Second Edition

# CRYOGENIC HEAT TRANSFER

RANDALL F. BARRON
GREGORY F. NELLIS

CRC Press
Taylor & Francis Group

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Second Edition

# CRYOGENIC HEAT TRANSFER

# Preface

There was a need for a second edition to *Cryogenic Heat Transfer* because of the advent of availability and use of computer-aided design in engineering fields, including cryogenic engineering. This topic needed strengthening from the first edition, and therefore, this second edition is tightly integrated with computer software. Also, there were several additional topics in cryogenic heat transfer that should be included in any complete coverage of the topic. The topics that are added in the second edition are discussed in the following paragraphs.

As was the case for the first edition, the objective of the second edition is to present and illustrate the use of design tools available to assist the cryogenic engineer in solving some of the thermal problems that are unique to the cryogenic field. Owing to the extensive use of computational tools in engineering design, examples of the use of these programs, most notably the *Engineering Equation Solver* (EES) software, have been incorporated in this edition. There is an appendix that provides an introduction to the tool, and many of the examples are accomplished using this software.

Chapter 1 of the first edition on thermal properties at cryogenic temperatures has been expanded to include latent heats (important in liquid boil-off problems) and superfluid helium (He-II). Knowledge of and the ability to estimate latent heats is essential, because these properties give a measure of the energy involved in a phase change, such as vaporizing or condensing (latent heat of vaporization) and melting or freezing (latent heat of fusion).

Chapter 2 of the first edition on conduction heat transfer has been expanded and divided into four separate chapters to facilitate the understanding of the separate features and computational techniques in conduction heat transfer. These include steady-state conduction heat transfer (one-dimensional and multidimensional) and transient conduction heat transfer (both lumped-capacity situations and situations in which the temperature varies with position and with time). The recognition that material properties, such as thermal conductivity, are often strong functions of the material temperature is retained in the second edition. The presentation of additional solution techniques, such as Laplace transforms for transient thermal conduction, has been added.

The use of the library of correlations in *EES* for convection heat transfer has been included, in addition to a discussion on heat transfer and pressure drop in oscillatory flow, which is experienced in the Gifford-McMahon cryocooler and other cryogenic applications.

Although some aspects of analysis of radiation and free molecular heat transfer are similar, these two topics have been assigned separate chapters (for clarity) in this edition. The extensive library of view factor function available in *EES* has been utilized for radiant heat transfer and free molecular heat transfer in networks.

My (Barron) deepest appreciation is extended to my wife Shirley (a retired piano teacher) for her support and help in proofreading the manuscript for typographical errors. After reading some of the material several times, she mentioned, "This stuff is actually beginning to make a little sense to me." It is hoped that the practicing cryogenic engineer and the engineering student using this text will be able to understand the topics much more than just a "little bit."

My (Nellis) appreciation goes to Sanford Klein, recently retired professor at the University of Wisconsin. Sandy developed EES and has been extremely receptive to modifying it for use in cryogenic heat transfer problems.

