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Modelling of bubble departure in flow boiling using equilibrium thermodynamics

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ABSTRACT

To improve the closure relations employed for component-scale Computational Fluid Dynamics simulation of boiling flows, a first-principles method for predicting bubble departure diameters in flow boiling has been developed. The proposed method uses minimisation of the free energy of a system in thermodynamic equilibrium to predict the contact angle and the resistance to sliding of a vapour bubble attached to a surface in the presence of a forced liquid flow. Predictions of the new method are compared with measurements from existing experimental databases, and agreement with data is shown to be comparable or superior to that obtained with previous bubble departure models that have generally used a force-balance approach. The main advantages of the energy-based method over the previous force-based methods are that its formulation is simpler, and that the new model does not require the use of *ad hoc* tunable parameters to define force terms, or geometrical characteristics of the attached bubble such as its base area, which cannot be confirmed experimentally. This increases confidence in the validity of the new approach when applied outside the rather limited range of current test data on bubble departure in flow boiling.

1. Introduction

Numerical simulations of boiling flows using phase-averaged Computational Fluid Dynamics (CFD) methods rely on sub-models of the wall-boiling process to describe the 'heat flux partitioning' between evaporation and single-phase heat transfer to the liquid [1–3]. Such models are sensitive to the assumed diameter of bubbles at the point of departure from a nucleation site [4], which must be calculated using separate sub-models. The accuracy of these bubble departure models ultimately determines the accuracy of a CFD simulation that uses heat-flux partitioning.

A number of empirical and semi-mechanistic methods have been developed in the past for predicting bubble departure diameters in flow boiling. Most of these use a force-balance approach originally proposed by Klausner et al. [5], who identified the point of bubble departure with the condition that the net force on the bubble due to buoyancy, surface tension and fluid drag and lift, in the direction either parallel or perpendicular to the surface, was equal to zero. Examples of force-balance models can be found in Refs. [6–10].

The force-balance approach has the significant disadvantage that it provides no means of determining the contact area between the bubble and the heated surface at the point of departure. This is a crucial omission since the contact area determines the magnitude of the wall adhesion force due to surface tension that resists departure. To determine the adhesion force, current force-balance models generally treat the bubble base area as an unknown parameter that is adjusted to fit the experimentally measured departure diameters. However, the absence of a method for determining *a priori* the bubble base contact area leads to concern that such models may give misleading results if applied outside the range of available databases, which generally exclude the industrially important case of high pressure boiling.

In a recent study [11], we used equilibrium thermodynamics to develop a first-principles method for predicting bubble growth and departure diameters in pool boiling, which used minimisation of free energy to find the time-dependent contact angle at the base of a growing bubble, and hence its base contact area. The method was shown to give reasonable agreement with departure diameters measured in pool boiling experiments for a broad range of fluids and pressures, but its applicability was limited to bubble departure in boiling on horizontal upward facing surfaces in the absence of any imposed flow.

In this paper, the Ref. [11] model is extended to the case of flow boiling on an inclined surface, in which bubble departure may be by sliding along the surface as well as by lift off. The extended model is validated against measurements of bubble departure diameter in flow boiling in a variety of fluids, and for various degrees of subcooling, fluid velocity, and surface inclination.

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The paper is structured as follows. The extension of the Ref. [11] bubble departure model to include an imposed liquid flow and an inclined surface is described in Section 2. Section 3 analyses the existing experimental database to establish an optimum value for the difference between the advancing and receding contact angles, for use as input data to the model. Section 4 demonstrates the capability of the model to capture experimental trends with flow velocity, inclination and pressure, and Section 5 compares the current model with existing models for predicting bubble departure. Finally, discussion and conclusions are provided in Section 6.

2. Model of bubble departure

2.1. Model assumptions

In the present work, the method of Ref. [11] for predicting the time evolution of the contact angle during bubble growth in horizontal pool boiling, is extended to the case of forced convective boiling on an inclined surface. As before, the fundamental assumption is made that an attached bubble is always in a state of thermodynamic equilibrium under the forces that it instantaneously experiences. Fig. 1 shows the assumed physical representation of the growing bubble and the forces acting on it.

