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Ding, W.; Zhang, J.; Sarker, D.; Hampel, U.;

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The role of microlayer for bubble sliding in nucleate boiling: a new viewpoint for heat transfer enhancement via surface engineering

Wei Ding[1], Jinming Zhang[1], Debasish Sarker[1], Uwe Hampel[1,2]*

[1] Institute of Fluid Dynamics, Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany
[2] Chair of Imaging Techniques in Energy and Process Engineering, Technische Universität Dresden, Germany

Abstract

In an experimental study with a stainless steel heater (surface with maximum roughness Rt = 0.82 µm and contact angle hysteresis θ_{hys} = 53°), we investigated the bubble growth and motion during nucleation and departure. Complementary to that we analysed the formation of microlayer during the bubble growth and motion with computational fluid dynamics (CFD) simulation. From the simulations we found that the bubble motion leads to an expansion of the microlayer. From the experiments we obtained the drag coefficient on the bubble during bubble growth with an assumption of the absence of the wall surface tension force. From the comparison of this drag coefficient and the proposed values from the literature, we conclude that the vapour bubble does not directly contact the solid wall during the sliding. Using well-known mechanistic bubble growth models for further analysis of available microlayer area with the experimental data we conclude that a microlayer exists and the bubble must slide completely on this microlayer after leaving its originating cavity. From the change of microlayer size we can also explain the bubble regrowth after departure.

Keywords: Wall boiling; Bubble sliding; Microlayer; Nucleation;

1 Introduction

In subcooled flow boiling the heat transfer is coupled to the growth and dynamics of vapor bubbles in a complex way (Figure 1). Hence, the understanding of the underlying mechanisms is vital for an accurate model-based prediction of heat transfer. Most of the prior studies focused on bubble growth and departure from the originating cavity (e.g. Dhir et al., 2007). Studies on the bubble sliding are relatively rare, though its strong impact on the heat transfer is known (Qiu and Dhir, 2002). Investigations of bubble sliding were already suggested by others such as Klausner et al. (1993), Zeng et al. (1993) and Basu et al. (2005). Amongst these studies of the bubble sliding only few addressed the quenching effect induced by sliding without consideration of any details of bubble or bubble surroundings (Basu et al. 2005). The others dealt with details like liquid film between the bubble and wall, but only for bubble impingement and bouncing on a surface.

Figure 1: Exemplary sketch of bubble activation, growth, sliding, departure, and lift-off on a vertical wall. U is the velocity of flow, V is bubble velocity, d_w is the base contact diameter of the bubble, β_{ad} and β_{re} are the macroscopic advancing and receding contact angles, θ_b is the bubble inclination angle, r_b is the equivalent bubble radius, A_L and A_W are the bubble surface area in contact with liquid and wall.

The bubble sliding after impingement on a wall was experimentally studied by Addlesee and Cornwell (1997), Addlesee and Kew (2002), Kenning et al. (2002), Bayazit et al. (2003) and Li et al. (2006). They captured the liquid film layer (10 ~ 100 µm scale) trapped between sliding vapor or air bubbles and the wall of an inclined heater. Further, Lin et al. (2007) and Donnelly et al. (2009) indicated that the evaporation of this thin liquid film was one of most important contributions to the enhancement of heat transfer during the bubble sliding. However, due to the absence of bubble nucleation and growth, these physical phenomena may differ from those in nucleate boiling.

In bubble nucleation there is another type of liquid film which develops due to the growth dynamics underneath the bubble. This is referred to as "microlayer" and plays an important role for bubble dynamics. In 1969, Cooper and Loyd (1969) identified this thin liquid microlayer underneath the bubbles and modeled it on the basis of their experimental findings. They concluded a linear slope of microlayer thickness to the radial distance to the originate cavity when the bubble growth following $r_b \propto t^{1/2}$. In recent investigations, this micrometre-scale microlayer has been clearly visualized on a heater (e.g. ITO on a sapphire) with an IR camera, laser interferometry, or laser extinction method. (Duan et al. 2013; Gao et al. 2012; Jung and Kim 2014, Jung and Kim 2018, Utaka et al. 2014, Chen et al. 2017). These investigations show that the microlayer is formed underneath a bubble at an early stage and further fully evaporates during bubble growth (see Figure 2 b)). From the experimental results, Utaka et al. 2014 demonstrated also a linear relationship between the microlayer thickness and radical position. The contribution of microlayer evaporation to bubble growth is also debated. Kim (2009) concluded that the microlayer contributes no more than 25% to the overall, while Gerardi (2009) indicated that for steam bubbles microlayer accounted for the majority of the bubble growth. Most experimental studies related to this subject are for horizontal pool boiling, but the microlayer phenomena should also be there in vertical boiling. Cooper and Loyd (1969) and Zhao et al. (2002) considered that the microlayer is only formed in the early stage and evaporated and depleted later where the bubble base size expands in former stage and keeps constant or shrinks in the later stage. However, recent experimental results (Gao et al. 2012; Jung and Kim 2018) show that the bubble base expansion presents as well in the period after the microlayer evaporation starts (See Figure 2 b)) with which the microlayer area extends simultaneously. This period is usually referred to as thermal diffusion controlled period. It is characterized by a lower bubble expansion speed compared to the inertia controlled period.

Figure 2: a) Sketch of the microlayer at a growing nucleate bubble b) Measured microlayer thickness of nucleating steam bubbles in water at 1 bar for horizontal pool boiling (Jung et al. 2018).

In 2015, Fischer et al. (2015) carried out an investigation of the thin evaporating liquid film underneath a vapor bubble in a capillary channel with a high-speed IR camera. They confirmed that during the bubble motion a thin evaporating liquid film exists under certain conditions. In the same year, Baltis and van der Geld (2015) applied MTMS (microthermomechanical systems) and stereoscopic high-speed imaging to investigate the heat transfer mechanisms for a vapor bubble in a saturated upward flow. They confirmed a microlayer region underneath the bubble during the bubble sliding. They used the subscripts "apparent" and "real" to distinguish the outer border of the dry out area and bubble base (seeFigure 3). "Real" stands for the triple phase contact line (outer border of dry out) captured by the top view camera and "apparent" stands for the outer border of bubble base from the side view camera (due to resolution limits the side view camera was not able to capture the microlayer directly). A dashed line, which has a distance of 50 µm

from the wall, indicates the microlayer in Figure 3b. However, there is no further consideration of this topic in the paper, though a microlayer expansion during the sliding was observed.
Figure 3: a) Side view of a sliding bubble b) Model view of the sliding bubble with indication of the micro-layer underneath. Both pictures are from Baltis and van der Geld (2015).

