Experimental study on the formation and break-up of fluid bubbles

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Abstract: *The study of fluid surfaces plays an important role in understanding the interfaces encountered in biological systems, as it allows for the investigation of the basic characteristics such as the formation, stability and permeability. Moreover, the adhesion and the fusion of biological membranes can be better understood by the experimental investigations of drops and bubbles formation in controlled dynamical processes. These studies have the potential to generate novel and value information for medical applications in the diagnosis and therapy using microfluidic-based biosensors and controlled drug-delivery micro-devices. In this paper, the dynamics of fluid interfaces have been studied experimentally and a method for determining the surface/interfacial tension is proposed. The analysis started with the investigation of the soap bubble formation and break-up. The rupture was triggered manually, by pinching the tip with a needle. The burst was recorded with high-speed cameras and the burst speed was determined. Furthermore, the thickness of the fluid membrane was approximated and the surface tension was calculated using the Culick-Taylor's law. The obtained values for the surface tension were in the same order of magnitude with that from the literature, thus, considering that the employed method can lead to adequate results. Subsequently, a set-up was created to automatically generate fluid bubbles, at different imposed flow rates. The spontaneous burst was analyzed for three different liquids: soap solution, vegetable oil and polyacrylamide. The phenomenon is characterized by the Ohnesorge number, which takes into account the influence of viscous forces in relation to the inertial and surface tension forces. For the soap bubbles, the obtained thickness of the membrane was in the range of (300-500) nm. The calculated surface tension was found to be 0.038 N/m. In the case of automatically generated fluid bubbles, the lowest Ohnesorge number was obtained for* *soap bubbles and the highest for oil bubbles. Moreover, soap bubbles had the highest break-up speed, while vegetable oil and polyacrylamide had lower and similar break-up speeds. The experimental study described in this paper is an alternative method for the identification of material parameters, such as density and surface tension, in a dynamical process. Numerical simulations are reported from the viewpoint of servo time constant performance.*

Key Words: *fluid bubbles, surface tension, break-up speeds, dynamical process*

1. INTRODUCTION

Fluid bubble bursts are spectacular processes, even more so if recorded with high speed cameras, and have major importance when trying to understand fundamental processes such as: glass furnaces, sea/atmosphere molecular exchanges (when wave breaking occurs, bubbles are formed and then these bubbles burst, projecting microdroplets into the atmosphere) [1] and foam production. Microbubbles have applications in drug delivery where ultrasounds are used in order to burst them (Ultrasound Molecular Imaging) [2]. Before being injected, thin films of biocompatible substances, polymers or phospholipids are being deposited on these microbubbles, in accordance to their application.

There are many works that deal with the formation and burst of fluid bubbles. J. Bico presented an overview on the bursting dynamics of fluid bubbles and made a comparison between the Taylor-Culick speed and the actual retraction speed of the film that was calculated [3]. M. Murano and K. Okumura investigated the burst of liquid thin films without circular symmetry in a confined geometry (Hele-Shaw cell) [4]. S. Poulain et. al. presented different factors that have effect on the ageing and bursting of fluid films [5].

In this paper, we present the formation of fluid bubbles with different substances and their rupture dynamics, considering their material properties. A set-up was put in place in order to automatically generate fluid bubbles.

A dynamical system is proposed from which one can obtain relevant and adequate values for material parameters, such as density or surface tension.

2. THEORETICAL BACKGROUND

The burst of soap films is theoretically described by a law which puts in balance the momentum and the surface tension forces. Applying this law, good results can be obtained if the viscous forces are negligible. This can be translated into an equation using Ohnesorge's number: $Oh = \frac{\eta}{\sqrt{\rho R_0 \sigma}}$, where η is the viscosity measured in Pas, ρ is the density measured in kg/m^3, R_0 is the initial radius of the film measured in m and σ is the surface tension measured in N/m. Nevertheless, small quantities of surfactant molecules present in the soap film may influence the surface rheology, thereby developing a complex behavior.

After puncturing a soap film, a hole will form, whose margins, due to the surface tension, will increase in time and the retraction process will occur apparently at constant rate. In order to obtain an equation which describes the retraction speed of the film, two assumptions are made: the thickness of the film, h, is uniform throughout the film and the surface tension, σ, has a constant value across the film.

