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A numerical study of quasi-static gas injected bubble growth: Some aspects of gravity

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ABSTRACT

In the present investigation, adiabatic gas bubble growth from a submerged orifice has been numerically simulated. The growth of the bubble is described by the full Navier–Stokes equations which have been solved by the finite-volume method using the commercial software package TransAT. The numerical simulations have been validated against detailed experimental measurements including the position of the centre of gravity, the curvature profiles and the departure volume. Subsequent to this the CFD platform was used to study some aspects of the influence of gravity level on bubble growth dynamics. In particular, the influence of gravity in the range of $0.1 \leqslant g/g^* \leqslant 1.5$ is investigated and the subsequent influence on the bubble formation and departure characteristics are discussed.

1. Introduction

Nucleate boiling is used in many heat transfer applications because of the comparatively low thermal resistance associated with it. It is characterized by the rapid formation of a large number of vapour bubbles on a superheated surface submersed in a liquid. The boiling phenomena has had a fundamental influence on the development of human kind, from early use in water purification and cooking to the development of the steam engine to its use in modern thermal management hardware in space technology. Currently and in the future boiling will play an important role in a vast array of domestic and industrial technologies.

Even though it has had a notable influence on the development of human technology and life in general, boiling as a science only commenced near the beginning of the last century. From the first theoretical study of Lord Rayleigh [1], to the boiling curves produced by Nukiyama [2] and onward to the parabolic flights and space gravity experiments of Lee and Merte [3] and Di Marco et al. [4], the *Science of Boiling* has and will continue to develop until the phenomenon is completely understood.

As technology has developed so has the sophistication of nucleate boiling research. Early analytical studies spanning the early to mid 1900s focussed on specific scenarios of boiling which required very simplified geometries and thermal–hydraulic conditions. Experimental nucleate boiling research matured in the 1960s as a result of the wave of experimental work that was largely driven by the space race. The ensuing 30 years of research had been predominantly experimental with some numerical simulations appearing in the 1990s and early 2000s [5–9]. For the earlier numerical work, the complexity of the problem and the computational techniques and resources available at the time necessitated that simplifications be made with regard to one or more aspects of the bubble geometry and/or empirical or adjustable parameters were used to deal with aspects of the physics which were too difficult to simulate at the time.

The study of bubble dynamics and associated heat transfer is still essential because our understanding of the fundamental physics is incomplete. This is partially due to difficulties in attaining measurements at the small time and length scales and partially due to the fact that the process is sensitive to many interdependent parameters which makes exhaustive experimentation and exact numerical simulations difficult to achieve. For example, due to the very limited information available, the influence of gravity on bubble dynamics and heat transfer is still an open question for the academic community.

Progression towards a complete understanding of this complex process has necessitated that simplified studies, which involve as few parameters as possible, be performed. This has the advantage of isolating specific parameters which can subsequently be varied to investigate their influence. The simplified adiabatic case whereby bubbles grow by gas injection from an orifice or needle is ideal

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Nomenclature

C	curvature (m^{-1})
d_o	orifice diameter (m)
g	gravitational acceleration (m/s^2)
g^*	terrestrial gravity (m/s^2)
F	force (N)
L_c	capillary length (m)
p	pressure (Pa)
r_o	orifice radius (m)
t	time (s)
u	velocity (m/s)
V	volume (m^3)
V_T	Tate volume (m^3)
$\dot{V}$	volumetric flow rate (mlph)
x	horizontal coordinate (m)
y	vertical coordinate (m)
z	centre of gravity (m)

Greek characters

Φ	Level Set function (–)
δ	layer thickness (m)
δ_s	Dirac delta function(–)
μ	dynamic viscosity (Pa s)
ν	kinematic viscosity (m^2/s)
θ	contact angle (o)
ρ	density kg/(m^3)
σ	surface tension (N/m)

Subscripts

b	body
B	buoyancy
C	capillary
CP	contact pressure
d	departure
eff	effective
g	gas
gr	growth
l	liquid
pr	predicted
s	surface tension
w	wall

because thermal effects, such as natural convection, interfacial heat and mass transfer and thermocapillary convection [10] are not present. Thus, the mechanical aspects of bubble growth can be investigated independently of the thermal ones.

