

Contents

List of Contributors xi

Preface xiii

1	Introduction	1
	<i>Xin-Rong Zhang</i>	
1.1	Background	1
1.1.1	Energy Shortage and Energy-Saving Technology – Heat Pump	1
1.1.2	Heat Pump Challenges and Natural Refrigerants	2
1.1.3	One of the Most Potential Natural Refrigerants – Carbon Dioxide (CO ₂)	3
1.1.4	Motivation for This Book	5
1.2	Fundamentals	5
1.2.1	Operating Processes of the Basic Transcritical CO ₂ Cycle	7
1.2.2	Characteristics of Transcritical CO ₂ Cycles	9
1.2.3	Modifications of Transcritical CO ₂ Cycles	10
1.3	Applications	11
1.4	A Guide to This Book	14
	References	14
2	Current Development of CO₂ Heat Pump	17
	<i>Hiroshi Yamaguchi and Xin-Rong Zhang</i>	
2.1	Introduction	17
2.2	CO ₂ Properties	20
2.3	Working Principle of Transcritical CO ₂ Heat Pump	25
2.4	A Brief History of CO ₂ Heat Pump	29
2.5	CO ₂ Cascade Heat Pump System	30
2.6	Advanced CO ₂ Heat Pump System with an Ejector	36
	Acknowledgments	38
	Nomenclature	38
	Greek Letters	39
	Subscripts	39
	Abbreviations	39
	References	40

3	Fluid Dynamics and Heat Transfer of Supercritical Carbon Dioxide Cooling	43
	<i>Brian M. Fronk</i>	
3.1	Supercritical Properties	43
3.2	Supercritical Heat Transfer Fluid Mechanics	44
3.2.1	Buoyancy, Flow Acceleration and Oscillations in Near-Critical Flows	45
3.2.2	Outline of Remainder of Chapter	47
3.3	Supercritical Gas Cooling Experiments	48
3.3.1	Single-Tube Studies	48
3.3.2	Mini/Microchannel Studies	50
3.3.3	Summary of Experimentally Observed Effects	50
3.4	Supercritical CO ₂ Heat Transfer Correlations	53
3.4.1	Constant Property Turbulent Correlations	54
3.4.2	Krasnoschekov et al. (1970) Correlation	54
3.4.3	Ghajar and Asadi (1986) Correlation	55
3.4.4	Pitla et al. (2002) Correlation	56
3.4.5	Son and Park (2006) Correlation	56
3.4.6	Oh and Son (2010) Correlation	56
3.4.7	Microchannel Correlations	57
3.4.8	Comparison of Correlations	58
3.5	Supercritical CO ₂ Pressure Drop	58
3.6	Supercritical CO ₂ Heat Transfer and Pressure Drop with Lubricants	60
3.6.1	CO ₂ /Lubricant Pressure Drop Correlations	61
3.6.2	CO ₂ /Lubricant Heat Transfer Correlations	62
3.7	Summary and Need for Additional Research	62
3.7	Nomenclature	63
3.7	Greek Symbols	63
3.7	Subscripts	64
	References	64
4	Boiling Flow and Heat Transfer of CO₂ in an Evaporator	73
	<i>Haruhiko Yamasaki</i>	
4.1	Introduction	73
4.2	Boiling Heat Transfer of Liquid CO ₂ in an Evaporator	76
4.3	Sublimation Heat Transfer of Dry Ice-Gas CO ₂ in an Evaporator/Sublimator	85
	Acknowledgments	92
	Nomenclature	92
	Greek Symbols	93
	Subscripts	93
	References	93
5	Theoretical Analysis of the CO₂ Expansion Process	99
	<i>Ammar M. Bahman, Riley B. Barta, Eckhard A. Groll and Davide Ziviani</i>	
5.1	Introduction	99

