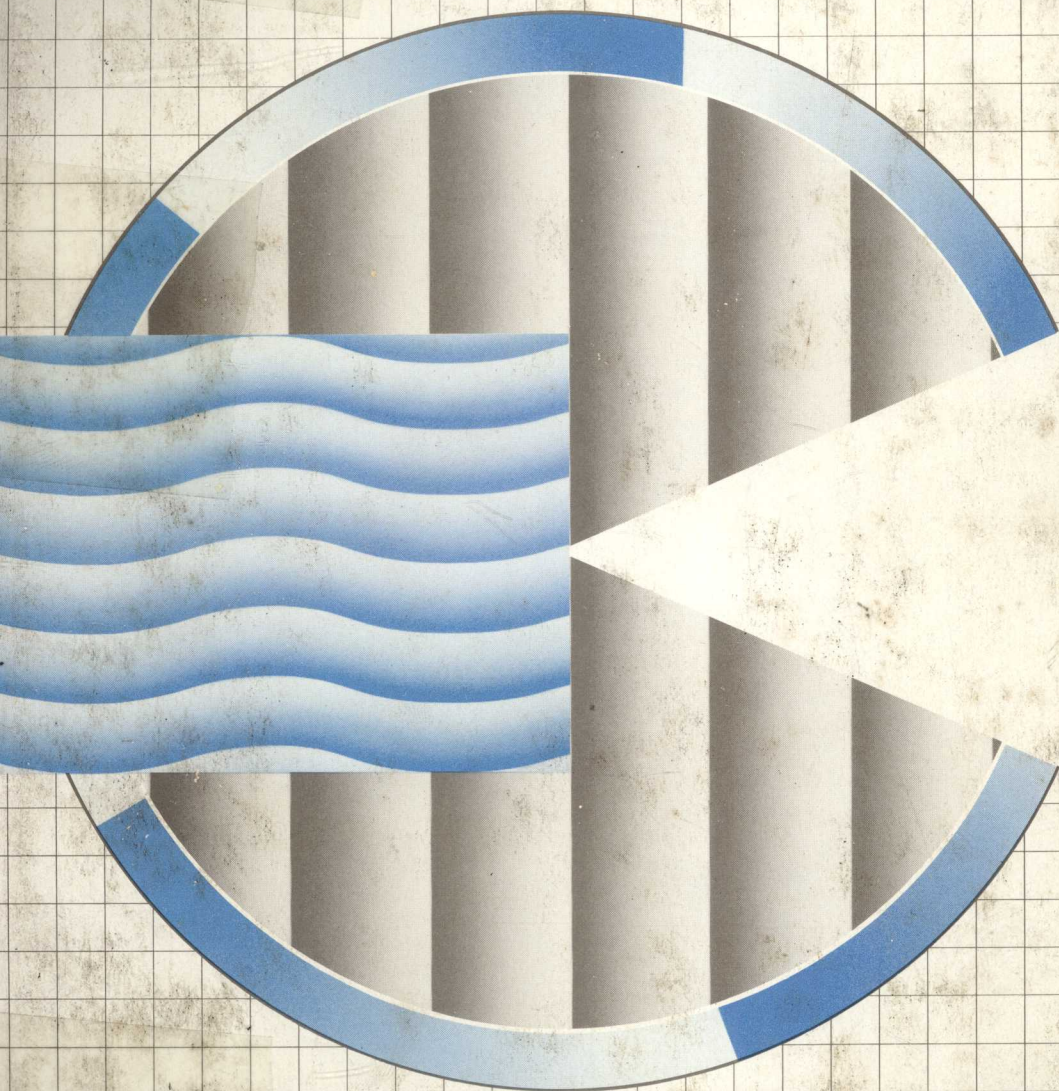


# **REFRIGERATION AND AIR CONDITIONING**



**WILBERT F. STOECKER  
JEROLD W. JONES**

---

# REFRIGERATION AND AIR CONDITIONING

---

Second Edition

**W. F. Stoecker**

*Professor of Mechanical Engineering  
University of Illinois at Urbana-Champaign*

