EXPERIMENTAL ANALYSIS OF A BUBBLE PLUME IN UPWARD FLOW NEAR A VERTICAL CYLINDER

Maria H. Farias, mhfarias@inmetro.gov.br
Fabio O. Costa, focosta@inmetro.gov.br
Marcos V. Ramos, mvramos@inmetro.gov.br
National Institute of Metrology, Standardization and Industrial Quality - Inmetro
Fluid Dynamics Division- Scientific Metrology – Dinam/Dimci
Av. N. Sra. das Graças, 50 – Predio 06 - Xerém - Duque de Caxias - RJ - Brazil - CEP: 25250-020

Abstract. *A complexity of multi-phase flow mixtures systems is encountered in many industrial applications. Due to the complexity, the hydrodynamic behavior of several types of multi-phase systems must be analyzed almost individually, because although there could be some similarity among a group of systems, a particular detail in kinematics of the flow makes each system different from the other. In special, for applications that involve controlled process of mixtures where plumes or jets are present, the features of the installation for gas or liquid injection points, as well as the geometry where the flow is set, play an important role in the quality of the expected final product. In order to contribute to the understanding of how this kind of mixture process could be optimized, the present work shows the flow characteristics of a single air bubble plume when a vertical surface is close to the upward plume in a stagnant Newtonian fluid. For that, a nozzle for air injection was placed at the bottom of a tank which contains the stagnant fluid. Two surfaces were separately placed near the plume: a flat and a cylindrical. The presence of the solid surface provokes the plume to cling in its direction. By using PIV technique for flow visualization, the field of velocity is investigated for the liquid, in a plane aligned to the symmetry axis of the surfaces, where the nozzle axis passes through simultaneously. The main goal of this work is to analyze the influence of the nearby geometry to the plume behavior. Results show a subtle difference between the resulting liquid flow when the surface close to the plume is flat and when it is convex (but with the longitudinal axis parallel to the nozzle axis). This work is an introductory part of a large campaign that is going be performed pursuing the understanding of a mixing process in order to improve it.*

Keywords*: Air Bubble Plume, PIV, Coanda Effect, Flow Attachment, Vertical Cylinder*

1. INTRODUCTION

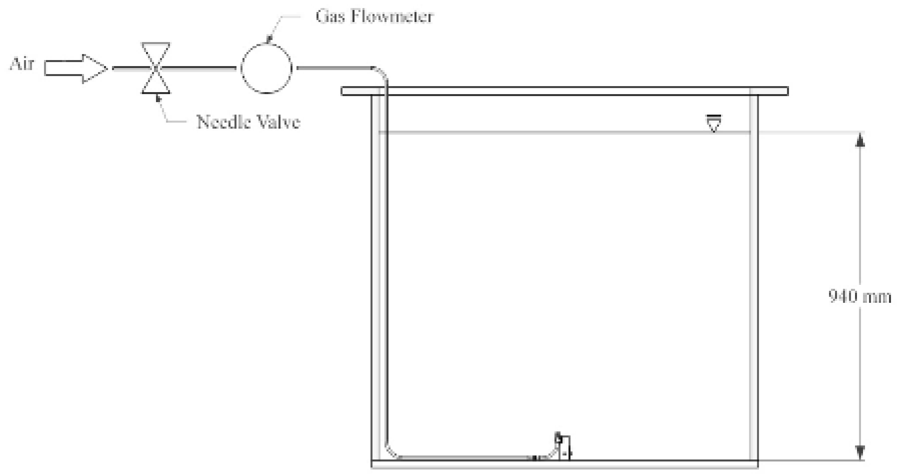
Gas bubble plumes are often present in several industrial processes, such as in chemical plants or nuclear power, where mixing in fluids plays an important role. Many of those applications still claim improvements in the mixing process, which depends on a best knowledge of the physics of the problem. Although in the practice some mixing processes results, which are based on gas bubble plume or jets, are considered acceptable, it is important to investigate the complexity of this kind of flow in order to understand how to control, acquire or predict a certain level of homogeneity in a mixture, in order to increase the quality of the results. The geometry where the bubble plume flow is conducted strongly influences the homogeneity of the resulting mixture of fluids, as the case of concentration. When the plume is near a solid surface, it can cling to the such surface, in a effect known as Coanda. There is a minimum distance of the solid surface to the air injection point (nozzle) above which the Coanda effect is not perceived. A similar behavior can be set between plumes or jets when two or more of them are in proximity to each one, as the case of multiport diffuser used to wastewater discharge into rivers or coastal waters. However, an advantage on using multiport diffusers could not be achieved if the distance between the injection points and their depth in the liquid are not well arranged. This arrangement is not trivial to be defined, due to the complexity of the established flow. In the literature, investigations on the attachment of bubble plumes is not so extensive. Most of the works about bubble plumes are related to axisymmetric condition and the entrainment rate is discussed as the main focus. We can cite some works as that of Neto *et a.l* (2008), whose studied experimentally an air water bubbly jets in stagnant water. They measured the bubble properties and water velocity, and concluded about the importance of the bubble interactions to the dynamics of the bubbly flow. Simiano *et al.* (2006) investigated the hydrodynamics of 3D oscillating bubble plumes inside a tank, by using several measurement techniques. In this case, the plume was generated by several needles. Kaye and Linden (2004) modeled the coalescence of two co-flowing axisymmetric turbulent plumes and compared it with experimental results. A rectangular bubble column was investigated by Liu *et al.* (2005) using PIV, and they analyzed the bubble rising trajectory. Other work is that of Freire *et al.* (2002), in which was analyzed the Coanda effect in a plume adjacent to another plume or a wall. They also present a theory for the plume deflection, based on variable entrainment coefficient.

