

Contents

Preface *xix*

Acknowledgments *xxi*

Symbols, Signs, and Abbreviations *xxiii*

1 Introduction *1*

1.1 Historical Background *3*

1.2 Cryogenic Applications *5*

1.2.1 Natural Gas Liquefaction *6*

1.2.2 Cryogenic Air Separation *6*

1.2.3 Helium Plants *7*

1.2.4 Aerospace *7*

1.2.5 Physics *7*

1.2.6 Medical Applications *8*

1.2.7 Liquid Hydrogen for Hydrogen Economy *8*

1.2.8 Devices Based on High-temperature Superconductors for Electrical Engineering *8*

References *9*

2 Basics of Process Design *11*

2.1 Design Procedure *12*

2.2 Process Simulators and Fluid Properties *15*

2.3 Optimization *15*

2.4 Control Concept *17*

References *18*

3 Cryogenic Fluids *19*

3.1 Air *19*

3.2 Nitrogen *22*

3.3 Oxygen *23*

3.4 Argon *24*

3.5 Methane *25*

3.6 Neon *26*

3.7	Hydrogen	27
3.7.1	Spin Isomers of Hydrogen (Ortho- and Para-Hydrogen)	28
3.7.2	Consequences for Liquefaction Processes	30
3.8	Helium	31
3.8.1	Phase Diagram (Pressure–Temperature Diagram) and Lambda Line	32
3.8.2	Superfluidity	32
3.8.3	High Thermal Conductivity of Superfluid	33
3.9	Temperature–Enthalpy Diagram	34
3.10	Temperature–Entropy Diagram	36
	References	38
4	Reversibility Concept	39
4.1	Reversibility and Irreversibility	39
4.1.1	Irreversibility	39
4.1.2	Reversibility	40
4.2	Carnot Engine	40
4.3	Reversible Process as Benchmark	42
4.4	Entropy	42
4.4.1	Entropy According to Rudolf Clausius	42
4.4.1.1	Extension of the Clausius Definition	43
4.4.2	Entropy According to Boltzmann	44
4.4.3	Entropy for Thermodynamic Analysis	44
4.5	Exergy Concept	45
4.5.1	Exergy of Mechanical and Electrical Energy	45
4.5.2	Exergy of Heat/Heat Flow	46
4.5.3	Exergy of Cold/Cooling Power	47
4.5.4	Exergy of Material/Material Stream	47
4.5.5	Reference States	48
4.5.6	Exergy for Multicomponent Materials/Material Flows	49
4.6	Application of Exergy Concept for Thermodynamic Analysis, Exergy Loss	49
5	Unit Operations for Cryogenic Processes	51
5.1	Isenthalpic Expansion	51
5.1.1	Joule–Thomson Effect	51
5.1.2	Expansion Valve	53
5.1.3	Joule–Thomson Coefficient	53
5.1.4	Isenthalpic Expansion in Temperature–Enthalpy Diagram	54
5.1.5	Isenthalpic Expansion in Temperature–Entropy Diagram	54
5.1.5.1	Learnings About the Joule–Thomson Coefficient from T,s -Diagram	54
5.1.6	Loss in an Isenthalpic Expansion Process	57
5.1.6.1	The Loss is Independent of Expansion Device Design	60
5.1.7	Joule–Thomson Expansion and Isenthalpic Expansion	60
5.1.8	Flashgas	61
5.1.9	Summary of Isenthalpic Expansion	61
5.2	Expansion in Expander	62

