21st Australasian Fluid Mechanics Conference
Adelaide, Australia
10-13 December 2018

Bubble Growth due to Convective Heat Transfer in Micro-gravity Environment

S.A. Sharif[1], M.K. Ho[2], V. Timchenko[1] and G.H. Yeoh[1,2]

[1]School of Mechanical and Manufacturing Engineering
University of New South Wales, Kensington, NSW 2052, Australia

[2]Australian Nuclear Science and Technology Organisation
Lucas Heights, NSW 2234, Australia

Abstract

Multiphase flows such as bubbles and/or bubbly flows exist in heat exchanger and other critical engineering systems. The performance of these systems, however, can be adversely effected in micro-gravity environment. In this paper, an advanced 3D numerical tool – namely the InterSection Marker (ISM) method was employed to simulate single evaporating vapour bubble (test sizes 2.5 mm, 4 mm) in uniformly superheated and quiescent water under the influence of micro-gravity and surface tension forces. During testing, various liquid superheats (1^0C, 15^0C, 35^0C) and micro-gravity levels ($g/g_e = 10^{-2}, 10^{-7}$) were applied to predict bubble properties such as size, shape, velocity and interfacial (convective) heat transfer coefficient. Dimensionless numbers, such as Grashof (*Gr*), Nussult (*Nu*), Rayleigh (*Ra*) and Prandtl (*Pr*), were also discussed. Obtained results were benchmarked with the past results, and found to be in good agreement.

Introduction

Space exploration including landing a human on Mars in near future is a serious agenda for the leading Space agencies around the world. A Lunar base camp is also on the wish list to support future space expedition and to mine asteroids. To achieve these, enabling technologies are needed in propulsion and power systems, navigation and communication systems, life support and thermal management systems among many other areas. These systems, however, will be exposed to a wide variety of gravitational fields during the space mission, and the functionality of some of these systems involving two-phase flows such as bubbly flows in heat exchager pipes, loop heat pipes and capillary-pumped loops could be adversely affected. A system designed and tested on Earth might not perform efficiently or might not even work under different gravitational conditions. Testing under the reduced gravity, especially micro-gravity condition, however, is complicated, expensive, and an elaborate, time-consuming exercise. Physical tests were carried out in the parabolic flights (e.g. KC-135, MU-300) with very short test duration and other limiting conditions. Tests were also carried out in NASA's Space Shuttles and most recently in the International Space Station (ISS). These tests, unfortunately, are not only very costly but also require lengthy development time and onboard safety certification. In these scenarios, numerical simulation can be a cost-effective and time-saving mechanism to simulate system performance in a wide variety of gravity levels including the micro-gravity environment.

A bubble can grow or expand for going through boiling process or due to the convective action or by means of other heat and mass transfer mechanism. Convective evaporation of vapour bubble is an important phenomena, and can exist in a favourable condition, e.g. in superheated liquid, bubble growth happens due to the evaporation at the fluid interface [14]. Most of the prior micro-gravity boiling research were carried out for nucleate pool boiling, and the experiments of flow boiling or in this case convective evaporation are very limited than those for pool boiling [3, 6]. This present study has investigated a single vapour bubble characteristics such as size, shape and natural convection data for convective evaporation in uniformly superheated water under the micro-gravity environment. The numerical simulation was done by using an advanced 3D numerical tool – namely the InterSection Marker (ISM) method [4]. Obtained results were benchmarked against the similar numerical tests carried out in normal earth gravity condition [14], and compared with other test cases performed in both normal earth gravity and micro-gravity conditions. These comparative studies would be useful for designing and optimising engineering systems for special circumstance such as in micro-gravity environment.

Micro-gravity Environment and its effect on Bubble Characteristics

Micro-gravity or near-weightlessness resembles to a free-fall situation, and various phenomena, for instance convection, buoyancy, hydrostatic pressure and sedimentation, are significantly effected in this distinctive condition [7]. A variety of micro-gravity levels can be experienced, from $10^{-2}g_e$ in a parabolic flight to $10^{-7}g_e$ in the ISS. See [7, 8] for more details.

