Process Heat Transfer

G. F. Hewitt
G. L. Shires
T. R. Bott

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G. F. Hewitt
Courtaulds Professor of Chemical Engineering
Imperial College of Science, Technology and Medicine
London, England

G. L. Shires
Visiting Professor
Department of Chemical Engineering and Chemical Technology
Imperial College of Science, Technology and Medicine
London, England

T. R. Bott
Reader in Chemical Engineering
School of Chemical Engineering
University of Birmingham
Birmingham, England

CRC

CRC Press
Boca Raton Ann Arbor London Tokyo

begell house

Library of Congress Cataloging-in-Publication Data

Hewitt, G. F. (Geoffrey Frederick)
Process heat transfer/G. F. Hewitt, G. L. Shires, T. R. Bott.
p. cm.
Includes bibliographical references and index.
ISBN 0-8493-9918-1
1. Heat—Transmission.. I. Shires, G. L. II. Bott, T. R.
(Theodore Reginald), 1957– . III. Title.
TJ260.H49 1993
621.402'2—dc20 93-23018
CIP

International Standard Book Number 0-8493-9918-1
Library of Congress Card Number 93-23018
Printed in the United States of America 1 2 3 4 5 6 7 8 9 0
Printed on acid-free paper

PREFACE

Heat transfer and the design of heat transfer equipment continues to be a centrally important issue in process engineering. In recent decades, there has been increased emphasis on the optimal use of energy and, with increased energy cost, efficient heat transfer has become of vital importance. It was with this in mind that the publisher who started this project (William Begell of Begell House) suggested the writing of this book. The project has taken over 5 years to come to fruition.

Anyone attempting to write a book on this subject must always have foremost in mind the classical text by D. Q. Kern, *Process Heat Transfer*, published by McGraw-Hill Book Company in 1950. In the 40-plus years since its publication, this book has had a central role in both teaching and practice in process heat transfer. Kern's book has been so seminal and successful that there has obviously been a lot of hesitation by us (and others) to tread the same path. However, one has to recognize that technical developments have continued over the past 40 years and that there have been considerable changes of emphasis in the process industry. It was for these reasons that we persevered with the present project.

We have aimed to provide a book that will serve as a textbook at the undergraduate and postgraduate level and that can also serve as a general source of information for engineers in the process industry. With these objectives in mind, we have started with the fundamentals of heat transfer (conduction, convection, and radiation), going on to consider heat transfer with phase change (boiling and condensation), and then dealing with heat transfer equipment and applications. Although there is still emphasis on heat exchangers of the tubular type, our book differs strongly from Kern's in presenting information on a wide variety of heat exchangers that have achieved prominence in recent decades. Emphasis is given to the selection between the heat exchanger types and to thermodynamic aspects such as process integration and thermodynamic cycles. These changes of emphasis (together with more recent data and correlations) reflect the developments both in technology and applications over recent decades. It would, perhaps, be too much to hope that this present book could have the impact that Kern's did, and the process industry surely must be indebted to his example.

We thought long and hard about the units for the present book. Clearly, much work is still carried out on heat transfer using what were formerly called Imperial Units, but now more commonly US Customary Units (namely, pound, mass, pound force, foot, inch, hour, etc.), and the temptation was to continue the tradition of using these units in the present book. However, throughout the world, modern teaching is in SI units (kilogram, meter, and second) and it is totally inappropriate, in our view, to start a new book without complying as closely as possible to the SI system. We are old enough to feel very sympathetic to those who find it difficult to visualize the magnitude of quantities in the SI system, having all worked in our earlier careers using Imperial Units. However, it is surprising how quickly one becomes familiar with the SI system, and its rationality, consistency, and reduced tendency to error makes it an excellent framework for technical work. To help students understand both the units and the basic calculational procedures, a very large number of worked examples and problems are presented!