5.2.1	Energy Conservation Law for Expander	63
5.2.2	Reversible Expansion	64
5.2.3	Nonreversible Expansion (Real Turboexpander)	66
5.2.3.1	Expander Efficiency in Terms of Enthalpy	66
5.2.3.2	Impact of the Inlet Temperature	67
5.2.3.3	Impact of Kappa	67
5.2.3.4	Impact of the Isentropic Efficiency	68
5.2.4	Exergy Loss in Expander	68
5.2.4.1	The Loss in Expander Depends on Mechanical Design of the Expander	69
5.2.5	Generated Power, Loading Devices	69
5.2.6	Comparison, Isenthalpic Expansion Versus Expansion in Expander	70
5.3	Heat Exchanger	72
5.3.1	Double-Tube (Multitube) Heat Exchanger	72
5.3.2	Definition: LTD and MTD	74
5.3.2.1	Logarithmic Temperature Difference LTD	74
5.3.2.2	Mean Temperature Difference MTD	74
5.3.3	Definition: Q/MTD and UA	75
5.3.3.1	What is the Q/MTD Good For?	76
5.3.4	Multi-Stream Heat Exchanger	77
5.3.4.1	Simplified Calculation Procedure	77
5.3.5	Exergy Loss in Heat Exchangers	78
5.3.5.1	General Consideration	78
5.3.5.2	Exergy Loss in Heat Exchanger, Deep Dive	79
5.3.6	Efficiency of Heat Exchanger	81
5.4	Single Adiabatic Compression Stage	81
5.4.1	Energy Conservation Law for Adiabatic Compression Stage	82
5.4.2	Reversible Adiabatic Compression Stage	83
5.4.3	Nonreversible Adiabatic Compression, Isentropic Efficiency	83
5.4.3.1	Impact of the Inlet Temperature	84
5.4.3.2	Impact of the Isentropic Efficiency	84
5.4.3.3	Impact of the Isentropic Exponent	84
5.4.4	Exergy Loss, Adiabatic Compressor Stage	85
5.5	Multi-Stage Compression, Isothermal Compression	86
5.5.1.1	Special Case: Main Air Compressor	86
5.5.2	Reversible Isothermal Compression	88
5.5.3	Nonreversible Isothermal Compression, Isothermal Efficiency	89
5.5.3.1	Typical Values	90
5.5.3.2	Connection to Adiabatic Single Compression Stage	90
5.5.3.3	Rigorous Calculation of Multi-Stage Compressor	90
5.5.4	Rule of Thumb for Isothermal Compression	91
5.5.5	Energy Conservation Law For Multi-Stage Compressor	92
5.5.6	Second Law for Multi-Stage Compressor	92
5.5.7	Exergy Loss, Isothermal Compression	93
5.5.8	Comparison, Adiabatic Versus Isothermal Compression	94
	References	94

6	Key Hardware Components	95
6.1	Thermal Insulation/Coldbox	95
6.1.1	Low-performance Insulation	97
6.1.2	High-performance Insulation	97
6.1.3	Dewar Vessel	99
6.2	Heat Exchanger	101
6.2.1	Aluminum Plate-fin Heat Exchanger	102
6.2.1.1	Mechanical Design	102
6.2.1.2	Thermal Design, Hydraulic Design	104
6.2.1.3	Attributes	105
6.2.1.4	Restrictions and Limitations	107
6.2.2	Spiral-wound Heat Exchanger	108
6.2.2.1	Mechanical Design	108
6.2.2.2	Thermal and Hydraulic Design	110
6.2.2.3	Restrictions and Limitations Relevant for Use and Operation	114
6.2.2.4	Summary: Spiral-wound Heat Exchanger	115
6.3	Expanders	115
6.3.1	General Issues	116
6.3.1.1	Expansion Process in Detail	116
6.3.1.2	Isentropic Efficiency	118
6.3.1.3	Bearing System	118
6.3.2	Requirements for Design of a Process with Expander	121
6.3.2.1	Limited Pressure Ratio	121
6.3.2.2	No Phase State Change	122
6.3.3	Large Turboexpanders with Oil Bearings	123
6.3.3.1	Mechanical Design	124
6.3.3.2	Bearings for Nitrogen Liquefiers, Labyrinth Sealing, and Seal Gas	125
6.3.3.3	Control and Instrumentation	126
6.3.4	Helium Expander	127
6.3.4.1	Mechanical Design	128
6.3.4.2	Bearing System	129
6.3.4.3	Utilization of Expander Power	132
6.3.4.4	Control and Instrumentation	133
6.3.4.5	Assessment of Helium Expander	133
6.3.5	Joule–Thomson Expander	133
6.3.5.1	Capacity	135
6.3.5.2	Techno-economics	135
6.3.5.3	Mechanical Design	136
6.4	Expansion Valve	136
6.5	Compressors	136
6.5.1	General Issues	136
6.5.1.1	Energy Transformation Chain for Compression	137
6.5.1.2	Compressor Lubrication	138

