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Prediction of bubble departure in forced convection boiling: A mechanistic model

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ABSTRACT

In the context of computational fluid dynamic simulations of boiling flows using time-averaged Eulerian multi-phase approaches, the many sub-models required to describe such a complex phenomena are of particular importance. Of interest here, wall boiling requires calculation of the contribution of evaporation to global heat transfer, which in turn relies on determination of the active nucleation site density, bubble departure diameter and frequency of bubble departure. In this paper, an improved mechanistic model for the bubble departure diameter during flow boiling is developed. The model is based on the balance of forces acting on a bubble at a single nucleation site, with a new equation governing bubble growth proposed. The formulation accounts for evaporation of the micro-layer under the bubble, heat transfer from superheated liquid around the bubble surface, and condensation on the bubble cap due to the presence of sub-cooled liquid. Validation of the growth equation is provided through comparison against experiments in both pool boiling and flow boiling conditions. Introduction of condensation on the bubble cap allows reproduction of the growth of the bubble for different sub-cooling temperatures of the surrounding liquid. In addition, a sensitivity study guarantees dependency of the bubble departure diameter on relevant physical quantities such as mass flow rate, heat flux, liquid sub-cooling and pressure, with any inclination of the channel walls correctly accounted for. Predictions of bubble departure diameter and bubble lift-off are validated against three different databases on sub-cooled flow boiling with water and an additional database on saturated boiling with refrigerant R113. The whole data set guarantees validation is performed over a range of parameters and operating conditions as broad as possible. Satisfactory predictive accuracy is obtained in all conditions. The present formulation provides an appropriate starting point for prediction of the behaviour of vapour bubbles under more general conditions which include lift-off after sliding, the frequency of bubble departure, bubble merging and bubble shrinking and collapse due to condensation.

1. Introduction

Nucleate boiling and two-phase flow are complex processes involving mass, momentum and energy transfer at the liquid–vapour interface, and frequently involve close interaction with solid walls. As a consequence, research in these areas is ongoing within many engineering disciplines, and in relation to thermal hydraulics in particular, despite them having been studied for decades. The ability to predict two-phase boiling flow is also of significant interest in many industrial fields, including the chemical and process industries, refrigeration and air conditioning among many others. In the nuclear energy sector, it is essential for the safe operation of boiling water reactors (BWRs) and the design of new passive nuclear reactor systems operating under natural circulation.

The development of computational fluid dynamic (CFD) approaches for predicting such flows has proved promising and of value in engineering design, in particular through the Eulerian time-averaged models generally used in practice. In such models the phases are treated as interpenetrating continua, and all the information on the interface structure is lost due to the averaging process [1]. Consequently, models are needed for the inter-phase exchanges of mass, momentum and energy to close the system of equations. In particular, a specific model is needed to describe nucleate boiling at the wall. Heat flux partitioning models, such as that of Kurul and Podowski [2], have been adopted in most CFD models of boiling flows to date. Heat flux from the wall is portioned into contributions due to single-phase convection, transient conduction and evaporation. This evaluates the amount of vapour

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Nomenclature

b	parameter
C_2	constant
C_p	specific heat
D_h	hydraulic diameter
d	diameter
d_w	bubble-heated wall contact diameter
F	force
G	mass flux
G_s	dimensionless shear rate
g	gravitational acceleration
h	heat transfer coefficient
i	enthalpy
Ja	Jakob number $[\rho_l C_{p,l}(T_l - T_{sat})/\rho_v i_{lv}]$
k	thermal conductivity
Pr	Prandtl number $[\mu_l C_{p,l}/k_l]$
p	pressure
Δp	pressure difference
q''	thermal flux
R	bubble radius
Re	Reynolds number $[\rho_l U_l R/\mu_l]$
Re_B	bubble Reynolds number $[\rho_l(U_v - U_l)d_B/\mu_l]$
S	suppression factor
T	temperature
ΔT	temperature difference
t	time
U	velocity
x	quality
y	wall distance
y^+	non-dimensional wall distance