**Randall F. Barron**
**Gregory F. Nellis**

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# Nomenclature

| | |
|---|---|
| $a$ | Rectangle side length, m or ft |
| | Inner radius of a spherical vessel, m or ft |
| | Correlation constant |
| | Accommodation coefficient (Chapter 9) |
| | Plate thickness, m or ft (Chapter 10) |
| $A$ | Area, $m^2$ or $ft^2$ |
| $A_c$ | Cross-sectional area, $m^2$ or $ft^2$ |
| | Surface area on cold side (Chapter 10), $m^2$ or $ft^2$ |
| $A_{ff}$ | Free-flow area, $m^2$ or $ft^2$ |
| $A_{fr}$ | Frontal area, $m^2$ or $ft^2$ |
| $b$ | Extinction coefficient, $m^{-1}$ or $ft^{-1}$ |
| | Outer radius of a spherical vessel, m or ft |
| | Correlation constant |
| | Rectangle side length, m or in. |
| | Distance between plates, m or ft (Chapter 10) |
| $b_h, b_c$ | Conductance ratios (Chapter 10) |
| $B = \frac{\Delta x}{\Delta y}$ | Finite difference shape factor |
| | Enclosure factor (Chapter 6) |
| | Dimensionless parameter (Chapters 7 and 10) |
| | Radiosity (Chapter 8), $W/m^2$ or $Btu/h\text{-}ft^2$ |
| $B_p$ | Heat transfer parameter (Chapter 10) |
| $B_1$ | Viscosity correction factor (Chapter 6) |
| | Dimensionless parameter (Chapter 10) |
| $Bi = \frac{h_c L_e}{k_t}$ | Biot number |
| $Bo$ | Bond number (Chapter 7) |
| $c_e$ | Electron specific heat, J/kg-K or $Btu/lb_m\text{-}°R$ |
| $c_0$ | Speed of light in vacuum, m/s or fps |
| $c_1, c_2$, etc. | Constants |
| $c_p$ | Specific heat at constant pressure, J/kg-K or $Btu/lb_m\text{-}°F$ |
| $c_v$ | Specific heat at constant volume, J/kg-K or $Btu/lb_m\text{-}°F$ |
| $C$ | Conductance (Chapter 9), $m^3/s$ or $ft^3/s$ |
| | Constant |
| $C_1, C_2, \ldots$ | Constants |
| $C_{11} = \frac{1}{R_1}$ | Radiation surface conductance, $m^2$ or $ft^2$ |
| $C_{12} = \frac{1}{R_{12}}$ | Radiation configuration conductance, $m^2$ or $ft^2$ |
| $C_D$ | Drag coefficient |
| $C_G$ | Vapor friction factor coefficient (Chapter 7) |
| $C_L$ | Liquid friction factor coefficient (Chapter 7) |
| $C_m$ | Matrix capacity rate ratio (Chapter 10) |
| $C_{max}$ | Maximum (larger) capacity rate, W/K or $Btu/h\text{-}°F$ |

| | |
|---|---|
| $C_{min}$ | Minimum (smaller) capacity rate, W/K or Btu/h-°F |
| $C_R = \dfrac{C_{min}}{C_{max}}$ | Capacity rate ratio |
| $C_s$ | Constant (Chapter 1) |
| $C_{sf}$ | Surface-fluid constant in boiling (Chapter 7) |
| $d$ | Thickness, m or ft |
| $d_c$ | Size of the foam cells, m or ft |
| $d_p$ | Diameter of perforations, m or ft |
| $d_s$ | Size of particles or fibers, m or ft |
| $d_t$ | Total flatness deviation, m or ft |
| $D_e = \dfrac{4A_c}{P_w}$ | Equivalent diameter, m or ft |
| $D_i$ | Inside diameter, m or ft |
| $D_0$ | Outside diameter, m or ft |
| $D_{12}$ | Diffusion coefficient, $m^2/s$ or $ft^2/h$ |
| $e$ | Emissivity |
| | Additional fin length (equivalent), m or ft |
| | Absolute roughness, m or in. |
| $e_f$ | Flame emissivity (Chapter 8) |
| $e_v$ | Void fraction (Chapter 10) |
| $e_w$ | Weld efficiency (Chapter 10) |
| $E$ | Young's modulus, Pa or psi |
| | Total radiant energy emitted per unit area, $W/m^2$ or $Btu/h\text{-}ft^2$ |
| $E_b$ | Blackbody emissive power, $W/m^2$ or $Btu/h\text{-}ft^2$ |
| $E_{b\lambda}$ | Monochromatic blackbody emissive power, $W/m^2$ or $Btu/h\text{-}ft^2$ |
| $E_t$ | Total energy transferred, J or Btu |
| $f$ | Number of degrees of freedom for a molecule |
| | Density ratio (Chapter 1) |
| | Friction factor |
| $f'$ | Friction factor for tube bundles |
| $f_0$ | Frequency of switching, Hz or cycles/s |
| $F$ | Condensation parameter (Chapter 7) |
| | Throughput (Chapter 9), $Pa\text{-}m^3/s$ or torr-L/s |
| | LMTD correction factor (Chapter 10) |
| $F_a$ | Accommodation coefficient factor (Chapter 9) |
| $F_D$ | Drag force, N or $lb_f$ |
| $F_e$ | Emissivity factor (Chapter 8) |
| $F_{m,n} = \dfrac{\alpha_{m,n}\Delta t}{(\Delta x)^2}$ | Finite difference dimensionless time parameter |
| $F_p$ | Pressure-drop parameter (Chapter 7) |
| $F_{tt}$ | Empirical factor (Chapter 7) |
| $F_{1,2}$ | Radiation configuration factor |
| $F(0 \rightarrow \lambda T)$ | Fraction of radiant energy in the range between 0 μm and λ |
| $Fo = \dfrac{\alpha t}{L^2}$ | Fourier number |
| $Fr = \dfrac{\bar{V}^2}{g D}$ | Froude number (Chapter 7) |
| $g$ | Local acceleration due to gravity, $m/s^2$ or $ft/s^2$ |
| $g_c$ | Conversion factor in Newton's Second Law of Motion, 1 $kg\text{-}m/N\text{-}s^2$ or 32.174 $lb_m\text{-}ft/lb_f\text{-}s^2$ |