A clear understanding of the microlayer evolution during bubble motion in nucleate boiling is important for the further improvement of boiling models. Moreover, as the microlayer is not only dependent on the vapor bubble evolution but also on the surface characteristics (Sarker et al. 2017, 2019) this gives way to design suitable surfaces to improve the heat transfer on the basis of an improved physical understanding. In this work, we report on an investigation of bubble sliding after nucleation, which was driven by the question, whether the microlayer still exists beneath the bubble during the sliding after the nucleation on certain designed surfaces. One condition of the microlayer presence is that the bubble motion (not only expansion) is able to extend the microlayer. Otherwise, the microlayer will be depleted by the evaporation during the sliding or even before the departure. We further analysed the bubble residence time and sliding area which also plays an important roles for the heat transfer. The investigation was done in three steps: 1. We used computational fluid dynamics (CFD) to prove that bubble motion extends the microlayer (see section 2.1 and 3.1), 2. We compared the experimentally derived drag force on the surface with designed roughness and wettability with values proposed in literature to prove that the bubble slides on the microlayer and is not in direct contact on the wall (See section 2.2 and 3.2), 3. We derived the available microlayer area to confirm the existence of the microlayer during the sliding. (See section 2.2 and 3.2.2).

2 Material and Methods

2.1 Computational fluid dynamics simulation of the microlayer

The present CFD simulation was carried out in ANSYS Fluent. The Volume of Fluid (VOF) method was applied to track the interface. Tracking is accomplished by the solution of a continuity equation for the volume fraction of phases (see Fluent theory guide (2018)). For phase i, the continuity equation is given as

$$\frac{1}{\rho_i}\left[\frac{\partial}{\partial t}(\alpha_i\rho_i) + \nabla\cdot(\alpha_i\rho_i\vec{v}_i)\right] = S_i + \sum_{p=1}^{n}\left(\dot{m}_{ij} - \dot{m}_{ji}\right) \quad (1)$$

where ρ_i is the density of phase i, $\vec{v}_i$ is the velocity, t is time, $\dot{m}_{ij}$ is the mass transfer from phase j to phase i and $\dot{m}_{ji}$ is that from phase i to phase j, S_i is the volumetric source term, α_i is the volume fraction of phase i and $\sum \alpha_i = 1$ for all phases.
The momentum equation for the mixture is given as

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla\cdot(\rho\vec{v}\vec{v}) = -\nabla p + \nabla\cdot[\mu(\nabla\vec{v} + \nabla\vec{v}^T)] + \rho\vec{g} + \vec{F}, \quad (2)$$

$\vec{v}$ is the mixture velocity, p is the pressure, μ is the viscosity, $\vec{g}$ is gravity and $\vec{F}$ is the external forces and ρ is the mixture density. The mixture density is determined by the presence of the component phases in each control volume, that is,

$$\rho = \sum \alpha_i \rho_i, \tag{3}$$

In Fluent, the compressive interface capturing scheme for arbitrary meshes (CICSAM) (see Ubbink 1997) is applied to produce an interface sharply.
To simulate the bubble expansion, in reference to the work of Guion et al. (2018), we applied an explicit expression for the volumetric source term (in 3D) in the vapour phase The energy equation is not involved here.

$$S_\alpha = \frac{\left(\frac{dV_b}{dt}\right)}{V_b} = 3U_b/R_b. \tag{4}$$

For the bubble expansion speed U_b we consider two different cases. Case 1: the bubble growth is considered as inertia controlled, that is,

$$U_b = \left(\frac{\pi}{7}\frac{h_{lv}\rho_v\Delta T_W}{\rho_l T_{sat}}\right)^{\frac{1}{2}}, \tag{5}$$

where h_{lv} is the latent heat, ρ_v is the density of the gas, ΔT_w is the wall superheat, ρ_l is the density of liquid and T_{sat} is the saturation temperature. In our experimental work we have water at 1 bar and $\Delta T_w = 7$ giving $U_b = 5.033\ \mathrm{m/s}$. We assume the bubble in this period is hemispherical with radius $R_b = U_b t$.
Case 2: In this work, we consider that the bubble growth consists of two stages: firstly is inertia controlled growth and later is thermal diffusion controlled according to Mikic (1970). In the thermal diffusion controlled stage, the bubble growth velocity is given as

$$U_b = \frac{1}{2}\left(\frac{12}{\pi}\alpha_l\right)^{\frac{1}{2}} Ja\, t^{-\frac{1}{2}}, \tag{6}$$

where α_l is liquid thermal diffusivity and $Ja = \frac{\Delta T_w c_l \rho_l}{h_{lv}\rho_v}$, c_l is specific heat capacity of liquid. Eq. (6) gives a hyperbolic profile of U_b meaning that U_b does initially rapidly decrease while this decrease becomes smaller with increasing time. Due to the size of the simulation domain (50 x 50 µm with the cavity located at $r = 25$ µm) the bubble growth time is in the range of microseconds. In this short growth period we may linearize the profile of U_b. Hence, the growth velocity is modelled as decreasing within the first 3 µs from 5.033 m/s to 0.5 m/s and remaining constant afterwards.
We followed the mesh sensitivity analysis of Guion et al. (2018) and set the mesh size to 12.5 nm and the time step to 0.1 ns. As the purpose of this CFD simulation is to qualitatively assess whether the bubble motion is able to extend the microlayer, the simulation domain has been kept rather small, that is, 50 x 50 µm with a of bubble nucleus of 4 µm diameter at the bottom (see Figure *4*). The simulation was carried out at two different conditions. One is the bubble growth in a pool boiling. The other is the bubble growth in a flow boiling where water flows from left to right. The latter is referred to be a cross-flow case. We set a symmetry boundary condition at the top to account for this cross-flow, a pressure boundary condition for no cross-flow simulation and a velocity boundary condition for cross-flow at the left and a pressure boundary condition at the right. The cross-flow velocity is set to 1 m/s.

Figure 4: Computational domain, boundary conditions and initial bubble nucleus for CFD .

The contact angle at the inner edge of microlayer where the liquid/vapor interface meets the solid wall determines the motion of the inner edge and further dictates whether the microlayer forms at the wall or not. In a sensitivity analysis of contact angle made by Guion et al. (2018) it was found that the microlayer thickness profile ($\delta_m = f(r)$) is influenced by the contact angle near the tripöe phase contact line but not further outside. In this work, we choose 20 degree as the value of contact angle to prove our hypothesis according to the work of Guion et al. (2018).