Articles investigating the plume attachment to a wall, in general, are related to a flat surface. The present work shows an introductory experimental investigation about the air bubble plume clinging to a convex surface (external surface of a cylinder) when the nozzle axis for air injection into a tank with stagnant liquid is near and parallel to the cylinder axis placed inside the tank. The preliminary goal is to understand if a convex geometry shows trends of one bubble plume to provide improvement in a mixing process of a fluid flowing over this solid surface, and to compare it with the case when the surface is flat. The experimental details are explained below.

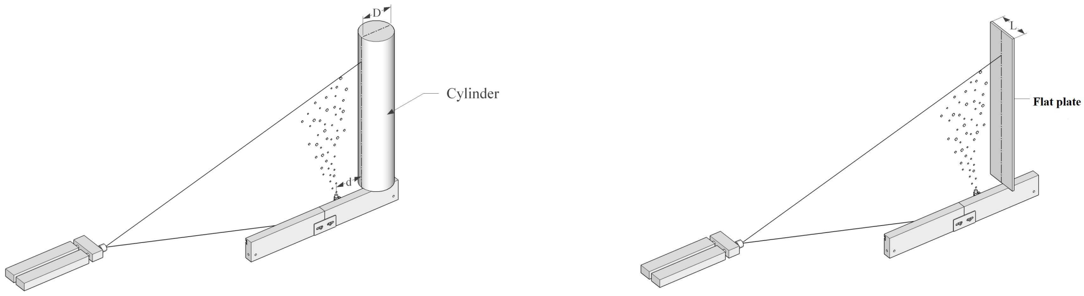
2. EXPERIMENTAL SETUP AND PROCEDURE

This work shows the preliminary measurements of an investigation on a single air bubble plume attachment to a round solid surface, when the environment is a stagnant liquid. Figure 1 illustrates the experimental setup. The bubble plume was produced in a glass-walled tank, with dimensions 1.2 x 1.0 x 1.0 m^3, respectively in height, width and length. Filtered water was the stagnant environment, where the average shallow water was 940mm. At 90 mm of the tank bottom air could be injected into the liquid through a centered round nozzle of 0.3mm in internal diameter. The choice for placing the nozzle in the middle of the tank bottom was for avoiding the influences of the tank wall on the bubble plume behavior. A gas flow meter containing a laminar flow element displayed the flow rate which was controlled by a needle valve, and the air flow rate was maintained in stability. For flow visualization PIV (Particle Image Velocimetry) system was used, where fluorescent particles (Rhodamine B/ PMMA-RhB) with diameter ranging from 20 to 50 µm were put in the liquid. It was used a Nd:YAG Dual Cavity pulsed laser (Big Sky Ultra PIV 120.2 x 120mJ/pulse at 532nm, 15 Hz pulse rate) and the images were taken, in double frames, through two CCD cameras (LaVision, Imager Pro X 2M, 1648 x 1214 pixel resolution, from 30 frames/sec up to 135 frames/sec (at reduced AOI), 110 nsec inter frame time; camera lens Nikon 50mm focal length, 1:1.4D; Scheimpflug camera lens adapter for full 360 degree adjustable) with glass filters (LP 540/50-3, high pass, cut–off at 540nm with effective suppression of 532nm). The hardware components, images acquisition and data processing were controlled by computer (dual-core, dual processor PC, 2Gb RAM , 250Gb HD, DaVis Software version 7.x, 32 bit).

