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A numerical investigation of nucleate boiling at a constant surface temperature

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HIGHLIGHTS

- A comprehensive heat transfer model for nucleate boiling is presented in this study.
- The nucleate boiling is studied numerically and compared with experimental results.
- The bubble dynamics and local phenomena are studied in detail.

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ABSTRACT

This study presents a 2D numerical investigation of nucleate boiling by a comprehensive model which includes systematic methods for multiphase simulation, e.g., the smoothed evaporation model, modified Height Function algorithm and the micro-layer model. The numerical framework employed in the present study is based on the VOF interface capture method, which is improved by implementing external functions. The modified Height Function yields a more accurate interface normal vector than the Youngs method and also presents smaller spurious velocities. Moreover, the Height Function shows good convergence with mesh refinement. In order to validate the comprehensive model, the growth of a bubble from a heated surface at a constant surface temperature is investigated. Based on the numerical results, the evolution of bubble size and local heat transfer at the contact line are quantified. The bubble shapes predicted in the numerical investigation agree well with experimental results; however, the departure time is longer than the experimental result. By considering the heat transfer within the bubble, it is shown that the vapor phase in the vicinity of the heating wall is superheated with a homogeneous gradient. Moreover, a detailed insight into bubble dynamics and local phenomena affecting the heat transfer during nucleate boiling is discussed.

1. Introduction

Pool boiling is an efficient mode of heat transfer with a wide variety of applications including steam boilers, refrigerators, electronic cooling, etc. However, fully theoretical description and numerical investigation of nucleate boiling still face big challenges, which are due to the difficulties of inclusion of many aspects of nucleate boiling, for examples, the interfacial and topological changes of each phase, the influence of contact angle, heat and mass transfer through the interface and the dynamic behavior of the rising bubble. All these phenomena should be investigated numerically.

In the past several decades, researchers have made great progresses in studies of the nucleate boiling in both the theoretical analysis and numerical investigations. At the early stage, Lee and Nydahl [1] conducted numerical study of a bubble growth by including a micro-layer model. However, they did not investigate the departing bubble on the wall. The first attempt to simulate boiling using a CFD technique is attributed to Welch [2]. The author investigated two-dimensional boiling flow, and the moving grid technique was implemented in the study, where a deformable bubble using a semi-implicit moving mesh during nucleate boiling was studied. However, because of the limited capability of restructured grids which cannot handle a topological change, the full boiling process including a bubble departure was not investigated. In order to capture large deformation of the liquid–vapor interface, interface tracking methods were introduced to phase-change investigations in

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Nomenclature

A	dispersion constant (J)
c_p	specific heat (kJ/kg K)
g	gravitational acceleration ($g = 9.8$ m/s^2)
H	Height Function (m)
h_{lv}	latent heat (kJ/kg)
P	pressure (Pa)
R_g	university gas constant (J/mol K)
R_{int}	thermal resistance at interface (K m^2/W)
T	temperature (K)
t	time (s)
u	velocity vector (m/s)
x, y	Cartesian coordinates
$\dot{m}$	mass evaporation rate (kg/m^2 s)
D	diffusion constant
N	number of cells/normalization factor
Q	integration of heat flux of micro-layer (W/m)

Greek symbols

α	volume fraction
γ	accommodation coefficient
σ	surface tension coefficient (N/m)
ψ	smoothed evaporation rate (kg/m^2 s)
λ	thermal conductivity (W/m K)
μ	dynamic viscosity (kg/m s)
ρ	density (kg/m^3)
κ	curvature (1/m)
δ	film thickness (m)

