FUNDAMENTALS *of* HEAT EXCHANGER DESIGN

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Preface

Over the past quarter century, the importance of heat exchangers has increased immensely from the viewpoint of energy conservation, conversion, recovery, and successful implementation of new energy sources. Its importance is also increasing from the standpoint of environmental concerns such as thermal pollution, air pollution, water pollution, and waste disposal. Heat exchangers are used in the process, power, transportation, air-conditioning and refrigeration, cryogenic, heat recovery, alternate fuels, and manufacturing industries, as well as being key components of many industrial products available in the marketplace. From an educational point of view, heat exchangers illustrate in one way or another most of the fundamental principles of the thermal sciences, thus serving as an excellent vehicle for review and application, meeting the guidelines for university studies in the United States and oversees. Significant advances have taken place in the development of heat exchanger manufacturing technology as well as design theory. Many books have been published on the subject, as summarized in the General References at the end of the book. However, our assessment is that none of the books available seems to provide an in-depth coverage of the intricacies of heat exchanger design and theory so as to fully support both a student and a practicing engineer in the quest for creative mastering of both theory and design. Our book was motivated by this consideration. Coverage includes the theory and design of exchangers for many industries (not restricted to, say, the process industry) for a broader, in-depth foundation.

The objective of this book is to provide in-depth thermal and hydraulic design theory of two-fluid single-phase heat exchangers for steady-state operation. Three important goals were borne in mind during the preparation of this book:

1. To introduce and apply concepts learned in first courses in heat transfer, fluid mechanics, thermodynamics, and calculus, to develop heat exchanger design theory. Thus, the book will serve as a link between fundamental subjects mentioned and thermal engineering design practice in industry.
2. To introduce and apply basic heat exchanger design concepts to the solution of industrial heat exchanger problems. Primary emphasis is placed on fundamental concepts and applications. Also, more emphasis is placed on analysis and less on empiricism.
3. The book is also intended for practicing engineers in addition to students. Hence, at a number of places in the text, some redundancy is added to make the concepts clearer, early theory is developed using constant and mean overall heat transfer coefficients, and more data are added in the text and tables for industrial use.

To provide comprehensive information for heat exchanger design and analysis in a book of reasonable length, we have opted not to include detailed theoretical derivations of many results, as they can be found in advanced convection heat transfer textbooks. Instead, we have presented some basic derivations and then presented comprehensive information through text and concise tables.

An industrial heat exchanger design problem consists of coupling component and system design considerations to ensure proper functioning. Accordingly, a good design engineer must be familiar with both system and component design aspects. Based on industrial experience of over three decades in designing compact heat exchangers for automobiles and other industrial applications and more than twenty years of teaching, we have endeavored to demonstrate interrelationships between the component and system design aspects, as well as between the needs of industrial and learning environments. Some of the details of component design presented are also based on our own system design experience.

Considering the fact that heat exchangers constitute a multibillion-dollar industry in the United States alone, and there are over 300 companies engaged in the manufacture of a wide array of heat exchangers, it is difficult to select appropriate material for an introductory course. We have included more material than is necessary for a one-semester course, placing equal emphasis on four basic heat exchanger types: shell-and-tube, plate, extended surface, and regenerator. The choice of the teaching material to cover in one semester is up to the instructor, depending on his or her desire to focus on specific exchanger types and specific topics in each chapter. The prerequisites for this course are first undergraduate courses in fluid mechanics, thermodynamics, and heat transfer. It is expected that the student is familiar with the basics of forced convection and the basic concepts of the heat transfer coefficient, heat exchanger effectiveness, and mean temperature difference.

Starting with a detailed classification of a variety of heat exchangers in Chapter 1, an overview of heat exchanger design methodology is provided in Chapter 2. The basic thermal design theory for recuperators is presented in Chapter 3, advanced design theory for recuperators in Chapter 4, and thermal design theory for regenerators in Chapter 5. Pressure drop analysis is presented in Chapter 6. The methods and sources for obtaining heat transfer and flow friction characteristics of exchanger surfaces are presented in Chapter 7. Surface geometrical properties needed for heat exchanger design are covered in Chapter 8. The thermal and hydraulic designs of extended-surface (compact and noncompact plate-fin and tube-fin), plate, and shell-and-tube exchangers are outlined in Chapter 9. Guidelines for selecting the exchanger core construction and surface geometry are presented in Chapter 10. Chapter 11 is devoted to thermodynamic analysis for heat exchanger design and includes basic studies of temperature distributions in heat exchangers, a heuristic approach to an assessment of heat exchanger effectiveness, and advanced topics important for modeling, analysis, and optimization of heat exchangers as components. All topics covered up to this point are related to thermal–hydraulic design of heat exchangers in steady-state or periodic-flow operation. Operational problems for compact and other heat exchangers are covered in Chapters 12 and 13. They include the problems caused by flow maldistribution and by fouling and corrosion. Solved examples from industrial experience and classroom practice are presented throughout the book to illustrate important concepts and applications. Numerous review questions and problems are also provided at the end of each chapter. If students can answer the review questions and solve the problems correctly, they can be sure of their grasp of the basic concepts and material presented in the text. It is hoped that readers will develop good understanding of the intricacies of heat exchanger design after going through this material and prior to embarking on specialized work in their areas of greatest interest.

