ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

NUMERICAL SIMULATION OF STRATIFIED, HORIZONTAL PLUG AND VERTICAL SLUG FLOW PATTERNS

F. H. J. Imada
F. Saltara
J. L. Baliño
Universidade de São Paulo, Departamento de Engenharia Mecânica, São Paulo, Brazil
fabiano.imada@usp.br

Abstract. *The flow pattern, i.e., the spatial distribution of phases in a gas-liquid two-phase flow is influenced by phase superficial velocities and duct orientation with respect to gravity acceleration, among other factors. In this work, air-water stratified, horizontal plug and vertical slug patterns were simulated by means of Computational Fluid Dynamics using the commercial finite-volume-based code FLUENT. The incompressible Volume of Fluid (VOF) formulation allied to a Piecewise Linear Interface Construction (PLIC) technique was applied to capture the transient distribution of phases throughout a three-dimensional domain, which consists of a mixer connected to a* $50\,mm$ *i.d. straight duct. Each phase enters the domain through separate inlets at superficial velocities determined to simulate different flow patterns in a flow regime map. Turbulence effects were accounted through the Realizable k-epsilon model. The simulated horizontal flow patterns observed through visualizations of the phase distributions were qualitatively compared against the flow regimes expected by the Baker chart; the Taitel & Dukler regime map was used as reference for the results obtained in the vertical slug simulation. All simulations gave good agreement with the flow regimes expected from both maps.*

Keywords: *multiphase flow, flow patterns, Computational Fluid Dynamics, Volume of Fluid.*

1. INTRODUCTION

The study of simultaneous flow of gas-liquid mixtures is of great interest for many research areas due to its occurrence in a wide range of industrial applications such as oil and gas transportation ducts, pressurized water reactors in nuclear plants and bubble column reactors in chemical industries. Depending on operational conditions (phase superficial velocities, flow orientation with respect to gravity acceleration) and on fluids properties, the phases distribution may assume different topological configurations, known as flow patterns or regimes.

In horizontal ducts, the flow may assume stratified, wavy, plug, slug, bubble, dispersed and annular regimes which are described by Spedding and Spence (1993). In vertical upward flow, the regimes are commonly classified as bubble, slug, churn, annular and dispersed bubble patterns. A description of such regimes is given by Spedding *et al.* (1998). In the present work, we focused on stratified, horizontal plug and vertical slug patterns, which will be briefly described next:

- Stratified (Fig. 1(a)): a clear separation of the fluids by an undisturbed horizontal interface is observed, with liquid flowing over the bottom region of the duct;
- Horizontal plug (Fig. 1(b)): it is an intermittent flow where the liquid phase, free of entrained gas bubbles, carries elongated bullet-shaped gas bubbles that flow in the upper region of the tube. Thus, a continuous liquid phase occupies the bottom portion of the duct;
- Vertical slug (Fig. 1(c)): it is also an intermittent flow where, due to break-up of liquid columns and the coalescence of small gas bubbles, the occurrence of bullet-shaped gas bubbles, known as Taylor bubbles, followed by liquid regions containing dispersed bubbles are observed. The net flow is upward but an annular-shaped liquid portion flows downward around the Taylor bubbles.

Many authors have gathered experimental data or proposed transition theories in order to establish the boundaries between distinct flow regimes. These frontiers are usually represented as flow regimes maps. Mandhane *et al.* (1974) suggested a regime map for horizontal gas-liquid flows, using gas and liquid superficial velocities as mapping parameters. They compared their map to other maps available in the literature by means of visual observations present in a experimental data compilation. Baker (apud. (De Schepper *et al.*, 2008)) proposed the regime map shown in Fig. 2, which relates the gas/vapor mass flux G and the ratio between the mass fluxes of the liquid and the gas/vapor phase L/G to the expected flow pattern. The Baker chart also incorporates two dimensionless parameters ψ and λ to allow its application for any gas/vapor-liquid combination different than the standard one (air-water at atmospheric pressure and room temperature) for which the both parameters equal unity. The Baker chart was used as reference for the simulation of horizontal flow regimes in the present study.

