing through several column coordinates
- Sheet 4—histograms at several column coordinates
- Sheet 5—detailed description of input data
- Sheet 6—reference data (such as experimental data) for comparison
- Sheet 7—evolution of coalescence events along the column
- Sheet 8—evolution of several flow parameters over time

The content of these sheets can be directly copied into any spreadsheet software for further processing.

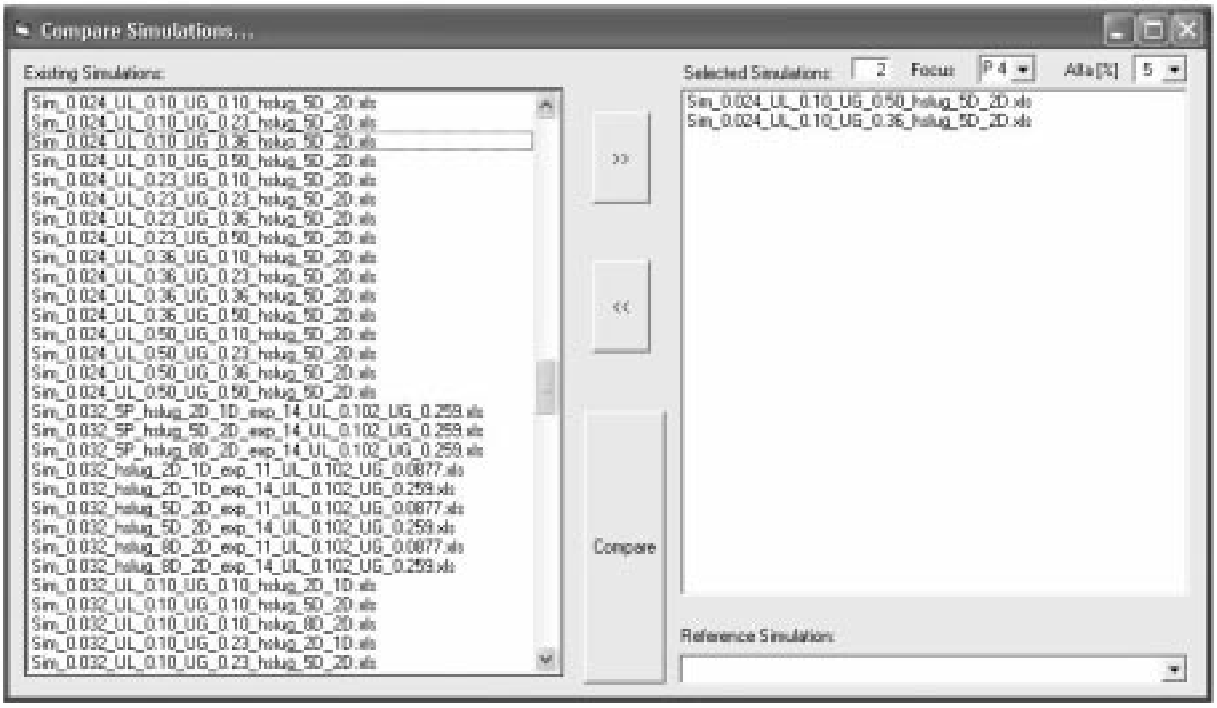
Compare Simulation Results window

After running several simulations, one can compare the resulting data in a straightforward way by using the slug flow simulator comparison routines (Fig. 6). These allow an enormous reduction in the time required for analysis, since the data comparisons are automatically compiled and shown according to the aforementioned visualization strategies (numerically and graphically). Note that, besides the numerical information displayed in the various sheets of the output window, comparative study of the evolution of the distribution along the column is further



	67	68	69	70	71	72
1					H_col [m] =	6.56895
2	t= 60	t= 60	t= 60	t= 60	t= 70	t= 70
3	Moles [mol]	Exp. [mm]	% of length	V-(U_G) [%]	Nose	Length
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						

Fig. 5. Main results of simulation routines.