5.2	Thermodynamic Analysis of the Expansion Process in Transcritical CO ₂ Cycles	100
5.2.1	Thermodynamic Losses	100
5.2.2	Effect of Expansion Process	102
5.2.3	Real Transcritical CO ₂ Expansion	108
5.3	Theory of Ejector-Expansion Devices	111
5.3.1	One-Dimensional Ejector Flow Model	113
5.3.1.1	Critical Two-Phase Flow Model	114
5.3.1.2	Motive Nozzle Flow Model	116
5.3.1.3	Suction Nozzle Flow Model	116
5.3.1.4	Mixing Section Flow Model	117
5.3.1.5	Diffuser Flow Model	118
5.3.2	Ejector Efficiencies	118
5.4	Expansion Work Recovery Devices for Transcritical CO ₂ Systems	119
5.4.1	Positive Displacement Expanders	120
5.4.1.1	Reciprocating Expanders	120
5.4.1.2	Rolling Piston and Rotary Vane Expanders	121
5.4.1.3	Scroll Expanders	122
5.4.1.4	Screw Expanders	125
5.4.2	Turbine-Type Expanders	127
	Nomenclature	131
	Greek Symbols	132
	Subscripts	132
	References	133
6	Transcritical Carbon Dioxide Compressors	137
	<i>Xin-Rong Zhang</i>	
6.1	Introduction	137
6.2	Sliding Vane CO ₂ Compressor	138
6.3	Screw CO ₂ Compressor	140
6.4	CO ₂ Rolling Rotor Compressor	141
6.4.1	CO ₂ Compressors Developed by the Company	141
6.4.2	Two-Stage Rolling Piston CO ₂ Compressor	142
6.5	SCO ₂ Scroll Compressor	143
6.6	SCO ₂ Turbo-Compressor	145
6.6.1	SCO ₂ Turbo-Compressor Applications and Challenges	145
6.6.2	The Two-Phase Axial-Flow Turbine	146
6.6.3	Application of Transcritical Turbine to CO ₂ Refrigeration Systems	148
6.7	SCO ₂ Piston Compressor	149
6.7.1	CO ₂ Challenges from a Compressor Perspective	149
6.7.1.1	High Polytropic Exponent and Discharge Temperatures	150
6.7.1.2	Lubricant	151
6.7.1.3	Discharge Plenum	151
6.7.1.4	Pistons and Compression Rings	152
6.7.2	Design Pressures	153

6.7.2.1	Materials	154
6.7.2.2	Wall Thickness and Envelope Shapes	155
6.7.2.3	Safety Valves	155
6.7.3	Performances	155
6.8	Future Trends	156
6.8.1	Two-Stage Compressor	156
6.8.2	Expander and Expander-Compressor	159
6.9	Some Key Technical Problems of CO ₂ Compressor	160
6.9.1	Mechanical Strength	160
6.9.2	Lubricant Problems	160
6.9.2.1	Miscibility of Lubricant and CO ₂	160
6.9.2.2	Lubricant Stability	161
6.9.2.3	Choice of Lubricant	161
6.9.3	Oil Dilution	162
6.9.4	Large Pressure Differences	162
6.9.4.1	Wrist Pin	162
6.9.4.2	Connecting Rod	164
6.9.4.3	Crankshaft	164
6.9.4.4	Bearings	164
6.9.4.5	Valve Plate	165
6.10	Conclusion and Perspectives	165
	Nomenclature	166
	References	166
7	CO₂ Subcooling	171
	<i>Rodrigo Llopis, Daniel Sánchez, Laura Nebot-Andrés, Jesús Catalán-Gil and Ramón Cabello</i>	
7.1	Introduction	171
7.2	CO ₂ Thermodynamic Properties and Approach	175
7.2.1	Thermodynamic Properties of CO ₂	175
7.2.2	CO ₂ Subcooling Approach	180
7.2.2.1	Subcritical CO ₂ Subcooling	182
7.2.2.2	Transcritical CO ₂ Subcooling	183
7.2.3	Benefits of Subcooling	184
7.2.3.1	Second Law Approach	185
7.2.3.2	Capacity	186
7.2.3.3	COP	187
7.2.3.4	Energy Input	188
7.2.4	Subcooling Optimization	188
7.3	Internal Heat Exchanger	189
7.3.1	Introduction	189
7.3.2	Description and Operation	189
7.3.3	Revision of Research of IHX	192
7.3.3.1	Predicting Methods	192
7.3.3.2	Theoretical and Experimental Analysis	193

