Experimental Study of the Growth of Bubbles in Corrugated Tubes

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Abstract In this chapter we study some experiments with different liquids to validate theoretical results on the growth of bubbles in corrugated pipes. These experiments were performed using a high range of capillary numbers *Ca*, as well as different values of the Bond number *Bo*, the purpose is to approach the cases of inviscid and viscous limits in liquids. The experiments are done in the tubes with different diameters and different lengths with periodic corrugations and different amplitudes. We also characterized the effect of the corrugated walls on the shape and size jets of bubbles for constant flow rate.

1 Introduction

In literature there are different works studying bubbles, most of the extensive research carried out on the generation of bubbles by injection of gas into a liquid at rest has been devoted to the important case of liquids of small viscosity, for which the flow induced by the expansion and rise of the bubbles is dominated by inertial effects; see Kumar and Kuloor (1970); Oguz and Prosperetti (1993); Clift et al. (1978);

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Räbiger and Vogelpohl (1986); Longuet-Higgins et al. (1991). Applications include direct-contact operations in chemical, metallurgical, and biomedical systems, among many others. The opposite case of bubble generation in very viscous liquids is of interest in connection with polymer melts (Bird et al. 1987; Davidson and Schuler 1960; Doshi et al. 2003; Higuera 2005) and molten glasses and magmas (Manga and Stone 1993, 1994).

Results may be expressed in terms of two dimensionless numbers, the Bond number and the Capillary number. Bond number is a measure of the intensity of flotation forces respect to the surface tension

$$Bo = \frac{\rho g a^2}{\sigma}, \tag{1}$$

where ρ is the density, g is the acceleration of gravity, a is the inner radius of the capillary and σ the surface tension.

Meanwhile the capillary number is a measure of the competition between viscous forces caused by the air inlet in fluid and the surface tension forces that keep the bubble adhered with the mouth of the air injection tube where

$$Ca = \frac{\mu Q}{\sigma a^2}, \tag{2}$$

where μ is the viscosity, Q the gas flow rate which is constant.

When expressing the results in terms of these two parameters we can have a wide variety of physical conditions under which bubbles grow.

2 Experiments

It is considered the simple case of incompressible gas (air) when it is injected at constant flow rate with viscosity and density negligible into a reservoir filled of quiescent and incompressible liquid of density ρ and viscosity μ.

In experiments the air is injected through a capillary tube with a 2 mm inner radius and 40 cm length, fed by a pump from a tank and a programmable syringe pump, that maintained a constant flow, has already been shown in a previous work (Corchero et al. 2006). The purpose of using two coupled pumps is to prevent the entry of liquid into the capillary tube when liquid is injected and to measure very accurately the flow can be performed in each test. The aquarium pump passes through a bypass valve its output to the syringe pump, then it joins the capillary tube as shown in Fig. 1. The bubbles are generated by injecting controlled air into a tube with periodic corrugations filled of viscous and non viscous liquids.

The process of growth and detachment was video recorded. Subsequently, each video was digitized to have photos of events every 1/30 s. The experiments were performed by using transparent plastic tubes with different periodic corrugations

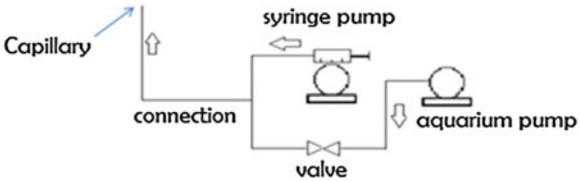

Fig. 1 Schematic array of the programmable syringe pump and the aquarium pump

and different diameters. Which were coaxially connected on the capillary pipes, perfectly upright and centered.

The liquids level in the container was always =100 mm, and its dimensions of length, width and height were 10 × 10 × 30 cm respectively.

The liquids used for the experiments were glycerin and honey for the viscous case and water for the near inviscid case.

At a temperature of about 25 °C the glycerin properties used are density $\rho = 1260\,\text{kg/m}^3$, $\mu = 1.2$ Pas and surface tension $\sigma = 6\,\text{mN/m}$. On the other hand, the honey properties depend on the type of honey at use, in this case $\rho = 1413\,\text{kg/m}^3$, $\mu = 10$ Pas and surface tension $\sigma = 33$ N/m.