Regarding vertical upward flows, Mishima and Ishii (1984) developed flow regime transition criteria suggesting geometric parameters, such as void fraction, as mapping variables. They provided a methodology to transform their map into

ISSN 2176-5480

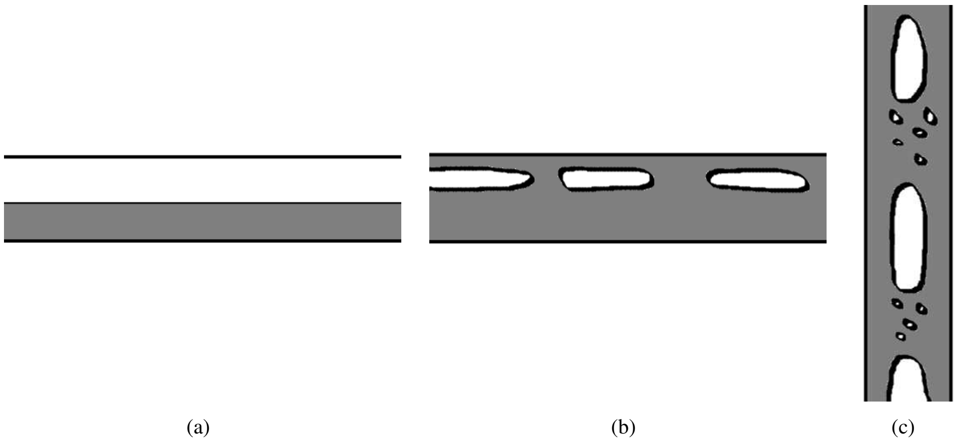

Figure 1. Representation of flow regimes: (a) stratified; (b) horizontal plug; (c) vertical slug - Grey color represents liquid phase and white color represents gas phase.

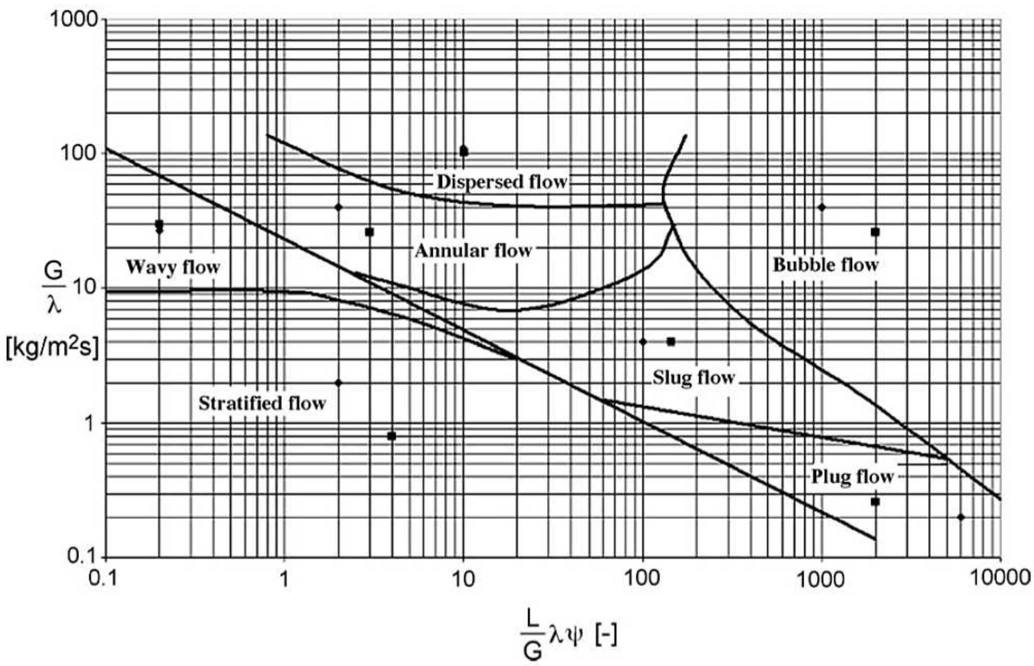

Figure 2. Baker chart (extracted from (De Schepper *et al.*, 2008)).

superficial velocities-based ones, comparing it to different maps available in the literature for air-water and water-vapor mixtures at different operational pressures. Spedding *et al.* (1998) summarized a collection of regime maps for vertical upward flows with different mapping parameters present in the literature, claiming that is unlikely that one could be nominated as a universal map. The maps were compared to own experimental data and the authors suggested new correlations for slug-churn and churn-annular transition boundaries. Analyzing different transition mechanisms, Taitel *et al.* (1980) proposed transition frontiers between different upward gas-liquid regimes in vertical tubes. They suggested correlations for positioning bubble to dispersed bubble, bubble to slug, slug to churn and annular pattern boundaries which, when combined, form the Tailel & Dukler regime map. This map, shown in Fig. 3, correlates the liquid and gas superficial velocities, j_f and j_g respectively, with the expected upward regime for a specific internal diameter D. The Taitel & Dukler map was used in the present work in order to provide operational conditions for the vertical slug flow simulation.

