Proceedings of the 18th UK Heat Transfer Conference
9-11 September 2024, Birmingham
UKHTC2024-031

Special Session: Nuclear Thermal Hydraulics

FULLY-RESOLVED INTERFACE CAPTURING SIMULATIONS OF SINGLE BUBBLE GROWTH AND MICROLAYER FORMATION ON AN ISOTHERMAL SUPERHEATED SURFACE IN POOL BOILING CONDITIONS

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1. INTRODUCTION

In an attempt to further characterise bubble microlayer dynamics, this paper presents fully-resolved simulations of single-bubble growth phenomena in pool boiling conditions, performed in OpenFOAM.

The characterisation and accurate prediction of boiling phenomena is crucial to nuclear thermal hydraulics applications. This is due to its elevated heat transfer coefficients, providing significant heat extraction capacity and making it a favoured method for cooling in the energy conversion industry. However, such physical events start and develop at length scales that are too small for direct optical observation, posing a major limitation for experimental work. In particular, when the degree of superheat in a fluid domain is high and rapid evaporation is therefore observed, the growing bubbles expand over a micrometric fluid bed that stays seemingly immobile on the hot surface. This is known as the microlayer, which ranges between 4-8 μm in maximum thickness.

This thin liquid film is believed to act as a buffer layer for both heat conduction and evaporation into the bubble. Nevertheless, its shape and dynamics vary depending on thermal and hydrodynamic characteristics of the fluid. Such events and attributes lack rigorous scientific delineation, hence the main drive of this work.

This paper presents a parametric analysis to further understand microlayer dynamics, as well as an attempt at quantifying the effect of its evaporation on growing bubbles. The factors to be considered are the degree of fluid superheat, the wettability of the solid surface (as quantified by the contact angle of a specific fluid-surface combination), and the effects of the degree of superheat of the solid surface under the growing bubble.

2. METHDOLOGY

The numerical procedure employed for the research hereby presented is founded on the addition of interface capturing methodology to an incompressible, time-dependent Newtonian fluid flow model. The approach chosen for tracking the behaviour of the vapour-liquid interface is the Volume of Fluid (VOF) method. The model hinges on a phase indicator to distinguish the vapour and liquid phases. With this incorporation, the momentum equation reads as follows:

$$\rho_m \frac{\partial U_i}{\partial t} + \rho_m \frac{\partial U_i U_j}{\partial x_i} = -\frac{\partial p}{\partial x_i} + \mu\left(\frac{\partial^2 U_j}{\partial x_i^2} + \frac{\partial^2 U_i}{\partial x_j^2}\right) + \rho_m g_i + \sigma\kappa\frac{\partial \alpha}{\partial x_i} \quad (1)$$

Here, ρ_m means mixture density, U indicates fluid velocity, p is pressure, μ is the dynamic viscosity of the fluid, t stands for time, and x is the spatial component. The variable α in the last term is the indicator function.

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The two rightmost terms represent the gravity vector (g_i), and the surface tension components, respectively, where σ is the surface tension coefficient, and κ is the local curvature of the liquid-vapour interface. For cases where phase change (interfacial evaporation or condensation) is present, continuity relation reads:

$$\frac{\partial U_i}{\partial x_i} = -\frac{\dot{m}}{\rho_l} \tag{2}$$

Where $\dot{m}$ is the volumetric rate of phase change. The mass transfer model used here is the one proposed by Hardt & Wondra [1], which is based on Schrage's derivation [2] of Boltzmann's Kinetic Gas Theory. According to the model, the volumetric rate of phase change is computed as

$$\dot{m} = \frac{\beta_e}{h_{lv}}(T_{if} - T_{sat}) \tag{3}$$

Where β_e is the evaporation heat transfer coefficient, h_{lv} is the latent heat of vaporisation, and subscripts if and sat indicate interfacial and saturation temperature, T, respectively. The temperature distribution is obtained via solution of the following energy balance:

$$\frac{\partial \rho_m c_p T}{\partial t} + \frac{\partial c_p T U_i}{\partial x_i} - \frac{\partial^2 kT}{\partial x_i^2} = -\dot{m}h_{lv} = S_h \tag{4}$$

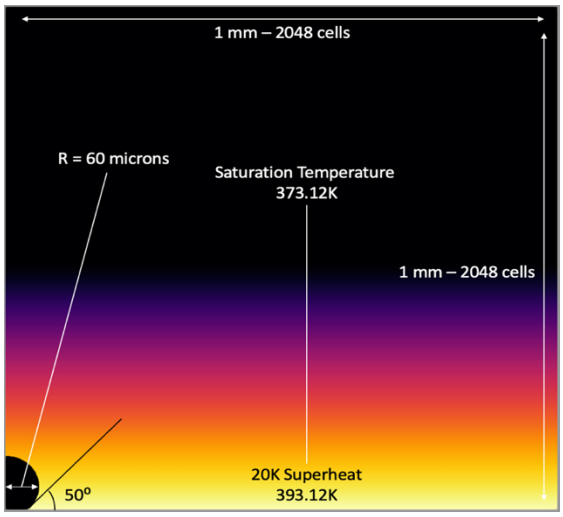

Figure 1: Simulation domain characteristics and initial conditions.

where c_p is the specific heat capacity, k is the fluid's thermal conductivity, and S_h is the energy source term for the exchange between phases.

With the current VOF interface capturing methodology, the indicator function advection equation reads as follows:

$$\frac{\partial \alpha}{\partial t} + \frac{\partial U_i \alpha}{\partial x_i} + \frac{\partial U_i^r \alpha(1-\alpha)}{\partial x_i} = -\frac{\dot{m}}{\rho_l} \tag{5}$$

The variable α in equation (5) defines the indicator function – its bounding values are 0 in the vapour, and 1 in the liquid; interface cells (typically 2-3 cells in thickness) have intermediate values of the indicator function. The third term from the left computes the compression of the interface that artificially counteracts numerical diffusion. The velocity U^r is that of the compression.