| | |
|---|---|
| $G = \frac{\dot{m}}{A_c}$ | Mass flow rate per unit cross-sectional area, kg/s-m$^2$ or lb$_m$/h-ft$^2$ |
| $G = \dot{q}_g(\Delta x)^2$ | Finite difference heat generation parameter, W/m or Btu/h-ft |
| $G$ | Property-dependent parameter (Chapter 9) |
| $G_{abs}$ | Total energy absorbed per unit area, W/m$^2$ or Btu/h-ft$^2$ |
| $G_\lambda$ | Monochromatic radiant energy absorbed per unit area, W/m$^2$ or Btu/h-ft$^2$ |
| $Gr$ | Grashof number (Chapter 6) |
| $Gr_b$ | Bubble Grashof number (Chapter 7) |
| $Gz = Re\,Pr\left(\frac{D}{L}\right)$ | Graetz number |
| $G_{tc}$ | Thermal contact parameter (Chapter 2) |
| $GTD$ | Greater (larger) terminal temperature difference (Chapter 10), K or °F |
| $h_c$ | Solid conductance in MLI, W/m$^2$-K or Btu/h-ft$^2$-°F |
| | Convective heat transfer coefficient, W/m$^2$-K or Btu/h-ft$^2$-°F |
| $h_K$ | Kapitza conductance, W/m$^2$-K or Btu/h-ft$^2$-°R |
| $h_P$ | Planck's constant, $6.625 \times 10^{-34}$ J-s |
| $h_{tc}$ | Thermal contact conductance, W/m$^2$-K or Btu/h-ft$^2$-°F |
| $H$ | Vertical height of an enclosure, m or in. |
| $H_B$ | Brinell hardness, MPa |
| $i_h$, $i_c$ | Enthalpy of the hot or cold fluid, kJ/kg or Btu/lb$_m$ |
| $i_{fg}$ | Latent heat of vaporization, kJ/kg or Btu/lb$_m$ |
| $i_{sf}$ | Latent heat of fusion (or melting), kJ/kg or Btu/lb$_m$ |
| $I$ | Rotational moment of inertia of the molecule, N-m-s$^2$ |
| | Electrical current, A |
| $I_n(x)$ | Modified Bessel function of the first kind and order $n$ |
| $j_H = \frac{Nu}{\mathrm{Re}\,\mathrm{Pr}^{1/3}}$ | Colburn *J*-factor for heat transfer |
| $J$ | Current density, A/m$^2$ |
| $J_n(x)$ | Bessel function of the first kind and order $n$ |
| $Ja$ | Jacob number (Chapter 7) |
| $k_B$ | Boltzmann constant, $1.3805 \times 10^{-23}$ J/K |
| $k_D$ | Dimensionless geometry parameter (Chapter 7) |
| $k_e$ | Extinction coefficient, Equation 8.62, m$^{-1}$ or ft$^{-1}$ |
| $k_0$ | Constant |
| $k_P$ | Dimensionless pressure parameter (Chapter 7) |
| $k_{sp}$ | Spring constant, N/m or lb$_f$/in. |
| $k_t$ | Thermal conductivity, W/m-K or Btu/h-ft-°F |
| $k_{\parallel}$ | Thermal conductivity parallel to the shields in MLI, W/m-K or Btu/h-ft-°F |
| $K$ | Thermal conductivity integral, W/m or Btu/h-ft |
| $K_n(x)$ | Modified Bessel function of the second kind and order $n$ |
| $K_c$ | Contraction coefficient (Chapter 10) |
| $K_D$ | Boiling geometry parameter (Chapter 7) |
| $K_e$ | Expansion coefficient (Chapter 10) |
| $K_1$ | Inlet loss coefficient (Chapter 10) |
| $K_2$ | Outlet loss coefficient (Chapter 10) |
| $Kn = \frac{\lambda}{L_e}$ | Knudsen number (Chapter 9) |
| $L$ | Length; insulation thickness, m or ft |
| $LTD$ | Lesser (smaller) terminal temperature difference (Chapter 10), K or °F |

