International Communications in Heat and Mass Transfer 91 (2018) 109–116

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Direct numerical simulations of film boiling heat transfer by a phase-change lattice Boltzmann method

Lining Dong[a,b], Shuai Gong[a,*], Ping Cheng[a]

[a] MOE Key Laboratory for Power Machinery and Engineering, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China
[b] Shanghai Institute of Satellite Engineering, Shanghai 200000, PR China

ARTICLE INFO

Keywords:
Film boiling
Numerical simulation
Lattice Boltzmann method
Nusselt number
Film thickness

ABSTRACT

Numerical simulations of film boiling heat transfer on a horizontal surface are conducted in this paper using a modified pseudo-potential liquid-vapor phase change lattice Boltzmann model. A conjugate heat transfer problem, including heat conduction in the heater and its thermal responses during the film boiling process, is investigated. Unlike previous numerical studies which needed to initialize the shape of the liquid-vapor interface wave at the beginning of the computation, the computation domain for fluid region is occupied initially by saturated liquid in this paper. Taylor instability at the liquid-vapor interface is triggered by small temperature perturbations imposed at the bottom of the heater during a short initial period. Consequently, this paper represents a more direct and complete numerical simulation for film boiling heat transfer on a horizontal heater. The simulated time- and space-averaged Nusselt number is found in good agreement with a previous correlation equation. Temporal and spatial variations of the vapor film thickness are also investigated numerically and compared with existing correlation equations. It is demonstrated that the temperature at the top surface of the heart changes with position and time during the film boiling process. Although the transient film boiling patterns may depend on temperature perturbations imposed on he bottom of the heater during an initial period, the time- and space-averaged film boiling heat flux is independent of initial temperature perturbations.

1. Introduction

Film boiling, with the entire heater surface being covered by a vapor blanket and vapor bubbles being released from the wavy liquid-vapor interface due to Taylor instability, is the simplest and an undesirable boiling pattern with low heat transfer coefficient. In 1960, Berenson [1] derived a solution for heat transfer coefficient of steady laminar film boiling from a large horizontal upward-facing surface by postulating that bubbles were released at the nodes of the most-dangerous Taylor wave with wavelength λ_d, which is given by [2]:

$$\lambda_d = 2\pi\sqrt{\frac{3\sigma}{g(\rho_l-\rho_v)}} \tag{1}$$

Assuming that heat is transferred across the thin vapor film only by conduction, Berenson [1] obtained the following space-averaged film boiling heat transfer coefficient

$$\bar{h}_{co} = \frac{Q}{T_w - T_{sat}} = 0.425\left[\frac{k_v^3 g\rho_v(\rho_l-\rho_v)h'_{fg}}{\mu_v(T_w-T_{sat})}\right]^{1/4}\left[\frac{\sigma}{g(\rho_l-\rho_v)}\right]^{-1/8} \tag{2}$$

where σ is the surface tension, h'_{fg} is the specific latent heat including sensible heating of the vapor film and is defined as $h'_{fg} = h_{fg} + 0.5c_{p,v}(T_w - T_{sat})$ [2], and 0.425 is a fitting constant obtained by matching with experimental data. The Nusselt number, defined based on the Taylor most-dangerous wavelength λ_d, is

$$\overline{\mathrm{Nu}} = \bar{h}_{co}\ \lambda_d/k_v \tag{3}$$

Substituting Eqs. (1) and (2) into Eq. (3)gives

$$\overline{\mathrm{Nu}} = 0.425\times 2\sqrt{3}\pi\left[\frac{\rho_v(\rho_l-\rho_v)gh'_{fg}}{k_v\mu_v(T_w-T_{sat})}\right]^{1/4}\left[\frac{\sigma}{g(\rho_l-\rho_v)}\right]^{3/8} \tag{4}$$

Based on the assumption that heat is transferred across the thin vapor film only by conduction, the vapor film thickness Π in film boiling can be predicted by

$$\Pi = k_v/\bar{h}_{co} \tag{5}$$

Substituing Eqs. (2)–(4) into Eq. (5) gives

$$\Pi = \lambda_d/\overline{\mathrm{Nu}} = 2.353\left[\frac{\rho_v(\rho_l-\rho_v)gh'_{fg}}{k_v\mu_v(T_w-T_{sat})}\right]^{-1/4}\left[\frac{\sigma}{g(\rho_l-\rho_v)}\right]^{1/8} \tag{6}$$

* Corresponding author.
E-mail address: shuaigong@sjtu.edu.cn (S. Gong).

https://doi.org/10.1016/j.icheatmasstransfer.2017.12.013

Nomenclature

c_p	specific heat at constant pressure (J Kg^{-1} K^{-1})
c_v	specific heat at constant volume (J Kg^{-1} K^{-1})
g	gravitational acceleration (m/s^2)
$g_i(\mathbf{x}, t)$	temperature distribution function (K)
h_{co}	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_o	capillary length (m)
L_x	length of the computation domain (m)
L_y	width of the computation domain (m)
Nu	Nusselt number
Pr	Prandtl number
R_0	dimensionless parameter representing the ratio of gravity force and viscous force
t	time (s)
t^*	dimensionless time
t_o	characteristic time (s)
T	temperature (K)
T'	dimensionless temperature
u_o	characteristic velocity (m/s)
V	magnitude of the velocity vector (m/s)
x	co-ordinates (m)
y	co-ordinates (m)

