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A saturated-interface-volume phase change model for simulating flow boiling

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ABSTRACT

High-fidelity simulation of flow boiling in microchannels remains a challenging problem, but the increasing interest in applications of microscale two-phase transport highlights its importance. In this paper, a volume of fluid (VOF)-based flow boiling model is proposed with features that enable cost-effective simulation of two-phase flow and heat transfer in realistic geometries. The vapor and liquid phases are distinguished using a color function which represents the local volume fraction of the tracked phase. Mass conservation is satisfied by solving the transport equations for both phases with a finite-volume approach. In order to predict phase change at the liquid–vapor interface, evaporative heat and mass source terms are calculated using a novel, saturated-interface-volume phase change model. This phase change model is formulated to anchor the interfacial temperature at saturation within each iteration, and thereby acts as a robust constant-temperature boundary condition. Unlike other available phase-change models, the source terms are coupled with the local temperature explicitly; therefore, numerical oscillations around the interface temperature are not observed during iterations within a time step, which reduces the numerical cost. In addition, the reference frame is set to move with the vapor slug to artificially increase the local velocity magnitude in the thin liquid film region in the relative frame. This reduces the influence of numerical errors resulting from calculation of the surface tension force, and thus suppresses the development of spurious currents. As a result, non-uniform meshes may be used which can efficiently resolve high-aspect-ratio geometries and flow features. The overall numerical expense is significantly reduced. The proposed saturated-interface-volume model is first validated against a one-dimensional Stefan problem, and then used to simulate the growth of a vapor bubble flowing in a heated, 2D axisymmetric microchannel. The bubble motion, bubble growth rate, liquid film thickness, and local heat transfer coefficient along the wall are compared against previous numerical studies. A three-dimensional flow boiling problem is studied to demonstrate the cost effectiveness of the present approach and to highlight the transport mechanisms it can reveal in more complex domains.

1. Introduction

Increasing recent attention to microchannel flow boiling has resulted from the demand for high-performance, compact cooling systems. The latent heat absorbed during vaporization confers flow boiling with higher heat transfer coefficients and more uniform surface temperatures than single-phase convective heat transfer, which allows for operation at a lower mass flow rate and thereby a smaller pressure drop. Accurate numerical simulations can reveal details of the heat and mass transfer processes that are not measureable in experiments; this would improve the understanding of key transport mechanisms as well as predictions of both global and local heat transfer performance.

A number of numerical methods have been developed to study phase change [1,2]. The interface is evaluated either by a Lagrangian [3,4] or an Eulerian method [5–8]. In Lagrangian methods, the interface is represented by mesh faces, which allows for an accurate evaluation of the interface normal gradient [9,10]. However, it is expensive to track complex interfacial deformation in transient problems using a moving mesh with Lagrangian methods. In Eulerian methods, the interface geometry is reconstructed from a color function that is used to track the phases, such as the volume fraction in volume-of-fluid (VOF) methods. This allows convenient tracking of complex interface deformations [11,12].

Among the various numerical techniques available, VOF methods are promising for resolving phase change heat transfer due

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Nomenclature

A	area (m^2)
C	volume fraction
c_p	heat capacity (J/kg K)
D	channel diameter (m)
F	volumetric body force (N/m^3)
h_{fg}	latent heat (J/kg)
K	thermal conductivity (W/m K)
L	channel length (m)
M	molecular weight (kg/mol)
m''	mass flux (kg/m^2s)
$\vec{n}$	unit normal vector
P	pressure (N/m^2)
q''	heat flux (W/m^2)
R	universal gas constant (J/mol K)
S_h	energy source (W/m^3)
S_m	mass source (kg/m^3s)
T	temperature (K)
T	time (s)
$\varDelta t$	time step (s)
U	velocity magnitude (m/s)
$\vec{U}$	velocity vector (m/s)
Δt	time step (s)
W	width (m)
X	axial location (m)
Δx	mesh size (m)
Y	radial location (m)
Z	flow direction location (m)