Bubble growth during boiling is generally quite stochastic since it is very difficult to control the thermal and hydrodynamic conditions prior and subsequent to bubble nucleation [11]. However, controlling the environmental conditions and mass transfer rates for gas injected bubble growth, either from orifices or needles, is fairly straight forward. This being the case, there has been a great deal of experimental work done with regard to adiabatic gas injected bubble growth dynamics [12–29]. Fairly recently, Duhar and Colin [27] studied quasi-static bubble growth in silicone for both quiescent and shear flow situations. The work detailed the development of a mechanistic model based on conservation of linear momentum for an idealized spherical bubble of the equivalent volume of the measured bubble. The work detailed relevant forces acting on the bubbles as they grew and subsequently departed. A model to predict the equivalent bubble radius at departure was proposed and validated against their experimental results. More recently, Di Bari and Robinson [29] studied quasi-static gas injected bubble growth into otherwise quiescent water. This study did not attempt to simplify or idealize the shape of the bubbles. In fact, 3D reconstructed bubble shapes were used as a tool to predict the Young–Laplace pressure drop profile along the bubble interface. This, together with measurement of the internal gas pressure, was sufficient to resolve the static and dynamic stress fields around the bubbles. These were subsequently integrated to compute the vertical forces acting on the bubbles during growth and departure. An empirical correlation was proposed to predict the bubble departure volume without making any assumption regarding the bubble shape.

Theoretical studies have also been performed to analyse bubble formation at submerged needles and orifices without considering the hydrodynamics of the gas and liquid phases. Oguz and Prosperetti [30] and others [31–34] numerically simulated the bubble shape during quasi-static growth using the boundary integral method. Mori and Baines [35] and Garlach et al. [36] numerically integrated the Capillary equation to predict the bubble shape profiles during quasi-static bubble growth. The former study was for gas injected growth and the later was for gas diffusion of carbonated water and both showed agreement with the experimental bubble shapes. Importantly, this theoretical approach was capable of predicting the bubble departure volumes and departure was assumed to occur at the moment when there no longer existed a solution to the Capillary equation. Yang et al. [37] implemented the Lattice-Boltzmann method to study the separate effects of gravity, gas injection rate and surface tension for both horizontal and vertical surfaces.

CFD simulations of adiabatic gas injected bubble growth dynamics involve the solution of the continuity and momentum equations of the gas and liquid phases. These types of simulations are complicated by the fact that the gas–liquid interface is in motion and must be described as part of the solution. Quan and Hua [38] utilized a finite-volume method based on the SIMPLE scheme coupled with a front tracking method to study the effects of varying fluid properties on bubble pinch-off. Das and Das [39] implemented the gridless smoothed particle hydrodynamics (SPH) technique to validate its use in the simulation of multiphase flow problems. Ohta et al. [40], Buwa et al. [41], Garlach et al. [42], Chekrabory et al. [43] and more recently Ohta et al. [44] and Chakraborty et al. [45] used the combined Level Set and Volume of Fluid (CLSVOF) method to determine the position of the gas liquid interface. Buwa et al. [41] investigated bubble growth dominated by inertia and its influence on the bubbling regimes, such as pairing and coalescence. Garlach et al. [42] studied the effect of orifice radius, wettability and fluid properties. Chekrabory et al. [43] studied the influence of gravity on bubble growth and departure whilst Chekrabory et al. [45] used the same basic code to study the influence of co-flowing liquids. Ohta et al. [40] studied the bubble formation process for low inlet gas flow rates whilst Ohta et al. [45] extended from their earlier work to investigate considerably faster inflow conditions and the influence of a released bubble on the one being formed.

All of the above CFD simulations rely on codes which were developed ‘in-house’, which is not convenient from an industry perspective. Furthermore, validation of the numerical simulations was generally based on previously published experimental measurements, such as equivalent departure diameter, which is limiting and in many cases the comparisons are only qualitative which then draws into question the correctness of the models and simulation techniques.