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Direct numerical simulations of pool boiling curves including heater's thermal responses and the effect of vapor phase's thermal conductivity

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ABSTRACT

Effects of heater's thermal properties and vapor phase's thermal conductivity on saturated pool boiling above a large horizontal heater are simulated numerically based on an improved pseudo-potential liquid-vapor phase change lattice Boltzmann model. A transient conjugate heat transfer problem is under consideration, where the conjugate thermal boundary condition is imposed and heater's thermal responses during boiling processes are investigated. Saturated pool boiling curves from onset of nucleate boiling to critical heat flux (CHF), to transition boiling regime to stable film boiling regime are obtained numerically. It is found that the simulated critical heat flux (CHF) agrees reasonably well with existing analytical models. Also, the simulated boiling heat fluxes in stable film boiling regime are shown to be in good agreement with the existing analytical solution. Thus, this improved pseudo-potential liquid-vapor phase change lattice Boltzmann model is quantitatively validated. Simulation results demonstrate that there is significant maldistribution in temperature distribution near the top of heater surface in nucleate boiling regime, CHF point and transition boiling regime. As a result, two-dimensional heat conduction can not be ignored when evaluating heat flux closely beneath the heater's top surface. It is also shown that both heater's thermal conductivity and thermal mass (the product of density and specific heat at constant pressure) have no effect on CHF value as well as the boiling curve in nucleate boiling regime and film boiling regime for a thick heater. However, the transition boiling regime of the boiling curve moves to the left with the increasing heater thermal conductivity and heater thermal mass for a thick heater. Increasing the vapor theraml conductivity has no effect on CHF but would increase boiling heat flux in film boiling regime, and hence shortening the transition boiling regime.

1. Introduction

In 1934, Nukiyama [1] performed his well-known experiments on pool boiling from a horizontal wire under constant heat flux, and published a paper in which a plot of boiling heat flux versus degree of superheat (i.e., the so-called "boiling curve") was presented. During the past 80 years, many experiments have been performed to study different effects on boiling curves under different conditions, and correlation equations for pool boiling heat transfer with fitting constants were proposed [2]. However, experimental results were sometimes contradictory among one another and many effects affecting boiling curves are not distinguishable in an experimental investigation [3,4]. Thus, numerical studies are needed for deeper understanding of the underlying mechanisms involved in boiling heat transfer processes.

By modifying the level-set formulation [5] to accommodate for the liquid-vapor phase change effect, Dhir and co-workers [6,7] proposed a numerical model for nucleate boiling heat transfer and simulated single bubble growth as well as bubble merging processes. Although simulation results of bubble dynamics were found to agree well with experiments, there are still many limitations in this approach for studying boiling heat transfer phenomena. As an interface tracking method, small bubbles have to be specified at a specific location at the beginning of the computation, and the waiting period between two ebullition cycles is needed to be assumed for simulation of multiple ebullition cycles. As a result, this method is unable to simulate boiling curves because the initial nucleation site distributions and number of bubbles on the heater for a given wall temperature or wall heat flux are unknown as initial conditions.

In recent years, the lattice Boltzmann method (LBM) has received extensive attention and shown great potentials in modeling complex fluid systems. Gong and Cheng [8,9] developed an improved phase-change lattice Boltzmann method based on modification of Shan and Chen's pseudo-potential multiphase model [10] and Hazi and Markus' phase-change model [11]. This pseudo-potential liquid-vapor phase-change lattice Boltzmann model can directly incorporate the contact angle of the heater surface and equation of state for real gases in the