Existing Simulations:

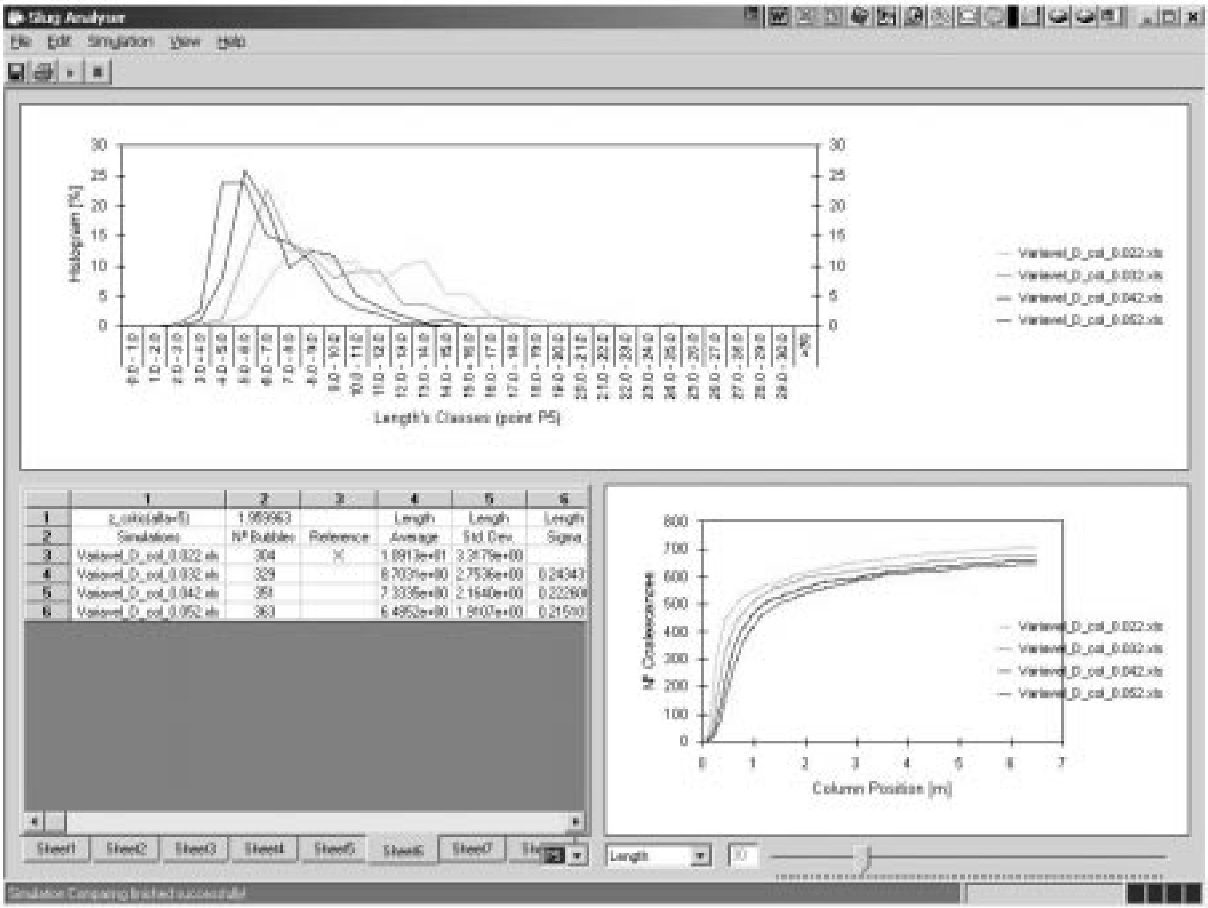
Sim_0.024_UL_0.10_UG_0.10_hslug_5D_2D.xls
Sim_0.024_UL_0.10_UG_0.23_hslug_5D_2D.xls
Sim_0.024_UL_0.10_UG_0.36_hslug_5D_2D.xls
Sim_0.024_UL_0.10_UG_0.50_hslug_5D_2D.xls
Sim_0.024_UL_0.23_UG_0.10_hslug_5D_2D.xls
Sim_0.024_UL_0.23_UG_0.23_hslug_5D_2D.xls
Sim_0.024_UL_0.23_UG_0.36_hslug_5D_2D.xls
Sim_0.024_UL_0.23_UG_0.50_hslug_5D_2D.xls
Sim_0.024_UL_0.36_UG_0.10_hslug_5D_2D.xls
Sim_0.024_UL_0.36_UG_0.23_hslug_5D_2D.xls
Sim_0.024_UL_0.36_UG_0.36_hslug_5D_2D.xls
Sim_0.024_UL_0.36_UG_0.50_hslug_5D_2D.xls
Sim_0.024_UL_0.50_UG_0.10_hslug_5D_2D.xls
Sim_0.024_UL_0.50_UG_0.23_hslug_5D_2D.xls
Sim_0.024_UL_0.50_UG_0.36_hslug_5D_2D.xls
Sim_0.024_UL_0.50_UG_0.50_hslug_5D_2D.xls
Sim_0.032_SP_hslug_2D_1D_exp_14_UL_0.102_UG_0.259.xls
Sim_0.032_SP_hslug_5D_2D_exp_14_UL_0.102_UG_0.259.xls
Sim_0.032_SP_hslug_8D_2D_exp_14_UL_0.102_UG_0.259.xls
Sim_0.032_hslug_2D_1D_exp_11_UL_0.102_UG_0.0877.xls
Sim_0.032_hslug_2D_1D_exp_14_UL_0.102_UG_0.259.xls
Sim_0.032_hslug_5D_2D_exp_11_UL_0.102_UG_0.0877.xls
Sim_0.032_hslug_5D_2D_exp_14_UL_0.102_UG_0.259.xls
Sim_0.032_hslug_8D_2D_exp_11_UL_0.102_UG_0.0877.xls
Sim_0.032_hslug_8D_2D_exp_14_UL_0.102_UG_0.259.xls
Sim_0.032_UL_0.10_UG_0.10_hslug_2D_1D.xls
Sim_0.032_UL_0.10_UG_0.10_hslug_5D_2D.xls
Sim_0.032_UL_0.10_UG_0.10_hslug_8D_2D.xls
Sim_0.032_UL_0.10_UG_0.23_hslug_2D_1D.xls
Sim_0.032_UL_0.10_UG_0.23_hslug_5D_2D.xls