Another departure from tradition in this book is the adoption of the new international standards for nomenclature. This standard nomenclature for heat transfer has been developed in a whole series of discussions at the International Heat Transfer Conferences and in the International Centre for Heat and Mass Transfer. It is hoped that, by adopting these new standards in the present book, a small contribution will have been made in the direction of reducing the chaos that previously existed. Some engineers will find some of the standard nomenclature difficult at first (e.g., the use of α rather than h for heat transfer coefficient and the following of the ISO lead in using η rather than μ for viscosity). However, in the present authors' views, the war on nomenclature has now largely been fought and we hope that by adapting the new standards, we are contributing to a lasting peace on this front! A good source of information on the standard nomenclature is the article by Y. R. Mayhew, Use of Physical Quantities, Units, Mathematics and Nomenclature in Heat Transfer Publications (*Experimental Heat Transfer*, 2:149, 1989).

We are greatly indebted to many colleagues for helpful suggestions and comments on the material contained in this book. Specifically, we would like to mention Dr. P. B. Whalley of the University of Oxford who was co-author (with GFH) of the original article on reboilers on which

Chapter 14 is based. R. H. Marsland of Johnson Hunt Ltd. and A. R. Guy of Brown Fintube Ltd. contributed considerably to the material from which Chapter 4 of this volume was ultimately developed. We would also like to express our sincere gratitude to the reviewers of the first draft of the book (Professor K. J. Bell of Oklahoma State University and R. A. Smith formerly of ICI Ltd.) for their most comprehensive and useful commentary on the material. We would like to thank all of these people for their help with the book, but would like to stress that any deficiencies are our responsibility.

We would like to thank our co-publishers, Begell House and CRC Press, for their help. William Begell started this project and gave us encouragement throughout, for which we are deeply grateful.

Finally, we would like to thank our wives for their patience and encouragement during the writing of this book, particularly in relation to the many working weekends that were involved!

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NOMENCLATURE

Symbol	Quantity	Coherent SI Unit
A	Surface area	m^2
a	Surface area per unit volume	m^{-1}
a	Amplitude of temperature cycle	K
b	Breadth	m
C	Heat capacity	$J/K = (kg \cdot m^2)/(s^2 \cdot K)$
C_r	$(\dot{M}C_p)_{min}/(\dot{M}C_p)_{max}$	
C_δ	Stefan-Boltzmann constant	$W/(m^2 \cdot K^4)$
c	Mass concentration	kg/m^3
c	Molar concentration	mol/m^3
c_v, c_p	Specific heat capacity at constant volume or pressure	$J/(kg \cdot K) = m^2/(s^2 \cdot K)$
$\tilde{c}_v, \tilde{c}_p$	Molar heat capacity at constant volume or pressure	$J/(kmol \cdot K) = (kg \cdot m^2)/(s^2 \cdot kmol \cdot K)$
D	Diameter	m
D	Diffusion coefficient	m^2/s
D_{12}	Diffusivity ($= \delta$)	m^2/s
d	Diameter	m
E	Emissive power (radiation)	W/m^2
E	Heat exchange effectiveness	
F	Force	$N = (kg \cdot m)/s^2$
F_{ij}	View factor (radiation)	
f	Frequency	s^{-1}
f_0	Friction factor	
G	Total radiation	W/m^2
g	Gravitational acceleration	m/s^2
H	Height	m
H	Enthalpy	$J = (kg \cdot m^2)/s^2$
h	Specific enthalpy	$J/kg = m^2/s^2$
$\tilde{h}$	Molar enthalpy	J/kmol
h_{LG}	Enthalpy of evaporation (latent heat)	$J/kg = m^2/s^2$
h	Height of fins	m
I	Irradiation intensity	W/m^2
J	Radiosity	W/m^2
L	Length	m
L_e	Equivalent length (= volume/surface area)	m
L_e	Entry length	m
l	Length	m
M	Mass	kg
$\tilde{M}$	Molar mass (molecular weight)	kg/kmol
$\dot{M}$	Mass flow rate	kg/s
$\dot{m}$	Mass flux (mass velocity) $= \dot{M}/S$	$kg/(m^2 \cdot s)$
$\dot{m}_i$	Mass flux of species i	$kg/(m^2 \cdot s)$
m	Mass of particle	kg
N	Number of tubes	
n	Number of tubes in row	
P	Periphery	m
p	Pressure	$Pa = N/m^2 = kg/(m \cdot s^2)$
Δp	Pressure drop	$Pa = N/m^2 = kg/(m \cdot s^2)$
p	Tube pitch	m

