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A universal wall-bubble growth model for water in component-scale high-pressure boiling systems

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ABSTRACT

Development of an accurate bubble growth model is central to the prediction of heat transfer coefficient in component scale wall-boiling formulations. The bubble growth models available in the literature are not generic enough to be applicable over a wide range of pressures. For example, pressurized water reactors operate at high pressures, where the experimental correlations are sparse. In this study, a framework for modeling wall bubble growth is developed, for water. This generalized model is synthesized in a form, which takes into account the factors that contribute to the bubble thermal layer deformation in a physically consistent way. These factors have been systematically evolved to account for a wide range of conditions (i) pressures of 1–180 bar, (ii) pool as well as flow boiling conditions, (iii) low as well as high subcooling, (iv) horizontal and vertical test section orientations, etc. Bubble growth predictions from the present model have shown very good agreement across a wide range of pressures. It was observed that, for pool boiling, the wake effect at the apex of the bubble has influenced the overall growth rate. On the contrary, for flow boiling, the flow induced distortions to the thermal layer were found to be dominant both at the base as well as the apex. In the latter case, bubble growth rate was found to be significantly dependent on the magnitude of these individual distortions.

1. Introduction

Subcooled flow boiling is a highly desired form of heat transfer in several industrial systems, since it is the most effective way to achieve high heat transfer rates at relatively low wall superheats. However, this phenomenon also has the potential to quickly transform and trigger critical safety concerns such as in the operation of high-pressure nuclear reactors. Due to the central role of subcooled flow boiling, both in efficient heat generation as well as in crisis events, there is a vast amount of literature trying to understand various facets of this phenomenon. However, the current state of understanding is far from complete, especially at high-pressure conditions, since experimental visualization techniques and measurement capabilities have considerable limitations in these conditions. Consequently, computational techniques are a sought after alternative for studying and predicting this phenomenon.

The coupled *EEMF-WHFP* mathematical framework is ideal for modeling subcooled flow boiling in component–scale systems. In this framework, *EEMF* denotes the Eulerian-Eulerian Multiphase Two-Fluid model, which is used to predict the vapour generated, within the bulk flow, in systems such as nuclear rod bundles. The vapour generation at the heated wall is modeled using the 'wall heat flux partitioning' (*WHFP*) model. Both *EEMF* and *WHFP* frameworks require inputs from a number of 'closure' models, which are in turn defined by low-pressure correlations. Since several industrial systems are operated at high pressures, model predictions based on low-pressure data often becomes questionable.

There is a real need to improve the range of applicability of the mostly low-pressure informed framework, to high pressure ranges, specifically, in the context of *WHFP* modeling. This was indeed attempted in our recent studies (see Murallidharan et al. [33,34]). The *WHFP* model essentially dictates the control and prediction of vapour, injected into the fluid domain. Hence, it is important to identify the facets of the wall boiling phenomenon that are key to achieving better prediction of high pressure subcooled flow boiling conditions and then to develop models having a wider range of applicability. The overall scope of the present work is as follows:

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Nomenclature

b_1	multiplier in $\boldsymbol{\psi_1}$ evaluation
c	multiplier in growth constant β computation
c	specific heat of liquid (J/kg K)
f_1, f_2	multiplier
g	gravity (m/s^2)
h	latent heat of vapourisation (J/kg)
Ja	Jakob number
n_1, n_2	power constants
P	pressure (bar)
Pr	Prandtl number
T	temperature (K)
U,u	velocity (m/s)
x	variable in integral (Eq. (2))

Greek symbols

β_{IP}	growth constant
δ	natural convection thermal boundary layer
Δ	difference operator
ε	ratio of difference in density of liquid and gas to liquid density
η	diffusivity (m^2/s)
ρ	density (kg/m^3)
τ	temperature ratio
ν	kinematic viscosity (m^2/s)
ξ	ratio of phase change to latent heat in Eq. (2)
χ	multiplier in subcooling effect term
ψ_1	multiplier in wall effect parameter
ψ_{bulk}	multiplier in subcooling effect parameter
Ω	strength of superheat relative to liquid temperature in Eq. (2)
ω	gas to liquid density ratio

