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Production of Gas Bubbles in Reduced Gravity Environments

Hasan N. Oğuz
Department of Mechanical Engineering
The Johns Hopkins University, Baltimore, MD 21218
Shu Takagi
Department of Mechanical Engineering
The University of Tokyo
7-3-1, Hongo, Bunkyo-ku,
Tokyo 113, Japan
and
Masaki Misawa
Mechanical Engineering Laboratory
1-2, Namiki, Tsukuba, Ibaraki 305, Japan

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Introduction

In a wide variety of applications such as waste water treatment, biological reactors, gas-liquid reactors, blood oxygenation, purification of liquids, etc., it is necessary to produce small bubbles in liquids. Since gravity plays an essential role in currently available techniques, the adaptation of these applications to space requires the development of new tools.

Under normal gravity, bubbles are typically generated by forcing gas through an orifice in a liquid. There is a large number of studies on this topic and a comprehensive review is given by Kumar & Kuloor (1970). In this reference and many other subsequent publications the common approach is to take the bubble as an isolated object and apply a force balance. In general, the relevant forces can be

- gravitational
- surface tensional
- inertial
- viscous
- due to stagnation pressure of the injected gas
- of Marangoni type (due to temperature field or surfactants)
- due to an applied electric field.

When a growing bubble becomes large enough, the buoyancy dominates the surface tension force causing it to detach from the orifice. In the case of small growth rates, the radius of the detached bubble, R, can be determined by a static force balance between surface tension and buoyancy (Fritz 1935)

$$R_F = \left(\frac{3\sigma a}{2\rho g}\right)^{1/3} \tag{1}$$

where σ is the surface tension, a the orifice radius, ρ the liquid density, g the gravitational acceleration. Although the radius given by (1) is of limited accuracy, it serves as a good reference point for a given orifice size. As the growth rate is increased, R remains relatively constant up to a certain critical rate beyond which it is approximately given by

$$R_Q = \left(\frac{9Q^2}{8\pi^2 g}\right)^{1/5} \tag{2}$$

where Q is the gas flow rate (Oguz & Prosperetti 1993).

In space, the process is quite different and the bubble may remain attached to the orifice indefinitely. To *simulate* gravity, anyone of the forces listed above can be used to promote bubble detachment. For instance, Pamperin & Rath (1995) found that very high gas injection velocities can lead to bubble

