EXPERIMENTAL STUDIES ON AIR BUBBLE PLUMES IN CROSSFLOW

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Abstract. Air bubble plumes and jets often are found in several industrial, technological and natural processes. Mixing of buoyancy, momentum and meandering effects are present in such flows. Due to the complexity of this flows, both experimental and theoretical investigations on the entrainment process are needed for improving the phenomena comprehension. In the present work, the hydrodynamics of air bubble plumes in crossflow inside an open water channel is discussed. Experimental studies were performed in the Circulating Water Channel of the Brazilian National Institute of Metrology, Quality and Technology-Inmetro. Single and multiple air injection nozzles were placed tangent to the water channel bottom surface, crossing the channel longitudinal axis. Particle Image Velocimetry technique was used for flow visualization and velocity field measurement. Velocity profile disturbances within the boundary layer, due to air injection, were analized. Furthermore, it was evaluated the plume bending and the fluid velocity behavior in different zones of the flow which is affected by the plume.

Keywords: air bubble plumes, plumes and jets in crossflow, particle image velocimetry

1. INTRODUCTION

Air bubble plumes and jets (Kobus, 1968; Rodi, 1982; Lee and Chu, 2003; Duarte et.al, 2007; Weiland and Vlachos, 2013) are types of flows which are present in several industrial, technological and natural processes. In recent years, these flows have been attracting significant attention due to the similarity of their behavior with blowouts that occur in the oil and gas industry (Mcnutt et al., 2012). Oil and gas spills in subsea generate strong impact in the environment, near and far from the leakage source, since the ocean currents provoke spreading of the leaking fluid, causing losses of fauna and marine flora, changing water quality, among others damages.

Gas and liquid generate complex flows (jet or plume in crossflow) when they are discharged on seabed (Dasanayaka and Yapa, 2009; Yapa et al., 2012). Due to the complexity of these flows and the variety of the way in which they can occur, there is much to be investigated, by scientific and metrological approaches.

This work has the purpose of investigating, experimentally, aspects of the behavior of air bubble plumes in crossflow. The experiments were conducted in the "Circulating Water Channel - CWC" (Alho et al., 2010) which belongs to the Fluid Dynamics Metrology Division (Dinam) of the National Institute of Metrology, Quality and Technology (Inmetro). The Particle Image Velocimetry (PIV) technique was employed for flow visualization and for velocity field measurement. Ocean currents (mean velocity 0.15 m/s) were simulated in the channel, and the gas leakage was simulated by injecting compressed air through three circular nozzles, which were arranged in series and attached to the channel floor.

The mixture processes and environmental themes are subjects which have received more attention, and the Inmetro's circulating water channel has the purpose of being a tool for these studies. In this work, the initial studies on crossflow can be associated to the dynamics of events such as those which occurs in bubble curtain systems (Naderi et al., 2013) or flows on submerged vegetations (Nikora and Nikora, 2010), as examples. Bubble curtains are gas barriers systems used for minimizing the mixture of fluid currents, contaminants dispersion, for breaking waves etc. It can be placed in rivers, estuaries etc. Submerged vegetations are very important resources for pollution control of water bodies. The vegetation acts as a filter in the environment, and its efficiency depends on the distribution, size and position of the vegetation in the aquatic ambient. In environmental flows, the boundary layer thickness generated in the main flow interferes on the resulting process, and this is an issue discussed in the present work.

2. THE CIRCULATING WATER CHANNEL

2.1 Facility Details

The Inmetro's Circulating Water Channel (CWC) (Fig.1a) has an innovative design (Alho et al., 2010; Santos et al, 2016). It was designed to be used in scientific and metrological investigations (Garcia, 2015), for dealing with hydrodynamics and metrological traceability dissemination issues. It has a long visualization window (12 m in length) made in glass, through which is possible to observe and to measure the flow at any position along the channel. The cross section is 0.60 m in wide and 0.70 m in height. A centrifugal pump (30 kW) drives the flow, and the maximum flow rate is 648 m³/h (with maximum mean velocity 0.5 m/s for water column 0.6 m). At the channel entrance region, an accommodation section contains flow straighteners and two stainless steel screens (one has 10.59 mm mesh aperture (square) and wire diameter 2.1 mm, while other has 5.31 mm mesh aperture (square) and 1.06 mm wire diameter). At the channel exit region, customized waves suppressors were installed in order to prevent stationary waves formation inside the channel (Santos et al., 2016).