For the thermal design of a heat exchanger for an application, considerable intellectual effort is needed in selecting heat exchanger type and determining the appropriate value of the heat transfer coefficients and friction factors; a relatively small effort is needed for executing sizing and optimizing the exchanger because of the computer-based calculations. Thus, Chapters 7, 9, and 10 are very important, in addition to Chapter 3, for basic understanding of theory, design, analysis, and selection of heat exchangers.

Material presented in Chapters 11 through 13 is significantly more interdisciplinary than the rest of the book and is presented here in a modified methodological approach. In Chapter 11 in particular, analytical modeling is used extensively. Readers will participate actively through a set of examples and problems that *extend* the breadth and depth of the material given in the main body of the text. A number of examples and problems in Chapter 11 require analytical derivations and more elaborate analysis, instead of illustrating the topics with examples that favor only utilization of the formulas and computing numerical values for a problem. The complexity of topics requires a more diverse approach to terminology, less routine treatment of established conventions, and a more creative approach to some unresolved dilemmas.

Because of the breadth of the subject, the coverage includes various design aspects and problems for indirect-contact two-fluid heat exchangers with primarily single-phase fluids on each side. Heat exchangers with condensing and evaporating fluids on one side can also be analyzed using the design methods presented as long as the thermal resistance on the condensing or evaporating side is small or the heat transfer coefficient on that side can be treated as a constant. Design theory for the following exchangers is not covered in this book, due to their complexity and space limitations: two-phase and multiphase heat exchangers (such as condensers and vaporizers), direct-contact heat exchangers (such as humidifiers, dehumidifiers, cooling towers), and multifluid and multistream heat exchangers. Coverage of mechanical design, exchanger fabrication methods, and manufacturing techniques is also deemed beyond the scope of the book.

Books by M. Jakob, D. Q. Kern, and W. M. Kays and A. L. London were considered to be the best and most comprehensive texts on heat exchanger design and analysis following World War II. In the last thirty or so years, a significant number of books have been published on heat exchangers. These are summarized in the General References at the end of the book.

This text is an outgrowth of lecture notes prepared by the authors in teaching courses on heat exchanger design, heat transfer, and design and optimization of thermal systems to senior and graduate students. These courses were taught at the State University of New York at Buffalo and the University of Novi Sad, Yugoslavia. Over the past fifteen years or more, the notes of the first author have been used for teaching purposes at a number of institutions, including the University of Miami by Professor S. Kakaç, Rensselaer Polytechnic Institute by Professors A. E. Bergles and R. N. Smith, Rochester Institute of Technology by Professor S. G. Kandlikar, Rice University by Professor Y. Bayazitoğlu, University of Tennessee Space Center by Dr. R. Schultz, University of Texas at Arlington by Professor A. Haji-Sheikh, University of Cincinnati by Professor R. M. Manglik, Northeastern University by Professor Yaman Yener, North Carolina A&T State University by Professor Lonnie Sharpe, Auburn

University by Dr. Peter Jones, Southern Methodist University by Dr. Donald Price, University of Tennessee by Professor Edward Keshock, and Gonzaga University by Professor A. Aziz. In addition, these course notes have been used occasionally at a number of other U.S. and foreign institutions. The notes of the second author have also been used for a number of undergraduate and graduate courses at Marquette University and the University of Kentucky.

The first author would like to express his sincere appreciation to the management of Harrison Thermal Systems, Delphi Corporation (formerly General Motors Corporation), for their varied support activities over an extended period of time. The second author acknowledges with appreciation many years of support by his colleagues and friends on the faculty of the School of Engineering, University of Novi Sad, and more recently at Marquette University and the University of Kentucky. We are also thankful for the support provided by the College of Engineering, University of Kentucky, for preparation of the first five and final three chapters of the book. A special word of appreciation is in order for the diligence and care exercised by Messrs. Dale Hall and Mack Mosley in preparing the manuscript and drawings through Chapter 5.

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We welcome suggestions and comments from readers.

Ramesh K. Shah

Dušan P. Sekulić

NOMENCLATURE

The dimensions for each symbol are represented in both the SI and English systems of units, where applicable. Note that both the hour and second are commonly used as units for time in the English system of units; hence a conversion factor of 3600 should be employed at appropriate places in dimensionless groups.

