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BUBBLE JET IMPINGEMENT IN DIFFERENT LIQUIDS

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An experimental setup for the study of bubbly jets collision in microgravity has been designed. On ground preliminary results are presented in order to be compared with those obtained in a near future in low gravity conditions. The opposed-jet configuration is used with the objective to force the collision of two jets, with an impact angle between them that can be changed from 0º (frontal collision) up to 90º. The colliding jets are introduced into a test tank full of liquid by means of two bubble injectors. The bubble generation method is based on the creation of a slug flow inside a junction of capillary tubes of 0.7 mm of diameter. Bubble velocities at the injector outlet and generation frequencies can be controlled by changing the gas and liquid flow rates. We present results on the role played by the impact angle and bubble velocities on the structure of the final jet. A systematic study for different gas and liquid flow rates has been carried out in liquids with different values of surface tension.

INTRODUCTION

In the last decades, the study of two-phase flows such as bubble plumes and bubbly jets has attracted special attention due to the numerous advantages presented by multiphase systems over the single-phase ones. Bubble jets have been the subject of theoretical and experimental studies since many applications such as aeration control or mixing devices require the use of small bubbles with high area-volume ratio. The size of the bubbles present in those jets depends on the fluid properties, gas and liquid flow rates, and the geometry of the injection system. Varely [1] investigated the bubble sizes in bubbly jets and found that bubble diameter decreases as the superficial liquid velocity increases, and the measured bubble size distributions were compared to normal, log-normal and gamma distributions. However, only size measurements were provided and no additional information such as bubble velocities or a study of the jet structure was described.

Concerning the global structure of bubbly jets, Lima Neto et al. [2,3] carried out recently an interesting investigation on the properties of bubbly jets injected both vertically and horizontally in stagnant water. In their work, bubble properties and the liquid flow structure have been detailed for a single bubbly jet injected in a normal gravity environment, but the size of the bubbles is much higher than those reported in the present work.

On the other hand, the opposed jet configuration has been used extensively for studying turbulent properties of fluids [4,5]. Industrial applications have to deal with the improvement of fluid mixing efficiency, and some of them require a flexible control according to operation conditions. As investigated by Tsujimoto et al. [6] such flexibility in the mixing processes can be achieved by changing the impact angle between the colliding jets: reducing the impact angle increases significantly the mixing efficiency. In this sense, the opposed-jet configuration with changeable orientation becomes an attractive method for enhancing mixing systems at low cost while maintaining high-efficiency and direct control.

An exhaustive study of the impact between opposed bubbly jets in water can be found in Suñol and González-Cinca [7].
The gravity force plays a crucial role when dealing with two-phase flows. In the particular case of bubbly jets, when the density difference between the gas bubbles and the surrounding liquid is large, buoyancy is dominant and governs the dynamics of the mean flow. In space, where gravity can be neglected and no buoyant forces are present, many kinds of gas-liquid flows are still poorly understood.
The understanding of the bubble behavior such as bubble generation or the structure of bubbly jets arise as one of the key points for the control of two-phase flows, both in normal and in low gravity.
In this work we conduct an experimental study of the interaction between gas-liquid jets, using the opposed-jet configuration, with changeable impact angle between jets and separation distances. The experimental setup is designed to study the behavior of such jets both on ground and in microgravity conditions. In particular, the setup is focused to be used on a drop tower platform. On ground preliminary results are presented both in distilled water and in ethanol. Bubble velocities at jet centerline and bubble sizes have been measured. The obtained results will be compared with those obtained in a near future in a low gravity environment.

EXPERIMENTAL SETUP

An sketch of the experimental setup is shown in Figure 1. A stainless steel test tank with dimensions of 160 mm length, 200 mm width and 250 mm height is filled with liquid. The size of the test tank is large enough (compared to bubble diameter which is of order of 1 mm) to minimize any possible wall effects on the motion of the bubbles and the resulting jet structure. This tank is equipped with two transparent methacrylate windows which allow the visualization of the bubble jets.