The lower boundary of the image plane that was acquired was positioned 30mm above the nozzle air exit. The images of the flow were taken in four different flow rates and, for each one, three different conditions for the air bubble plume in upward flowing: i) axisymmetric air bubble plume; ii) bubble plume near to vertical cylinder and iii) bubble plume near to vertical flat plate. In all these configurations, the laser plane of the PIV system was vertically positioned , aligned to the air nozzle longitudinal axis. The laser plane passes through the air injection point center cutting the symmetry axis of the solid geometries. Figures 1b and 1c show the schematic of such solid surfaces set near the nozzle, as well the incidence direction of the laser sheet. As the solid surfaces were in Plexiglas, the laser plane crossed the flat plate and the cylinder when each one was both inside the tank and aside the nozzle. Tab. 1 summarizes the experimental conditions for the measurements. Although the measurements were performed on four flow rates, only the results for two of those are presented in this article, as it is considered sufficiently representative for an introductory analysis.



a)



b) c)

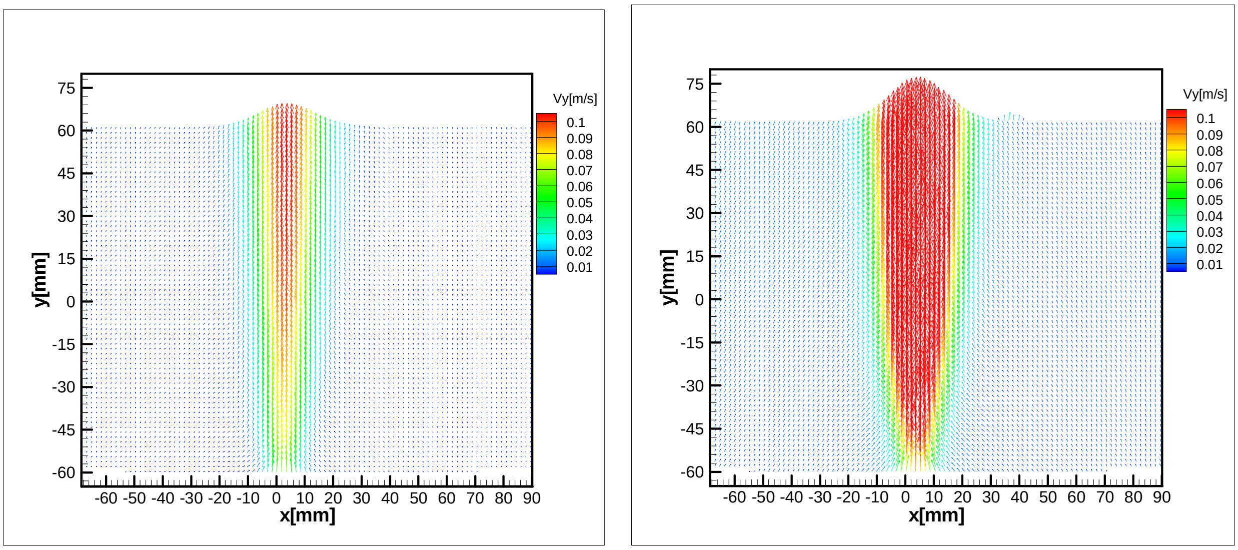
Figure 1- Schematic of experimental set up: a) tank; b and c) laser sheet on the solid surfaces

Table 1. Measurement conditions

Nozzle	**Solid surfaces**		**Horizontal distance from the nozzle axis to the solid surfaces**	**Average air flow rate**
Stainless steel	**Flat plate**	**Cylinder**		0.072Lpm
	Plexiglas	Plexiglas	d=19mm	0.140Lpm
Round, I.D = 0.3mm	L=25.4mm	E.D = 25.4mm	(see Fig. 1)	0.283Lpm
	H (submerged) = 940mm	H (submerged) = 940mm		0.333Lpm
• For each flow rate the Stereo PIV was used and 1190 images were recorded in double frame. The results were processed with interrogation window size of 32x 32 pixels .				

