The Principles and Practice of Heat Transfer
The Principles and Practice of Heat Transfer

By

Ali H. Tarrad
This book is dedicated to my wife Layla, who was always there for me, even on the tough days. Her steadfast commitment, kindness, devotion, and endless support will not be forgotten.
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## USEFUL INFORMATION

### Unit Conversion Factors

**Useful conversion factors**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>SI to English conversion</th>
<th>English to SI conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>$1 , m = 3.2808 , ft$</td>
<td>$1 , ft = 0.3048 , m$</td>
</tr>
<tr>
<td>Area</td>
<td>$1 , m^2 = 10.7639 , ft^2$</td>
<td>$1 , ft^2 = 0.092903 , m^2$</td>
</tr>
<tr>
<td>Volume</td>
<td>$1 , m^3 = 35.3147 , ft^3$</td>
<td>$1 , ft^3 = 0.028317 , m^3$</td>
</tr>
<tr>
<td>Velocity</td>
<td>$1 , m/s = 3.2808 , ft/s$</td>
<td>$1 , ft/s = 0.3048 , m/s$</td>
</tr>
<tr>
<td>Mass</td>
<td>$1 , kg = 2.2046 , lbm$</td>
<td>$1 , lbm = 0.45359237 , kg$</td>
</tr>
<tr>
<td>Density</td>
<td>$1 , \frac{kg}{m^3} = 0.06243 , \frac{lbm}{ft^3}$</td>
<td>$1 , \frac{lbm}{ft^3} = 16.018 , \frac{kg}{m^3}$</td>
</tr>
<tr>
<td>Force</td>
<td>$1 , N = 0.2248 , lb_f$</td>
<td>$1 , lb_f = 4.4482 , N$</td>
</tr>
<tr>
<td>Pressure</td>
<td>$1 , \frac{N}{m^2} = 1.45038 \times 10^{-4} , \frac{lb_f}{in^2}$</td>
<td>$1 , \frac{lb_f}{in^2} = 6894.76 , \frac{N}{m^2}$</td>
</tr>
<tr>
<td>Heat, Energy, work</td>
<td>$1 , kJ = 0.94783 , Btu$</td>
<td>$1 , Btu = 1.05504 , kJ$</td>
</tr>
<tr>
<td>Heat transfer rate, Power</td>
<td>$1 , W = 3.4121 , \frac{Btu}{h}$</td>
<td>$1 , \frac{Btu}{h} = 0.29307 , W$</td>
</tr>
<tr>
<td>Heat flux</td>
<td>$1 , \frac{W}{m^2} = 0.317 , \frac{Btu}{h., ft^2}$</td>
<td>$1 , \frac{Btu}{h., ft^2} = 3.154 , \frac{W}{m^2}$</td>
</tr>
<tr>
<td>Specific energy, Specific enthalpy</td>
<td>$1 , \frac{kJ}{kg} = 0.4299 , \frac{Btu}{lbm}$</td>
<td>$1 , \frac{Btu}{lbm} = 2.326 , \frac{kJ}{kg}$</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>$1 , \frac{kJ}{kg., K} = 0.2384 , \frac{Btu}{lbm., ^\circ F}$</td>
<td>$1 , \frac{Btu}{lbm., ^\circ F} = 4.1869 , \frac{kJ}{kg., K}$</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>$1 , \frac{W}{m., K} = 0.5778 , \frac{Btu}{h., ft., ^\circ F}$</td>
<td>$1 , \frac{Btu}{h., ft., ^\circ F} = 1.7307 , \frac{W}{m., K}$</td>
</tr>
<tr>
<td>Heat transfer coefficient</td>
<td>$1 , \frac{W}{m^2., K} = 0.1761 , \frac{Btu}{h., ft^2., ^\circ F}$</td>
<td>$1 , \frac{Btu}{h., ft^2., ^\circ F} = 5.6782 , \frac{W}{m^2., K}$</td>
</tr>
<tr>
<td>Dynamic viscosity</td>
<td>$1 , \frac{kg}{m., s} = 0.672 , \frac{lbm}{ft., s}$</td>
<td>$1 , \frac{lbm}{ft., s} = 1.4881 , \frac{kg}{m., s}$</td>
</tr>
<tr>
<td>Kinematic viscosity, thermal diffusivity</td>
<td>$1 , \frac{m^2}{s} = 10.7639 , \frac{ft^2}{s}$</td>
<td>$1 , \frac{ft^2}{s} = 0.092903 , \frac{m^2}{s}$</td>
</tr>
</tbody>
</table>
Temperature

