Second Edition

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Heat Transfer and Fluid Flow in Minichannels and Microchannels

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Preface

We are pleased to bring this second edition with an updated coverage of the recent developments in this field. After the initial questions regarding the applicability of macroscopic formulation were addressed, the research has focused on topics that utilize the microscale behavior for understanding the transport processes. New advances are reported on the fundamental understanding and experimental analysis of the gas flow and heat transfer at microscale, transport modeling and roughness effects. Sections on enhancement of single-phase liquid heat transfer, axial conduction effects, entrance region effects, nanofluids, and roughness effects have been updated to include some of the recent work. The chapter on electrokinetic flows has been updated to include a new section on electroosmotic flows considering the Joule heating effects. Significant new developments made in flow boiling in microchannels, including scale effects, nanofluids, enhancements, stability considerations, CHF modeling, flow boiling enhancement techniques, and a new configuration providing a new level of enhancement exceeding 500 W/cm2 limit have been included. The chapter on condensation has been streamlined to focus more closely on mini and microchannel geometries, and expanded to include some of the latest developments in experimentation and modeling efforts. The biomedical applications in Chapter 7 have been expanded significantly to present the advancements in fluid mechanics modeling in this field.

The authors are thankful to many researchers who have provided feedback on the second edition. We believe that the readers will find this edition as a timely and updated resource that is useful to researchers as well as designers of microfluidic transport devices.

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Nomenclature

A	Section area, m^2 (Chapters 2 and 6).
A, B, C, D, F	Equation coefficients and exponents (Chapters 3 and 7).
A_1	First-order slip coefficient, dimensionless (Chapter 2).
A_2	Second-order slip coefficient, dimensionless (Chapter 2).
A_3	High-order slip coefficient, dimensionless (Chapter 2).
A_c	Cross-sectional area, m^2 (Chapter 3).
A_p	Total plenum cross-sectional area, m^2 (Chapter 3).
A_T	Total heat transfer surface area (Chapter 5).
a	Speed of sound, m/s (Chapter 2); channel width, m (Chapter 3); equation constant in Eqs. (6.71), (6.83), and (6.87) (Chapter 6); coefficient in entrance length equations, dimensionless (Chapter 7).
a^*	Aspect ratio of rectangular sections, dimensionless, $a^* = h/b$ (Chapter 2).
a_1, a_2, a_3	Coefficients for the mass flow rate in a rectangular microchannel, dimensionless (Chapter 2).
$a_1 \ldots a_5$	Coefficients in Eq. (6.107) (Chapter 6).
B	Parameter used in Eqs. (6.9) and (6.41) (Chapter 6).
B_B	Parameter used in Eq. (6.21) (Chapter 6).
B_n	Coefficient in cell surface oxygen concentration equation (Chapter 7).
b	Half-channel width, m (Chapter 2); channel height, m (Chapter 3); constant in Eqs. (6.71), (6.83), and (6.87) (Chapter 6).
Bo	Boiling number, dimensionless, $\mathrm{Bo} = q''/(Gh_{LV})$ (Chapter 5).
Bo	Bond number, dimensionless, $Bo = (\rho_L - \rho_V)gD_h^2/\sigma$ (Chapter 5); $Bo = g(\rho_L - \rho_G)((d/2)^2/\sigma)$ (Chapter 6).
C, C	Constant, dimensionless (Chapter 1); coefficient in a Nusselt number correlation (Chapter 3); concentration, mol/m^3 (Chapters 4 and 7); Chisholm's parameter, dimensionless (Chapter 5); constant used in Eqs. (6.39), (6.40), and (6.157) (Chapter 6).
C	Reference concentration, mol/m^3 (Chapter 4).
C^*	Ratio of experimental and theoretical apparent friction factors, dimensionless, $C^* = f_{app,ex}/f_{app,th}$, (Chapter 3); nondimensionalized concentration, $C^* = C(x, y)/C_{in}$ (Chapter 7).
C_0	Oxygen concentration at the lower channel wall, mol/m^3 (Chapter 7).
C_1, C_2	Empirically derived constants in Eq. (6.35) (Chapter 6); parameter, used in Eq. (6.54) (Chapter 6).
C_C	Coefficient of contraction, dimensionless (Chapter 6).
C_{in}	Nondimensionalized gas phase oxygen concentration, $C_{in} = \tilde{C}_g/C_g$ (Chapter 7).

