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Numerical investigation on bubble evolution during nucleate boiling using diffuse interface method

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ABSTRACT

Nucleate boiling is an important heat transfer model that has a high thermal flux density at small temperature difference. Thus, it has been widely used in the nuclear industry, aerospace and many other fields. However, it is also a complex phenomenon containing heat and mass transfer, phase change and multiphase flow which make it difficult to study its principle or carry out experiments. In the present study, the phase change model is added to the Navier-Stokes equation, mass equation and energy equation by the source item. These three basic equations are solved in the fixed mesh and the vapor-liquid interface is captured by diffuse interface method. During the numerical simulation, the calculation not only contains the multiphase fluid but also considers the solid heat transfer domain for heating wall which makes the simulation closer with reality. The influence of bubble growing period, departure diameter and the temperature distributed of the heating wall with different static contact angles are studied. The wettability effect is also considered in the present study. The results show that with no-wettability condition, the bubble departure diameter and growing period will decrease when the contact angle decrease. The contact points of the interface and wall surface has the lowest temperature. The bubble is detached from the neck region under the wettability condition. The bubble departure diameter is larger and the growing period is longer than the no-wettability condition. The contact point of the interface and wall surface also has the lowest temperature, but the temperature of the wall center is much higher because there is always covered by the vapor.

1. Introduction

During the stages of pool boiling, the nuclear boiling has the largest heat transfer coefficient and the heat transfer effect is better than other regions. Thus, it is commonly used in the nuclear engineering, electrical engineering and aerospace engineering to strengthen the heat transfer. During the process of nucleate boiling, the tiny bubbles create from a cavity and grow up. The heat would be taken away from the wall by the phase change. When the bubble grows to a certain condition it would depart from the wall and float up. The growth period and the departure radius of the bubble are affected by various factors. Among them, the contact angle and wettability are two very important factors.

In recent years, researchers have simulated the nucleate boiling process by different interface capturing methods. Kunkelmann and Stephan have used Volume of Fluid (VOF) method to study the boiling flows by the open source software OpenFOAM [1–3]. In these studies, the emphasis was put on the contact line (the length between the steam and the wall) evaporation and the growth of the bubble from a heated steel foil. Son has simulated a sliding bubble on a vertical surface by level-set method [4–6]. The effects of contact angle, wall superheat and phase change on a sliding bubble are quantified. Forster and Smith used the Arbitrary Lagrangian-Eulerian (ALE) moving mesh to directly track the interface [7,8]. They investigated the evolution of a single bubble growth, pinch-off, and condensation during the sub-cooled boiling. Tian et al. studied the bubble dynamics of the flow boiling and condensation by using moving particle semi-implicit (MPS) method [9,10]. The Lattice Boltzmann Method (LBM) has shown great potentials in simulating nucleate pool boiling, because of its kinetic nature and avoided tracking the interface explicitly. Gong and Cheng have done a series of studies on nucleate boiling of heat transfer, wettability and rough surface by using LBM [11–14]. There are also many other researchers studied the nucleate boiling by using different methods [15–20]. However, the different interface capturing method has its own advantages and disadvantages. The Level-Set method has smoother interface than VOF. The VOF method has better mass conservation than Level-Set method. The ALE method takes fewer grids, but it is difficult to deal with the

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Nomenclature

C	initial regulation constant
C_p	specific heat capacity
G	chemical potential
ΔH_{vl}	enthalpy of vaporization
k	thermal conductivity
l	moving distance
$\dot{m}$	rate of vaporization
M_w	molecular weight of the vapor
p	pressure
r	bubble equivalent radius
r_0	bubble initial radius
S	area of the bubble
t	time
T	temperature
V_f	volume fraction
x_0	initial bubble horizontal position
y_0	initial bubble vertical position
Matrix	
$\boldsymbol{F_g}$	gravity
$\boldsymbol{F_{st}}$	volume force
$\boldsymbol{I}$	unit vector
$\boldsymbol{n}$	the unit normal vector
$\boldsymbol{u}$	velocity field
Greek letters	
γ	mobility
δ	interface smoothing function
ε_{pf}	the thickness of the diffuse interface
λ	mixing energy density
μ	viscosity coefficient
ρ	density
σ	interfacial tension
ϕ	phase function variable
φ	contact angle
χ	transfer adjustment parameter
ψ	auxiliary variable functions
Superscript/subscript	
int	interface
l	liquid
sat	saturation
v	vapor