Bubble Size

During boiling, bubble inception to growth mechanism is so intense and unique that there is no effect of gravity, at least to a certain extent [9, 16]. After the initial stage, bubble however continues to grow bigger and growth period gets longer in micro-gravity condition for reduced buoyancy and dominant inertia forces acting on the bubble. In a pool boiling experiment (media: water; gravity level: $0.02g_e$), it was found vapour bubble grew as large as 20 mm in diameter during lift-off with compared to just 2.5 mm at normal gravitational condition [12]. On the other hand in micro-gravity environment, bubble growth due to convective evaporation is significantly reduced for lack of velocity, and the bubble growth is limited [15]. In fact for zero-gravity condition, there will be no natural or gravity-driven convection at all [7, 8]. In this scenario, bubble growth will solely dependent on the temperature gradient and liquid superheat. Contact angle, in micro-gravity condition, is also slightly lower than that of earth gravity condition [12].

Bubble Velocity and Travel Direction

Bubble rise velocity and corresponding distance travel are significantly reduced due to lack of buoyance force (lack of gravity) in micro-gravity condition [15]. In earth gravity condition, bubble rises upward if released from a stationary position. Saidi et al. [13], however, reported in their study, bubble travelled upward and then later downward for a change of direction of the lift force in micro-gravity condition.

Bubble Shape and Rise Path

Bubble at normal earth gravity condition exhibits various rise paths, for instance: rectilinear (straight), zig-zag, spiral and unpredictable (chaotic) [2, 17]. In micro-gravity condition, however, bubble rise path is always rectilinear (straight). While rising in the presence of the buoyancy and the surface tension forces at normal earth gravity condition, bubble attains a variety of shapes (e.g. spherical, ellipsoidal and spherical-cap or ellipsoidal-cap) based on their sizes [2]. Bubble on the other hand retains their original spherical shape for lack of gravity in micro-gravity condition for the dominant surface tension force [15].

Mathematical Formulation

Both the water (continuous) and the vapour (dispersed) phases can be assumed to have the same 'mixture velocity' at any local point within the computational domain, and the two-fluid system can be approximated as a one-fluid mixture. The mixture density and viscosity can be calculated based on the volume fraction (α) which has the following values:

$$\alpha = \begin{cases} 1 & \text{continuous phase} \\ 0 < \alpha < 1 & \text{interface} \\ 0 & \text{dispersed phase} \end{cases} \quad (1)$$

The variable density and viscosity are expressed in terms of the α value:

$$\rho = (1-\alpha)\rho_d + \alpha\rho_c \quad (2)$$

$$\mu = (1-\alpha)\mu_d + \alpha\mu_c \quad (3)$$

Where: Subscripts c and d indicate continuous (liquid: water) and dispersed (gas: vapour) phases.

When the bubble growth due to the mass transfer at the interface is considered, a source term needs to be added to the α-transport equation:

$$\frac{\partial\alpha}{\partial t} + \nabla.(\alpha V) = \left(\frac{1}{\rho}\right) S_{mass} \quad (4)$$

Where: S_{mass} is the interfacial mass transfer source term [kg/m^{3}s].

Incorporating the source them, the continuity equation is:

$$\nabla.V = \left(\frac{1}{\rho_d} - \frac{1}{\rho_c}\right) S_{mass} \quad (5)$$

And, the Momentum equation has the following form:

$$\frac{\partial\rho V}{\partial t} + \nabla(\rho V.V) = -\nabla p + \rho g + \nabla.\mu(\nabla V + \nabla V^T) + F_\sigma \quad (6)$$

Where: p, g and F_σ are the pressure [Pa], gravity [m/s^2] and surface tension force [N/m] respectively.

