Process Heat Transfer

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 Press
Boca Raton New York

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 978-1-56700-149-5
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

This book contains information obtained from authentic and highly regarded sources. Reprinted material is quoted with permission, and sources are indicated. A wide variety of references are listed. Reasonable efforts have been made to publish reliable data and information, but the author and the publisher cannot assume responsibility for the validity of all materials or for the consequences of their use.

Neither this book nor any part may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, microfilming, and recording, or by any information storage or retrieval system, without prior permission in writing from the publisher.

The consent of CRC Press LLC does not extend to copying for general distribution, for promotion, for creating new works, or for resale. Specific permission must be obtained in writing from CRC Press LLC for such copying.

Direct all inquiries to CRC Press LLC, 2000 Corporate Blvd., N.W., Boca Raton, Florida 33431.

Trademark Notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation, without intent to infringe.

© 1994 by CRC Press LLC

No claim to original U.S. Government works

International Standard Book Number: 978-1-56700-149-5
Library of Congress Card Number 93-23018
Printed in the United States of America 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!

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

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	$J/(kmol \cdot K) = (kg \cdot m^2)/(s^2 \cdot kmol \cdot K)$
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

CONTENTS

1. **Introduction** 1
   1.1 Aim of this Book 1
   1.2 Process Industries 1
   1.3 Applications of Heat Transfer in the Process Industries 2
      1.3.1 Chemical Reactions 2
      1.3.2 Biological Reactions 2
      1.3.3 Physical Changes 3
      1.3.4 Power Generation 3
      1.3.5 Air Conditioning and Space Heating 4
      1.3.6 Waste Heat Recovery 4
   1.4 Heat Exchangers 4
      1.4.1 Heat Exchanger/Process Configurations 4
      1.4.2 Classification of Heat Exchangers 4
      1.4.3 Heat Exchanger Family Tree 7
   1.5 Structure of this Book 7
References 9

2. **Mechanisms of Heat Transfer** 11
   2.1 Introduction 11
   2.2 Modes of Heat Transfer 11
   2.3 Heat Conduction 12
      2.3.1 Introduction 12
      2.3.2 Thermal Conductivity in Solids, Liquids, and Gases 13
      2.3.3 General Equation of Heat Conduction 16
      2.3.4 Steady-State Heat Conduction 19
      2.3.5 Heat Conduction in Fins 27
      2.3.6 Two-Dimensional Steady-State Heat Conduction 32
      2.3.7 Conduction with Internal Heat Generation 36
      2.3.8 Transient Heat Conduction 42
   2.4 Convective Heat Transfer 55
      2.4.1 Introduction 55
      2.4.2 Fluid Motion and Convective Heat Transfer 56
      2.4.3 Nondimensional Parameters 58
      2.4.4 Heat Transfer To, or From, a Body in a Flowing Stream 64
      2.4.5 Heat Transfer in Cross-Flow Heat Exchangers 73
      2.4.6 Internal Flow: Friction Factor and Pressure Drop 93
      2.4.7 Internal Flow: Heat Transfer 98
      2.4.8 Natural Convection 108
      2.4.9 Heat Transfer Coefficients for Natural Convection 111
   2.5 Thermal Radiation 120
      2.5.1 Introduction 120
      2.5.2 Blackbody Radiation 120
      2.5.3 Radiation Intensity and Its Relationship to Emissive Power 123
      2.5.4 Real Surfaces: Radiation 126
      2.5.5 Real Surfaces: Irradiation 131
      2.5.6 Kirchhoff's Law 132
      2.5.7 Radiation between Surfaces: View Factor 135
      2.5.8 Radiation between Reflecting Surfaces 141
      2.5.9 Combination of Radiation and Natural Convection 143
      2.5.10 Absorption and Emission by Gases 144
Problems 150
References 152

3. **Basic Theory of Heat Exchangers** 155
3.1 Introduction 155
3.2 Overall Heat Transfer Coefficient 155
3.3 Temperature Profiles in Heat Exchangers and the General Method for Heat Exchanger Area Calculation 162
3.4 Special Solutions for Constant Heat Transfer Coefficient and Heat Capacities 167
3.4.1 Pure Counterflow Heat Exchanger 167
3.4.2 Pure Cocurrent Flow 169
3.4.3 Shell-and-Tube Heat Exchanger with Two Tube-Side Passes 170
3.4.4 Multiple Shell-and-Tube Heat Exchangers 176
3.4.5 Cross-Flow Heat Exchangers 180
3.5 Maximum Heat Transfer Rate and Heat Exchanger Effectiveness 182
3.6 Number of Transfer Units 183
3.7 Alternative Representations of Heat Exchanger Performance 184
3.8 Utilization of F-θ-NTU-P Charts 189
Problems 193
References 194