**J. W. Jones**

*Associate Professor of Mechanical Engineering  
University of Texas at Austin*

**McGraw-Hill Book Company**

New York St. Louis San Francisco Auckland Bogotá Hamburg  
Johannesburg London Madrid Mexico Montreal New Delhi  
Panama Paris São Paulo Singapore Sydney Tokyo Toronto

This book was set in Press Roman by Jay's Publishers Services, Inc.  
The editors were Diane D. Heiberg and David A. Damstra;  
the production supervisor was Diane Renda.  
The drawings were done by George Morris, Scientific Illustrators.  
R. R. Donnelley & Sons Company was printer and binder.

## **REFRIGERATION AND AIR CONDITIONING**

Copyright © 1982, 1958 by McGraw-Hill, Inc. All rights reserved.  
Printed in the United States of America. Except as permitted under the United States  
Copyright Act of 1976, no part of this publication may be reproduced or  
distributed in any form or by any means, or stored in a data base or  
retrieval system, without the prior written permission of the publisher.

234567890 DODO 898765432

**ISBN 0-07-061619-1**

### **Library of Congress Cataloging in Publication Data**

Stoecker, W. F. (Wilbert F.), date

Refrigeration and air conditioning.

(McGraw-Hill series in mechanical engineering)

Includes bibliographical references and indexes.

1. Refrigeration and refrigerating machinery.

2. Air conditioning. I. Jones, J. W. (Jerold W.)

II. Title. III. Series.

TP492.S8 1982 621.5'6 81-19385

ISBN 0-07-061619-1 AACR2

---

# REFRIGERATION AND AIR CONDITIONING

---

## **McGraw-Hill Series in Mechanical Engineering**

**Jack P. Holman**, *Southern Methodist University*  
*Consulting Editor*

- Anderson:** *Modern Compressible Flow: With Historical Perspective*  
**Barron:** *Cryogenic Systems*  
**Eckert:** *Introduction to Heat and Mass Transfer*  
**Eckert and Drake:** *Analysis of Heat and Mass Transfer*  
**Eckert and Drake:** *Heat and Mass Transfer*  
**Ham, Crane, and Rogers:** *Mechanics of Machinery*  
**Hartenberg and Denavit:** *Kinematic Synthesis of Linkages*  
**Hinze:** *Turbulence*  
**Hutton:** *Applied Mechanical Vibrations*  
**Jacobsen and Ayre:** *Engineering Vibrations*  
**Juvinall:** *Engineering Considerations of Stress, Strain, and Strength*  
**Kays and Crawford:** *Convective Heat and Mass Transfer*  
**Lichty:** *Combustion Engine Processes*  
**Martin:** *Kinematics and Dynamics of Machines*  
**Phelan:** *Dynamics of Machinery*  
**Phelan:** *Fundamentals of Mechanical Design*  
**Pierce:** *Acoustics: An Introduction to Its Physical Principles and Applications*  
**Raven:** *Automatic Control Engineering*  
**Schenck:** *Theories of Engineering Experimentation*  
**Schlichting:** *Boundary-Layer Theory*  
**Shames:** *Mechanics of Fluids*  
**Shigley:** *Dynamic Analysis of Machines*  
**Shigley:** *Kinematic Analysis of Mechanisms*  
**Shigley:** *Mechanical Engineering Design*  
**Shigley:** *Simulation of Mechanical Systems*  
**Shigley and Uicker:** *Theory of Machines and Mechanisms*  
**Stoecker and Jones:** *Refrigeration and Air Conditioning*

---

## PREFACE

---

There are conventional as well as special reasons for writing a second edition of "Refrigeration and Air Conditioning." The conventional reason is that in the 24 years since the appearance of the first edition some of the equipment and systems have slipped to lesser importance while new products and concepts have emerged. An updating is therefore timely. A special reason for a new edition is the impact that energy effectiveness now exerts on heating and cooling systems. Energy consciousness has perceptibly changed the equipment and design concepts in refrigeration and air conditioning. Also, since most engineers predict that the days of low-cost energy will never return, energy-conservative strategies are now permanent.