topology changes. Thus, some researchers combine both methods together to track the interface [21,22]. Besides these various numerical simulations, other researchers have also performed the experiments. Jung and Kim obtained the boiling curves for various surface orientations in the low heat flux nucleate boiling [23]. They have also performed the experiment to simultaneously measure the dynamics and heat transfer by the high speed infrared camera and high speed camera [24]. Hai's experiment used the nanocoating to study the effects by the wettability on pool boiling [25]. These results provide a useful reference for numerical simulation.

In the present study, interface diffusion method has been used to track the interface, which has been proposed by Van de Waals in 1893 [26]. The sharp interface is replaced by the thin diffusion region. In the interface region, the interfacial tension is added in partial differential equations by volume force source term. The method can solve the effect of interfacial tension on the two phase interface, and has good mass conservation. At present, though some basic problems of two-phase flow have been studied by using diffuse interface method [27–29], there are few literatures studied in bubble nucleate boiling by using this method.

The effects of contact angle and wettability on the single bubble growth process are studied by simulation using the interface diffusion method in this paper. At the same time, the solid heat transfer of the wall surface is also considered in the numerical simulation, the temperature distribution of the wall surface is simulated and analyzed.

2. Numerical and physics model

In the multiphase flow, the physical behavior is very complicated which is driven by the interface dynamics. During the nucleate boiling, the interface is a moving boundary that not only contains the bubble dynamics but also considers the phase change. The numerical simulation is performed by solving the complete incompressible Navier-Stokes equation based on fixed mesh. The finite element method and PARDISO solver are used to calculate the model. The interface is tracked by the diffuse interface method. The phase change is added into the governing equations by the source term. In this section, a brief description of the governing equations, calculation domain, initial conditions and boundary conditions is presented.

2.1. Physical parameters

Because the thin diffuse region is used to replace the sharp interface, the physical property parameters are transformed continuously from liquid to vapor at the interface. Thus it is very important to define the volume fraction which could make it easy to express the physical property parameters in different regions.

$$V_{f,l} = \frac{1+\phi}{2}; \quad V_{f,v} = \frac{1-\phi}{2} \tag{1}$$

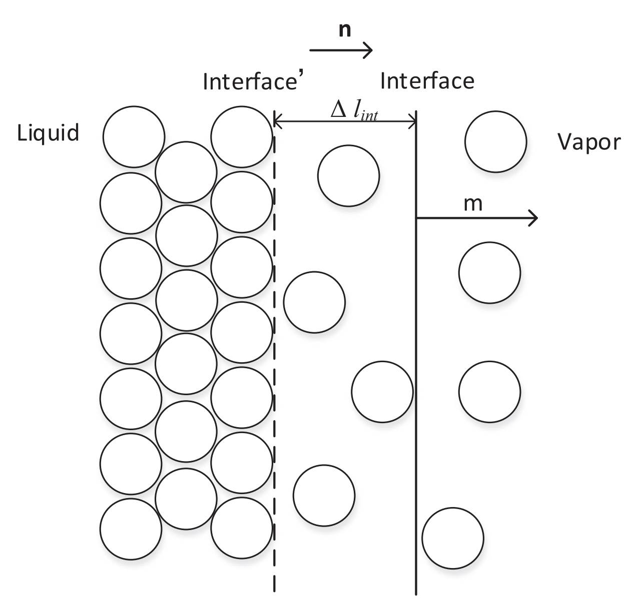

Fig. 1. Interface moving influenced by the rate of mass transfer.