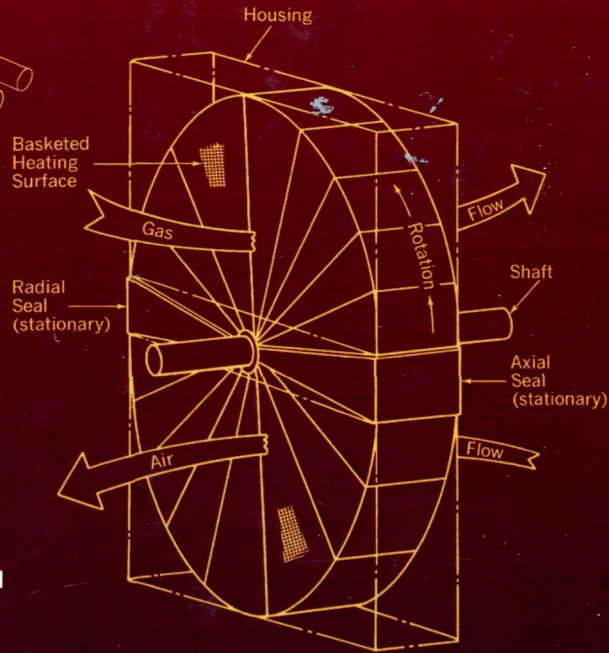
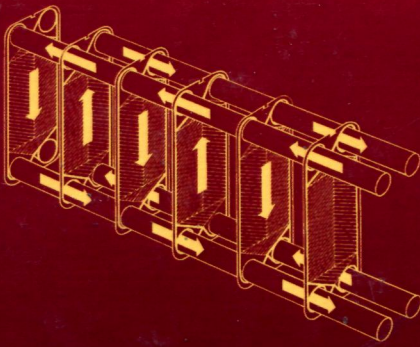


Third Edition



HEAT EXCHANGERS

Selection, Rating, and Thermal Design

Sadık Kakaç
Hongtan Liu
Anchasa Pramuanjaroenkij

Third Edition

HEAT EXCHANGERS

Selection, Rating, and
Thermal Design

Sadık Kakaç
Hongtan Liu
Anchasa Pramuanjaroenkij

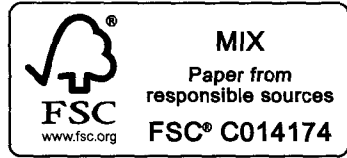


CRC Press

Taylor & Francis Group

Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **Informa** business



CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

© 2012 by Taylor & Francis Group, LLC
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works

Printed in the United States of America on acid-free paper
Version Date: 20120110

International Standard Book Number: 978-1-4398-4990-3 (Hardback)

This book contains information obtained from authentic and highly regarded sources. Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access www.copyright.com (<http://www.copyright.com/>) or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

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

Visit the Taylor & Francis Web site at
<http://www.taylorandfrancis.com>

and the CRC Press Web site at
<http://www.crcpress.com>

Contents

Preface.....	xiii
1. Classification of Heat Exchangers.....	1
1.1 Introduction.....	1
1.2 Recuperation and Regeneration.....	1
1.3 Transfer Processes.....	6
1.4 Geometry of Construction.....	8
1.4.1 Tubular Heat Exchangers.....	8
1.4.1.1 Double-Pipe Heat Exchangers.....	8
1.4.1.2 Shell-and-Tube Heat Exchangers.....	9
1.4.1.3 Spiral-Tube-Type Heat Exchangers.....	12
1.4.2 Plate Heat Exchangers.....	12
1.4.2.1 Gasketed Plate Heat Exchangers.....	12
1.4.2.2 Spiral Plate Heat Exchangers.....	14
1.4.2.3 Lamella Heat Exchangers.....	15
1.4.3 Extended Surface Heat Exchangers.....	17
1.4.3.1 Plate-Fin Heat Exchanger.....	17
1.4.3.2 Tubular-Fin Heat Exchangers.....	18
1.5 Heat Transfer Mechanisms.....	23
1.6 Flow Arrangements.....	24
1.7 Applications.....	25
1.8 Selection of Heat Exchangers.....	26
References.....	30
2. Basic Design Methods of Heat Exchangers.....	33
2.1 Introduction.....	33
2.2 Arrangement of Flow Paths in Heat Exchangers.....	33
2.3 Basic Equations in Design.....	35
2.4 Overall Heat Transfer Coefficient.....	37
2.5 LMTD Method for Heat Exchanger Analysis.....	43
2.5.1 Parallel- and Counterflow Heat Exchangers.....	43
2.5.2 Multipass and Crossflow Heat Exchangers.....	47
2.6 The ϵ -NTU Method for Heat Exchanger Analysis.....	56
2.7 Heat Exchanger Design Calculation.....	66
2.8 Variable Overall Heat Transfer Coefficient.....	67
2.9 Heat Exchanger Design Methodology.....	70
Nomenclature.....	73
References.....	78