7.3.4	Experimental Analysis	197
7.3.4.1	Refrigerant System	197
7.3.4.2	Experimental Results and Discussion	198
7.4	Dedicated Mechanical Subcooling	201
7.4.1	Optimum Parameters of the DMS Cycle	205
7.4.1.1	Subcooling Degree	205
7.4.1.2	Heat Rejection Pressure	207
7.4.2	Theoretical Studies	209
7.4.3	Experimental Studies	210
7.5	Integrated Mechanical Subcooling	212
7.5.1	Optimum Parameters of the IMS Cycle	215
7.5.1.1	Subcooling Degree	215
7.5.1.2	Heat Rejection Pressure	216
7.5.2	Theoretical Studies	219
7.6	Summary	219
	Nomenclature	220
	Greek Symbols	220
	Subscripts	221
	References	221
8	High Temperature CO₂ Heat Pump System and Optimization	229
	<i>Lin Chen and Dipankar N. Basu</i>	
8.1	Background	229
8.2	Basic System Design	230
8.2.1	Key Features in High Temperature CO ₂ Heat Pump	230
8.2.2	Overall System Design	231
8.2.3	Real System Construction	231
8.3	High Temperature Operation and Key Equipment	232
8.3.1	Basic High Temperature CO ₂ Heat Pump Operations	232
8.3.1.1	Water Source Heat Pump	233
8.3.1.2	Air Source Heat Pump	234
8.3.1.3	Ground Source Heat Pump	234
8.3.1.4	Hybrid Heat Pump	234
8.3.2	Compressors	234
8.3.3	Heat Exchanger/Gas Cooler	236
8.3.4	Expander	238
8.4	System Optimization	238
8.4.1	Basic System Components Optimization	238
8.4.2	Discharge Pressure Optimization	238
8.4.3	System Optimization	239
8.5	Applications and Challenges	239
8.5.1	Heating and Cooling	239
8.5.2	Other Industrial Sectors	240
8.5.3	COP Analysis and Comparison	241
8.6	Commercialized Products by High Temperature CO ₂ Heat Pump	242

8.7	Summary	243
	Acknowledgments	243
	Nomenclature	244
	Greek Symbols	244
	Subscripts	244
	References	245

9 Performance Analysis and Optimization of a CO₂ Heat Pump Water Heating System 249

Ryohei Yokoyama

9.1	Introduction	249
9.2	System Configuration	250
9.3	System Modeling	251
9.4	Numerical Solution	252
9.5	Conditions for Performance Analysis and Optimization	253
9.6	Performance Analysis Under Periodically Steady State	256
9.7	Performance Enhancement by Extracting Tepid Water	261
9.8	Performance Analysis Under Unsteady State	266
9.9	Performance Estimation Under Unsteady State	268
9.10	Performance Optimization Under Unsteady State	273
9.11	Other Issues on Performance Analysis and Optimization	278
	Nomenclature	280
	Subscripts	281
	Abbreviations	281
	References	281

10 Transcritical CO₂ Heat Pump Space Heating 283

Feng Cao and Yulong Song

10.1	Attempts Toward Space Heating Used a Transcritical CO ₂ Heat Pump	283
10.2	Thermodynamic Analysis of the Subcooler-Based CO ₂ Heat Pump	287
10.3	Comparison Between the Subcooler-Based CO ₂ System and the Cascade Cycle	289
10.4	Optimal Discharge Pressure	292
10.5	Optimal Medium Temperature	295
10.6	Conclusion and Prospects	296
	References	298

Index 299