A NEW HYBRID APPROACH FOR SIMULATION OF THE DEPLETABLE MICROLAYER FOR SINGLE BUBBLE NUCLEATE BOILING UNDER MICROGRAVITY CONDITIONS

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ABSTRACT

Nucleate boiling constitutes high heat flux with considerably low wall-superheat. During this phase, evaporation of a thin liquid layer trapped between the vapor bubble and the heater wall is a significant contributor to the phase change and thus the bubble growth rate and heat-flux. Direct modeling of the micro layer is challenging because the thin micro layer requires very fine grid, making the simulations computationally expensive. A new approach is proposed for simulating the liquid micro layer in microgravity conditions. In this approach we do not directly model the thin liquid layer but instead we calculate its contribution to vapor bubble growth by estimating the micro layer size at each time step then integrating the temperature gradient across the thin triangular region to finally solve the conduction equation and get the volume of vapor generated. Our approach also models the thin layer depletion with an added evaporation term in the equation for the determining the microlayer thickness. The added term is able to model the reduction in the thickness of the microlayer. Results for nucleate boiling simulations under microgravity conditions are reported using the proposed micro layer approach in comparison with experiments performed on the International Space Station using perfluoro-n-hexane as the test liquid. Results for bubble growth rate, bubble shape and heat-flux are in good agreement with experiments and are verified with two different time-instants in the bubble life cycle. Similar to experiments, our simulation results do not exhibit bubble departure due to reduced buoyancy in microgravity conditions.

1 Introduction

Nucleate boiling is known for high heat-flux at considerably lower wall super-heats. This makes it an efficient mode of heat transfer for cooling applications, nuclear applications, etc. It is significant in microgravity conditions, specifically in space exploration applications to make the components more compact. During the initial phase of bubble growth, the vapor-liquid interface grows faster than the bubble base, as surface tension inhibits the growth of the bubble base. Thus, the interface bends towards the base and a thin layer of liquid gets trapped between the vapor bubble and the heater wall. The thickness of this liquid layer is typically in the order of microns, hence the name “microlayer” which was first proposed by [1]. [2] confirmed its existence with experimental results. The typical life-cycle of the liquid microlayer consists of formation, growth (while it continues to contribute to the bubble growth through its evaporation), reduction and complete depletion during bubble departure. [3] and [5] proposed predictions for the initial microlayer thickness from experiments. However, these correlations are for the specific case of water under earth gravity conditions. The coefficients are based on empirical calculations. There are some analytical correlations reported as well. Most of the analytical expressions are for hydrodynamic thickness, which is the thickness of the microlayer if there was no vapor flux into the bubble from the microlayer being considered by the evaporation of the microlayer. [2] among others proposed a correlation of the hydrodynamic microlayer thickness. These correlations did not consider the relation to be dependent on the bubble base radius and wall temperature. [6] provided an analytical formulation considering the above factors. Although, this correlation takes into account the radial location and wall super-heat into the formulation it does not consider the effect of evaporation of the microlayer. As far as numerical simulations are concerned, there are considerable challenges in estimating the contribution of the microlayer due to the range of length scales (∼ \textmu m in microlayer to ∼ mm in bubble diameter). This would make the computations very expensive. In order to solve this issue some form of modeling has been used in the re-
search community. [7] proposed the triple line model to consider the microlayer contribution which was later modified by [8] and [9]. An example of the triple line model is shown in figure 1. The image on the right shows a zoomed in portion near the triple point. As can be seen from figure 1, the length of the microlayer in the radial extent consists of a very small region. Experiments have shown that the microlayer exists almost along the entire radial extent of the bubble base and its thickness varies with time, both of which is not considered by this model. [10] proposed a depletable whole microlayer model. They simulated the growth and departure for a single vapor bubble from a heated surface using a sub-grid scale modeling approach for the microlayer for earth gravity. Although this model produces results which are in good agreement in comparison to experiments with respect to bubble growth rate, heat transfer rate and other bubble dynamics parameters in general, there are two major limitations with this model. The model uses the below equation to predict the microlayer thickness:

\[ \delta = C_{\text{slope}} R \]  