Selected Simulations: 2 Focus: P 4 Alfa [%]: 5

Sim_0.024_UL_0.10_UG_0.50_hslug_5D_2D.xls
Sim_0.024_UL_0.10_UG_0.36_hslug_5D_2D.xls

Reference Simulation:

Fig. 6. Comparison Simulations window.



	1	2	3	4	5	6
1	z_crit(alfa=5)	1.959963		Length	Length	Length
2	Simulations	Nº Bubbles	Reference	Average	Std Dev.	Sigma
3	Variavel_D_col_0.022.xls	304	X	1.0913e+01	3.3179e+00	
4	Variavel_D_col_0.032.xls	329		6.7031e+00	2.7536e+00	0.24343
5	Variavel_D_col_0.042.xls	351		7.3336e+00	2.1640e+00	0.22260
6	Variavel_D_col_0.052.xls	363		6.4852e+00	1.9107e+00	0.21510

Simulation Comparing finished successfully!

Fig. 7. Main results of comparison routines.

boosted by having the mouse scroll wheel controlling the column vertical coordinate (P1, P2, etc.) displayed in the charts (as in Fig. 7, displaying data compiled at the fifth horizontal "watcher", P5). This means that, by a single movement of the mouse scroll wheel, students can directly observe the evolution of the distribution of different simulations along the vertical coordinate. This possibility not only speeds up the comparisons but also promotes deeper comprehension of the dynamic evolution of the slug flow pattern.

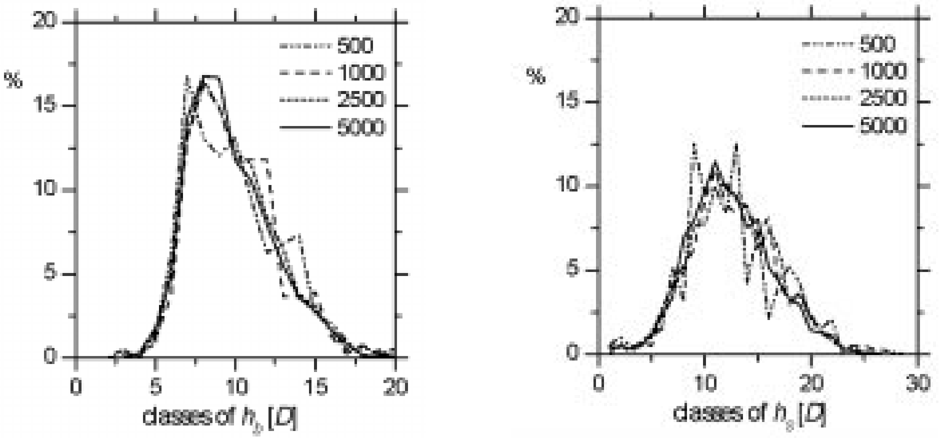
As for the Simulation Results window, the numerical data resulting from the comparison of several simulations (shown in the sheets) can be easily exported into any spreadsheet software (such as Microsoft® Excel) for further processing.