| | |
|---|---|
| $m$ | Mass, kg or $lb_m$ |
| | Fin parameter (Chapter 2), $m^{-1}$ or $ft^{-1}$ |
| | Exponent (Chapters 6 and 7) |
| $\dot{m}$ | Mass flow rate, kg/s or $lb_m$/h |
| $M$ | Molecular (or atomic) mass, g/mol or $lb_m$/lbmole |
| | Fin parameter (Chapter 10), $m^{-1}$ or $ft^{-1}$ |
| $M_n$ | Parameter (Chapter 4) |
| $n$ | Integer (Chapter 4) |
| | Exponent (Chapters 6 and 7) |
| $n_{d,f}$ | Design factor for the friction factor (Chapter 10) |
| $n_{d,h}$ | Design factor for the heat transfer coefficient (Chapter 10) |
| $N$ | Convection parameter |
| $\dot{N}$ | Molecular flow rate, molecules/s |
| | $= \frac{h_c \Delta x}{k_f}$, finite difference convection parameter |
| $N_{BR}$ | Burning rate number (Chapter 8) |
| $N_0$ | Avogadro's number, 6.0225 $mol^{-1}$ or 2.7318 $lbmole^{-1}$ |
| $N_f$ | Number of fins per unit length, fins/m or fins/ft |
| $N_L$ | Number of tube rows (Chapter 6) |
| $N_p$ | Number of tube passes (Chapter 10) |
| $N_{tc} = \frac{h_{tc} L}{k_t}$ | Thermal contact parameter |
| $N_{tu}$, $NTU$ | Number of heat transfer units (Chapters 6 and 10) |
| $N_{VH}$ | Number of velocity heads (Chapter 10) |
| $N_w$ | Wind speed number (Chapter 8) |
| $Nu = \frac{h_c L}{k_t}$ | Nusselt number |
| $\frac{N}{V}$ | Number of atoms per unit volume, $m^{-3}$ or $ft^{-3}$ |
| $\frac{N}{\Delta x}$ | Number of layers per unit thickness, layers/m or layers/ft |
| $p$ | Absolute pressure, Pa or psia |
| | Dimensionless parameter (Chapter 10) |
| $p_a$ | Apparent contact pressure, Pa or psi |
| $p_c$ | Thermodynamic critical pressure, Pa or psia |
| | Collapsing pressure (Chapter 10) |
| $p_R = \frac{p}{p_c}$ | Reduced pressure, dimensionless |
| $P_f$ | Perimeter of a fin, m or ft |
| $P_0 = \frac{1}{f_0}$ | Total period for a regenerator, s or h |
| $P_w$ | Wetted perimeter, m or in. |
| $\Delta p$ | Pressure drop or pressure difference, kPa or psi |
| $Pr = \frac{\mu c_p}{k_t}$ | Prandtl number |
| $q$ | Dimensionless parameter (Chapter 10) |
| $q = \frac{\dot{Q}}{A_w}$ | Heat flux, $W/m^2$ or $Btu/h\text{-}ft^2$ |
| $\dot{q}_g$ | Energy dissipation per unit volume, $W/m^3$ or $Btu/h\text{-}ft^3$ |
| $\dot{Q}$ | Heat transfer rate, W or Btu/h |