6.5.2	Centrifugal Compressor	139
6.5.2.1	Mechanical Design and Principle of Compression in a Centrifugal Compressor Stage	139
6.5.2.2	Impeller Design	141
6.5.2.3	Multi-staging	142
6.5.2.4	Thermodynamics of Centrifugal Compressors	143
6.5.2.5	Control of Centrifugal Compressors	146
6.5.2.6	Driver for Compressor	149
6.5.3	Screw Compressor	149
6.5.3.1	Screw Compressor, Design, and Working Principle	150
6.5.3.2	Tuning of Available Screw Compressors	152
6.5.3.3	Process Parameters	152
6.5.3.4	Oil Removal System (ORS)	153
6.5.3.5	Compressor Control	153
6.5.3.6	Assessment of Screw Compressors	153
6.5.4	Reciprocating Compressor	154
6.5.4.1	Design and Working Principle	154
6.5.4.2	Process-relevant Aspects	159
6.5.4.3	Mechanical Design	161
6.5.4.4	Load Range	162
6.5.4.5	Control	165
6.5.4.6	Pulsations and Pulsation Control	165
6.5.4.7	Short Assessment of Reciprocating Compressors	166
	References	167
7	Cryogenic Refrigeration	169
7.1	Principle of Cryogenic Refrigeration	172
7.1.1	Refrigerator and Definitions Around It	172
7.1.2	Energy Conservation Law for Refrigerator	173
7.1.2.1	Energy Conservation Law for Refrigerator	173
7.1.2.2	Three Interfaces	174
7.1.2.3	The Pump Analogy	174
7.1.3	Parasitic Heat Flow Through Thermal Insulation	176
7.1.4	Exercise: Energy Conservation for Refrigerator	177
7.1.5	Reversible Refrigerator and Carnot Equation	177
7.1.5.1	Reversible Refrigerator	177
7.1.5.2	Carnot Equation	178
7.1.5.3	Extension of Carnot Equation to Irreversible Refrigerator	178
7.1.5.4	What Carnot Equation Expresses?	178
7.1.6	The Second Law of Thermodynamics for Refrigerator	179
7.1.7	Minimum Power Requirement for Typical Cooling Temperatures	179
7.1.8	Key Performance Indicators for Refrigerators	180
7.1.8.1	Coefficient of Performance	180