THE APPROACH

Research assignment: series of tasks using the SFS tool

As already mentioned, several small research assignments based on the use of simulation tools are given to students as a complement to the theoretical and laboratory classes. The use of a simulator (SFS) to demonstrate the slug flow pattern is discussed here. After lecturing students on the theoretical fundamentals governing such a flow pattern and introducing them to a real slug flow facility (6.5 m long/high; see Sotto Mayor *et al.* [2] for more details), a series of tasks of increasing complexity are given to the students. The aim is to go from a "worked-out" example (i.e. an example whose solution is shown worked out step-by-step, following Simon [16]) to an "open" problem (an example whose solution is to be decided and investigated by the students). The tasks are summarized below.

1. *To simulate a slug flow pattern for a given set of input parameters.* A set of input parameters such as the ones in Fig. 3 are introduced into the SFS code. Upon completion of the simulation, the output data are compared with pre-obtained simulation results. Any difficulties arising while using the simulator should be overcome at this stage.
2. *To understand the use of histograms and coalescence curves for the description of the flow pattern characteristics.* Different sets of input parameters can be tested freely by students. Changes over bubble length, slug length and bubble velocity are recorded by "reading" the histogram and coalescence curves.



(a) (b)

Fig. 8. Frequency distribution curves of (a) bubble length and (b) slug length, for simulations with 500, 1000, 2500 and 5000 bubbles (0.032 m ID; $U_L \approx 0.1$ m/s, $U_G \approx 0.26$ m/s).

3. *To learn how to compare different simulation data using simulator internal routines.* After selecting the simulations to be compared in the SFS window shown in Fig. 6, their systematic comparison is performed using simulator internal routines. Fig. 7 gives an example of the resulting data (regarding, in this case, simulations for increasing internal diameters of the column).
4. *To estimate adequate time increments and number of bubbles for representative flow pattern simulation.* The aim is for students to understand the notions of a grid test and a representative sample of bubbles. Regarding grid testing, several simulations with decreasing time increments are compared in order to determine the highest time increment producing accurate results. Using a similar approach, several simulations with an increasing number of bubbles are compared in order to determine the smallest number of bubbles needed to obtain representative results. Fig. 8 shows an example of the latter.
5. *To study the effect of several parameters over the flow pattern.* The effect on the flow pattern of column length and superficial gas and liquid velocities is described. The students are expected to use the slug flow simulator systematically in order to determine the extent of the influence of each of these parameters on the flow pattern characteristics. Several simulations differing only on a single parameter can be prepared, and the resulting data can be compared using the custom-made routines. Fig. 9 displays bubble length data gathered under this strategy (regarding, in this case, the superficial gas velocity, U_G).
6. *To study the influence of inlet parameter distributions on the results along the column.* The influence of initial distributions (of h_s for instance) on the evolution of the flow pattern along the column is studied. Comparing simulations featuring different inlet slug length distributions, students are expected to observe that initial differences tend to dissipate along the column. Fig. 10 illustrates this approach.
7. *To study the influence of different coalescence correlations on the evolution of the flow characteristics.* Several bubble-to-bubble interaction correlations are tested by students in order to assess the influence of interaction phenomena on the evolution of the flow. Using, for instance, correlations implying diverse bubble-to-bubble interaction for different distances (h_s), a chart like the one shown in Fig. 11 can be obtained, showing the evolution of bubble length and slug length parameters along the column. This approach highlights the influence of coalescence events in the evolution of these parameters.