| | |
|---|---|
| $r$ | Reflectivity |
| | Recovery factor |
| | Radial coordinate, m or ft |
| $r_e$ | Electrical resistivity, Ohm-m |
| $r_1, r_2$ | Dimensionless parameters (Chapter 10) |
| $R$ | Specific gas constant, $R_u$/M, J/kg-K or ft-lb$_f$/lb$_m$-°R |
| $Ra$ | Rayleigh number |
| $Re$ | Reynolds number |
| $R_e$ | Electrical resistance, ohm |
| $R_h, R_c$ | Conductance ratios (Chapter 10) |
| $R_k$ | Conduction thermal resistance, K/W or °F-h/Btu |
| $R_u$ | Universal gas constant, 8.31447 J/mol-K or 1545.37 ft-lb$_f$/lbmole-°R |
| $R_{11}$ | Radiation surface resistance, m$^{-2}$ or ft$^{-2}$ |
| $R_{12}$ | Radiation configuration resistance, m$^{-2}$ or ft$^{-2}$ |
| $s$ | Laplace transform parameter, s$^{-1}$ |
| $S$ | Conduction shape factor, m or ft |
| $S_a$ | Allowable stress, Pa or psi |
| $S_D$ | Diagonal pitch (Chapter 6), m or in |
| $S_L$ | Longitudinal pitch (Chapter 6), m or in |
| $S_T$ | Transverse pitch (Chapter 6), m or in |
| $S_S$ | Mass per unit area, kg/m$^2$ or lb$_m$/ft$^2$ |
| $t$ | Transmissivity of foam, dimensionless |
| | Time, s or h |
| | Transmissivity (Chapter 8) |
| | Tube wall thickness (Chapter 10) |
| $t_d$ | Dwell time, s or h |
| $t_p$ | Thickness of the perforated plate, m or ft |
| $t_r$ | Shield thickness in MLI, m or ft |
| $t_s$ | Thickness of one separator layer in MLI, m or ft |
| $T$ | Absolute temperature, K or °R |
| $T_b$ | Boiling point temperature, K or °R |
| $T_C^*$ | Transposed critical temperature, K or °R |
| $T_R = \frac{T}{T_c}$ | Reduced temperature, dimensionless |
| $\Delta T = T_w - T_{sat}$ | Boiling temperature difference, K or °F |
| $\Delta T_m$ | Log mean temperature difference, K or °F |
| $u$ | Specific internal energy, J/kg or Btu/lb$_m$ |
| | $x$-component of fluid velocity, m/s or fps |
| $u = \frac{\delta}{r_1}$ | Dimensionless parameter (Chapter 7) |
| $U$ | Total internal energy, J or Btu |
| $U_0$ | Overall heat transfer coefficient, W/m$^2$-K or Btu/h-ft$^2$-°F |
| $v = \frac{1}{\rho}$ | Specific volume, m$^3$/kg or ft$^3$/lb$_m$ |
| $v$ | $y$-component of fluid velocity, m/s or fps |
| | Variable (Chapter 5) |
| $\bar{v}$ | Average molecular velocity, m/s or ft/s |
| $V$ | Volume, m$^3$ or ft$^3$ |
| $\bar{V}$ | Velocity, m/s or ft/s |

