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Review

Review of computational studies on boiling and condensation

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ABSTRACT

Developments in many modern applications are encountering rapid escalation in heat dissipation, coupled with a need to decrease the size of thermal management hardware. These developments have spurred unprecedented interest in replacing single-phase hardware with boiling and condensation counterparts. While computational methods have shown tremendous success in modeling single-phase systems, their effectiveness with phase change systems is limited mostly to simple configurations. But, given the complexity of phase change phenomena important to many modern applications, there is an urgent need to greatly enhance the capability of computational tools to tackle such phenomena. This article will review the large pool of published papers on computational simulation of boiling and condensation. In the first part of the article, popular two-phase computational schemes will be discussed and contrasted, which will be followed by discussion of the different methods adopted for implementation of interfacial mass, momentum and energy transfer across the liquid-vapor interface. This article will then review papers addressing computational modeling of bubble nucleation, growth and departure, film boiling, flow boiling, and flow condensation, as well as discuss validation of predictions against experimental data. This review will be concluded with identification of future research needs to improve predictive computational capabilities, as well as crucial phase change phenomena found in modern thermal devices and systems that demand extensive computational modeling.

Contents

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Nomenclature

A_i	interfacial area
C	color function
c	parameter in Eq. (18a); wave speed
c_p	specific heat at constant pressure
C_{PF}	phase-field parameter
D	diameter of circular channel; bubble diameter
d	distance of liquid-vapor interface from wall
D_d	departure diameter during nucleate boiling
E	specific internal energy (J/kg)
F	force
Fo_{bi}	Fourier number based on initial bubble diameter
G	mass velocity (kg/m^2 s)
g	gravitational acceleration
g_e	earth gravity
H	heaviside function
h	cell width or grid spacing; heat transfer coefficient
$\bar{h}$	average heat transfer coefficient
h_{fg}	latent heat of vaporization
h_i	interfacial heat transfer coefficient
I	indicator function
Ja	Jacob number
k	effective thermal conductivity
M	molecular weight
$\dot{m}$	mass transfer rate (kg/m^2 s)
Mo	Morton number
$\vec{n}$	unit vector normal to interface
Nu	Nusselt number
p	pressure
Pr	Prandtl number
Q	energy source term for energy equation (W/m^3); volume flow rate
q''	heat flux
q''_i	heat flux across interface
$\bar{q}''_w$	average wall heat flux
R	universal gas constant (8.314 J/mol K)
r	radial coordinate
Re	Reynolds number
R_{gas}	gas constant
r_i	mass transfer intensity factor (s^{-1})
$r_{i,m}$	modified mass transfer intensity factor (K^{-1} s^{-1})
R_0	radius of dry region below bubble in micro-region
R_1	radial location of interface at $y = h/2$
S	volumetric mass source in continuity equation (kg/m^3 s)
T	temperature
t	time
t_d	bubble growth time period during nucleate boiling
T_{sat}	saturation temperature
ΔT_{sub}	inlet subcooling, $\Delta T_{sub} = T_{sat} - T_{in}$
ΔT_w	wall superheat, $\Delta T_w = T_w - T_{sat}$
U	velocity
$\vec{u}$	velocity vector
$\vec{u}_{front}$	velocity of front
V	volume
$\vec{v}_f$	liquid velocity normal to liquid-vapor interface
x	x-coordinate; dimensionless parameter in Fig. 2
x_e	thermodynamic equilibrium quality
$\vec{x}_{front}$	position of front
y	y-coordinate; distance from wall; dimensionless parameter in Fig. 2
z	z-coordinate

Greek symbols

α	volume fraction
γ	accommodation coefficient
δ	liquid film thickness; thickness of liquid micro-layer
δ_s	Dirac delta function
δ_0	liquid film thickness at R_0
ε_m	eddy momentum diffusivity
λ	interfacial wavelength
κ	curvature given by Eq. (18b)
κ_m	diffusion parameter
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
σ	surface tension
τ	shear stress
φ	chemical potential
ϕ	contact angle
ψ	level set function

Superscripts

$\rightarrow$	vector
$*$	dimensionless

Subscripts

b	bubble
c	condensation
e	evaporation
f	liquid
g	vapor
i	interfacial
in	inlet
k	$k = f$ for liquid, $k = g$ for vapor
s	surface
sat	saturated
T	turbulent
$unsat$	unsaturated
w	wall