A	total heat transfer surface area (both primary and secondary, if any) on one side of a direct transfer type exchanger (recuperator), total heat transfer surface area of all matrices of a regenerator,† m^2, ft^2
A_c	total heat transfer area (both primary and secondary, if any) on the cold side of an exchanger, m^2, ft^2
A_{eff}	effective surface area on one side of an extended surface exchanger [defined by Eq. (4.167)], m^2, ft^2
A_f	fin or extended surface area on one side of the exchanger, m^2, ft^2
A_{fr}	frontal or face area on one side of an exchanger, m^2, ft^2
$A_{fr,t}$	window area occupied by tubes, m^2, ft^2
$A_{fr,w}$	gross (total) window area, m^2, ft^2
A_h	total heat transfer surface area (both primary and secondary, if any) on the hot fluid side of an exchanger, m^2, ft^2
A_k	fin cross-sectional area for heat conduction in Section 4.3 ($A_{k,o}$ is A_k at the fin base), m^2, ft^2
A_k	total wall cross-sectional area for longitudinal conduction [additional subscripts c, h, and t, if present, denote cold side, hot side, and total (hot + cold) for a regenerator] in Section 5.4, m^2, ft^2
A_k^*	ratio of A_k on the C_{min} side to that on the C_{max} side [see Eq. (5.117)], dimensionless
A_o	minimum free-flow (or open) area on one fluid side of an exchanger, heat transfer surface area on tube outside in a tubular exchanger in Chapter 13 only, m^2, ft^2
$A_{o,bp}$	flow bypass area of one baffle, m^2, ft^2
$A_{o,cr}$	flow area at or near the shell centerline for one crossflow section in a shell-and-tube exchanger, m^2, ft^2
$A_{o,sb}$	shell-to-baffle leakage flow area, m^2, ft^2
$A_{o,tb}$	tube-to-baffle leakage flow area, m^2, ft^2
$A_{o,w}$	flow area through window zone, m^2, ft^2
A_p	primary surface area on one side of an exchanger, m^2, ft^2
A_w	total wall area for heat conduction from the hot fluid to the cold fluid, or total wall area for transverse heat conduction (in the matrix wall thickness direction), m^2, ft^2
a	short side (unless specified) of a rectangular cross section, m, ft
a	amplitude of chevron plate corrugation (see Fig. 7.28), m, ft

† Unless clearly specified, a regenerator in the nomenclature means either a rotary or a fixed-matrix regenerator.

B parameter for a thin fin with end leakage allowed, h_e/mk_f, dimensionless

Bi Biot number, $\text{Bi} = h(\delta/2)/k_f$ for the fin analysis; $\text{Bi} = h(\delta/2)/k_w$ for the regenerator analysis, dimensionless

b distance between two plates in a plate-fin heat exchanger [see Fig. 8.7 for b_1 or b_2 (b on fluid 1 or 2 side)], m, ft

b long side (unless specified) of a rectangular cross section, m, ft

$\mathscr{C}$ some arbitrary monetary unit (instead of \$, £, etc.), money

C flow stream heat capacity rate with a subscript c or h, $\dot{m}c_p$, W/K, Btu/hr-°F

C correction factor when used with a subscript different from c, h, min, or max, dimensionless

$\mathbf{C}$ unit cost, $\mathscr{C}$/J($\mathscr{C}$/Btu), $\mathscr{C}$/kg ($\mathscr{C}$/lbm), $\mathscr{C}$/kW [$\mathscr{C}$/(Btu/hr)], $\mathscr{C}$/kW · yr($\mathscr{C}$/Btu on yearly basis), $\mathscr{C}/\text{m}^2(\mathscr{C}/\text{ft}^2)$

$\boldsymbol{C}$ annual cost, $\mathscr{C}$/yr

C^* heat capacity rate ratio, $C_{\min}/C_{\max}$, dimensionless

$\bar{C}$ flow stream heat capacitance, Mc_p, $C\tau_d$, W · s/K, Btu/°F

C_D drag coefficient, $\Delta p/(\rho u_\infty^2/2g_c)$, dimensionless

$C_{\max}$ maximum of C_c and C_h, W/K, Btu/hr-°F

$C_{\min}$ minimum of C_c and C_h, W/K, Btu/hr-°F

C_{ms} heat capacity rate of the maldistributed stream, W/K, Btu/hr-°F

C_r heat capacity rate of a regenerator, $M_w c_w \mathbf{N}$ or $M_w c_w/P_t$ [see Eq. (5.7) for the hot- and cold-side matrix heat capacity rates $C_{r,h}$ and $C_{r,c}$], W/K, Btu/hr-°F

C_r^* total matrix heat capacity rate ratio, $C_r/C_{\min}$, $C_{r,h}^* = C_{r,h}/C_h$, $C_{r,c}^* = C_{r,c}/C_c$, dimensionless