C_f	Friction factor, dimensionless (Chapter 2).
Co	Convection number, dimensionless, $C_o = [(1-x)/x]^{0.9}\ [\rho_V/\rho_L]^{0.5}$ (Chapter 5).
Co	Confinement number, dimensionless, $C_o = \sqrt{\sigma/g(\rho_l - \rho_v)}/D_h$ (Chapter 6).
C_o	Contraction coefficient, dimensionless (Chapter 5); distribution parameter in drift flux model, dimensionless, $C_o = <\alpha j>/(<\alpha><j>)$ (Chapter 6).
C_p	Specific heat capacity at a constant pressure, J/kg K (Chapter 6).
C_S	Saturation oxygen concentration, mol/m^3 (Chapter 7).
c	Mean square molecular speed, m/s (Chapter 2); constant in the thermal entry length equation, dimensionless (Chapter 3); constant in Eq. (6.57) (Chapter 6).
$\mathbf{c'}$	Molecular thermal velocity vector m/s (Chapter 2).
$\overline{c'}$	Mean thermal velocity, m/s (Chapter 2).
c_1, c_2	Coefficients used in Eq. (6.133) (Chapter 6).
c_p	Specific heat at a constant pressure, J/kg K (Chapters 2, 3, and 5).
c_v	Specific heat at a constant volume, J/kg K (Chapter 2).
Ca	Capillary number, dimensionless, $Ca = \mu V/\sigma$ (Chapter 5).
CHF	Critical heat flux, W/m^2 (Chapter 5).
D	Diameter, m (Chapters 1, 3, 5 and 6).
D, D^+, D^-	Diffusion coefficient, diffusivity, m^2/s (Chapters 2 and 4).
D_{cf}	Diameter constricted by channel roughness, m, $D_{cf} = D - 2\varepsilon$ (Chapter 3).
D_h, D_H	Hydraulic diameter, m (Chapters 1–5).
D_{le}	Laminar equivalent diameter, m (Chapter 3).
d	Mean molecular diameter, m (Chapter 2); diameter, m (Chapter 6).
d_B	Departure bubble diameter, m (Chapter 5).
E	Applied electrical field strength, V/m (Chapter 4); total energy per unit volume, J/m^3 (Chapter 2); diode efficiency, dimensionless (Chapter 2); parameter used in Eq. (6.141) (Chapter 6).
E_1, E_2	Parameter used in Eq. (6.22) (Chapter 6).
E_x	Electric field strength, V/m (Chapter 4).
e	Internal specific energy, J/kg (Chapter 2); charge of a proton, $e = 1.602 \times 10^{-19}$ C (Chapter 4).
$Eo, E\ddot{o}$	Eotvos number, dimensionless, $Eo = g(\rho_L - \rho_V)L^2/\sigma$ in case of liquid gas contact (Chapters 5 and 6).
F, F	Nondimensional constant accounting for an electrokinetic body force (Chapter 4); general periodic function of unit magnitude (Chapter 4); force, N (Chapters 5 and 6); modified Froude number, dimensionless, $F = \sqrt{\left(\frac{\rho_g}{\rho_l - \rho_g}\right)}\left(\frac{U_{GS}}{\sqrt{D_g}}\right)$ (Chapter 6); stress ratio, dimensionless, $F = \tau_w/(\rho_L g\delta)$ (Chapter 6); parameter used in