The first three steps, while simple to accomplish, provide students with a basic understanding of the simulator and its features/outputs. The remaining steps aim at a deeper understanding of the flow pattern characteristics. Items 4 and 5 can be

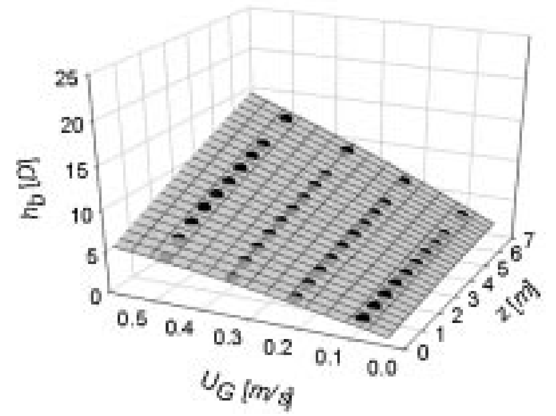
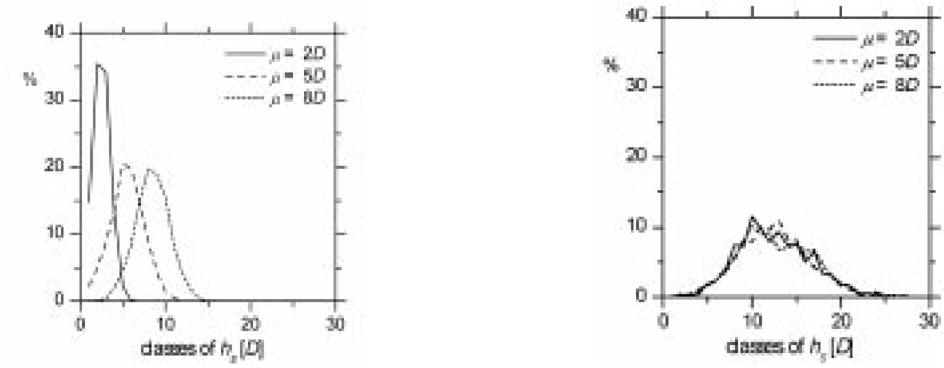


Fig. 9. Evolution along the column of the most probable bubble length, for simulations with $U_L \approx 0.23$ m/s and $U_G \approx 0.10$, 0.23, 0.36 and 0.50 m/s.



(a) (b)

Fig. 10. Frequency distribution curves of slug length at (a) inlet and (b) outlet (vertical coordinate: 5.4 m), for simulations with different inlet average slug length (2*D*, 5*D* and 8*D*); $U_L \approx 0.1$ m/s, $U_G \approx 0.26$ m/s; 0.032 m ID.

presented at undergraduate level, as they cover relatively simple notions/approaches. Items 6 and 7 should be presented at graduate level, since they require a more independent attitude and abstract approach from students. Regardless of the educational level, students' findings should be presented and discussed in writing as well as orally.

Remarks regarding the underlying pedagogy

Several authors argue that the majority of engineering students are visual learners (e.g. [17, 18]). This stresses the importance of integrating visualization into the process of teaching/learning [15]. The use of the SFS tool for the study of slug flow is an attempt to address this.

Following the four-stage learning model proposed by Kolb [19], the traditional theoretical lectures concern *reflective observation*. Ideally, it would be better to have the *active experimentation* and *concrete experience* stages grounded in real hands-on experiments. However, a 6.5 m height experimental facility poses serious scale, time and functional difficulties if experiments are to be performed by students, even under supervision. The use of a slug flow simulator is therefore the best feasible solution. While it overcomes the aforementioned difficulties, it provides a concrete experience on the topic and enables active experimentation by the students. The oral discussions following students' presentations of the research assignment findings facilitate *abstract conceptualization*. From theoretical lectures to research assignments (pseudo hands-on experiments) and subsequent discussions, an attempt is made to cover all four stages of Kolb's learning model and, thus, to stimulate students' learning experiences. Stice [20] reports a considerable increase in the students' knowledge retention when Kolb's four stages are present in a pedagogical approach (90% retention), in comparison to when only the abstract conceptualization stage (20% retention) is present.