The channel floor is made of glass, however, for this work, PVC flat plates were installed on the bottom ("false floor"), as shown in Figs. 1a and 1c, due to the need of installing air injection points tangent to the channel floor. In this work, three circular nozzles (1 mm in diameter) for compressed air injection were placed as shown in Fig.1b (highlighted in red color). Care was taken to ensure a flat floor, for avoiding effects of small steps on the flow.
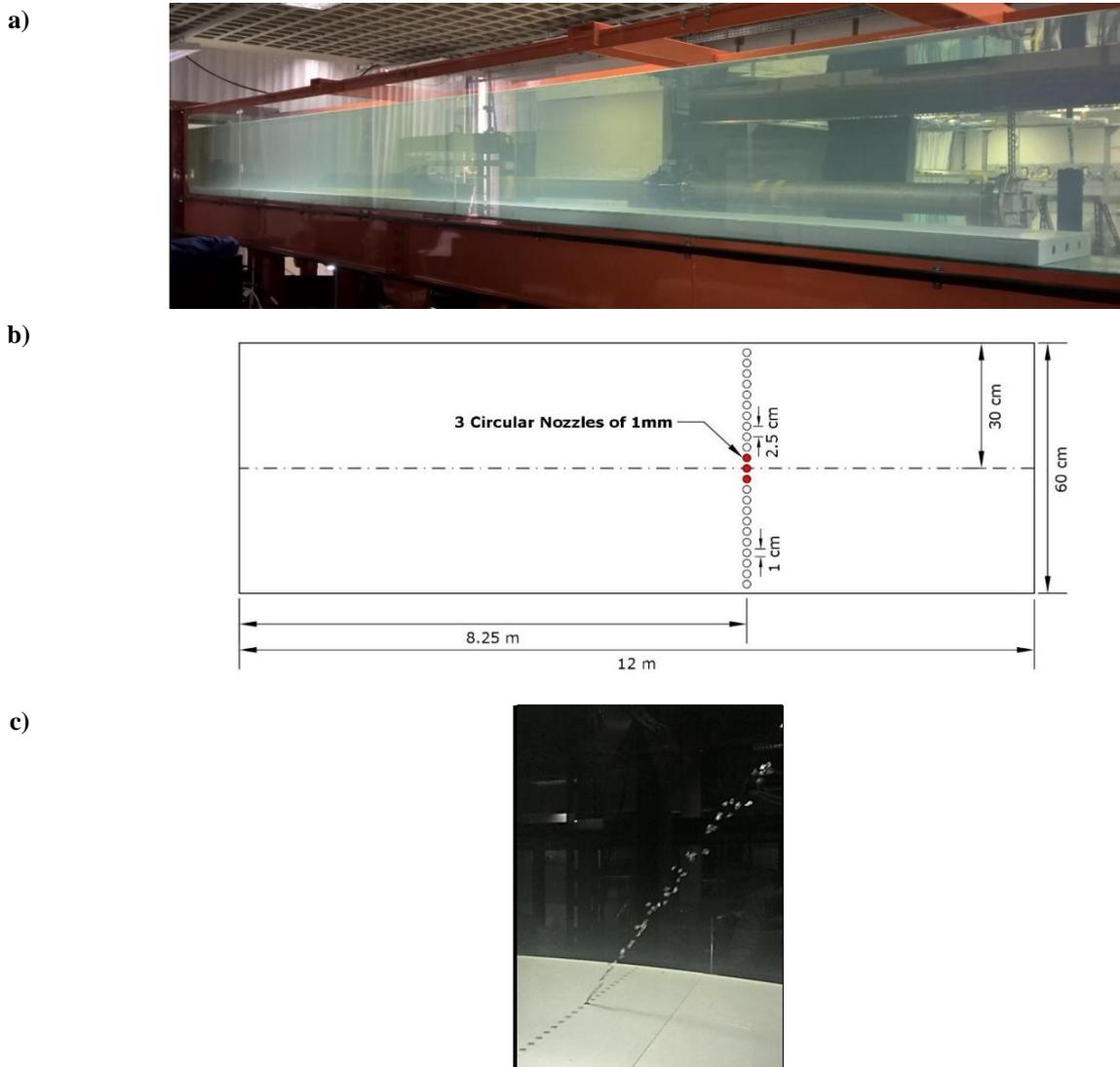
a)

b)

c)

Figure 1. **a)** The Circulating Water Channel of Inmetro; **b)** PVC plate dimensions and the three circular nozzles (highlighted in red color); **c)** Nozzle of 1 mm in diameter, installed in the PVC false floor.