The simulation domain utilised in the current work is a wedge-shaped domain used to mimic the characteristic axisymmetric configuration of the phenomenon of interest. The wedge has a 5º angle and consists of 0.5 by 0.5-micron cells across a 1x1 mm space, corresponding to 4 million cells.

A bubble seed of 60-micron radius is initialised at the bottom of the domain cornering the axis side in a way where a 50º contact angle can be observed between the interfacial tangent and the domain's floor. Moreover, an isothermal boundary condition (Dirichlet) at 393.12 K (20 K superheat) is set at the bottom of the domain, see Figure 1. This arrangement replicates that of Urbano et al. [3], which the authors aim to reproduce.

3. RESULTS

The outcome of the aforementioned setup is qualitatively presented in Figure 2, which shows the state of the bubble after 0.1 ms. The left-hand side of the domain (the green and purple coloured half) indicates the velocity field, with the right-hand side showing the temperature.

Furthermore, a comparison of the equivalent diameter versus time against the reference solution of Urbano et al. [3] can be seen in Figure 3(a). The blue plot shows a relative error of 10% when set against their calculations (orange). Comparable closeness can be observed between the two curves, indicating a successful (yet improvable) outcome of the physical replication of single-bubble phenomena in free, open-source software. Lastly, Figure 3(b) shows the microlayer profile that forms under the growing steam bubble. This is a comparison against the results presented in [3]. The horizontal axis represents the radial distance from the root of the microlayer i.e., from the point where the liquid-vapour interface intersects the solid surface at the inner edge of the microlayer. A clear match in shape can be noticed. However, slight deviations around the 25- and

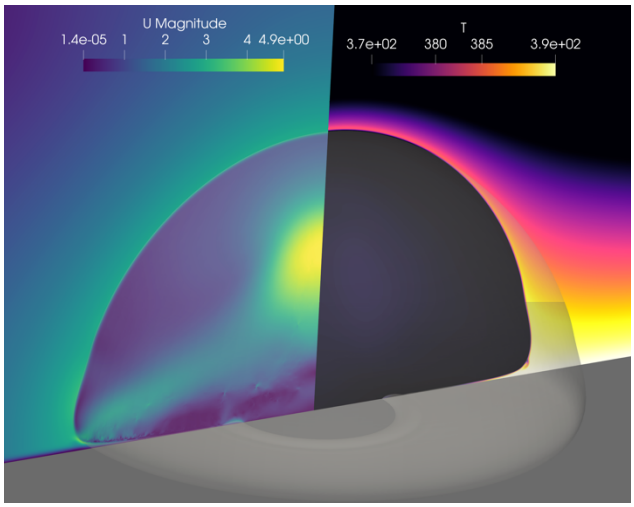

Figure 2: Bubble at 0.1 ms. Velocity (left – [m/s]) and temperature (right – [K]) fields.

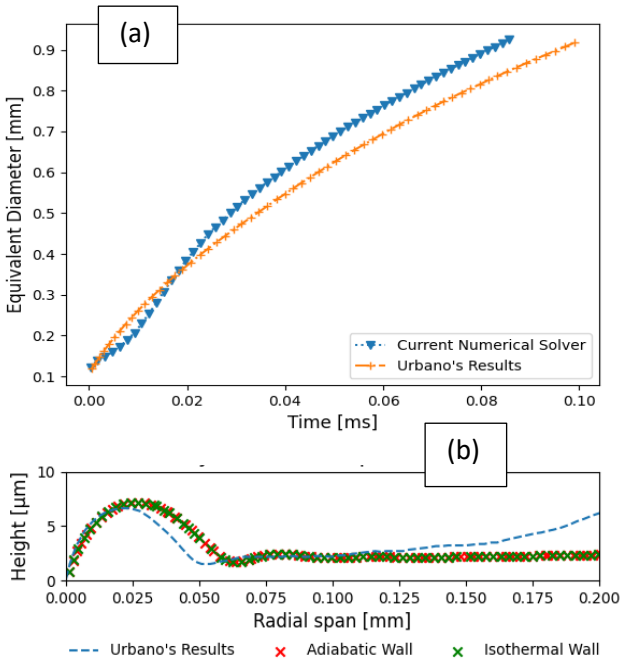

Figure 3: (a) equivalent bubble diameter versus time compared against Urbano et al. results [3], (b) microlayer profile comparison at 0.1 ms against Urbano et al. results [3]. Adiabatic versus isothermal wall contours.

125-micron regions can be observed. No obvious difference can be seen between the adiabatic and isothermal setups, indicating no thermal interference with the hydrodynamics of the microlayer. However, at later times into the simulation, beyond 0.1 ms (yet to be explored), a difference in microlayer behaviour between the isothermal and adiabatic configurations is expected.

For the oral presentation, the authors plan on having completed the aforementioned parametric analysis involving different degrees of superheating, as well as bubble contact angles and thermal boundary conditions.

4. CONCLUSIONS

This work presented characterization of bubble microlayer dynamics as a combination of both thermal and hydrodynamic [4] effects. A parametric analysis is to be carried out, where bubble contact angle values and varying levels of superheat will be explored. The key outcomes of this research are yet to be obtained, as the authors plan on having completed a full analysis of bubble growth under different superheated environments, thermal boundary conditions, and contact angles by the time of the presentation. The current preliminary results increase the confidence in the proposed interface capturing methodology to simulate microlayer formation and depletion in nucleate boiling.

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