With the advance of digital computers, multiphase flows have been extensively studied by means of Computational Fluid Dynamics. Amongst the multiphase modeling approaches available, the Volume of Fluid (VOF) formulation (Hirt and Nichols, 1981) has been applied to simulate immiscible fluids interaction in ducts. Gao *et al.* (2003) applied the

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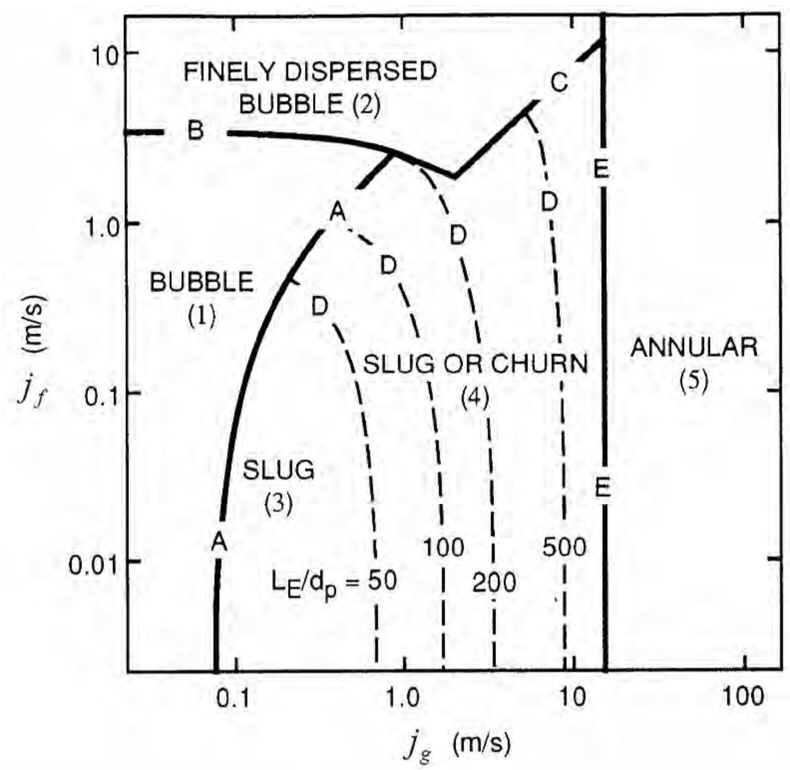


Figure 3. Taitel & Dukler regime map for upward gas-liquid flows - $D = 50\,mm$ (Taitel *et al.*, 1980).

VOF method to simulate oil-water stratified flows evaluating the pressure drop, slip ratio between fluids and local phase fraction for different inlet mass flowrates. The Piecewise Linear Interface Construction (PLIC) algorithm, first proposed by Youngs (1982), was used to calculate the interface while surface tension was modeled through the Continuum Surface Force (CSF) proposed by Brackbill *et al.* (1992). Turbulence effects were accounted by means of the Renormalization Group (RNG) k-epsilon model (Yakhot and Orszag, 1986). The authors suggested correlations for predicting the pressure drop and mean oil holdup. Ghorai and Nigam (2006) simulated air-water wavy regime flow also with the VOF method. They evaluated the pressure drop, velocity profiles and interfacial roughness at different superficial velocities, developing a correlation for the ratio between the interfacial friction factor and the wall friction factor.