| | |
|---|---|
| $w$ | $z$-component of fluid velocity, m/s or fps |
| | Dimensionless parameter (Chapter 10) |
| $W$ | Fin width, m or ft |
| $x$ | Dimensionless variable (Chapter 1) |
| | Coordinate, m or ft |
| | Quality (vapor mass fraction) |
| $\Delta x$ | Finite difference element size, m or ft |
| $X$ | Separation of variables function (Chapter 4) |
| | Lockhart–Martinelli parameter (Chapter 7) |
| | Dimensionless regenerator parameter (Chapter 10) |
| $y$ | Coordinate, m or ft |
| | Liquid fraction |
| $Y$ | Separation of variables function (Chapter 4) |
| | Dimensionless parameter (Chapter 8) |
| | Parameter (Chapter 10) |
| $Y_n(x)$ | Bessel function of the second kind and order $n$ |
| $\Delta y$ | Finite difference element size, m or ft |
| $z = \frac{x}{L}$ | Dimensionless coordinate (Chapter 10) |
| $z_f, z_h$ | Gaussian probability parameter for the friction factor and convective heat transfer coefficient data (Chapter 10) |

## Greek Symbols

| | |
|---|---|
| $\alpha$ | Thermal diffusivity, $m^2/s$ or $ft^2/h$ |
| | Thermal expansion coefficient, $K^{-1}$ or $°R^{-1}$ |
| | Eigenvalue |
| | Void fraction (Chapter 7) |
| | Absorptivity (Chapter 8) |
| $\beta$ | Rate of change of fluid temperature (Chapter 3), K/s or °F/h |
| | Constant (Chapter 4) |
| $\beta_t$ | Volumetric thermal expansion coefficient, $K^{-1}$ or $°R^{-1}$ |
| $\gamma$ | $= \frac{c_p}{c_v}$, specific heat ratio, dimensionless |
| | Dimensionless parameter (Chapter 10) |
| $\gamma_e$ | Electronic specific heat coefficient (Chapter 1), J/kg-$K^2$ or Btu/$lb_m$-$°R^2$ |
| $\delta$ | Fin thickness, m or ft |
| | Stratified layer thickness, m or ft |
| $\delta_c$ | Coating thickness, m or ft |
| $\delta_{fr}$ | Frost layer thickness, m or ft |
| $\varepsilon$ | Heat exchanger effectiveness |
| $\eta$ | Dimensionless variable (Chapter 7) |
| $\eta_f$ | Fin effectiveness |
| $\eta_0$ | Surface effectiveness (Chapter 10) |
| $\xi = 1\frac{h_c\sqrt{\alpha t}}{k_t}$ | Dimensionless parameter (Chapter 5) |
| $\Theta = T - T_a$ | Temperature difference parameter, K or °R |
| $\Theta = K(x, y) - K_1$ | Variable (Chapter 4), W/m or Btu/h-ft |
| $\Theta_a$ | Dimensionless ambient temperature ratio (Chapter 10) |