2.2 Experimental Study

2.2.1 Setup

Because we need a modified heater surface (wettability and roughness), we are not able to use the current available measurement method e.g. laser interferometry technique to capture the microlayer during the bubble nucleation (Gao et al. 2012, Jung and Kim 2014, Jung and Kim 2018). A 0.5 mm thick x 10 mm x 22.5 mm stainless steel plate was placed vertically as heater in this work (see Figure 5). A cylindrical artificial cavity of approximately $r_c = 25\ \mu m, h = 50\ \mu m$ was prepared in the centre of the stainless steel heater with a micro-laser. The experiments were carried out at 1 atm with degassed water. The subcooling was set to 2.5 K. K-type thermocouples were applied to measure the bulk liquid and wall temperature. Particle Image Velocimetry (PIV) (20-50 µm size particles, frequency of 4.9 Hz) was applied to monitor the bulk liquid velocity fields. The average liquid velocity $(\bar{u})$ was found to be ~ 0.025 m/s. A Motion Pro high speed video camera with a combination of a close-up lens and a Canon macro zoom lens (V6X16) was used (2500 fps and 30 µm per pixel with a standard deviation <±0.109 mm for bubble dimension measurement). Parameters of bubble dimensions were ensemble-averaged for at least 25 single bubbles (see Sarker et al., 2017).

Figure 5: Sectional diagram of the test section, a) front view b) top view, c) microstructure of the heater surface (for more details see Sarker et al., 2017)

2.2.2 Surface Preparation

Different methods were applied to change the surface roughness and wettability of the heater plate. These are polishing, wet-etching, and self-assembled monolayer (SAM) coating. Laser polishing gives a surface with roughness of Rt = 0.167 µm. Then samples were etched in an acid solution (H_2O: HCL: HNO_3= 6:6:1) for different periods to get different surface roughness. The SAM technique was applied to make the surface hydrophilic or hydrophobic. As the thickness of the deposited chemical layer is in the nanometre range, the SAM technique does not change roughness but only surface wettability. The dynamic contact angle, that is, the advancing liquid contact angle θ_{adv} and the receding liquid contact angle θ_{rec} were measured with a goniometer (DataPhysics OCA 30) by applying the sessile drop method. The difference between the averaged advancing and receding angles is referred to as hysteresis liquid contact angle $\theta_{hys} = \theta_{adv} - \theta_{rec}$. More details can be found in the work of Sarker et al. (2017). Heater plate surface parameter for this study are given in Table 1.

Table 1: Parameters of the designed surface

3 Results and Discussion

3.1 Computational Fluid Dynamics Simulations

As introduced in section 2.1, there are two cases for the CFD simulation: 1) a constant expansion rate of the bubble with 5.033 m/s and 2) a continuously decreasing expansion rate from 5.033 to 0.5 m/s within the first 3 µs followed by a constant rate. Figure 6 shows the results for case 1 and Figure 7 for case 2. The interface has been post-processed by MATLAB 2018.

Figure 6: Bubble geometry with and without cross-flow (1 m/s) at a constant bubble growth velocity (5.033 m/s) at a) t = 0.05 µs, b) t = 0.15 µs, c) t = 0.2 µs and d) microlayer thickness profile in r+ direction for different time steps with and without cross-flow, e) comparison of the microlayer profile when the bubble has the similar size between the present calculation and the results from Fig. 1 in Guion et al. 2018 with an adaption of nucleus size, f) Microlayer thickness profile for a 0.5 mm size bubble with $\mathrm{U_b} = 42\ m/s$ *by Guion et al. 2018 b.*

As shown in Figure 6, the bubble is pushed to the right side in the cross-flow cases. Compared to the cases without cross-flow, the microlayer extends at the bubble receding (right) side and shortens at the advancing (left) side. That is, the bubble motion due to cross-flow leads to the formation of an extra microlayer at the bubble receding side. With the exception of the meniscus structure (see Figure 2 a)) the main body of the microlayer at different time t has a same microlayer thickness profile ($\delta_m = f(r)$ see the red dashed line in Figure 6 d)) with or without cross-flow at a constant bubble growth velocity. In this work, the microlayer thickness profile is defined as the distribution of microlayer thickness along the wall radial direction ($\delta_m = f(r)$) from the inner edge of microlayer (triple phase contact line see Figure 2 a)) to the inner border of bubble meniscus see the red circle in Figure 6 d)). The inner border of bubble meniscus is referred to the starting point of the interface curvature rapidly increase. That is, the microlayer extension due to the bubble motion still follows the microlayer thickness profile in the case without bubble motion. Additionally, it is found the simulated result in the present work has very slight difference to that of Guion et al. 2018 when the bubble size is similar with an adaption of the nucleus size (see Figure 6 e)). For a mm scale simulation from Guion et al 2018, it shows the microlayer expansion during the bubble growth also follows certain fix thickness profile where is considered as linear by Cooper and Loyd 1969 and Utaka et al. 2014.

Figure 7: Bubble geometry with and without cross-flow (1 m/s) at a continuously decreasing expansion velocity (5.033 to 0.5 m/s in 0.3 µs and then constant) at a) t = 0.15 µs, b) t = 0.35 µs, c) t = 0.55 µs and d) microlayer thickness profile in r+ direction for different time steps with and without cross-flow.

Similar happens in the cases when the bubble growth velocity decreases rapidly (see Figure 7). As it is shown, the rapid decrease of the bubble growth velocity or the bubble motion affects the bubble base expansion and also microlayer expansion. However, neither the rapid decrease of the bubble growth velocity nor the bubble motion impacts the microlayer thickness profile in the microlayer main body (see the red dashed line).

The simulation results confirm that the expansion of the microlayer is due to both bubble expansion and bubble motion. Different expansion rate, with or without cross-flow, do not change the microlayer thickness profile. However, due to computational complexity we were not able to simulate the whole bubble life cycle until lift-off with such a high spatial and temporal resolution. Also, the model for evaporation at the gas-liquid interfaces may be critical for such a simulation. Hence, we continued our analyses with experimental data.

3.2 Experiments

Using the high-speed camera we could capture the bubble motion and dimensions for different heater plate samples.

Figure 8: a) Measured acceleration of the bubble for the listed heater surfaces given in Table 1 at $\dot{q}_w = 24\ kW/m^2, \Delta T_{sub} = 2.5\ K$, *b) Characteristic bubble parameters (position of mass center, outer borders of bubble base, calculated bubble equivalent diameter and base diameter) for the surface with Rt = 0.821 μm,* θ_{hys} *= 53°, c) residence time of the bubble on the wall, d) maximum bubble base diameter and residence time when bubble slides through the y position along the wall.*

From experiment, we captured the position of the bubble center and further calculated the moving velocity of the bubble center and finally derived the acceleration of the bubble. It was found that the acceleration of the bubble for the surface with Rt = 0.821 μm, θ_{hys} = 53° is always positive during the bubble life-cycle from nucleation to sliding until lift-off at a heat flux of 24 kW/m² (See Figure 8 a)). This finding confirms that it is possible to have very low negative forces (surface tension force) during the whole bubble life-cycle. We chose this surface for further analysis of the forces particularly the drag force on the bubble to prove whether the bubble moves on a microlayer during the sliding.