Lu *et al.* (2007) used the VOF formulation to simulated gas-oil horizontal flows, obtaining the stratified, wavy and slug regimes. Surface tension was modeled through the CSF model. They compared the numerical results of pressure drop with own experimental data. De Schepper *et al.* (2008) simulated horizontal gas-liquid flow regimes for air-water and gasoil liquid-vapor mixtures with the VOF methodology. They obtained numerical results of phase distribution for bubble, stratified, wavy, plug, slug, annular and dispersed flow patterns. The PLIC algorithm was used to capture the interface shape and evolution. Parvareh *et al.* (2010) conducted simulations of air-water horizontal and vertical flow regimes using the VOF method. The calculated phase distributions associated with the stratified, slug and annular patterns were compared to experimental observations obtained through an Electrical Resistance Tomography (ERT) system. Ratkovich *et al.* (2012) simulated vertical slug flows with Newtonian and non-Newtonian mixtures for different inlet superficial velocities. The VOF formulation was also applied. Surface tension force was represented through CSF model and turbulence was accounted through the k-epsilon model. Results of void fraction were compared to correlations present in the literature and own experimental data.

In the present work, the VOF method implemented in the commercial finite-volume-based code FLUENT was used to simulate the stratified, horizontal plug and vertical slug patterns. The Baker chart (Fig. 2) and the Taitel & Dukler regime map (Fig. 3) were used in order to determine the operational conditions for the horizontal and vertical cases respectively. The calculated phases spatial distributions and the interface shapes were compared to experimental observations available in the literature.

2. MULTIPHASE FLOW MODELING

Hirt and Nichols (1981) derived the VOF formulation, which is based on a scalar indicator function with values between 0 and 1 to distinguish between distinct immiscible fluids. The application of the VOF method is recommended in situations where the interface between the fluids is much larger than the computational mesh cell; around $4-9$ cells are required to compose a bi-dimensional round bubble. Hence, small bubbles such as the ones present in bubble flows are not suitable to be identified by the VOF method unless a very fine computational grid is used.

In a two-phase mixture simulation through VOF modeling, a value of zero indicates presence of one phase and a unity value represents the other phase. The values between them indicate the presence of an interface and measure the relative concentration of the fluids. In general, the approach of applying volume fractions is computationally more economical than using markers following the interface since only one value is assigned to each computational cell (Yeoh and Tu, 2010). Other advantage of the VOF method is that only one conservation equation is required to be solved for the evolution of the volume fraction field throughout the domain, in addition to a single set of mass and momentum conservation equations.

2.1 Governing equations

In the VOF formulation, all the fluids share a single set of governing equations. The mass and momentum conservation equations are given as:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0 \tag{1}$$

$$\frac{\partial (\rho \mathbf{U})}{\partial t} + \nabla \cdot (\rho \mathbf{U}\mathbf{U}) = -\nabla p + \nabla \cdot \underline{\mathbf{T}} + \rho \mathbf{g} + \mathbf{F}_\sigma \tag{2}$$

where ρ is the mixture density and $\mathbf{U}$ is the mixture velocity vector.

In Eq. (2), the first term on the left hand side (LHS) indicates the rate of increase in momentum per unit volume while the second term represents change in momentum due to convection. First term on the right hand side (RHS) is the pressure gradient; second term represents viscous and turbulent effects contribution; third term is the gravitational force per unit volume and last term gathers the interfacial forces, being represented by the force due to surface tension, which is modeled through the CSF formulation.

For the cells lying at the interface, the mixture density ρ and dynamic viscosity μ are related to the volume fraction α and individual properties of phase k as:

$$\rho = \sum \alpha_k \rho_k, \quad \mu = \frac{\sum \alpha_k \rho_k \mu_k}{\sum \alpha_k \rho_k} \tag{3}$$

Mixture velocity is defined as a combination of phase-weighted and mass-weighted variables:

$$\mathbf{U} = \frac{\sum \alpha_k \rho_k \mathbf{U}_k}{\sum \alpha_k \rho_k} \tag{4}$$

For each additional phase k present in the mixture, an additional transport equation for its volume fraction is included in the calculation:

$$\frac{\partial (\rho \alpha_k)}{\partial t} + \nabla \cdot (\rho \mathbf{U} \alpha_k) = 0 \tag{5}$$

In Eq. 5, first term on LHS is the accumulation while second term represents convection. Equation (5) is solved for $N-1$ phases with the constraint $\sum \alpha_k = 1$.