4. **Selection of Heat Exchangers** 197
4.1 Introduction 197
4.2 Types of Heat Exchangers 198
4.2.1 Shell-and-Tube Heat Exchangers 198
4.2.2 Double-Pipe Heat Exchangers 200
4.2.3 Gasketed Plate Heat Exchangers 201
4.2.4 Spiral Heat Exchangers 203
4.2.5 Lamella Heat Exchangers 204
4.2.6 Welded Plate Exchangers 205
4.2.7 Special Designs for Hot Gas-to-Liquid Duties 205
4.2.8 Special Designs for Gas-to-Gas Recuperative Duties 207
4.2.9 Heat-Pipe Heat Exchangers 210
4.2.10 Cyclic Regenerators 212
4.2.11 Rotary Regenerators 212
4.2.12 Air-Cooled Heat Exchangers 213
4.2.13 Compact Heat Exchangers 213
4.2.14 Scraped Surface Heat Exchangers 215
4.3 Initial Selection 215
4.4 Selection between Feasible Types 215
4.5 Heat Transfer Fluids 231
Problems 232
References 232

5. **Double-Pipe Heat Exchangers** 233
5.1 Introduction 233
5.2 Mechanical Design 233
5.2.1 Double-Pipe Straight Tube Heat Exchangers 233
5.2.2 Double-Pipe U-Tube Heat Exchangers 233
5.2.3 Multitube Units 233
5.2.4 Fins 233
5.3 Advantages of Double-Pipe Heat Exchangers 235
5.3.1 Simplicity of Construction 235
5.3.2 Ease of Access for Maintenance 235
5.3.3 Countercurrent Flow 235
5.3.4 Feasibility of Finned Tubes 235
5.3.5 High-Pressure Applications 235
5.4 Thermal Performance Assessment 236
5.4.1 Introduction 236

5.4.2 Simple Double-Pipe Heat Exchanger 236
5.4.3 Parallel/Series Arrangements of Double-Pipe Heat Exchangers 247
5.4.4 Effect of Longitudinal Fins 253
5.4.5 Multitube Units 260
Problems 260
References 260

6. **Shell-and-Tube Heat Exchangers** 263
6.1 Introduction: The Design Process 263
6.2 Definitions and Basic Mechanical Features 265
6.2.1 Shell Type 265
6.2.2 Tube Bundle 265
6.2.3 Tube Diameter 267
6.2.4 Tube Length 267
6.2.5 Tube Layout and Pitch 267
6.2.6 Baffle Design 267
6.3 Heat Transfer and Pressure Loss Calculations 269
6.3.1 Kern Method 271
6.3.2 Bell-Delaware Method 275
6.3.3 Flow Stream-Analysis Method 285
6.4 Rating and Design 292
References 295

7. **Plate-Fin Heat Exchangers** 297
7.1 Introduction 297
7.2 Structural Characteristics 297
7.2.1 Basic Features and Applications 297
7.2.2 Extended Surface Geometries 298
7.3 Heat Transfer and Frictional Pressure Drop 298
7.3.1 Laminar Flow 301
7.3.2 General Heat Transfer and Frictional Pressure Drop Relationships 307
7.3.3 Interrupted Plate-Fin Systems 308
7.3.4 Comparison of Surface Geometries in Terms of Thermal/Hydraulic Performance . . 310
7.4 Procedure for Performance Calculations 312
7.4.1 Geometrical Parameters 312
7.4.2 Calculation of Heat Transfer in Plate-Fin Heat Exchangers 314
7.4.3 Calculation of Pressure Drop in Plate-Fin Heat Exchangers 314
7.4.4 Summary of Procedure for Calculating Performance 315
Problems 324
References 324

8. **Plate-and-Frame Heat Exchangers** 327
8.1 Introduction 327
8.2 Applications of the Plate-and-Frame Heat Exchanger 327
8.3 Advantages and Disadvantages of Plate Heat Exchangers 329
8.3.1 Flexibility 330
8.3.2 Compactness 330
8.3.3 Low Fabrication Costs 330
8.3.3 Ease of Cleaning 330
8.3.5 Temperature Control 330
8.4 Plate Corrugations 330
8.4.1 Forms of Corrugation 330
8.4.2 Plate Heat Transfer 331
8.4.3 Plate Pressure Drop 335
8.4.4 Pressure Loss at Inlet and Outlet 335
8.5 Plate-and-Frame Heat Exchanger Configurations 335