\[ T \, (^\circ C) = (^\circ F - 32) \times \frac{5}{9} \]
\[ T \, (^\circ F) = \left( ^\circ C \times \frac{9}{5} \right) + 32 \]

Temperature difference

\[ \Delta T \, (^\circ C) = \Delta T \, (^\circ F) \times \frac{5}{9} \]
\[ \Delta T \, (^\circ F) = \Delta T \, (^\circ C) \times \frac{9}{5} \]

---

**Mathematical Multiple Symbols**

Decimal multiples and sub-multiples of SI units

<table>
<thead>
<tr>
<th>Prefix</th>
<th>Symbol</th>
<th>Equivalent</th>
<th>Prefix</th>
<th>Symbol</th>
<th>Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>zetta</td>
<td>Z</td>
<td>10^{21}</td>
<td>deci</td>
<td>d</td>
<td>10^{-1}</td>
</tr>
<tr>
<td>exa</td>
<td>E</td>
<td>10^{18}</td>
<td>centi</td>
<td>c</td>
<td>10^{-2}</td>
</tr>
<tr>
<td>peta</td>
<td>P</td>
<td>10^{15}</td>
<td>milli</td>
<td>m</td>
<td>10^{-3}</td>
</tr>
<tr>
<td>tetra</td>
<td>T</td>
<td>10^{12}</td>
<td>micro</td>
<td>µ</td>
<td>10^{-6}</td>
</tr>
<tr>
<td>giga</td>
<td>G</td>
<td>10^{9}</td>
<td>nano</td>
<td>n</td>
<td>10^{-9}</td>
</tr>
<tr>
<td>mega</td>
<td>M</td>
<td>10^{6}</td>
<td>pico</td>
<td>p</td>
<td>10^{-12}</td>
</tr>
<tr>
<td>kilo</td>
<td>k</td>
<td>10^{3}</td>
<td>femto</td>
<td>f</td>
<td>10^{-15}</td>
</tr>
<tr>
<td>hecto</td>
<td>h</td>
<td>10^{2}</td>
<td>atto</td>
<td>a</td>
<td>10^{-18}</td>
</tr>
<tr>
<td>deca</td>
<td>da</td>
<td>10^{1}</td>
<td>zepto</td>
<td>z</td>
<td>10^{-21}</td>
</tr>
</tbody>
</table>
# LIST OF SYMBOLS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>Design parameter</td>
</tr>
<tr>
<td>$a_1, a_2, a_3$</td>
<td>Coefficients in Eq. 3.39</td>
</tr>
<tr>
<td>$A$</td>
<td>Area, (m$^2$)</td>
</tr>
<tr>
<td>$b$</td>
<td>Design parameter</td>
</tr>
<tr>
<td>$B.C.$</td>
<td>Boundary condition</td>
</tr>
<tr>
<td>$C, C_1, C_2$</td>
<td>Constants in equations</td>
</tr>
<tr>
<td>$C_{C-N}$</td>
<td>Crank–Nicolson coefficient defined in Eq. A.21.b</td>
</tr>
<tr>
<td>$C_{FZ}$</td>
<td>Forster-Zuber coefficient defined in Eq. 7.27</td>
</tr>
<tr>
<td>$CS$</td>
<td>Control system</td>
</tr>
<tr>
<td>$CV$</td>
<td>Control volume</td>
</tr>
<tr>
<td>$cp$</td>
<td>Specific heat, (kJ/kg.$^\circ$C)</td>
</tr>
<tr>
<td>$d$</td>
<td>Diameter, (m)</td>
</tr>
<tr>
<td>$D$</td>
<td>Diffusion coefficient, (m$^2$/s)</td>
</tr>
<tr>
<td>$e$</td>
<td>Total energy per unit mass, (kJ/kg)</td>
</tr>
<tr>
<td>$E$</td>
<td>Parameter defined in Eq. 8.32.b</td>
</tr>
<tr>
<td>$f$</td>
<td>Friction factor</td>
</tr>
<tr>
<td>$fp$</td>
<td>Fin pitch, (m)</td>
</tr>
<tr>
<td>$F$</td>
<td>Convective factor multiplier in Eq. 7.39.a or parameter defined elsewhere</td>
</tr>
<tr>
<td>$F_c$</td>