S_{mass} can be modelled in a variety of ways depending on the nature of the application. See Sharif et al. [15] for more details. In the present study, S_{mass} is modelled considering the convective heat transfer mechanism [18] to simulate the Vapour bubble growth as:

$$S_{mass} = a_{if}.\frac{h_{if}\Delta T_{super}}{h_{fg}} \quad (7)$$

Where: a_{if} is the interfacial area between phases per unit volume [m^2/m^3], h_{if} is the interfacial (convective) heat-transfer coefficient [W/(m$^{2 0}$C)], ΔT_{super} is the liquid superheat [^{0}C], and h_{fg} is Enthalpy for vaporization [kJ/kg].

h_{if} can be calculated by the following Evaporative Nusselt number correlation:

$$Nu_{evap} = \frac{h_{if}D_b}{k_l} \quad (8)$$

Where: D_b is the Bubble diameter [m], and k_l is Thermal conductivity [W/m^{0}C].

For Nu_{evap}, numerous correlations are available – see Sharif et al. [14] for details. For the present study, Hughmark [5] is used:

$$Nu = 2 + 0.6Re^{0.5}Pr^{0.33} \quad \begin{cases} 0 \le Re < 776.06 \\ 0 \le Pr < 250 \end{cases} \quad (9a)$$

$$Nu = 2 + 0.27Re^{0.62}Pr^{0.33} \quad \begin{cases} 776.06 \le Re \\ 0 \le Pr < 200 \end{cases} \quad (9b)$$

Where: Re_b is the Bubble Reynolds number, and is defined as:

$$Re_b = \frac{\rho_l U_b D_b}{\mu_l} \quad (10)$$

Where: U_b is the Bubble velocity [m/s] and can be obtained from the ISM numerical simulation.

For added mass, bubble size will increase continuously and its velocity will change accordingly. As such, h_{if} and correspodning S_{mass} have to be calculated at each time-step.

Equation (7) can be further deduced to the below relationship (see Sharif et al. [14] for details):

$$S_{mass} \propto \frac{U_b}{D_b}.\Delta T_{super} \quad (11)$$

From Equation (11), it is clear that bubble growth due to the convective evaporation is dependent on the buble velocty, size and liquid superheat.

Numerical Features & Test Conditions

The bubble interface was tracked by using an advanced and new type of hybrid Lagrangian-Eulerian Front-Tracking method, called the InterSection Marker (ISM) method [4]. This method can model an arbitrary 3D shape immersed inside an array of uniform hexahedral control volumes by using a combination of planar polygons. Peskin's [11] Immersed boundary method was used to model surface tension and buoyancy forces as a smoothed volumetric source term in the momentum equation. The local 3D surface curvature calculation was achieved by way of paraboloid least-squares fitting method using the cell-edge intersection points of the local and surrounding interface cells. The pressure field was evaluated using the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) algorithm [10], and Finite volume formulation – hybrid and central schemes were used for the discretisation schemes.

Coupled with an in-house variable-density and variable-viscosity single-fluid flow solver, the ISM interface tracking method was employed to simulate single evaporating vapour bubble (test sizes 2.5 mm, 4 mm) in quiescent water under the influence of micro-gravity and surface tension forces. Simulation was carried out in a computational domain of 31 × 51 × 31 cubic control volumes (CCV). The initial bubble shape was spherical with radius of 5h (where h is the width of the non-dimensional CCV). Various micro-gravity levels from low ($g/g_e = 10^{-2}$) to high quality ($g/g_e = 10^{-7}$) were applied, and all fluid properties were taken at 100^{0}C saturation temperature. Marangoni convection was not considered for isothermal condition. Instead, from low (1^{0}C), medium (15^{0}C) to high (35^{0}C) liquid superheats were used during the simulation to investigate the effect of the temperature change on the bubble growth.

Results and Discussions

Grashof (Gr) number is a dimensionless parameter which is the ratio of buoyancy to viscous forces. With increase of Gr number, buoyancy overcomes friction and induces flow. However in micro-gravity environment, Gr number becomes smaller. Figure 1 shows this decreasing trend analytically and reveals the releationship between Gr number with the gravity level for various bubble sizes with different liquid superheats. For lack of buoyancy in micro-gravity environment, the magnitude of the bubble velocity is thus redcued significantly and the convective evaporation growth is severly restricted. Figure 2(a) shows the comparison of 2.5 mm bubble growth in normal earth gravity condition with various micro-gravity levels. The bubble was barely growing in high quality micro-gravity level (g/g_e = 10^{-7} for reduced velocity). In lack of velocity and related redcued interfacial (convective) heat trasnfer coefficient (h_{if}), the bubble growth will largly be dependent on the liquid supetheat (see equation (11)). Figure 2(b) shows how large liquid superheat contributed to the bigger growth of the bubble size (for 4 mm bubble). With the same test condition, the bubble grows bigger for higher liquid superheat.

