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Direct numerical simulation of nucleate boiling in micro-layer regime

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ABSTRACT

The physical mechanisms associated with the evolution of a micro-layer beneath a bubble and the transition between contact line and micro-layer regimes are investigated with fully resolved numerical simulations, in the framework of nucleate pool boiling. Capturing the transition between these two regimes has been possible for the first time using very refined grids and parallel computations. Indeed, grids with a cell size under 1 μm must be used in order to capture thermal and dynamical effects in the micro-layer. Such multiscale computations require advanced code capabilities. The present simulations are used to analyse the physical processes involved in the formation and depletion of a micro-layer. A parametric study is carried out to investigate the impact of the main parameters affecting the presence of the micro-layer. From these results, the limit conditions between nucleate boiling in micro-layer and contact line regimes are deduced. Neglecting the micro-layer would lead to erroneous results because it has a strong influence on the overall bubble growth. Therefore the present results could be of major interest for designing models of nucleate pool boiling in larger scales computations, when the micro-layer cannot be resolved.

1. Introduction

Nucleate boiling is a physical phenomenon encountered in a large number of engineering applications. Its features are sometimes required, like in some heat transfer devices, and in other circumstances not desirable, like for instance in cryogenics tanks in microgravity conditions. Despite the large amount of studies concerning nucleate boiling, there is still a number of unanswered questions, in particular related to the region beneath a bubble where for some conditions a micro-layer is formed and persists during the first part of the bubble growth. It is a tiny film, which has a thickness smaller than ten microns and a length up to the millimetre. Actually, we can distinguish between two regimes of nucleate boiling, like schematically illustrated in Fig. 1 where the region around the bubble foot is represented: the contact line (*CL*) regime and the micro-layer (*ML*) regime [26]. In contact line regime the bubble maintains a quasi-static equilibrium shape during its growth [10,19]. The contact line moves while the bubble grows and the interface maintains a slope with respect to the wall given by the contact angle θ_1. On the other hand, when the bubble growth is fast enough, it may happen that the contact line cannot move as fast as the bubble: consequently the interface is bended and a micro-layer is formed. We can thus distinguish between two angles: the contact angle θ_1 formed at the contact line between the interface and the wall, and an apparent contact angle θ_2 which is given by the inclination of the interface outside the micro-layer.[1] By locally inducing high temperature gradients, the presence of a micro-layer strongly enhances the heat transfer between the solid heater and the bubble [21,9]. Therefore, one major difference between the two regimes is the wall heat flux profile q_w which has only a peak at the contact line in the *CL* regime whereas it exhibits a peak at the contact line followed by a plateau along the micro-layer in the *ML* regime [9], as schematically shown in Fig. 1. As a consequence, the micro-layer strongly affects the growth of the bubble, its departure diameter and frequency as well as its shape. Micro-layer effects have been observed experimentally since the pioneer work of Cooper and Lloyd [5]. However, micro-layers are thin and long and have a life time of only a few milliseconds which make the measurements tedious. More recently, the advance in techniques like high speed infrared thermography [25] and laser interferometry [12] together with high-speed cameras, have permitted to obtain interesting experimental analysis showing the formation and depletion of micro-layers with quantitative data on their thickness and length temporal evolutions [3,21,55]. Experimental

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[1] Note that θ_1 is also an apparent contact angle at the outlet of a micro-region and it is related to a smaller microscopic angle θ_{mic} [26,27,38,11]. The micro region around the contact line, smaller than the micron, is not the focus of the present work and will not be considered in our discussion. See Appendix A for more details.

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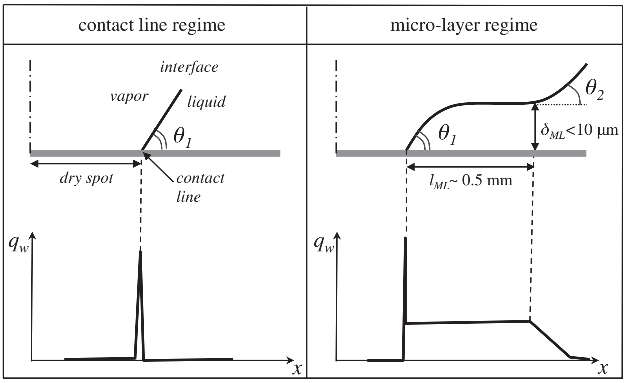

Fig. 1. Scheme of the different nucleate boiling regimes, contact line (left) and micro-layer (right), in terms of interface shape at the bubble foot (up) and wall heat flux profile (down).

evidences of the transition between contact line and micro-layer regime have been reported recently in [9] for a configuration involving a liquid meniscus moving on a heated wall. All these works have emphasised the importance of the micro-layer in the heat transfer process and the evidence that if a micro-layer exists it has to be taken into account in the nucleate boiling calculations [16]. Indeed numerical models have been developed to account for the micro-layer effects without directly solving it and are usually introduced in the numerical computations as boundary conditions [4,55] or as local source terms [43,44]. Recently, Hänsh and Walker [17] carried out a direct numerical simulation of the nucleation of a bubble with a resolved micro-layer beneath a bubble. However, they consider a purely hydrodynamic modelling without accounting for heat and mass transfer in their computation, but evaluating the evaporative mass flow rate from an offline computation. Differently, for what concerns *CL* regime, for which the grid refinement requirements are less stringent, fully resolved DNS simulations are available in the literature and have demonstrated their capability in correctly reproducing the phenomenon [27,45,48].