As the water channel of Inmetro was thought to be a bench for using in calibrations (ISO, 2007), as well as for investigations in hydrodynamics, the most important focus was to seek for conditions of getting the velocity field as close as possible of an uniform profile at the channel entrance, within the flowrate range of the channel operation. This was an important aim since metrological application of the CWC is expected. So, this meant to work carefully on accessories calculation, mainly on those which would be introduced in the bench accommodation and entrance regions. But as it is known, differences between the bench as designed and as it is after constructed can exist, and the bench use limitations will depend on its actual performance.

3. EXPERIMENT

3.1 Measurement Technique

The PIV technique (Raffel et al., 2007), from LaVision ®, 2D, was used to measure the flow velocity field. The light source was furnished by a double pulsed Nd:YAG laser that produced short duration (5 ns) high energy (120 mJ) pulses of green light (532 nm). The tracer particles seeded in the flow were silver coated hollow glass spheres, with a density of approximately 0.9 g/cm³ and mean diameter 17 μm. The flow images were captured in a frequency of 15 Hz by a CCD camera with 1600 x 1200 pixels and 14-bit in resolution. The camera was fitted with a AF Nikkor 50 mm f/1.4D lens and an optical low-pass filter (cut-off at 532 nm). In each run of measurement were captured 2000 images, in double frame with inter-frame time of 5500 μs.

Since the channel bottom had been recovered with no transparent plates (PVC), the laser incidence on the flow was made through the upper edge of the channel, with the light source positioned (tilted approximately 50°) on the top and then illuminating the central nozzle of the bottom, as shown in Fig. 2. However, as the free surface oscillation would interfere in the light sheet behavior, an acrylic device (500 mm x 100 mm x 55 mm), Fig 3a., was laid on a certain part of the water surface, in such a way that the laser light could cross this device and not be affected by the free surface oscillations. The acrylic device did not provoke significant interference in the flow at the studied region. Figure 3b shows the camera, which was positioned perpendicularly to the channel wall and 51 cm away from the measurement plane.
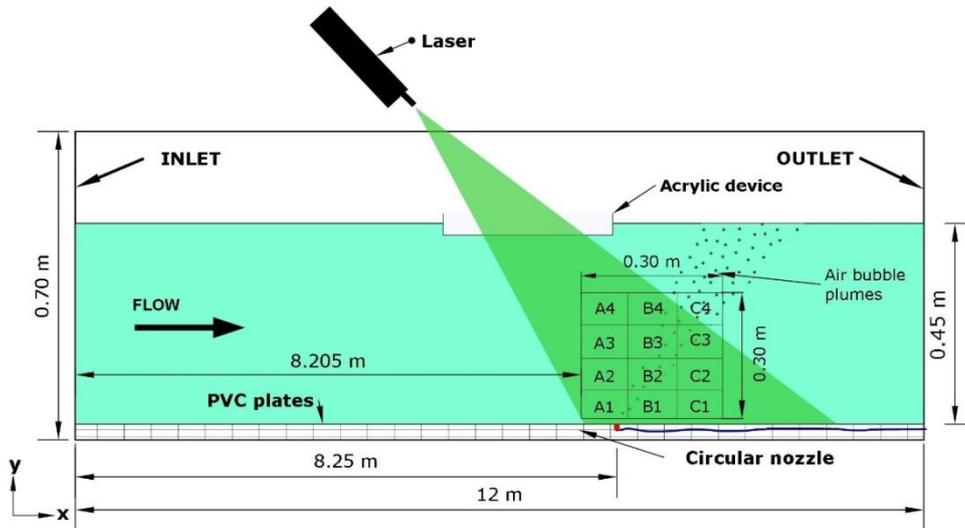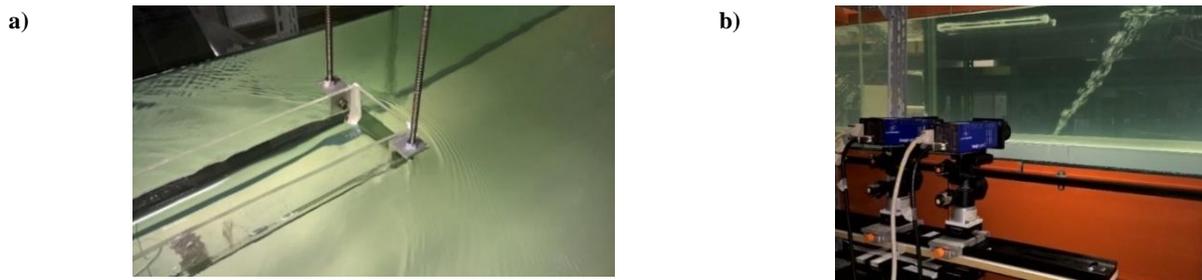