where \( \delta \) is the microlayer thickness, and \( R \) is the radius of the bubble base. \( C_{\text{slope}} \) is a constant value which is estimated from the empirical coefficient. It should also be noted that their experiment was performed under earth gravity conditions, using water as the test liquid. So, the value of the parameter \( C_{\text{slope}} \), used in this model would be valid only under the assumptions of these specific conditions. The model has not been tested under microgravity conditions where other liquids are used for the experiments. Later [11; 12], proposed a modification to the model, by replacing the \( C_{\text{slope}} \) term with an expression for the initial microlayer thickness by performing a back calculation from the rate of microlayer depletion and the thickness of the depleted microlayer to generate the initial thickness. The depleted microlayer thickness value is used from experimental results. Additionally, this model requires very fine resolution. They report that at the liquid-solid interface the grid size is 0.5 \( \mu \)m, and time-step size of 2 \( ns \) was used. Such fine resolution and small time-step size, would make the computation very expensive, specifically in microgravity conditions where the simulations are needed to run for about 90-100s in order to provide meaningful comparison with experiments.

All models have been used only for earth gravity cases, none of them have been shown to work under microgravity conditions. Typically, under earth gravity the bubble growth rate is found to be \( t^{1/2} \) where, \( t \) is the time, but in microgravity conditions, the bubble growth rate in single bubbles has been observed to be initially \( t^{1/2} \), and later \( t^{1/3} \) (details about this is provided later in the paper), which makes it different from earth gravity cases.

Description of the novel hybrid approach for the depletable microlayer for microgravity is proposed in section 2. The reported microlayer approach does not technically model the microlayer, but only estimates the contribution of the microlayer evaporation to the bubble growth. Using this approach the microlayer is depletable, of variable thickness, and maintains the initial \( t^{1/2} \), and later \( t^{1/3} \) growth rate in microgravity. Results and discussion for bubble growth rate, and heat flux are presented in section 3 using the model for microgravity conditions along with comparisons from experiments performed on ISS, which shows reasonable agreement in bubble shape at different time-instants, growth rate as well as heat-flux. Finally, conclusions are summarized in section 4.

2 Numerical Method and Hybrid Micro-layer Approach

Numerical simulations have been performed using Moment of Fluid (MoF) method which is based on the works of [13]. The solver employs the state of the art moment of fluid method (MoF) to represent multi-phase interfaces ([14], [13]). A brief description of the MoF method is provided in section 2.1, followed by a description of the hybrid microlayer approach for microgravity in section 2.2.

2.1 Governing Equations

The governing equations to be solved are the mass conservation equation, momentum conservation equation, and the energy conservation equation for each material for in-compressible, immiscible, multi-phase flows, which are given as follows: For each material \( m \):

\[ \nabla \cdot \vec{u} = 0 \]  

\[ (\Phi_m)_t + \vec{V}_I \cdot \nabla \Phi_m = 0, \quad m = 1, 2, \cdots, M \]  

\[ \frac{\partial}{\partial t} (\rho_m \vec{u}) + \nabla \cdot (\rho_m \vec{u} \otimes \vec{u}) = -\nabla \cdot \vec{p} + \nabla \cdot \vec{\tau} + \rho_m \vec{g} \]  

if \( \Phi_m(x,t) > 0 \)

\[ \frac{\partial}{\partial t} (\rho_m C_{p,m} T) + \nabla \cdot (\vec{u}_m \rho_m C_{p,m} T) = \nabla \cdot (k_m \nabla T) \]

if \( \Phi_m(x,t) > 0 \) where for material \( m \):

\[ \rho_m \] is the density, \( p \) is the pressure, \( \vec{g} \) is the acceleration due to gravity. \( \vec{u} (u, v, w) \) is the velocity field, \( C_{p,m} \) is the heat capacity per unit mass at constant pressure, \( k_m \) is the thermal conductivity. \( \vec{V}_I \) is the interfacial velocity:

\[ \vec{V}_I = \vec{V}_{vap} - \frac{m}{\rho_{vap}} \vec{n}_{lv} \]