$\bar{C}_r$ total matrix wall heat capacitance, $M_w c_w$ or $C_r P_t$ [see Eq. (5.6) for hot- and cold-side matrix heat capacitances $\bar{C}_{r,h}$ and $\bar{C}_{r,c}$], W · s/K, Btu/°F

$\bar{C}_r^*$ ratio of $\bar{C}_r$ to $\bar{C}_{\min}$, dimensionless

C_{UA} cost per unit thermal size (see Fig. 10.13 and Appendix D), $\mathscr{C}$/W/K

C_{us} heat capacity rate of the uniform stream, W/K, Btu/hr-°F

C_w matrix heat capacity rate; same as C_r, W/K, Btu/hr-°F

$\bar{C}_w$ total wall heat capacitance for a recuperator, $M_w c_w$, W · s/K, Btu/°F

$\bar{C}_w^*$ ratio of $\bar{C}_w$ to $\bar{C}_{\min}$, dimensionless

CF cleanliness factor, U_f/U_c, dimensionless

c specific heat of solid, J/kg · K,† Btu/lbm-°F

$\mathbf{c}$ annual cost of operation percentile, dimensionless

c_p specific heat of fluid at constant pressure, J/kg · K, Btu/lbm-°F

c_w specific heat of wall material, J/kg · K, Btu/lbm-°F

$\mathscr{D}$ exergy destruction rate, W, Btu/hr

D_{baffle} baffle diameter, m, ft

D_{ctl} diameter of the circle through the centers of the outermost tubes, $D_{\text{otl}} - d_o$, m, ft

D_h hydraulic diameter of flow passages, $4r_h$, $4A_o/\mathbf{P}$, $4A_oL/A$, or $4\sigma/\alpha$, m, ft

† J = joule = newton × meter = watt × second; newton = N = kg · m/s^2.

$D_{h,w}$	hydraulic diameter of the window section, m, ft
D_{otl}	diameter of the outer tube limit (see Fig. 8.9), m, ft
D_p	port or manifold diameter in a plate heat exchanger, m, ft
D_s	shell inside diameter, m, ft
d	differential operator
d_c	collar diameter in a round tube and fin exchanger, $d_o + 2\delta$, m, ft
d_e	fin tip diameter of a disk (radial) fin, m, ft
d_i	tube inside diameter, m, ft
d_o	tube (or pin) outside diameter, tube outside diameter at the fin root for a finned tube after tube expansion, if any, m, ft
d_w	wire diameter, m, ft
d_1	tube hole diameter in a baffle, m, ft
$\dot{\mathscr{E}}$	exergy rate, W, Btu/hr
E	energy, J, Btu
E	activation energy in Chapter 13 [see Eq. (13.12)], $\text{J/kg} \cdot \text{mol}$, Btu/lbm-mole
E	fluid pumping power per unit surface area, $\dot{m}\,\Delta p/\rho A$, W/m^2, hp/ft^2
Eu	row average Euler number per tube row, $\Delta p/(\rho u_m^2 N_r/2g_c)$ or $\Delta p/(G^2 N_r/2g_c\rho)$, dimensionless
e	surface roughness size, m, ft
e^+	roughness Reynolds number, eu^*/ν, dimensionless
F	log-mean temperature difference correction factor [defined by Eq. (3.183)], dimensionless
f	Fanning friction factor, $\tau_w/(\rho u_m^2/2g_c)$, $\Delta p \rho\, g_c D_h/(2LG^2)$, dimensionless
f_D	Darcy friction factor, 4f, dimensionless
f_{tb}	row average Fanning friction factor per tube for crossflow to tubes, used in Chapter 7, $\Delta p/(4G^2 N_r/2g_c\,\rho)$, Eu/4, dimensionless
G	fluid mass velocity based on the *minimum* free area, $\dot{m}/A_o$ (replace A_o by $A_{o,c}$ for the crossflow section of a tube bundle in a shell-and-tube heat exchanger), $\text{kg/m}^2 \cdot \text{s}$, lbm/hr-ft^2
Gr	Grashof number [defined by Eq. (7.159)], dimensionless
Gz	Graetz number, $\dot{m}c_p/kL$ [see Eqs. (7.39) and (12.53)], dimensionless
Gz_x	local Graetz number, $\dot{m}c_p/kx$, dimensionless
g	gravitational acceleration, m/s^2, ft/sec^2
g_c	proportionality constant in Newton's second law of motion, $g_c = 1$ and dimensionless in SI units, $g_c = 32.174$ lbm-ft/lbf-sec^2
H	head or velocity head, m, ft
H	fluid enthalpy, J, Btu
$\dot{\mathbf{H}}$	enthalpy rate, used in Chapter 11, W, Btu/hr
Hg	Hagen number, defined by Eq. (7.23), dimensionless
Ⓗ	thermal boundary condition referring to constant axial as well as peripheral wall heat flux; also constant peripheral wall temperature; boundary condition valid only for the circular tube, parallel plates, and concentric annular ducts when symmetrically heated