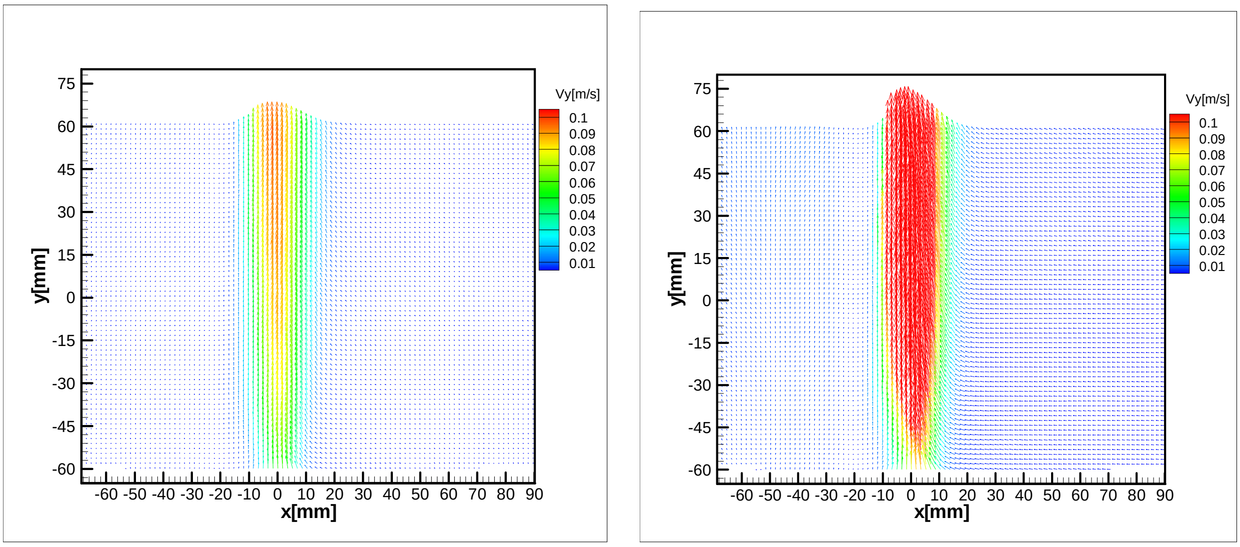
3. RESULTS AND DISCUSSION

During the experimental execution, only after all flow rates were applied for each configuration of the plume cited above, such configuration was later changed to another one. The region of the plane which was selected to be visualized by the cameras is about 160x 160mm, but the main focus was in its central area because there passed the plume and the surfaces. In the pictures below, Vx, Vy, and Vz are the components of the velocity vector in the Cartesian coordinate system, in which the vertical direction is y (upward is positive) and the horizontal is x (positive to the right). The Figs 2 to 4 show the averaged field of velocity of the liquid for those three cases of bubble plume under investigation, and as mentioned before, for only two different flow rates.



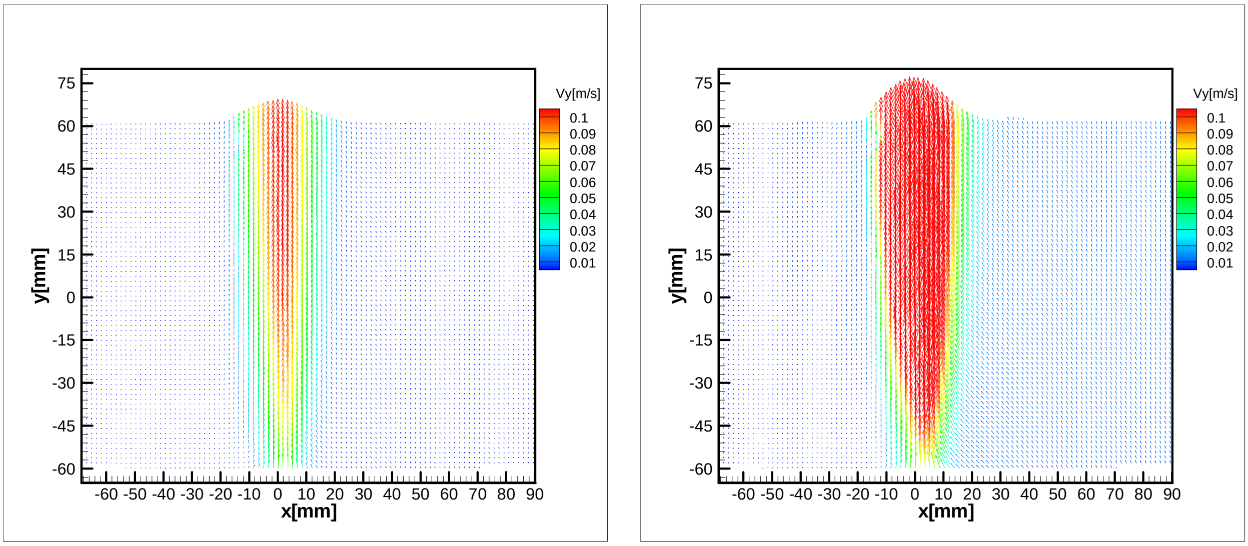
a) b)

Figure 2 - Axisymmetric bubble plume. Average of the velocity field for liquid phase.
a) Air flow rate: 0.072 Lpm . b) Air flow rate: 0.283 Lpm



a) b)

