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Nomenclature

Latin

A	surface of a volume
A	frontal area of bubble
$A^{\alpha\beta}$	surface metric tensor (Aris, 1962)
\mathcal{A}	turbulence anisotropy tensor
A_b	interfacial area of bubble
A_B	area of bubble-layer region
A_C	cross-sectional area of boiling channel
A_d	projected area of a typical particle
A^F	free surface on boundary of control volume
A_i	mathematical surface between A_1 and A_2
A_i	surface area
A_k	surface bounding the interfacial region and adjacent to phase k
A_m	surface of fixed mass volume
A_p	projected area of a particle
A^S	structural material surface on boundary of control volume
A^T	total boundary surface of control volume
a	cross sectional radius of cap or slug bubble
a_c^i	mobility of the fluid at the interface

a_i	interfacial area concentration
a_{sk}, a_{tk}	isentropic and isothermal sound velocities based on the average thermodynamic properties
B_d	volume of a typical particle
B_S	balance at an interface
B_V	balance in each phase
B_{sf}	bubble size factor
b	constant
$b_k^{\Gamma}, b_k^M, b_k^E$	transport coefficients associated with interfacial transfer of mass, momentum and energy
C	wave velocity
C	constant
C_D	drag coefficient
$C_{D\infty}$	ideal drag coefficient
C_g	variable defined by $\sqrt{2g\Delta\rho/\rho_f}$
C_{gf}	momentum transfer coefficient for interphase drag force
C_{hk}	distribution parameter
C_{hm}	mixture-enthalpy-distribution parameter
C_i	closed curve on an interface
C_K	kinematic wave velocity
C_L	lift coefficient
C_M	virtual mass constant
C_T	adjustable parameter
C_{vk}	distribution parameter
C_{vm}	virtual volume coefficient
C_{vm}	mixture-momentum-distribution parameter
C_τ	distribution parameter
$C_{\psi k}$	distribution parameter for flux
C^i	shape factor
C_0	distribution parameter
C_∞	propagation velocity
C_∞	asymptotic value of distribution parameter
c_k	mass concentration of phase k

c_{pk} , c_{vk}	specific heat at constant pressure and density based on averaged properties
D	hydraulic-equivalent diameter
D^*	length scale ratio
D_b	bubble diameter
D_b^*	non-dimensional bubble diameter
D_{bc}	critical bubble size
D_{c1}^*	ratio of D_{crit} to D_{Sm1}
$D_{c,max}$	maximum diameter of stable bubble
D_{crit}	volume-equivalent diameter of a bubble at boundary between groups 1 and 2
D_d	bubble departure diameter
D_{dF}	bubble departure diameter calculated by Fritz correlation
$D_{d,max}$	maximum distorted bubble limit
D_d^*	ratio of bubble diameter to bubble diameter at distorted bubble limit
D_e	volume-equivalent diameter of a fluid particle
D_e	eddy diameter
D_E	effective diameter of mixture volume that contains one bubble
D_H	hydraulic-equivalent diameter
D_H^*	non-dimensional hydraulic-equivalent diameter
D_k	diffusion coefficient
D_k	total deformation tensor of phase k
D_{kb}	bulk deformation tensor
D_{ki}	interfacial extra deformation tensor
D_k^α	drift coefficient
D_{Sm}	Sauter mean diameter
D_s	surface-equivalent diameter of a fluid particle
D_0	initial bubble diameter
D_0	rod diameter
d_B	bubble diameter
d_b	bubble diameter