(H1)	thermal boundary condition referring to constant axial wall heat flux with constant peripheral wall temperature
(H2)	thermal boundary condition referring to constant axial wall heat flux with constant peripheral wall heat flux
h	heat transfer coefficient [defined by Eqs. (7.11) and (7.12)], $W/m^2 \cdot K$, Btu/hr-ft^2-°F
$\mathbf{h}$	specific enthalpy, J/kg, Btu/lbm
h_e	heat transfer coefficient at the fin tip, $W/m^2 \cdot K$, Btu/hr-ft^2-°F
$\mathbf{h}_{\ell g}$	specific enthalpy of phase change, J/kg, Btu/lbm
$\dot{I}_{\text{irr}}$	irreversibility rate (defined in Table 11.3), W, Btu/hr
$I_n(\cdot)$	modified Bessel function of the first kind and nth order
i_j	flow direction indicator, $i_j = +1$ or -1, fluid $j = 1$ or 2, dimensionless
J	mechanical to thermal energy conversion factor, $J = 1$ and dimensionless in SI units, $J = 778.163$ lbf-ft/Btu
J_i	correction factors for the shell-side heat transfer coefficient for the Bell–Delaware method [see Eq. (9.50)]; $i = c$ for baffle cut and spacing; $i = \ell$ for baffle leakage effects, including both shell-to-baffle and tube-to-baffle leakage; $i = b$ for the bundle bypass flow (C and F streams); $i = s$ for variable baffle spacing in the inlet and outlet sections; $i = r$ for adverse temperature gradient buildup in laminar flow, dimensionless
j	Colburn factor, St Pr$^{2/3}$, $(h/Gc_p)\text{Pr}^{2/3}$, dimensionless
K	pressure loss coefficient, $\Delta p/(\rho u_m^2/2g_c)$; subscripts: b for a circular bend, s for a miter bend, and v for a screwed valve in Chapter 6, and br for branches in Chapter 12, dimensionless
$K(\infty)$	incremental pressure drop number for fully developed flow (see Table 7.2 for the definition), dimensionless
K_c	contraction loss coefficient for flow at heat exchanger entrance, dimensionless
K_e	expansion loss coefficient for flow at heat exchanger exit, dimensionless
$K_n(\cdot)$	modified Bessel function of the second kind and nth order
k	fluid thermal conductivity for fluid if no subscript, $W/m \cdot K$, Btu/hr-ft-°F
k_f	thermal conductivity of the fin material in Chapter 4 and of the foulant material in Chapter 13, $W/m \cdot K$, Btu/hr-ft-°F
k_w	thermal conductivity of the matrix (wall) material, $W/m \cdot K$, Btu/hr-ft-°F
L	fluid flow (core) length on one side of an exchanger, m, ft
L_f	fin flow length on one side of a heat exchanger, $L_f \leq L$, m, ft
L_h	plate length in a PHE for heat transfer (defined in Fig. 7.28), m, ft
L_p	plate length in a PHE for pressure drop (defined in Fig. 7.28), m, ft
L_1	flow (core) length for fluid 1 of a two-fluid heat exchanger, m, ft
L_2	flow (core) length for fluid 2 of a two-fluid heat exchanger, m, ft
L_3	noflow height (stack height) of a two-fluid heat exchanger, m, ft
L_q	Lévêque number, defined by Eq. (7.41), dimensionless

ℓ fin height or fin length for heat conduction from primary surface to either fin tip or midpoint between plates for symmetric heating, $\ell = (d_e - d_o)/2$ for individually finned tubes, ℓ with this meaning used only in the fin analysis and in the definition of η_f, m, ft

ℓ_c baffle cut, distance from the baffle tip to the shell inside diameter (see Fig. 8.9), m, ft

ℓ_{ef} effective flow length between major boundary layer disturbances, distance between interruptions, m, ft

ℓ_s strip length of an offset strip fin, m, ft

ℓ^* flow length between interruptions, $\ell_{ef}/(D_h \cdot \text{Re} \cdot \text{Pr})$, dimensionless

ℓ_c^* baffle cut, ℓ_c/D_s, dimensionless

$\mathscr{M}$ molecular weight (molar mass) of a gas, kg/kmol, lbm/lb mole

M_A foulant material mass per unit heat transfer surface area in Chapter 13, m/A, kg/m^2, lbm/ft^2

M_w mass of a heat exchanger core or the total mass of all matrices of a regenerator, kg, lbm

m fin parameter [defined by Eqs. (4.62) and (4.65); see also Table 4.5 for other definitions], 1/m, 1/ft

m mass of a body or fluid in a control volume, kg, lbm

$\dot{m}$ fluid mass flow rate, $\rho u_m A_o$, kg/s, 1bm/hr

$\dot{m}_n$ fluid mass flow rate for nominal flow passages in Chapter 12, kg/s, 1bm/hr