Subscripts

fg	fluid-gas
g	gas
IP	infinite pool of liquid
l	liquid
sat	saturated
sub	subcooled
sup	superheat

Abbreviations

AD	apex thermal layer distortion factor
BD	base thermal layer distortion factor
HS	high subcooling
HV	high velocity
LS	low subcooling
LV	low velocity
TBL/TL	thermal boundary layer/thermal layer

- A detailed study of the EEMF-*WHFP* framework to determine the most important parameters that influence the predictions under high-pressure conditions. Following the recent study of Murallidharan et al. [33], components within the *WHFP* framework requiring improvement were identified. It was concluded that the presence of the following terms aided better overall prediction of *EEMF-WHFP* model at high pressure conditions,

i. Initial embryo size of the bubble at the time of nucleation and
ii. bubble growth rate

- Following this, a mechanistically accurate model for initial size of the embryo formation was developed [34]. This model can account for embryo formation in both diffusive as well as stable surface nanobubble cases.
- As a continuation, of this series of work, in the present study, we propose a bubble growth model, for pressures ranging from 1 to 180 bar and for different flow conditions and bulk temperatures.
- Eventually, the embryo formation model should feed into the wall bubble growth model, which in turn should be integrated back into the EEMF-WHFP framework. Given such a holistic objective, the present study explores only the bubble growth modeling aspects of the whole.

2. Literature review

Most bubble growth models can be classified into three broad categories based on the operating conditions in which the bubble grows: (i) growth in an infinite medium, (ii) pool boiling growth and (iii) flow boiling growth. Based on this major classification, relevant background literature is categorized and elaborated in this section.

2.1. Bubble growth models in an infinite liquid medium

Bubbles growing in an infinite medium are modeled as perfect spheres growing symmetrically in a quiescent, uniformly superheated liquid medium. Although such an assumption is highly idealized, most bubble growth models follow this approach due to its simplicity. This would facilitate clear set of governing equations, with a closed-form solution to the problem on hand. Lord Rayleigh was one of the first to address a problem description of this nature. He modeled the variation of pressure inside a bubble cavity as it collapses [39]. This was achieved by equating the kinetic energy required for the motion of the inner boundary of the cavity from an initial size of radius r_o to a final radius r to the work done in forming the cavity. Plesset and Zwick [35] were the first to propose a heat-transfer/vaporization based 'growth' model for the bubble. Here, they modified the original equation of Rayleigh [39] to account for the cooling effect caused by evaporation at the bubble interface. The growth is assumed to occur due to conduction heat transfer across the thermal boundary layer between the superheated bulk fluid and the bubble interface. Thus, the bubble growth is limited by the rate at which the heat of evaporation is supplied to the interface (heat diffusion controlled). Forster and Zuber [16] also developed a growth formulation that is similar to the model of Plesset and Zwick [35]. Though their equations handle the temperature condition for the asymptotic growth differently, there is physical equivalence [52]. Both these models are, however, approximate [52] and require the input of tuning constants. Scriven [42], unlike the previous models, presents an exact solution for bubble growth. He included in his model the effect of radial convection on growth (due to unequal phase densities) and also defined the bubble growth constant 'β_{IP}' in terms of phenomenological parameters. However, his formulation for the growth constant 'β_{IP}'is complex and the alternate (approximate) versions suggested in his work are accurate, only for a specific portion of the bubble growth curve [42]. Board and Duffey [6] proposed a spherical bubble growth model in a uniformly superheated liquid by proposing a theory based on thermal equilibrium at the bubble interface. This theory was used for predicting bubble growth for cases, where different fluids having similar growth rates are involved. Their model predicted growth of sodium vapour bubbles in water reasonably well. Theofanous et al. [47]