7.1.8.2	Carnot Efficiency	181
7.1.8.3	Specific Power	181
7.2	Joule–Thomson Process (Nitrogen Joule–Thomson Process)	181
7.2.1	Main Elements	182
7.2.1.1	Thermal Insulation/Coldbox	182
7.2.1.2	Heat Exchanger	182
7.2.1.3	Compressor	183
7.2.1.4	Expansion Valve	183
7.2.1.5	Evaporator	183
7.2.1.6	Joule–Thomson Refrigerator Assembled	184
7.2.2	Process and Process Features	185
7.2.2.1	Cool-Down Procedure	185
7.2.2.2	Joule–Thomson Process Description	187
7.2.2.3	Cooling Capacity of the Joule–Thomson Process	187
7.2.2.4	Typical Process Pressure Levels	192
7.2.3	Example Process Calculation, Nitrogen-Joule–Thomson Process	194
7.2.3.1	Task Definition	194
7.2.3.2	Process and Hardware Concept	194
7.2.3.3	Process Simulation	196
7.2.3.4	Process Units	199
7.2.3.5	Overall Performance of the Designed Process	202
7.2.3.6	Process Analysis	202
7.2.4	Process Optimization	208
7.2.4.1	Variables	208
7.2.4.2	Example of Process Optimization	209
7.2.4.3	In Summary	210
7.2.5	Control of a Joule–Thomson Refrigerator	211
7.2.6	Assessment of the Joule–Thomson Process	213
7.3	Brayton Process	213
7.3.1	Main Elements	214
7.3.1.1	Comment About Compression	215
7.3.2	Process and Process Features	215
7.3.2.1	Process Description	215
7.3.2.2	Phase State Conditions	216
7.3.2.3	Working Fluids	216
7.3.2.4	Cooling Temperature	217
7.3.2.5	Typical Process Pressure Levels	217
7.3.2.6	Cooling Capacity	217
7.3.2.7	Reversible Brayton Process	219
7.3.3	Example, Process Calculation, Helium Brayton Process	220
7.3.3.1	Task Definition	220
7.3.3.2	Properties Data	220
7.3.3.3	Process and Hardware Concept	220
7.3.3.4	Process Simulation	223
7.3.3.5	Process Units	224

7.3.3.6	Overall Performance of the Process	227
7.3.3.7	Process Analysis	227
7.3.4	Process Optimization	230
7.3.4.1	Variables	230
7.3.4.2	Constraints	230
7.3.4.3	Example of Process Optimization	230
7.3.4.4	In Summary	232
7.3.5	Control of a Brayton Refrigerator	233
7.3.6	Hardware Components	233
7.3.6.1	Heat Exchanger	233
7.3.6.2	Compressor	234
7.3.6.3	Expander	234
7.3.7	Applications	235
7.3.7.1	Air Separation	235
7.3.7.2	Hydrogen Liquefaction	235
7.3.7.3	Turbo-Brayton Refrigerator	235
7.3.8	Assessment of the Brayton Process	235
7.4	Claude Process	236
7.4.1	Basic Claude Process, Main Elements	236
7.4.1.1	Morphology	237
7.4.1.2	Special Feature	238
7.4.1.3	Extended Definition of the Claude Process	238
7.4.2	Process and Process Features	238
7.4.2.1	Main Idea of the Claude Process	238
7.4.2.2	Basic Claude Process, Process Description	239
7.4.2.3	Typical Process Pressure Levels	240
7.4.2.4	Cooling Capacity	241
7.4.3	Nitrogen Claude Process	243
7.4.3.1	Process Description	243
7.4.4	Example, Process Calculation, Nitrogen Claude Process	245
7.4.4.1	Task Definition	245
7.4.4.2	Process and Hardware Concept	245
7.4.4.3	Properties Data	247
7.4.4.4	Process Simulation	247
7.4.4.5	Process Units	249
7.4.4.6	Overall Performance	254
7.4.4.7	Process Analysis	254
7.4.5	Helium Claude Process	257
7.4.5.1	Process Description	259
7.4.5.2	Special Feature	260
7.4.5.3	Staging	260
7.4.6	Example, Process Calculation, Helium Claude Process	261
7.4.6.1	Task Definition	261
7.4.6.2	Process and Hardware Concept	261
7.4.6.3	Properties Data	264