Greek

Δ	film thickness (m)
δ_s	delta function
$\varGamma$	accommodation coefficient
M	dynamic viscosity ($N\,s/m^2$)
K	interface curvature (m^{-1})
P	density (kg/m^3)
Σ	surface tension (N/m)

Subscript

0	static reference
Ax	axial component
C	critical
Cell	center value of the cell
I	the *i*th phase
In	initial
Int	interface
L	liquid
La	latent
N	time step
R	relative
Ra	radial component
Ref	reference frame
S	surface tension
Sat	saturated
Tar	target
V	vapor
W	wall

to the intrinsic mass conservation achieved, unlike with other Eulerian methods. However, fixed-grid approaches must estimate the interface profile; VOF methods may thereby induce unphysical flows (referred to as spurious currents) due to the numerical error in estimating the interfacial surface tension. Numerous approaches have been proposed to suppress spurious currents: Gupta et al. [13] suggested a square mesh and a Green-Gauss node-based method for calculating pressure gradients; Magnini et al. [14,15] coupled VOF with a height-function method [16] using a uniform mesh; and Sussman and Puckett [17] and Sun and Tao [18]coupled VOF with a level-set (LS) method to improve the interface profile accuracy. However, the underlying need for uniform square mesh cells in these approaches has high computational cost. Most recently, Pan et al. [19] demonstrated that spurious currents can be suppressed by increasing the local velocity near the interface by employing an artificial moving reference frame. This specific treatment uniquely allows the use of high-aspect-ratio mesh elements, and thus can significantly reduce the computational expense when simulating high-aspect-ratio physical features, such as thin liquid films and rectangular microchannels.

Formulating the interface phase change model is another primary challenge in the modeling of flow boiling, and typically results in an inevitable tradeoff between physical accuracy and computational cost. A simplifying saturated model is commonly employed [20] where the evaporative mass source is defined as

$$S_m = rC_l\rho_l\frac{(T - T_{sat})}{T_{sat}}, \tag{1}$$

where r is an empirical coefficient used to bring the temperature of the cells containing the interface close to saturation, and can range from 0.1 s^{-1} to 100 s^{-1} [21–23]. In general, an overly large or small value of r shifts the interfacial temperature away from the saturation temperature; a large value of r may also induce numerical instabilities that cause the interfacial temperature to oscillate around the saturation temperature. Later improvements to the saturated phase change model [24–28] introduced physics-based expressions that avoid empiricism. The phase change mass source is calculated based on the local heat flux on the interface as

$$S_m = \left(k_l\frac{\partial T}{\partial \vec{n}_l}\bigg|_{int} + k_v\frac{\partial T}{\partial \vec{n}_v}\bigg|_{int}\right)\frac{A_{int,cell}}{V_{cell}}, \tag{2}$$

where $\vec{n}_i$ is the unit normal vector pointing to the ith phase and $A_{int,cell}$ is the interface area in the cell. The temperature gradient on the interface $\partial T/\partial \vec{n}_i$ can be calculated as $\partial T/\partial \vec{n}_i = (T_{cell} - T_{sat})/d$ where d is the distance from the cell center to the interface [25], or simplified as the temperature gradient in the cell ∇T_{cell} [26,28].

During the evaporation process, the interfacial temperature exceeds the saturation temperature to overcome the interfacial evaporative resistance. This interfacial resistance is typically much smaller than the thermal resistance of the adjacent liquid phase, and this temperature rise is usually only important in three-phase-contact-line regions with a submicron-scale liquid film [29]. The interfacial temperature rise above saturation can be evaluated as [30]

$$M'' = \phi(T - T_{sat}), \phi = \frac{2\gamma}{2-\gamma}\left(\frac{M}{2\pi R}\right)^{1/2}\left(\frac{\rho_v h_{fg}}{T_{sat}^{3/2}}\right) \tag{3}$$

By coupling Eqs. (2) and (3), Kunkelmann and Stephan [31] and Magnini et al. [14,15] investigated boiling with a non-equilibrium phase change model that includes the temperature rise above the saturation temperature at an evaporating interface. Both the equilibrium and non-equilibrium phase change models suffer from