	Eq. (6.141) (Chapter 6); external force acting on a spherical cell, N (Chapter 7).
F	External force per unit mass vector, N/kg (Chapter 2).
F'_M	Interfacial force created by evaporation momentum, N (Chapter 5).
F'_S	Interfacial force created by surface tension, N (Chapter 5).
F_{F1}	Fluid-surface parameter accounting for the nucleation characteristics of different fluid surface combinations, dimensionless (Chapter 5).
F_g	Function of the liquid volume fraction and the vapor Reynolds number, used in Eq. (6.128) (Chapter 6).
F_T	Dimensionless parameter of Eq. (6.112) (Chapter 6).
F_x	Electrical force per unit volume of the liquid, N/m^3 (Chapter 4).
f	Volume force vector, N/m^3 (Chapter 2).
f	Fanning friction factor, dimensionless (Chapters 1, 3, and 5); single-phase friction factor, dimensionless (Chapter 6).
f_{app}	Apparent friction factor accounting for developing flows, dimensionless (Chapter 3).
f	Frequency, Hz (Chapter 2); velocity distribution function (Chapter 2).
f_{ls}	Superficial liquid phase friction factor, dimensionless (Chapter 6).
F_p	Floor distance to mean line in roughness elements, m (Chapter 3).
Fr_l	Liquid Froude number, dimensionless, $Fr_l^2 = \overline{V}_l^2/g\delta$ (Chapter 6).
Fr_m	Modified Froude number, dimensionless (Chapter 6).
Fr_{so}	Soliman modified Froude number, dimensionless (Chapter 6).
F_t	Froude rate, dimensionless $F_t = [G^2x^3/(1-x)\rho_g^2 gD]^{0.5}$ (Chapter 6).
G	Mass flux, kg/m^2 s (Chapters 1, 5, and 6).
G_{eq}	Equivalent mass flux, kg/m^{2}s, $G_{eq} = G_l + G'_l$ (Chapter 6).
G'_l	Mass flux that produces the same interfacial shear stress as a vapor core, kg/m^2 s, $G'_l = G_v\sqrt{\rho_l/\rho_v}\sqrt{f_v/f_l}$ (Chapter 6).
G_t	Total mass flux, kg/m^2 s (Chapter 6).
g	Acceleration due to gravity, m/s^2 (Chapters 5 and 6).
Ga_l	Liquid Galileo number, dimensionless, $Ga_l = gD^3/\nu_l{}^2$ (Chapter 6).
H	Maximum height, m (Chapter 4); distance between parallel plates or height, m (Chapter 7); parameter used in Eq. (6.141) (Chapter 6).
h	Heat transfer coefficient, W/m^2 K (Chapters 1, 3, 5, and 6); channel half-depth, m (Chapter 2); specific enthalpy, J/kg (Chapters 2 and 5); wave height, m (Chapter 7).
$\overline{h}$	Average heat transfer coefficient, W/m^2 K (Chapters 3 and 6).
h_c	Film heat transfer coefficient, W/m^2 K (Chapter 6).
h_{fg}	Latent heat of vaporization, J/kg (Chapter 6).
h_G	Gas-phase height in channel, m, $h_G \leq \pi/4\sqrt{\sigma/\rho g(1-\pi/4)}$ (Chapter 6).

h_{LV}	Latent heat of vaporization at p_L, J/kg (Chapter 5).
h_{lV}	Specific enthalpy of vaporization, J/kg (Chapter 6).
h'_{lV}	Modified specific enthalpy of vaporization, J/kg (Chapter 6).
I	Unit tensor, dimensionless (Chapter 2).
I	Current, A (Chapter 3).
i	Enthalpy, J/kg (Chapter 5).
J	Mass flux vector, kg/m^2 s (Chapter 2).
J	Electrical current, A (Chapter 4).
j	Superficial velocity, m/s (Chapters 5 and 6).
j_g^*, j_G^*	Wallis dimensionless gas velocity, $j_g^* = G_t x/\sqrt{Dg\rho_v(\rho_l - \rho_v)}$ (Chapter 6).
Ja	Jakob number, dimensionless, $Ja = (\rho_L/\rho_v)\ (c_{p,L}\Delta T/h_{LV})$ (Chapter 5).
Ja_l	Liquid Jakob number, dimensionless, $Ja_l = c_{pL}(T_{sat} - T_s)/h_{lv}$ (Chapter 6).
K	Nondimensional double layer thickness, $K = D_h\kappa$ (Chapter 4); constant in Eqs. (6.56) and (6.95) (Chapter 6).
$K(x)$	Incremental pressure defect, dimensionless (Chapter 3).
$K(\infty)$	Hagenbach's factor, dimensionless, $K(x)$ when $x > L_h$ (Chapter 3).
K_1	Ratio of evaporation momentum to inertia forces at the liquid–vapor interface, dimensionless, $K_1 = (q''/Gh_{LV})^2\rho_L/\rho_V$ (Chapter 5).
K_2	Ratio of evaporation momentum to surface tension forces at the liquid–vapor interface, dimensionless, $K_2 = (q''/h_{LV})^2\ D/\rho_V\sigma$ (Chapter 5).
K_{90}	Loss coefficient at a 90° bend, dimensionless (Chapter 3).
K_c	Contraction loss coefficient due to an area change, dimensionless (Chapter 3).
K_e	Expansion loss coefficient due to an area change, dimensionless (Chapter 3).
K_m	Michaelis constant, mol/m^3 (Chapter 7).
k	Thermal conductivity, W/mK (Chapters 1–3, 5, and 6); constant, dimensionless (Chapter 7).
k_1	Coefficient in the collision rate expression, dimensionless (Chapter 2).
k_2	Coefficient in the mean free path expression, dimensionless (Chapter 2).
k_B, κ_b	Boltzmann constant, k_B = 1.38065 J/K (Chapters 2 and 4).
Kn	Knudsen number, $Kn = \lambda/L$, dimensionless (Chapters 1 and 2).
Kn'	Minimal representative length Knudsen number, $Kn' = \lambda/L_{min}$ (Chapter 2).
Ku	Kutateladze number, dimensionless $Ku = C_p\ \Delta\ T/h_{fg}$ (Chapter 6).
L	Length or characteristic length in a given system, m (Chapters 1–3 and 5–7); Laplace constant, m, $L = \sqrt{\sigma/g(\rho_l - \rho_v)}$ (Chapter 6).