The second edition differs from the first in the following major ways. A heavier presentation of air-conditioning *systems* is provided, but the technical emphasis on vapor-compression systems is not only maintained but strengthened. The new material directed toward the air conditioning of buildings replaces several chapters (cryogenics, steam jet, and air-cycle) which are of admitted importance, but the engineering of these systems in professional practice is normally handled by other engineers than those working in comfort air conditioning and industrial refrigeration and air conditioning. The digital computer is now a standard tool of engineers, and where appropriate calculations and problems use the computer.

Some sections and particularly the style of the first edition have been maintained. The first edition achieved a certain degree of acceptance throughout the world and apparently meets the need of those seeking a technical book that goes beyond pure descriptions into quantitative treatment of the subjects. At the same time the second edition attempts to maintain an emphasis on qualitative evaluations and trends, yet introducing no additional complexity unless there is a payoff of improved understanding.



## xvi PREFACE

The authors are indebted to numerous professional associates whose views have influenced the topic selection, emphases, and technical presentations in this book. Special thanks are due the following colleagues: Larry G. Berglund, John B. Pierce Foundation; John C. Chato, University of Illinois at Urbana-Champaign; Arthur M. Clausing, University of Illinois at Urbana-Champaign; James E. Shahan, Transco, Inc.; Gary C. Vliet, University of Texas at Austin; and James E. Woods, Iowa State University.

*W. F. Stoecker*

*J. W. Jones*

---

# CONTENTS

---

## Preface

xv

## Chapter 1 Applications of Refrigeration and Air Conditioning

	1
1-1 Major Uses	1
1-2 Air Conditioning of Medium-Sized and Large Buildings	2
1-3 Industrial Air Conditioning	3
1-4 Residential Air Conditioning	4
1-5 Air Conditioning of Vehicles	5
1-6 Food Storage and Distribution	6
1-7 Food Processing	8
1-8 Chemical and Process Industries	8
1-9 Special Applications of Refrigeration	9
1-10 Conclusion	12
References	12

## Chapter 2 Thermal Principles

	13
2-1 Roots of Refrigeration and Air Conditioning	13
2-2 Concepts, Models, and Laws	13
2-3 Thermodynamic Properties	14
2-4 Thermodynamic Processes	18
2-5 Conservation of Mass	19
2-6 Steady-Flow Energy Equation	20
2-7 Heating and Cooling	21
2-8 Adiabatic Processes	22
2-9 Compression Work	22



## vi CONTENTS

2-10	Isentropic Compression	22
2-11	Bernoulli's Equation	23
2-12	Heat Transfer	24
2-13	Conduction	24
2-14	Radiation	25
2-15	Convection	26
2-16	Thermal Resistance	28
2-17	Cylindrical Cross Section	33
2-18	Heat Exchangers	33
2-19	Heat-Transfer Processes Used by the Human Body	34
2-20	Metabolism	35
2-21	Convection	36
2-22	Radiation	36
2-23	Evaporation	36
	Problems	37
	References	39
<b>Chapter 3</b>	<b>Psychrometry and Wetted-Surface Heat Transfer</b>	<b>40</b>
3-1	Importance	40
3-2	Psychrometric Chart	40
3-3	Saturation Line	42
3-4	Relative Humidity	42
3-5	Humidity Ratio	43
3-6	Enthalpy	44
3-7	Specific Volume	46
3-8	Combined Heat and Mass Transfer; the Straight-Line Law	47
3-9	Adiabatic Saturation and Thermodynamic Wet-Bulb Temperature	48
3-10	Deviation between Enthalpy and Wet-Bulb Lines	49
3-11	Wet-Bulb Thermometer	50
3-12	Processes	51
3-13	Comment on the Basis of 1 kg of Dry Air	53
3-14	Transfer of Sensible and Latent Heat with a Wetted Surface	53
3-15	Enthalpy Potential	54
3-16	Insights Provided by Enthalpy Potential	55
	Problems	56
	References	58
<b>Chapter 4</b>	<b>Heating- and Cooling-Load Calculations</b>	<b>59</b>
4-1	Introduction	59
4-2	Health and Comfort Criteria	59
4-3	Thermal Comfort	59
4-4	Air Quality	61
4-5	Estimating Heat Loss and Heat Gain	63
4-6	Design Conditions	64
4-7	Thermal Transmission	66
4-8	Infiltration and Ventilation Loads	69
4-9	Summary of Procedure for Estimating Heating Loads	70