Figure 2. Schematic of experimental setup.

Figure 3. **a)** Acrylic device in the CWC; **b)** Camera localization.

3.2 Experimental Procedure and Conditions

In the experiments, the environment fluid was water under a column of 450 mm. The studied region was divided in 12 small regions (A1 to C4), Fig. 2, which were individually mapped. At the end, the small regions were put together for mapping the air bubble plume region and its vicinity. The measuring reagion covered a vertical plane (30 mm x 30 mm) placed on the channel centerline, 10 mm far from the channel bottom and 8.25 m away from the channel entrance (see Fig. 2). The measurements were carried out under the following conditions: *i)* no crossflow; *ii)* crossflow due to a single air discharge into the main flow; *iii)* crossflow generated by three points of air discharge into the main flow. The air flowrate of each injector was individually monitored by calibrated thermal mass flowmeters, which indicate values referenced to standard conditions, i.e., 21 °C and 1 atm. Air pressure in the supply line was maintained in 6 bar. A calibrated electromagnetic flowmeter monitored the water flowrate. The Table 1 shows the references values for velocity range of the main flow and air injection, which were based on the works of Yapa et al. (2012), McNutt et al. (2012), Zhang (2012) and Zhang and Zhu (2014). In this table, the air velocity and respective Reynolds number were calculated as referenced to standard conditions.

Table 1. Flow conditions.

	Water Flow Rate [m³/h]	Air Flow Rate [SL/min]	Section Area [m²]	Calculated Velocity [m/s]	Reynolds Number Re
Mean Flow	147	----	0.27	0.15	$\cong 122000$
Compressed Air Injection per Nozzle	----	0.70	7.85×10^{-7}	$\cong 15$	$\cong 980$

4. RESULTS AND DISCUSSION

In the following charts, the nozzles are located at $x = 10\ mm$ and $y = 0\ mm$ position. Figure 4a shows the velocity field of the main flow without crossflow. It was observed that the boundary layer thickness was around 150 mm, since above 150 mm the velocity was uniform. Besides that, it was concluded that in this measuring region the main flow was developed, since the velocity Vx profiles are coincident for different horizontal positions, as shown in Figure 4b.
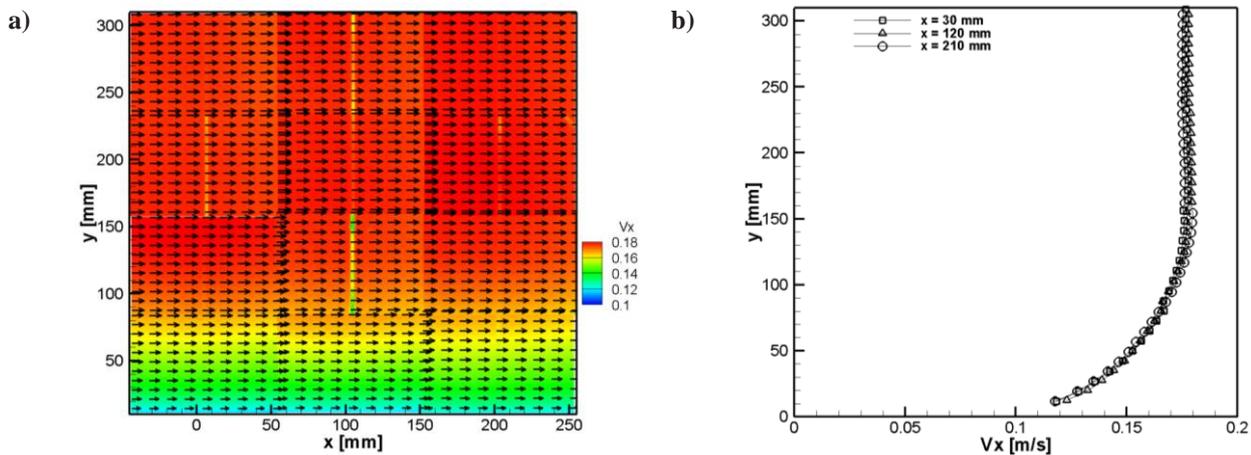

Figure 4. **a)** Velocity field of the main flow, in m/s; **b)** Boundary layer profile at x = 30, 120 and 210 mm.