In the surface with Rt = 0.821 μm, θ_{hys} = 53°, the bubble departs from the originating cavity at t = 8.4 ms and slides ~ 3.2 mm along the wall in the next 18 ms (see mass center in Figure 8 b)). The bubble base increases until t = 20.4 ms and starts then to shrink (See Figure 8 b)). At the nucleation position (y = 0 mm) the bubble has a maximum base diameter of 0.97 mm and a residence time of 7.95 ms. At positions y = {1 mm, 2 mm, 3 mm} it has a maximum base diameter of {109%, 103%, 77%} and a residence time of {96%, 75%, 23%} (See Figure 8 c) and d)). That is, the bubble has a countable contact area and residence time when sliding. As is shown in Figure 2 a), the microlayer has only < 10 µm thickness. From the heat conduction law, the heat transfer rate will be inverse proportional to the thickness of microlayer. That is, the microlayer contributes noticeably to an enhancement of heat transfer which is also the reason for the second peak of bubble size shown in Figure 8 b).

3.2.1 Drag on the bubble

The drag coefficient was derived in the bulk of a bubbly flow by different groups. These derivations consider only the interfacial force between liquid and gas (Moore 1963, Clift et al. 1987 and Ishii and Zuber 1979). In the last section it was found that the acceleration of the bubble remains positive for the surface with Rt = 0.821 μm, θ_{hys} = 53°. So we may assume that the dry-out may cease to exist during the sliding. In other words, the bubble may slide on a microlayer completely. If it is true, the derived drag coefficient from the experimental data which will approach the proposed value from the literature.

As was stated by Klausner et al. (1993) and Thorncroft et al. (2001), there are five forces acting on an isolated bubble: body force, surface tension force, liquid stress at the interface, normal stress due to vapor pressure at the interface and a reaction force. The total force is given as

$$\vec{F} = \vec{F}_{Body} + \vec{F}_S + \int_{A_F} \underline{\underline{\sigma}} \cdot \vec{n} dA + \int_{A_W} p_v \left(-\vec{n}\right) dA + \vec{F}_R . \tag{7}$$

$\vec{F}_{Body} = \rho_v \frac{4}{3}\pi r_b^3 \vec{g}$ is the body force, $\vec{F}_S$ is surface tension force, $\underline{\underline{\sigma}}$ is the liquid stress tensor on the vapor-liquid interface of the bubble surface A_F, $\vec{n}$ is the outward normal vector on the surface. The vapour pressure p_v in the vapour wall contact area is used to calculate the impact of wall and reaction force $\vec{F}_R$. Different to the previous study (Klausner et al, 1993; Thorncroft et al., 2001), in this work we consider that the surface tension force should be determined by the vapor-wall contact area (i.e dryout area) (see Figure 9) instead of base diameter, because this force should be determined by the balance of the interfacial tensions of triple phases (liquid vapor: γ_{lv}, liquid solid: γ_{lw} and vapour solid: γ_{vw}). The integration of total surface tension along the triple phase contact line in the wall tangential direction is given as

$$\vec{F}_{S,t} \approx -1.25 * L_t^d * \gamma_l \frac{\pi(\beta'_{ad}-\beta'_{re})}{\pi^2-(\beta'_{ad}-\beta'_{re})^2}(\sin(\beta'_{ad}) - \sin(\beta'_{re})). \quad (8)$$

Here, γ_l is the surface tension of the liquid, and β'_{ad} and β'_{re} are the advancing and receding contact angles of the microlayer, L_t^d is the characteristic dry-out length of the vapor wall contact area. If the bubble completely slides on a microlayer, then, $L_t^d = 0$ (diameter when it is circular), and $\vec{F}_{S,t} = 0$.

Figure 9: Schematic view of the process of bubble sliding on the wall with the contact area A_L with liquid, the contact area A_W with the wall, the considered forces and the reference point C at the triple phase contact line underneath the bubble.

Thorncroft et al. (2001) classified that $\vec{F}_R$ is due to the London-van der Waals force "acting on the vapor through the triple phase common line". When the vapor wall contact area is zero, this force becomes also zero. In the other three terms, the liquid stress tensor in the surface area A_L of the bubble is

$$\underline{\underline{\sigma}} \cdot \vec{n} = -(p - \rho_l g y)\vec{n} + \underline{\underline{\tau}} \cdot \vec{n}, \quad (9)$$

where p is the hydrodynamic pressure, and $\underline{\underline{\tau}}$ is the deviatoric stress tensor. With that, Eq. (7) can be given as

$$\vec{F} = \vec{F}_{Body} + \vec{F}_S + \int_{A_F} \left(-\left(p - \rho_l g y\right)\right)\vec{n}dA + \int_{A_F} \underline{\underline{\tau}}\,\vec{n}dA + \int_{A_W} p_v\left(-\vec{n}\right)dA + \vec{F}_R\,. \quad (10)$$

Thorncroft et al. (2001) took a point C as a reference (see Figure 9) and further added and subtracted $\int_{A_W} \left(p_C - \rho_l g y\right)\vec{n}dA$ in Eq. (7), giving

$$\vec{F} = \vec{F}_{Body} + \vec{F}_S + \underbrace{\int_{A_F} -\left(p - p_C\right)\vec{n}dA + \int_{A_F} \underline{\underline{\tau}}\,\vec{n}dA}_{hydrodynamic\ force} \quad (11)$$

$$-\underbrace{\int_{A_F+A_W}\left(p_C-\rho_l gy\right)\vec{n}dA}_{\vec{F}_B}+\underbrace{\int_{A_W}\left(p_C-\rho_l gy-p_v\right)\vec{n}dA}_{\vec{F}_{CP}}+\vec{F}_R.$$

In the present work, we paid more attention to the sliding along the wall. Hence, we neglected the term of the contact pressure force ($\vec{F}_{CP}$), which acts only in wall perpendicular direction. Then, Eq. (11) can be given as

$$\vec{F}=\vec{F}_{Body}+\underbrace{\int_{A_F}\left(-\left(p-p_C\right)\right)\vec{n}dA+\int_{A_F}\underline{\underline{\tau}}\,\vec{n}dA}_{hydrodynamic\ force}-\underbrace{\int_{A_F+A_W}\left(p_C-\rho_l gy\right)\vec{n}dA}_{\vec{F}_B}. \tag{12}$$