| | |
|---|---|
| $\Theta_c$ | Dimensionless cold-fluid temperature ratio (Chapter 10) |
| $\Theta_D$ | Debye characteristic temperature, K or °R |
| $\Theta_h$ | Dimensionless hot-fluid temperature ratio (Chapter 10) |
| $\Theta_r$ | Characteristic rotation temperature, K or °R |
| $\Theta_w$ | Dimensionless wall temperature ratio (Chapter 10) |
| $\hat{\Theta}(s)$ | Laplace transform of the function $\Theta(t)$ |
| $\lambda$ | Wavelength, μm or ft |
| | Mean free path, m or ft |
| | Baker diagram parameter (Chapter 7) |
| | Dimensionless conduction parameter (Chapter 10) |
| $\lambda_{max}$ | Wavelength at maximum monochromatic blackbody emissive power, μm |
| $\mu$ | Viscosity, Pa-s or $lb_m$/ft-h |
| $\mu_1, \mu_2$ | Capacity rate ratios (Chapter 10) |
| $\nu$ | Poisson's ratio |
| $\nu = \frac{\mu}{\rho}$ | Kinematic viscosity, $m^2$/s or $ft^2$/h |
| $\rho$ | Density, $kg/m^3$ or $lb_m/ft^3$ |
| $\rho_G$ | Vapor density, $kg/m^3$ or $lb_m/ft^3$ |
| $\rho_L$ | Liquid density, $kg/m^3$ or $lb_m/ft^3$ |
| $\sigma$ | Stefan–Boltzmann constant, $56.69 \times 10^{-9}$ W/m$^2$-K$^4$ or $0.1714 \times 10^{-8}$ Btu/h-ft$^2$-°R$^4$ |
| | Ratio of free-flow area to frontal area (Chapter 10) |
| $\hat{\sigma}_f, \hat{\sigma}_h$ | Standard deviation for the friction factor and heat transfer coefficient data |
| $\sigma_K$ | Kapitza conductance coefficient, W/m$^2$-K$^4$ or Btu/h-ft$^2$-°R$^4$ |
| $\sigma_L$ | Surface tension, N/m or $lb_f$/ft |
| $\sigma_{th}$ | Thermal stress, Pa or psi |
| $\tau_0$ | Time constant, s or h |
| $\tau_k$ | Conduction time constant, s |
| $\tau_c$ | Time constant, s |
| $\Phi$ | Porosity, dimensionless |
| | Function (Chapter 2) |
| | Dimensionless parameter (Chapter 10) |
| $\Phi_a$ | Dimensionless ambient heat transfer (Chapter 10) |
| $\Phi_g$ | Energy dissipation function (Chapter 6) |
| $\Phi_h, \Phi_c$ | Dimensionless parameters (Chapter 10) |
| $\Phi_L$ | Lockhart–Martinelli parameter (Chapter 7) |
| $\Phi_M$ | Momentum pressure-drop parameter (Chapter 7) |
| $\Phi_0$ | Critical heat flux parameter (Chapter 7) |
| $\psi$ | Baker diagram parameter (Chapter 7) |
| $\Psi$ | Dimensionless parameter (Chapter 10) |

## Subscripts

| | |
|---|---|
| *a* | Ambient (surroundings) |
| *c* | Thermodynamic critical point |
| | Cold side |
| *fr* | Frost property |
| | Freezing point |
| *g* | Gas |

| | |
|---|---|
| *G* | Vapor |
| *h* | Warm side |
| *L* | Liquid phase |
| | Property at $x = L$ |
| *m* | Mean or average value |
| *ss* | Steady state |
| *S* | Solid material |
| *sat* | Saturation conditions |
| *sl* | Slush |
| *V* | Vapor phase |
| *w* | Wall or solid surface |
| 1 | Inner surface for enclosures |
| | Inlet temperature |
| 2 | Outer surface for enclosures |
| | Outlet temperature |
| $\infty$ | Free stream conditions |

# *Authors*

**Randall F. Barron** is professor emeritus of mechanical engineering at Louisiana Tech University in Ruston, Louisiana. He received his BS in mechanical engineering from Louisiana Tech University, his MS and PhD in mechanical engineering from The Ohio State University in Columbus, Ohio. He is the author of three other college-level textbooks: *Cryogenic Systems, Industrial Noise Control,* and *Design for Thermal Stresses*. Dr. Barron has served on the Cryogenic Engineering Conference Board and the editorial board of *Cold Facts* (Cryogenic Society of America). He is a fellow of the American Society of Mechanical Engineers.

**Gregory F. Nellis** is professor of mechanical engineering at the University of Wisconsin, Madison. He received his MS and PhD from the Massachusetts Institute of Technology and is a member of the Cryogenic Society of America (CSA) and the American Society of Heating Refrigeration and Air conditioning Engineers (ASHRAE). Professor Nellis is the coauthor of two other college textbooks: *Heat Transfer* (2009) and *Thermodynamics* (2012), both published by the Cambridge University Press. He is a fellow of ASHRAE and received the Boom Award for excellence in cryogenic research.