8.6 Thermal Performance 336
8.6.1 Methods of Calculation 337
8.6.2 Single-Pass Plate Heat Exchanger in Countercurrent Flow 339
8.6.3 Two-Pass/Two-Pass Plate Heat Exchanger in Countercurrent Flow 345
8.6.4 Two-Pass/One-Pass Plate Heat Exchanger 347
8.6.5 Designing a Plate Heat Exchanger for a Specific Duty 357
Problems 362
References 363

9. **Air-Cooled Heat Exchangers** 365
9.1 Introduction 365
9.2 Advantages and Disadvantages of Air Cooling 365
9.2.1 Advantages 365
9.2.2 Disadvantages 365
9.3 Air-Cooled Heat Exchanger Construction 365
9.3.1 Arrangement of Tube Bundles and Provision of Air Flow 366
9.3.2 Bundle Construction and Flow Configuration 367
9.3.3 Finned Tube Construction 368
9.4 Thermal Performance of Air-Cooled Heat Exchangers 371
9.4.1 Thermal Performance Calculations 371
9.4.2 Calculation of ΔT_M 372
9.4.3 Effects of Tube Configuration on Performance 387
Problems 387
References 388

10. **Two-Phase Flow** 391
10.1 Introduction 391
10.2 Two-Phase Flow Patterns 391
10.2.1 Vertical Round Tubes 391
10.2.2 Flow Patterns in Horizontal Tubes 391
10.2.3 Flow Patterns in Inclined Tubes 394
10.2.4 Flow Patterns in Cross-Flow and in Shell-and-Tube Heat Exchangers 394
10.3 Basic Equations 396
10.3.1 Definitions 396
10.3.2 Balance Equations for Homogeneous Flow 399
10.3.3 Balance Equations for the Separated-Flow Model 400
10.4 Pressure Drop Calculations Based on the Homogeneous Model 401
10.4.1 Frictional Pressure Drop Calculation for In-Tube Flow 401
10.4.2 Use of the Homogeneous Model for the Calculation of Pressure Differences across Changes of Cross Section and around Bends 401
10.5 Frictional Pressure Drop Calculation Method Based on the Separated-Flow Model 403
10.5.1 Definitions 403
10.5.2 In-Tube Separated-Flow Friction Pressure Drop Correlations 403
10.5.3 Use of the Separated-Flow Model for the Calculation of Pressure Difference across Changes of Cross Section and around Bends 410
10.5.4 Pressure Drop Correlation for Shell-and-Tube Heat Exchangers 412
10.6 Void Fraction Calculation 413
10.7 Calculation of Critical Mass Flow Rate 416
10.8 Flooding 417
Problems 420
References 420

11. **Boiling Heat Transfer** 423
11.1 Introduction 423
11.2 Vapor-Liquid Equilibrium and Vapor Formation 423
11.3 Pool Boiling 428

11.4 Forced Convective Boiling 429
11.5 Cross-Flow Boiling 430
11.6 Multicomponent Boiling 433
  11.6.1 Multicomponent Equilibrium 434
  11.6.2 Pool Boiling 436
  11.6.3 Forced Convective Boiling 438
11.7 Correlations for Boiling Coefficient 442
  11.7.1 Nucleate Boiling 442
  11.7.2 Coefficients in Forced Convection 448
  11.7.3 Combined Nucleate Boiling and Forced Convection 449
  11.7.4 Postdryout Heat Transfer 453
11.8 Critical Heat Flux 454
  11.8.1 Definition 454
  11.8.2 Mechanism in Pool Boiling 454
  11.8.3 Mechanisms in Forced Convective Boiling 455
  11.8.4 Correlations for Critical Heat Flux in Pool Boiling 455
  11.8.5 Correlations for Forced Convective Critical Heat Flux in Vertical Channels 458
  11.8.6 Critical Heat Flux in Horizontal Channels 464
Problems 465
References 466

12. **Heat Exchangers with Vapor Generation** 469
12.1 Introduction 469
12.2 Classification of Heat Exchangers with Vapor Generation 469
  12.2.1 Classification According to Function 469
  12.2.2 Classification According to Mode of Heat Transfer 470
  12.2.3 Source of Heat 474
  12.2.4 Geometry 475
  12.2.5 Circulation 475
12.3 Temperature Profiles in Heat Exchangers with Vapor Generation 479
12.4 Basic Design Procedure 479
12.5 Limiting Factors to be Considered in Design 481
  12.5.1 Dryout and Critical Heat Flux 482
  12.5.2 Counterflow Flooding 482
  12.5.3 Maldistribution 483
  12.5.4 Instability in Heat Exchangers with Vapor Generation 483
References 485