Considering these assumptions, the dynamics of the retraction will be ideal and symmetrical with respect to the origin, the puncturing point *A*. It has been observed experimentally that the rim of the retracting fluid engulfs the film, but no disturbance is transmitted upstream (Fig. 1).

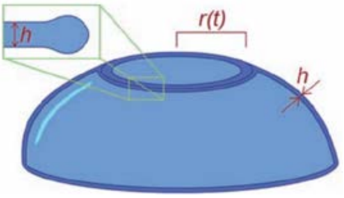

Fig. 1 – Rupture of a soap film of thickness *h* [6]

The rim is considered to be located at a distance *r*, from the origin *A*, inclined at the angle α and can be considered as a system with variable mass $m(r) = (\frac{\rho h r^2 \alpha}{2})$, which retracts with the velocity $v = \frac{dr}{dt}$. With regard to point *A*, the sum of the forces that act on the rim, not taking into account the gravitational and aerodynamical effects, can be written as:

$$F = \frac{d}{dt}(mv) \tag{1}$$

$$dt = \frac{dr}{v} \tag{2}$$

$$F = v\frac{d}{dr}(mv) = v^2\frac{dm}{dr} + mv\frac{dv}{dr} = \frac{v^2}{2}\frac{dm}{dr} + \frac{d}{dr}\left(\frac{mv^2}{2}\right) \tag{3}$$

$$Fdr = d\left(\frac{mv^2}{2}\right) + \frac{v^2}{2}dm \tag{4}$$

Integrating from 0 to *r*, it is obtained the following:

$$\int_0^r Fdr = \frac{1}{4}\rho r^2 h v^2 \alpha + \frac{\rho h \alpha}{2}\int_0^r v^2 r dr \tag{5}$$

The integral in the left part of the equation represents the mechanical work done by the rim of the fluid from A to r so it is equal to the energy associated with the surface that disappeared $\sigma r^2 \alpha$. The force that acts on the rim is $F = 2\sigma r \alpha$. If the velocity is considered constant, independent of *r*, $\int_0^r v^2 r dr = \frac{r^2 v^2}{2}$, then:

$$\sigma r^2 \alpha = \frac{1}{2}\rho\left(\frac{r^2 h \alpha}{2}\right)v^2 + \frac{1}{2}\rho\left(\frac{r^2 h \alpha}{2}\right)v^2 \tag{6}$$

As mentioned, the left part of the equation represents the energy output resulted from the burst of the film, the first term from the right side of the equation represents the kinetic energy of the rim of the fluid and the second term is associated with the acceleration process of the fluid, from upstream, where no disturbance is occurring, until the rim of the fluid. The final expression of the retraction speed, called also the Taylor-Culick speed, is obtained:

$$v = \sqrt{\frac{2\sigma}{\rho h}} \tag{7}$$

In practice, the calculated value of the speed may differ from the one measured and this is in most cases due to the method that one uses in order to calculate the film thickness [7].

It is well known by adding a small extra quantity of soap one can increase the stability of the bubbles. Surfactant molecules are amphiphilic, having both hydrophobic groups (ex. hydrocarbons) and hydrophilic groups (ex. ions). These molecules tend to absorb at water-oil or water-air interfaces where they act as a bidimensional gas, resulting in a pressure at the surface. This results in the lowering of the surface tension. Considering the before mentioned, it can be said that it is sufficient to know how the surface tension changes in time under the action of different forces to describe the burst of soap films [3, 8]. However surfactant molecules have other effects, too. Their presence limits the thinning of the film and determines a forces which puts in equilibrium the weight of the fluid. Surfactant molecules can also induce at the interface a spring like, oscillating behaviour. More so, if the surface is stretched, the concentration of the surfactant molecules will decrease and the surface tension will increase locally. These are the reasons why surfactants induce a complex and nonlinear interfacial rheology [3, 8].

3. MATERIALS AND METHODS

For the study on the triggered break-up of manually created soap bubbles and the study on the spontaneous break-up of automatically generated fluid bubbles, two set-ups have been created (Fig. 2). The fast camera used to record the phenomena is Phantom VEO 340L and the recording speed used went up to 14000 fps. At such recording speeds, the quantity of light needs to be high enough, therefore the illumination system consisted of a Fiber-Lite MI-150 (Dolan Jenner Industries) halogen lamp, which has an output power of 150 W and the light is transmitted through an optical fiber. For the generated fluid bubbles, the air was pumped by Harvard Apparatus Pump 33, through a 2 mm thick plexiglas plate, which had an orifice of 0.6 mm in the centre. The data were analysed using the ImageJ software.