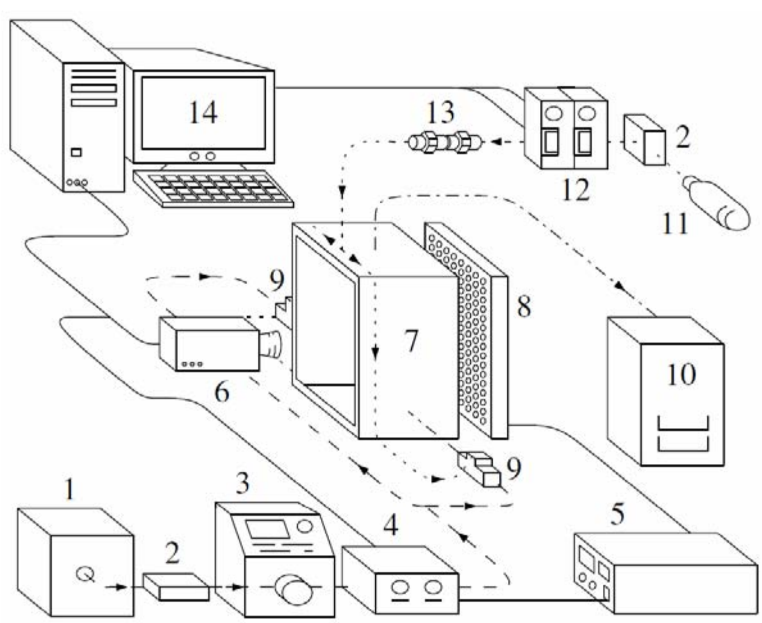


Figure 1: Experimental setup. Solid lines: electric connections, dotted lines: Gas tubes, dashed lines: liquid tubes, dash-dotted lines: gas-liquid tubes. 1: Liquid tank, 2: Filter, 3: Pump, 4: Flow meter, 5: Power supply, 6: HS Camera, 7: Test tank, 8: LEDs, 9: Injectors, 10: Residual tank, 11: Gas bottle, 12: Pressure controller and flow meter, 13: Choked orifice, 14: PC.

Two bubble injectors, whose operation is described below, are placed one in front of each other near the test tank. Gas and liquid are introduced to each of these injectors, which generate a slug flow that is driven into the test tank through a capillary tube, creating therefore the bubbly jets. The angle and separation between jets can be changed manually using a mechanic fixation placed inside the test tank.

Filtered air (CO_2) is injected from a pressure bottle through a pressure controller (Bronkhorst P-702CV) and a choked orifice, setting the gas flow rate Q_G from 5 ml/min to 20 ml/min for each bubble injector. Gas flow rate is measured by an air flow meter (Bronkhorst F-201CV). The liquid is injected using a high-accuracy pump (Ismatec MCP-Z Standard). Liquid flow rate Q_L is measured by a liquid flow meter (Bronkhorst L30), ranging from 15ml/min to 30ml/min for each injector. Two different liquids have been used in this work: distilled water (with a density of $\rho = 998$ Kg/cm^3, surface tension $\gamma = 0.0728$ N/m, and viscosity $\nu = 1.52 \cdot 10^{-6}$ cm^2/s) and ethanol (with a density of $\rho = 789$ Kg/cm^3, surface tension $\gamma = 0.0224$ N/m, and viscosity $\nu = 1.52 \cdot 10^{-6}$ cm^2/s).

A high-speed video camera (RedLake MotionXtra HG-SE) is necessary to account for the bubble processes such as coalescence events and the individual bubble motion. Lighting is provided by a matrix of 280 ultra-bright LEDs and homogenized by a diffuser sheet. A more detailed explanation of the experimental setup can be found in Suñol et al. [8].

Preliminary on ground tests were conducted at room temperature and ambient pressure. All the movies were recorded at 1000 fps with a resolution of 640x512 pixels, and post-processed by image processing software. The basic experiment operations (full control of the gas and liquid lines, lighting and camera) can be controlled remotely from a computer via wireless, but the change of the impact angle φ and separation distances between jets s has to be manipulated manually between two consecutive experiments. A snapshot of two colliding bubble jets with a schematic definition of φ is shown in Figure 2.

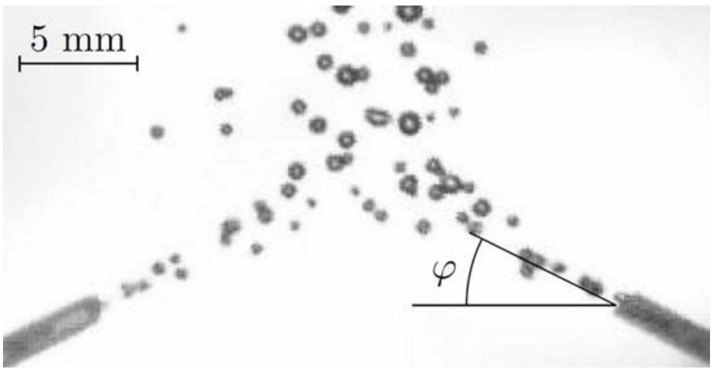


Figure 2: Snapshot of two colliding air bubble jets in distilled water and definition of the impact angle φ.