N number of subexchangers in gross flow maldistributed exchanger or a number of differently sized/shaped passages in passage-to-passage nonuniformity, used in Chapter 12

$\mathbf{N}$ rotational speed for a rotary regenerator, rev/s, rpm

N_b number of baffles in a plate-baffled shell-and-tube exchanger

N_c number of fluid channels in a plate heat exchanger

N_f number of fins per unit length in the fin pitch direction, l/m, l/ft

N_p number of fluid 1 passages in a two-fluid heat exchanger

N_p number of pass divider lanes through the tube field that are parallel to the crossflow stream in a shell-and-tube exchanger

N_p' number of separating plates in a plate-fin exchanger, number of pass divider lanes in a shell-and-tube exchanger

N_r number of tube rows in the flow direction

$N_{r,c}$ number of effective tube rows crossed during flow through one baffle section, $N_{r,cc} + N_{r,cw}$

$N_{r,cc}$ number of effective tube rows crossed during flow through one crossflow section (between baffle tips)

$N_{r,cw}$ number of effective tube rows crossed during flow through one window zone in a segmental baffled shell-and-tube heat exchanger

N_t total number of tubes in an exchanger, total number of holes in a tubesheet, or total number of plates in a plate heat exchanger

$N_{t,b}$ total number of tubes associated with one segmental baffle

$N_{t,c}$ number of tubes at the tube bundle centerline cross section
$N_{t,p}$ number of tubes per pass
$N_{t,w}$ number of tubes in the window zone
N_t' number of tubes in a specified row
NTU number of exchanger heat transfer units, $UA/C_{\min}$ [defined by Eqs. (3.59) through (3.64)], it represents the total number of transfer units in a multipass unit, dimensionless
NTU_1 number of exchanger heat transfer units based on fluid 1 heat capacity rate, UA/C_1; similarly, $\mathrm{NTU}_2 = UA/C_2$, dimensionless
NTU_c number of exchanger heat transfer units based on C_c, UA/C_c, dimensionless
NTU_h number of exchanger heat transfer units based on C_h, UA/C_h, dimensionless
NTU_o modified number of heat transfer units for a regenerator [defined by Eq. (5.48)], dimensionless
NTU* number of heat transfer units at maximum entropy generation, dimensionless
Nu Nusselt number [defined by Eqs. (7.26) and (7.27)], dimensionless
n, n_p number of passes in an exchanger
n_c number of cells of a regenerator matrix per unit of frontal area, 1/m², 1/ft²
n_f total number of fins on one fluid side of an extended-surface exchanger
n_t number of tubes in each pass
ntu_c number of heat transfer units based on the cold fluid side, $(\eta_o hA)_c/C_c$, dimensionless
$\mathrm{ntu}^*_{\mathrm{cost}}$ reduction in ntu [defined by Eq. (12.44)], dimensionless
ntu_h number of heat transfer units based on the hot fluid side, $(\eta_o hA)_h/C_h$, dimensionless
$\mathcal{P}$ fluid pumping power, $\dot{m}\,\Delta p/\rho$, W, hp
P temperature effectiveness for one fluid stream [defined by Eqs. (3.96) and (3.97)], dimensionless
P wetted perimeter of exchanger passages on one fluid side, $\mathbf{P} = A/L = A_{\mathrm{fr}}\beta$, m, ft
$\wp$ deposition probability function, dimensionless
P_c cold-gas flow period, duration of the cold-gas stream in the matrix or duration of matrix in the cold-gas stream, used in Chapter 5, s, sec
P_h hot-gas flow period, duration of the hot-gas stream in the matrix or duration of matrix in the hot-gas stream, used in Chapter 5, s, sec
P_r reversal period for switching from hot- to cold-gas stream, or vice versa, in a fixed-matrix regenerator, used in Chapter 5, s, sec
P_t total period between the start of two successive heating (or cooling) periods in a regenerator, used in Chapter 5, $P_t = P_h + P_c + P_r \approx P_h + P_c$, s, sec
Pe Péclet number, Re · Pr, dimensionless
Pr Prandtl number, $\mu c_p/k$, $u_m D_h/\alpha$, dimensionless
p fluid static pressure, Pa, lbf/ft² (psf) or lbf/in² (psi)†

† Pa = Pascal = N/m² = kg/m · s²; N = newton = kg · m/s²; psf = lbf/ft³; psi = lbf/in³.

