International Journal of Multiphase Flow 74 (2015) 59–78

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

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

Numerical investigation of quasi-static bubble growth and detachment from submerged orifices in isothermal liquid pools: The effect of varying fluid properties and gravity levels

A. Georgoulas [a,b,*], P. Koukouvinis [c,d], M. Gavaises [c], M. Marengo [a,e]

[a] Department of Engineering, University of Bergamo, Viale Marconi 5, 24044 Dalmine (BG), Italy
[b] Engine Research and Development Centre, Caterpillar Inc., Frank Perkins Parkway, PE1 5FQ Peterborough, UK
[c] School of Engineering and Mathematical Sciences, City University London, Northampton Square, London EC1V 0HB, UK
[d] Caterpillar Fuel Systems (CFS), Mossville, IL, USA
[e] School of Computing, Engineering and Mathematics, Cockcroft Building, Lewes Road, University of Brighton, Brighton, UK

ARTICLE INFO

Article history:
Received 28 December 2014
Received in revised form 4 April 2015
Accepted 19 April 2015
Available online 29 April 2015

Keywords:
Two-phase flow
Numerical simulation
VOF method
Adiabatic bubble dynamics
Bubble detachment characteristics

ABSTRACT

The present investigation, identifies the exact quantitative effects of fundamental parameters, on the detachment characteristics of isolated bubbles, emanating quasi-statically from submerged orifices into isothermal liquid pools. For this purpose, a Volume of Fluid (VOF) based interface capturing approach is further improved, for the conduction of axisymmetric and 3D numerical experiments on adiabatic bubble growth dynamics. The predictions of the model, are quantitatively validated against literature available experimental data, showing excellent agreement. Two series of numerical experiments are performed, quantitatively exploring the parametric effects of the liquid phase properties in five different gravity levels, and the effect of the gravity vector direction inclination angle, respectively. It is found that the bubble detachment characteristics, are more sensitive in the variation of the surface tension, liquid phase density and gravity, while the effect of liquid phase dynamic viscosity is generally minimal. From dimensionless analysis, two correlations are derived, which for the examined range of Eötvos numbers, are able to predict the equivalent bubble detachment diameter and the bubble detachment time, respectively. It is also found that the bubble detachment characteristics, reduce significantly as the gravity vector direction gradually deviates from being parallel to the bubble injection orifice, following a non-linear decrease.

Introduction

The investigation of bubble growth and detachment has received a lot of attention over the last years, due to its occurrence in a wide range of domestic and industrial applications as well as because it is considered to be a fundamental process, for understanding more complicated phenomena such as boiling. Application examples include amongst others, heat exchangers, electronic cooling, chemical processing, emulsion preparation in boilers, beer production and waste water remediation. Also in space technology the bubble dynamics are important for cryocoolers and for two-phase thermal systems, like thermosyphons. However, there is still an incomplete understanding of the fundamental physics of bubble dynamics, at small scales as well as at non-trivial geometrical configurations. Therefore, the isolation and understanding of the influence of various fundamental controlling parameters individually, is necessary. In order to investigate bubble dynamics, an adiabatic/isothermal approach is often used, where gas/vapour bubbles are injected into liquid pools at isothermal/saturation conditions, from a submerged orifice. With such an approach, the bubble growth and detachment process can be carefully controlled, allowing thus the detailed quantitative investigation of the effect of fundamental controlling parameters.

During bubble formation at the tip of an orifice, the interaction between the gas/liquid or vapour/liquid phases is governed by a balance between aiding and restraining forces (Albadawi et al., 2013a; Di Bari and Robinson, 2013a; Di Bari et al., 2013). In more detail, the gas injection momentum, the pressure difference and the buoyancy forces are aiding the bubble growth and detachment process, while the inertia, viscous and surface tension forces tend to keep the bubble attached to the orifice. For the case of single bubble growth and detachment two different regimes have been identified (Benzing and Myers, 1955; Oguz and Prosperetti, 1993). In the first regime, where the gas injection flow rates are

* Corresponding author at: Department of Engineering, University of Bergamo, Viale Marconi 5, 24044 Dalmine (BG), Italy. Tel.: +39 0352052067.
E-mail address: anastasios.georgoulas@unibg.it (A. Georgoulas).

http://dx.doi.org/10.1016/j.ijmultiphaseflow.2015.04.008
0301-9322/

smaller than a critical value, the gas momentum and liquid inertia have much smaller influence compared to the surface tension and viscous forces. As a result, the buoyancy force is balanced mainly by surface tension and viscous effects, and the bubble detachment diameters are almost independent of gas flow rate in this regime. This regime is also known as quasi-static bubble growth regime (Di Bari et al., 2013; Gerlach et al., 2005). In contrast, beyond the critical gas flow rate (for a given orifice size), the effects of gas momentum, gas shear, pressure force, and liquid inertia are important. Therefore, in this second regime the bubble-departure diameter increases with respect to the flow rate, being also strongly dependent upon the orifice size (Subramani et al., 2007). Below a critical orifice size, the bubble detachment diameter increases with the corresponding increase of the orifice diameter, while an opposite behaviour is observed for higher orifice diameters (Di Marco, 2005; Kasimsetty et al., 2007; Subramani et al., 2007). The present numerical investigation, focuses on the first regime of quasi-static bubble growth.