In microgravity conditions there is no buoyancy, and the creation of bubbles of controlled size and generation frequency is still a challenging task. The method proposed here to generate the bubbles is a simple device which consists of a methacrylate T-junction with a diameter of $d_C = 0.7$ mm (see Figure 3). Gas and liquid are injected at constant flow rates through the

Figure 3: Schematics of the bubble generation method.

crossed capillary tubes of the T-junction, creating therefore a regular slug-flow which results in a nearly fixed bubble size and generation frequency [8]. This slug flow is driven through a capillary tube to the test tank, completely filled with liquid, where the air bubbles are released.

This method is insensitive to gravity force and is mainly dominated by capillary forces since Bond number is very low

$$Bo = \frac{\Delta\rho g d_C^2}{\gamma} << 1, \tag{1}$$

where $\Delta\rho$ is the density difference between the two phases, g is the acceleration of gravity, d_C is the capillary diameter and γ is the surface tension. An extensive range of bubble generation frequencies (up to 600 bubbles per second in this study) can be achieved.

The reader may refer to Carrera et al. [9] and Arias et al. [10] for a detailed study of this bubble generation method.

ON GROUND RESULTS AND DISCUSSION

The horizontal injection of a single bubbly jet in a stagnant liquid is mainly characterized by the distinction of two zones (as observed also by Lima Neto et al. [3] and Suñol et al. [7,8]): first, an approximately conical zone near the injector nozzle, where the inertial effects are predominant and buoyancy can be neglected. Single bubble motion inside this zone is irregular and unpredictable. Secondly, a bubbly plume zone in which the bubbles rise with a uniform velocity and buoyancy is compensated by the drag force. In this zone, inertial effects are no longer significant and the bubble motion is predictable, consisting mainly of a straight rise with uniform velocity.

We initially focus on the first region, the jet zone in which gravity is negligible. According to Schlichting [10], the momentum flux J can be regarded as the main parameter that characterizes the jet structure for a single-phase jet. The momentum flux reads

$$J = 2\pi\rho\int_0^\infty v_x^2 r dr, \tag{2}$$

where cylindrical coordinates (r, θ, x) are used, ρ is the density of the fluid and v_x is the bubble velocity at jet centerline.

Considering the effects of both gas and liquid, the momentum flux can be computed by

$$J = J_G + J_L = \frac{4}{\pi d_C^2}\left(\rho_G Q_G^2 + \rho_L Q_L^2\right), \tag{3}$$

where the subscripts G and L correspond to the gas and liquid phases, respectively.

Concerning the velocity field of the bubbly jets, we make the assumption that near the injector nozzle, bubbles follow the liquid motion in a passive way without perturbing significantly the liquid flow field. In this case, one can consider the Schlichting [11] solution for the velocity field of a turbulent single-phase jet, where the x component reads

$$v_x = \frac{3J}{8\pi\varepsilon_0\rho_L}\frac{1}{\left(1+\eta^2/4\right)^2}\frac{1}{x}, \tag{4}$$

where ε_0 is the virtual kinematic viscosity, and

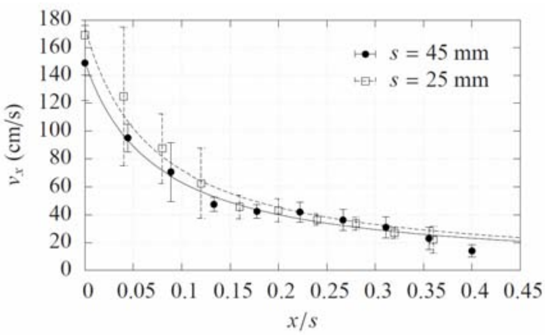
$$\eta = \frac{1}{4\varepsilon_0}\sqrt{\frac{3J}{\pi\rho_L}\frac{y}{x}}. \tag{5}$$

In order to avoid the divergence at $x=0$, a parameter x_0 is introduced with the aim to take into account the finite size of the injector nozzle. In the jet centerline, $y=0$ and the modified equation becomes

$$v_x = \frac{3J}{8\pi\varepsilon_0\rho_L}\left(\frac{1}{x+x_0}\right) \equiv \theta(J)\frac{1}{x+x_0}. \tag{6}$$

In Figure 4, the experimental values of the bubble velocities at the jet centerline are shown. The solid lines correspond to a fit of the measured velocities using the latter equation. Bubble velocities have been measured at different separation distances between injectors, and at 0º impact angle.