Figures 5a and 5b show, respectively, the velocity field when air is injected into the channel by single and three nozzles. With a single nozzle (Fig. 5a), the maximum value of the vertical component of the water velocity was around 0.11 m/s along the plume axis, while the minimum was around 0 m/s in the region outside the crossflow (i.e., the liquid moving upward was very slow). When injecting air through three nozzles (Fig. 5b), the maximum vertical velocity of the liquid was approximately 0.14 m/s along the plume axis, and the minimum was -0.01 m/s in the region close to the injection point, indicating that the liquid was moving down and slowly.

Based on the graphs of figure 5, as first analysis one could say that the flow pattern in the channel was not changed after the number of air injector was increased while was maintained the same air flowrate in all injectors. However, an analysis of the horizontal velocity profile in determined positions of the flow section must be considered, as shown in Fig. 6.
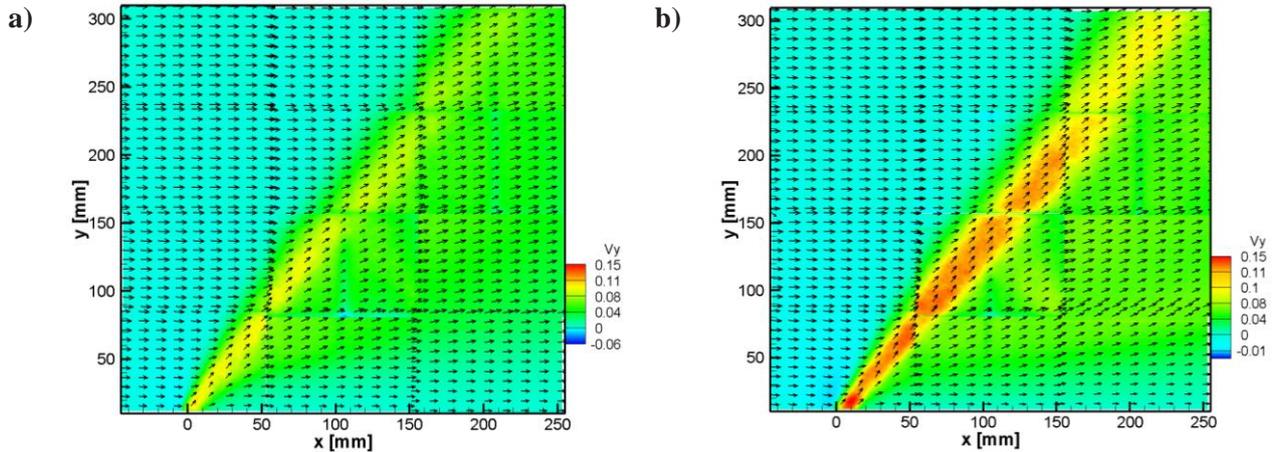
a)

b)

Figure 5. Velocity field of the flow under **a)** crossflow due to single point of air injection **b)** crossflow due to three points of air injection. The color scale shows the vertical velocity (Vy) level, in m/s.

The Figure 6 depictures the behavior of the flow inside the bottom boundary layer, in three different cross sections along the channel axis, including upstream and downstream the air injection point (remind that the nozzles are located at x = 10 mm and y = 0 mm position).

