European Journal of Mechanics B/Fluids 53 (2015) 24–36

Contents lists available at ScienceDirect

European Journal of Mechanics B/Fluids

journal homepage: www.elsevier.com/locate/ejmflu

The formation of a bubble from a submerged orifice

Jonathan A. Simmons [a,*], James E. Sprittles [b], Yulii D. Shikhmurzaev [a]

[a] School of Mathematics, University of Birmingham, Edgbaston, Birmingham, B15 2TT, United Kingdom

[b] Mathematics Institute, University of Warwick, Coventry, CV4 7AL, United Kingdom

ARTICLE INFO

Article history:
Received 25 February 2014
Received in revised form
12 September 2014
Accepted 13 January 2015
Available online 23 March 2015

Keywords:
Bubble formation
Pinch-off
Singular flows
Finite element method

ABSTRACT

The formation of a single bubble from an orifice in a solid surface, submerged in an incompressible, viscous Newtonian liquid, is simulated. The finite element method is used to capture the multiscale physics associated with the problem and to track the evolution of the free surface explicitly. The results are compared to a recent experimental analysis and then used to obtain the global characteristics of the process, the formation time and volume of the bubble, for a range of orifice radii; Ohnesorge numbers, which combine the material parameters of the liquid; and volumetric gas flow rates. These benchmark calculations, for the parameter space of interest, are then utilised to validate a selection of scaling laws found in the literature for two regimes of bubble formation, the regimes of low and high gas flow rates.

© 2015 Elsevier Masson SAS. All rights reserved.

1. Introduction

The controlled production of small gas bubbles is of critical importance to many processes found in the chemical, petrochemical, nuclear, metallurgical and biomedical industries. Subsequently, a vast body of research exists on the subject [1–5]. Due to the complex mechanisms involved in this fundamental process, the computational, experimental and theoretical literature has focused on the case of generating a bubble by pumping gas through a single formation site, namely a submerged nozzle [6–10] or, as is the case in this work, an upward facing orifice in a submerged solid surface [11–14].

Some authors have considered the case of inflating a bubble under a constant gas pressure with the volumetric gas flow rate varying as the bubble inflates [15–18]. Others have considered the case where the volumetric gas flow rate is determined by the difference between some ambient pressure away from the bubble and the gas pressure in a chamber that is connected to the formation site [19,7]. However, the most popular method, and the method employed here, is to apply a constant volumetric gas flow rate through the formation site and allow the gas pressure to vary in time [8,20,21,13].

1.1. Experimental observations

The majority of experimental studies examine a continuous chain of bubbles [11,12,14]. A bubble grows whilst attached to the formation site as gas is pumped through the site at a constant flow rate. As the volume of the bubble increases, the influence of buoyancy becomes more important. The bubble seeks to minimise its surface area at a given volume and so a 'neck' develops in the bubble as the longitudinal curvature of the free surface changes sign at some point just above the three phase solid–liquid–gas contact line. The difference in pressure between the base and the apex of the bubble then drives the thinning of this neck as the free surface begins to pinch-off (see Fig. 1). This leads to the eventual break up of the bubble into two parts; a new bubble is released and rises away from the formation site under buoyancy, whilst the residual bubble, that is left attached to the formation site, begins to grow. This process repeats itself, thus producing a chain of bubbles.

The aim of many studies has been to find the global characteristics of the formation process, such as the frequency of formation and the volume of the bubbles that are formed, for a given set of material parameters (e.g. liquid density and viscosity), design parameters (e.g. orifice radius, wettability of substrate) and regime parameters (e.g. gas flow rate). These studies provide potentially useful material for comparing theoretical results with experiments. However, global characteristics of bubble formation in a chain accumulate several complex phenomena, and it is desirable to have a more detailed picture of each of them and of their interaction.

* Corresponding author.
E-mail addresses: simmonsj@maths.bham.ac.uk (J.A. Simmons), j.e.sprittles@warwick.ac.uk (J.E. Sprittles), y.d.shikhmurzaev@bham.ac.uk (Y.D. Shikhmurzaev).

http://dx.doi.org/10.1016/j.euromechflu.2015.01.003
0997-7546/© 2015 Elsevier Masson SAS. All rights reserved.

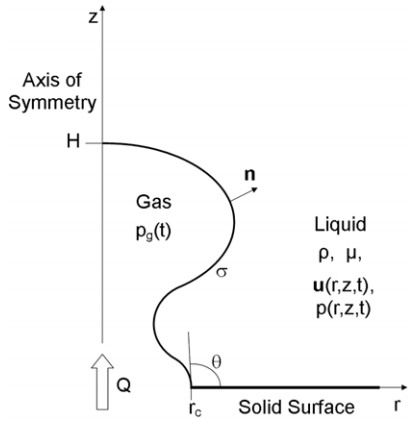

Fig. 1. A sketch of the flow domain in the (r, z)-plane.

Theoretical and early computational studies focused on the behaviour of a single bubble which grows from some initial state up until the break up of the free surface is approached [6,8,22]. The mathematical difficulties of handling the topological change associated with the complete break up of the bubble prohibited any further progress and so, in this case, the formation time period and the volume of the bubble above the point of minimum neck radius are of interest and have been investigated. Here, the break up is assumed to be a local effect that does not affect the global dynamics of the formation process.

