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Evaporative thermal resistance and its influence on microscopic bubble growth

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ABSTRACT

Simulations of the formation of small steam bubbles indicate that the rate of growth of bubbles is very sensitive to the rate of evaporation of the micro-layer of liquid beneath the bubble. Such evaporation is rapid, and is modelled as being driven by the large heat flux through the thin liquid layer caused by the difference in temperature between the solid–liquid interface, and the saturation temperature in the interior of the bubble. However, application of this approach to recent experimental measurements of Jung and Kim generated anomalous results. In this paper we demonstrate that a model of the micro-layer heat flux that includes an allowance for the finite evaporative thermal resistance is able to eliminate these anomalies. This evaporative thermal resistance is a consequence of near-interface molecular dynamics, characterised by a quantity termed 'evaporation coefficient'. Whilst in most engineering applications evaporative thermal resistance is small compared to conductive resistance, here, with the micro-layer thickness ranging from a few microns down to zero, it becomes of considerable importance. Selection of a molecular 'evaporation coefficient' to restore consistency to the anomalous measurements allows a plausible numerical value to be inferred. For the several times and multiple locations studied, a fairly consistent value of between 0.02 and 0.1 is indicated, (for saturated water in laboratory conditions), which itself is consistent with earlier literature values of this rather difficult quantity. It is shown that the evaporative resistance always represents a large fraction of the conductive resistance, and for important phases of the process dominates it. The need for inclusion of this phenomenon in the micro-layer models used in bubble analysis is clear.

1. Introduction

1.1. Our current understanding of the early stages of vapour bubble development

Nucleate boiling has received considerable attention in recent years due to its intrinsic scientific interest, and the need for greater fundamental understanding [1]. From a practical point of view, also, a good predictive capability will be beneficial to inform macroscopic, component scale modelling of boiling in CFD [2].

In what is termed nucleate boiling, a vapour bubble nucleates at a solid wall from a pre-existing pocket of gas or vapour (a nucleation site) and grows as steam is generated. Two asymptotic regimes of expansion are possible. Very early bubble growth is essentially an isothermal process [3], during which the factor limiting bubble growth rate is not the rate of production of vapour, but the rate at which momentum is transferred to the surrounding body of fluid ("inertial bubble growth"). Subsequent bubble growth is limited by the transport of heat to the bubble surface ("heat diffusion controlled bubble growth" [4]), and that is the focus of the present work.

When a vapour bubble grows on a superheated solid substrate steam is generated via two complementary mechanisms (Fig. 1).

Much of the steam is generated by evaporation from the curved surface, via relaxation of the temperature of the superheated liquid layer surrounding the liquid–vapour interface.

As the bubble grows, (under at least some conditions) a thin layer of liquid is observed to be left beneath it [6] (Fig. 2). This liquid film is generally termed the "micro-layer". Being such a thin layer, the flow of heat through it is large. This is because heat flow is driven by the temperature difference between the substrate-liquid interface and the liquid–vapour interface, and this difference exists over a very small distance [7]. Consequently, the micro-layer is believed to be responsible for a significant fraction of the vapour generation under many circumstances, such as the boiling of

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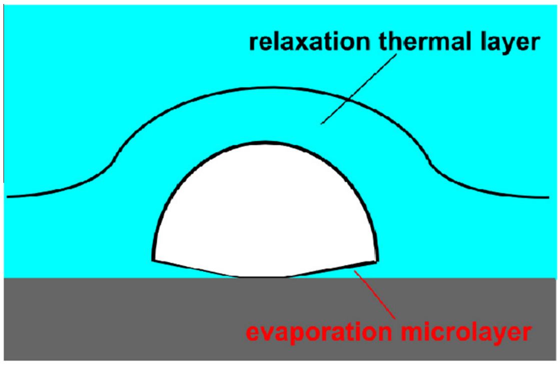

Fig. 1. Current understanding of the early stages of bubble development, adapted from [5].

atmospheric water at a superheat around 10 K [8]. For water at atmospheric pressure, its radial extent is a few hundreds of microns, and its thickness a few microns, increasing slightly with radial distance from the nucleation site. It is believed that there is essentially no flow of liquid into or out of the micro-layer, and thus its evaporation results in its thickness reducing, and the eventual disappearance of the layer. Since this occurs first at its inner radius, where the initial thickness of the film was least, there is an associated progressive increase in the radius of the dry patch around the nucleation site [9].