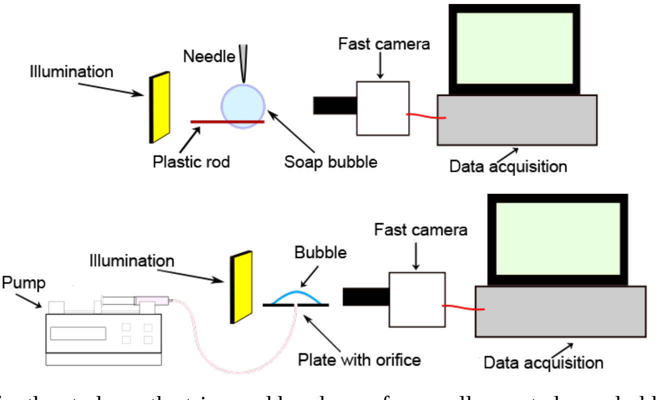

Fig. 2 – Set-ups for the study on the triggered break-up of manually created soap bubbles (up) and on the spontaneous break-up of automatically generated fluid bubbles (down)

For the study of the triggered break-up, the bubbles were created manually using a commercial soap bubble solution and they were held still, using a plastic rod. Subsequently, the bubbles were punctured with a metallic needle, in order to trigger the break-up. The phenomenon was recorded for bubbles that were held on top of the plastic rod and below it. For the bubbles that were held on top, the movement of the fluid membrane was quantified by measuring the variation of the distance from the plastic rod to the tip of the bubble, thus the break-up speed was calculated. For the bubbles that were held below the rod, the process was seen to be more complex and therefore the movement of the membrane was measured along two lines, defined as OP1 and OP2.

A method for approximating the average thickness of the membrane was also implemented. It is known that in reality variations of hundreds of nanometres exist between different regions of the membrane, but in this model the thickness of the fluid membrane was considered to be constant. The first step consisted of determining the density of the fluid used.

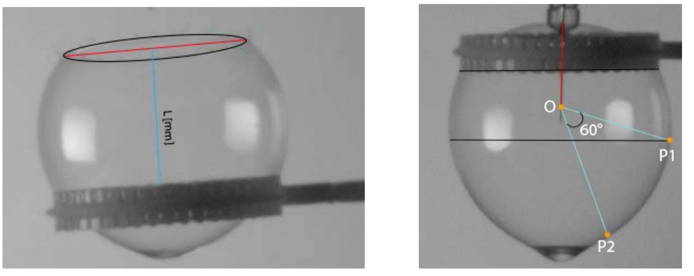

Fig. 3 – Measurements for determining the break-up speed for the bubbles on top (left) and below the plastic rod (right). In the second case, the black line defines the middle of the bubble and the red on is the needle

Using a graded syringe a known volume of fluid was weighted and the mass of the syringe was subtracted.

The density of the fluid was calculated as being the ratio between the mass and the volume.

Afterwards, bubbles of different diameters were kept on the plastic rod and weighted and the mass of the rod was subtracted (Fig. 4). The equation for the membrane thickness was obtained by knowing that the volume of fluid which forms the bubble is equal to the product between the surface of the bubble, A and the thickness of the membrane, δ and is also equal to the ratio between the mass, m and density, ρ.

$$V = \frac{m}{\rho} = A \cdot \delta \tag{8}$$

$$\delta = \frac{m}{\rho \cdot A} = \frac{m}{\rho \cdot \pi \cdot d^2} \tag{9}$$

Fig. 4 – Set-up for weighting the bubbles. The photographs were used to measure the diameter of each weighted bubble

For the study of the spontaneous break-up, the bubbles have been created from 3 fluids: commercial soap solution, vegetable oil and a polyacrylamide (PAM) solution of 10000 ppm. A few drops of these fluids have been placed upon the orifice in the plexiglas plate. Air has been pumped at different rates through the orifice and led to the formation of singular bubbles on the plate.