\widehat{d}_B	cross-sectional mean diameter of bubbles
E_B	average energy required for bubble breakup
E_d	area fraction of liquid entrained in gas core from total liquid area at any cross section
E_e	average energy of a single eddy
E_k	total energy gain through interfaces for phase k
E_m	mixture total energy source from interfaces
E_m^H	mixture energy gain due to changes in mean curvature
e^A	surface porosity
$\widehat{e}_k, \widehat{e}_{ki}$	weighted mean virtual internal energy (with turbulent kinetic energy included) at the bulk phase and at the interfaces
e^V	volume porosity
$F(\mathbf{x}, t)$	general function
\mathbf{F}^B	Basset force
\mathbf{F}^D	standard drag force
\mathbf{F}^L	lift force
\mathbf{F}^T	turbulent dispersion force
\mathbf{F}^V	virtual mass force
\mathbf{F}^W	wall lift force
F_D	drag force
F_k, \mathcal{F}_k	general function associated with phase k
F_{du}	unsteady drag force
F_g	gravity force
F_p	pressure force
F_{qs}	quasi-steady force
F_s	surface tension force
F_{sl}	shear lift force
$f(\mathbf{x}, t)$	function for interface position
$f(\mathbf{x}, t, \xi)$	molecular density function
$f(\rho^*)$	factor
f	collision frequency
f	friction factor

f	bubble departure frequency
f^*	correction factor for drag coefficient
f_i	interfacial friction factor
f_k	Helmholtz potential
$f_{kn}(\mathbf{x}, t, \xi)$	particle density function of the n^{th} -kind particles
f_{TW}	two-phase friction factor
G	mass velocity
G	cap bubble thickness
G_s	non-dimensional velocity gradient
\mathbf{g}	gravity field
\mathbf{g}_k	body force field
$g_k, \widehat{g}_k, \widehat{g}_{ki}$	Gibbs free energy: local instant, bulk mean and interfacial mean values
g_{ln}	space metric tensor (Aris, 1962)
g_N	normal gravitational acceleration
$H_{21}, \overline{H}_{21}$	local instant and averaged mean curvature ($\overline{H}_{21} > 0$ if phase 2 is the dispersed phase)
h	bubble height
h_1, h_2	average thickness of upper (1) and lower (2) fluid layers
h_c	condensation heat transfer coefficient
$\widehat{h}_k, \widehat{h}_{ki}$	weighted mean virtual enthalpy (with turbulent kinetic energy included) at the bulk phase and at the interfaces mixture virtual enthalpy
h_m	mixture virtual enthalpy
I	unit tensor
I_k	interfacial source term in the balance equations for phase k
I_m	interfacial source term for mixture balance equations
I_{ka}, I_{ma}	interfacial source terms in the shock conditions for phase k and for mixture latent heat
i_{fg}	latent heat
i_k, \widehat{i}_k	local instant and mean enthalpies
\widehat{i}_{ki}	mean enthalpy of phase k at interfaces
i_m	mixture enthalpy

i_a	local instant surface enthalpy per area
J	flux
J^D	drift flux
J_a	line flux for interface
J_k	surface flux for phase k
J_k^T, J^T	turbulent fluxes
J_k, J_m	Jacobians based on macroscopic field
j_k, j	volumetric fluxes of phase k and mixture
j^*	non-dimensional mixture volumetric flux
j^+	non-dimensional mixture volumetric flux
K	constant
K_k	thermal conductivity
K_k^T	thermal conductivity tensor
K_k^{T*}	turbulent conductivity
k	thermal mixing length coefficient
k^{SI}	wave number
k_e	turbulent kinetic energy due to shear-induce turbulence
k_f	wave number of eddy
L	thermal conductivity
L_b	pitch of slug unit
$1/L_j$	cylindrical bubble length
$1/L_s$	area concentration of j^{th} -interface
L_T	total area concentration
L_W	mean traveling distance between two bubbles for one collision
l	effective wake length
l_B	mixing length
l_{SP}	mixing length due to bubble-induced turbulence
l_{TP}	mixing length of single-phase flow
m_e	mixing length of two-phase flow
$\dot{m}_k, \overline{\dot{m}}_k$	mass per a single eddy
	local instant and mean mass transfer rates per unit area (mass loss)