L_G, L_L	Gas and liquid slug lengths in the slug flow regime, m (Chapter 6).
L_{ent}, L_h, L_{hd}	Hydrodynamically developing entrance length, m, $L_{ent} = aHRe$ (Chapters 2, 3, and 7).
L_t	Thermally developing entrance length, m, $L_t = cRePrD_h$ (Chapter 3).
L_{eq}	Total pipette length, m (Chapter 7).
l	Microchannel length, m (Chapter 2).
l_{SV}	Characteristic length of a sampling volume, m (Chapter 2).
$l_{x,\ y,\ z}$	Channel half height, m (Chapter 4).
LHS	Left-hand side (Chapter 7).
M	Molecular weight, kg/mol (Chapter 2).
M	Ratio of the electrical force to frictional force per unit volume, dimensionless, $M = 2n_\infty ze\xi D_h^2/\mu UL$ (Chapter 4).
M, N	Equation exponents, dimensionless (Chapter 3).
MW	Molecular weight, g/mol (Chapter 7).
m	Molecular mass, kg (Chapter 2); liquid volume fraction, dimensionless (Chapter 6); dimensionless constant in Eq. (6.57) (Chapter 6).
$\dot{m}$	Mass flow rate, kg/s (Chapters 2, 3, and 5).
$\dot{m}^*$	Mass flow rate, $\dot{m}/\dot{m}_{ns}$, dimensionless (Chapter 2).
$\dot{m}_{ns}$	Mass flow rate for a no-slip flow, kg/s (Chapter 2).
Ma	Mach number, dimensionless, Ma = u/a (Chapter 2).
N	Avogadro's number, $6.022137 \cdot 10^{23}$ mol^{-1} (Chapter 2).
$\dot{N}$	Molecular flux, s^{-1} (Chapter 2).
N^+	Nondimensional positive species concentration (Chapter 4).
N^-	Nondimensional negative species concentration (Chapter 4).
N_{conf}	Confinement number, dimensionless, $N_{conf} = \sqrt{\sigma/(g(\rho_l - \rho_v))}/D_h$ (Chapter 6).
N_0	Cellular uptake rate, mol/m^2 s (Chapter 7).
n	Number density, m^{-3} (Chapter 2); number or number of channels, dimensionless (Chapter 3); number of channels (Chapter 5); constant in Eqs. (6.41) and (6.57) (Chapter 6); number (Chapter 7).
n_1, n_2, n_3	Constant in Eq. (6.21) (Chapter 6).
n_i	Number concentration of type-i ion (Chapter 4).
n_{io}	Bulk ionic concentration of type-i ions (Chapter 4).
$\mathbf{n}_x$	Normal vector in the x direction (Chapter 4).
Nu	Nusselt number, dimensionless, $Nu = hD_h/k$ (Chapters 1–3, 5, and 6).
Nu_H	Nusselt number under a constant heat flux boundary condition, dimensionless (Chapter 3).
Nu_i	Nusselt number for high interfacial shear condensation, dimensionless (Chapter 6).
$\overline{Nu}_L$	Average Nusselt number along a plate of length L, dimensionless (Chapter 6).