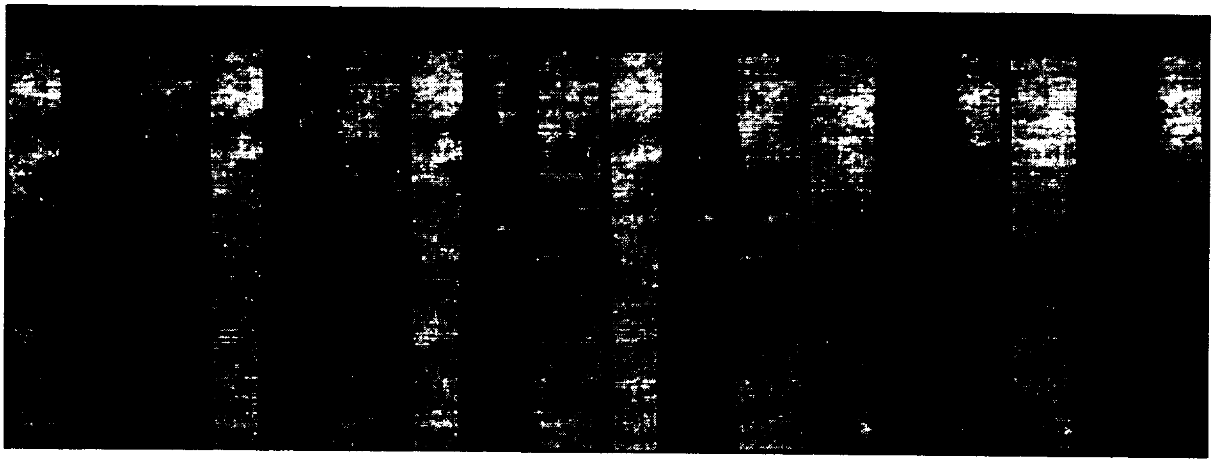


Figure 1: Selected frames from a high speed video film showing six cases of bubble growth and detachment from a needle in a tube. The inner diameter of the tube is 1.6 mm, and the inner and outer diameter of the needle is 0.58 and 0.90 mm. The air flow rate is 5 ml/mn and the water flow rates are from left to right 25, 50, 75, 99, 130, 162 ml/mn.

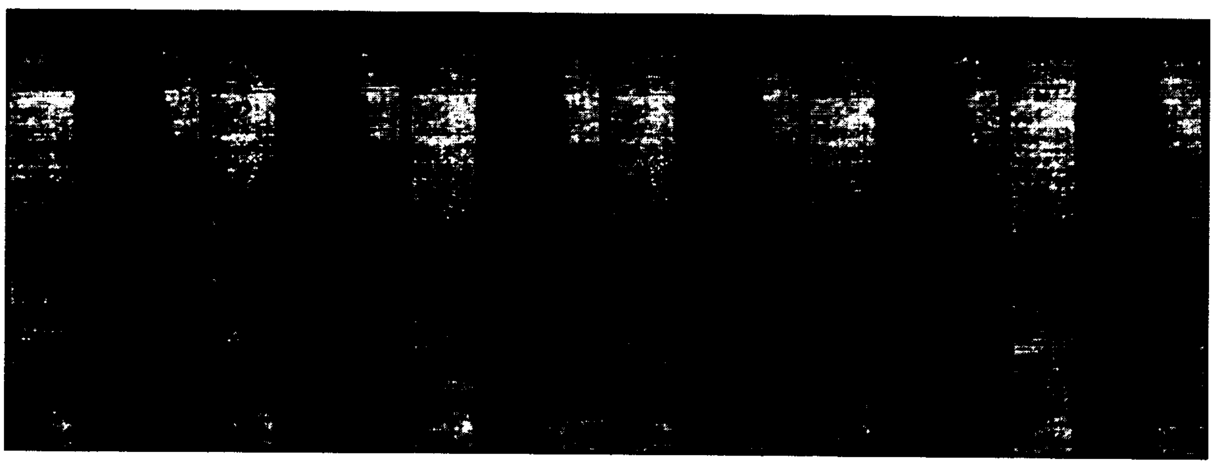
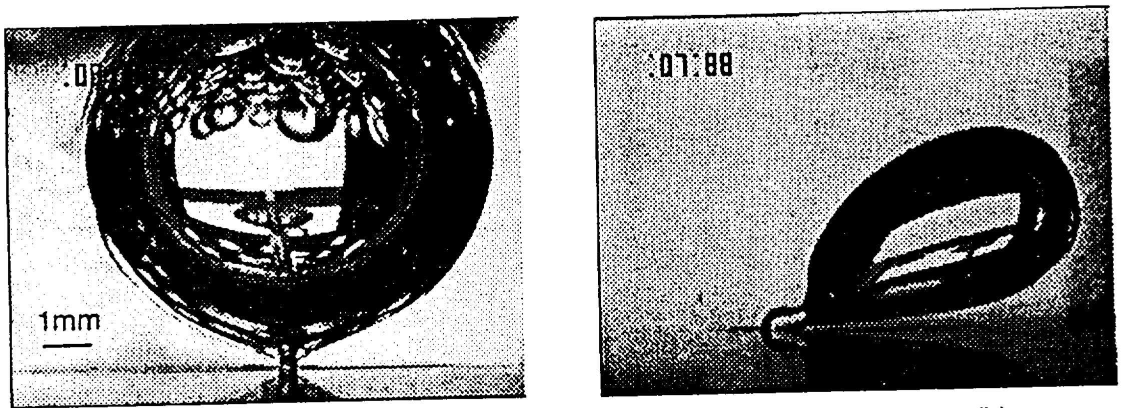