The main assumptions of the model are as follows:

1. The bubble is assumed to be growing at an active nucleation site on an inclined heated surface in the presence of a forced flow of subcooled or saturated liquid. A layer of superheated liquid is assumed to exist adjacent to the heated surface, beyond which the liquid temperature decreases to the bulk liquid temperature. The bubble is assumed to grow due to formation of vapour by evaporation from its surface.
2. Referring to Fig. 1, the external forces acting on the bubble are assumed to be (i) a buoyancy force $\boldsymbol{F}_B$ that acts vertically upward, (ii) a hydrodynamic reaction force $\boldsymbol{F}_H$ due to bubble radial growth that acts in the negative z direction, (iii) a lift force $\boldsymbol{F}_L$ due to the liquid velocity gradient close to the surface, that acts in the positive z direction and (iv) a fluid drag force $\boldsymbol{F}_{DF}$ due to the imposed liquid flow that acts in the positive x direction.
3. The bubble is assumed to always approximate to the shape of a spherical cap with a unique radius of curvature R and unique base contact angle θ, both of which are assumed to vary with time. In the presence of an imposed flow and/or surface inclination, θ is expected to vary slightly around the base of the bubble due to the action of buoyancy and fluid forces: in forming the equation for θ this variation is neglected, so the value of θ calculated is to be regarded as an average value around the bubble base.
4. It is assumed that bubble detachment from the nucleation site can occur by lifting off from the surface or by sliding along it. Bubble lift-off is identified as the point at which the base contact angle θ falls to zero, as in the earlier model [11]. Bubble sliding is identified with the point at which the bubble becomes unstable against a small displacement in positive x direction, resulting in unconstrained motion along the surface. The bubble diameter at the point of detachment from the nucleation site, irrespective of whether it is by lift-off or sliding, is termed the 'departure diameter'.
5. As in the earlier model [11], the temperature of the vapour inside the bubble is assumed to be uniform and equal to the saturation temperature at the externally imposed pressure. The vapour in the bubble is assumed always to be in thermal equilibrium with the liquid at the bubble curved surface [12].
6. Also as in [11], spatial variations of the pressure inside the bubble, due to fluid dynamic and hydrostatic forces, are assumed negligible, as in the classic theory of Plesset [13]. Pressure variations in the liquid at the bubble wall due to the hydrodynamic and hydrostatic forces are taken into account in the model.

2.2. Equation for dynamic contact angle

2.2.1. Summary of Ref. [11] model

The Ref. [11] model calculates the contact angle θ at each point in time by using the condition $\delta\widetilde{A} = 0$, where $\widetilde{A}$ is the thermodynamic availability (free energy) of the system represented by the bubble and its surroundings. The change $\delta\widetilde{A}$ in availability due to a small perturbation from the bubble's equilibrium shape is calculated as:

$$\delta\tilde{A} = -\delta V_B \Delta p + \sigma \delta A_S + (\sigma_g - \sigma_f)\delta A_b + \delta W_s, \tag{1}$$

where V_B is the bubble volume, Δp is the pressure difference between the vapour inside the bubble and the ambient pressure, σ is the surface tension coefficient of the liquid-vapour interface,

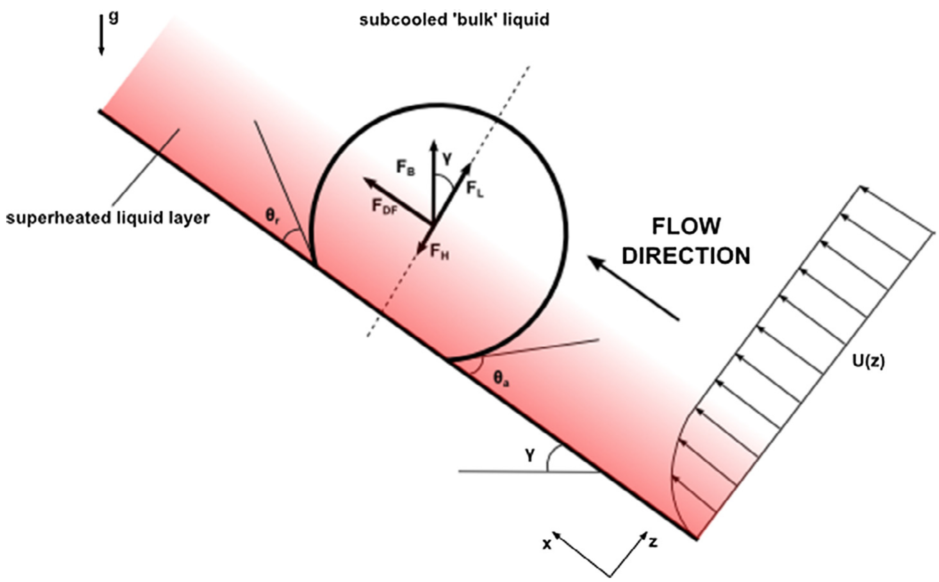

Fig. 1. System considered: a steam bubble growing at a heated surface into subcooled fluid flowing tangential to the surface.