\[ m = \frac{[k \nabla T \cdot \vec{n}_{lv}] \Gamma}{h_{fg}} \]

where \( \vec{n}_{lv} \) is the normal vector at the interface \( \Gamma \), which points from liquid to vapor phase, \( h_{fg} \) is the latent heat of vaporization and \( \Phi_m \) is the level-set function. Temperature at the phase change front (vapor-liquid interface) is always assumed to be the saturation temperature \( T_{sat} \). \( \vec{\tau} \) is the deviatoric stress tensor for a Newtonian fluid,

\[ \vec{\tau} = \mu_m (\nabla \vec{u} + (\nabla \vec{u})^T) \]

At the vapor-liquid interface, jump conditions have been applied at the boiling front \( \Gamma \) to maintain the conservation of mass, momentum and energy. Perfluoro-n-hexane is the test liquid for the numerical simulations which was also used in experiments on the ISS.
2.2 Hybrid approach to calculate contribution of microlayer under microgravity conditions

This approach calculates the flux of vapor if the microlayer were to be present in an ad-hoc way and adds the flux term to the cells where the microlayer would have been. This approach uses the benefits of both methods, the microlayer life-cycle is in line to the actual physical process, and there is no additional sub-grid modeling necessary as only the contribution of the microlayer is considered. For the hybrid approach implementation, a typical microlayer is shown in figure 2. It should be noted that in figure 2, the microlayer length considered is denoted as \( r_{mic} \), the microlayer thickness at the outer edge of the bubble is \( h_{mac} \), and microlayer thickness at the inner edge is \( h_{mic} \), which is set to a very small value of \( 10^{-9} \text{m} \), corresponding to a few molecule’s thickness or the adsorption layer thickness. The dry out radius of the neck of the bubble is denoted as \( r_{mic} \), calculated from above mentioned \( h_{mic} \) value and using the same slope as that of \( h_{mac} \) and \( r_{mac} \). Initial thickness \( h_{mac} \) is estimated in a two step process. First, the microlayer thickness is estimated using the analytical formulation of [6], which is given as:

\[
h_{mac,1}(r) = \frac{\pi}{4\sqrt{3}} \frac{\rho_l h_{fg}}{\rho_l c_p \Delta T} \sqrt{\frac{v_l}{\alpha_l}} r_{mac}\n\]

where \( h_{mac,1} \) denotes the first step of the thickness determination. \( v_l \) is the kinematic viscosity of the liquid, and \( \alpha_l \) is the liquid thermal diffusivity. This equation maintains a linear relationship between the radius and thickness of the microlayer. The linearity in the relationship has been verified by [5] using experiments. The two major drawbacks of this equation includes the fact that it makes an assumption that the bubble shape is spherical. This assumption is not accurate under earth gravity conditions, as the bubble shapes are typically elongated in the vertical direction which would then change the microlayer thickness as the base radius would be different. But in microgravity conditions, the bubble shapes have been found to be more oblate shaped and hence resembles a sphere. [15] provided images which showed bubble shapes at different time instants from experiments on the ISS making the assumption accurate. Second drawback of the equation is that it does not consider the depletion or evaporation of the microlayer. Our hybrid approach uses an evaporation term [11; 12] in determination of the thickness. This is the second step of the estimation of the microlayer thickness.

\[
h_{mac}(r, t) = \sqrt{(h_{mac,1}(r))^2 - \frac{2k_l(T_w - T_{int})}{\rho_l h_{fg}} t}\n\]

Using this equation, the microlayer thickness becomes variable with time, based on the evaporation. Once the microlayer thickness is known, the contribution of microlayer in form of vapor flux is calculated. The derivation of the equation used for that is provided starting with the microlayer geometry in figure 3. A portion of the microlayer is shown in figure 3 (left), where \( T_{wall} \) and \( T_{interface} \) denote the temperature of the wall and the interface (which is set to be the saturation temperature) respectively. Two axis perpendicular to each other are chosen as \( \xi \) and \( \psi \). In order to better visualize the calculation, the image on the left is rotated so that \( \psi \) is along the x-axis and \( \xi \) is along the y-axis. Based on the figure, the following can be formulated:

\[
h_{mac}/L = \tan \left( \theta_{mic} / 2 \right) = m\n\]

where \( m \) is the slope. Thus, \( \psi_{wall} = h(\xi) = m\xi \) and \( \psi_{interface} = -h(\xi) = -m\xi \). So, using interpolation, temperature as a function of \( \psi \), and \( \xi \) can be written as:

\[
T(\psi, \xi) = T + \frac{(T - T_s)}{h(\xi)} \psi\n\]

where \( T = \frac{T_s + T_w}{2} \). Thus, for gradient side from the liquid:

\[
\nabla T \cdot \vec{n} = \left[ \frac{T_{\psi}}{T_s} \right] \cdot \vec{n} \cdot \left[ \frac{\tilde{T} - T_s}{h(\xi)} \right] \cdot \frac{1}{m} \sqrt{\frac{1}{1 + m^2}} = \frac{\tilde{T} - T_s}{h} \sqrt{\frac{1}{1 + m^2}}\n\]

Now,

\[

Figure 1. Micro-layer in Triple Line Model or Contact Line Model
\[
\frac{1}{L - \delta} = \int_{0}^{L} \frac{1}{h(\xi)} d\xi = \frac{1}{L - \delta m} \ln \frac{L}{\delta} \frac{m(L - \delta)}{\ln \delta} \tag{14}
\]

where \(2\delta \delta = h_{\text{mic}}\). The average flux can be calculated as:

\[
\bar{T} - T_s = \frac{\bar{T} - T_s}{m(L - \delta)} \left( \ln \frac{L}{\delta} \right) \sqrt{1 + m^2} = \frac{T_w - T_s}{h_{\text{mac}} - h_{\text{mic}}} \left( \ln \frac{h_{\text{mac}}}{h_{\text{mic}}} \right) \sqrt{1 + m^2} \tag{15}
\]

Since \(m\) is very small, \(\sqrt{1 + m^2} \approx 1\), so the total mass of liquid from the region using the conduction equation becomes:

\[
\dot{m}_{\text{tot}} = m_{\text{tot}} \Delta T \log \left( \frac{h_{\text{mac}}}{h_{\text{mic}}} \right) \sqrt{1 + m^2} \tag{16}
\]

where \(k_l\) is the thermal conductivity of the liquid, \((r_{\text{mac}} - r_{\text{mic}})\) is the area in 2-d, and \(h_{fg}\) is the latent heat of vaporization which converts heat energy to mass. Next, mass-flux contribution from each time-step is then computed and distributed across the relevant cells. Finally, Average Vapor volume flux is calculated by multiplying a factor \(f\).

\[
\dot{v}_{\text{avg}} = f \times \frac{\dot{m}_{\text{avg}}}{\rho_v} \tag{17}
\]

The factor \(f\) ensures the \(t^{1/3}\) growth rate for microgravity by limiting the vapor volume flux after \(r_{\text{base}}\) reaches a certain size \((\text{size}_{\text{perim}})\). This variable \((\text{size}_{\text{perim}})\) is a user defined value, and the simulations are run with different values and based on the comparison with experiments a final value is determined. A study on the effect of this parameter will be discussed later in this chapter. The algorithm for the factor, \(f\) can be summarized as:

\[
\text{if} \ (r_{\text{base}} \leq \text{size}_{\text{perim}}) \ \text{then} \ f = 1 \\
\text{else if} \ (r_{\text{base}} > \text{size}_{\text{perim}}) \ \text{then} \ f = \frac{\text{size}_{\text{perim}}}{r_{\text{base}}} \tag{18}
\]