Figure 2: Selected frames from a high speed video film showing six cases of bubble growth and detachment from a needle in a tube. The inner diameter of the tube is 1.6 mm, and the inner and outer diameter of the needle is 0.58 and 0.90 mm. The air flow rate is 29 ml/mn and the water flow rates are from left to right 25, 50, 75, 99, 112, 130 ml/mn.

formation even under weightlessness conditions. Conceivably, one can also impose an electric field or a temperature field to replace the buoyancy force. However, the most practical approach seems to impose an ambient flow to force bubbles out the orifice (Kim et al 1994). The usefulness of this idea has been recognized a long time ago (Chuang & Goldschmidt 1970). In this paper, we are interested in the effect of an imposed flow in 0 and 1 g. Specifically, we investigate the process of bubble formation subject to a parallel and a cross flow. In the case of parallel flow, we have a hypodermic needle in a tube from which bubbles can be produced. On the other hand, the cross flow condition is established by forcing bubbles through an orifice on a wall in a shear flow. The first series of experiments have been performed under normal gravity conditions and the working fluid was water. A high quality microgravity facility has been used for the second type and silicone oil is used as the host liquid.



(a) (b)

Figure 3: Images of a bubble growing from an orifice of diameter 1.7 mm in 0.0005 g under (a) quiescent conditions and (b) a shear flow of U/L=15 cm/s.cm. Average growth rate of the bubble is about 1.5 cm^3/s.

1 Experiments

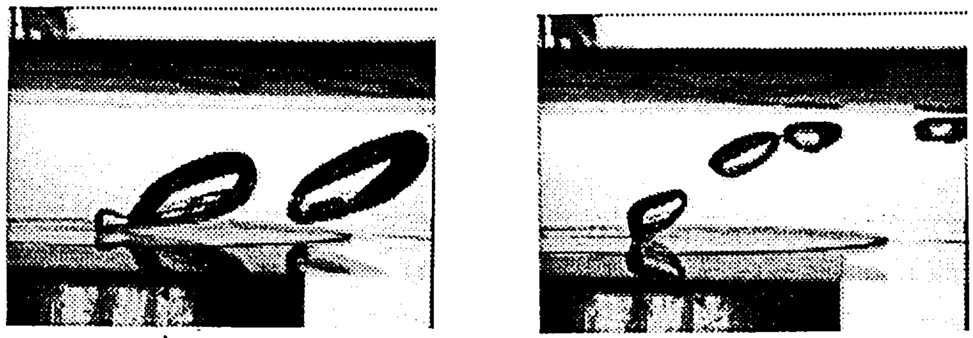
Here we report on some preliminary experiments of air bubble formation from a needle in a plexiglass tube filled with water. In Fig. 1 we show selected frames from a series of high speed movies. In all the cases shown in the figure the gas flow rate is held constant at 0.083 cm^3/s and the water flow rate is increased from 0.42 cm^3/s (left) to 2.7 cm^3/s (right). We have observed a substantial reduction in bubble size as the water flow rate is increased while the gas flow rate is kept constant. This behavior is common to other gas flow rates as well (Fig. 2). For sufficiently low water flow rates, bubble formation is quite regular with little or no variation from one bubble to another. This regime is ideal for reliable production of bubbles of specified size. However, above a certain critical flow rate an elongated bubble is seen to remain attached to the needle.