Nu_o	Nusselt number for quiescent vapor condensation, dimensionless, $Nu_o = [(Nu_L^{n_1}) + (Nu_T^{n_1})]^{1/n_1}$ (Chapter 6).
Nu_T	Nusselt number for a turbulent film, dimensionless (Chapter 6).
Nu_T	Nusselt number under a constant wall temperature boundary condition, dimensionless (Chapter 3).
Nu_x	Combined Nusselt number, dimensionless, $Nu_x = [(Nu_o^{n_2}) + (Nu_i^{n_2})]^{1/n_2}$ (Chapter 6).
ONB	Onset of nucleate boiling (Chapter 5).
P	Wetted perimeter, m (Chapter 2); dimensionless pressure (Chapter 4); heated perimeter, m (Chapter 5); pressure, Pa (Chapter 6).
P_w	Wetted perimeter, m (Chapter 3).
p	Pressure, Pa (Chapters 1–3 and 5–7).
p_R	Reduced pressure, dimensionless (Chapter 6).
Pe	Péclet number, dimensionless, Pe = UH/D (Chapter 7).
Pe_F	Péclet number of fluid, dimensionless (Chapter 4).
Po	Poiseuille number, dimensionless, $Po = f\,Re$ (Chapters 2 and 3).
Pr, Pr	Prandtl number, dimensionless, $Pr = \mu c_p/k$ (Chapters 2, 3, 5, and 6).
Q	Heat load, W (Chapter 3).
Q	Volumetric flow rate, m^3/s (Chapters 2, 3 and 7).
q	Heat flux vector, W/m^2 (Chapter 2).
q	Heat flux, W/m^2 (Chapter 2); dissipated power, W (Chapter 3); constant in Eq. (6.60) (Chapter 6).
q	Volumetric flow rate per unit width, m^2/s (Chapter 7).
q	Oxygen uptake rate on a per-cell basis, mol/s (Chapter 7).
q''	Heat flux, W/m^2 (Chapters 5 and 6).
q''_{CHF}	Critical heat flux, W/m^2 (Chapter 5).
R	Gas constant (Chapter 1); upstream to downstream flow resistance, dimensionless (Chapter 5).
R	Specific gas constant, J/kg K, $R = c_p - c_v$ (Chapter 2); radius, m (Chapter 6).
R	Universal gas constant, 8.314511 J/mol K (Chapter 2).
R^+	Dimensionless pipe radius (Chapter 6).
R_1, R_2	Radii of curvature of fluid–liquid interface, m.
R_p	Mean profile peak height (Chapter 3); pipette radius, m (Chapter 7).
$R_{p,i}$	Maximum profile peak height of individual roughness elements, m (Chapter 3).
R_{pm}	Average maximum profile peak height of roughness elements, m (Chapter 3).
r	Distance between two molecular centers, m (Chapter 2); radial coordinate, radius, radius of cavity, m (Chapters 2 and 4–7); constant in Eq. (6.60) (Chapter 6).
r_b	Bubble radius, m (Chapter 5).