Several points remain unclear about the physical processes involved in the formation and depletion of micro-layers. In particular, it is not fully understood for which conditions nucleate boiling occurs in contact line or in micro-layer regime. The main motivation of the present work is to provide detailed informations in order to characterise the transition between the regimes, using fully resolved Direct Numerical Simulations (DNS). The-in house solver $\mathcal{DIVA}$ has been used to solve the incompressible Navier-Stokes equations for two phase flows and to account for phase change. Axisymmetric configurations have been employed, with very refined grids allowing the description of a possible micro-layer having a thickness of the order of the micron, beneath a bubble having a radius of the order of the millimetre. Simulations of this multi-scale phenomenon are challenging and require using massively parallel supercomputers and suitable numerical tools to verify that the results are not affected by grid dependence effects. Moreover, it is noteworthy that micro-layers involve locally very high heat fluxes in the range of several MW, that could induce stability issues for numerical solvers if the thermal gradients are not sufficiently resolved. To the authors knowledge, there are no other DNS results with phase change available in the literature showing the formation and depletion of a micro-layer and the present work is the first attempt to carry out a fully resolved DNS of nucleate boiling in micro-layer regime.

In the next section the numerical solver is introduced, recalling the mathematical formalism and giving some details on the numerical methods that are implemented in the code. A simple axisymmetric domain is considered: details on the boundary conditions and mesh requirements are given. A convergence study and a first comparison with experimental data in micro-layer regime are presented. The simulation of a bubble nucleation in micro-layer regime, showing the formation and depletion of the micro-layer, is deeply analysed and the basic physical mechanisms driving the phenomenon are interpreted. The influence of the main parameters is thus investigated with a parametric study varying the wall superheat, the contact angle, the surface tension and the liquid viscosity, and looking for the limit between *CL* and *ML* regimes. Eventually, a correlation for the frontier between the two regimes is proposed.

2. Numerical solver

2.1. Mathematical formalism

To describe the nucleate boiling at atmospheric pressure, in a isobaric environment, we consider an incompressible two-phase flow of a single component liquid-vapour system, with spatially uniform fluid densities ρ and thermophysical properties in each phase (viscosity μ, thermal conductivity k and specific heat at constant pressure c_p). Moreover, we assume that the heat produced by viscous dissipation is negligible. Under these hypothesis the flow can be described by the following form of the conservation equations of mass, momentum and energy in each phase:

$$\nabla \cdot \vec{V} = 0 \tag{1}$$

$$\rho \frac{D\vec{V}}{Dt} = -\overrightarrow{\nabla p} + \nabla \cdot (2\mu \boldsymbol{D}) + \rho \vec{g} \tag{2}$$

$$\rho c_p \frac{DT}{Dt} = \nabla \cdot (k \nabla T) \tag{3}$$

where $\vec{V}$ is the velocity field, p is the pressure, T is the temperature, $\boldsymbol{D}$ is the deformation tensor and $\vec{g}$ is the gravity acceleration. The corresponding mass, momentum and energy jump conditions that must be satisfied at the interface Γ, accounting for the phase change, are:

$$\left[\vec{V}\right]_\Gamma = \dot{m}\left[\frac{1}{\rho}\right]_\Gamma \vec{n} \tag{4}$$

$$[p]_\Gamma = \sigma\kappa + 2\left[\mu \frac{\partial V_n}{\partial n}\right]_\Gamma - \dot{m}^2\left[\frac{1}{\rho}\right]_\Gamma \tag{5}$$

$$[-k\nabla T \cdot \vec{n}]_\Gamma = \dot{m} L_{vap} \tag{6}$$

where σ is the surface tension, κ denotes the local interface curvature, $\vec{n}$ is the normal vector at the interface, pointing towards the liquid phase, V_n is the velocity component in the $\vec{n}$ direction, $\dot{m}$ is the boiling mass flow rate and L_{vap} is the latent heat of vaporisation. The operator $[.]_\Gamma$ indicates the jump across the interface Γ and is defined by:

$$[f]_\Gamma = f_v - f_l \tag{7}$$

with the subscripts l and v referring respectively to the liquid and vapour phases. Note that the present form of the energy jump condition Eq. (6) assumes that the interface temperature is equal to the saturation temperature ($T_\Gamma = T_{sat}$) in accordance with the second law of thermodynamics for a pure liquid-vapour system at local thermodynamic equilibrium. Moreover, for the sake of simplicity, we assume that T_{sat} is constant, which implies that the surface tension σ is constant. As a consequence, Marangoni convection effects (due to Kelvin effects for instance) are neglected. Interested readers can find more details on this specific point in [22].