p	porosity of a matrix, a ratio of void volume to total volume of a matrix, $r_h\beta$, dimensionless
p^*	ratio of cold-fluid inlet pressure to hot-fluid inlet pressure, $p_{c,i}/p_{h,i}$, dimensionless
p_d	fin pattern depth, peak-to-valley distance, excluding fin thickness (see Fig. 7.30), m, ft
p_f	fin pitch, $1/N_f$, m, ft
p_t	tube pitch, center-to-center distance between tubes, m, ft
Δp	fluid static pressure drop on one fluid side of a heat exchanger core [see Eq. (6.28)], Pa, psf (psi)
Δp^*	$= \Delta p/(\rho u_m^2/2g_c)$, dimensionless
Δp_b	fluid static pressure drop associated with a pipe bend, Pa, psf (psi)
$\Delta p_{b,i}$	fluid static pressure drop associated with an ideal crossflow section between two baffles, Pa, psf (psi)
Δp_c	fluid static pressure drop associated with the tube bundle central section (crossflow zone) between baffle tips, Pa, psf (psi)
Δp_{gain}	pressure drop reduction due to passage-to-passage nonuniformity [defined by Eq. (12.36)], Pa, psf (psi)
Δp_s	shell-side pressure drop, Pa, psf (psi)
$\Delta p_{w,i}$	fluid static pressure drop associated with an ideal window section, Pa, psf (psi)
Q	heat transfer in a specified period or time, J, Btu
q	total or local (whatever appropriate) heat transfer rate in an exchanger, or heat "duty," W, Btu/hr
q^*	normalized heat transfer rate, $q/[(\dot{m}c_p)(T_{2,i} - T_{1,i})]$, dimensionless
q'	heat transfer rate per unit length, q/L, W/m, Btu/hr-ft
q''	heat flux, heat transfer rate per unit surface area, q/A, W/m^2, Btu/hr-ft^2
q_e	heat transfer rate through the fin tip, W, Btu/hr
q_0	heat transfer rate at the fin base, W, Btu/hr
q_{max}	thermodynamically maximum possible heat transfer rate in a counterflow heat exchanger as expressed by Eq. (3.42), and also that through the fin base as expressed by Eq. (4.130), W, Btu/hr
$\mathfrak{R}$	universal gas constant, 8.3143 kJ/kmol · K, 1545.33 1bf-ft/1b mole-°R
R	heat capacity rate ratio [defined by Eqs. (3.105) and (3.106)], dimensionless
R	thermal resistance based on the surface area A; $\mathbf{R} = 1/UA$ = overall thermal resistance in a two-fluid exchanger, $\mathbf{R}_h = 1/(hA)_h$ = hot-side film resistance (between the fluid and the wall), $\mathbf{R}_c$ = cold-side film resistance, $\mathbf{R}_f$ = fouling resistance, and $\mathbf{R}_w$ = wall thermal resistance [definitions found after Eq. (3.24)], K/W, hr-°F/Btu
$\hat{\mathbf{R}}$	unit thermal resistance, $\hat{\mathbf{R}} = \mathbf{R}A = 1/U$, $\hat{\mathbf{R}}_h = 1/(\eta_o h)_h$, $\hat{\mathbf{R}}_w = 1/(\eta_o h)_c$, $\hat{\mathbf{R}}_w = \delta_w/A_w$, m^2 · K/W, hr-ft^2 °F/Btu
R*	ratio of thermal resistances on the C_{min} to C_{max} side, $1/(\eta_o hA)^*$; it is also the same as the ratio of hot to cold reduced periods, Π_h/Π_c, Chapter 5, dimensionless

R*	total thermal resistance (wall, fouling, and convective) on the enhanced (or plain with subscript p) "outside" surface side normalized with respect to the thermal resistance $[1/(hA_{i,p})]$ of "inside" plain tube/surface (see Table 10.5 for explicit formulas), dimensionless
$\tilde{R}$	gas constant for a particular gas, $\mathfrak{R}/\mathscr{M}$, J/kg · K, 1bf-ft/1bm-°R
$\hat{\mathbf{R}}_f$	fouling factor or unit thermal resistance ("fouling resistance"), $1/h_f$, $m^2 \cdot K/W$, hr-ft^2-°F/Btu
R_i	pressure drop correction factor for the Bell–Delaware method, where $i = b$ for bundle bypass flow effects (C stream), $i = \ell$ for baffle leakage effects (A and E streams), $i = s$ for unequal inlet/outlet baffle spacing effects, dimensionless
Ra	Rayleigh number [defined by Eq. (7.160)], dimensionless
Re	Reynolds number based on the hydraulic diameter, GD_h/μ, dimensionless
Re_d	Reynolds number based on the tube outside diameter and mean velocity, $\rho u_m d_o/\mu$, dimensionless
Re_{dc}	Reynolds number based on the collar diameter and mean velocity, $\rho u_m d_c/\mu$, dimensionless
Re_o	Reynolds number based on the tube outside diameter and free stream (approach or core upstream) velocity, $\rho u_\infty d_o/\mu$, dimensionless
r	radial coordinate in the cylindrical coordinate system, m, ft
r_c	radius of curvature of a tube bend (see Fig. 6.5), m, ft
r_f	fouling factor or fouling resistance $r_f = \hat{\mathbf{R}}_f = 1/h_f = \delta_f/k_f$, $m^2 \cdot K/W$, hr-ft^2-°F/Btu
r_h	hydraulic radius, A_oL/A or $D_h/4$, m, ft
r_i	tube inside radius, m, ft
S	entropy, J/K, Btu/°R
S^*	normalized entropy generation rate, $\dot{S}_{irr}/C_2$ or $\dot{S}_{irr}/C_{max}$, dimensionless
$\dot{S}_{irr}$	entropy generation rate, W/K, Btu/hr-°R
St	Stanton number, h/Gc_p, $\mathrm{St}_o = U/Gc_p$, dimensionless
s	specific entropy in Chapter 11, J/kg · K, Btu/lbm-°R
s	complex Laplace independent variable with Laplace transforms only in Chapter 11, dimensionless
s	spacing between adjacent fins, $p_f - \delta$, m, ft
T	fluid static temperature to a specified arbitrary datum, except for Eqs. (7.157) and (7.158) and in Chapter 11 where it is defined on an absolute temperature scale, °C, °F
Ⓣ	thermal boundary condition referring to constant wall temperature, both axially and peripherally
$T_{c,o}$	flow area average cold-fluid outlet temperature unless otherwise specified, °C, °F
$T_{h,o}$	flow area average hot-fluid outlet temperature unless otherwise specified, °C, °F
T_ℓ	temperature of the fin tip, °C, °F
T_m	fluid bulk mean temperature, °C, °F

