MEASUREMENTS OF THE TURBULENT BREAK-UP OF BUBBLES USING HIGH SPEED VIDEO IMAGES

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Abstract
A new method has been developed to experimentally measure the break-up of bubbles immersed in a turbulent flow using digital processing of images taken with a high speed camera. The method combines particle tracking velocimetry with particle size measurements to automatically detect break-up events. Thus, the life time, as well as the number and size of fragments resulting from the breakage are measured for a large number of particles. The method has been employed to study the turbulent break-up of a cloud of bubbles immersed in a fully developed turbulent jet.

Introduction
The spatio-temporal evolution of the number density of bubbles, $n(D;x,t)$, immersed in a turbulent flow may be described by the so-called *population balance equation* (pbe) [15]. When the only changes in the population of bubbles are supposed to be caused by break-up, the equation simplifies to (Martínez-Bazán 1999 [10]),

$$\frac{\partial n(D,\vec{x},t)}{\partial t} + \nabla \cdot \left[\vec{U} n(D,\vec{x},t)\right] = \int_D^\infty m(D_0) f(D,D_0) g(D_0) n(D_0,\vec{x},t) dD_0 - g(D) n(D,\vec{x},t) \qquad (1)$$

where $g(D)$ is the break-up frequency, $m(D_0)$ the number of fragments resulting from the break-up of a bubble of diameter D_0, and $f(D,D_0)$ is the size probability density function of the fragments, commonly named *daughter* bubbles p.d.f. Reliable models for $m(D_0)$, $g(D)$ and $f(D,D_0)$ are crucial to describe the evolution of the family of bubbles accurately.

If the Ohnesorge number is small, viscous effects are negligible, and the main parameter which controls the process is the turbulent Weber number, defined as [5]

$$We = \frac{\rho u'^2 D}{\sigma} \qquad (2)$$

which is simply the ratio between the deforming stresses due to the pressure fluctuations and the confining stresses due to surface tension. Most of the authors agree in the existence of a critical Weber number We_c, such that bubbles whose $We > We_c$ are unstable and eventually break in a given time.

Several closure models for (1) have been developed in the past to describe the turbulent break-up of particles based on the idea of competition between turbulent and surface tension stresses. Some authors proposed models based on kinetic theory where the break-up of a particle is caused by particle-eddy collisions ([9], [13], [2], [14]). In all these models the break-up is assumed to be binary.

Konno et al. [7], proposed a tertiary break-up model in which a mother bubble is supposed to be composed of "unit volumes". Furthermore, the resulting *daughter* bubbles are composed of an integer number of those volumes. The size distribution of the *daughter* particles minimizes the total energy, and the number of fragments is chosen to be 3 by best fitting the available experimental data.

Moreover, Martínez-Bazán et al. ([11], [12]) developed a binary model based on dimensional and energy considerations under which the frequency is given by the inverse of the characteristic time, scaled with the bubble

diameter D, the continuous phase density ρ and the difference between the turbulent and the surface tension stresses $\Delta\tau$

$$g(D) \propto \frac{\sqrt{\Delta\tau/\rho}}{D} \tag{3}$$

The *daughter* size probability density function is derived by minimizing the surface energy of the resulting fragments. A comprehensive study of the existing turbulent break-up models can be found in Lasheras et al. [8].

The above described models disagree in various points:

1. Number of fragments resulting from the break-up $\Longrightarrow$ dependence of $m(D_0)$ on the turbulent Weber number.
2. Dependence of the bubble diameter on the break-up frequency $g(D_0)$.
3. Shape of the *daughter* particle p.d.f, $f^*(D/D_0) = f(D, D_0)/D_0$. While some authors have proposed models where f^* follows a $\cup$-shaped, other models exhibit a $\cap$-shaped curves.