a)

x = -30 mm

b)

x = 10 mm

c)

x = 50 mm
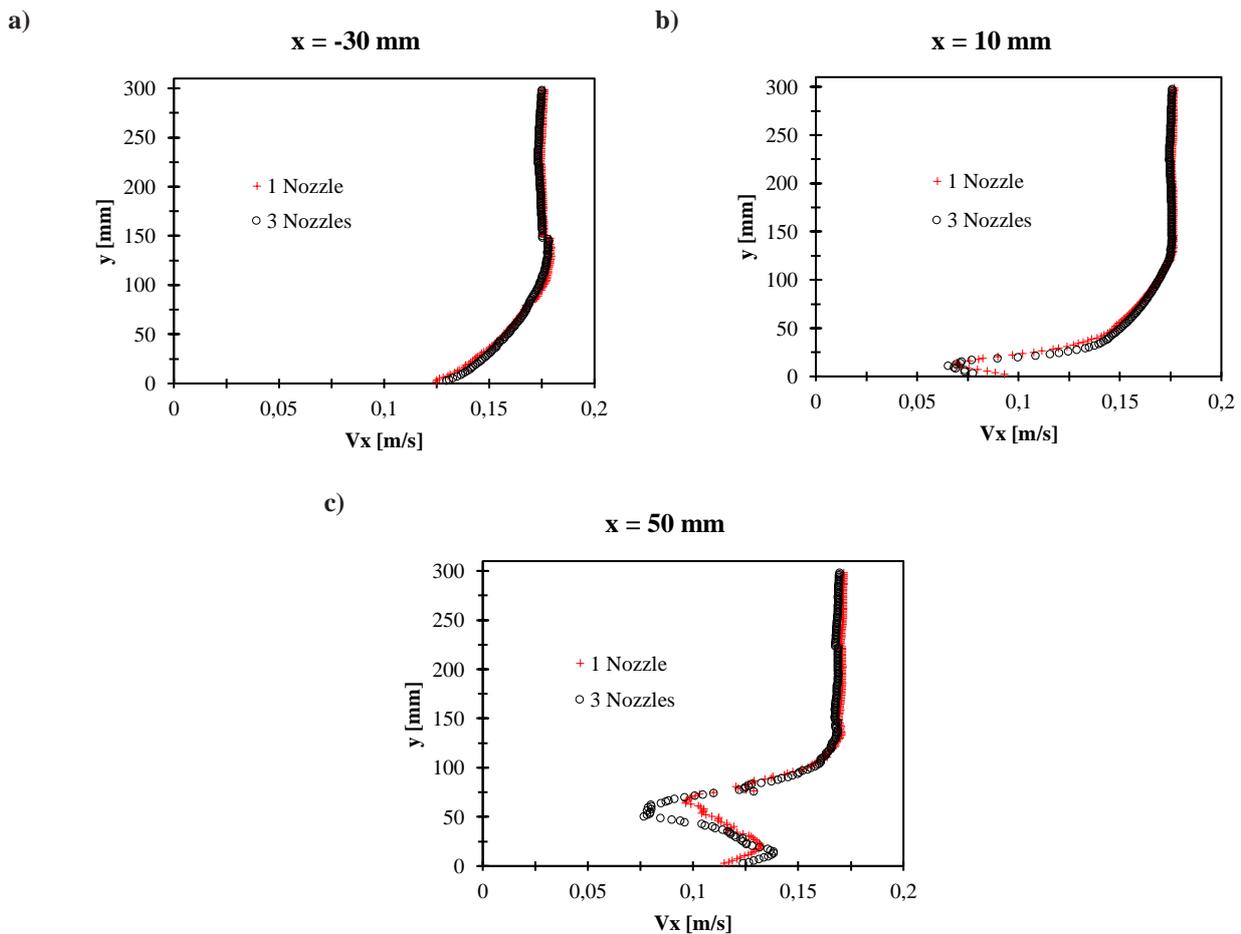

Figure 6. Horizontal velocity profile of the flow inside the bottom boundary layer at **a)** x = -30 mm (upstream the nozzles), **b)** x = 10 mm (contains the nozzles axes) and **c)** x = 50 mm (downstream the nozzles).

As observed, the horizontal velocity profiles are very similar when considering single and three points of air injection. Upstream the nozzles, the velocity profiles and respective velocity ranges inside the boundary layer are the same as those depictured without crossflow (Fig. 4b). But, in the cross section which contains the nozzles axes, the velocity profile

within the boundary layer was strongly affected. So, in a position very close to the air discharge, the plume acts as a kind of barrier to the main flow displacement, since the horizontal velocity component decreases while the upward movement of the liquid occurs. Downstream the nozzles, within a certain liquid layer located close to the channel bottom, the horizontal velocity component tends to recover, and almost reaches the velocity levels observed in the boundary layer which was set upstream the nozzles. However, the Figure 6c shows that the horizontal velocity value decays while the y height increases (up to reach approximately a little more than 1/3 of the boundary layer thickness). It is due to the fact that the main flow tilts the plume, and the liquid portion which is inside the boundary layer and at same time close to the plume centerline is favored to be entrained into the plume. In the case of "x = 50 mm", there are differences between the velocities ranges if a single or multiple injectors generated the plume.