Greek symbol

α	thermal diffusivity (m^2/s)
ρ	density (Kg/m^3)
υ	kinematic viscosity (m^2/s)
μ	dynamic viscosity (Kg m^{-1} s^{-1})
γ	thermal mass ratio of the solid and the fluid
λ	wavelength (m)
σ	surface tension (N/m)

Subscripts or superscripts

b	base
cr	critical
f	fluid
l	liquid
s	solid
sat	saturation
v	vapor
w	wall
x	co-ordinate
y	co-ordinate

In 1981, Klimenko [3] proposed the following correlation for film boiling heat transfer in laminar flow region based on Reynolds analogy

$$\overline{\mathrm{Nu}} = 0.19\sqrt{3}R_0^{1/3}\mathrm{Pr}_v^{1/3}f_1(\mathrm{Ja}_v) \tag{7a}$$

where R_0 is a dimensionless parameter representing the ratio of gravity force and viscous force given by

$$R_0 = \frac{g\lambda_d^3}{3\sqrt{3}\upsilon_v^2}\cdot\frac{\rho_l-\rho_v}{\rho_v} \tag{7b}$$

and $f_1(\mathrm{Ja}_v)$ is given as

$$f_1(\mathrm{Ja}_v) = \begin{cases} 1, & \text{for } \mathrm{Ja}_v = \frac{c_{p,v}(T_w - T_{sat})}{h_{fg}} \geq 0.714 \\ 0.89\mathrm{Ja}_v^{-1/3}, & \text{for } \mathrm{Ja}_v < 0.714 \end{cases} \tag{7c}$$

Substituting Eqs. (3) and (7a) into Eq. (5) gives the vapor film thickness for a laminar flow as

$$\Pi = \lambda_d/\overline{\mathrm{Nu}} = 33.07R_0^{-1/3}\mathrm{Pr}_v^{-1/3}[f_1(\mathrm{Ja}_v)]^{-1}\left[\frac{\sigma}{g(\rho_l-\rho_v)}\right]^{1/2} \tag{7d}$$

Note that laminar flow region corresponds to $R_0 < 10^8$ in Klimenko [3] model.

In 1997, Son and Dhir [4] simulated the evolution of the liquid-vapor interface up to the point of bubble departure during saturated film boiling under constant temperature condition, using a moving body-fitted coordinate system. The simulated Nusselt number was found to be 34% lower than the Berenson model [1] given by Eq. (4). In 1998, Juric and Tryggvason [5] investigated the film boiling heat transfer under constant wall heat flux condition, based on a finite difference/front tracking method. Subsequently, level set and VOF based models were adopted for the simulation of film boiling by Son and Dhir [6] and by Welch and Wilson [7], respectively. Welch and Rachidi [8] extended the VOF based model for film boiling heat transfer proposed by Welch and Wilson [7] by including a conjugate heat transfer boundary condition at the fluid-solid interface.

In recent years, the lattice Boltzmann method (LBM) has shown great potentials in numerical modeling of complex fluid systems. In 2009, Dong et al. [9] proposed a free energy based lattice Boltzmann model for phase change and simulated the growth and rising of a single vapor bubble through a uniformly superheated liquid. At approximately the same time, Hazi and Markus [10,11] developed a phase change model based on pseudo-potential lattice Boltzmann method and investigated bubble departure diameter and bubble departure frequency from a heated horizontal plate. Cheng and coworkers [12–14] proposed an improved pseudo-potential liquid-vapor phase change lattice Boltzmann model based on Hazi and Markus [10,11]'s work, and later obtained numerically complete boiling curves from onset of nucleate boiling (ONB) to stable film boiling regime for the first time [15–18]. Subsequently, Li et al. [19], Tao and coworkers [20,21] also proposed modified pseudo-potential liquid-vapor phase change lattice Boltzmann models. Most recently, Begmohammadi et al. [22] studied film boiling heat transfer based on the extension of the phase-field lattice Boltzmann model for multiphase flows proposed by Lee [23]. However, conjugate heat transfer at the fluid-solid interface was not included and a constant and uniform wall temperature boundary condition was used in their work.

In this paper, numerical simulations of film boiling heat transfer including conjugate heat transfer at the fluid-solid interface [24] will be conducted using a modified pseudo-potential liquid-vapor phase change lattice Boltzmann model proposed by Cheng and coworkers [12,14,16,17]. The key characteristic in this model is the direct incorporation of the equation of state for real gases, which enables the automatic phase change/phase separation determined by thermodynamic relations. Thus, there is no need to track the liquid-vapor interface explicitly and the computation cost is greatly reduced. In all previous numerical work [4–8,22] for film boiling simulation based on VOF, level set and phase-field lattice Boltzmann method etc., a wavy vapor film is needed to be specified as the initial condition. In this work, however, the fluid region is occupied by saturated liquid at the beginning of the computation. Small temperature perturbations are imposed at the bottom of the heater during an initial period so as to trigger the Taylor instability. In addition, including conjugate heat transfer at the fluid-solid interface makes the simulation more realistic since the spatial and temporal variations of the temperature and heat flux at the top