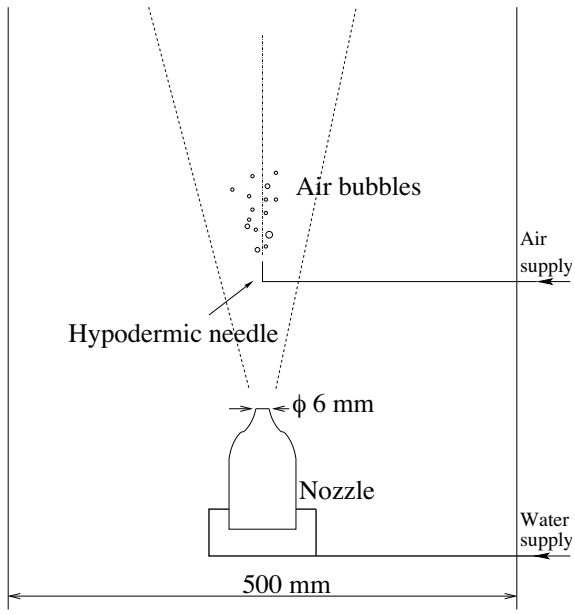

Figure 1: Esquema del sistema de inyección.

Experimental facility

In order to study experimentally the influence of the surrounding turbulence in the atomization of bubbles, an air flow was injected at the axis of a free turbulent jet (*see* Fig. (1)). Along the center line of the jet, the turbulence can be considered nearly isotropic and slowly decaying with downstream distance. Under those conditions, when both, the jet Reynolds number and the turbulent Weber number are sufficiently large to neglect viscous effects during the break-up process, the break-up properties of bubbles whose diameter ranges from the kolmogorov length scale to the integral length scale, $\eta \ll D_0 \ll \ell$, only depend on the turbulent dissipation rate, ε, and on the bubble diameter, D_0.

The turbulent field of the free jet has been widely studied ([3], [4]). At the jet axis, the turbulent intensity is nearly constant, and the mean velocity U_c and turbulent dissipation rate ε are given by ([5], [3])

$$U_c(X) = \frac{U_J\, B}{x/d - x_0/d} \tag{4}$$

$$\varepsilon(X) \sim \frac{C\, U_J^3/d}{(x/d - x_0/d)^4}\,, \tag{5}$$

where U_J is the injection velocity of the jet throughout the nozzle of diameter d and C, B, x_0 are constants to be determined experimentally.

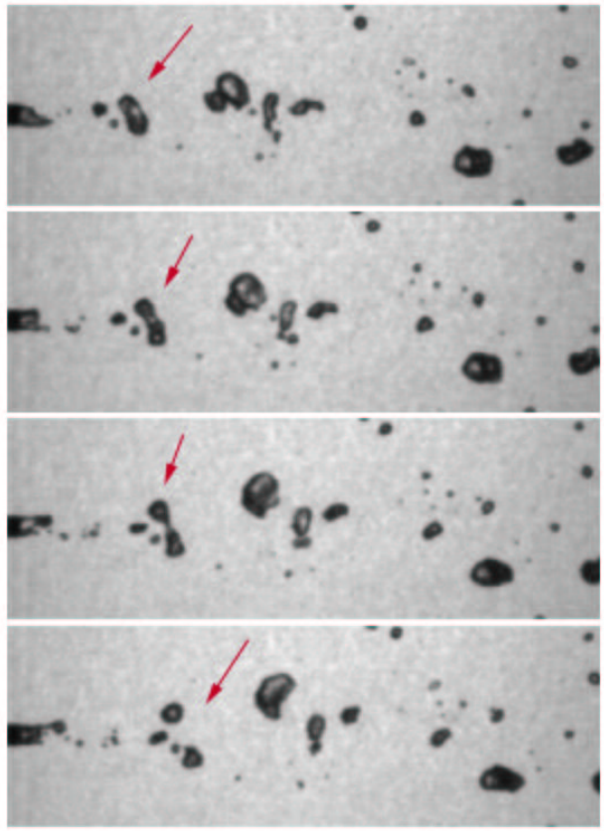

Figure 2: A typical break-up sequence.

The spatio-temporal evolution of the bubbles have been recorded at 1000 frames per second with a Kodak Ektapro high speed camera. A characteristic sequence is shown in Fig. 2 where it can be observed a break-up event of a bubble splitting in two *daughter* bubbles on the fourth frame. The time step between frames is $\Delta t = 1$ ms. The obtained images were stored in a PC for later postprocessing and analysis.