The same experiments were performed with water at a temperature of about 25 °C, the properties of water at that temperature are $\rho = 998\,\text{kg/m}^3$, $\mu = 1.002$ mPa and surface tension $\sigma = 72.8\,\text{mN/m}$.

3 Results and Discussions

The corrugated tube walls have a great friction which causes the bubbles to growth slowly, ip to they reach a volume that allows the buoyance force equals to the force exerted by the viscous drag of the walls.

In this work it can be seen as in other earlier works that the volume bubble increases as the pipe radius, *R* is reduced, where *R* is the mean distance of the corrugate tube walls from the center and *R/a* is the dimensionless radius. The ratio increases non linearly with the capillary number growth and is faster than that found in a semi infinite or conical vessel (Ortiz et al. 2009; López-Villa et al. 2011).

In experiments with glycerin when $R/a = 3.7$ and the corrugation wavelength is $c/a = 7.33$ it was observed that the film thickness in between the bubble and the tube wall increases with the volume of the bubble, i. e., the capillary number increase, as shown in Fig. 2.

When the Bond number is constant and the Capillary number changes, by varying the flow provided by a programmable syringe pump, we found the behavior shown in Fig. 3. The volume grows in a near linear form with the increase of the capillary number (the flow rate increase), the behavior is shown for $R/a = 3.7$ and $Bo = 0.2$.

Figure 4 shows the bubble profiles with the values used in Fig. 3.

Others experiments were bubble performed at constant flow rate and diameter, with variations only in the wavelength of the corrugations, values were $R/a = 4.5$,

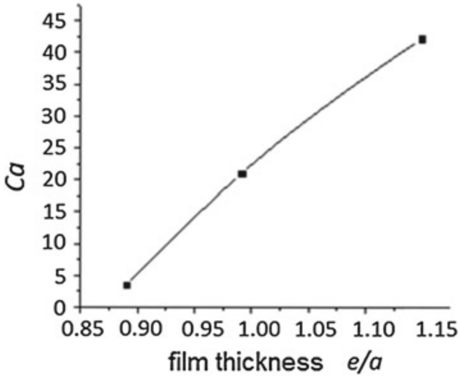

Fig. 2 plot of the capillary number against the dimensionless film thickness for in dimensionless radius $R = 3.7$ of corrugated tube and a wavelength $c/a = 7.33$ and a Bond number $Bo = 0.2$

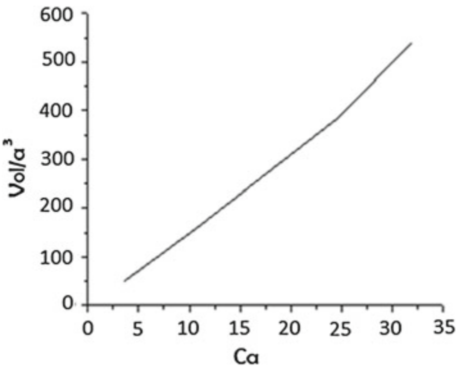

Fig. 3 Plot of the dimensionless bubble volume versus Ca, with $R/a = 3.7$ and $Bo = 0.2$

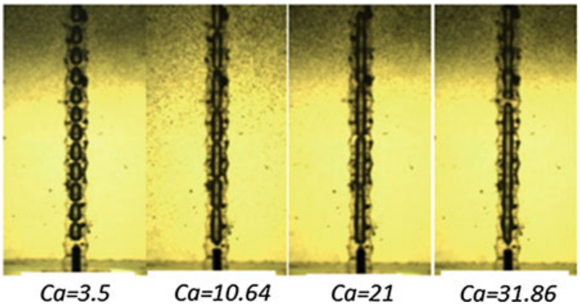

Fig. 4 Profiles of bubbles growing into tubes with wavelength $c/a = 7.33$, dimensionless radius $R/a = 3.7$ and $Bo = 0.2$ with different capillary numbers

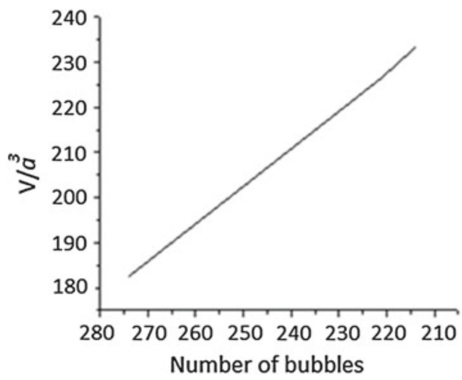

Fig. 5 Plot of the bubble volume versus the number of bubbles generated each minute, with $R/a = 3.7$, $Bo = 0.2$ and $Ca = 10.64$