Symbol	Quantity	Coherent SI Unit
Q	Quantity of heat	$J = (kg \cdot m^2)/s^2$
$\dot{Q}$	Rate of heat transfer	$W = (kg \cdot m^2)/s^3$
$\dot{q}$	Heat flux ($\dot{Q}/A$)	$W/m^2 = kg/s^2$
$\tilde{R}$	Molar (universal) gas constant	$J/kmol = (kg \cdot m^2)/(s^2 \cdot kmol \cdot K)$
R_i	Specific gas constant	$J/kg \cdot K) = m^2/(s^2 \cdot K)$
R	Electrical resistance	ohms (Ω) = V/A
R_t	Thermal resistance	K/W
r	Radius, polar coordinate	m
S	Cross-sectional area	m^2
S	Entropy	$J/K = (kg \cdot m^2)/(s^2 \cdot K)$
S	Rate of internal heat generation per unit volume	W/m^3
s	Specific entropy	$J/(kg \cdot K) = m^2/(s^2 \cdot K)$
$\tilde{s}$	Molar entropy	$J/(kmol \cdot K)$
s	Space between fins	m
T	Temperature, absolute temperature	K
ΔT	Temperature difference or interval	K
ΔT_M	Mean temperature difference	K
ΔT_{LM}	Logarithmic mean temperature difference	K
t	Time	s
U	Overall heat transfer coefficient	$W/(m^2 \cdot K) = kg/(s^3 \cdot K)$
U	Flux velocity	m/s
u	Velocity, velocity component (x axis)	m/s
V	Volume	m^3
$\dot{V}$	Volumetric flow rate	m^3/s
V	Fluid velocity	m/s
v	Specific volume	m^3/kg
$\tilde{v}$	Molar volume	$m^3/kmol$
v	Velocity, velocity component (y axis)	m/s
W	Work	$J = (kg \cdot m^2)/s^2$
$\dot{W}$	Rate of work (power)	$W = (kg \cdot m^2)/s^3$
w	Velocity, velocity component (z axis)	m/s
w	Thickness of fins	m
x	Dryness fraction (quality)	
x	Distance, Cartesian coordinate	m
x_i	Mass fraction of species i	
$\tilde{x}_i$	Mole fraction of species i in liquid phase	
y	Cartesian coordinate	m
y_i	Mass fraction of species i	
$\tilde{y}_i$	Mole fraction of species i in vapor phase	
z	Height, Cartesian coordinate	m

Greek Symbols

α	Heat transfer coefficient	$W/(m^2 \cdot K) = kg/(s^3 \cdot K)$
α	Absorptivity (radiation)	
β	Mass transfer coefficient	m/s
Γ	Film flow rate per unit width	$kg/(m \cdot s)$

Symbol	Quantity	Coherent SI Unit
γ	Ratio c_p/c_v	
δ	Thickness, liquid film thickness	m
δ	Diffusivity	m^2/s
δ	Boundary layer thickness	m
ϵ	Emissivity (radiation)	
ϵ	Phase fraction	
ϵ_L	Liquid fraction (holdup)	
ϵ_G	Gas fraction (void fraction)	
ϵ_f	Fin effectiveness	
ζ	Coefficient of thermal expansion	K^{-1}
η	Viscosity	$Pa \cdot s = (N \cdot s)/m^2 = kg/(m \cdot s)$
η_f	Fin efficiency	
θ	Polar coordinate	rad
θ	Temperature difference	K
θ	$\Delta T_M/(T_{h,\text{in}} - T_{c,\text{in}})$	
κ	Thermal diffusivity	m^2/s
λ	Thermal conductivity	$W/(m \cdot K) = (kg \cdot m)/(s^3 \cdot K)$
λ	Wavelength	m
ν	Kinematic viscosity ($= \eta/\rho$)	m^2/s
ρ	Density	kg/m^3
$\tilde{\rho}$	Molar density	mol/m^3
ρ	Reflectivity (radiation)	
σ	Surface tension	$N/m = kg/s^2$
σ	Stefan Boltzmann constant	$W/(m^2 \cdot K^4)$
τ	Shear stress	$Pa = N/m^2 = kg/(m \cdot s^2)$
ϕ	Polar coordinate	rad
Ψ	Geometrical factor for calculating fin efficiency	
ω	Rotational speed	rad/s
Ω	Solid angle	sr

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