13. **Steam Generators** 487
13.1 Introduction 487
13.2 Fossil Fuel Fired Boilers 487
13.3 Waste Heat Boilers 491
  13.3.1 Flue Gas Heated Boilers 491
  13.3.2 Process Gas Heated Boilers 492
References 498

14. **Reboilers** 499
14.1 Introduction 499
14.2 Types of Reboilers 499
  14.2.1 Internal Reboiler 499
  14.2.2 Kettle Reboiler 499
  14.2.3 Vertical Thermosyphon Reboiler 501
  14.2.4 Horizontal Thermosyphon Reboiler 504
  14.2.5 Selection of Type 505
14.3 Detailed Experimental Studies 506
  14.3.1 Kettle Reboilers 506
  14.3.2 Vertical Thermosyphon Reboilers 512

- 14.4 Problems in Design 515
  - 14.4.1 Kettle and Internal Reboilers 515
  - 14.4.2 Vertical Thermosyphon Reboilers 516
  - 14.4.3 Horizontal Thermosyphon Reboilers 516
  - 14.4.4 Pumped Reboilers 516
- 14.5 A Design Strategy 516
  - 14.5.1 Simulation Calculation 516
  - 14.5.2 Design Calculation 526
- 14.6 Design Methods 527
  - 14.6.1 Void Fraction in Cross-Flow 527
  - 14.6.2 Boiling in Cross-Flow 527
  - 14.6.3 Critical Heat Flux in Cross-Flow 528
  - 14.6.4 Instability 530
  - 14.6.5 Use of the Homogeneous Model of Two-Phase Flow 531
- 14.7 Conclusions 534

References 534

15. **Evaporators** 537
- 15.1 Introduction 537
- 15.2 Classification of Evaporators 537
- 15.3 Evaporation from Liquid Films 537
  - 15.3.1 Film Evaporators 537
  - 15.3.2 Falling Film Evaporators 539
  - 15.3.3 Heat Transfer Equations for Falling Film Evaporators 541
  - 15.3.4 Climbing Film Evaporators 550
- 15.4 Evaporation of Liquid with Nucleate Boiling at the Heated Surface 552
  - 15.4.1 Evaporators Employing Boiling inside Tubes and Passages 552
  - 15.4.2 Evaporators Employing Boiling outside Tubes and Passages 558
- 15.5 Flash Evaporation 560
- 15.6 Direct Contact Evaporation 563
- 15.7 Selection of Type of Evaporator 565
- 15.8 Multiple Effect Evporation 565
  - 15.8.1 Multiple Effect Evaporation: Forward Feed 566
  - 15.8.2 Multiple Effect Evaporation: Backward Feed 567
  - 15.8.3 Multiple Effect Evaporation: Parallel Feed 567

References 571

16. **Condensation** 573
- 16.1 Introduction 573
- 16.2 Modes of Condensation 573
- 16.3 Filmwise Condensation on Vertical Surfaces 574
  - 16.3.1 Gravity-Controlled Condensation 574
  - 16.3.2 Shear-Controlled Condensation 580
  - 16.3.3 Condensation Under Combined Gravity and Shear Control 589
- 16.4 Horizontal Tube Systems 590
  - 16.4.1 Condensation outside Tubes and Tube Banks 590
  - 16.4.2 Condensation on the inside of Horizontal Tubes 593
- 16.5 Condensation in Multicomponent Systems 599
  - 16.5.1 Equivalent Laminar Film Model and the Effect of Condensation Rate on Interfacial Shear Stress 599
  - 16.5.2 Effect of Mass Flux on Heat Transfer between Gas Phase and Interface 604
  - 16.5.3 Mass Transfer in Binary Mixtures 606
  - 16.5.4 Dimensionless Relationships in Momentum, Heat, and Mass Transfer 615
  - 16.5.5 Colburn-Hougen and Colburn-Drew Methods for Calculation of Local Heat Flux in Condensation and Application in Condenser Design 619
  - 16.5.6 Multicomponent Vapor Condensation 628