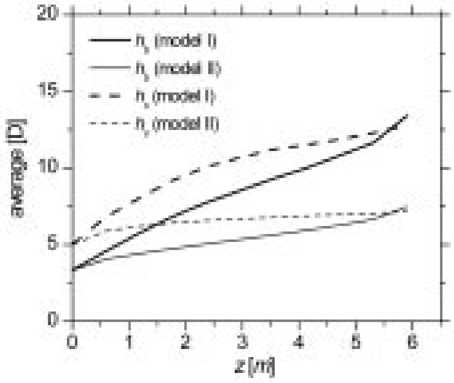


Fig. 11. Evolution of bubble length and liquid slug length along the column, for simulations with different bubble-to-bubble interaction correlations (column height: 6.5 m; internal diameter: 0.032 m; $U_L \approx 0.1$ m/s and $U_G \approx 0.2$ m/s).

Advantages of the research assignment based on the SFS

The advantages of implementing research assignments based on the use of simulators are twofold. There are pedagogical and practical benefits. Such student involvement is generally believed to enhance learning and skill development. Assuredly, the students' critical thinking and their ability to analyse and solve problems are substantially enhanced by a proactive and engaged approach. Moreover, the necessary teamwork stimulates the development of cooperative strategies, which are ever more important in the increasingly competitive real work environment. Additionally, by diversifying the learning channels/opportunities, different learning styles can be accommodated and encouraged. It is also very important to support students as they progress from a simple worked-out problem to increasingly more complex problems, as this helps to develop self-confidence, thus fostering the methodical approach one hopes to inspire in engineering students.

But there are other benefits of this via-simulation approach, particularly elimination of the cost, time and physical constraints related to experimental study of slug flow. Large and often expensive facilities, which usually constitutes a serious obstacle to implementing slug flow experiments in laboratory classes, can be avoided. Slow-paced experiments (for instance with low superficial gas and liquid velocities) can be squeezed into one-hour lessons by avoiding the real-time conditions of the experimental work. Furthermore, the absence of physical constraints allows for broadening the operating conditions to ranges that would otherwise be impossible (for instance comprising a very long test column), thus enabling the study of eventual asymptotical behaviours. And finally, by significantly reducing the time required for analysing results, a simulation tool like SFS avoids students' natural antipathy towards dense numerical data.

The outcome of the approach

The students' response to the use of the SFS code was very positive. The motivation and engagement of all the research teams (groups of three of four students, in classes of up to 10 students) culminated in dynamic presentations/discussions on the topic. We believe that a deeper and lasting understanding of the flow governing rules emerged from this approach, which has stimulated us to widen the range of engineering topics to be addressed in this way.

SUMMARY

This paper describes an attempt to complement traditional lectures with small research assignments based on the use of simulation tools. The use of the SFS code in the context of a research assignment on slug flow should be seen as more than a simple simulation task. All the activities contained in this approach address different aspects of the learning process and aim at reinforcing students' learning experiences. It is an approach that could also be applied to other engineering topics at both undergraduate and graduate level.

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Tiago Sotto Mayor graduated in Chemical Engineering in 1999 from the University of Porto (Faculty of Engineering). He is pursuing his Ph.D. studies at CEFT—Centro de Estudos de Fenómenos de Transporte—at the same university. His main research interests include multiphase flows (experimental and simulation), image analysis and education-related issues.

Alexandra M. F. R. Pinto graduated in Chemical Engineering from the University of Porto (Faculty of Engineering) in 1983 and received her Ph.D. in 1991 from the same university. She is presently Associate Professor at the same institution. She has taught courses in heat and mass transfer and ChE laboratories. Her main research interests are in transport phenomena, namely the hydrodynamics of multiphase flows. In the past few years she has worked mainly in the hydrodynamic characterisation of the slug flow pattern using the Particle Image Velocimetry technique in the context of a protocol of collaboration with the von Karman Institute for Fluid Dynamics (Brussels). Recently, she has developed interests in the fuel cell area, namely the direct methanol fuel cell (modelling and experimental studies) and hydrogen generators.

João B. L. M. Campos graduated in Chemical Engineering from the University of Porto (Faculty of Engineering) in 1980, and received his Ph.D. in 1987 from the same university. He is presently Associate Professor at that institution. He has taught courses in fluid mechanics, heat and mass transfer and ChE laboratories. His main research interests are in fluid mechanics, namely multiphase flows. In the past few years, he has worked in the experimental (using Particle Image Velocimetry) and numerical characterisation of slug flow in vertical and horizontal tubes. He also has interests in membrane separation and combustion.