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Nucleate pool boiling simulations using the interface tracking method: Boiling regime from discrete bubble to vapor mushroom region

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ABSTRACT

A numerical simulation method to model nucleate pool boiling from multiple nucleation sites has been developed and applied to different boiling-water regimes, ranging from discrete bubbles to the vapor mushroom region. The method is based on an interface tracking method in which the liquid–vapor interface is resolved by a color function within the framework of Computational Fluid Dynamics (CFD). Conjugate heat transfer between the wall and the fluid is included in order to capture the temperature field appropriately, since this has a significant influence on the bubble growing process. The micro-layer, which is the thin liquid film existing beneath a growing bubble, is taken into account using a specialized model specifically developed by the authors. A validation case is chosen to test the model, based on an experiment by Gaertner, featuring the boiling of water from a heated, horizontal plate under atmospheric pressure. Estimation of the nucleation site density and the local activation temperatures are taken from experimental measurement, and introduced into the simulation through an in-built, nucleation-site model. The applied heat flux ranges from 50 to 300 kW/m^2, the heat-transfer surface being of dimensions 20 mm $\times$ 20 mm. The computed heat transfer coefficient agrees well with the measured value, demonstrating the capability of the described CFD model to predict boiling heat transfer in a mechanistic sense for the flow regimes examined. Comparison of bubble shapes between experiment and computation also shows good agreement. In addition, a variety of statistical data, such as the heat flux partitioning and the ratio of vapor-to-liquid area over the heat transfer surface, which cannot be measured in the experiments, but can be derived from the results of the simulations.

1. Introduction

The concept of the *boiling curve* was first introduced 80 years ago by Nukiyama [1,2], based on a series of experiments he had performed. Today, accurate prediction of boiling heat transfer still relies heavily on such empirical data, since direct numerical analysis/simulation of the boiling process, even using advanced modeling techniques such as Computational Fluid Dynamics (CFD), are not yet sufficiently mature to guarantee trustworthy results in all circumstances. Among the three modes of boiling – nucleate, transient and film boiling – nucleate and transient boiling are generally considered the more complex processes [3], because of the micro-scale interactions between the liquid–vapor interface of the growing vapor bubble and the solid surface beneath: the so-called *triple line* (i.e. the line in which the liquid, vapor and solid phases jointly come into contact). Film pool boiling has already been successfully simulated numerically using interface tracking methods (ITMs) within the framework of CFD computations in three dimensions [4,5], while nucleate pool boiling simulations using an ITM approach currently remain limited to one or just a few nucleation sites [6,7], due to the lack of a suitable model for the interaction of bubbles emerging from multiple nucleation sites. In this paper, we propose a new numerical method, but one still based on the ITM approach to nucleate boiling, in which the number of nucleation sites is, in principle, unlimited. The simulation of transient boiling using this approach will be the subject of a future study.

The first work on the application of CFD to simulate single-bubble growth in nucleate boiling appears to have been reported by Lee and Nydahl [8]. Here, the growth and subsequent bubble motion of a single bubble were captured using a moving mesh system for structured grids in cylindrical polar coordinates (i.e. one in which the bubble surface always coincided with a grid line of the underlying computational mesh). This moving mesh system can be categorized as an option within the generalized Arbitrary Lagrangian–Eulerian (ALE) approach [9]. Vaporization from the thin *micro-layer*, assumed to exist beneath the growing bubble, was explicitly taken into account in this work, adopting the initial

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micro-layer thickness according to Cooper and Lloyd's formulation [10]. Evidence for the existence of such a thin film had been obtained experimentally by Sharp [11] and Jawurek [12] in the 1960s. Recent measurements of water boiling at atmospheric pressure [13] indicate that the heat flux through such a micro-layer can exceed 1 MW/m^2, signifying that the vaporization from the micro-layer must be properly taken into account in any mechanistic model of the boiling process. The computed bubble growth obtained in the pioneering work of Lee and Nydahl [8] showed good agreement with the experimental data available at the time, and the contribution of micro-layer vaporization to the total boiling heat transfer process was evaluated quantitatively; in this work, an assumption of constant temperature over the heat-transfer surface had been employed. Following this initial study, Welch [14] simulated single-bubble growth under nucleate boiling conditions using the ALE method for an unstructured grid, but without suitable modeling of the detachment of the bubble from the heated surface. The main advantage in this approach is that conjugate heat transfer between the fluid and the solid could be taken into account (i.e. the temperature distribution in the solid domain was simultaneously computed alongside that in the fluid during the bubble expansion process), though the specific influence of the micro-layer on the process was not considered specifically. Later, again using the ALE method, Fuchs et al. [15] also simulated nucleate boiling taking into account conjugate-heat transfer, and numerically simulated the successive detachment of bubbles from a single nucleation site.

Application of the above-mentioned ALE method for the bubble dynamics additionally requires a robust algorithm for the underlying mesh generation, especially when simulating multiple bubbles. To avoid difficulties in the mesh generation process, other ITMs have been employed for nucleate boiling simulation: the Level Set Method (LSM) [16]; the Volume Of Fluid (VOF) method [17]; the Front Tracking Method (FTM) [18]; a method using the color/-density function (e.g. [19]); the Phase Field Method (PFM) [20]; and the Lattice Boltzmann (LB) approach [21].