Here it is assumed that the contribution of the microlayer is proportional to the bubble growth rate. This is a reasonable approximation as for microgravity cases, the growth rate is \(\approx t^{1/2}\) initially and then \(\approx t^{1/3}\) as opposed to earth gravity in which case the growth rate is \(\approx t^{1/2}\). This can be seen from figure 4. As seen in figure 4, the \(t^{1/2}\) curve gives a good match initially, however it over predicts the diameter later. For the \(t^{1/3}\) curve, the diameter is over predicted in the initial phase, but gives a good match in the later stage. A linear combination of these two powers gives
the best match which follows \( t^{1/2} \) initially, and \( t^{1/3} \) later. The \( size_{perim} \) variable determines when to switch from \( t^{1/2} \) rate to \( t^{1/3} \) from the perspective of the contribution of the microlayer. Other assumptions in this approach include the fact that the bubble shape is spherical (as per the Olander and Watts equation), and the liquid in the microlayer is the stagnant. One final assumption is that the microlayer thickness does not depend on the surface tension. The last two assumptions are somewhat related and are explained below. Typically, the fluid flow in the microlayer is driven by the pressure difference between the liquid and vapor pressure, it is denoted by the below equation:

\[
p_l = p_v - \sigma \kappa - \frac{A}{\delta^3}
\]  

(18)

The third term on the Right Hand Side (RHS) of equation 18 is the disjoining pressure, which arises from attractive forces between molecules in the fluid and the solid. This term is very small as these forces typically act in the range of few molecular diameters (on the order \(< 1 \text{nm}\)), and thus can be neglected. The surface tension contribution only comes into the picture due to the second term on the RHS. However, since the liquid film is almost flat, the curvature of the vapor-liquid interface can be assumed to negligible, which makes the capillary pressure term \( \sigma \kappa \) to be \( \approx 0 \). So the above equation reduces to \( p_l \approx p_v \) indicating almost stagnant liquid flow.

3 Results and Discussion

Boiling results for a single vapor bubble in microgravity conditions is provided in this section with comparison to the results from [15], who performed the experiments on the ISS. The wall super-heat varied from \(4^\circ - 7^\circ \text{C} \) in the experiments. In the reported simulations a constant wall super heat of \(7^\circ \text{C} \) is used. Grid convergence study is reported in figure 5, where the resolutions of \(128 \times 128\), \(192 \times 192\), and \(256 \times 256\) are reported and the latter two seem to have converged. Although \(128 \times 128\), reports some difference, the maximum percentage difference between it and \(192 \times 192\) at any point is \( < 4.8\% \). Thus \(128 \times 128\) can be considered to be a reasonable approximation and it is selected as the default resolution for the remaining reported results. Domain size in each direction is \(0.064 \text{ meters} \), which makes the cell size \( \Delta x = 5.0 \times 10^{-4} \). This corresponds to 8 points inside the initial bubble along the diameter. The \( size_{perim} \) variable is set to a value of \(0.04 \text{m} \) for the cases in figure 5. The simulations are in good agreement with the experimental results for the bubble growth rate. Next, the effect of the \( size_{perim} \) variable is reported in figure 6. As can be observed from figure 6, as the value of \( size_{perim} \) increases, the bubble growth rate flattens at a lower position and with a lower slope. From figure 6, it can be seen that \( size_{perim} = 0.035 \text{m} \) gives a better agreement with the experimental results. Bubble shape comparison with experiment of [15] at time, \( t = 15 \text{s} \) and MoF simulation are reported in figure 7. The bubble shape is in good agreement with the experiments. Also reported in the figure are the heat-flux and temperature distribution. A peak of the heat-flux can be observed at the triple point for the simulations as majority of the phase change takes place at this specific location. Similar comparison is also reported for time, \( t = 60 \text{s} \) in figure 8. [15] reports a peak value of heat-flux
of 574W/m² at both \( t = 15s \) and \( t = 60s \) time instants, and the MoF simulations reports 384W/m² at \( t = 15s \) and 388W/m² at \( t = 60s \) time instants. These values are in comparable range. The proposed microlayer approach addresses the disadvantages of both the triple line model as well as the whole microlayer models available in the literature for microgravity conditions.

4 Conclusion

A new hybrid approach for calculation of the depletable microlayer contribution is proposed for microgravity conditions. This approach is in-line with the actual physical process of the microlayer life cycle. The microlayer in this approach is depletable due to the inclusion of an evaporation term. Results of bubble growth rate, bubble shape and heat-flux at different time instants report good agreement with experiments on ISS.

REFERENCES