The buoyancy is given as $\vec{F}_B=-\rho_l\frac{4}{3}\pi r_b^3\vec{g}$. The hydrodynamic force mainly consists of history force, the quasi drag force $\vec{F}_{QS}=\frac{1}{2}\rho_l\pi {r_b}^2 C_D|U-V|(U-V)$, added mass force $\vec{F}_{AM}$ and a force from free acceleration $\vec{F}_{FS}=\frac{4}{3}\rho_l\pi r_b^3\frac{dU}{dt}$ due to pressure gradient. Here, U is the velocity of the supposed streamline through the mass center of the bubble and V is the bubble sliding velocity of the center-of-mass on the wall. As stated by Mei and Klausner et al. (1992), for a clean bubble the history force is very small and negligible. Thorncroft et al. (2001) also stated that the wall has a limited impact on the hydrodynamic force of the sliding bubble in the wall tangential direction. The added mass force $\vec{F}_{AM}$ is associated with the rate of change of the liquid velocity $\frac{dU}{dt}$ and the rate of change of the bubble velocity $\frac{dV}{dt}$, the rate of change of bubble size $\frac{dr_b}{dt}$ and the free stream acceleration force (Thorncroft et al. 2001 and Ohl et al., 2003), which is described as

$$\vec{F}_{AM}=(2\pi\rho_l){r_b}^2\frac{dr_b}{dt}(U-V)+\frac{2}{3}\pi\rho_l {r_b}^3\frac{d}{dt}[(U-V)]. \tag{13}$$

The Eq. (12) can be further given as

$$\rho_v\frac{4}{3}\pi r_b^3\frac{dV}{dt}= \rho_l\frac{4}{3}\pi r_b^3\frac{dU}{dt}+(2\pi\rho_l){r_b}^2\frac{dr_b}{dt}(U-V)+\frac{2}{3}\pi\rho_l{r_b}^3\frac{d}{dt}[(U-V)]-\rho_v\frac{4}{3}\pi r_b^3\vec{g}+\rho_l\frac{4}{3}\pi r_b^3\vec{g}+\frac{1}{2}\rho_l\pi{r_b}^2C_D|U-V|(U-V). \tag{14}$$

Due to the large density ratio of liquid and vapor $\frac{\rho_l}{\rho_v}$, it can be further simplified to

$$0=3\frac{dU}{dt}-\frac{dV}{dt}+\frac{3}{r_b}\frac{dr_b}{dt}(U-V)+2\vec{g}+\frac{3C_D}{4r_b}|U-V|(U-V), \tag{15}$$

with the drag force coefficient given as

$$C_D=\frac{4r_b\left(3\frac{dU}{dt}-\frac{dV}{dt}+\frac{3}{r_b}\frac{dr_b}{dt}(U-V)+2\vec{g}\right)}{3|U-V|(V-U)}. \tag{16}$$

In the present study, the Reichardt's turbulent single-phase flow model (Reichardt, 1951) is applied to calculate the time-average velocity near the wall according to

$$\frac{U(x)}{u^*} = \frac{1}{\kappa}\ln\left(1+\kappa\frac{xu^*}{\nu}\right) + c\left[1-\exp\left(-\frac{\frac{xu^*}{\nu}}{\chi}\right) - \frac{\frac{xu^*}{\nu}}{\chi}\exp\left(-0.33\frac{xu^*}{\nu}\right)\right], \tag{17}$$

where ν is the kinematic viscosity, $\kappa = 0.4$, $\chi = 11$ and $c = 7.4$. Further $\frac{u^*}{\bar{u}}$ is considered to be 0.04 (Klausner et al., 1993), 0.05 (Zeng et al. 1993), and $\sqrt{\frac{C_f}{2}}$ (Thorncroft et al. 2001) where u^* is the friction velocity and $\bar{u}$ is the mean liquid velocity for the two-phase flow which is 0.025 m/s measured by PIV in this work and $\frac{C_f}{2} = (2.236 ln Re_l - 4.639)^{-2}$.

As is stated before, if the bubble indeed completely slides on its microlayer the drag coefficient should approach to the value proposed by known correlations. We assessed this with the four following correlations. Although Moore (1963) and Clift et al. (1987) proposed a drag coefficient for bubbly flow with low Reynolds number (Re_b<1), Kurose et al (2001) found it was also valid when Re_b> 50. Later Ishii and Zuber (1979) considered the impact of the bubble geometry for sphere, ellipse and cap and proposed a more universal drag correlation. Klausner et al. (1993) proposed a drag coefficient based on their own experiments of bubbly flow. More recently, Perron et al. (2006) investigated the impact of the wall on the bubble sliding along the inclined wall and proposed a drag coefficient depending on Bo and wall inclination angle θ_w (2° ~ 10 °). Details are given in Table 2

Table 2: Proposed Drag coefficient C_D from the literature.

The derived drag coefficient from the experiment and the proposed literature values are shown in Figure 10. The experimentally derived values and the proposed ones approach each other gradually, particularly after 9.2 ms.

Figure 10: Comparison of the drag coefficient derived from our experiments with proposed values from the literature.

When we assume that the surface tension force $\vec{F}_{S,t}$ is always zero, the drag coefficient must be overestimated in the early stage of the bubble when the dry-out area is still present due to the longer residence time (See Figure 8 d)). As was confirmed by the CFD simulation, during bubble sliding, the bubble motion leads to a formation of an extra microlayer at the bubble receding side. In this process, if the microlayer expansion is faster than its depletion due to evaporation, the dry-out area will reduce. That is, based on Eq. (8), the surface tension decreases. Meanwhile, the derived drag coefficient should approach to the proposed value from the literature until the dry-out area completely ceases to exist. This is shown in Figure 10. We take the $\frac{u^*}{\bar{u}}$= 0.04 as an example. At 9.2 ms we get the drag coefficient from Klauser et al. (1993), 10.8 ms we get the one from Perron et al. (2006) and after t = 12 ms the one of Ishii and Zuber (1979). Compare to other three correlations, Clift's underestimated the drag coefficient at high Re_b. It is contrary to the conclusion of Kuros et al. 2001 where Clift's correlation is also valid when Re_b> 50. After the approach, the derived drag coefficient differs to the proposed value again which may be due to the present of wall. That is also the reason that Perron et al.. 2006 has the best agreement. The impact of $\frac{u^*}{\bar{u}}$ value applied in Eq. 17 on the drag coefficient is also considered and compared in Figure 10 b). Different $\frac{u^*}{\bar{u}}$ from Klausner et al. (1993), Zeng et al- (1993) and Thorncroft et al. (2002) changes the derived drag coefficient but not impacts the whole story. The equalisation of the derived value to the proposed one shows that the bubble does very likely slide without any direct contact on the wall. However, as an indirect proof, it still has some weakness. So we continued our analysis as described in the next section.