4-10	Components of the Cooling Load	71
4-11	Internal Loads	71
4-12	Solar Loads through Transparent Surfaces	73
4-13	Solar Loads on Opaque Surfaces	79
4-14	Summary of Procedures for Estimating Cooling Loads	84
	Problems	85
	References	86
<b>Chapter 5</b>	<b>Air-Conditioning Systems</b>	<b>88</b>
5-1	Thermal Distribution Systems	88
5-2	Classic Single-Zone System	89
5-3	Outdoor-Air Control	90
5-4	Single-Zone-System Design Calculations	92
5-5	Multiple-Zone Systems	95
5-6	Terminal-Reheat System	95
5-7	Dual-Duct or Multizone System	96
5-8	Variable-Air-Volume Systems	97
5-9	Water Systems	100
5-10	Unitary Systems	101
	Problems	101
	References	102
<b>Chapter 6</b>	<b>Fan and Duct Systems</b>	<b>103</b>
6-1	Conveying Air	103
6-2	Pressure Drop in Straight Ducts	103
6-3	Pressure Drop in Rectangular Ducts	106
6-4	Pressure Drop in Fittings	109
6-5	The $V^2\rho/2$ Term	109
6-6	Sudden Enlargement	110
6-7	Sudden Contraction	111
6-8	Turns	113
6-9	Branch Takeoffs	114
6-10	Branch Entries	116
6-11	Design of Duct Systems	117
6-12	Velocity Method	117
6-13	Equal-Friction Method	118
6-14	Optimization of Duct Systems	119
6-15	System Balancing	120
6-16	Centrifugal Fans and Their Characteristics	120
6-17	Fan Laws	123
6-18	Air Distribution in Rooms	124
6-19	Circular and Plane Jets	125
6-20	Diffusers and Induction	127
	Problems	127
	References	129
<b>Chapter 7</b>	<b>Pumps and Pumping</b>	<b>130</b>
7-1	Water and Refrigerant Piping	130
7-2	Comparison of Water and Air as Heat-Conveying Media	131

## **viii CONTENTS**

7-3	Water Heaters	132
7-4	Heat Distribution from Hot-Water Systems	133
7-5	High-Temperature Water Systems	134
7-6	Available Pipe and Tubing	135
7-7	Pressure Drop of Water Flowing in Pipes	136
7-8	Pressure Drop in Fittings	137
7-9	Refrigerant Piping	137
7-10	Pump Characteristics and Selection	140
7-11	Design of a Water-Distribution System	142
7-12	Sizing the Expansion Tank	144
	Problems	145
	References	146
<b>Chapter 8</b>	<b>Cooling and Dehumidifying Coils</b>	<b>147</b>
8-1	Types of Cooling and Dehumidifying Coils	147
8-2	Terminology	147
8-3	Condition of Air Passing through the Coil (Ideal)	148
8-4	Heat and Mass Transfer	149
8-5	Calculating the Surface Area of a Coil	151
8-6	Moisture Removal	153
8-7	Actual Coil Condition Curves	154
8-8	Solving for Outlet Conditions	155
8-9	Partially Dry Coil	155
8-10	Coil Performance from Manufacturers' Catalogs	157
	Problems	158
	References	160
<b>Chapter 9</b>	<b>Air-Conditioning Controls</b>	<b>161</b>
9-1	What Controls Do	161
9-2	Pneumatic, Electric, and Electronic Control	162
9-3	Pneumatic Control Hardware	162
9-4	Direct- and Reverse-Acting Thermostats	163
9-5	Temperature Transmitter with Receiver-Controller	164
9-6	Liquid Valves	165
9-7	Fail-Safe Design	167
9-8	Throttling Range	168
9-9	Dampers	169
9-10	Outdoor-Air Control	170
9-11	Freeze Protection	172
9-12	Sequencing of Operations	172
9-13	Other Valves, Switches, and Controls	173
9-14	Building Up a Control System	175
9-15	Humidistats and Humidifiers	176
9-16	Master and Submaster Thermostats	177
9-17	Summer-Winter Changeover	179
9-18	Valve Characteristics and Selection	180
9-19	Stability of Air-Temperature Control Loops	182
9-20	Temperature Reset Based on Zone Load	183