Figure 3 - Bubble Plume when the flat plate is near the nozzle. Average of the velocity field for liquid phase.
a) Air flow rate: 0.072 Lpm . b) Air flow rate: 0.283 Lpm

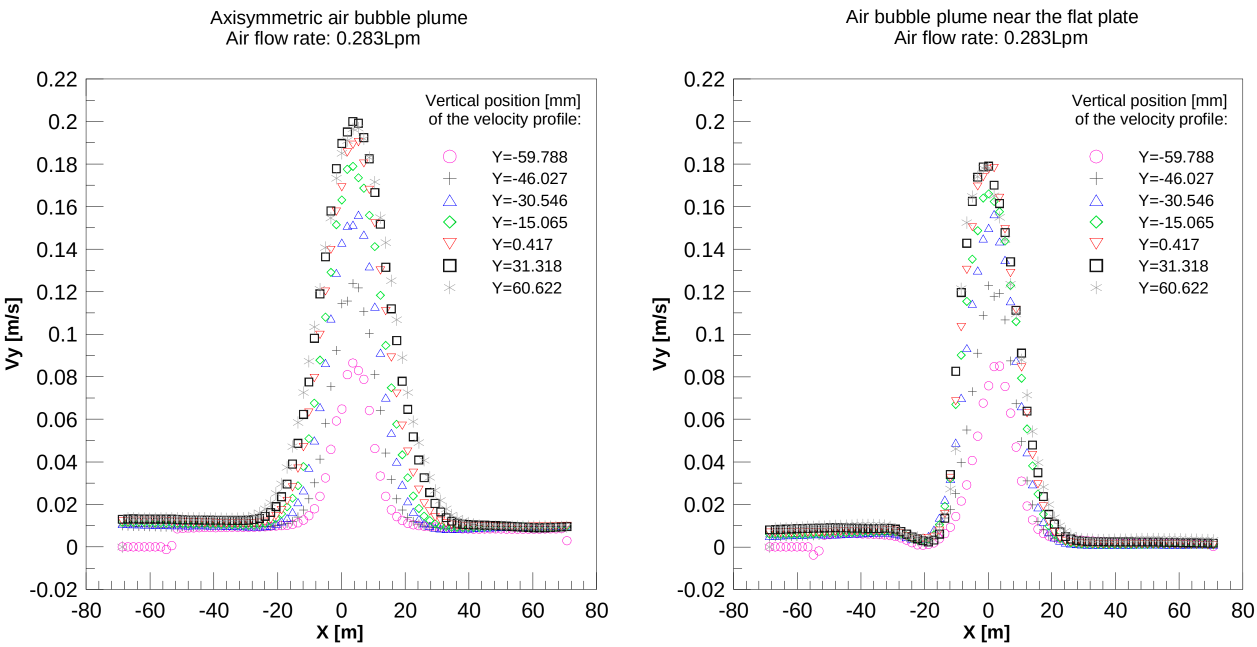


a) b)

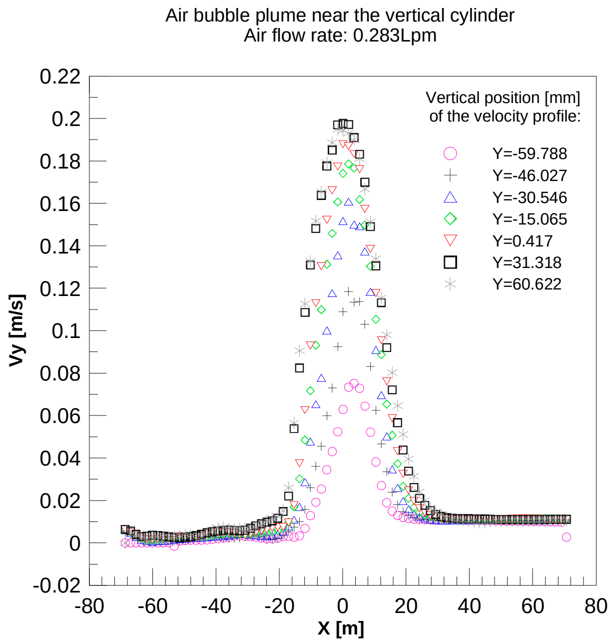
Figure 4 - Bubble Plume when the cylinder is near the nozzle. Average of the velocity field for liquid phase.