<td>Mixture correction factor ($F_c$) is equal to (1.0) for pure fluids and azeotropes; it is less than (1.0) for mixtures, Eq. 6.16</td>
</tr>
<tr>
<td>$F_e$</td>
<td>Fin efficiency equals (1.0) for the plain tube and is close to unity for the finned tube structure, Eq. 6.16</td>
</tr>
<tr>
<td>$F_t$</td>
<td>Temperature difference correction factor</td>
</tr>
<tr>
<td>$Fr$</td>
<td>Froud number</td>
</tr>
<tr>
<td>$g$</td>
<td>Gravitational converging factor</td>
</tr>
<tr>
<td>$G$</td>
<td>Mass velocity, (kg/m$^2$ s)</td>
</tr>
<tr>
<td>$Ga$</td>
<td>Galileo number</td>
</tr>
<tr>
<td>$h$</td>
<td>Heat transfer coefficient, (W/m$^2$ K)</td>
</tr>
<tr>
<td>$h_{fo}$</td>
<td>Fouling coefficient, (W/m$^2$ K)</td>
</tr>
<tr>
<td>$H$</td>
<td>Heat exchanger height or vertical tube length, (m)</td>
</tr>
<tr>
<td>$H.F$</td>
<td>High flow velocity</td>
</tr>
<tr>
<td>$H.T$</td>
<td>High-temperature</td>
</tr>
<tr>
<td>$i$</td>
<td>Fluid specific enthalpy, (kJ/kg)</td>
</tr>
<tr>
<td>$i_{fg}$</td>
<td>Latent heat of vaporization, (kJ/kg)</td>
</tr>
</tbody>
</table>
\( j \) Colburn j-factor defined by Eq. 5.65, or y-axis node coordinate
\( J_{TP} \) The mixture volumetric flux
\( k \) Thermal conductivity, (W/m K)
\( K_1 \) Constant defined in Eq. 5.34.c
\( K_2 \) Constant defined in Eq. 5.34.d
\( l \) Length, (m)
\( \ell \) Height of circular fin or plate fin length in the flow direction, (m)
\( L \) Front length of heat exchanger or tube length, (m)
\( L.T \) Low-temperature
\( m \) Index in equations or fluid mass
\( \dot{m} \) Mass flow rate, (kg/s)
\( n \) Index in Eq. 5.33 or a constant defined elsewhere
\( N \) Number of tube rows or tubes
\( N_r \) Number of tubes in a vertical column
\( N_{Sn} \) Scriven number defined in Eq. 6.32
\( N_t \) Total number of tubes
\( NTU \) Number of transfer units, Dimensionless.
\( Nu \) Nusselt number, Dimensionless
\( p \) Fluid pressure, (kpa, bar)
\( P \) Power, (kW)
\( p_t \) Tube pitch in heat exchanger
\( Pe \) Peclet number
\( Pr \) Prandtl number (Dimensionless)
\( p + 1 \) Iteration number in the time domain
\( q, \dot{Q} \) Heat transfer rate, (kW)
\( \dot{q} \) Heat transfer rate per unit length, (kW/m)
\( \dot{q} \) Heat generation per unit volume, (kW/m³)
\( \dot{q} \) Heat flux, (kW/m²)
\( r \) Radius, (m)
\( \Delta r, \Delta \theta, \Delta z \) Discretization in cylindrical coordinates
\( \Delta r, \Delta \theta, \Delta \phi \) Discretization in spherical coordinates
\( R \) Resistance, (m °C/W)
\( \mathcal{R} \) Circulation ratio, Eq. 7.7
\( Ra \) Roughness scale
\( Re \) Reynolds number (Dimensionless)
\( St \) Stanton number
\( S_p \) Center to center tube spacing
\( t \) Fin thickness (m) or time (s)
\( T \) Temperature, (°C)
### List of Symbols