Bubble shape evolution in micro-gravity is compared against the result of earth gravity condition [14]. Table 1 shows the effects of various gravity levels on the bubble shape. AR is the aspect ratio and is defined by bubble height by width. At t=0, bubble has an AR value of 1 (perfectly sheprical). AR value close to 1 indicates the bubble shape to be completely spherical. In absence of the strong gravitational field and for the dominant surface tension force in micro-gravity environment, the bubble keeps its original spherical shape during the very slow rise in the upward direction. It was found there is negligible effect of the micro-gravity levels on the bubble shape. Even with low quality micro-gravity level ($g/g_e = 10^{-2}$), the bubble was nearly spherical during the simulation period. Also, regardless of the bubble size, the bubble was spherical. Whereas in normal earth gravity condition (g/g_e = 1), the bubble deformed to various shapes during its rise. For example, 2.5 mm bubble transformed into an elliptical shape (see table 1(a)). For the larger bubble (4 mm), an early stage of re-entrant jet on the bottom of the bubble was also clearly visible (see table 1(b)).

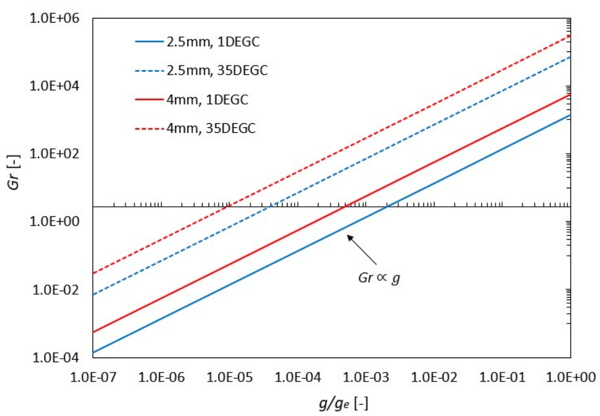
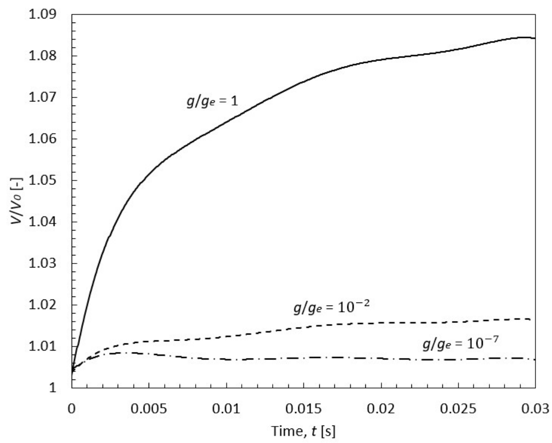
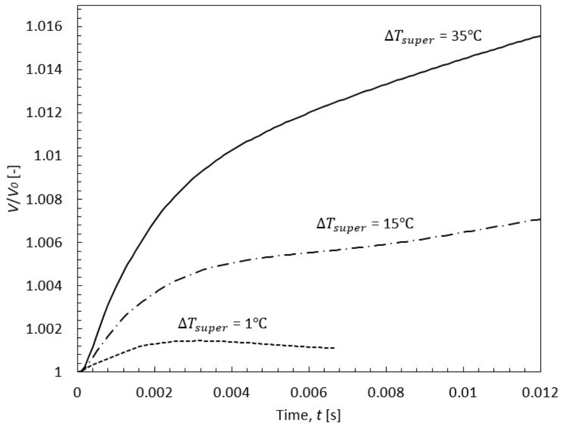


Figure 1. Effects of various gravity levels on Grashof (Gr) number.

