FORMATION OF BUBBLES IN PLANAR CO-FLOWING AIR-WATER SHEETS

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Summary An experimental and numerical study of the periodic breakup of an air sheet surrounded by a co-flowing water stream with an innovative planar geometry is presented in this work. The experimental results obtained by image analysis of high speed video recordings, are compared with those calculated numerically for a fixed liquid-to-gas thickness ratio, $h = h^*_{w,0}/h^*_{a,0} \simeq 5.27$, where $h_{a,0}$ and $h^*_{w,0}$ denote half-thicknesses of the air and water flows at the exit respectively, as a function of the control parameters, namely the Weber number, $We = \rho_w u^{*2}_{w,0} h^*_{a,0}/\sigma$, and the velocity ratio, $\Lambda = u^*_{w,0}/\bar{u}^*_{a,0}$, where $u^*_{w,0}$ and $\bar{u}^*_{a,0}$ are the water velocity and the mean air velocity at the exit, respectively. Subsequently, the numerical simulations are used to describe the bubbling process through a two-stage mechanism governed by distinct physical phenomena: firstly, an incipient neck is formed, which moves downstream at the liquid velocity, and it finally collapses during a second stage.

INTRODUCTION

Bubble formation constitutes a physical phenomenon of high interest due to its numerous industrial applications which are demanding more efficient devices to produce bubbles as small as possible. The coflow configuration, where the air flow discharges into a co-flowing liquid stream, is an effective method to control the bubble size. The cylindrical geometry has been previously studied [1] and is well-understood nowadays. In this work we investigate a co-flow configuration with an innovative planar geometry, which could represent an alternative method to produce bubbles in a massive way.

EXPERIMENTAL AND NUMERICAL TECHNIQUES

The co-flowing air-water sheets were generated with the experimental set-up described in detail in Bolaños-Jiménez *et al.* [2]. It basically consists of two central plates to confine the air film separated 0.47 mm from each other, whose wall thickness at the tip is 0.22 mm. Since the air interface attaches to the outer side of the walls, the thickness of the air sheet at the outlet is $2h^*_{a,0} = 0.91$ mm. The co-flowing water sheets were produced by two outer channels located at both sides of the air channel, shaping a nozzle, and separated $2h^*_{w,0} = 4.8$ mm from each other at the exit. The spanwise length is 41.75 mm long, two orders of magnitude larger than the thickness of the air sheet, with the aim of obtaining a two-dimensional configuration. Since the water and the air Reynolds numbers are very high, the air-to-water density ratio, $S = \rho_a/\rho_w = 0.0012$, and the water-to-air thickness ratio, $h = h^*_{w,0}/h^*_{a,0} = 5.27$, have a constant value, and the Froude number is also very large, the control parameters of the present configuration are the Weber number, $\mathrm{We} = \rho_w {u^*_{w,0}}^2 h^*_{a,0}/\sigma$, and the water-to-air velocity ratio, $\Lambda = u^*_{w,0}/\bar{u}^*_{a,0}$. The experiments were performed by increasing the air flow rate for a given water velocity, that is, varying Λ for a fixed We, and recording high-speed movies in the spanwise view for different values of the control parameters. The experimental results were extracted by image processing.

In addition to the experimental study, we have performed numerical simulations of the bubble formation process using OpenFOAM (http://www.openfoam.com), a free, open source CFD software package developed by the OpenFOAM Team at SGI Corp and distributed by the OpenFOAM Foundation, and implementing the Volume of Fluid technique to determine the air-water interface. A two-dimensional approach has been adopted, and therefore the variations in the spanwise direction are neglected. Moreover, an incompressible and laminar flow has been assumed.

RESULTS

Bubble characteristics

The evolution of the bubbling frequency, f^*_b, with the air velocity, $\bar{u}^*_{a,0}$, determined from the experiments and the numerical simulations is plotted in Fig. 1(a), for different values of the water velocity. The figure shows that f^*_b increases with both the air and the water velocity. It can be observed that the bubbling frequencies given by the numerical simulations agree very well with those obtained experimentally in the range of air and water velocities explored. Furthermore, the agreement is remarkable considering that the numerical simulations are two-dimensional and, thus, possible transverse perturbations present in the experiments are not included.