The Figure 7 shows the vertical velocity profile evolution along the tilted plume axis (for several vertical positions), when 03 sources of air injection create the plume. The Vy velocity profile follows a Gaussian curve, and its peak value is on the plume centerline. However, due to the plume bending and spreading in the main flow direction, there is no symmetry of the minimum Vy velocity in each curve. Although there is this non symmetry, the Vy in the region covered by the plume tends to a certain value, while the peak of Vy decreases almost linearly along the main flow direction.
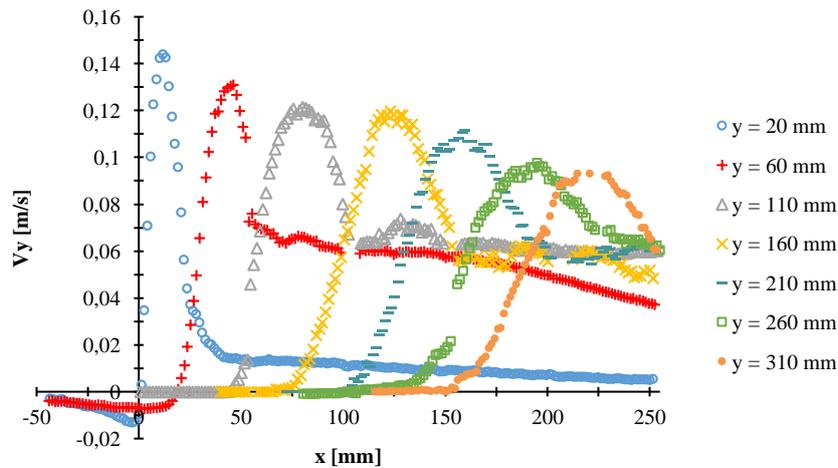

Figure 7. Vertical velocity along the plume centerline to three air injectors.

While the Vy peak diminishes almost linearly along the channel longitudinal axis, in this work the results showed that the plume bending angle is quasi-linear and not dependent on the total air flowrate. The plume centerline inclination for both air injection conditions is shown in Fig. 8, where the experimental data are the positions of a Vy peak.

Zhang (2012) reported an experimental work in which pure air bubble plume, pure water jets and bubbly jets in crossflow were studied in a water channel. Among the flow properties investigated, the author analyzed the plume and jets trajectories, and was found a linear profile for the pure bubble plume and the bubbly jets. The author also observed that the tilting angle of the bubble plume does not depend on the air flowrate or bubble size. In the present work, the experimental data also showed the same tendency, as illustrated in Fig. 8. The Table 2 presents some data for comparison.
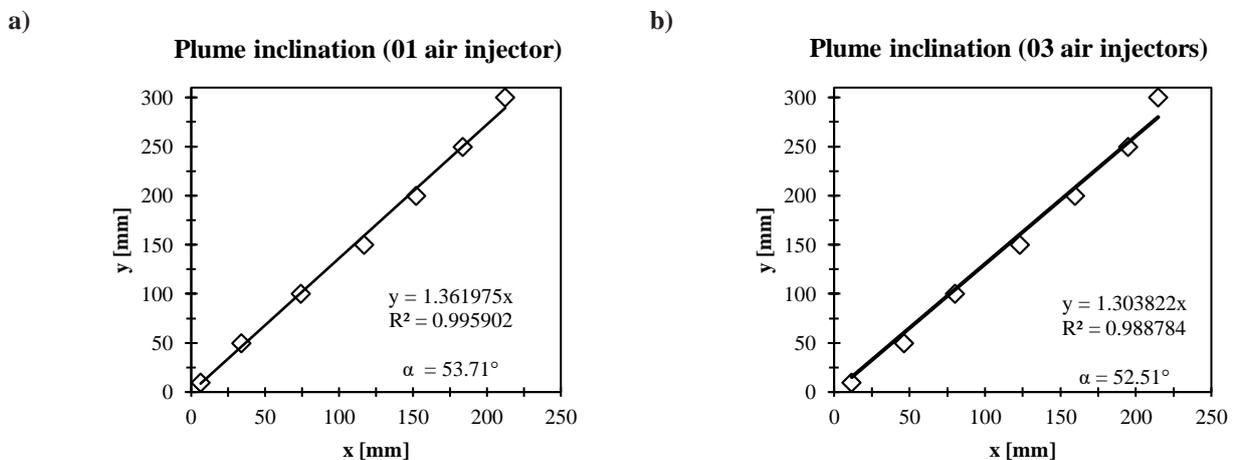
a)