r_c	Cavity radius, m (Chapter 5).
r_1	Inner radius of an annular microtube, m (Chapter 2).
r_2	Outer radius of annular microtube or a circular microtube radius, m (Chapter 2).
R_a	Average surface roughness, m (Chapter 3).
Re, Re	Reynolds number, dimensionless, $Re = GD/\mu$ (Chapters 1–5 and 7).
Re^*	Laminar equivalent Reynolds number, dimensionless, $Re^* = \rho u_m D_{le}/\mu$ (Chapter 3).
Re^+	Friction Reynolds number, dimensionless (Chapter 6).
Re_{Dh}	Reynolds number based on hydraulic diameter, dimensionless (Chapter 6).
$Re_{g,\ si}$	Reynolds number based on superficial gas velocity at the inlet, dimensionless (Chapter 6).
$Re_{l,\ si}$	Reynolds number based on superficial liquid velocity at the inlet, dimensionless (Chapter 6).
Re_l	Liquid film Reynolds number, dimensionless, $Re_l = G(1 - x)D/\mu_l$ (Chapter 6).
Re_m	Mixture Reynolds number, dimensionless, $Re_m = GD/\mu_m$ (Chapter 6).
Re_t	Transitional Reynolds number, dimensionless (Chapter 3).
RS_m	Mean spacing of profile irregularities in roughness elements, m (Chapter 3).
S	Slip ratio, dimensionless, $S = U_G/U_L$ (Chapter 6).
s	Fin width or distance between channels, m (Chapter 3); constant in Eq. (6.60) (Chapter 6).
Sc	Schmidt number, dimensionless, $Sc = \mu/(\rho D)$ (Chapter 2).
Sh	Sherwood number, dimensionless, $Sh = \alpha H/D$ (Chapter 7).
Sm	Distance between two roughness element peaks, m (Chapter 3).
St	Stanton number, dimensionless, $St = h/c_pG$ (Chapter 3).
T	Temperature, K or °C (Chapters 1–6).
T_s	Liquid surface temperature, K or °C (Chapters 3 and 5); surface temperature of tube wall, K or °C (Chapter 6).
T_{sat}	Saturation temperature, K or °C (Chapters 5 and 6).
ΔT_{Sat}	Wall superheat, K, $\Delta T_{Sat} = T_W - T_{Sat}$ (Chapter 5).
ΔT_{Sub}	Liquid subcooling, K, $\Delta T_{Sub} = T_{Sat} - T_B$ (Chapter 5).
T_δ^+	Dimensionless temperature in condensate film (Chapter 6).
t	Time, s (Chapters 2 and 7).
U	Uncertainty (Chapter 3); reference velocity, m/s (Chapter 4); potential, such as gravity (Chapter 7); average velocity, m/s (Chapter 7).
U_{SL}, $V_{L,\ S}$	Superficial liquid velocity, m/s (Chapter 6).
U_{Gj}, V_{Gj}	Drift velocity in drift flux model, m/s, $\nu_G = j_G/\alpha = C_{oj} + V_{Gj}$ (Chapter 6).

U_{GS}, $V_{G,S}$	Superficial gas velocity, m/s (Chapter 6).
u	Velocity, m/s (Chapters 2–4, 6, and 7).
u	Velocity vector, m/s (Chapter 2).
$\overline{u}_{ave}$	Average electroosmotic velocity, m/s (Chapter 4).
$\overline{u_z}$	Mean axial velocity, m/s (Chapter 2).
$\overline{u_z^*}$	Mean axial velocity, $\overline{u_z^*} = \overline{u_z}/u_{z0}$, dimensionless (Chapter 2).
u^*	Friction velocity, m/s, $u^* = \sqrt{\tau_i/\rho_l}$ (Chapter 6).
u_m	Mean flow velocity, m/s (Chapters 3 and 5).
u_r	Relative velocity between a large gas bubble and liquid in the slug flow regime, m/s, $u_r = u_S - (j_G + j_L)$ (Chapter 6).
u_S	Velocity of large gas bubble in slug flow regime, m/s (Chapter 6).
u_{z0}	Maximum axial velocity with no-slip conditions, m/s (Chapter 2).
U_A	Overall heat transfer conductance, W/K (Chapter 6).
V	Voltage, V (Chapter 3); velocity, m/s (Chapters 5 and 6).
V	Nondimensional velocity, $V = \nu/\nu_0$ (Chapter 4).
$\overline{V}_l$	Average velocity of a liquid film, m/s (Chapter 6).
V_m	Zeroth-order uptake of oxygen by the hepatocytes (Chapter 7).
v	Velocity, m/s (Chapter 4).
ν	Specific volume, $\nu = 1/\rho$, m^3/kg (Chapters 2 and 5); velocity, m/s (Chapters 6 and 7).
ν_0	Reference velocity, m/s (Chapter 4).
ν_{LV}	Difference between the specific volumes of the vapor and liquid phases, m^3/kg, $\nu_{LG} = \nu_G - \nu_L$ (Chapter 5).
W	Maximum width, m (Chapters 3 and 4).
w	Velocity, m/s (Chapter 7).
We	Weber number, dimensionless, $We = LG^2/\rho\sigma$ (Chapter 5).
We	Weber number, dimensionless, $We = \rho V_S{}^2 D/\sigma$ (Chapter 6).
X	Cell density (Chapter 7).
X	Martinelli parameter, dimensionless, $X = \{(dp/d_Z)_L/(d_p/d_Z)_G\}^{1/2}$ (Chapters 5 and 6).
X, Y, Z	Coordinate axes (Chapter 4).
X_{tt}	Martinelli parameter for turbulent flow in the gas and liquid phases, dimensionless (Chapter 6).
x	Mass quality, dimensionless (Chapters 5 and 6).
x	Position vector, m (Chapter 2).
x, y, z	Coordinate axes (Chapters 2–7); length (Chapter 6).
x^*, y^*	Cross-sectional coordinates, dimensionless (Chapter 2).
x^*	Dimensionless version of x, $x^* = x/RePrD_h$ (Chapter 3).
x^+	Dimensionless version of x, $x^+ = x/D_h/Re$ (Chapter 3).
Y	Chisholm parameter, dimensionless, $y = [dP_F/dz]_{GO}/(dP_F/dz)_{LO}]$ (Chapter 6).
y	Dimensionless parameter in Eq. (6.22) (Chapter 6).
y_b	Bubble height, m (Chapter 5).