- $T(x, y, z, t)$: Temperature transient function in cartesian coordinates
- $T(x, \theta, z, t)$: Temperature transient function in cylindrical coordinates
- $T(x, \theta, \phi, t)$: Temperature transient function in spherical coordinates
- $\Delta T$: Temperature difference, (deg C)
- $v$: Fluid velocity, (m/s)
- $V$: Volume
- $\dot{V}$: Fluid volumetric flow rate, (m$^3$/s)
- $U$: Overall heat transfer coefficient, (W/m$^2$ K)
- $\dot{U}$: Superficial velocity, (m/s)
- $W$: Heat exchanger width, (m)
- $\dot{W}$: Work rate, (kW)
- $We$: Weber number; $We = \frac{m^2 d}{\sigma \rho_l}$
- $x$: x-axis or position along a plat length, (m) or liquid mass fraction in mixtures, or flow quality
- $\Delta x$: The difference between the mass fractions of vapor and liquid of the more volatile component
- $X$: Liquid mole fraction of a component in a mixture
- $X_L$: Longitudinal tube spacing in the flow direction, (m)
- $X_T$: Transverse tube spacing perpendicular to the flow direction, (m)
- $\Delta x, \Delta y, \Delta z$: Discretization in cartesian coordinates
- $y$: y-coordinate, (m), or vapor mass fraction
- $Y$: Vapor mole fraction of a component in a mixture
- $z$: z-axis coordinate or elevation, (m)

### Subscript

- $a$: Air
- $act$: Actual value
- $ap$: Apparent value
- $ass$: Assumed value
- $aug$: Augmentation or enhancement
- $b$: Boiling
- $bore$: Borehole
- $B$: Bulk fluid, tube bundle
- $c$: Cold side, cross-sectional, or characteristic
- $cal$: Calculated value
- $co$: Corrected
- $cond$: Condenser
- $cr$: Critical
$d$  Value calculated at the tube diameter
$des$  Desuperheating process
$e$  Exit port
$enh$  Enhanced or enhancement
$eq$  Equivalent or Equilibrium
$est.$  Estimated value
$evap$  Evaporator
$f$  Film value or defined elsewhere
$fo$  Fouling
$g$  Gas state
$G-T$  Gewa-TX or Gewa-T
$h$  Hot side or homogeneous
$ho$  Horizontal
$H$  Hydraulic or heater
$H.E$  Heat Exchanger
$H-F$  HighFlux
$i$  Interior, inside, or inlet
$id$  Ideal
$iso$  Isothermal
$l$  Liquid state
$L-F$  Low Finned
$lo$  Liquid phase only
$in$  Inlet
$m$  Mean value
$m_1, m_2, m_3$  Constants in Eq. 6.17
$max$  Maximum
$min$  Minimum
$m,n$  Node number in the x-y plane in a finite difference scheme
$mix$  Mixture
$net$  Net value
$o$  Outside, outlet, or defined elsewhere
$out$  Outlet port value
$p$  Plate or particle in a porous surface
$pla$  Plain surface
$po$  Pore
$r$  Reduced
$Ref$  Refrigerant
$s$  Surface value or measured at surface condition
$S$  Nucleate boiling suppression factor
$sat$  Saturated at operating pressure
$sp$  Single-phase
### List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Str</em></td>
<td>Stratified flow</td>
</tr>
<tr>
<td><em>sub</em></td>
<td>Subcooled process</td>
</tr>
<tr>
<td><em>sur</em></td>
<td>Surrounding environment</td>
</tr>
<tr>
<td><em>t</em></td>
<td>Total, bare tube value or thermal</td>
</tr>
<tr>
<td><em>T-B</em></td>
<td>Turbo-B</td>
</tr>
<tr>
<td><em>th</em></td>
<td>Thermal value</td>
</tr>
<tr>
<td><em>TP</em></td>
<td>Two-phase flow</td>
</tr>
<tr>
<td><em>tur</em></td>
<td>Turbulent</td>
</tr>
<tr>
<td><em>vr</em></td>
<td>Vertical</td>
</tr>
<tr>
<td><em>w</em></td>
<td>Water-side or wall</td>
</tr>
</tbody>
</table>