Problems .639
References .640

17. **Heat Exchangers with Vapor Condensation** .643
  17.1 Introduction .643
  17.2 Selection of Process Condensers .644
  17.3 Survey of Condenser Type .646
    17.3.1 Shell-and-Tube Condensers for Process Application .646
    17.3.2 Air-Cooled Condensers .650
    17.3.3 Gasketed Plate Exchangers for Condensation .652
    17.3.4 Plate-Fin Heat Exchangers .653
    17.3.5 Direct Contact Heat Transfer .654
References .657

18. **Shell-and-Tube Condensers** .659
  18.1 Introduction .659
  18.2 Heat Transfer Coefficients .659
    18.2.1 Tube Side .659
    18.2.2 Shell Side .660
  18.3 Mean Temperature Difference and Area Calculation .662
    18.3.1 Isothermal Condensation .662
    18.3.2 Condensation with Desuperheating and Subcooling .663
    18.3.3 Multicomponent Mixtures .668
  18.4 Pressure Drop .673
    18.4.1 Tube-Side Pressure Drop .673
    18.4.2 Shell-Side Pressure Drop .673
    18.4.3 Nozzle Pressure Drop .673
  18.5 Flooding in Reflux Condensers .674
References .674

19. **Air-Cooled Condensers** .675
  19.1 Introduction .675
    19,1.1 Application of Air-Cooled Condensers .675
  19.2 Mounting Arrangements for Air-Cooled Condensation .676
    19.2.1 Ground-Mounted Unit .676
    19.2.3 Column-Mounted Unit .676
  19.3 Flow Arrangements for Air-Cooled Condensation .676
    19.3.1 Downflow (Inclined Tube) Condensers .678
    19.3.2 Reflux (Inclined Tube) Condensers .679
    19.3.3 Combined Downflow and Reflux Condensers .679
    19.3.4 Horizontal Tube Condensers .679
    19.3.5 Vertical Tube Condensers .679
  19.4 Design of Air-Cooled Condensers .680
  19.5 Maldistribution Effects .684
    19.5.1 Air Flow Maldistribution .684
  19.6 Noise Generation .684
References .685

20. **Condensation in Plate-and-Frame Plate-Fin Heat Exchangers** .687
  20.1 Introduction .687
  20.2 Plate-and-Frame Heat Exchangers for Condensing Duties .687
    20.2.1 Pressure Drop Calculations .689
    20.2.2 Heat Transfer Calculations .690
  20.3 Plate-Fin Heat Exchangers for Condensing Duties .690
References .692

21. **Direct Contact Heat Transfer** 693
  - 21.1 Introduction 693
  - 21.2 Classification of Direct Contact Heat Transfer 694
    - 21.2.1 Gas-Liquid Heat Transfer 695
    - 21.2.2 Liquid-Liquid Heat Transfer 696
    - 21.2.3 Solid-Gas or Solid-Liquid Heat Transfer 696
    - 21.2.4 Classification Table 697
  - 21.3 Direct Contact Heat Exchangers 698
    - 21.3.1 Gas-Liquid Contactors 698
    - 21.3.2 Liquid-Liquid Contactors 704
    - 21.3.3 Solid-Gas or Solid-Liquid Contactors 704
  - 21.4 Direct Contact Heat Transfer Models 706
    - 21.4.1 Basic Heat Transfer Equation 706
    - 21.4.2 Heat Transfer Unit Approach 712
    - 21.4.3 Heat and Mass Transfer Analogy 714
  - 21.5 Direct Contact Fluid Dynamic Models 715
    - 21.5.1 Fluid Dynamics of Bubble Columns 715
    - 21.5.2 Fluid Dynamics of Spray Columns 717
    - 21.5.3 Counterflow Flooding in Tubes and Orifices 718
    - 21.5.4 Flooding in Packed Columns 719

Problems 722
References 722

22. **Direct Contact Condensers** 725
  - 22.1 Introduction 725
  - 22.2 Applications of Direct Contact Condensation 725
  - 22.3 Classification of Direct Contact Condensers 725
    - 22.3.1 Drop-Type Direct Contact Condensers 725
    - 22.3.2 Jet- and Sheet-Type Direct Contact Condensers 726
    - 22.3.3 Film-Type Direct Contact Condensers 726
    - 22.3.4 Bubble-Type Direct Contact Condensers 726
  - 22.4 Thermal Hydraulics of Direct Contact Condensers 729
    - 22.4.1 Theoretical Model of a Drop Condenser 729
    - 22.4.2 Theoretical Models of Sheet, Jet, and Fan Condensers 734
    - 22.4.3 Correlations for Film-Type Condensers 738
    - 22.4.4 Theoretical Models of Bubble-Type Condensers 738
    - 22.4.5 Comparison of Thermal Performance of Different Types of Direct Contact Condensers 744