Greek symbols

α	advancing contact angle
β	receding contact angle
γ	bubble inclination angle
δ	boundary layer thickness
θ	channel inclination angle
θ^+	non-dimensional temperature
μ	viscosity
ν	kinematic viscosity
ρ	density
σ	surface tension

Subscripts

B	bubble
c	condensation
$conv$	convection
d	departure
exp	experimental
l	liquid
lo	lift-off
nb	nucleate boiling
p	pool
sat	saturation
sub	sub-cooling
tp	two-phase
v	vapour
x	x-direction
y	y-direction

generated from several parameters, such as the active nucleation site density, the bubble departure diameter and the bubble departure frequency. A review of heat flux partitioning models can be found in [3,4].

In this type of model, the proper evaluation of bubble growth is particularly important. In the initial stages of the growing transient, growth of the bubble is controlled by the inertia of the surrounding liquid, whereas it is later limited by the amount of heat that can be transferred from the surroundings [5]. Numerous mechanisms occur in heat transfer from the wall [6]. During bubble growth, a thin liquid micro-layer is trapped under the bubble which then evaporates as heat flows from the superheated wall. Diffusion of heat from the superheated layer surrounding the bubble cap also takes place. Partial dry-out of the micro-layer due to evaporation can form a dry patch on the wall surface and a three-phase contact line. Evaporation at the latter contact line supplies heat to the bubble that in turn contributes to bubble growth. In addition, growth of the bubble can perturb the flow field around the bubble itself, resulting in additional energy transfer by micro-convection. Further complexity is added by condensation at the top of the bubble in the case of sub-cooled boiling. The dominant heat transfer mechanisms have been debated over many years, and a number of different bubble growth models have been proposed, although no general agreement has been reached as yet. Recently, Kim [6] stated that experiments suggest that a bubble gains the great majority of the energy from the bubble cap rather than from processes at the wall. In contrast, Gerardi et al. [7] observed during pool boiling of water that a bubble gains a significant amount of the heat required for its growth through direct heat transfer from the wall. Therefore micro-layer evaporation is considered the dominant mechanism. In addition, various authors have suggested a dependency on fluid properties, based, for example, on observations in [6] related to refrigerants.

Forster and Zuber [8], and Plesset and Zwick [9], modelled bubble growth in a uniform superheated liquid. In their models, which only differ in a numerical constant, after an initial period when hydrodynamic forces are dominant, bubble growth is governed by heat diffusion from a thin superheated boundary layer around the bubble. Zuber [10] extended this model to non-uniform temperature fields, while Mikic et al. [11], and Prosperetti and Plesset [12], derived dimensionless relations valid throughout both inertia-controlled and heat diffusion-controlled growth. Cooper and Loyd [13], and Cooper [14], identified the evaporation of a thin liquid micro-layer trapped under the bubble as the major heat source sustaining bubble growth and modelled it accordingly. The same concept was later adopted by Unal [15] to derive correlations for bubble growth rate and maximum bubble diameter in a sub-cooled boiling flow of water. Van Stralen et al. [16] proposed a model based on the mutually dependent contributions of evaporation of the micro-layer under the bubble and heat diffusion from a relaxation micro-layer around the bubble surface.

Despite efforts to derive a more mechanistic description of bubble growth, the nucleation site density, bubble departure diameter and bubble departure frequency are most frequently predicted through empirical correlations. A thorough review of available correlations can be found in Cheung et al. [17]. For bubble departure diameter, in particular, such correlations are normally implemented in commercial CFD packages. Among the most frequently used are the Tolubinsky and Kostanchuk [18] and the Kocamustafaogullari [19] correlations, both of which were developed from pool boiling experiments. Tolubinsky and Kostanchuk [18] developed a correlation that evaluates the bubble departure diameter from a reference value as a function of sub-cooling. On the other hand, in [19] bubble departure diameter is considered a function of the system pressure and fluid conditions.