y_s	Distance to bubble stagnation point from heated wall, m (Chapter 5).
Z	Ohnesorge number, dimensionless, $Z = \mu/(\rho L \sigma)^{1/2}$ (Chapter 5).
z	Heated length from the channel entrance, m (Chapter 5).
z^*	Axial coordinate, dimensionless (Chapter 2).
z_i	Valence of type-i ions (Chapter 4).

Greek Symbols

α	Convection heat transfer coefficient, W/m^2 K (Chapter 2); coefficient in the VSS molecular model, dimensionless (Chapter 2); aspect ratio, dimensionless (Chapter 6); void fraction, dimensionless (Chapter 6).
$\alpha_1, \alpha_2, \alpha_3$	Coefficients for the pressure distribution along a plane microchannel, dimensionless (Chapter 2).
α_c	Channel aspect ratio, dimensionless, $\alpha_c = a/b$ (Chapter 3).
α_i	Eigenvalues for the velocity distribution in a rectangular microchannel, dimensionless (Chapter 2).
α_r	Radial void fraction, dimensionless, $a_r = 0.8372 + [1 - (r/r_w)^{7.316}]$ (Chapter 6).
β	Coefficient in the VSS molecular model, dimensionless (Chapter 2); fin spacing ratio, dimensionless, $\beta = s/a$ (Chapter 3); angle with horizontal (Chapter 5); homogeneous void fraction, dimensionless (Chapter 6); velocity ratio, dimensionless (Chapter 6); multiplier to transition line, dimensionless, $\beta(F, X) =$ constant, used by Sardesai et al. (1981) (Chapter 6).
$\beta_1, \beta_2, \beta_3$	Coefficients for the pressure distribution along a circular microtube, dimensionless (Chapter 2).
β_A, β_B	Empirically derived transition points for the Kariyasaki et al. void fraction correlation (Chapter 6).
Γ	Euler or gamma function (Chapter 2).
γ	Area ratio, dimensionless (Chapter 6); dimensionless length ratio, $\gamma = L/H$ (Chapter 7); Specific heat ratio, dimensionless, $\gamma = c_p/c_v$ (Chapter 2).
ΔP	Pressure drop, Pa (Chapter 6).
$\Delta P_2/\Delta P_1$	Ratio of differential pressure between two system conditions (Chapter 6).
Δp	Pressure drop, pressure difference, Pa (Chapters 1–3, 5, and 7).
ΔT	Temperature difference, K (Chapter 6).
ΔT_{Sat}	Wall superheat, K, $\Delta T_{Sub} = T_{Sat} - T_B$ (Chapter 5).
ΔT_{Sub}	Liquid subcooling, K, $\Delta T_{Sat} = T_W - T_{Sat}$ (Chapter 5).
Δt	Elapsed time, s (Chapter 4).
Δx	Quality change, dimensionless (Chapter 6).