3. Forced Convection Correlations for the Single-Phase Side of Heat Exchangers.....	81
3.1 Introduction.....	81
3.2 Laminar Forced Convection.....	84
3.2.1 Hydrodynamically Developed and Thermally Developing Laminar Flow in Smooth Circular Ducts.....	84
3.2.2 Simultaneously Developing Laminar Flow in Smooth Ducts	85
3.2.3 Laminar Flow through Concentric Annular Smooth Ducts	86
3.3 Effect of Variable Physical Properties	88
3.3.1 Laminar Flow of Liquids.....	90
3.3.2 Laminar Flow of Gases	92
3.4 Turbulent Forced Convection.....	93
3.5 Turbulent Flow in Smooth Straight Noncircular Ducts	99
3.6 Effect of Variable Physical Properties in Turbulent Forced Convection	103
3.6.1 Turbulent Liquid Flow in Ducts	103
3.6.2 Turbulent Gas Flow in Ducts	104
3.7 Summary of Forced Convection in Straight Ducts	107
3.8 Heat Transfer from Smooth-Tube Bundles	111
3.9 Heat Transfer in Helical Coils and Spirals	114
3.9.1 Nusselt Numbers of Helical Coils—Laminar Flow.....	116
3.9.2 Nusselt Numbers for Spiral Coils—Laminar Flow	117
3.9.3 Nusselt Numbers for Helical Coils—Turbulent Flow.....	117
3.10 Heat Transfer in Bends.....	118
3.10.1 Heat Transfer in 90° Bends	118
3.10.2 Heat Transfer in 180° Bends	119
Nomenclature.....	120
References	125
4. Heat Exchanger Pressure Drop and Pumping Power.....	129
4.1 Introduction	129
4.2 Tube-Side Pressure Drop	129
4.2.1 Circular Cross-Sectional Tubes.....	129
4.2.2 Noncircular Cross-Sectional Ducts.....	132
4.3 Pressure Drop in Tube Bundles in Crossflow	135
4.4 Pressure Drop in Helical and Spiral Coils	137
4.4.1 Helical Coils—Laminar Flow	138
4.4.2 Spiral Coils—Laminar Flow	138
4.4.3 Helical Coils—Turbulent Flow.....	139
4.4.4 Spiral Coils—Turbulent Flow.....	139
4.5 Pressure Drop in Bends and Fittings.....	140
4.5.1 Pressure Drop in Bends	140
4.5.2 Pressure Drop in Fittings.....	142

4.6	Pressure Drop for Abrupt Contraction, Expansion, and Momentum Change.....	147
4.7	Heat Transfer and Pumping Power Relationship.....	148
	Nomenclature.....	150
	References.....	155
5.	Micro/Nano Heat Transfer.....	157
5.1	PART A—Heat Transfer for Gaseous and Liquid Flow in Microchannels.....	157
5.1.1	Introduction of Heat Transfer in Microchannels.....	157
5.1.2	Fundamentals of Gaseous Flow in Microchannels.....	158
5.1.2.1	Knudsen Number.....	158
5.1.2.2	Velocity Slip.....	160
5.1.2.3	Temperature Jump.....	160
5.1.2.4	Brinkman Number.....	161
5.1.3	Engineering Applications for Gas Flow.....	163
5.1.3.1	Heat Transfer in Gas Flow.....	165
5.1.3.2	Friction Factor.....	169
5.1.3.3	Laminar to Turbulent Transition Regime.....	173
5.1.4	Engineering Applications of Single-Phase Liquid Flow in Microchannels.....	177
5.1.4.1	Nusselt Number and Friction Factor Correlations for Single-Phase Liquid Flow.....	179
5.1.4.2	Roughness Effect on Friction Factor.....	185
5.2	PART B—Single-Phase Convective Heat Transfer with Nanofluids.....	186
5.2.1	Introduction of Convective Heat Transfer with Nanofluids.....	186
5.2.1.1	Particle Materials and Base Fluids.....	187
5.2.1.2	Particle Size and Shape.....	187
5.2.1.3	Nanofluid Preparation Methods.....	188
5.2.2	Thermal Conductivity of Nanofluids.....	188
5.2.2.1	Classical Models.....	189
5.2.2.2	Brownian Motion of Nanoparticles.....	191
5.2.2.3	Clustering of Nanoparticles.....	193
5.2.2.4	Liquid Layering around Nanoparticles.....	196
5.2.3	Thermal Conductivity Experimental Studies of Nanofluids.....	203
5.2.4	Convective Heat Transfer of Nanofluids.....	207
5.2.5	Analysis of Convective Heat Transfer of Nanofluids.....	212
5.2.5.1	Constant Wall Heat Flux Boundary Condition... ..	212
5.2.5.2	Constant Wall Temperature Boundary Condition.....	214
5.2.6	Experimental Correlations of Convective Heat Transfer of Nanofluids.....	216