Tracking computer code and statistical data processing

In order to study the influence of both the bubble diameter D_0 and the turbulent dissipation ε in the bubble break-up, a computer program has been developed to track the bubbles and automatically detect break-up events, as they are convected downstream by the motion of the turbulent jet . The high degree of automation of this process, allows us to statistically analyze the break-up process for a large number of events and for a wide range of both D_0 as well as ε.

The tracking software consists of:

1. Digital image processing. The bubbles are detected in each frame of the movie. Among other parameters of interest, the projected area of the bubble is measured to define the characteristic size D as

$$D = \sqrt{4A/\pi} \tag{6}$$

2. The images of a single bubble obtained at different times are analyzed to construct its history. In each frame we have a number of bubbles and, therefore, we need to distinguish the bubble we are tracking. To identify the bubble in a frame $k+1$ which corresponds to the selected one in the previous frame k, a pseudodistance between the image of each bubble in a frame k (labelled bubble 0) and the rest of bubbles in the following one $(k+1)$ is minimized. This pseudodistance Δ_j^* is defined by

$$\Delta_j^{*2} = \Delta_j^2 + K_A \left(\frac{A_j - A_0}{A_0} \right)^2 \tag{7}$$

where $j = 1, \ldots, J$ is the number of bubbles in the frame $k+1$, Δ_j is the minimum distance between the pixels defining the perimeter of bubble labelled as "0" and the pixels defining the perimeter of bubble j (*see* Fig. 3) and A is the bubble's projected area.

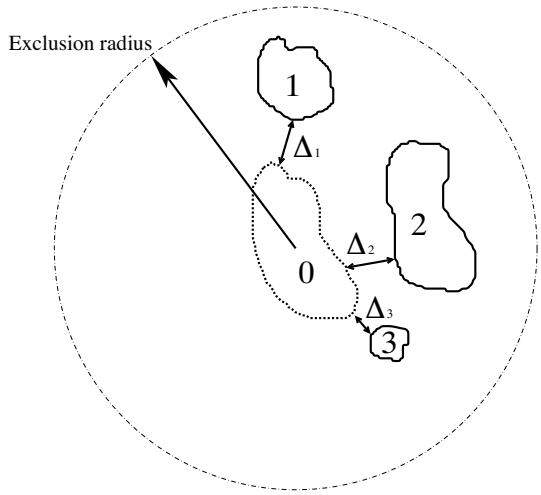

Figure 3: Object in frame k (bubble 0) and the closest objects in frame $k+1$.

As can be seen in Fig. 3, an exclusion radius is defined for the geometrical distance Δ_j to avoid connection of bubbles far apart from each other.

3. To ensure that the program selects the right bubble, a similar, inverse process is performed between each frame of the movie and the previous one.

4. To conclude, the history of each recorded bubble is extracted. A break-up event is detected when a bubble in a frame produces two different corresponding bubbles in the following image.

The data obtained for each bubble using the tracking code are the bubble life time, the number of fragments produced after a break-up event and the size as well as the mean velocity of those fragments. Using this data, the closure functions (f, g, m) can be measured:

- The number of fragments m is measured directly, and consequently a mean value can be obtained for each bubble size.

- The *daughter* bubble p.d.f. $f(D, D_0) = f^*(D/D_0)/D_0$ of the fragments can be also obtained by computing the probability of a given size D to be generated from the break-up of a bubble of diameter D_0.

- Measurements of the break-up frequency need more analysis. Let $N(x; D)$ be the number of bubbles of size D which entered the measuring window at $x = 0$. Since $N(x; D)$ does not account for those bubbles produced in the breakage of bubbles larger than D, the equation (1) for $N(x; D)$ can be written as

$$\frac{\partial\left(U(x)N(x;D)\right)}{\partial x} = -g(x;D)\,N(x;D) \tag{8}$$

The number of bubbles of a given size reaching a given position x can be easily computed from the data obtained with the tracking code. Therefore the break-up frequency can be obtained from (8) for each bubble size as a function of the position.

