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Evaluation of the microlayer contribution to bubble growth in horizontal pool boiling with a mechanistic model that considers dynamic contact angle and base expansion

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ABSTRACT

Recently a new mechanistic model for pool and nucleate flow boiling was developed in our group. This model is based on the balance of forces acting on a bubble and considers the evaporation of the microlayer underneath the bubble, thermal diffusion around the cap of bubble due to the super-heated liquid and condensation due to the sub-cooled liquid. Compared to other models we particularly consider the temporal evolution of the microlayer underneath the bubble during the bubble growth by consideration of the dynamic contact angle and the dynamic bubble base expansion. This enhances, in our opinion, the model accuracy and generality. In this paper we further evaluate this model with experiments and direct numerical simulation (DNS) in order to prove the importance of dynamic contact angle and bubble base expansion.

1. Introduction

Nucleate boiling is an efficient heat transfer process. Its physical modeling is still not fully mature as it involves complex two-phase fluid dynamics with mass, momentum and energy transfer at the liquid-vapor interface and further heat conduction through solid walls. The bubble dynamics of nucleation boiling has been heavily investigated since the 1950s, first in pool boiling. In the 1950s Forster and Zuber (1954) as well as Plesset and Zwick (1954) modelled the bubble growth in a uniformly superheated liquid. Zuber (1961) extended this model to non-uniform temperature fields. Then Mikic et al. (1970), Prosperetti and Plesset (1978), and Labuntsov (1974), derived dimensionless relations for inertia controlled and heat (or thermal diffusion) controlled growth. Cooper and Lloyd (1969) identified a thin liquid microlayer underneath the bubbles and modelled it on the basis of experimental findings. Then van Stralen et al. (1975) proposed a model based on the evaporation of the microlayer underneath the bubble and heat diffusion from a relaxation microlayer around the bubble. In 1993, Klausner et al. (1993) developed a model based on the balance of the forces acting on the bubble to predict its departure and lift-off. The authors obtained satisfactory prediction accuracy against their own data of flow boiling with refrigerant R113. They recommended a fixed bubble base diameter (contact diameter) of 0.09 mm, an advancing contact angle of $\pi/4$ and a receding contact angle of $\pi/5$. Later, modified versions of the Klausner model have been brought up by others with other values of base diameter, advancing and receding contact angle to predict their own experimental data. Examples are Yun et al. (2012), Situ et al. (2005), Sugrue (2012), Thorncroft et al. (2001) and Chen et al. (2012). Klausner applied the Mikic model to simulate the bubble growth while Situ and most of the latter authors employed the Zuber (Mikic et al., 1970) formulation. Zuber included in his formulation a parameter b to account for bubble sphericity. This parameter has been used by the latter authors with different values between 0.24 and 24 to fit the models with their experimental data (Colombo and Fairweather, 2015). Yun et al. (2012) improved Klausner's model by incorporating a bubble condensation model as well as evaluating the model for a wider range of pressure, temperature, and flow rates for water. More recently, in 2015, Colombo and Fairweather (2015) developed a mechanistic model to simulate the bubble growth and departure. In the model, they considered the contribution of the microlayer, the superheated thermal liquid layer and the condensation to bubble growth (Fig. 1). Based on the suggested contact angles from Klausner et al. (1993) and other empirically measured contact angles, the model gave a good agreement with data from different experiments. Later in 2017, Raj et al. (2017) tried to formulate a similar model as an analytical solution with countable validations. In 2018, Mozzocco et al. (2018) developed a model for the mechanistic prediction of bubble departure and lift off.