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Nomenclature

a	constant in P-R equation of state
b	constant in P-R equation of state
c	lattice speed (m/s)
c_p	specific heat at constant pressure (J Kg^{-1} K^{-1})
$c_{p,l}$	specific heat of the liquid at constant pressure (J Kg^{-1} K^{-1})
c_s	lattice sound speed (m/s)
c_v	specific heat at constant volume (J Kg^{-1} K^{-1})
$\mathbf{e}$	lattice velocity vector (m/s)
$f_i(\mathbf{x}, t)$	density distribution function (Kg/m^3)
$\mathbf{F}$	force (N)
$\mathbf{F}_g$	gravitational force (N)
$\mathbf{F}_{int}$	interparticle interaction force (N)
$\mathbf{F}_s$	fluid-solid interaction force (N)
$g_i(\mathbf{x}, t)$	temperature distribution function (K)
$\mathbf{g}$	gravitational acceleration vector (m/s^2)
g	gravitational acceleration (m/s^2)
G_s	fluid-solid interaction strength for adjusting the contact angle
h	specific enthalphy (J/Kg)
$\bar{h}_{co}$	averaged heat transfer coefficient (W m^{-2} K^{-1})
h_{fg}	specific latent heat (J/Kg)
h'_{fg}	specific latent heat including sensible heating of the vapor film (J/Kg)
H_b	thickness of the heater (m)
Ja	Jacob number
k	thermal conductivity (W m^{-1} K^{-1})
l_0	capillary length (m)
L_x	length of the computation domain (m)
L_y	width of the computation domain (m)
$\overline{Nu}$	averaged Nusselt number
p	pressure (pa)
Pr	Prandtl number
$Q(t)$	space-averaged heat flux (W/m^2)
$Q'(t)$	space-averaged dimensionless heat flux
Q''	space- and time-averaged dimensionless heat flux
R	constant in P-R equation of state
R_d	radius (m)
s	specific entropy (JKg^{-1} K^{-1})
t	time (s)
t^*	dimensionless time
t_0	characteristic time (s)
T	temperature (K)
T'	dimensionless temperature
u	specific internal energy (J/Kg)
u_0	characteristic velocity (m/s)
$\mathbf{u}$, $\mathbf{U}$	velocity vector (m/s)
v	specific volume (m^3/Kg)
x	co-ordinates (m)
y	co-ordinates (m)

Greek symbol

β	weighting factor of the interparticle interaction force
ρ	density (Kg/m^3)
θ	static contact angle (°)
ψ	effective mass (Kg$^{1/2}$ m$^{-1/2}$ s^{-1})
ω	acentric factor in P-R equation of state
ω_i	weighting coefficients in D2Q9 lattice
ϕ	source term (K/s)
γ	thermal mass ratio of the solid and the fluid
λ_d	most dangerous wavelength (m)
τ	relaxation time
σ	surface tension (N/m)
δ	lattice spacing (m)
∇	the gradient operator

Subscripts or Superscripts

cr	critical
eq	equilibrium
f	fluid
l	liquid
r	receding
s	solid
sat	saturation
v	vapor
w	wall
x	co-ordinate
y	co-ordinate

governing equations, enabling the automatic phase change/phase separation determined by thermodynamic relations. Hence, there is no need to track the liquid-vapor interface explicitly, and the entire ebullition cycle including bubble nucleation process can be simulated automatically by this model. Based on this newly developed model, Cheng and co-workers [12–14] have simulated effects of wettability, heater size, subcooling, and heating methods on pool boiling curves. In these papers, the boiling heat flux was either evaluated at the fluid side [9] or evaluated at the heater surface beneath the fluid-solid interface where 1D heat conduction was assumed [12–14], and simulations were carried out for $T_{sat} = 0.85T_{cr}$ or $0.9T_{cr}$ at a vapor/liquid thermal conductivity ratio of $k_v/k_l = 1/3$. It was found that the simulated transition boiling regime was rather short and the entire simulated film boiling curve had an upward shift from Berenson's analytical solution [15]. As a result, the shape of simulated boiling curves at high superheats looked very much different from the classical Nukiyama's boiling curves [1]. Recently, Li et al. [16] as well as Tao and co-workers [17,18] also proposed similar pseudo-potential liquid-vapor phase change lattice Boltzmann models. With the imposition of a conjugate thermal boundary condition at the wall, Tao and co-workers [17,18] investigated effects of cavity shape on boiling heat transfer performances and simulated the boiling curves in nucleate boiling regime and transition boiling regime. However, they did not present simulated curves in the film boiling regime and simulated boiling curves were not quantitatively validated [18]. Also, thermal responses inside the heater were not investigated in these papers [16–18].

In this paper, direct numerical simulations of saturated pool boiling curves will be conducted using the pseudo-potential liquid-vapor phase change lattice Boltzmann model proposed by Cheng and co-workers [8,14]. The problem is treated as a conjugate heat transfer problem at the fluid-solid interface and the boiling heat flux is evaluated accurately at the bottom of a thick heater where 1D heat conduction is accurately satisfied. In addition, effects of heater's thermal properties (thermal mass and thermal conductivity) with a low thermal conductivity of the vapor phase $k_v = k_l/17$ on boiling curves are illustrated. It is shown that both the simulated CHF and simulated film boiling heat fluxes in the present paper match well with analytical solutions, and simulated transition boiling regime is much longer than those obtained previously [12–14]. As a result, the shape of simulated boiling curves in transition boiling and film boiling obtained under such conditions looks closer to the shape of classical boiling curves. Therefore, the correctness and accuracy of Cheng and co-workers' phase-change lattice Boltzmann model [8,14] for boiling heat transfer are validated quantitatively in this paper for the first time.