Results

Preliminary results have been obtained using the above described techniques for moderate Weber numbers ($We \sim 10 - 20$). The jet Reynolds number was about $Re = 70,000$. The air flow was injected at 33 nozzle diameters downstream from the jet's nozzle throughout a hypodermic needle of diameter $D_a = 0.838$ mm. The air injection velocity was the same as the local mean water jet velocity at the injection point $U_c = 2.65$ m/s. The measured turbulent dissipation rate was $\varepsilon = 14\,\mathrm{m}^2/\mathrm{s}^3$.

The breakage was found to be binary in all the experiments reported here. The measured break-up frequency as a function of the evolution time ($t = x/U$) has been plotted for different bubble sizes in Fig. 4, using the following scaled function,

$$G(t) = g(t; D) \left(\frac{D}{D_c} \right)^{-13/5} \tag{9}$$

where D_c is a characteristic size of the bubbles population. Notice that in Fig. 4 the measured frequencies collapse on the same curve when scaled as in equation (9). In Fig. 5 the measured mean frequency (symbols) is plotted

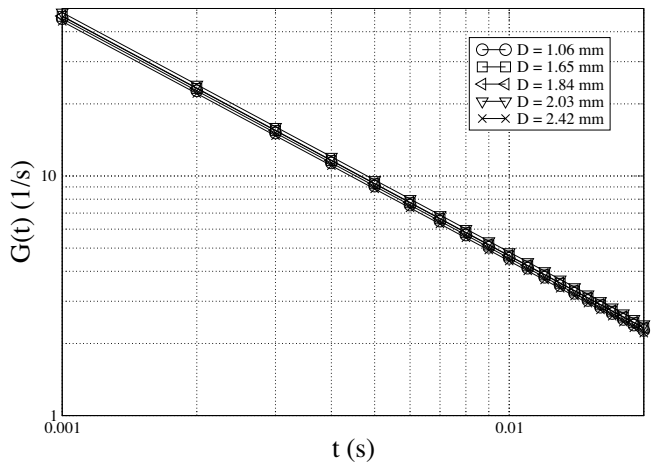

Figure 4: Scaled break-up frequency for different bubble diameters as a function of the bubble life time.

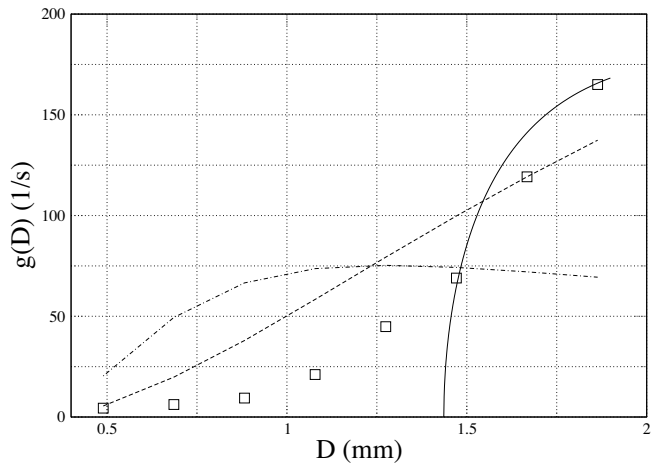

Figure 5: Mean break-up frequency measured (symbols) as a function of the bubble size, compared with predicted values using three existing models, Martínez-Bazán et al. (solid line), Luo & Svendsen. (dashed line) and Konno et al. (dot-dashed line).

along with the predictions of three different models, namely, Martínez-Bazán et al. (solid line), Konno et al. (dot-dashed line) and Luo & Svendsen (dashed line). It may be observed that none of these models seems to predict the experimental results adequately.

Conclusions

A simple novel technique to measure the break-up properties of particles in turbulent flows has been presented. The technique has proven to give satisfactory results in dispersed two-phase flows, although its performance is questionable when the bubble concentration increases considerably. Although there are algorithms to overcome this problem (Bongiovanni 1996 [1]), in our case we can simply exclude from the statistics overlapping bubbles.

The measured break-up frequency does not seem to agree with predictions of existing models. Further experiments for higher Weber numbers are required to determine the existence of the maximum in the break-up frequency, the exact shape of the *daughter* bubble p.d.f, $f^*(D/D_0)$, and to determine the limitations of the binary break-up assumption.

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