So far, many experimental, analytical and lately numerical works in the literature have been focused on the adiabatic gas/vapour injected bubble growth dynamics. In the early work of Davidson and Schüler (1960), an attempt is made to understand the phenomenon of bubble growth in both water and mineral oil, from various orifice diameters through experimental investigations. Later, several works have been focused in tracking the bubble shape and departure frequency for a variety of surrounding liquids (McCann and Prince, 1969; Swope, 1971; Walters and Davidson, 1962, 1963). The advancement of experimental measuring techniques the following decades, provided a great number of experimental works focusing on the adiabatic bubble growth and detachment characteristics, giving detailed insight regarding the influence of various controlling parameters such as orifice diameter, gas injection flow rate, surface tension, gas–liquid contact angles, viscosity and density ratios (Di Bari and Robinson, 2013b; Byakova et al., 2003; Tsuge et al., 2006; Zhang and Shoji, 2001; Zhu et al., 2010). Moreover, several researchers have also been focused in the process of adiabatic bubble formation and detachment under reduced gravity conditions (Chakraborty et al., 2009; Kim et al., 1994; Pamperin and Rath, 1995; Tsuge et al., 1997), identifying three distinct regimes during bubble growth in micro-gravity, the static, the dynamic and the turbulent regime. Finally, a considerable number of experimental works have been also focused in the effect of the presence of electric fields in the bubble growth and detachment characteristics (Di Bari and Robinson, 2013b; Di Marco et al., 2003).

All the above experimental efforts, have also generated a large number of different theoretical models that describe the process of adiabatic bubble growth and detachment from submerged orifices, based on different equations and laws. The early theoretical works on bubble growth were focused on the investigation of gas/liquid interfaces to predict the bubble behaviour, assuming that the bubble maintains a spherical shape (Davidson and Schüler, 1960; Walters and Davidson, 1963). Oguz and Prosperetti (1993) predicted the bubble volume, considering a force balance between buoyancy and surface tension, applying a Boundary Integral Method for the interface position. The Young–Laplace equation has also been applied for tracking the interface position during the process of bubble growth (Gerlach et al., 2005; Lee and Tien, 2009). However, the main limitation of the majority of these theoretical approaches is their inability to account for the viscous effects as well as the necking and pinch-off stages, before detachment.

Over the last decades, the continuous improvement in the available computational resources and the development of robust numerical methods, allowed the simulation of complex gas/liquid interface deformation in viscous fluid flows, by using either the Eulerian interface capturing or the Lagrangian front tracking approaches. Both of these numerical techniques treat the two phases as a mixture, following a single fluid approach and solving a single set of Navier–Stokes equations typically on a fixed grid, with the mixture properties calculated in terms of the interface position. In front tracking methods (Unverdi and Tryggvason, 1992), the front is represented by a Lagrangian interface which is tracked using suitable adaptive marker elements, and advected using the flow field that is solved on a stationary mesh. Then, the details of the new position of the front are transferred to the fluid flow on the fixed grid, using a smooth distribution function. An extended version of this method (Hua and Lou, 2007), has been used for the study of bubble pinch-off, from a nozzle immersed in quiescent water by Quan and Hua (2008). On the other hand, with interface capturing methods, the interface is reconstructed from a volume fraction field which is advected by the fluid mixture velocity, on a fixed Eulerian grid. The most widely used interface capturing approaches are the Volume of Fluid (VOF) method and the Level Set (LS) method or a combination of these two, known as Combined Level Set and Volume of Fluid (CLSVOF) method. All these three methods, have been extensively developed and validated for a broad range of two-phase flows, including bubble flows. Worth mentioning examples on adiabatic bubble growth and detachment include the works of Gerlach et al. (2007), Pianet et al. (2010), Chakraborty et al. (2011), Albadawi et al. (2012, 2013a,b), Di Bari et al. (2013). Other, different but quite promising numerical techniques for the investigation of bubble dynamics, that differ from the widely used, grid based CFD techniques of VOF, LS and CLSVOF, are the Smooth Particle Hydrodynamics (SPH) method (Das and Das, 2009, 2013) and the Lattice Boltzmann Method (LBM) (Frank et al., 2005).

It is worth mentioning that despite the large number of the experimental, analytical and numerical works so far, most of them deal with the formation, growth, and departure of spherical or non-spherical bubbles that follow a symmetric growth and detachment over the orifice mouth, using mainly water and air as the working fluids. In more detail, most of these works examine the effect of vapour injection mass flow rate and/or orifice geometrical characteristics and some works address the effects of surface tension, density and viscosity ratios as well as micro-gravity and/or hyper-gravity conditions but not in a comprehensive, quantitative manner. Furthermore, asymmetry in bubble shape during its growth and detachment is not uncommon, in real technological applications. Phase change induced bubble nucleation over inclined surfaces, can easily generate asymmetric bubble growth and detachment. Therefore, the numerical simulation of asymmetric bubble growth and detachment can provide valuable insight regarding the formation, sliding and detachment of bubbles over inclined surfaces.

Usually, the generated bubbles become asymmetric either when the orifice plane is inclined to the horizontal or under the influence of a cross flow. Gas/vapour bubble growth and detachment from an orifice mouth in a liquid cross flow is a quite common situation and it has already been investigated by various researchers throughout the years (Marshall et al., 1993; Forrester and Rielly, 1998), providing great insight regarding the shape evolution of the generated bubbles in different gas/liquid mass flow rates. However, the influence of orifice or orifice plate inclination on adiabatic bubble growth and detachment characteristics, has not yet been fully investigated. According to the authors' best knowledge, the only efforts in this direction are made by Kumar and Kuloor (1970), Das and Das (2013) and Di Marco et al. (2013). The understanding of the influence of orifice inclination on the bubble volume evolution as well as on its departure frequency can be considered to be essential. The orifice inclination is expected to alter significantly the hydrodynamics of the growing