9-21	Electric, Electronic, and Computer Control	184
	Problems	184
	References	186
<b>Chapter 10</b>	<b>The Vapor-Compression Cycle</b>	<b>187</b>
10-1	Most Important Refrigeration Cycle	187
10-2	Carnot Refrigeration Cycle	187
10-3	Coefficient of Performance	188
10-4	Refrigerant	190
10-5	Conditions for Highest Coefficient of Performance	190
10-6	Temperature Limitations	191
10-7	Carnot Heat Pump	192
10-8	Using Vapor as a Refrigerant	193
10-9	Revisions of the Carnot Cycle	193
10-10	Wet Compression versus Dry Compression	193
10-11	Expansion Process	195
10-12	Standard Vapor-Compression Cycle	195
10-13	Properties of Refrigerants	196
10-14	Performance of the Standard Vapor-Compression Cycle	197
10-15	Heat Exchangers	200
10-16	Actual Vapor-Compression Cycle	202
	Problems	203
	Reference	204
<b>Chapter 11</b>	<b>Compressors</b>	<b>205</b>
11-1	Types of Compressors	205
	<i>Part I: Reciprocating Compressors</i>	205
11-2	Hermetically Sealed Compressors	206
11-3	Condensing Units	207
11-4	Performance	207
11-5	Volumetric Efficiency	207
11-6	Performance of the Ideal Compressor	210
11-7	Power Requirement	211
11-8	Refrigeration Capacity	213
11-9	Coefficient of Performance and Volume Flow Rate per Kilowatt of Refrigeration	213
11-10	Effect of Condensing Temperature	215
11-11	Performance of Actual Reciprocating Compressors	216
11-12	Actual Volumetric Efficiency	217
11-13	Compression Efficiency	217
11-14	Compressor Discharge Temperatures	218
11-15	Capacity Control	219
	<i>Part II: Rotary Screw Compressors</i>	220
11-16	How the Screw Compressor Functions	220
11-17	Performance Characteristics of Screw Compressors	222
11-18	Capacity Control	222
	<i>Part III: Vane Compressors</i>	222

11-19	Vane Compressors	222
	<i>Part IV: Centrifugal Compressors</i>	224
11-20	Role of Centrifugal Compressors	224
11-21	Operation	225
11-22	Flash-Gas Removal	225
11-23	Performance Characteristics	225
11-24	Tip Speed to Develop Pressure	226
11-25	Choice of Impeller and Refrigerant	227
11-26	Surging	228
11-27	Capacity Control	229
11-28	How Various Types of Compressors Share the Field	230
	Problems	231
	References	231
<b>Chapter 12</b>	<b>Condensers and Evaporators</b>	<b>233</b>
12-1	Condensers and Evaporators as Heat Exchangers	233
12-2	Overall Heat-Transfer Coefficient	233
12-3	Liquid in Tubes; Heat Transfer and Pressure Drop	236
12-4	Liquid in Shell; Heat Transfer and Pressure Drop	238
12-5	Extended Surface; Fins	239
12-6	Gas Flowing over Finned Tubes; Heat Transfer and Pressure Drop	243
12-7	Condensers	244
12-8	Required Condensing Capacity	244
12-9	Condensing Coefficient	245
12-10	Fouling Factor	247
12-11	Desuperheating	247
12-12	Condenser Design	248
12-13	Wilson Plots	251
12-14	Air and Noncondensables	252
12-15	Evaporators	252
12-16	Boiling in the Shell	254
12-17	Boiling Inside Tubes	255
12-18	Evaporator Performance	256
12-19	Pressure Drop in Tubes	256
12-20	Frost	257
	Problems	257
	References	259
<b>Chapter 13</b>	<b>Expansion Devices</b>	<b>260</b>
13-1	Purpose and Types of Expansion Devices	260
13-2	Capillary Tubes	260
13-3	Selection of a Capillary Tube	263
13-4	Analytical Computation of Pressure Drop in a Capillary Tube	264
13-5	Calculating the Length of an Increment	266
13-6	Choked Flow	268
13-7	Graphical Method of Capillary-Tube Selection	270
13-8	Constant-Pressure Expansion Valve	271