T_s steam temperature, °C, °F

T_w wall temperature, °C, °F

T_∞ ambient fluid temperature, free stream temperature beyond the extent of the boundary layer on the wall, °C, °F

T^* ratio of hot-fluid inlet temperature to cold-fluid inlet temperature, $T_{h,i}/T_{c,i}$, dimensionless

T_c^* $= (T_c - T_{c,i})/(T_{h,i} - T_{c.i})$, dimensionless

T_h^* $= (T_h - T_{c,i})/(T_{h,i} - T_{c.i})$, dimensionless

T_w^* $= (T_w - T_{c,i})/(T_{h,i} - T_{c,i})$, dimensionless

T_0 temperature of the fin base, °C, °F

ΔT local temperature difference between two fluids, $T_h - T_c$, °C, °F

ΔT_c temperature rise of the cold fluid in the exchanger, $T_{c,o} - T_{c,i}$, °C, °F

ΔT_h temperature drop of the hot fluid in the exchanger, $T_{h,i} - T_{h,o}$, °C, °F

ΔT_{lm} log-mean temperature difference [defined by Eq. (3.172)], °C, °F

ΔT_m true (effective) mean temperature difference [defined by Eqs. (3.9) and (3.13)], °C, °F

$\Delta T_{\max}$ inlet temperature difference (ITD) of the two fluids, $(T_{h,i} - T_{c,i})$, $(T_{w,i} - T_{a,i})$ in Section 7.3.1, °C, °F

U, U_m overall heat transfer coefficient [defined by Eq. (3.20) or (3.24)], subscript m represents mean value when local U is variable (see Table 4.2 for the definitions of other U's), $\text{W/m}^2 \cdot \text{K}$, Btu/hr-ft^2-°F

u, u_m fluid mean axial velocity, u_m occurs at the minimum free flow area in the exchanger unless specified, m/s, ft/sec

u_c fluid mean velocity for flow normal to a tube bank based on the flow area of the gap $(X_t - d_o)$; evaluated at or near the shell centerline for a plate-baffled shell-and-tube exchanger, m/s, ft/sec

u_{cr} critical gap velocity for fluidelastic excitation or critical axial velocity for turbulent buffeting, m/s, ft/sec

u_z, u_w effective and ideal mean velocities in the window zone of a plate-baffled shell-and-tube exchanger [see Eq. (6.41)], m/s, ft/sec

u_∞ free stream (approach) velocity, m/s, ft/sec

u^* friction velocity, $(\tau_w g_c/\rho)^{1/2}$, m/s, ft/sec

V heat exchanger total volume, V_h = volume occupied by the hot-fluid-side heat transfer surface area, V_c defined similarly for the cold fluid side, m^3, ft^3

V^* ratio of the header volume to the matrix total volume, dimensionless

$\dot{V}$ volumetric flow rate, $\dot{V} = \dot{m}/\rho = u_m A_o$, m^3/s, ft^3/sec

V_m matrix or core volume, m^3, ft^3

V_p heat exchanger volume between plates on one fluid side, m^3, ft^3

V_v void volume of a regenerator, m^3, ft^3

v specific volume, $1/\rho$, m^3/kg, ft^3/1bm

W plate width between gaskets (see Fig. 7.28), m, ft

w_p width of the bypass lane (see Fig. 8.9), m, ft

X^* axial distance or coordinate, x/L, dimensionless