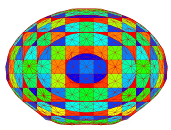
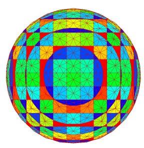
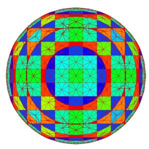


(a) For various gravity levels (2.5 mm bubble, ΔT_{super} = 35^{0}C)

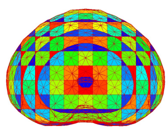
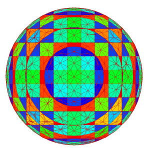
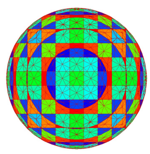


(b) For various liquid superheats (4 mm bubble, $g/g_e = 10^{-2}$)

Figure 2. Normalised bubble volume over the simulation time period.

$g/g_e = 1$	$g/g_e = 10^{-2}$	$g/g_e = 10^{-7}$
 AR = 0.732	 AR = 1.007	 AR = 1.004

(a) 2.5 mm bubble, ΔT_{super} = 35^{0}C, Simulation time = 0.30 s

$g/g_e = 1$	$g/g_e = 10^{-2}$	$g/g_e = 10^{-7}$
 AR = 0.732	 AR = 0.996 (t=0.07s)	 AR = 1.005

(b) 4 mm bubble, ΔT_{super} = 1^{0}C, Simulation time = 0.134 s

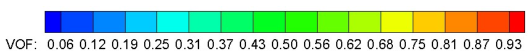


Table 1. Bubble shape evolution

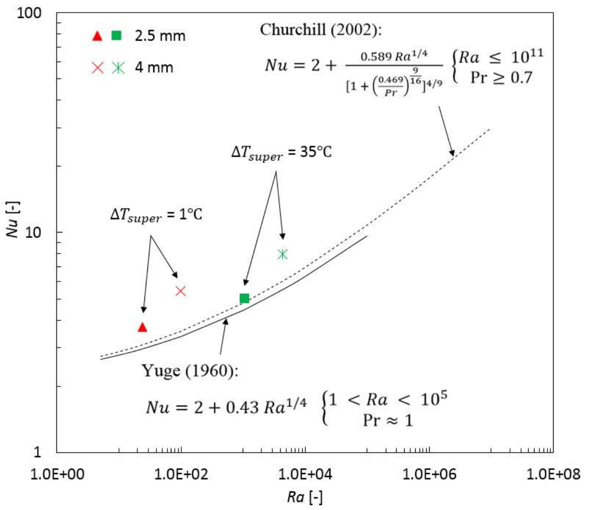


Figure 3. Natural Convection data for vapour bubble in micro-gravity environment ($g/g_e = 10^{-2}$)

Numerically obtained bubble velocity (U_b), although small in magnitude and acting upward, and its corresponding interfacial (convective) heat transfer coefficient (h_{if}) were validated by comparing the numerical results against the past natural convection heat and mass transfer Nussult number correlations [1, 19]. Figure 3 shows the comparison where numerical results are overall in good agreement with the past data, specially for 2.5 mm bubble.

Conclusions

The characteristics of 2.5 and 4 mm evaporating bubbles were numerically investigated in uniformly superheated and quiescent water under the influence of micro-gravity and surface tension forces. Bubble rise velocity was significantly reduced for lack of buoyancy in micro-gravity condition which resulted in a restricted growth. In this scenario, a more significant bubble growth could only be achieved from larger liquid superheat. It was found regardless of size, bubbles kept their original spherical shape during their slow rise in micro-gravity condition, and the effect of various micro-gravity levels on the bubble shape was negligible. Bubble velocity and corresponding interfacial (convective) heat transfer coefficient obtained from the ISM numerical simulation were also validated against the past correlations and found to be in good agreement. The ISM method demonstrated to be a reliable, economical and efficient tool to carry out various bubble simulations in micro-gravity environment.

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