13-9	Float Valves	272
13-10	Superheat-Controlled (Thermostatic) Expansion Valve	273
13-11	Manufacturers' Ratings of Thermostatic Expansion Valves	275
13-12	Electric Expansion Valves	278
13-13	Application	278
	Problems	279
	References	280
<b>Chapter 14</b>	<b>Vapor-Compression-System Analysis</b>	<b>281</b>
14-1	Balance Points and System Simulation	281
14-2	Reciprocating Compressor	282
14-3	Condenser Performance	284
14-4	Condensing-Unit Subsystem; Graphic Analysis	284
14-5	Condensing-Unit Subsystem; Mathematical Analysis	286
14-6	Evaporator Performance	288
14-7	Performance of Complete System; Graphic Analysis	289
14-8	Simulation of Complete System; Mathematical Analysis	290
14-9	Some Performance Trends	291
14-10	The Expansion Device	292
14-11	Sensitivity Analysis	293
	Problems	294
	References	295
<b>Chapter 15</b>	<b>Refrigerants</b>	<b>296</b>
15-1	Primary and Secondary Refrigerants	296
15-2	Halocarbon Compounds	296
15-3	Inorganic Compounds	297
15-4	Hydrocarbons	297
15-5	Azeotropes	297
15-6	Thermodynamic Comparison of Some Common Refrigerants	297
15-7	Physical and Chemical Comparison	299
15-8	Thermal Conductivity and Viscosity of Refrigerants	300
15-9	Ozone Depletion	300
15-10	Basis of Choice of Refrigerant	301
15-11	Secondary Refrigerants	301
	Problems	306
	References	307
<b>Chapter 16</b>	<b>Multipressure Systems</b>	<b>308</b>
16-1	Multipressure Systems in Industrial Refrigeration	308
16-2	Removal of Flash Gas	308
16-3	Intercooling	310
16-4	One Evaporator and One Compressor	314
16-5	Two Evaporators and One Compressor	315
16-6	Two Compressors and One Evaporator	317
16-7	Two Compressors and Two Evaporators	319
16-8	Auxiliary Equipment	323
16-9	Compound Compressors	323

16-10	Liquid-Recirculation Systems	323
16-11	Summary	324
	Problems	325
<b>Chapter 17</b>	<b>Absorption Refrigeration</b>	<b>328</b>
17-1	Relation of the Absorption to the Vapor-Compression Cycle	328
17-2	The Absorption Cycle	329
17-3	Coefficient of Performance of the Ideal Absorption Cycle	330
17-4	Temperature-Pressure-Concentration Properties of LiBr-Water Solutions	331
17-5	Calculation of Mass Flow Rates in the Absorption Cycle	333
17-6	Enthalpy of LiBr Solution	334
17-7	Thermal Analysis of Simple Absorption System	336
17-8	Absorption Cycle with Heat Exchangers	336
17-9	Configuration of Commercial Absorption Units	338
17-10	Crystallization	339
17-11	Capacity Control	341
17-12	Double-Effect System	344
17-13	Steam-Driven Combination with Vapor Compression	344
17-14	Aqua-Ammonia System	347
17-15	Role of the Absorption Unit in Refrigeration Practice	348
	Problems	349
	References	350
<b>Chapter 18</b>	<b>Heat Pumps</b>	<b>351</b>
18-1	Types of Heat Pumps	351
18-2	Package Type, Reversible Cycle	351
18-3	Heat Sources and Sinks for Package-Type Reversible Heat Pumps	353
18-4	Heating Performance of an Air-Source Heat Pump	354
18-5	Comparative Heating Costs	356
18-6	Matching Heating Capacity to the Heating Load	356
18-7	Sizing the Heat Pump	357
18-8	Decentralized Heat Pump	358
18-9	Double-Bundle Condenser	359
18-10	Industrial Heat Pumps	361
18-11	The Future of the Heat Pump	362
	Problems	363
	References	364
<b>Chapter 19</b>	<b>Cooling Towers and Evaporative Condensers</b>	<b>365</b>
19-1	Heat Rejection to Atmosphere	365
19-2	Cooling Towers	365
19-3	Analysis of Counterflow Cooling Tower	367
19-4	Stepwise Integration	368
19-5	Acceptance Tests	371
19-6	Predicting Outlet Conditions from a Tower	372
19-7	State Points of Air through a Cooling Tower	372