3.2.2 Available microlayer area

In the following, we introduce the calculation of microlayer area (length) during the bubble growth based on the experimental results and a bubble growth model. The work consists of two steps: 1. we characterize the microlayer based on the available bubble growth models. 2. We apply the characterized microlayer thickness coefficient to calculate the microlayer area based on measured bubble dimensions.

Copper and Lloyd (1969) derived the following equation for the initial microlayer thickness

$$\delta_{mi}^{0}(\mathrm{r}) = C_2\sqrt{\nu \cdot t_g}, \tag{18}$$

with a constant C_2 = 0.8, the kinematic viscosity ν of the liquid, and the time t_g that is takes for the bubble to grow to position r. The authors further argued that C_2 may differ between 0.3 and 1.0 depending on the experimental conditions. In the study of Sarker et al. (2019) it was found that the constant C_2 in Eq. (18) is strongly dependent on the surface characteristics. They proposed a coefficient C_{eff} instead of C_2 to account for surface characteristics. The way of calculating C_{eff} is illustrated in the Figure 11.

Figure 11: Flow chart to determine the coefficient C_{eff} *that accounts for the surface characteristics effects on the bubble growth. (Sarker et al., 2019)*

Here, we consider that the bubble growth first under inertia control and then under thermal diffusion control according to Mikic et al. (1970), whereby $t^+ = 1$ is considered as transition from inertia control to thermal diffusion control. The contribution of the microlayer is accounted for by Cooper's formula (Cooper, 1969) that also considers the impact of dry-out. Condensation is taken into account by Yun's formula (Yun et al., 2012). The involved bubble growth models are given in Table 3.

Table 3: Bubble growth models (Sarker et al., 2019).

Considering all the above-mentioned facts, we have formulated the expressions for the bubble growth in the work of Sarker et al. (2019). In that work, the effective microlayer thickness constant $C_{eff} = 0.5$ has been derived for sample 4 at 24 kW/m².

The calculation of available microlayer length during the bubble growth has to consider two physical processes: 1. the new extended microlayer thickness, 2. the conjugate heat to the wall during the evaporation of microlayer. Based on Cooper's formula, Zhao et al., (2002) described the microlayer thickness at different positions (r) underneath the bubble as

$$\delta_{mi}^{0}(r) = \frac{C\alpha_l \rho_g h_{lv} r}{2k_l \Delta T_w} \tag{19}$$

with $C = C_{eff}{}^{2} Pr$.

In the paper of Cooper and Lloyd (1969) and Zhao et al. (2002), they consider that the microlayer is only formed in the initial stage. After that, the evaporation of microlayer supports the bubble growth, while the base is always constant until shrinking starts. However, as it was observed in the study of Jung et al. (2018) the bubble base expansion after the microlayer starts evaporation leads to a simultaneous microlayer expansion (See Figure 2). We would like to further derive the new extended microlayer thickness based our first conclusion of the CFD simulation (see section 3.1).

The heat balance between the liquid microlayer evaporation and the heat conducted through the microlayer was described by Zhao et al. (2002) as

$$-\rho_l h_{lv} \frac{d\delta_{mi}(t,r)}{dt} = \frac{k_l \Delta T_w}{\delta_{mi}(t,r)}. \tag{20}$$

So the microlayer thickness at the position r and at time t is given as

$$\delta_{mi}(t,r) = \frac{C\alpha_l \rho_v h_{fg} r}{2k_l \Delta T_w} \cdot \left[1 - \frac{8c_{pl} k_l{}^{2} \Delta T_w{}^{3}(t-t_g)}{C^2 \alpha_l h_{lv}{}^{3} \rho_v{}^{2} r^2}\right]^{1/2}. \tag{21}$$

The microlayer evaporation and microlayer expansion take place simultaneously. If the microlayer expansion follows the slope of $\frac{r}{\delta_{mi}}$ including the evaporation, the new extended microlayer thickness can be calculated based on Eq. (21). In our previous and present studies we evaluated t_g at $t^+ = 1$ for Mikic's approach, which means that the bubble growth turns from inertia control to thermal diffusion control. This idea has been tested in the previous study by Ding et al. (2018) for horizontal pool boiling, and was compared and validated with experimental data from Duan et al. (2013) and quasi DNS calculation with PSI boiling code from Sato et al. (2015). As we stated in Section 2, the bubble motion extends the microlayer while it does not change the microlayer thickness profile. Hence, Eq. (21) is also valid for the extended microlayer due to bubble motion.

The conjugated heat transfer to the wall during the microlayer evaporation is also considered in our work. Due to the large heat transfer induced by the evaporation of microlayer, the wall temperature decreases, which leads to an additional heat transfer inside the wall. As the wall acts as a thermal buffer with a high thermal conductivity it can impact the hot spot (dry-out) underneath the bubble. The heat flux in the wall tangential direction is considered as

$$\dot{Q}_{t,w} = k_w \Delta T_{w,t} \delta_w . \tag{22}$$

There, k_w is the thermal conductivity of wall, δ_w is the thickness of the wall, $\Delta T_{w,t}$ is the temperature gradient between two neighboring cells in wall tangential direction, while the total heat flow rate is given as

$$\dot{Q}_{total} = \dot{Q}_{t,w} + \dot{Q}_{out} + \dot{Q}_{in}. \quad (23)$$

Here, $\dot{\mathrm{Q}}_{\mathrm{in}} = \dot{\mathrm{q}}_{\mathrm{w}}\Delta\mathrm{L}_{\mathrm{w}}$ is the feed heat flow rate, $\dot{\mathrm{Q}}_{\mathrm{out}}$ is the heat flow rate transferred from wall to microlayer (Eq. (20)). Considering energy conservation, the temperature at the calculated location follows

$$\frac{dT_w}{dt} = \dot{Q}_{total}/(c_{pw}\rho_w\delta_w\Delta L_w). \quad (24)$$

Figure 12:a) Scheme of the conjugate heat transfer to the wall underneath the bubble, b) Temperature distribution on the wall at different times at zero gravity, that is, for a bubble growth without lift-off or departure, and at $T_w = 7\ K$, $\dot{q}_w = 24\frac{kW}{m^2}, C_{eff} = 0.5$.