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Nomenclature

A_b	bubble surface area
A_{ma}	area of macrolayer
C	constant from Cooper
c_D	friction drag coefficient
c_{pl}	specific heat capacity of liquid
c_{pw}	specific heat capacity of wall
d_l	bubble lateral diameter
d_w	bubble base diameter
$F_{b,\ v,\ y}$	buoyancy in wall perpendicular direction
$F_{cp,\ y}$	contact pressure force in wall perpendicular direction
$F_{drag,\ y}$	drag force in wall perpendicular direction
$F_{growth,\ b}$	growth force in bulk
$F_{growth,\ y}$	growth force in wall perpendicular direction
$F_{sl,\ y}$	sliding lift force in wall perpendicular direction (flow boiling)
$F_{surf,\ y}$	surface tension in wall perpendicular direction
$F_{total,\ x}$	total force in wall tangential direction
$F_{b,\ x}$	buoyancy in wall tangential direction
$F_{drag,\ x}$	drag force in wall tangential direction
$F_{growth,\ x}$	growth force in wall tangential direction
$F_{surf,\ x}$	surface tension in wall tangential direction
$F_{sl,\ x}$	sliding lift force in wall tangential direction
f_{sub}	the portion of the bubble surface in contact with sub cooled liquid
h_b	height of bubble top to the wall
h_{bt}	height of bottleneck
h_c	height of bubble center to the wall
h_{fg}	latent heat
k_l	thermal conductivity of fluid in liquid phase
k_g	thermal conductivity of fluid in gas phase
k_w	thermal conductivity of wall
$\dot{m}_{ma}$	mass flow of evaporated liquid in macrolayer
$\dot{m}_{mi}$	mass flow of evaporated liquid in microlayer
P_l	pressure difference on the bubble interface
P_r	Prandtl number
$\dot{Q}_{in}$	heat flux entering into wall
$\dot{Q}_{out}$	total heat flux from wall to fluid
$\dot{Q}_{e,mi}$	heat flux due to evaporation of microlayer
$\dot{Q}_{e,ma}$	heat flux due to evaporation of macrolayer
$\dot{Q}_{dryout}$	heat flux due to dryout
$\dot{Q}_q$	heat flux due to quenching
$\dot{Q}_g$	heat flux due to gas film (hotspot)
$\dot{Q}_{n,c}$	heat flux due to natural convection
$\dot{Q}_{total,w}$	total heat flux of a wall segment
$\dot{Q}_{n,w}$	conduction heat flux between neighboring wall segments
r	r coordinate/position
r_b	bubble radius
r_d	bubble dryout radius
$r_{m,\ g}$	maximum radius in initial growth regime
r_w	bubble contact radius (base radius)
Re_b	Reynold's number of bubble
T_b	bulk temperature
T_w	wall temperature
T_∞	temperature in the bubble in the inertia controlled growth regime
T_{sat}	saturation temperature
T_{sub}	subcooling temperature
t	time
t_d	time of departure
t_g	maximal inertia controlled growth time
τ_g	maximal inertia controlled growth time at different r position
τ_d	time counted from dryout starting
τ_q	time counted from quenching starting
v_b	bubble velocity in wall perpendicular direction
V_b	volume of bubble
$\dot{V}_{mi,g}$	total volume of formed gas
$\dot{V}_{mi,l}$	total volume of evaporated liquid
ΔL_w	distance between two neighboring wall segments
ΔT_w	temperature difference between two neighboring wall segments
ΔT_{sat}	super heating
ΔT_{sub}	subcooling
α_l	thermal diffusivity of fluid in liquid phase
α_g	thermal diffusivity of gas in liquid phase
β	contact angle of macrolayer in horizontal pool boiling
β_{ad}	advancing contact angle of macrolayer in flow boiling
β_{re}	receding contact angle of macrolayer in flow boiling
β_s	expected contact angle
θ	contact angle of microlayer
θ_w	wall orientation angle
σ	surface tension
$\rho_g$density of vapor	density of vapor
ρ_l	density of vapor
ρ_w	density of wall
δ_{mi}^0	initial microlayer thickness at time t_g
δ_{mi}	microlayer thickness
δ_w	wall thickness
δ_{th}	thickness of thermal layer

Subscript

dryout	at dryout area
e	evaporation
g	gas phase
l	liquid phase
mi	microlayer
ma	macrolayer
n,c	natural convection
w	wall
y	wall perpendicular direction
x	wall tangential direction

Different to the models of Colombo and Fairweather (2015) and Raj et al. (2017), where the condensation is being modelled with the correlation of Ranz and Marshall (1952), the author applied a parametric constant to capture the effect of convective heat transfer for saturated and subcooled flow conditions. The model was also validated with different experimental data. It was found that the bubble dynamics models still require some empirical constants under different conditions. For the force analysis in the models, the bubble is always considered as a hemisphere or truncated sphere and the impact of bubble deformation during the bubble growth is not considered.

Basing on previous studies, e.g. of Colombo and Fairweather (2015), Raj et al. (2017) and Mozzocco et al. (2018), our group recently developed a mechanistic model to simulate and predict the bubble departure in pool boiling and flow boiling on a smooth wall. The model considers the heat transfer contributions from the microlayer, the superheated layer surrounding the bubble and condensation at the bubble's top. Moreover, the formation, evaporation and depletion of the microlayer (dryout formation) as well as the change of the bubble geometry during the bubble growth are considered in this model. In our opinion, this enhances the model accuracy and generality. The