Problems 744
References 745

23. **Water Cooling Towers** 747
  - 23.1 Introduction 747
  - 23.2 Forms of Cooling Towers 747
  - 23.3 Air-Water System 751
    - 23.3.1 Humidity 751
    - 23.3.2 Wet Bulb Temperature and Adiabatic Saturation Temperature 752
    - 23.3.3 Enthalpy Relationships and the Psychrometric Chart 756
  - 23.4 Determination of Water-Air Flow-Rate Ratio: The Merkel Method 762
  - 23.5 Pressure Drop and Tower Height 772

Problems 775
References 776

24. **Furnaces** 777
  - 24.1 Introduction 777
  - 24.2 Types of Furnaces Used in Process Plants 777
  - 24.3 Boilers 777

24.4 Furnace Heat Transfer 778
  24.4.1 Furnace Heat Balance 779
  24.4.2 Hot Gases as Heat Source 781
  24.4.3 Heat Sink 784
  24.4.4 Effect of Tube Geometry on the Heat Sink Characteristics 786
24.5 Furnace Models 789
  24.5.1 "Well Stirred" Furnace Model 789
  24.5.2 General Equation of Furnace Performance 791
  24.5.3 Allowance for Incomplete Mixing and Wall Losses 791
  24.5.4 Plug-Flow Furnace Model 798
Problems 804
References 804

25. **Heat Transfer Associated with Thermodynamic Cycles** 807
25.1 Introduction 807
25.2 Heat Engines and Heat Pumps 807
25.3 Efficiency and Coefficients of Performance 808
25.4 Heat Engines 811
  25.4.1 Gas Turbines 811
  25.4.2 Steam Turbines 818
25.5 Heat Pumps 820
  25.5.1 Vapor Compression Cycle 820
  25.5.2 Refrigerators 823
  25.5.3 Liquefaction of Gases by Recycling 829
  25.5.4 Heating 829
25.6 Absorption Cycles 835
  25.6.1 Simple Absorption Cycle Refrigerator 835
  25.6.2 Electrolux Refrigeration Cycle 837
Problems 838
References 839

26. **Process Integration** 841
26.1 Introduction 841
26.2 Composite Curves and Minimum Energy Requirements 841
  26.2.1 Two-Stream Case 841
  26.2.2 Six-Stream Case 845
26.3 Heat Exchanger Network Design 849
26.4 Heat Engines and Heat Pumps 851
26.5 Process Change 854
26.6 Limitations 854
Problems 854
References 855

27. **Fouling of Heat Exchangers** 857
27.1 Introduction 857
27.2 Heat Transfer Problems 857
27.3 Effect of Fouling on Heat Transfer 860
27.4 Pressure Drop Problems 860
27.5 Fouling Phenomena 862
  27.5.1 Crystallization 862
  27.5.2 Particulate Deposition 862
  27.5.3 Biological Growth 863
  27.5.4 Chemical Reaction at a Fluid-Surface Interface 863
  27.5.5 Corrosion 864
  27.5.6 Freezing 864
  27.5.7 Mixed Fouling 864

27.6 Factors of Importance in the Fouling Process 864
  27.6.1 Temperature 864
  27.6.2 Temperature Distribution 865
  27.6.3 Effects of Velocity 865
  27.6.4 Concentration of Foulant or Foulant Precursors Leading to Fouling 866
27.7 Operation of Heat Exchangers 866
27.8 Fouling Resistance Concept 867
  27.8.1 Fouling Data 871
27.9 Economic Penalties of Fouling 875
  27.9.1 Additional Surface 875
  27.9.2 Corrosion 875
  27.9.3 Operation and Maintenance 875
  27.9.4 Loss of Production 875
  27.9.5 Cleaning 875
  27.9.6 Additional Pumping Power 876
  27.9.7 Utilization of Energy 876
  27.9.8 Use of Antifoulants 876
References 876

28. **Enhancement of Heat Transfer** 879
28.1 Introduction 879
  28.1.1 Classification of Enhancement Techniques 879
28.2 Passive Methods 879
  28.2.1 Passive Augmentation Applied to Free Convection Heat Transfer 881
  28.2.2 Forced Convective Heat Transfer 881
  28.2.3 Passive Augmentation Applied to Multiphase Flow Heat Transfer 885
28.3 Active Methods 886
  28.3.1 Augmentation of Heat Transfer in Laminar Flow and Natural Convection by Mechanical Means 886
  28.3.2 Mechanical Augmentation Techniques for Forced Convection Heat Transfer 889
28.4 Compound Techniques 890
28.5 Enhancement of Condensation 890
28.6 Enhancement of Boiling and Evaporation Heat Transfer 891
28.7 Acceptance Criteria 893
References 893