When the microlayer thickness becomes 0, the location is considered to belong to the dry-out area. When there is no bubble motion, the dry-out area (characterized by diameter D_t^d or length L_t^d) is clearly of a circular shape:

$$L_t^d = D_t^d. \quad (25)$$

D_t^d is calculated based on an ideal bubble growth at zero gravity considering the microlayer expansion but no lift-off or departure. Because the bubble expansion and motion does not impact the microlayer thickness profile, the D_t^d calculated above will be equal to that of a sliding bubble (See Figure 13 a)). The details of the calculation and sensitivity analysis of the wall length discretization were given in the work of Ding et al. (2018).
With bubble motion, when the $L_s > \left(\frac{\mathrm{d}_w}{2} - \frac{D_t^d}{2}\right)$, the dry-out length L_t^d is given as

$$L_t^d = D_t^d - L_s + \left(\frac{\mathrm{d}_w}{2} - \frac{D_t^d}{2}\right), \quad (26)$$

where L_s is the distance of the bubble base moving from the originating cavity and d_w is the base diaemter. Both L_s and d_w are obtained from the experiment.
Figure 13: a) Schematic view of the microlayer expansion process during bubble growth and sliding on the wall, b) dry-out area calculation considering the conjugated heat transfer to the wall in horizontal pool boiling and that considering the bubble motion at $\Delta T_w = 7\ K$, $\dot{q}_w = 24\frac{kW}{m^2}, C_{eff} = 0.5$.

The difference between the base diameter and dry-out length is the available microlayer length (L_{am}) is

$$\mathrm{L}_{am} = \mathrm{d}_w - \left(D_t^d - \max\left(L_s - \left(\frac{d_w}{2} - \frac{D_t^d}{2}\right), 0\right)\right). \quad (27)$$

Figure 14: Evolution of the microlayer area (length), dry-out and bubble equivalent diameter when the bubble motion extends the microlayer at $T_w = 7\ K,\ \dot{q}_w = 24\frac{kW}{m^2}, C_{eff} = 0.5$.

As shown in Figure 14, at $t = 13.2\ ms$, the microlayer area approaches the base area. In other words, from $t = 13.2\ ms$, the bubble slides completely on the microlayer without any direct contact with the wall. In the last section, this time point derived from the drag coefficient comparison is 10.8 ms with the data of Perron et al. (2016) and 12 ms with Ishii and Zuber (1979) respectively. An acceptable agreement ($\pm 10\ \%$ to averaged value) on the starting point of complete bubble sliding on the microlayer was yielded from two independent proofs.

We further compared our calculated microlayer area (length) with the measured bubble equivalent diameter. According to the growth models (Table 3) the bubble growth velocity should decrease with time due to the microlayer depletion and the heat loss at the bubble cap. In the work of Yoo et al. 2016, the second peak of bubble size is explained by the change of evaporation and condensation rate. However, different to the work of Yoo et al. 2019, the bubble in the present work does not bounce from the wall. That is the evaporation and condensation rate should not have a sudden change here. Consequently, the bubble has no chance of a second growth as shown in Figure 14. From our present work, the microlayer area is found to decrease at first and increase further. It seems to be the corresponding reason for the regrowth of the bubble equivalent diameter

Consequently, when we consider these two independent experimental proofs together, we are able to conclude that, in the experiment with the surface with Rt = 0.821 µm, θ_{hys} = 53°, the bubble completely moves on a microlayer during sliding which has also a countable residence time on the countable sliding area.

4 Conclusion

In this work, we investigated the role of microlayer during bubble sliding after nucleation with both CFD simulation and experiments. In the CFD part, the extended microlayer profile was studied at different expansion and motion speed. In the experimental study, the derived drag coefficient was compared with the proposed values from the literature. The available microlayer area was also calculated based on the experimental captured bubble dimensions to show the microlayer change during the sliding.

Consequently, we conclude our work as follows:

1. The microlayer expansion at the bubble receding side is not only due to the bubble base expansion but also due to the bubble motion.
2. The microlayer underneath the bubble plays a role not only during the growth of the originating cavity but also in the sliding.
3. During the sliding, the bubble moves partially or completely on a microlayer.
4. The bubble may have a comparable or even more residence time and sliding area during the sliding than that on the originating cavity on an engineered surface.
5. The bubble sliding may lead to increase of microlayer area which makes the bubble regrow after departure on an engineered surface.

Conventionally, the evaporation of a thin liquid film (10 ~ 100 µm measured from experiments) was one of most important contributions to the enhancement of heat transfer during the bubble sliding from the studies with bubble impingement on a wall. As a "µm" thick, microlayer beneath the bubble during the sliding should be also important for the heat transfer enhancement where a "µm" thickness means MW/m² scale heat transfer. It offers a new key viewpoint to enhance the heat transfer process via surface structure engineering.

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Nomenclature

A_F	bubble surface area in contact with liquid flow
A_W	bubble surface area in contact with wall
b	sphericity of bubble
Bo	Bond number $Bo = \frac{(\rho_l - \rho_g) g (2r_b)}{\sigma}$
c_D	friction drag coefficient
c_{pl}	liquid specific heat capacity
C	constant defined as $C = {C_{eff}}^2 Pr$
C_2, C_{eff}	microlayer constant, effective microlayer constant considering surface characteristics
d_w	base diameter
D_t^d	dry-out diameter
Eo	Eötvös number = Bo
$\vec{F}$	external forces
$\vec{F}_{AM}$	added mass force
$\vec{F}_B$	buoyancy
$\vec{F}_{Body}$	body force
$\vec{F}_{CP}$	contact pressure force
$\vec{F}_{FS}$	free acceleration force
$\vec{F}_{QS}$	the quasi stead drag force
$\vec{F}_R$	reaction force
$\vec{F}_S$	surface tension force
$\vec{F}_{S,t}$	surface tension force in wall tangential direction
$\vec{g}$	gravity
h	cavity depth
h_{lv}	latent heat
h_c	heat transfer coefficient due to condensation
Ja	Jacob number $= \frac{\Delta T_w c_l \rho_l}{h_{lv} \rho_v}$
k_l	liquid thermal conductivity
$\boldsymbol{I}$	Kelvin impulse
L_{am}	microlayer area (length) underneath the bubble during the sliding
L_s	sliding length of the bubble base
L_t^d	characteristic length of the dry-out area
$\dot{m}_{ij}$	the mass transfer from phase j to phase i
$\dot{m}_{ji}$	the mass transfer from phase i to phase j
$\vec{n}$	the outward normal vector on the surface