1.2. Current modelling of the early stages of vapour bubble development

The evaporation from the curved surface is limited by the rate at which heat diffuses across the relaxation layer. It is most common to take the liquid–vapour interface to be at the equilibrium saturation temperature at the system ambient pressure. (In a rather different approach [11], addressing largely refrigerants not water, some workers [12] have included deviations of the interface temperature from equilibrium, although micro-layer models did not feature in this analysis.)

The normal heat flux so computed in the liquid is used to determine a corresponding rate of vaporisation, and a corresponding vapour flux into the bubble [13].

The usual approach to modelling heat transfer through and vaporisation from the micro-layer is to treat it as a thin film, through which the heat flux is determined by its upper and lower surface temperatures, and where this heat flux in turn is used to compute the local vapour generation rate. This rate is used both to contribute to the increasing bubble volume, and to compute the gradual thinning and eventual disappearance of the micro-layer from the centre outwards.

1.3. Evaporative thermal resistance

In the above discussion, for both the main curved surface of the bubble and for the micro-layer, the taking of the vapour–liquid interface temperature to be equal to the saturation temperature is equivalent to assuming that the evaporative heat transfer process is "infinitely effective", or equivalently can be modelled by an infinite value of heat transfer coefficient.

Some temperature difference is actually required to drive the flux of molecules from the liquid into the vapour. Expressing this in terms of an 'evaporative heat transfer coefficient', its value is indeed usually large, and the resistance to heat transfer it represents is a tiny fraction of the other resistances involved (such as the diffusive resistance impeding flow of heat from the bulk liquid to the bubble).

However, the thermal resistance of a thin micro-layer is itself small, and becomes vanishingly small as it thins. If the micro-layer plays a significant role in bubble development, neglect of the evaporative resistance might be expected to have a measurable influence on its contribution to predicted bubble growth.

In this work we will focus on the micro-layer during nucleate boiling of water at atmospheric pressure and investigate the significance of the inclusion of the evaporative thermal resistance.

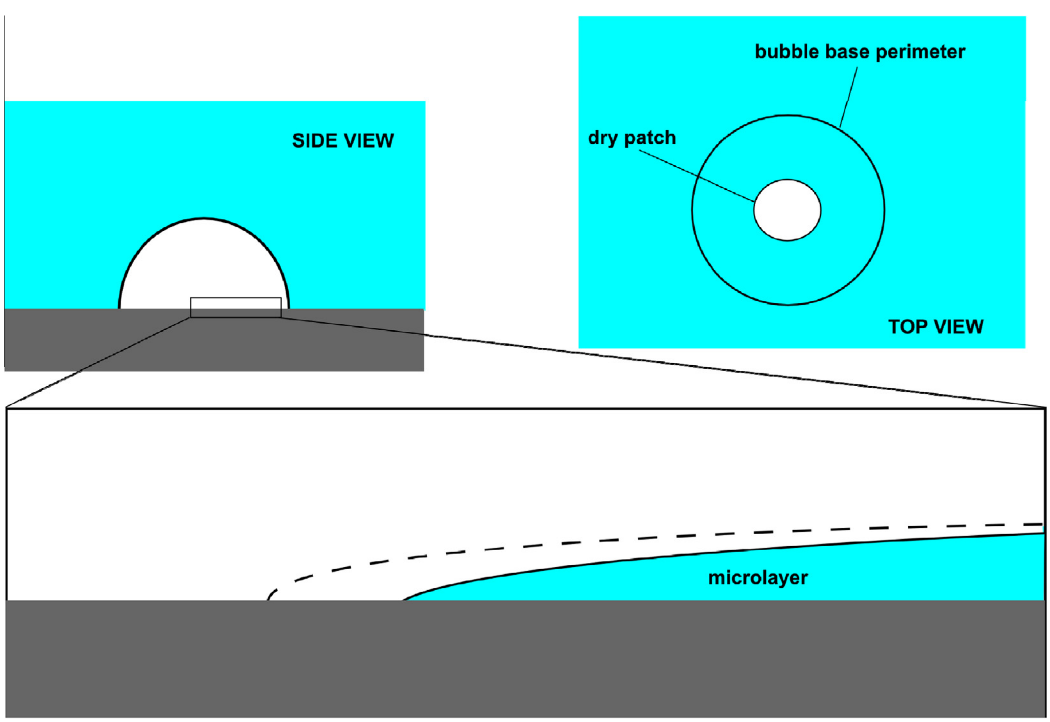

Fig. 2. Current understanding of the micro-layer [10].