a) Air flow rate: 0.072 Lpm . b) Air flow rate: 0.283 Lpm

Based on these figures, the effects of the presence of the solid surfaces near the air injection point is clear, the air bubble plume clings to the flat and to the cylindrical surfaces. This causes the velocity profile be narrower than it is when the plume is axisymmetric. Due to these effects, when the plume is near a surface, it is mainly observed a little more concentration of the highest values of the velocity vectors Vy in horizontal positions near such surfaces. Otherwise, the axisymmetric plume evidences a symmetric overture of the velocity profile while the distance of the air injection point is increased, and shows a Gaussian distribution. In order to emphasize the difference between the centerline behavior of the plume when it is close to a flat surface and when this occurs with a cylinder, seven positions in the vertical direction were chosen to remark the velocity profiles. The heights values indicated in the next pictures were chosen between the values available in the table of processed results made by the software of PIV system. The reference point of the scale (zero) is in the middle of the vertical plane. Upward is positive. It is important also to highlight that the lowest horizontal line of the plane visualized by the cameras was 30mm above the air injection point. So, the reader can attempt to the difference between the flow behavior in the three configurations of the plume in the lowest region of the visualization plane. That region shows the vertical position where the Coanda phenomenon is evident.

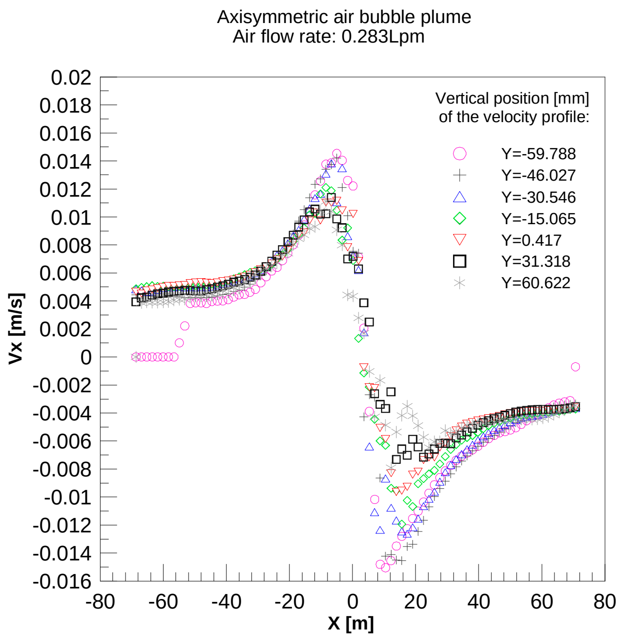


a) b)

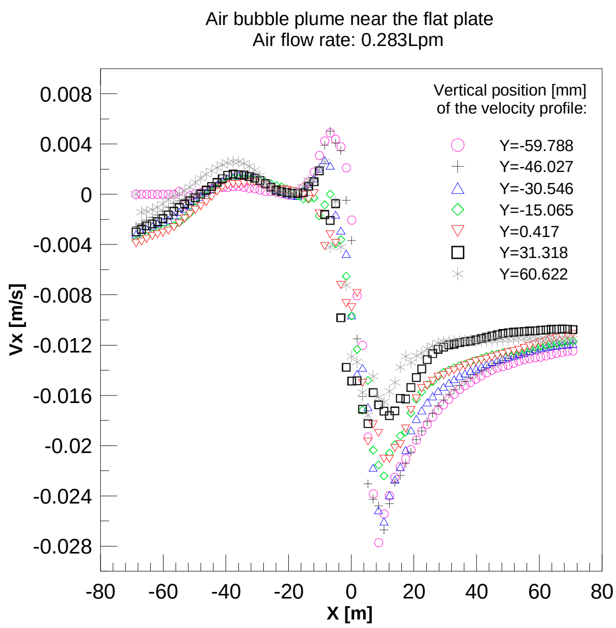


c)

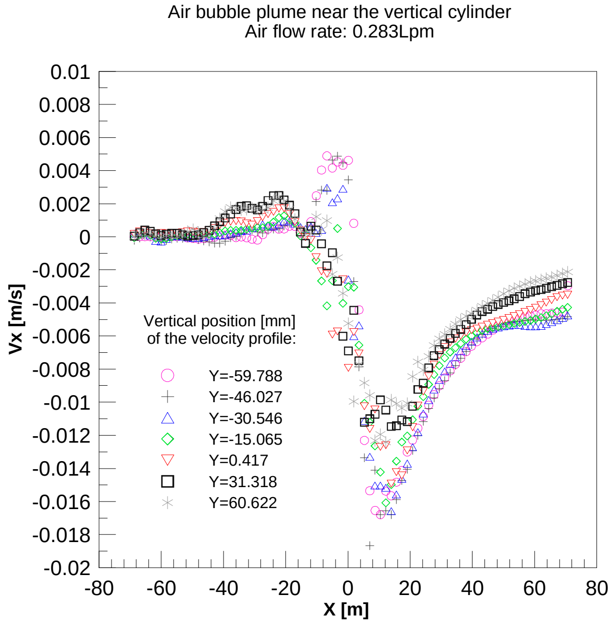
Figure 5- Velocity profile **Vy** of the liquid along the plane of the laser sheet, in several height **Y**. Air flow rate: 0.283Lpm. a) Axisymmetric bubble plume; b) Flat plate near the nozzle; c) Cylinder near the nozzle;



a)