As the liquid flow rate is increased further the size of the detached bubbles starts showing substantial variance and the average bubble size tends to be higher than the minimum size of the regular regime. The lower part of the bubble is stable while the upper part oscillates and sheds occasional bubbles much like a flame and hence we use the term "bubble flame" to refer to it. This phenomenon can be explained in light of the studies by Frankel & Weihs (1985, 1987). They investigated the effect of stretching for inviscid and viscous jets. In the present case, the axial velocity at the top of the bubble is higher than at its bottom causing a fair amount of stretching that stabilizes the bubble. Although we have a gas jet in a confined geometry, the analysis of Frankel & Weihs is applicable to our case at least qualitatively. It must be noted that theoretical models that rely on the sphericity of the bubble will fail in this regime.

If the object is to minimize bubble size, the liquid flow rate must be maintained at the critical level that defines the boundary between the regular formation and the bubble flame regimes. We have found that the minimum bubble radius is always greater than the needle radius and increases with increasing gas flow rates.

Microgravity experiments

In the second set of experiments the effect of a shear flow on a bubble growing from an orifice is investigated. This situation is of particular interest to two-phase flow studies in relation to boiling heat transfer.



(a) (b)

Figure 4: Comparison of bubble growth and detachment from an orifice of diameter 1.7 mm in (a) 0.0005 g and (b) 1 g subject to a shear flow of U/L=15 cm/s.cm. Average growth rate of the bubble is about 1.5 cm^3/s.

A series of experiments have been performed under normal and micro gravity conditions in Japan and more are planned for this year.

The system consists of a small plexiglass reservoir filled with silicon oil. A thin belt tensioned between two solid cylinders is installed in the middle of the reservoir providing a shear flow across the 15mm gap between the moving belt and the bottom wall of the reservoir. Bubbles are injected into silicone oil from the bottom through a hole of diameter 1.7 mm.

The apparatus has been installed in a bus module at the Japan Microgravity Center (JAMIC: Hokkaido, Japan) and subjected to a series of experiments with gravity levels as low as $10^{-4}g$ for 10 seconds. Such a long duration of high quality microgravity has been achieved during free fall in a mine shaft about 710 m deep.

A number of free fall experiments have been conducted and bubble growth and detachment has been recorded by means of a CCD camera. The details of this experiment will be published elsewhere. Here, we give a brief summary of the important features of this experiment. Figure 3 shows snapshots of the bubble formation process with and without an imposed shear flow under 0.0005 g. It is noted that when both the gravity and the flow are absent, detachment does not take place. This is consistent with Pamperin & Rath (1995) who reported that no detachment is possible when the Weber number

$$We = \frac{2u_g^2 a \rho_g}{\sigma} < 8, \tag{3}$$

where u_g is the gas velocity at the orifice. Another factor inhibiting bubble departure is viscosity of the liquid which is much higher in our experiments. However, when a shear flow is applied, viscous forces are acting favorably to promote detachment (see panel (b) of fig. 3). In this case, bubble pinchoff seems to be triggered by the deformation of the bubble under viscous drag and inertial forces.

Theory

We have carried out boundary-integral simulations of the formation of a bubble in a tube. Comparison with the experiment is favorable when the water flow rate is sufficiently small. In fig. 5 we show two sequences of computed bubble shapes corresponding to the cases (c) of fig. 1 and (c) of fig. 2. At

(a)

(b)