One drawback of the VOF method is that special interpolation schemes are required while solving the volume fraction advection equation in order to preserve accurate results in the mass conservation equation. The usual advection schemes, such as the Second-order Upwind and the Quadratic Upstream Interpolation for Convective Kinetics (QUICK) algorithms, smear the step profile of the interface over several computational cells due to numerical diffusion (Yeoh and Tu, 2010). To overcome this situation, specific methods such as the Compressive Interface Capturing Scheme for Arbitrary Meshes (CICSAM) scheme (Ubbink, 1997) or line techniques are needed. In this study, the Piecewise Linear Interface Construction (PLIC) algorithm, a line technique first proposed by Youngs (1982), was applied due to its ability to render a sharp and well-defined interface without numerical diffusion (Yeoh and Tu, 2010). This scheme is briefly presented next.

2.2 Near-interface treatment

The PLIC algorithm relies on the construction of a sequence of discontinuous oblique or piecewise line segments/planes to represent the interface between the fluids. Firstly, the slope of the segment/plane is determined by the interface normal usually obtained from the volume fraction gradients. The next step of the scheme is to position the segment/surface in a way such that the volume of the resultant polygon formed by the segment/plane and cell faces is equal to the volume fraction of the mesh cell under evaluation. From this polygon, fluid mass fluxes are then calculated through the cell sides. Finally, the volume fraction in the cell is updated from the balance of fluid fluxes calculated in the previous step. Figure 4 illustrates an example of interface reconstructed by the PLIC method.

By means of the PLIC scheme, volume fraction fields physically bounded by the constraints of values between $0-1$ can be obtained while capturing a clear interface, essential for getting adequate results with the VOF formulation.

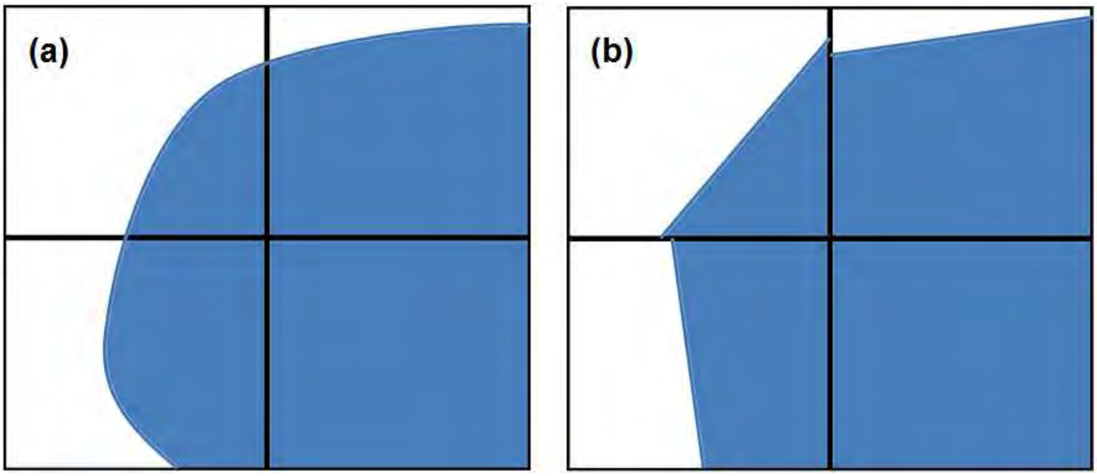


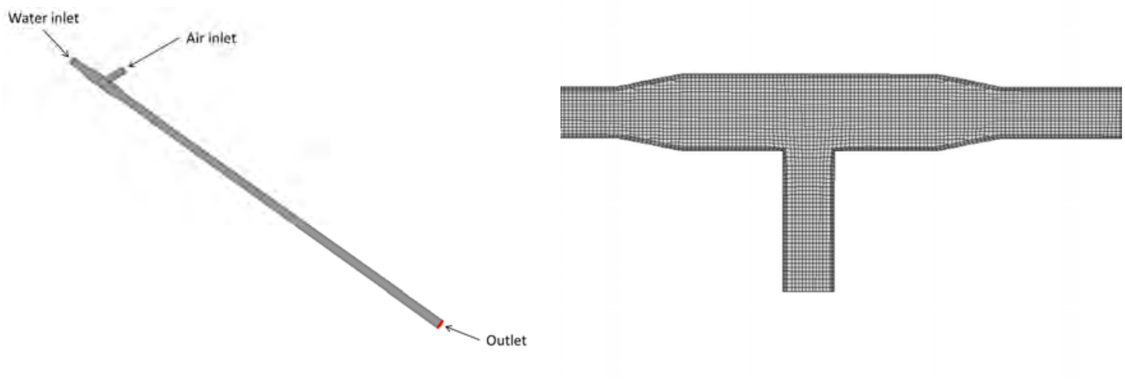
Figure 4. Interface reconstruction: (a) actual interface shape, (b) interface reconstructed through PLIC algorithm.