M_F	frictional pressure gradient in multi-particle system
$M_{F\infty}$	frictional pressure gradient in single particle system
\mathbf{M}_{ik}	generalized interfacial drag
M_k, M_s	state density functions for phase k and interface
$\mathbf{M}_k, \mathbf{M}_m$	momentum sources for phase k and mixture
\mathbf{M}_m^H	force due to changes in mean curvature
$\mathbf{M}_k^n, \mathbf{M}_k^t, \mathbf{M}_k^d$	form, skin and total drag forces
$\mathbf{M}_{\tau m}$	force associated with mixture transverse stress gradient
\dot{m}_c	mass transfer rate due to condensation
\mathbf{N}	unit normal vector to a curve on an interface
N	number of samples
N_b	number of bubbles
N_D	drift number
N_{drag}	drag number
N_e	number of eddies of wave number k_e per volume of fluid
N_{Ec}	Eckert number
N_{Eo}	Eötvös number
N_{Eu}	Euler number
N_{Fr}	Froude number
N_{fd}	non-dimensional bubble departure frequency
N_i	converted enthalpy ratio
N_{jk}	Jakob number
N_{jke}	effective Jakob number
N_M	Morton number
N_n	active nucleation site density
\overline{N}_n	average cavity density
N_{nc}	active nucleation site density in forced convective flow
N_{np}	active nucleation site density in pool boiling
N_{Nuc}	condensation Nusselt number
N_{pch}	phase change number
N_{pch}^i	interfacial phase change effect number
N_{Pe}	Peclet number

N_{Pr}	Prandtl number
N_{Prk}^T	turbulent Prandtl number
N_q	interface heating number
N_{qNB}	non-dimensional heat flux representing nucleate boiling heat transfer
N_{Re}	Reynolds number
N_{Re}^i	interfacial Reynolds number
N_{Sct}	turbulent Schmidt number
N_{Sl}	Strouhal number
N_{St}	Stokes number
N_W	number of bubbles inside effective volume
N_{We}	Weber number
N_μ	viscosity number
N_ρ	density ratio
N_σ	surface tension number
n	fluid particle number per unit mixture volume
\mathbf{n}	unit normal vector
n_b	bubble number density
n_e	number of eddies of wave number per volume of two-phase mixture
\mathbf{n}^F	unit vector perpendicular to surface
\mathbf{n}^I	unit vector perpendicular to structural material surface
\mathbf{n}_k	within boundary of control volume
P^{SI}	outward unit normal vector for phase k
P_C	production of shear-induced turbulence
	probability for a bubble to move toward neighboring bubble
\overline{P}_k	partial pressure tensor
P_i	interfacial wetted perimeter
P_{wf}	wall wetted perimeter
P_0	pitch distance
p	pressure
p_c	critical pressure
p_c	probability

p_k , $\overline{\overline{p}}_k$, $\overline{\overline{p}}_{ki}$	partial, bulk mean and interfacial mean pressure
p_m	mixture pressure
\mathbf{q}	heat flux
\mathbf{q}^D	diffusion (drift) heat flux
$\overline{\overline{\mathbf{q}}}_k$, \mathbf{q}_k^T	mean conduction and turbulent heat fluxes
$\overline{\overline{\mathbf{q}}}, \mathbf{q}_k^T$	mixture conduction and turbulent heat fluxes
\dot{q}_k	local instant body heating
$\overline{\overline{q}}''_k$	average heat transfer pert interfacial area (energy gain)
\mathbf{q}_k^C	mean conduction heat flux
q''_{qNB}	nucleate boiling heat flux
R	ideal gas constant
R	radius of a pipe
R	radius of curvature
R	radius of outer round tube
R^+	variable defined by Rv_f^*/ν_f
R_0	radius of heater rod
R_c	minimum cavity size
$\overline{\overline{R}}_d$	mean radius of fluid particles
R_j	particle number source and sink rate
\mathcal{R}_k	quantity of scalar, vector or tensor
R_{\max}	maximum cavity size
R_w	tube radius
Re	Reynolds number
$(Re)_d$	particle Reynolds number
r	radial coordinate
r	radial coordinate measured from heater rod surface
r	cavity radius
r_b	bubble radius
r_d^*	non-dimensional radius
S	suppression factor
S_B , S_C	surface available to collision
S_j	particle source and sink rates per unit mixture volume due to j^{th} -particle interactions such as disintegration