The air continued to be pumped at the same rate until the bubble would break on its own, phenomenon which was recorded. The break-up speed of this bubbles was calculated as well as the Ohnesorge (Oh) number.

4. RESULTS AND DISCUSSIONS

a. Experimental measurements of density and thickness

The first step consisted of the experimental determination of the density and this was obtained to be 1006.74 kg/m^3 for the commercial soap bubble solution. This value is in agreement with the expectations, as the water density is 998.23 kg/m^3, and for a dishwasher solution is about 1120 kg/m^3 [9]. As commercial soap bubble solutions have a lower concentration of soap, it is expected that its density will be closer to that of water.

The thickness obtained for different bubbles ranges from between (300 – 500) nm and the thickness versus the diameters is presented in Fig. 5. It was observed that a linear function can be defined (10) where a = $2.23 \cdot 10^{-6}$ and b = $-4.62 \cdot 10^{-6}$.

This function has been further used to approximate the average thickness of other bubbles for which only the diameter was known. However, given the limited data set, no definite conclusion can be drawn regarding the existence of a dependency between the thickness and diameter of a fluid bubble.

$$\delta = a + b \cdot d \tag{10}$$

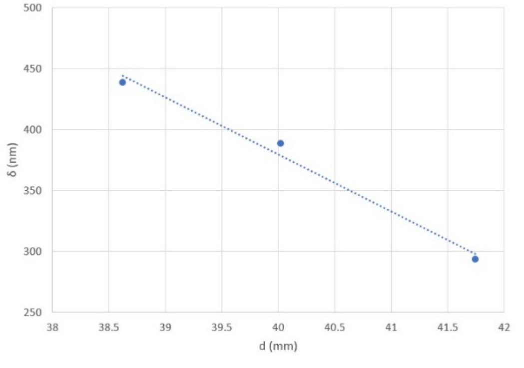

Fig. 5 – Plotted values of the membrane thickness obtained for different bubble diameters.

The obtained results were compared with results from the literature, obtained by interferometric methods; Afanasyev et al. [10] obtained for a bubble of 140 mm diameter, local thicknesses varying between (100 - 800) nm. The thicknesses obtained by them are very similar to those obtained in this paper, although the bubble evaluated by Afanasyev et al. is larger by an order of magnitude, than the ones presented here. This fact confirms the initial conclusion that between diameter and thickness there is no strict relationship of linear dependency.

b. Study on the triggered bursts

The triggered burst for the bubbles placed on top of the plastic rod has been observed to be symmetrical to the central ax of the bubble and also uniform (Fig. 6), while for the bubbles below the rod, the phenomena could be described more like a deflating of the bubble than an actual break-up (Fig. 7).

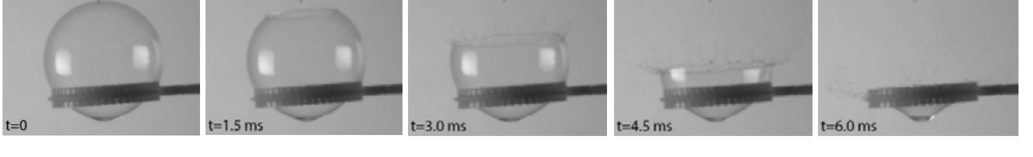

Fig. 6 – The movement of the fluid membrane after the burst for bubbles held on top of the plastic rod

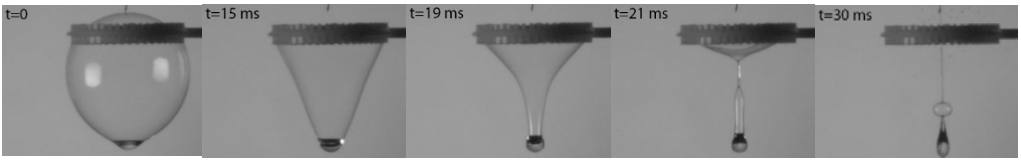

Fig. 7 – The movement of the fluid membrane after the burst for bubbles held below the plastic rod

The variation of the distance on which the membrane retracted after the break-up was measured for two bubbles on top of the rod and three bubbles below it (Fig. 8). For the bubbles held on top, the variation was approximated to be linear and the ramp was calculated, leading to the value of the break-up speed.