3. SIMULATIONS

The VOF method allied to the PLIC algorithm was used to simulate stratified, horizontal plug and vertical slug flows in three-dimensional domains.

3.1 Computational domain and boundary conditions

The three-dimensional geometry under study consisted of a mixer with two inlets connected to a $D = 50\,mm$ internal diameter straight duct with length $L = 50D$ as shown in Fig. 5(a). The domain was discretized in hexahedral cells with prismatic elements in the region close to the wall to adequately capture near-wall gradients. Mesh size is around 363,500 cells and portion of the mixer region grid can be observed in Fig. 5(b).



(a) (b)

Figure 5. (a) Mixer with tube geometry; (b) hexahedral mesh of the mixer region.

Air and water enters through the separate inlets with the properties shown in Tab. 1. Uniform velocity profiles are defined at the inlets with the mean velocities determined by the Baker and Taitel & Dukler regime maps according to the case being simulated. Table 2 shows the inlet velocity values for each calculated flow regime. Surface tension coefficient is assumed constant as $0.07\,N/m$. Gravitational acceleration vector, with magnitude equal to $g = 9.81\,m/s^2$, is considered accordingly to the simulated case: transversal to the tube length for horizontal flow patterns and longitudinal to the tube length for vertical slug flow simulation. Atmospheric pressure is considered at the tube outlet.

Turbulence was considered by means of the Realizable k-epsilon model proposed by Shih *et al.* (1995). Wall functions are used to provide turbulence boundary conditions at smooth walls which experience the no slip condition. Pressure-velocity coupling was calculated via the Pressure Implicit with Splitting of Operators (PISO) algorithm (Issa, 1985). Pressure and velocities values were interpolated by means of a staggered grid method (Ferziger and Peric, 2002). Volume fraction field is calculated with PLIC algorithm while all other variables were interpolated with Second-order Upwind

ISSN 2176-5480

Table 1. Fluid properties.

	Water	Air
$\rho\,[kg/m^3]$	998.2	1.225
$\mu\,[Pa.s]$	$1.0\,e-3$	$1.79\,e-5$

Table 2. Inlet velocity conditions.

Flow Regime	U_{Water}	U_{Air}	Reference Map
Stratified	$0.002\,m/s$	$1.60\,m/s$	Baker chart (Fig. 2)
Horizontal Plug	$0.60\,m/s$	$0.25\,m/s$	Baker chart (Fig. 2)
Vertical Slug	$0.05\,m/s$	$0.5\,m/s$	Taitel & Dukler map (Fig. 3)

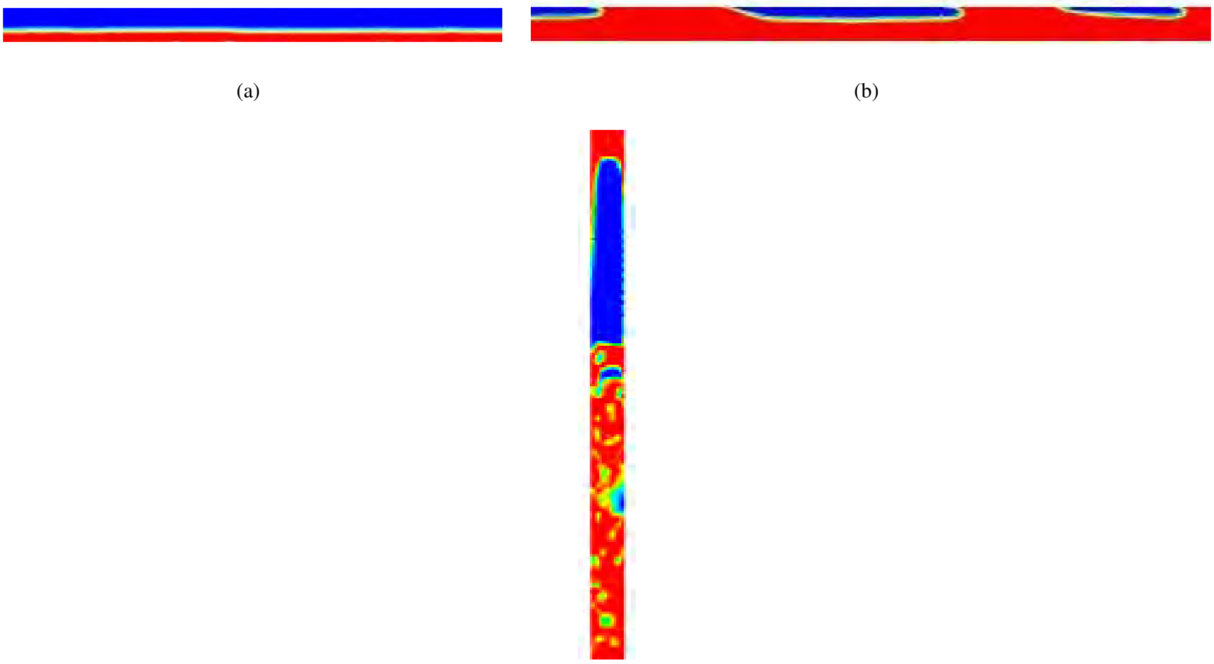
method (Ferziger and Peric, 2002).