p	pressure
Pr	Prandtl number
$\dot{Q}_{in}$, $\dot{Q}_{total}$, $\dot{Q}_{out}$, $\dot{Q}_{t,w}$	Feed heat, total heat for a cell of wall, heat transferred from wall to liquid, heat transfer to neighboring wall cell
$\dot{q}_w$	wall heat flux
q_i''	heat flux due to condensation
R_b	the bubble radius when it is assumed to be hemispheric
r	coordinate
r_b	bubble equivalent radius
r_c	radius of cavity
Re_b	Reynold's number $\frac{\rho_{l\|U-V\|2r_b}}{\mu_l}$
R_q, R_t	roughness and maximum roughness height of the surface
$\acute{s}$	bubble surface portion in contact with the subcooling liquid
S_{α_i}, S_α	the volumetric source of phase i, the volumetric source of vapor
t	time
t_a	the time when the microlayer formed in the initial growth time is completely evaporated
t_g	bubble initial growth time
t_w	bubble waiting time
T_w, T_l, T_{sat}	wall temperature, bulk liquid temperature and saturation temperature
U	the liquid velocity; the liquid velocity of the supposed streamline through the mass center of the bubble
U_b	bubble expansion speed
u^*	friction velocity
$\bar{u}$	mean liquid velocity for two phase flow
$\vec{v}$, $\vec{v_i}$	velocity field, velocity field for phase i
V	the bubble sliding velocity of the center-of-mass on the wall
x, y	coordinate
ΔT_w	wall superheat
ΔT_{sub}	liquid subcooling
α, α_i	volume fraction, volume fraction of phase i
α_l	liquid thermal diffusivity
β_{ad}	advancing contact angle of macrolayer
β_{re}	receding contact angle of macrolayer
β'_{ad}	advancing contact angle of the microlayer
β'_{re}	receding contact angle of the microlayer
θ	a term of $\frac{T_w-T_l}{T_w-T_{sat}}$
θ_b	inclined angel of a bubble in flow boiling
θ_{adv}	advancing liquid contact angle
θ_{rec}	receding liquid contact angle
θ_{hys}	hysteresis liquid contact angle
θ_w	wall inclination angle

$\gamma_l, \gamma_{lv}, \gamma_{lw}, \gamma_{vw}$	surface tension of liquid, on the liquid vapor, liquid solid and vapor solid interface,
$\rho,\ \rho_l,\ \rho_v,\ \rho_i$	density, density of the liquid and vapor, density of phase i
δ_{mi}	microlayer thickness
δ_{mi}^0	microlayer initial thickness
$\mu,\ \mu_l$	viscosity, viscosity of liquid
$\underline{\underline{\sigma}}$	liquid stress stensor
$\underline{\underline{\tau}}$	deviatoric stress tensor
τ_g	microlayer formation time at position r
ν	kinematic viscosity of liquid
$\kappa, \chi, c,$ n	constant
$\emptyset$	a term of $\frac{\rho_v}{\rho_l}\frac{h_{fg}}{C_{pl}}Pr\cdot\left\{1+\frac{2}{C^2}\frac{C_{pl}(\Delta T_w)}{h_{fg}}.\frac{1}{Pr}\right\}$

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Tables

Table 4: Parameters of the designed surface

Designed surface			
Maximum roughness height (Rt) [µm]	Advancing (θ_{adv}) [°]	Receding (θ_{rec}) [°]	Hysteresis (θ_{hys}) [°]
0.167	62	28	34
0.167	60	21	39
0.167	105	34	71
0.821	66	13	53
3.65	77	12	65

Table 5: Proposed Drag coefficient C_D from the literature.

	Drag coefficient C_D
Moore (1963) Clift et al. (1987)	$C_D = \frac{16}{Re_b}\left(1 + 0.15{Re_b}^{0.5}\right)$
Ishii and Zuber (1979)	$C_D = max\left(C_{D,sphere}, min\left(C_{D,ellipse}, C_{D,cap}\right)\right)$ $C_{D,sphere} = \frac{24}{Re_b}\left(1 + 0.1{Re_b}^{0.75}\right)$ $C_{D,ellipsoid} = \frac{2}{3}\sqrt{Eo}$, $C_{D,cap} = \frac{8}{3}$
Klausner et al. (1993)	$C_D = \left(\frac{2}{3} + \left[\frac{12}{Re} + 0.75\left(1 + \frac{3.315}{Re^{1/2}}\right)\right]^{-1}\right)$
Perron (2006)	$C_D = 0.04 \cdot {\theta_w}^{0.773} Bo^{0.45}$

Table 6: Bubble growth models (Sarker et al., 2019).

Author	Model	Features
Mikic et al. 1970	$dr_b(t)=A.dt\ ;\ t^+\ll 1$ $dr_b(t)=1/2Bt^{-1/2}dt\ ;\ t^+\gg 1$ $t^+=\frac{A^2t}{B^2}.$ $A=\left(\frac{\pi}{7}\frac{h_{lv}\rho_v\Delta T_w}{\rho_l T_{sat}}\right)^{\frac{1}{2}},\ B=\left(\frac{12}{\pi}\alpha_l\right)^{\frac{1}{2}}Ja.$	• Bubbles grows from zero. • Includes both inertia and thermal diffusion controlled growth stages.
	$\frac{dr_b(t)}{dt}=\frac{1}{2}\frac{B}{\sqrt{t}}\left[\frac{T_w\text{-}T_{sat}}{\Delta T}\text{-}\theta\left(\frac{t}{t+t_w}\right)^{1/2}\right].$ $\theta=\frac{T_w-T_l}{T_w\text{-}T_{sat}}.$	
Cooper 1969	$\frac{dr_b(t)}{dt}=\frac{2}{C_2}\frac{T_{w,0}\text{-}T_{sat}}{\phi}\left(\frac{v_l}{t}\right)^{0.5}.$ $\phi=\frac{\rho_v}{\rho_l}\frac{h_{lv}}{c_{pl}}Pr\left\{1+\frac{2}{C_2^2}\frac{c_{pl}(T_{w0}\text{-}T_{sat})}{h_{lv}}.\frac{1}{Pr}\right\}.$ $C_2=0.8.$	• Bubble grows only by evaporation of the microlayer underneath the bubble. • Dry-out area in the microlayer is included. • Thermal capacity of the microlayer is neglected.
Yun et al. 2012	$\frac{dr_b(t)}{dt}=\frac{2b}{\sqrt{\pi}}Ja\left(\frac{\alpha}{t}\right)^{0.5}\text{-}\frac{b\acute{S}\,q_i''}{h_{lv}\rho_v}.$ $q_i''=h_c\left(T_{sat}\text{-}T_i\right),$ $h_c=\frac{k_l}{d_b}\left(2+0.6Re^{0.5}Pr^{0.3}\right).$ $b=1.56,\ \acute{S}=0.5.$	• Includes thermal diffusion controlled growth and condensation simultaneously. • b is bubble sphericity and $\acute{S}$ is bubble surface portion in contact with the subcooled liquid • $\acute{S}$ is assumed to be 50%.

Figures