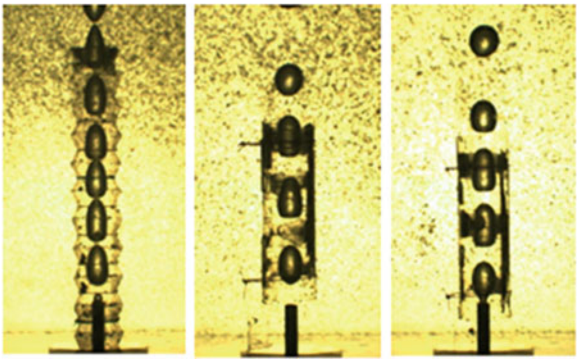

Fig. 6 Bubble profiles growing in tubes with $c/a = 6.4, 11.0$ and 15.1, dimensionless radius $R/a = 4.5$, $Bo = 0.2$, $Ca = 10.64$. Number of bubbles/min $= 274, 221, 214$, $\text{Vol}/a^3 = 182.5, 226.6, 233.3$

flow rate $25.28\,\text{cm}^3/\text{min}$, $Bo = 0.2$, $Ca = 10.64$ and $c/a = 6.4, 11.0$ and 15.1. In such experiments it was found that the bubbles reached a maximum volume at a function of the wavelength. When this distance is large, the bubble attains a volume greater than the reached when the wavelength is shorter. The bubble generation rate is a function of the period of corrugation thus if we know the flow rate and know this rate, we can know the volume of the bubbles. As a consequence the rate at which bubbles are generated decreases linearly with the increasing volume of the bubbles, this is shown in Figs. 5 and 6. We can observe the bubbles profiles with different wavelength, the same used in the plot of the Fig. 5.

We observed different bubbles profiles growing in tubes with corrugated walls at constant flow rate, in which $Ca = 10.64$, $Bo = 0.2$, and the dimensionless radii are $R/a = 3.7$, 4.5 and 5.5 (see Fig. 7). In experiments with honey we also observed dimensionless profiles similar to those observed with glycerin, but with flow rate

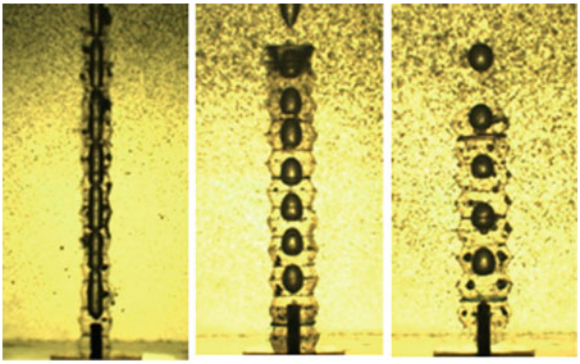

Fig. 7 Bubble profiles growing in tubes, are maintained at a constant flow rate of 25.28 cm^3/min with dimensionless radii $R/a = 3.7, 4.5, 5.5$, $Bo = 0.2$ and $Ca = 10.64$

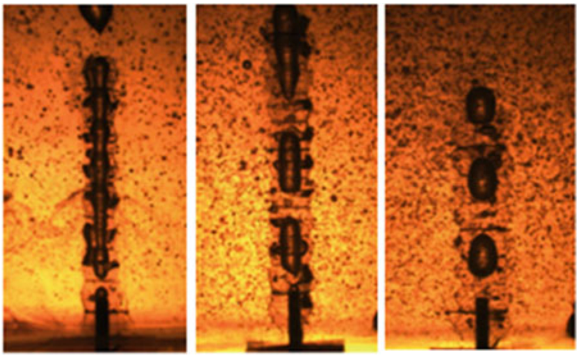

Fig. 8 Bubble profiles in tubes growing at constant flow rate of 25.28 cm^3/min with dimensionless radii $R/a = 3.7, 4.5, 5.5, 0.42$ and $Bo = 0.42$ and $Ca = 127.72$

of magnitude 25.28 cm^3/min (equal to that used with the glycerine) are bubbles of larger volume obtained for $Ca = 127.72$, $Bo = 0.42$, and dimensionless radii are $R/a = 3.7$, 4.5 and 5.5, respectively, see Fig. 8.