Experimental and theoretical studies identified three regimes for the formation of bubbles under a constant gas flow rate [23,11]. For a given set of material and design parameters, the first of these regimes occurs at small gas flow rates and is known as the 'static' regime. In this regime, the volume of the bubbles formed is independent of flow rate, and therefore a decrease in the flow rate results in an increase in the formation time. Consequently, it is not possible to produce a bubble with a volume smaller than this limiting volume. Fritz [24] suggested that this limiting final volume is proportional to the orifice radius. This, as well as other scaling laws are considered in Section 5.

At greater flow rates, bubble formation enters the 'dynamic' regime. It is now the formation time that approaches a limiting value, resulting in an increase of bubble volume V_d with flow rate Q. In this regime, some authors used spherical bubble models to propose scaling laws for the bubble volume. Davidson and Schüler [16] and Oğuz and Prosperetti [7] proposed that $V_d \propto Q^{\frac{6}{5}}$ for bubble formation in an inviscid liquid, whilst, Wong et al. [8] suggested that $V_d \propto Q^{\frac{3}{4}}$ in the case of a highly viscous liquid.

Finally, under even greater flow rates, bubble formation enters the 'turbulent' regime. Here the motion is chaotic with successive bubbles coalescing with each other above the formation site. The transition between these three regimes is dependent on all of the material and design parameters involved. For instance, in the case of an orifice, the wettability of the substrate is important to the formation process if it is not sufficiently large enough and so the contact line is free to move along the solid surface [25–29].

1.2. Theoretical progress

Under sufficiently small gas flow rates, the initial growth of a single bubble may be accurately modelled as a quasi-static process, an approach that has also been utilised for the description of the formation of liquid drops [30,31]. By assuming that the fluid velocities are negligible, one can derive the Young–Laplace equation, which balances the difference in the gas and hydrostatic pressures with the capillary pressure. This can be solved to find the free surface profile of a bubble at a particular volume. A series of successive profiles can be found which are in very good agreement with experiments that describe the initial evolution of a bubble [32,6, 33–40].

However, once the neck forms and the pinch-off process begins, the liquid velocities adjacent to the point of minimum neck radius are no longer negligible. Due to the dynamics associated with the relatively large liquid velocities involved at this stage, the quasi-static approach is no longer valid and thus, in general, one cannot expect to accurately predict the final volume of a newly formed bubble this way.

In an attempt to describe some aspects of the dynamic problem, early mathematical models of single bubble formation under a constant gas flow rate were based upon global force balances. The first 'one-stage' models for highly viscous [15] and inviscid liquids [16,41], which involved the bubble growing spherically, were developed into various 'two-stage' models for highly viscous [42,43] and inviscid liquids [44,45] by adding a detachment stage to the spherical expansion stage. Once the spherical bubble had reached a certain volume, it translates away from the formation site but remains in contact with it via a cylindrical column of gas. The bubble is said to detach when certain criteria are met, such as the column reaches a certain height. Although these semi-empirical models are seen to give good agreement in certain regimes [4], to accurately describe the whole parameter space of interest, the use of complex computational techniques is needed.

1.3. Computational approaches

To solve the unsteady free-boundary problem of bubble formation from an orifice or nozzle, subject to the forces of gravity, inertia, viscosity and capillarity, the development of computational fluid dynamics techniques is required. Much of the early work in this direction was concerned with the axisymmetric generation of a single bubble. The first non-spherical methods involved various finite difference schemes to solve equations imposed on the bubble surface [46–50] before the boundary integral method, which can be used to reduce the problem's dimensionality to one, was used to study bubble formation in either the inviscid [51,7,22,52] or highly viscous flow regime [8,53].

Since then, the majority of work on bubble generation has focused on the influence of the material, design and regime parameters on the global characteristics of the flow using the volume-of-fluid method [54], and its improved variants which utilise level-set methods [55,13,56–59]. Due to the simple manner in which topological changes are 'automatically' handled, such techniques have proved successful at describing many features of the bubble formation phenomenon, including the wake effect of a preceding bubble on subsequent bubbles in a chain, where the size of forming bubbles are assumed sufficiently large and hence the details of how the topological transition (i.e. the break up of the bubble) takes place are relatively unimportant. However, as noted in [60], there is no guarantee that the physics associated with this transition has been properly accounted for. This aspect becomes more important when the size of forming bubbles is small.

Despite the advantages of volume-of-fluid based methods, as a relatively simple way of handling the global dynamics, it is well known that this class of numerical techniques are not well suited to resolving the multiscale physics which becomes critical in 'singular' flows, i.e. those in which liquid bodies coalesce [61,62] or divide [63,64]. For instance, for a millimetre-sized bubble, experiments are able to resolve the minimum neck radius down to tens of microns [65,9,66,67], whilst numerical methods have thus far failed to capture these scales and often artificially truncate the simulation far above the scales which are still well within the realm of

Download English Version:

https://daneshyari.com/en/article/7051300

Download Persian Version:

https://daneshyari.com/article/7051300

Daneshyari.com