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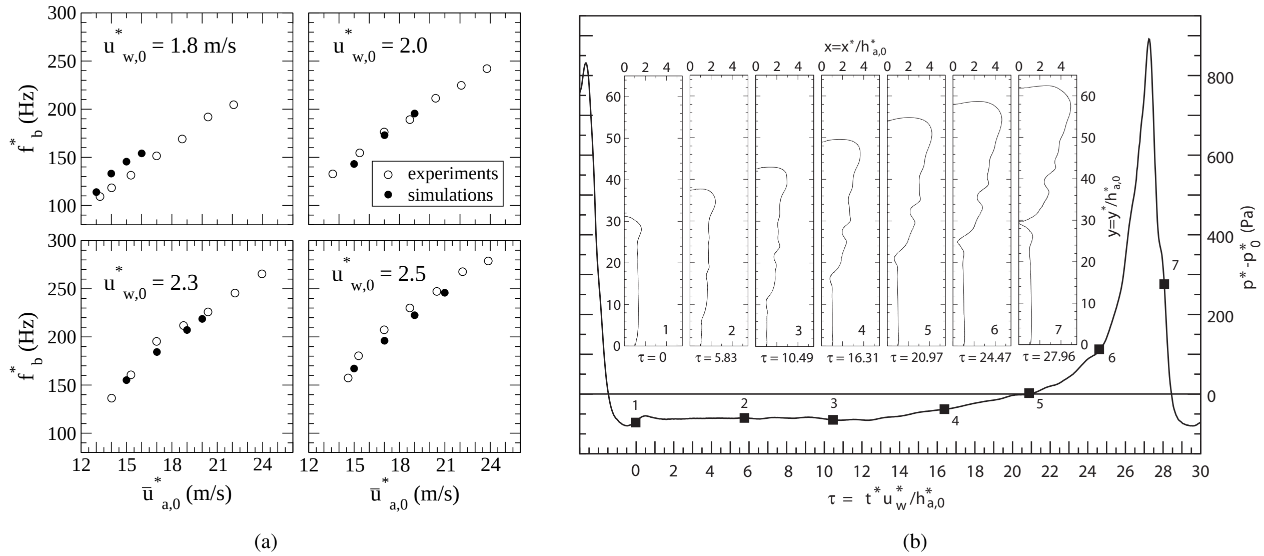

Figure 1. (a) Comparison of the experimental and numerical bubbling frequencies as a function of the air velocity for four different water velocities. (b) Gauge pressure, $p^* - p_0^*$, at the exit of the air stream as a function of the dimensionless time, $\tau = t^* u_{w,0}^* / h_{a,0}^*$ corresponding to $We = 38$, $\Lambda = 0.147$ for a bubbling event. Insets (1)-(7): Air-water interfaces in dimensionless form corresponding to different instants of the bubbling process.

Description of the bubbling process

The periodic bubbling phenomenon can be described with the information extracted from the numerical simulations, shown in Fig.1(b), where the temporal evolution of the manometric air pressure at the exit is plotted together with the shape of the forming bubble at different instants (insets Figs. 1b 1-7). Thus, the bubbling process can be described through a two-stage process: a *neck formation stage* followed by a *neck collapse stage*. The *neck formation stage* starts just after the detachment of the previous bubble (Fig. 1b 1), when an air ligament keeps attached to the outer edge of the air nozzle. The thickness of the air ligament is equal to the outer thickness of the air nozzle, but it remains noticeably inflated downstream. At this point, since the gas ligament is exposed to a negative pressure, an incipient neck is shortly formed (Fig. 1b 2), which moves downwards at the water velocity while its thickness decreases (Figs. 1b 2-7). As a consequence, similar to what happens when we close a valve in a pipe, a pressure drop takes place across the neck and, in order to keep the air flow rate constant (a condition imposed in both the experiments and the numerical simulations), the pressure supplied at the exit of the gas nozzle starts to increase (from $\tau \sim 16$). The neck formation stage ends when the pressure difference at the nozzle exit becomes zero (Fig.1b 5), and then, the *neck collapse stage* is considered to start. As the neck collapses, the process described above becomes more pronounced: while the neck accelerates inwards, a quick pressure increase takes place in the gas ligament (from $\tau \sim 21$). The overpressure makes the gas ligament inflate transversely and, consequently, the gas pressure starts to decrease (from $\tau \sim 27$) until it becomes negative again, the neck collapses and a new bubble is released (Fig.1b 1).

CONCLUSIONS

We have studied in this work the bubble formation in an air-water co-flow configuration with an innovative planar geometry. We performed experimental measurements processing images acquired with a high-speed camera. In addition, the problem was numerically analyzed with the code OpenFOAM, by assuming a two-dimensional flow. The good agreement between both results validates the numerical code. Finally, the bubbling process has been described using the information extracted from the simulations through a two-stage process: a neck formation and a neck collapse stage.

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