For the bubbles held below, the speed was also calculated as the ramp from the linear sections of the variations obtained on the OP1 and OP2 lines. Using the Taylor-Culick law (7), the surface tension has been calculated for all these bubbles. The values obtained are presented in Table 1.

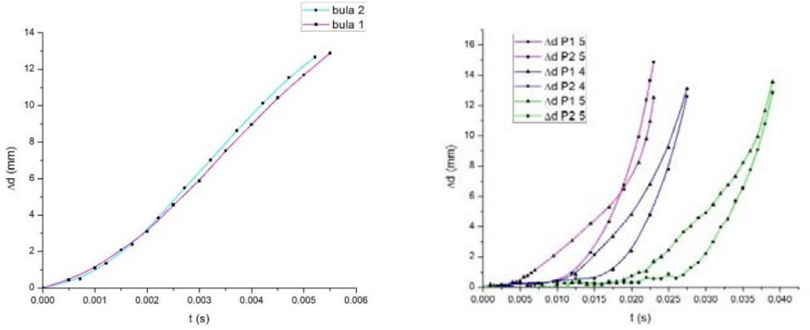

Fig. 8 – The variation in time of the distance on which the membrane retracted after the break up for bubbles on top (left) and below the rod (right).

Table 1. – The results obtained experimentally for the 5 bubbles
(“1” and “2” being those positioned on top and “3”, “4” and “5” those below the rod)

Bubble count	Initial diameter (m)	Membrane thickness (m)	Break-up speed (m/s)	Surface tension obtained (N/m)
1	0.27	$8.33 \cdot 10^{-7}$	2.8	0.039
2	0.30	$9.48 \cdot 10^{-7}$	3.0	0.037
3	0.27	$9.67 \cdot 10^{-7}$	P1 - 0.4, P2 - 1.5	P1 - 0.00008, P2 - 0.0010
4	0.26	$9.88 \cdot 10^{-7}$	P1 - 0.6, P2 - 1.4	P1 - 0.00021, P2 - 0.0009
5	0.30	$8.31 \cdot 10^{-7}$	P1 - 0.6, P2 - 1.0	P1 - 0.00013, P2 - 0.0004

The results obtained for the surface tension are close to the values reported in literature, but only for the bubbles held on top of the rod.

For the ones held below it, the values have been considered incorrect, and therefore it has been concluded that only the first type of break-up mechanism can be described by the Taylor-Culick law. Also, it has been noted that the first phenomenon happens much faster, although the initial diameter of all the bubbles is similar.

c. Study on the spontaneous bursts

Two main mechanisms have been observed over all types of fluid: break-up from the tip, which was the most expected mechanism, and from the side, which was more frequent. An average break-up speed for each fluid and the Oh number have been calculated (Table 2).

Table 2 – The break-up speeds and the Oh number obtained for the 3 fluids at different air flow rates

Fluid	Break-up speed (m/s)	Oh
Soap bubble solution	5.7	0.0015
Vegetable oil	1.4	0.154
PAM (10000 ppm)	1.05	0.038

It was observed that the highest break-up speed was recorded at the lowest Oh number, and as the Oh number increases, the speed goes to lower values until a limit is reached.

5. CONCLUSIONS

In this paper, the fluid membranes of bubbles have been studied by recording the triggered and spontaneous bursts with a speed of 14000 fps. The fluids used in this study have been a commercial soap solution, vegetable oil and a polyacrylamide solution of 10000 ppm. For the first fluid, the density has been experimentally determined. Moreover, a method for experimentally determining the thickness of the membrane has been implemented and the results obtained are in good agreement with the ones in literature. A dependency between the diameter of the bubbles and the calculated thickness has not been clearly observed.

In the case of the triggered burst, two types of break-up mechanisms have been observed, which depend on the position of the bubble. The break-up speed has been calculated for both and knowing that this speed obeys the Taylor-Culick law, the surface tension has been calculated. For the bubbles that were held on top of the plastic rod, the values obtained are close to the literature ones, whereas for the ones below the rod it has been concluded that the process cannot be described by the Taylor-Culick law, and therefore the surface tension cannot be determined by this method. In the case of the spontaneous bursts, the Oh number has been calculated and it has been concluded that the highest break-up speed was obtained for the smallest Oh number. This second type of study will be further detailed in an upcoming work.

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