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Experimental and numerical analysis of quasi-static bubble size and shape characteristics at detachment

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ABSTRACT

When investigating the physical mechanisms responsible for pool boiling heat transfer, individual bubbles are commonly assumed to be spherical. This is done in order to ease the computational expense when solving the Navier–Stokes equations. However, bubbles are observed to deviate from spherical depending on fluid properties, cavity sizes and gravitational field strengths. Since it is bubble detachment volume that dictates ebullition frequency, improvements in detachment size and shape predictions would improve nucleate pool boiling heat and mass transfer models.

Recent studies have shown that a numerical treatment of the capillary equation's detachment criterion – which is a result of an interfacial pressure balance analysis – generates profiles corresponding to axis-symmetric quasi-static bubbles for adiabatic conditions. In the present work, this criterion is validated for heat induced bubbles providing the basis for a full analysis of size and shape characteristics of a detaching vapour bubble. A volume detachment correlation is validated for heat induced vapour bubbles and detachment correlations for other size and shape characteristics such as bubble height, width, apex principal radius of curvature, contact angle, and degree of sphericity are developed. Furthermore, a local stress analysis reveals detachment regimes and bubble profile regions.

1. Introduction

Nucleate pool boiling is commonly used in industry to transport heat. In this process, a heated surface stores energy into an adjacent superheated layer of liquid. This initiates vaporization at surface nucleation sites – which are either manufactured or imperfections of the applied surface – causing bubbles to form, grow and detach thereby transferring heat and mass away from the surface. Due to the fact that this phenomenon is highly complex, a systematic approach to improving our understanding of it is to isolate certain parameters. In this study, axis symmetric quasi-static bubble detachment characteristics that may be a result of vaporization, gas diffusion, or gas injection are investigated.

In single bubble growth dynamics, it is the bubble detachment volume and waiting time which dictate the mass transport and detachment frequency implying that it is the bubble detachment volume which partially dictates its associated heat and mass transfer rates [1]. Due to the complexity in modeling shape and size characteristics associated with nucleate pool boiling heat transfer rates, as detailed by [2], many empirical correlations of bubble detachment volume assume the bubble to be spherical (e.g., [3–11]) while analytical models have brought insight to bubble formation by investigating this idealized case. For example, for spherical bubble formations in a pool of superheated liquid, [12–14] provided extended versions of Rayleigh's equation (e.g., [15]) by describing the momentum balance driving a bubble during the inertia-controlled growth regime. They also provided analytical solutions to spherical bubble detachment within the heat-transfer controlled growth regime. Since a bubble may transition from one regime to another [16] developed a relation that is applicable to spherical bubble growth transitioning from the heat-transfer controlled regime to the inertia controlled regime. Spherical bubble growth was also assumed when [17] examined the influence of the curved vapour-liquid interface on the temperature field during heat-induced bubble growth. These studies are useful in investigating bubble growth from a heated plane since, despite noteworthy differences, bubble growth in an infinite pool of superheated liquid exhibits similar growth regimes [1]. However, in assuming a bubble to be a perfect sphere, solutions to the problem require correction factors such as in the analytical models of vapour bubble growth on a heated plane of [18,19,16].

As discussed in [20], other simplifying shape assumptions are used to ease the computational expense of numerical treatments

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Nomenclature

A	surface area (m^2)	P	pressure ($N\,m^{-2}$)
Bo_b	bond number with characteristic length b	R_i	principle radii of curvature (m)
b	orifice radius; Cavity radius (m)	V	volume (m^3)
c, cap	capillary	y	perpendicular distance from cavity (m)
cr	critical	z	h–y (m)
d	detachment	Z	centre of gravity (m)
F	force (N)	α	thermal diffusivity ($m^2\,s^{-1}$)
ft	bubble foot	ρ	fluid density ($kg\,m^{-3}$)
g	gravitational constant ($m\,s^{-2}$)	σ	surface tension ($N\,m^{-1}$)
gm	gas momentum	Ψ	bubble degree of sphericity
h	bubble height (m)	θ	contact angle (rad)
hy	hydrostatic	$\tilde{\theta}$	$\tilde{\theta} = \theta/\pi$
l	liquid	ζ^*	$\zeta^* = \zeta/b$
J	Jakob number	${}^*\zeta$	${}^*\zeta = \zeta/b^3$
o	apex origin	ζ^+	$\zeta^+ = \zeta/h_d$

of the problem. For example, the numerically generated bubbles of [21–27] are simulated to be very large relative to the nucleation site to ensure that the vapour temperature is maintained at the saturation temperature. These shape and size assumptions – while alleviating the computational expense – compromise the thermal transport predictions of single bubble formations.