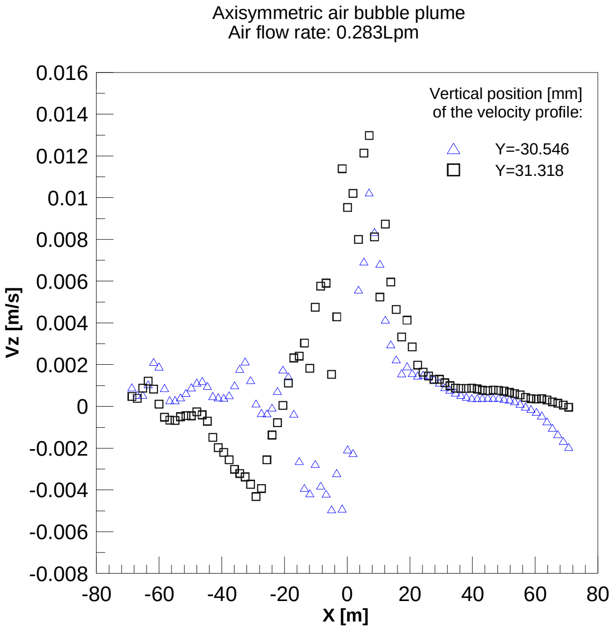


b)

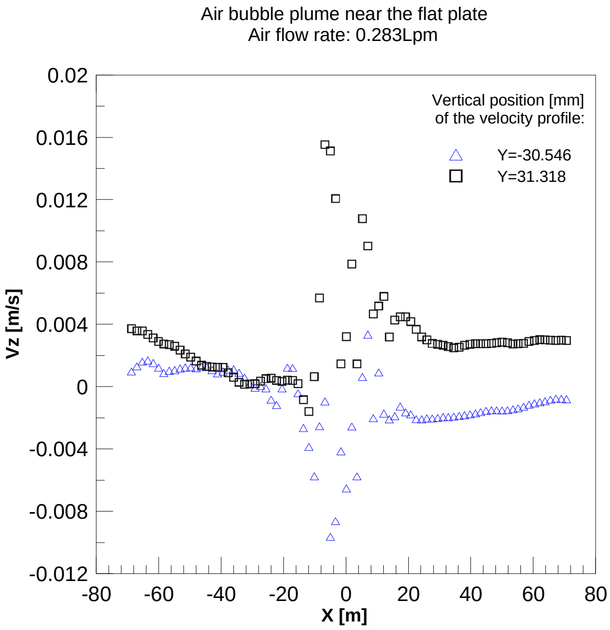


c)

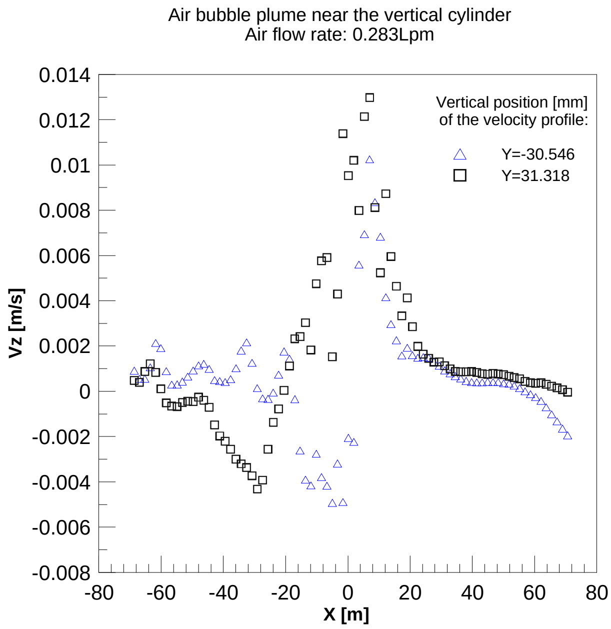
Figure 6 - Velocity profile **Vx** of the liquid along the plane of the laser sheet, in several height **Y**. Air flow rate 0.283Lpm . a) Axisymmetric bubble plume; b). Flat plate near the nozzle; c) Cylinder near the nozzle.



a)



b)



c)

Figure 7- Velocity profile **Vz** of the liquid along the plane of the laser sheet, in two different height **Y**. Air flow rate 0.283Lpm . a) Axisymmetric bubble plume; b). Flat plate near the nozzle; c) Cylinder near the nozzle.