Plume inclination (01 air injector)

$y = 1.361975x$
$R^2 = 0.995902$

$\alpha = 53.71°$

b)

Plume inclination (03 air injectors)

$y = 1.303822x$
$R^2 = 0.988784$

$\alpha = 52.51°$

Figure 8. Tilting angle of bubble plume centerline in crossflow to **a)** 01 and **b)** 03 air injectors.

Table 2. Comparison of results

Source of data	Water Channel Dimensions (W x H x L) [m].	Water column	Mean water flow rate (ambient)	Mean water velocity (ambient)	Air flow rate (per nozzle)	Number of nozzles / nozzle exit position	Total air flow rate	Nozzle diameter	Plume Centerline angle
This work	0.6 x 0.7 x 12	0.45 m	147 m³/h ≈ 40.83 L/s	0.15 m/s	0.7 SL/min	01 / tangent to the channel floor	0.7 SL/min	1 mm	$\alpha^{(1)} \approx 53.7°$
						03 /tangent to the channel floor	2.1 SL/min		$\alpha^{(2)} \approx 52.5°$
Zhang (2012)	1.2 x 0.8 x 25	0.65 m	155.4 L/s	0.2 m/s	1 L/min	01 / 120 mm above the flume bed	1 L/min	6 mm	$\alpha^{(3)} \approx 50°$ $\alpha^{(4)} \approx 47°$
					3 L/min		3 L/min	6 mm	$\alpha^{(3)} \approx 52°$ $\alpha^{(4)} \approx 51°$
					5 L/min		5 L/min	6 mm	$\alpha^{(3),(4)} \approx 53°$

[1], [2] Based on the experimental data (Vy peak positions); [3] Based on the *arctangent* model; [4] Based on the flow images.

5. CONCLUSIONS

Aspects of a crossflow generated by air injection upward inside a circulating water channel were experimentally characterized by using the PIV technique. The pure bubble plume in crossflow was generated by a single and 03 circular nozzles for air injection. The angle of the centerline plume bending was analyzed, and the experiments showed that the air flowrate range did not play important role on the angle of bubble plume bending, in agreement with literature data.

The results also showed that in the investigated area of the channel, the main flow was developed and the boundary layer thickness was approximately 150 mm. It was observed the level of influence of the injected air on the flow dynamics within the boundary layer. Although the air injection has disturbed the boundary layer region, the boundary layer thickness was not remarkably modified.

During the Inmetro's water channel design process, it was not determined previously any target value for the channel bottom boundary layer thickness. The main concern was to construct a reliable bench for scientific and metrological applications, within its use limitation. As the boundary layer thickness of the channel bottom plays an important role on the definition of the limits for using the channel for instruments calibrations (since an uniform velocity profile in the measurement section is required for calibration activities), the maximum size of the instruments which could be calibrated in this water channel must be evaluated by considering the size of the cross sectional area which has uniform velocity, and also the flowrate stability and the acceptable levels of water surface oscillation. So, as example, based on the boundary layer thickness estimate in the present work, with the water column and flowrate range in which the tests were made, there is an indication that the calibration of pygmy type current meter would be possible, since it can have diameter around 30mm. However, a more precise confirmation about this possibility will depend on the boundary layer thickness set on the vertical walls of the channel, because the minimum area size of the cross section which has uniform velocity must be in accordance with standards exigencies. In the continuation of this work, these details will be investigated.

Summarizing the achievements of this work, it is possible to confirm that the bench has good characteristics for working as a facility for instruments calibrations, as well as for complex flow investigations. Nevertheless, more tests should be made in order to know deeply the limits conditions for this channel application, and also, its best capabilities. Studies aiming the understanding of pollutant dispersion processes will be continued, in parallel to the facility characterization.

This work corresponds to the introductory stage of studies on crossflow in the Inmetro´s circulation water channel, and the complete characterization of such CWC is an activity that will be pursued, as well as the investigations on crossflow processes in surface water bodies.

4. ACKNOWLEDGEMENTS

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