Experiments made with water at a flow rate of 25.28 cm^3/min show a different behavior to that of highly viscous liquids, experiments were performed with $Ca =$ 0006, $Bo = 0.134$, and the dimensionless radius $R/a = 3.7$, 4.5 and 5.5 as shown in Fig. 9.

The bubble volume is approximately constant for a wide range of capillary number (small capillary number), which has not been possible to identify with precision (see López-Villa et al. 2011). On the other hand an increasing flow, the bubbles are obtained have non-symmetrical shape see Fig. 9.

In previous works, such as Higuera (2005) and Corchero et al. (2006) we have observed the same results with a small flow.

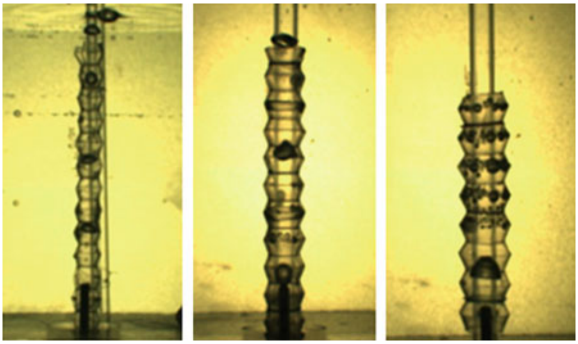

Fig. 9 Bubble profiles in tubes growing at constant flow rate of 25.28 cm^3/min with dimensionless radii $R/a = 3.7, 4.5, 5.5$, $Bo = 0.134$ and $Ca = 0.006$

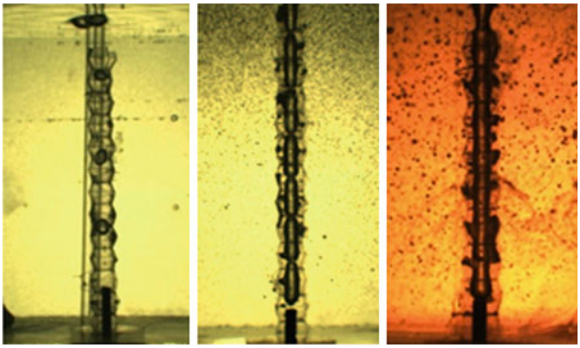

Fig. 10 Bubble profiles in water, honey and glycerin, growing in tubes with $R/a = 3.7, c/a = 7.33$, at 25.28 cm^3/min, $Bo = 0.134, 0.2, 0.42$, $Ca = 0.006, 10.64, 127.72$, dimensionless volume $V/a^3 = 61.3$, 158 and 1336 respectively

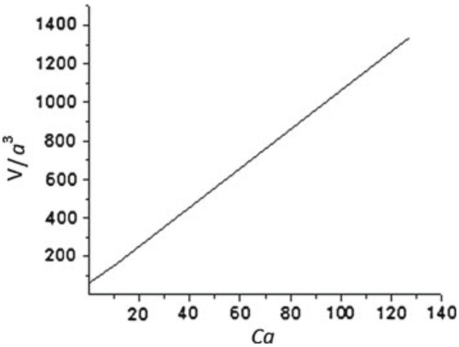

Fig. 11 Dimensionless Plot volume as a function of capillary number, *Ca,* with $R/a = 3.7$

We also performed a comparison of the three fluids used before, maintaining a constant flow rate of 25.28 cm^3/min and a dimensionless radius $R/a = 3.7$ in order to observe the difference in volume of the bubbles with a same flow rate see Fig. 10. We plot the capillary number vs the bubble volume and we compare the graph obtained to those reported in the literature, see Fig. 11.

4 Conclusions

We have found that the final volume of the bubbles depend on the dimensionless numbers *Bo* and *Ca*, therefore the increased viscosity creates a bubble of a large volume and on the other hand a greater film thickness formed between the wall and the bubble.

When Bond and Capillary numbers are kept and the radius of the tube is decreased, the volume of bubbles increases, it is similar to the fact when the wavelength of corrugations is increasing.

Thus, the corrugations of the pipe are very important in the final bubble shape.

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