



## 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.

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**Nomenclature**

$A_i$	interfacial area	$\vec{u}$	velocity vector
$C$	color function	$\vec{u}_{front}$	velocity of front
$c$	parameter in Eq. (18a); wave speed	$V$	volume
$c_p$	specific heat at constant pressure	$\vec{v}_f$	liquid velocity normal to liquid-vapor interface
$C_{PF}$	phase-field parameter	$x$	$x$ -coordinate; dimensionless parameter in Fig. 2
$D$	diameter of circular channel; bubble diameter	$x_e$	thermodynamic equilibrium quality
$d$	distance of liquid-vapor interface from wall	$x_{front}$	position of front
$D_d$	departure diameter during nucleate boiling	$y$	$y$ -coordinate; distance from wall; dimensionless parameter in Fig. 2
$E$	specific internal energy (J/kg)	$z$	$z$ -coordinate
$F$	force		
$FO_{bi}$	Fourier number based on initial bubble diameter		
$G$	mass velocity ( $\text{kg}/\text{m}^2 \text{ s}$ )		
$g$	gravitational acceleration	<b>Greek symbols</b>	
$g_e$	earth gravity	$\alpha$	volume fraction
$H$	heaviside function	$\gamma$	accommodation coefficient
$h$	cell width or grid spacing; heat transfer coefficient	$\delta$	liquid film thickness; thickness of liquid micro-layer
$\bar{h}$	average heat transfer coefficient	$\delta_s$	Dirac delta function
$h_{fg}$	latent heat of vaporization	$\delta_0$	liquid film thickness at $R_0$
$h_i$	interfacial heat transfer coefficient	$\epsilon_m$	eddy momentum diffusivity
$I$	indicator function	$\lambda$	interfacial wavelength
$Ja$	Jacob number	$\kappa$	curvature given by Eq. (18b)
$k$	effective thermal conductivity	$\kappa_m$	diffusion parameter
$M$	molecular weight	$\mu$	dynamic viscosity
$\dot{m}$	mass transfer rate ( $\text{kg}/\text{m}^2 \text{ s}$ )	$\nu$	kinematic viscosity
$Mo$	Morton number	$\rho$	density
$\vec{n}$	unit vector normal to interface	$\sigma$	surface tension
$Nu$	Nusselt number	$\tau$	shear stress
$p$	pressure	$\varphi$	chemical potential
$Pr$	Prandtl number	$\phi$	contact angle
$Q$	energy source term for energy equation ( $\text{W}/\text{m}^3$ ); volume flow rate	$\psi$	level set function
$q''$	heat flux		
$q''_i$	heat flux across interface	<b>Superscripts</b>	
$\bar{q}''_w$	average wall heat flux	$\rightarrow$	vector
$R$	universal gas constant (8.314 J/mol K)	*	dimensionless
$r$	radial coordinate		
$Re$	Reynolds number	<b>Subscripts</b>	
$R_{gas}$	gas constant	$b$	bubble
$r_i$	mass transfer intensity factor ( $\text{s}^{-1}$ )	$c$	condensation
$r_{i,m}$	modified mass transfer intensity factor ( $\text{K}^{-1} \text{ s}^{-1}$ )	$e$	evaporation
$R_0$	radius of dry region below bubble in micro-region	$f$	liquid
$R_I$	radial location of interface at $y = h/2$	$g$	vapor
$S$	volumetric mass source in continuity equation ( $\text{kg}/\text{m}^3 \text{ s}$ )	$i$	interfacial
$T$	temperature	$in$	inlet
$t$	time	$k$	$k = f$ for liquid, $k = g$ for vapor
$t_d$	bubble growth time period during nucleate boiling	$s$	surface
$T_{sat}$	saturation temperature	$sat$	saturated
$\Delta T_{sub}$	inlet subcooling, $\Delta T_{sub} = T_{sat} - T_{in}$	$T$	turbulent
$\Delta T_w$	wall superheat, $\Delta T_w = T_w - T_{sat}$	$unsat$	unsaturated
$U$	velocity	$w$	wall

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