Subscript

sat	saturation
int	interface
st	surface tension
g	gravity
v	vapor
l	liquid
ev	evaporation
w	wall
ex	exact
micro	micro-region
macro	macro-region

the late 1990s. A level set (LS) method was introduced by Son et al. [3], a Front Tracking method (FT) by Juric and Tryggvason [4], and a Volume of Fluid (VOF) method by Welch and Wilson [5]. The work presented by Stephan and Hammer [6] was, probably, the first numerical investigation of heat transfer in the so called ‘micro-layer’. By the numerical analysis, the liquid film thickness and heat flux distribution in the vicinity of the contact line in micro-region have been obtained. Based on these pioneering works, the numerical studies of boiling have made big progresses in the past decades. The phase change model coupled with LS method has been continuously improved mainly due to the efforts of Dhir's group [7], and it has also been applied to nucleate boiling. Son et al. [3] have performed an entire numerical study of a growing and departing bubble in nucleate boiling using the level set method which was modified to include the phase change and micro-layer evaporation. They compared the numerical results with previous experimental data and found good agreement between them. Furthermore, Dhir's group extended the the above method to bubble merging process [8], film boiling [9] and sub-cooled pool boiling [10]. In these studies, phase-change phenomena could be investigated under various conditions using a contact-angle treatment, a micro-region model, or an immersed boundary method to represent the solid surfaces. However, the drawback of the phase-change model coupled with LS method is that the mass conservation is not guaranteed, because LS is a non-conservative approach. In addition, the temperature variation in the vapor phase was neglected which also played a very important role in heat transfer of whole domain. It is worth noting that Sato and Niceno [11] developed a mass–conservative interface tracking method based on LS method in which the mass transfer rate was directly calculated from the heat flux at the liquid–vapor interface, and the phase change took place only in the cells which included the interface. Recently, Zhang et al. [12] have conducted a detailed study of the bubble dynamics and local heat transfer on a heating wall during pool boiling based on LS method. A clear temperature “hollow” with periodic expansion and contraction was observed.

Shin et al. [13] have conducted a fully direct numerical investigation of nucleate boiling in a 3D flow using the Level Contour Reconstruction Method, which is a simplified front tracking method handling interface merging and breakup in 3D flows proposed by Juric and Tryggvason [4]. They have predicted heat flux in nucleate boiling more accurately on a surface by including the effect of nucleation site density and topological change. Also, they showed that 3D numerical results were more accurate than those of 2D for wall heat flux prediction. However, for simplicity, they did not include micro-layer evaporation and contact line dynamics, which are very essential to the heat transfer mechanism.

Kunkelmann and Stephan [14] have investigated nucleate boiling of water on a heating wall based on VOF method. They proposed a micro-layer boiling model and performed the preliminary numerical study for the boiling of HFE-7100. They considered the conjugate heat transfer on the wall and found qualitatively good agreement with the measurements. Most recently, Yang et al. [15] studied the pool boiling under different micro-gravity conditions by the VOF method. They found that the effects of gravity on the detachment of the bubble were significant. Moreover, the results showed that the temperature profile at the vapor–liquid interface was no longer a uniform distribution, and the Marangoni flows were more obvious at the vapor–liquid interface.

The coupled VOF and LS method has also been implemented by many researchers. Recently, Ling et al. [16] studied a 2D nucleate boiling using VOSET method with micro-layer model. They presented a temperature interpolation method which was used to solve the temperature field in cells containing liquid–vapor interface. The temperature on the vapor side can be solved continuously by using this method.

Lattice Boltzmann method (LBM) which was based on a kinetic Boltzmann equation has been proposed since the 1980s [17]. The study of nucleate boiling by lattice Boltzmann method has been conducted by Yang et al. [18], Hazi and Markus [19], and Dong et al. [20]. Yang et al. [15] have studied the boiling regime transition without the effect of heat transfer, which was called pseudo boiling. Hazi and Markus [19] developed a lattice Boltzmann model and investigated boiling on a horizontal surface in a stagnant and slowly flowing fluid. However, the results showed no dependence of the bubble departure diameter on contact angle, contrary to the studies of Dong et al. [20]. Recently, Gong and Cheng [21] have studied the bubble growth on and departure from a superheated wall using an improved hybrid lattice Boltzmann method, which was based on the free energy two-phase model combined with the thermal hybrid model.

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