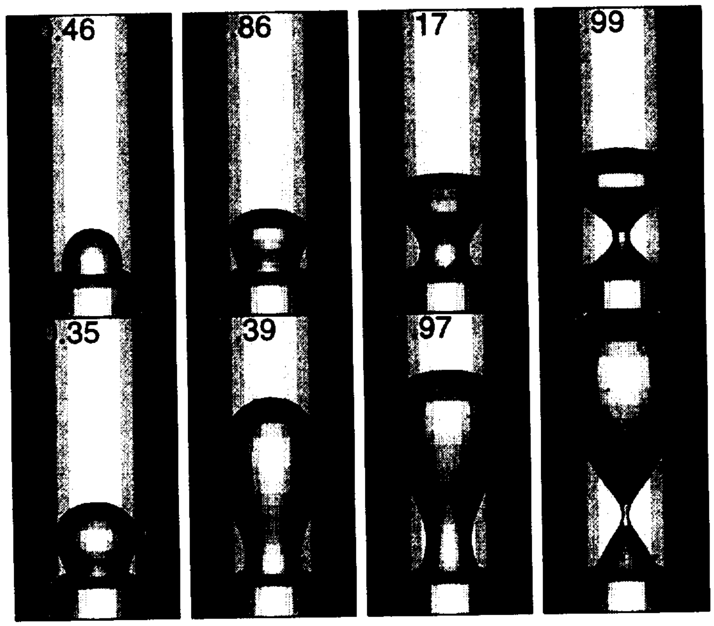


Figure 5: Axisymmetric boundary integral simulations of bubble growth and detachment from a needle in a tube. The inner diameter of the tube is 1.6 mm, and the inner and outer diameter of the needle is 0.58 and 0.90 mm. The air flow rate is (a) 5 and (b) 29 ml/mn. The water flow rate is 75 ml/mn. Times in ms.

higher flow rates the experimentally observed behavior cannot be duplicated by the boundary integral simulations because the inviscid flow assumption leads to numerical artifacts. For instance, our present simulations indicate that the needle wall thickness causes the bubble to detach prematurely. This may be due to the high stagnation pressures generated by the corner flow around the needle. In reality, flow separation prevents high speed corner flows. There are other discrepancies between the simulations and the experiments especially for small bubbles. The neglect of viscous drag is the primary cause. Despite these difference, a very good agreement between the experiment and the numerical simulations has been obtained for cases with relatively low liquid flow rates.

Within the framework of the assumptions, potential-flow boundary-integral method is very accurate but of limited use due to reasons stated above. Ultimately, one needs solve the Navier-Stokes equations with a free surface. There are several approaches to this problem and, most notably, the front tracking method of Unverdi & Tryggvason (1992) is particularly appealing to us because the bubble liquid interface is discretized in the same way as in the boundary integral method. In fig. 6 we show front tracking simulations of gas injection in a shear flow. The main problem with this type of code is the limitation for the viscosity and density ratios and the inaccurate way with which the surface tension effects are handled. These factors inhibit the pinchoff and an elongated bubble is predicted by the simulation. By the use of higher resolution and better algorithms we hope to solve this problem in the future.

Acknowledgment

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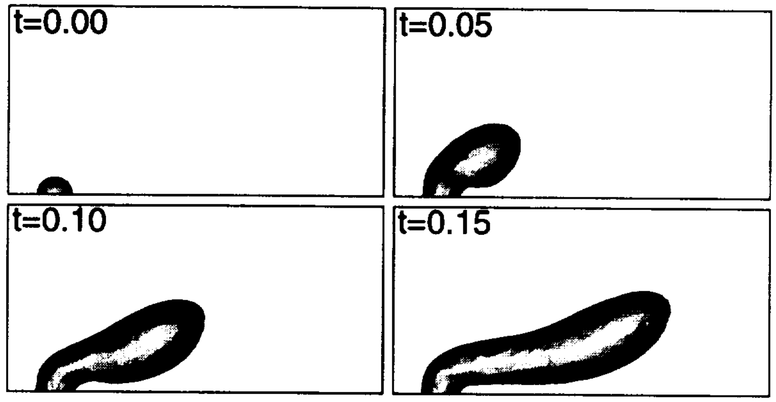

Figure 6: Simulations of bubble injection in a shear flow of 37 cm/s.cm as computed by a front tracking code based on Unverdi & Tryggvason (1992). The orifice diameter is 1.5 mm and the injection rate is 1.5 cm^3/s. The surface tension is 21 dyn/cm. The viscosity of the liquid is 0.49 gm/cm.s and the viscosity/density ratios are 100. Times in seconds.

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