Nomenclature.....	224
References	228
6. Fouling of Heat Exchangers.....	237
6.1 Introduction.....	237
6.2 Basic Considerations.....	237
6.3 Effects of Fouling	239
6.3.1 Effect of Fouling on Heat Transfer	240
6.3.2 Effect of Fouling on Pressure Drop.....	241
6.3.3 Cost of Fouling	243
6.4 Aspects of Fouling	244
6.4.1 Categories of Fouling	244
6.4.1.1 Particulate Fouling.....	244
6.4.1.2 Crystallization Fouling.....	245
6.4.1.3 Corrosion Fouling	245
6.4.1.4 Biofouling.....	245
6.4.1.5 Chemical Reaction Fouling.....	246
6.4.2 Fundamental Processes of Fouling	246
6.4.2.1 Initiation	246
6.4.2.2 Transport	246
6.4.2.3 Attachment.....	247
6.4.2.4 Removal	247
6.4.2.5 Aging.....	248
6.4.3 Prediction of Fouling.....	248
6.5 Design of Heat Exchangers Subject to Fouling.....	250
6.5.1 Fouling Resistance.....	250
6.5.2 Cleanliness Factor.....	256
6.5.3 Percent over Surface	257
6.5.3.1 Cleanliness Factor	260
6.5.3.2 Percent over Surface.....	260
6.6 Operations of Heat Exchangers Subject to Fouling	262
6.7 Techniques to Control Fouling.....	264
6.7.1 Surface Cleaning Techniques.....	264
6.7.1.1 Continuous Cleaning.....	264
6.7.1.2 Periodic Cleaning.....	264
6.7.2 Additives.....	265
6.7.2.1 Crystallization Fouling.....	265
6.7.2.2 Particulate Fouling.....	266
6.7.2.3 Biological Fouling.....	266
6.7.2.4 Corrosion Fouling	266
Nomenclature.....	266
References	270
7. Double-Pipe Heat Exchangers	273
7.1 Introduction	273

- 7.2 Thermal and Hydraulic Design of Inner Tube 276
- 7.3 Thermal and Hydraulic Analysis of Annulus 278
 - 7.3.1 Hairpin Heat Exchanger with Bare Inner Tube 278
 - 7.3.2 Hairpin Heat Exchangers with Multitube Finned Inner Tubes 283
- 7.4 Parallel–Series Arrangements of Hairpins 291
- 7.5 Total Pressure Drop 294
- 7.6 Design and Operational Features 295
- Nomenclature 297
- References 304

- 8. Design Correlations for Condensers and Evaporators 307**
 - 8.1 Introduction 307
 - 8.2 Condensation 307
 - 8.3 Film Condensation on a Single Horizontal Tube 308
 - 8.3.1 Laminar Film Condensation 308
 - 8.3.2 Forced Convection 309
 - 8.4 Film Condensation in Tube Bundles 312
 - 8.4.1 Effect of Condensate Inundation 313
 - 8.4.2 Effect of Vapor Shear 317
 - 8.4.3 Combined Effects of Inundation and Vapor Shear 317
 - 8.5 Condensation inside Tubes 322
 - 8.5.1 Condensation inside Horizontal Tubes 322
 - 8.5.2 Condensation inside Vertical Tubes 327
 - 8.6 Flow Boiling 329
 - 8.6.1 Subcooled Boiling 329
 - 8.6.2 Flow Pattern 331
 - 8.6.3 Flow Boiling Correlations 334
 - Nomenclature 353
 - References 356