In the case of distilled water (Figure 4, left), the velocities corresponding to a separation between jets of $s=25$ mm are lower than those corresponding to $s=45$ mm for $J=54$ g cm/s^2 (note that in the plots the x axis is normalized by the separation between jets s). This fact can be due to the interaction with the opposing jet: when s is small the jets are closer to each other and the flow field generated by the opposed jet can decrease the mean velocity in the jet centerline. The same behavior is observed in ethanol (Figure 4, right) although using different values of separations between jets.



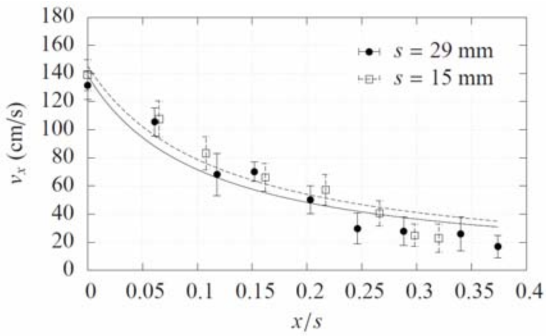


Figure 4: Bubble velocities at jet centerline, for different separations between injectors. Left: distilled water. Right: ethanol.

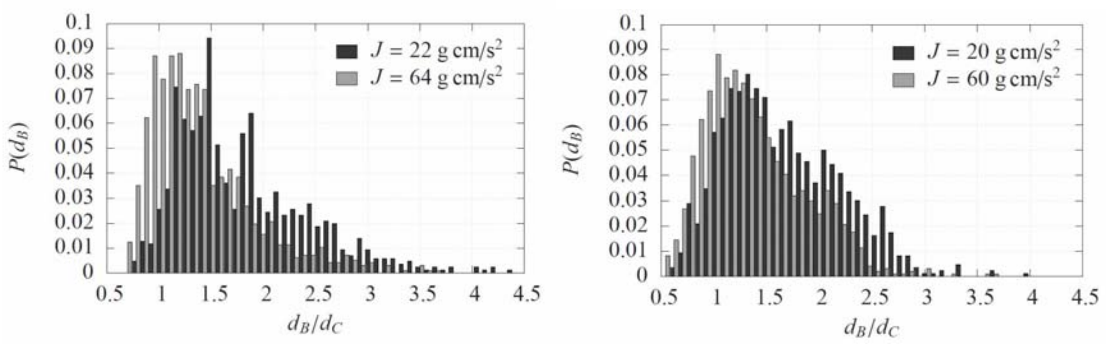


Figure 5: Histogram of bubble diameters. Left: distilled water. Right: ethanol.

In the case of ethanol, the variation of bubble velocities with the distance from the nozzle is very similar than in the case of water. The value of the momentum flux is $J = 55$ g cm/s^2, and the velocity decrease is higher when the separation between injectors is lower.

The presence of the opposed jet decreases the average jet velocity as it reaches the central zone where the two jets are colliding. The interaction between jets is thus not negligible and the velocity field can only be compared with that of a single jet in a small zone near the injector nozzle.

In Figure 5, bubble size distributions are presented for two values of the momentum flux both in distilled water (left) and in ethanol (right). In both cases the majority of the bubbles have a size slightly larger than the capillary diameter. Coalescence events are the main responsible of the dispersion in size, creating a large tail in the bubble size distribution.

In ethanol, more coalescence events have been observed, and the bubble size distribution is thus wider than in the case of distilled water.

It is important to note that larger values of the momentum flux correspond to bubbles with smaller diameters. This is due to the fact that higher values of the momentum flux correspond to higher liquid flow rates, while an increase of the gas flow rate results in an increase of the bubble generation frequency, and not on the bubble sizes. Increasing the gas flow rate does not increase significantly the momentum flux, since the gas flow rate is multiplied by the gas density. This phenomenon was also observed by Varely [1] investigating bubbly jets: smaller bubbles were created using larger values of the liquid flow rate.

CONCLUSIONS

The design of an experimental setup for the study of bubble jet interactions on ground and in microgravity is described. On ground preliminary results are presented in order to be compared with those obtained in low gravity conditions. Bubble velocities at jet centerline have been measured and compared with the velocity field of a single-phase jet. A slight decrease of bubble velocities is observed near the stagnation point of the opposed-jets, due to the interaction between them. The sizes of the air bubbles inside the collision zone of the opposed jets have also been measured, reporting a larger degree of coalescence in ethanol than in water.

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