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Technical Note

A reassessed model for mechanistic prediction of bubble departure and lift off diameters

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ABSTRACT

Heat transfer models in multiphase flow with wall boiling rely on closure relations for bubble departure and lift-off diameters. The approach proposed in this paper reassesses the physical representation of each term of the force balance model, eliminating inconsistent assumptions and redundant calibration, leading to a more general methodology to predict lift-off and departure diameters. The validation against available datasets shows improved applicability when compared to existing models. The mechanistic model proposed in this work is expected to be implemented in CFD codes, to improve predictive performance of heat partitioning models.

1. Introduction

Detailed modeling of local phenomena of subcooled boiling in heated tubes or channels normally involves combining a multidimensional model of two-phase flow and heat transfer inside the channel with a wall boiling model, that couples single-phase and boiling heat transfer phenomena in the near-wall region [1]. The methods are implemented in the Eulerian multiphase framework available in most commercial CFD codes, and are widely used to simulate flow boiling applications in industry. The wall boiling models rely on the concept of partitioning the total wall heat flux [2,3] to different components that represent different mechanisms of heat transfer at the wall.

Recent work at MIT [4] has leveraged novel experimental evidences in order to extend the generality of such heat flux partitioning approaches. A fully consistent mechanistic representation of the relevant physics has been proposed that takes into account several boiling phenomena that were not considered in previous works including:

- additional heat transfer due to sliding bubbles;
- evaporation of the microlayer under the bubble;
- static interaction of nucleation sites;
- change of substrate temperature over the bubble cycle.

Availability of closure models that capture the relevant physics is key to the accuracy of such approaches. In particular, the modeling of additional heat transfer due to a sliding bubble requires the knowledge of bubble history and detachment diameters. The volume of vapor generated at the wall (and consequently the evaporation heat flux) is sensitive to the predicted bubble detachment diameters and thus, the accurate determination of bubble departure as well as lift-off diameters are pivotal for a heat partitioning approach.

Currently, CFD codes adopt empirical correlations such as the Tolubinsky and Kostanchuk [5] or Kocamustafaogullari [6]. The applicability of empirical correlations remains low in CFD as they do not account for local fluctuations in flow quantities and need access to bulk flow quantities, which are not always possible to compute. To address these shortcomings, various mechanistic force balance models have been proposed in the literature such as the works of Klausner et al. [7], Zeng et al. [8], Situ et al. [9], Colombo et al. [10] and Sugrue et al. [11]. These mechanistic force balance models compute the bubble departure diameter by computing the force balance on the growing bubble, and estimate the diameter for which the balance of forces is violated. However, the current mechanistic models suffer from insufficient representation of physics and fitting of constants to specific databases, which limits their applicability to general flow cases. Moreover, the existing models do not capture all modes of bubble detachment that are required to resolve the effect of a sliding bubble, which has a huge contribution to the heat transfer near the wall [4].

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List of symbols

χ	coefficient for flow boiling phenomena
ν_l	liquid kinematic viscosity
ϕ	bubble growth inclination angle
ρ_l	liquid density
ρ_v	vapor density
θ	wall inclination
ζ	dimensionless subcooling
C_D	drag coefficient
C_L	lift coefficient
c_{pl}	specific heat capacity
h_{fg}	latent heat of vaporization
Ja_*	modified Jakob number
K	bubble growth rate
m	bubble mass
Pr_l	liquid Prandtl number
R	bubble radius
R_0	bubble departure radius
R_{lo}	bubble lift-off radius
Re	bubble Reynolds number
Re_*	bulk Reynolds number
T	temperature
t	time
u	fluid local velocity
v	bubble velocity
w	bubble-to-fluid relative x-axis velocity

In this work, a mechanistic model to predict the bubble departure and lift-off diameters is proposed by reassessing the physical representation of each force acting on the bubble. The model is tested with available experimental databases to demonstrate the robustness and generality of the proposed approach.

2. Reassessed forces on the bubble

In an attempt to clarify the nomenclature adopted in previous literature, we have defined *departure* as the event when a bubble detaches from the nucleation site either by sliding or to bulk, and *lift-off* as the event when a sliding bubble lifts-off the surface. An illustration of the different forces acting on the bubble is shown in Fig. 1. The coordinate axes are defined at the bubble center with the X axis oriented in the direction of flow and the Y axis perpendicular to heater surface. We have *departure to bulk* when:

$$\begin{cases} \sum F_x < 0 \\ \sum F_y > 0 \end{cases} \tag{1}$$

and *departure by sliding* when:

$$\begin{cases} \sum F_x > 0 \\ \sum F_y < 0 \end{cases} \tag{2}$$

When a bubble departs by sliding, it continues to grow and slide along the surface and *lifts-off* when the sum of forces in Y direction $\sum F_y > 0$. Table 1 summarizes the different modes of bubble detachment that are accounted for, in the existing mechanistic force balance models. Modeling all the three modes of bubble detachment is a novel feature of the current work.

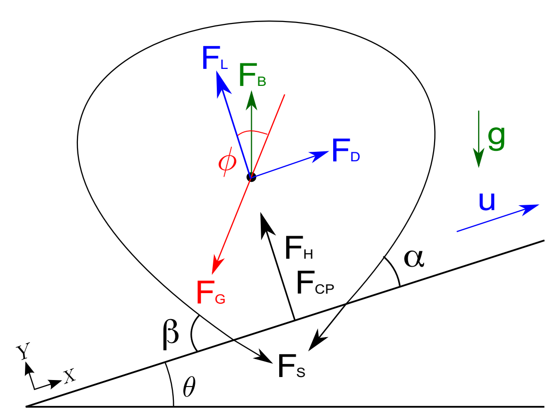

Fig. 1. Forces acting on a growing bubble attached to the nucleation site.

Table 1
Bubble detachment modes captured by different mechanistic models.

Model	Dep. by sliding	Dep. to bulk	Lift-off
Klausner [8]	X		X
Sugrue [11]	X	X	
Situ [9]			X
Proposed model	X	X	X

2.1. Modeling bubble growth

Accurate modeling of bubble growth is necessary to estimate the added mass force on the growing bubble. A theoretical determination of the vapor bubble growth history $R(t)$ should include a detailed analysis of both mass and energy transfer between the liquid and vapor phases. This approach is generally considered too complex, and the determination of $R(t)$ based on empiricism is used in mechanistic force balance models. In general, it is accepted to express the vapor bubble growth history as a power law of time:

$$R = Kt^n \tag{3}$$

where K and n must be determined. Most of the existing mechanistic force balance models rely on the Plesset-Zwick [12] treatment of bubble growth (Eq. (4)), with an additional data-fitted constant to account for the effect of the wall in flow boiling.

$$R = 2\sqrt{\frac{3}{\pi}}Ja_*\sqrt{\eta_l t} \tag{4}$$

where

$$Ja^* \equiv \frac{\rho_l c_{pl} \Delta T}{\rho_v h_{fg}} \tag{5}$$

The Plesset-Zwick treatment can be rigorously applied only for a pool boiling scenario, where a thin layer of super-heated liquid surrounding the bubble fuels its growth, with a purely conductive heat transfer. In flow boiling cases of interest, such treatment is too simple to capture all the different phenomena involved in the heat transfer between the growing bubble and the fluid. In this work, a new approach to model bubble growth is proposed taking into account the different mechanisms of heat transfer to a growing bubble in subcooled flow boiling, which includes:

1. heat addition due to microlayer evaporation
2. heat transfer with the surrounding liquid

as illustrated in Fig. 2. Each of these components and their modeling is discussed below and the final expression used to estimate bubble growth is shown in the following.