	or coalescence
S_{ph}	particle source and sink rates per unit mixture volume
	due to phase change
s	entropy
s_a	surface entropy per area
$\widehat{s}_k, \widehat{s}_{ki}$	weighted mean entropy at bulk phase and at interfaces
s_m	mixture entropy
T	temperature
$T_i, \overline{\overline{T}}_i$	instant and mean interface temperature
$\overline{\overline{T}}_k, \overline{\overline{T}}_{ki}$	mean temperature at bulk phase and at interface
\overline{T}_k	stress tensor
t	time
t^*	non-dimensional time
t_C	time required for bubble coalescence
t_c	bubble residence time in heat transfer-controlled region
t_j	time when the j^{th} -interface passes the point
t_α^m (or t_α)	hybrid tensor of interface, see Aris (1962)
\mathbf{U}	velocity of shock in mixture
U_0	velocity of stream
U_B, U_C	volume available to collision
u	internal energy
u_a	surface energy per area
u_b	mean fluctuation velocity
u_B, u_C	bubble velocity
u_e	eddy velocity
$\widehat{u}_k, \widehat{u}_{ki}$	weighted mean internal energy at bulk phase and at interfaces
u_m	mixture internal energy
u_{rW}	averaged relative velocity between leading bubble and bubble in wake region
u_t	root-mean-square approaching velocity of two bubbles
$u_{t,crit}$	critical fluctuation velocity
V	volume
\dot{V}	time derivative of volume V

V_b	volume of bubble
V_c	critical bubble volume
V^F	free volume
V_{gj}^+	non-dimensional drift velocity
V_i	interfacial region
\mathbf{V}_{kj}	drift velocity
\mathbf{V}_{km}	diffusion velocity
V_m	fixed mass volume
V_s^*	ratio of $V_{s,min}$ to $V_{s,max}$
V^S	structural material volume
V^T	total volume of control volume
V_W	effective wake volume
V_{1p}	peak bubble volume in group 1
\mathbf{v}	velocity
v'_f	liquid velocity fluctuation independent of bubble agitation
v''_f	liquid velocity fluctuation dependent on bubble agitation
v_f^*	friction velocity
\mathbf{v}_g	average center-of-volume velocity of dispersed phase
\mathbf{v}_i	velocity of interface
$\widehat{\mathbf{v}}_k, \widehat{\mathbf{v}}_{ki}$	weighted mean velocity at bulk phase and at interfaces
$\widehat{(v'_k)^2}/2$	mean turbulent kinetic energy
\mathbf{v}_m	mixture center of mass velocity
\mathbf{v}_{pm}	average local particle velocity weighted by particle number
\mathbf{v}_r	relative velocity
$\overline{v_r}$	difference between area averaged mean velocities of phases
$v_{r\infty}$	relative velocity of a single particle in an infinite medium
\mathbf{v}_s	velocity of interfacial particles
W_{ki}^T	work due to fluctuations in drag forces

We	Weber number
We_{crit}	critical Weber number
X	convective coordinates
x	spatial coordinates
x	spatial coordinate
x	radial coordinate measured from center of heater rod
x_{WP}	surface
y	bubble-layer thickness
y^+	spatial coordinate
z	variable defined by yv_f^*/ν_f
	spatial coordinate

Greek

α_b	void fraction in slug bubble section
α_{core}	ratio of liquid-film cross-sectional area to total cross-sectional area
α_d	average overall void fraction
α_{drop}	ratio of cross-sectional area of drops to cross-sectional area of core
α_f	thermal diffusivity
$\alpha_{g,crit}$	critical void fraction when center bubble cannot pass through free space among neighboring bubbles
$\alpha_{g,max}$	maximum void fraction
α_k	time (void) fraction of phase k
α_{WP}	void fraction at assumed square void peak
β	ratio of mixing length and width of wake
β	half of cone angle
β_C	variable to take account of overlap of excluded volume
β_k	thermal expansivity based on averaged properties
Γ	constant
Γ_k	mass generation for phase k
γ	constant
γ_k	ratio of specific heats
Δ_a	interfacial entropy generation per area