According to the Figs. 5, for a same flow rate, it is clear the difference between the axisymmetric bubble plume behavior and the other configurations of the plume. Nevertheless, for the flow rate range here studied, in the vertical plane of characterization analized the differences between the plume behaviors are not immediately obvious when it is close to the flat plate and when it is close to the cylinder

In the Figs. 6 and 7, which show the horizontal velocity profiles, as the vertical distance of the air injection point to a certain horizontal plane considered increases, we can see that in the investigated vertical plane the attraction of the bubble plume by the solid surface is a little more intense when the surface is flat than when it is convex. On the other hand, the trends of the velocity profiles in z direction, considering a certain vertical position on the plume axis while traveling on the x axis direction, show that the plume "opens" more when the bubble is attracted by a cylindrical geometry than by a flat one. One reason for this effect is that, in the case of vertical cylinder placed parallel to a bubble plume, part of the bubble experiences the tendency of being attracted to the surface, but as the surface is circular, the bubble comes off while coming up, because traveling around a circular section, the bubble detaches from the surface in a certain angle. The consequence of this fact could be perceived clearly during the experiments, since, at the horizontal plane of the free surface of the liquid, the size of the region of bubbles which still were close to the solid surface was smaller when such surface was cylindrical than when it was flat. On that horizontal plane, the group of bubbles attached to the cylinder could cover less than a half of the cylinder circumference, while in the case of the flat plate, all width of the plate was covered by bubbles attached to it. Such effect can also be observed by Figs. 2 and 3, where the velocity profile of the plume close to the flat plate is narrower than it is when close to the cylinder, mainly near the free surface of the liquid, showing that the liquid moves faster very close to the flat plate than it moves when it is close to the cylinder.

4. CONCLUSION

Experiments with air bubble plume inside a square tank were conducted in a stagnant environment for three different conditions of the plume: axisymmetric, near a flat plate and near a cylinder. The cited geometries were placed close to the air injection point, in the vertical position inside the tank. Stereoscopic Particle Image Velocimetry (PIV) technique was used in the experiments and the present work reports the results of flow visualization for two different air flow rates injected at the tank bottom for bubble plume generation. Qualitative differences between the behaviors of the plume flow under the three conditions of the air injection point neighborhood could be seen, although only one position of the laser plane of the PIV system was considered in this introductory study. It was observed a clear difference between the velocity profiles of the liquid when the plume was axisymmetric and when there was a solid surface near the air injector. However, in the vertical analyzed plane, the difference between the impact to the liquid flow due to the behavior of the air bubble plume generated near the flat plate and near the cylinder is subtle, but it cannot be neglected at all.

The results here reported are the initial part of a campaign of experiments which pursues a best understanding of the mixing processes due to upward bubble plume flowing along vertical cylindrical surface. Several industrial processes use this kind of mixing mechanism on that geometry, and the knowledge of the process in details can provide best control and results in the homogeneity of such mixtures. In the continuity of this investigation, measurements in several vertical planes and also in planes crossed to the plume axis will be performed for the same conditions which were studied here.

5. ACKNOWLEDGEMENTS

The authors are grateful to FAPERJ, FINEP, CNPq, Petrobras and Inmetro for the financial support.

6. REFERENCES

Neto, I.E.L, Zhu, D.Z. and Rajaratnam, N., 2008, “Bubbly jets in stagnant water”, International Journal of Multiphase Flow, No.12, Vol. 34, pp. 1130–1141.

Simiano, M., Zboray, R., Cachard, F., Lakehal, D. and Yadigaroglu, G., 2006, “Comprehensive experimental hydrodynamics of large-scale, 3D oscullating bubble plumes”, Intenational Journal of Multiphase Flow, Vol.32, No.10-11, pp. 1160-1181.

Kaye, N.B. and Linden, P.F., 2004, “Coalescing axisymmetric turbulent plumes”, Journal of Fluid Mechanics, Vol. 502, pp. 41–63.

Liu, Z., Zheng, Y., Jia, L. and Zhang, Q., 2005, “Study of bubble induced flow structure using PIV”, Chemical Engineering Science, Vol. 60, No.2, pp 3537 – 3552.

Freire, A.P. S., Miranda, D.D., Luz, L. M. S. and França, G. F. M, 2002, “ Bubble plumes and the Coanda effect”, International Journal of Multiphase Flow, Vol. 28, No.8, pp. 1293–1310.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.