### Greek Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>α</em></td>
<td>Thermal diffusivity, (m²/s) or void fraction (%)</td>
</tr>
<tr>
<td><em>β</em></td>
<td>Ration percentage Parameter</td>
</tr>
<tr>
<td><em>γ</em></td>
<td>Number of fins per meter (m⁻¹)</td>
</tr>
<tr>
<td><em>Γ</em></td>
<td>Friction factor defined in Eq. 5.34.b or condensation loading (kg/m s)</td>
</tr>
<tr>
<td><em>δ_ε</em></td>
<td>Thickness of porous layer, (m)</td>
</tr>
<tr>
<td><em>ε</em></td>
<td>Emissivity in radiation concept defined in Eq. 1.25 or roughness (m)</td>
</tr>
<tr>
<td><em>ε</em></td>
<td>Heat exchanger effectiveness</td>
</tr>
<tr>
<td><em>ξ</em></td>
<td>Accuracy or discrepancy, (%) or surface factor in Eq. 6.17</td>
</tr>
<tr>
<td><em>η</em></td>
<td>Efficiency or improvement factor</td>
</tr>
<tr>
<td><em>θ</em></td>
<td>Inclination heating element angle</td>
</tr>
<tr>
<td><em>μ</em></td>
<td>Fluid viscosity, (Pa.s)</td>
</tr>
<tr>
<td><em>ρ</em></td>
<td>Fluid density, (kg/m³)</td>
</tr>
<tr>
<td><em>σ</em></td>
<td>Surface tension, (N/m)</td>
</tr>
<tr>
<td><em>τ_p</em></td>
<td>Number of tubes per row</td>
</tr>
<tr>
<td><em>ϑ</em></td>
<td>Froud rate defined in Eq. 7.20.b</td>
</tr>
<tr>
<td><em>φ</em></td>
<td>Porosity of matrix, (%)</td>
</tr>
<tr>
<td><em>ψ</em></td>
<td>Deviation value, (%)</td>
</tr>
<tr>
<td><em>ω</em></td>
<td>Constant in Eq. 7.43.c and Eq. 7.43.d</td>
</tr>
<tr>
<td><em>ω_{vent}</em></td>
<td>Air vent capacity in surface condensers, (kg/s)</td>
</tr>
<tr>
<td><em>ω_m</em></td>
<td>Mass transfer coefficient, (m/s)</td>
</tr>
<tr>
<td><em>∞</em></td>
<td>Free stream value</td>
</tr>
<tr>
<td><em>ζ_0</em></td>
<td>Nondimensional Laplace constant is defined in Eq. 7.21.b</td>
</tr>
</tbody>
</table>
## Abbreviations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACC</td>
<td>Air-Cooled Condenser</td>
</tr>
<tr>
<td>BTCS</td>
<td>Backward Time, Centered Space</td>
</tr>
<tr>
<td>CHF</td>
<td>Critical Heat Flux</td>
</tr>
<tr>
<td>CHP</td>
<td>Combined Heat and Power</td>
</tr>
<tr>
<td>C.M</td>
<td>Cooling Medium</td>
</tr>
<tr>
<td>CTCS</td>
<td>Central Time, Centered Space</td>
</tr>
<tr>
<td>DNB</td>
<td>Departure from Nucleate Boiling</td>
</tr>
<tr>
<td>DWC</td>
<td>Dropwise Condensation</td>
</tr>
<tr>
<td>E.S</td>
<td>Energy Source</td>
</tr>
<tr>
<td>FPD</td>
<td>Frictional Pressure Drop</td>
</tr>
<tr>
<td>FD</td>
<td>Finite Difference</td>
</tr>
<tr>
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