Δ_k	entropy generation for phase k
$\Delta\dot{m}_{12}$	inter-group mass transfer rates from group 1 to group 2
ΔT_e	effective liquid superheat
ΔT_{sat}	gas superheat
ΔT_{sub}	liquid subcooling
ΔT_w	wall superheat
Δt	time interval of averaging
Δt_B	time interval to drive daughter bubble apart with characteristic length of D_b
Δt_C	time interval for one collision
Δt_c	residence time
$\Delta t_k, \Delta t_s$	time intervals associated with phase k and interfaces
Δt_W	average time interval for a bubble in wake region to catch up with preceding bubble
δ	thickness of interface
δ	film thickness
δ'	collective parameter
δ_{crit}	critical film thickness where rapture occurs
δ_{init}	initial film thickness
δp_k	pressure deviation from saturation pressure
$\delta\mu$	volume element in μ space
ε	energy dissipation rate per unit mass
2ε (or $2\varepsilon_j$)	time associated with the j^{th} -interface
ε^{SI}	dissipation of shear-induced turbulence
$\varepsilon', \varepsilon''$	eddy diffusivity
η_{ph}	rate of volume generated by nucleation source per unit mixture volume
η_0	amplitude
Θ	contact angle
θ	contact angle
θ	angle in cylindrical coordinates
θ_i	inclination angle
θ_R	contact angle at room temperature
θ_w	wake angle

κ_{fr}	variable defined by $1 - \exp\left(-C_{fr} V_s^{*1/2} / D^{1/2}\right)$
κ_{Sk}, κ_{Tk}	isentropic and isothermal compressibilities of phase k
Λ_k	interfacial thermal energy transfer term in the averaged equation
λ	wavelength
λ	constant
λ	characteristic length scale
λ_B	breakup efficiency
λ_C	coalescence efficiency
λ_c	critical wavelength
λ_k	bulk viscosity
μ	viscosity
μ	characteristic cone angle scale
$\overline{\overline{\mu}}_k, \mu_k^T$	mean molecular and turbulent viscosities
μ_k^{T*}	mixing length coefficient
μ_m	mixture viscosity
ν	kinematic viscosity
ν_t	turbulent kinematic viscosity
ξ	particle (phase) velocity in Boltzmann statistical average
ξ	ratio of V_{1p} to V_c
ξ	variable defined by $2\left(1 - 0.2894D_{cl}^{*3}\right)^2$
ξ	variable defined by P_i/P_{wf}
ξ_H	heated perimeter
ξ_∞	modification factor
ρ	density
ρ^*	non-dimensional density difference
ρ^+	non-dimensional density ratio
ρ_a	surface mass per area
$\overline{\rho}_k, \overline{\overline{\rho}}_k$	partial and mean densities
ρ'_k	modified density defined by $\rho_k \coth(kh_k)$
ρ_m	mixture density
σ	surface tension

\mathcal{T}	viscous stress tensor
\mathcal{T}^D	diffusion (or drift) stress tensor
\mathcal{T}_f^{BI}	bubble-induced turbulent stress tensor
\mathcal{T}_f^{SI}	shear-induced turbulent stress tensor
$\overline{\mathcal{T}}, \mathcal{T}^T$	mixture viscous and turbulent stress tensors
$\overline{\overline{\mathcal{T}}}_k, \mathcal{T}_k^T$	average viscous and turbulent stress tensor
\mathcal{T}_k^μ	average viscous stress
$\overline{\overline{\mathcal{T}}}_{ki}, \mathcal{T}_{ki}$	interfacial shear stress
τ	time scale of Basset force
τ_b	relaxation time of bubbles
τ_c	contact time for two bubbles
τ_e	relaxation time of eddies
τ_{ec}	crossover time of eddies
τ_{et}	turnover time of eddies
τ_i	interfacial shear stress
τ_o	reference time constant
τ_{tk}, τ_{nk}	tangential and normal stresses at interface
τ_{wf}	wall shear
Φ	velocity potential
Φ_k^T	turbulent work effect in enthalpy energy equation
Φ_m^i	interfacial mechanical energy exchange effect in the mixture thermal energy equation
Φ_k^μ	viscous dissipation
Φ_m^μ	mixture viscous dissipation
Φ_m^σ	surface tension effect in the mixture thermal energy equation
ϕ	source term
ϕ_a	interfacial source per area
ϕ_j	source and sink rate for interfacial area concentration
ϕ_k	velocity potential
χ	coefficient accounting for contribution from inter-group transfer
ψ	property of extensive characteristics
ψ	shape factor