3.2 Solution procedure

In a first moment, single phase steady state flows were simulated with convergence criteria being the decay of four orders of magnitude of the normalized residuals and the settling of flow measures such as outlet mass flow rate, mean velocity at the exit and mean wall shear stress. From the obtained pressure and velocities fields, transient calculations were performed considering the injection of the secondary phase. Simulated time was 20 seconds with a time-step of 0.001 second. The phases distribution in the tube longitudinal plane was recorded at a ten time-steps rate, from which the evolution of the interface could be followed and the development of the flow regimes could be observed.

4. RESULTS

The calculated results for the distinct flow patterns can be observed in Fig. 4. The figures show the simulated contours of water volume fraction, with the blue color representing 100% air while the red color indicates regions with 100% water for the three simulated flow patterns. The lines between both colors indicate the presence of an interface.



(a) (b) (c)

Figure 6. Water volume fractions of calculated air-water regimes: (a) stratified; (b) horizontal plug; (c) vertical slug (operational conditions in Tab. 2. Blue color means 100% air, red color represents 100% water.

Figure 6(a) shows the water volume fraction contours of the simulation corresponding to the stratified flow according to the Baker chart (Fig. 2 and Tab. 2). A clear and smooth separation between the fluids can be observed with a continuous layer of water lying in the lower region of the tube and a continuous medium of air flowing in the upper region, characterizing the stratified flow.

The results for the calculated horizontal plug flow according to the Baker regime map (Fig. 2 and Tab. 2) can be found in Fig. 6(b). A intermittent behavior is observed where large elongated air bubbles are formed and, due to gravitational effects, tend to flow in the upper region of the duct. A continuous medium of water can be identified carrying the air bubbles, which is a typical characteristic of the plug flow regime.

Finally, the results for the vertical slug flow are show in Fig. 6(c). Taylor bubbles can clearly be viewed followed by liquid slugs with dispersed small bubbles entrained in it. The oscillatory motion of the liquid phase can be observed in Fig. 7, where the downward flow of water around the air bubble is shown. Through these results, the vertical slug flow can be recognized.

Figure 7. Velocity vectors of water flow around the nose of a Taylor bubble.

5. CONCLUDING REMARKS

Transient simulations of three air-water flow regimes, namely stratified, horizontal plug and vertical slug, were performed with the VOF method. The obtained results of phases distributions for the distinct patterns were in good agreement with experimental observations (Spedding and Spence, 1993), (Spedding *et al.*, 1998) and also with numerical simulations available in the literature (De Schepper *et al.*, 2008), (Parvareh *et al.*, 2010).

The results reveal the ability of the VOF method in handling complex immiscible fluids interactions, such as phase break-up and coalescence. Special attention must be addressed to the volume fraction interpolation scheme; the use of the PLIC interface reconstruction method was essential to adequately determine the location and geometry of the interface and therefore provide meaningful results.

6. ACKNOWLEDGEMENTS

This work was granted by *Petróleo Brasileiro S.A.* (Petrobras). The authors wish to thank to *Agência Nacional do Petróleo* (ANP) and *Conselho Nacional de Desenvolvimento Científico e Tecnológico* (CNPq).

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