The difficulties can be pinpointed to the fact that a spherical assumption implies that the bubble's point of contact with the nucleation site is a singularity. As a result, the model making this assumption cannot account for the size of the nucleation cavity and any surface tension prediction that does not consider the contact angle to be at 180 Degrees with the plane – effectively nullifying the capillary action – is contradicting its own geometric model. Such is the case for the numerous detachment correlations outlined in [10,28]. It is therefore necessary to include the cavity size and its contact with the bubble in the modeling of single bubble heat and mass transfer since the ebullition frequency and detachment volume of bubble formations on a heated plane are observed to vary depending on the nucleation site (e.g., [1]).

In order to include cavity size into a detachment condition, many have postulated that bubble detachment is when the surface tension at the foot of the bubble and the buoyancy force equate. In an apparent geometric contradiction, the most common formulation of this criterion assumes a bubble to be spherical for the buoyancy force calculation while assuming the bubble foot to be in contact with the cavity perimeter for the surface tension calculation (e.g., [3,4,29–34]). The resulting detachment criterion may be stated in terms of a volume normalized by a cube of characteristic length equal to the cavity radius b,

$$ {}^*V_d = 2\pi Bo_b^{-1}. \tag{1} $$

In Eq. (1) Bo_b is the Bond number with characteristic length b such that,

$$ Bo_b = \frac{\Delta\rho g b^2}{\sigma}. \tag{2} $$

The usefulness of Eq. (1), often referred to as the Tate volume [35], is its ability to predict detachment of experimentally measured results. Indeed, [31] showed experimentally that detachment criterions based on a net force changing sign, such as those of [36–39], are less accurate.

Assuming a detaching bubble to be spherical in shape, [40] developed a correlation dependant on the Bond, Froude and Galileo numbers that was within an absolute mean average error of 3.2% with available data. For quasi-static formations, the Froude and Galileo numbers are negligible reducing their correlation to,

$$ {}^*V_d = 4.69 Bo_b^{-1.08}. \tag{3} $$

The shortcoming of Eq. (1) and (3) is that they do not provide insight into the physical mechanism responsible for detachment since they assume the bubble to be a perfect sphere and yet be in contact with the perimeter of the cavity.

It is therefore common to include Eq. (1) in the modeling of single bubble growth and detachment and to search for physical meaning that would explain its applicability. For example, in an effort to modify the Tate volume detachment correlation in order for it to account for bubble deformation from spherical, [41] suggested the following detachment criterion,

$$ {}^*V_d = 2\pi Bo_b^{-1} \cdot \psi(Bo_b) \tag{4} $$

in which ψ is a function of the Bond number, is dependent on shape, and is always less than unity. In this way, [41] conserves the notion of the Tate Volume by arguing that the hydrostatic and capillary force balance that it represents is correct yet askew due to the shape of the bubble. Indeed, the shape influences both the buoyancy and the surface tension acting on the bubble.

Recently, [42] empirically developed a correlation for quasi-static adiabatic gas injected bubble detachment. Their resulting correlation can be expressed as

$$ {}^*V_d = 3.78 Bo_b^{-1.058} \tag{5} $$

implying that ψ from Eq. (4) is the function $0.602 Bo_b^{-0.058}$. Eq. (5) is experimentally shown in [42] to approach the Tate volume for smaller orifices. Physically, [42] observed that smaller orifices yield more spherical bubble formations at detachment and argued that this suggests bubble detachment volumes converge to the Tate volume with decreasing Bond numbers. This reasoning suggests that the Tate volume is more valid for more spherical shapes. However, if this were the case, the function $\psi = 0.602 Bo_b^{-0.058}$ would converge to unity rather than infinity for Bond numbers approaching zero.

In this work, the detachment condition of the numerical treatment of the Capillary Equation is validated for gas injected bubble formations and for heat induced vapour bubble formations. This condition states that bubble detachment occurs at the profile of greatest height for which a solution to the Capillary Equation is feasible. The goal of this study is to clarify its applicability to quasi-static bubble formations. Indeed, [43] observed the Capillary equation detachment condition to predict detachment of quasi-static gas injected bubbles whereas, [44] did not observe it to predict detachment of gas diffusion bubbles. It is important to note that the gas diffusion bubbles of [44] experienced coalescence interaction with neighbouring bubbles and that the applicability