Son et al. [22] succeeded in simulating nucleate boiling from a single nucleation site using the Level Set Method (LSM) to track the liquid/vapor interface, and incorporating the micro-region model developed by Lay and Dhir [23]. Using LSM, the liquid–vapor interface (i.e. the bubble surface) could be captured without deformation of the underlying computational grid. In the micro-region model used in this work, vaporization from the layer was assumed to arise from evaporation at the triple line [22]. The governing equations for the micro-layer were thereby simplified, resulting in a set of ordinary differential equations, which were then integrated. The use of empirical parameters was avoided by assuming steady-state conditions (i.e. constant temperature over the heat-transfer surface, and constant micro-layer thickness profile). Results from the situation are illustrated in Fig. 1a, which shows that all the mass transfer on the heat-transfer surface took place at the triple line (the red circle in the figure). Despite the simplicity of the model, the computed bubble growth turned out to be in good agreement with measurement, and, in addition, the effect of the contact angle on bubble growth could also be evaluated. However, as admitted by the authors themselves later [3], the constant-temperature assumption for the heat-transfer surface meant that the model lacked the capability to predict the bubble waiting time, the bubble release frequency, and the temperature distribution in the solid domain; here, *bubble waiting time* refers to the period between bubble departure and the start of nucleation of the next bubble. Despite its simplicity, use of this LSM-based approach, and including the micro-region model, the research group of Dhir successfully simulated the bubble merging process during nucleate boiling [24,25], single-bubble dynamics in convective nucleate boiling [26], and single-bubble dynamics in sub-cooled pool boiling [27]. However, in all the above-cited works, the number of nucleation sites was limited to one or two only.

Following on from this work, in 2008 Son and Dhir [28] presented results from a nucleate pool boiling simulation for a horizontal surface at high heat flux incorporating multiple nucleation sites. However, due to the restriction imposed by the constant-temperature assumption over the heat-transfer surface, the bubble waiting time could not be computed, and had to be prescribed *a priori*. Nonetheless, the authors were able to obtain acceptable results for nucleate pool boiling of water for applied heat fluxes up to 800 kW/m^2 at atmospheric pressure [28].

A similar micro-region model to that of Lay and Dhir [23], but one neglecting the recoil force, was proposed by Busse and Stephan [29], and used for their nucleate boiling flow simulations of refrigerants from a single nucleation site [30,31]; here, the Volume Of Fluid method (VOF) had been employed for the ITM. This approach is based on a quasi-steady-state assumption for the micro-region model, so that conjugate heat transfer between fluid and solid, and the temperature at the heat-transfer surface were allowed to vary. Because the computed temperature field could not be compared against experimental measurement in these studies, the accuracy of the numerical method remains uncertain. Though there are several other nucleate boiling models based on VOF described in the literature [32–35], vaporization from the micro-layer is not taken into account in any of these works.

Using a color function to represent the volume fraction of liquid in a computational cell, which is basically equivalent to VOF, Sato and Niceno [36] were able to develop a somewhat different numerical approach to nucleate pool boiling. The difference between VOF and the color function approach lies essentially in the reconstruction of the liquid–vapor interface. Piecewise Linear Interface Calculation (PLIC) [37] is typically used in VOF, whereas an interface sharpening algorithm [38] is introduced into our approach, based on the color function. We strictly take into account conjugate heat transfer between the solid and fluid domains, and vaporization from the micro-layer is also computed using our own *depletable micro-layer model*; details are given in [36]. Using this model, the micro-layer can vaporize completely, thus resulting in the creation of a dry spot underneath the bubble, as illustrated schematically in Fig. 1b. Using this model approach, the authors were able to show that the bubble growth rate and the temperature distribution over the heat-transfer surface were in good agreement with experimental data, though, at that stage of development of the model, the number of nucleation sites was still limited to just one.

The Front Tracking Method (FTM) [18] has also been applied to nucleate pool and convective flow boiling [39], but progress here appears still to be lacking somewhat, and conjugate heat transfer and vaporization from the micro-layer are still not being accounted for, it seems, and, to the authors' knowledge, no validation tests have been presented in support of the model development. In short, development is ongoing.

The Phase Field Method (PFM) appears to be in a similar state of development. Though several phase-field approaches are currently being employed for the simulation of boiling [20,40,41], nucleate boiling from a heated surface has not yet been reported. Based on the Lattice Boltzmann Method (LBM) [21], in which the Boltzmann equation is solved for the fluid flow field instead of the Navier–Stokes equations, Hazi and Markus [42] have reported the simulation of two-dimensional nucleate pool and convective boiling, and Li et al. [43] calculated two-dimensional nucleate pool boiling and film boiling. However, in both of these cases, neither conjugate heat transfer nor vaporization of the micro-layer beneath the bubble were taken into account.

As reviewed above, various approaches have been reported to simulate nucleate boiling in the framework of the interface tracking method (ITM). According to the authors' personal involvement