29. **Regenerative Heat Exchangers** 895
29.1 Introduction 895
29.2 Application of Regenerative Heat Exchangers 895
  29.2.1 Fixed Bed Regenerators 895
  29.2.2 Rotary Regenerators 896
29.3 Regenerator Design 897
  29.3.1 Theoretical Model of Regenerators 897
  29.3.2 Design Parameters 900
  29.3.3 Performance of Symmetric Counterflow Regenerators 901
  29.3.4 Effects of Geometry on Reduced Length 908
  29.3.5 Effects of Material Thermal Conductivity on Regenerator Performance 909
Problems 912
References 913

30. **Electrical Heating** 915
30.1 Introduction 915
30.2 Common Techniques of Electrical Heating 915
30.3 Resistance Heating 915
  30.3.1 Basic Theory 916
  30.3.2 Indirect Heating 917
  30.3.3 Direct Heating 923

30.4 Induction Heating 923
  30.4.1 Basic Concepts 924
  30.4.2 Practical Aspects 926
30.5 Dielectric Heating 928
  30.5.1 Simple Theory 928
  30.5.2 Energy Penetration and Uniform Heating 929
  30.5.3 Practical Aspects 929
  30.5.4 Types of Microwave Applicators 931
  30.5.5 Types of Radiofrequency Applicators 931
  30.5.6 Equipment Selection 932
30.6 Infrared Heating 932
  30.6.1 Selection of Infrared Equipment for Process Heating 936
30.7 Conclusion 936
References 936

31. **Heat Transfer in Agitated Vessels** 937
31.1 Introduction 937
31.2 Agitation within the Vessel 937
  31.2.1 Nonproximity Systems 939
  31.2.2 Proximity Systems 939
  31.2.3 Construction 939
31.3 Heat Transfer in the Jacket (and Limpet Coils) 940
31.4 Heat Transfer and Pressure Drop in Coils 940
31.5 Heat Transfer on the inside of the Vessel Wall and on Immersed Helical Coils 945
  31.5.1 Nonproximity Mechanical Agitation 945
  31.5.2 Proximity Agitation 948
References 953

Appendix I. Heat Exchanger Performance: Equations and Charts 955
I.1 Effective Temperature Difference, ΔT_M 955
I.2 Heat Exchanger Effectiveness, E 956
I.3 References to Other Data on Effectiveness 957
References 980

Appendix II. Thermophysical Properties of Substances 981

Index 1027

Process
Heat
Transfer

CHAPTER 1

Introduction

1.1 AIM OF THIS BOOK

Heat transfer is a subject that confronts engineers and designers in the process industries throughout their working lives. It is therefore essential that they have a thorough understanding of the physical principles that govern it, an up to date knowledge of the experimental data upon which plant design is based, and a familiarity with the basic features of modern heat exchangers. The aim of this book is to provide, within one cover, a comprehensive account of all three aspects of heat transfer at a level suitable for both the student and the practicing engineer or designer.

1.2 PROCESS INDUSTRIES

The word "process" is one that we all understand yet may find difficult to define. In general usage it simply implies a series of ongoing actions, but when applied to industry it has a specific meaning, i.e., a sequence of actions brought about deliberately with the purpose of forming a product.

The major process industries are listed in Table 1.1. By convention they exclude industries devoted to the production of primary fuels, coal, oil, and gas, and the generation of power from these and other sources. The products of many process industries, steel, chemicals, and refractories, for example, become the primary construction materials for manufacturing industries; in other cases the products are finished items requiring only packaging and marketing, for example, foods and textiles.

The common feature of all process industries is that they aim to convert raw materials into a new form by means of chemical and physical changes. Some of these "processes" are also listed in Table 1.1; most require heat, some in very large quantities.

An idea of the amount of heat and power consumed by the process industries can be obtained from Figure 1.1, taken from a recent CEC publication (Commission of the European Community, 1988). It shows the consumption of energy in the Community by various sections of industry during 1984. The total energy used in all process industries was equivalent to that contained in 190 million tons of oil. It is interesting to note that the preparation and forming of metals (including nonferrous) takes the lion's share of energy, i.e. almost 40%, with chemicals as the next biggest consumer at almost 20%.