- 9. Shell-and-Tube Heat Exchangers 361**
 - 9.1 Introduction 361
 - 9.2 Basic Components 361
 - 9.2.1 Shell Types 361
 - 9.2.2 Tube Bundle Types 364
 - 9.2.3 Tubes and Tube Passes 366
 - 9.2.4 Tube Layout 368
 - 9.2.5 Baffle Type and Geometry 371
 - 9.2.6 Allocation of Streams 376
 - 9.3 Basic Design Procedure of a Heat Exchanger 378
 - 9.3.1 Preliminary Estimation of Unit Size 380
 - 9.3.2 Rating of the Preliminary Design 386
 - 9.4 Shell-Side Heat Transfer and Pressure Drop 387
 - 9.4.1 Shell-Side Heat Transfer Coefficient 387

9.4.2	Shell-Side Pressure Drop	389
9.4.3	Tube-Side Pressure Drop	390
9.4.4	Bell–Delaware Method.....	395
9.4.4.1	Shell-Side Heat Transfer Coefficient.....	396
9.4.4.2	Shell-Side Pressure Drop	407
	Nomenclature	419
	References	425
10.	Compact Heat Exchangers	427
10.1	Introduction	427
10.1.1	Heat Transfer Enhancement.....	427
10.1.2	Plate-Fin Heat Exchangers.....	431
10.1.3	Tube-Fin Heat Exchangers.....	431
10.2	Heat Transfer and Pressure Drop.....	433
10.2.1	Heat Transfer	433
10.2.2	Pressure Drop for Finned-Tube Exchangers	441
10.2.3	Pressure Drop for Plate-Fin Exchangers	441
	Nomenclature	446
	References	449
11.	Gasketed-Plate Heat Exchangers.....	451
11.1	Introduction	451
11.2	Mechanical Features	451
11.2.1	Plate Pack and the Frame.....	453
11.2.2	Plate Types	455
11.3	Operational Characteristics.....	457
11.3.1	Main Advantages.....	457
11.3.2	Performance Limits	459
11.4	Passes and Flow Arrangements.....	460
11.5	Applications	461
11.5.1	Corrosion.....	462
11.5.2	Maintenance	465
11.6	Heat Transfer and Pressure Drop Calculations.....	466
11.6.1	Heat Transfer Area	466
11.6.2	Mean Flow Channel Gap.....	467
11.6.3	Channel Hydraulic Diameter.....	468
11.6.4	Heat Transfer Coefficient.....	468
11.6.5	Channel Pressure Drop.....	474
11.6.6	Port Pressure Drop	474
11.6.7	Overall Heat Transfer Coefficient.....	475
11.6.8	Heat Transfer Surface Area	475
11.6.9	Performance Analysis	476
11.7	Thermal Performance.....	481
	Nomenclature	484
	References	488

12. Condensers and Evaporators	491
12.1 Introduction.....	491
12.2 Shell and Tube Condensers	492
12.2.1 Horizontal Shell-Side Condensers.....	492
12.2.2 Vertical Shell-Side Condensers	495
12.2.3 Vertical Tube-Side Condensers	495
12.2.4 Horizontal in-Tube Condensers.....	497
12.3 Steam Turbine Exhaust Condensers.....	500
12.4 Plate Condensers.....	501
12.5 Air-Cooled Condensers.....	502
12.6 Direct Contact Condensers	503
12.7 Thermal Design of Shell-and-Tube Condensers	504
12.8 Design and Operational Considerations	515
12.9 Condensers for Refrigeration and Air-Conditioning	516
12.9.1 Water-Cooled Condensers.....	518
12.9.2 Air-Cooled Condensers	519
12.9.3 Evaporative Condensers	519
12.10 Evaporators for Refrigeration and Air-Conditioning	522
12.10.1 Water-Cooling Evaporators (Chillers).....	522
12.10.2 Air-Cooling Evaporators (Air Coolers).....	523
12.11 Thermal Analysis.....	525
12.11.1 Shah Correlation	526
12.11.2 Kandlikar Correlation.....	528
12.11.3 Gngr and Winterton Correlation.....	529
12.12 Standards for Evaporators and Condensers.....	531
Nomenclature.....	536
References	540
13. Polymer Heat Exchangers	543
13.1 Introduction	543
13.2 Polymer Matrix Composite Materials (PMC).....	547
13.3 Nanocomposites.....	551
13.4 Application of Polymers in Heat Exchangers	552
13.5 Polymer Compact Heat Exchangers.....	563
13.6 Potential Applications for Polymer Film Compact Heat Exchangers.....	567
13.7 Thermal Design of Polymer Heat Exchangers.....	570
References	573
Appendix A	577
Appendix B	583
Index	607