$\widehat{\psi}, \widehat{\psi}_k$	mass weighted mean values for mixture and phase k
ψ_a	property per interfacial area
Ω	potential function

Subscripts and Superscripts

a	surface (property per area)
BC	bulk condensation
c	continuous phase
d	dispersed phase
f	liquid phase
g	vapor phase
HC	heat transfer controlled
i	interface
IC	inertial controlled
j	j^{th} -interface
k	each phase : ($k=1 \& 2$), ($k=c \& d$), ($k=f \& g$)
ki	k^{th} -phase at interfaces
m	$\begin{cases} \text{mixture (in macroscopic formulation)} \\ \text{fixed mass (in local instant formulation)} \end{cases}$
n	normal to interface
o	reference
RC	random collision
r, θ, z	cylindrical coordinate
sat	saturation
s	$\begin{cases} \text{surface (surface property per mass)} \\ \text{solid phase} \end{cases}$
SI	surface instability
SO	shearing off
TI	turbulent impact
WE	wake entrainment
t	tangential to interface
W	wall nucleation
w	wall
x, y, z	rectangular coordinate
$+, -$	+ and - side of shock in macroscopic field

1, 2	phase 1 and phase 2
*	dimensionless
∞	single particle

Symbols and Operators

A	tensor
\mathbf{A}	vector
A	scalar
$\mathbf{A} \cdot \mathbf{B}$	dot product
\mathbf{AB}	dyadic product of two vectors (=tensor)
$A:\mathcal{B}$	double dot product of two tensors (=scalar)
$\nabla \cdot$	divergence operator
∇	gradient operator
$\nabla_s \cdot$	surface divergence operator (Aris, 1962)
$(\mathbb{A})^+$	transposed tensor
$\frac{D_k}{Dt}$	$= \frac{\partial}{\partial t} + \widehat{\mathbf{v}}_k \cdot \nabla$
$\frac{D}{Dt}$	$= \frac{\partial}{\partial t} + \mathbf{v}_m \cdot \nabla$
$\frac{D_c}{Dt}$	$= \frac{\partial}{\partial t} + \mathbf{C}_k \cdot \nabla$
$\frac{D_i}{Dt}$	$= \frac{\partial}{\partial t} + \widehat{\mathbf{v}}_i \cdot \nabla$
$\frac{d_s}{dt}$	surface convective derivative with $\widehat{\mathbf{v}}_s$ (Aris, 1962)
\overline{F}	time average
\overline{F}^w	weighted mean value
\overline{F}^{w_k}	k^{th} -phase weighted mean value
$\overline{\overline{F}}$	phase average
$\widehat{\psi}_k$	k^{th} -phase mass weighted mean value
$\widehat{\psi}$	mixture mass weighted mean value
F'_k	fluctuating component with respect to mean value
F'_{ki}	fluctuation component with respect to surface mean value

$\overline{\overline{F}}_{(i)}, \overline{\overline{F}}_{ki}$	surface average
\widehat{F}_{ki}	mass flux weighted mean value at interfaces
$(\cdot)_{,\beta}$	surface covariant derivative (Aris, 1962)
$[\Delta t]_k$	with ($k=T,S,1,2$) ; sets of time intervals
\sum_k	summation on both phases
\sum_j	summation on the interfaces passing in Δt at x
$[\cdot]^A$	average over local surface area
$\llbracket \cdot \rrbracket^A$	intrinsic surface average
$[\cdot]^V$	phase average
$\llbracket \cdot \rrbracket^V$	intrinsic phase average

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