The use of energy in the transformation of materials on the scale that is practiced in the process industries means that great care must be taken to ensure that the maximum efficiency of utilization is achieved. Heat discarded from a process not only represents a waste of the world's most valuable fuel reserves but it also adds to the increasing thermal pollution of our environment. The process industries have a particularly important responsibility in this respect, because the waste heat is often associated with waste products that are potentially harmful to human, animal, and plant life. Prevention of pollution is now a prime factor in the design and operation of process plant, and recycling and reprocessing of effluents become increasingly important features. Improved design of heat exchangers and their wider application to waste heat recovery and recycling can contribute enormously to fuel saving and reduction of pollution. It is hoped that the information provided in this book will assist designers to achieve these aims and so help in the important task of preserving our environment.

The preceding quoted figures are for total energy consumption, some in the form of electricity and some in the form of fuel. Electrical energy is used for lighting and driving machinery and, to a limited extent, for process heating (see Chapter 30), but the major source of heating is fuel. It is estimated (UK Department of Energy) that in the United Kingdom about 70% of the energy supplied to the process industries as fuel is used in process heating, half of this being employed to raise steam. Space heating accounts for about 20% of the total fuel usage, most of which is burned in boiler houses. Although precise figures are not available, it is clear that very large amounts of energy are

Table 1.1. Process Industry Examples of Processes Using Heat

Process Industry	Examples of Processes Using Heat
Steel making	Smelting of ores, refining, alloying, melting, casting, forging, rolling, annealing
Chemicals (Includes pharmaceuticals, toilet preparations, soap and detergents, paints, resins and plastics, dye-stuffs and pigments, and fertilizers)	Chemical reactions, hydrogenation, pyrolysis, distillation, purification, evaporation, crystallization, polymerization, drying
Nonmetallic minerals (Includes bricks, pottery, glass, cement, and other refractory materials)	Firing, kilning, drying, calcining, melting, forming (e.g., plate glass), annealing
Metal manufacture (Includes iron and steel, and nonferrous metals)	Blast furnaces and cupolas, soaking and heat treatment, melting, sintering, casting, forging, rolling, annealing
Food and drink (Includes dairy products, brewing, farinaceous products, meat and vegetables, soft drinks, and tobacco)	Milling, blending, drying, forming as liquids, powders, or composite solids, purification, sterilization, pasteurization, fermentation, refrigeration
Paper and printing (Paper, board, stationary, etc.)	Wood pulping and liquification, rolling, drying, coating, and forming
Textiles (Includes fibers and fabrics, rope and net, carpets, and furnishings)	Production of manmade fibers, spinning and weaving, dyeing, and finishing

Note: This list does not include the oil and gas industries, which are also large scale energy users and employ a wide range of heat transfer equipment.

used to generate heat in the process industries, and that steam is the predominant medium of heat transfer and heat transport.

1.3 APPLICATIONS OF HEAT TRANSFER IN THE PROCESS INDUSTRIES

Although the majority of industrial processes require energy input in the form of heat, there are other processes that need energy to achieve the extraction of heat, e.g., refrigeration (Chapter 25). All processes have in common the need to transfer heat. The requirements for heat transfer are manifold, but can be divided into a number of categories, as follows.

1.3.1 Chemical Reactions

Input of heat is needed to bring about chemical reactions that require a high temperature and to increase the rate of reaction in order to reduce the plant size. Examples of this are the following:

- Combustion and gasification
- Pyrolysis, polymerization, and synthesis
- Chemical purification and separation
- Smelting of ores, alloying of metals, and sintering
- Firing of ceramics, glazes, and coatings

1.3.2 Biological Reactions

Heat is transferred out of or into the process in order to maintain temperatures that either inhibit or enhance biological activity, for example:

- Cooling and freezing of foodstuffs
- Pasteurization and purification
- Fermentation, brewing, and baking
- Production of enzymes

chapter on the specific type. For example, the chapter on shell-and-tube condensers is best approached via those on two-phase flow (Chapter 10), condensation (Chapter 16), and heat exchangers with condensation (Chapter 17).

Finally, it should be noted that although the book has been written primarily with the process plant engineer or designer in mind, much of the material is directly relevant to other industries, for example power generation. The chapters on basic heat transfer and fluid dynamics are, of course, universally applicable.

References

Commission of the European Community (1988), Energy efficiency in industrial processes: Future R & D requirements, Proceedings of CEC Seminar, Brussels, Report EUR 12046 EN.