19-8	Crossflow Cooling Towers	374
19-9	Evaporative Condensers and Coolers	376
19-10	When to Use a Cooling Tower and Evaporative Condenser or Cooler	377
	Problems	378
	References	378
<b>Chapter 20</b>	<b>Solar Energy</b>	<b>380</b>
20-1	Some Fields of Solar Energy	380
20-2	Radiation Intensity: An Overview	381
20-3	Solar Geometry	381
20-4	Direct Radiation from the Sun, $I_{DN}$	384
20-5	Glazing Characteristics	385
20-6	Solar Collectors	386
20-7	Thermal Storage	390
20-8	Integration of Solar and Building Systems	392
20-9	Passive Solar Design	395
20-10	Economics of Solar Installations	399
	Problems	399
	References	400
<b>Chapter 21</b>	<b>Acoustics and Noise Control</b>	<b>401</b>
21-1	The Study of Sound and Acoustics	401
21-2	One-Dimensional Sound Waves	402
21-3	Standing Waves	403
21-4	Energy in a Sound Wave	404
21-5	Intensity, Power, and Pressure	404
21-6	Sound Power Level	406
21-7	Intensity Level and Sound Pressure Level	406
21-8	Sound Spectrum	407
21-9	Combination of Sound Sources	407
21-10	Absorptivity	409
21-11	Room Characteristics	411
21-12	Acoustic Design in Buildings	412
21-13	Fan- and Air-Noise Transmission in Ducts	413
21-14	Conclusions	414
	Problems	414
	References	415
	<b>Appendix</b>	<b>416</b>
Table A-1	Water: Properties of Liquid and Saturated Vapor	416
Table A-2	Moist Air 2: Thermodynamic Properties of Saturated Air at Atmospheric Pressure of 101.325 kPa	418
Table A-3	Ammonia: Properties of Liquid and Saturated Vapor 3	420
Table A-4	Refrigerant 11: Properties of Liquid and Saturated Vapor 4	422
Table A-5	Refrigerant 12: Properties of Liquid and Saturated Vapor 5	424
Table A-6	Refrigerant 22: Properties of Liquid and Saturated Vapor 6	426

**xiv CONTENTS**

Table A-7	Refrigerant 22: Properties of Superheated Vapor 6	428
Table A-8	Refrigerant 502: Properties of Liquid and Saturated Vapor 7	431
Figure A-1	Pressure-Enthalpy Diagram of Superheated Ammonia Vapor	433
Figure A-2	Pressure-Enthalpy Diagram of Superheated Refrigerant 11 Vapor	434
Figure A-3	Pressure-Enthalpy Diagram of Superheated Refrigerant 12 Vapor	435
Figure A-4	Pressure-Enthalpy Diagram of Superheated Refrigerant 22 Vapor	436
Figure A-5	Pressure-Enthalpy Diagram of Superheated Refrigerant 502 Vapor	437
	References	438
Indexes		439
	Name Index	
	Subject Index	