7.4.6.4	Process Simulation	264
7.4.6.5	Process Units	264
7.4.6.6	Overall Performance	270
7.4.6.7	Process Analysis	270
7.4.6.8	Review of Simulation Procedure	275
7.4.7	Process Optimization	276
7.4.8	Control of a Claude Refrigerator	277
7.4.9	Hardware Components	277
7.4.9.1	Compressor	277
7.4.9.2	Heat Exchanger	277
7.4.9.3	Expander	278
7.4.9.4	Commercial Availability	278
7.4.10	Applications	279
7.4.11	Assessment of the Claude Process	279
7.5	Mixed-Fluid Joule–Thomson Process	279
7.5.1	Main Elements	280
7.5.2	Mixed Fluid as Refrigerant, Properties	280
7.5.2.1	Main Components of Mixed Fluid	281
7.5.2.2	Thermodynamic Fundamentals for Mixed Fluids	281
7.5.2.3	T,s -Diagram for Typical Mixed Fluid	282
7.5.2.4	T,h -Diagram for a Typical Mixed Fluid	286
7.5.2.5	Isobaric Cooling/Heating Of Mixed Fluid	289
7.5.2.6	Comparison Mixed Fluid Versus Nitrogen	291
7.5.3	Process Features	294
7.5.3.1	Phase State Conditions	294
7.5.3.2	Difference Between the Mixed-Fluid-Based and Nitrogen-Based Joule–Thomson Process	297
7.5.3.3	Temperature Profile in Heat Exchanger	297
7.5.3.4	Location of Pinch Point(S)	300
7.5.3.5	Cooling Capacity of a Mixed-Fluid Joule–Thomson Process	301
7.5.3.6	Typical Process Pressure Levels	303
7.5.4	Example Process Calculation, Mixed-Fluid Joule–Thomson Process	304
7.5.4.1	Task Definition	305
7.5.4.2	Properties Data	305
7.5.4.3	Process and Hardware Concept	305
7.5.4.4	Process Simulation	307
7.5.4.5	Process Units	308
7.5.4.6	Overall Performance of the Designed Process	311
7.5.4.7	Process Analysis	311
7.5.5	Design of the Mixed Fluid	315
7.5.5.1	Mixed-Fluid Composition	315
7.5.5.2	Ballast Gas Addition	319
7.5.5.3	Solidification	320
7.5.6	Optimization of a Mixed-Fluid Joule–Thomson Process	323

7.5.7	Control of a Mixed-Fluid Joule–Thomson Refrigerator	323
7.5.7.1	A New Option	324
7.5.8	Hardware Components	324
7.5.8.1	Compressor for Mixed-Fluid Refrigerator	325
7.5.8.2	Heat Exchanger for Mixed-Fluid Joule–Thomson System	327
7.5.9	Assessment of the Mixed-Fluid Joule–Thomson Process	330
7.5.9.1	Challenging Issues	330
7.5.9.2	Applications	330
7.6	Cryogenic Refrigeration Processes, Life Cycle	330
7.6.1	Joule–Thomson Process	330
7.6.2	Brayton Process	331
7.6.3	Claude Process	331
7.6.4	Mixed-Fluid Joule–Thomson Process	331
	References	331
8	Liquefaction of Cryogenic Gases	333
8.1	Thermodynamic Basics for Liquefaction	333
8.1.1	Definitions for Liquefaction Processes	333
8.1.1.1	Isobaric Liquefaction Process in T,s-Diagram	333
8.1.1.2	Liquefier	334
8.1.1.3	Liquefaction Capacity	335
8.1.1.4	Connection to Refrigeration Processes	335
8.1.2	Minimum Liquefaction Power/Work	335
8.1.2.1	Minimum Liquefaction Power via Carnot Equation	335
8.1.2.2	Minimum Liquefaction Power via Exergy	336
8.1.2.3	Minimum Liquefaction Work for Typical Cryogenic Gases	337
8.1.2.4	Key Performance Indicators for Liquefiers	337
8.1.3	Specifics of Process Design for Liquefaction	338
8.1.3.1	Early Liquefaction Processes	338
8.1.3.2	Process Design Approaches for Recent Liquefaction Plants	343
8.1.4	Classification of Liquefaction Processes	348
8.1.5	Liquefaction with External Cooling	348
8.1.5.1	Principle of External Cooling	348
8.1.5.2	Management of Flashgas	353
8.1.5.3	Internal Versus External Cooling	354
8.2	Nitrogen Liquefaction	355
8.2.1	General Setup, Feed Gas, and Products	355
8.2.2	Power Requirements	356
8.2.3	Main Elements	356
8.2.3.1	Compressor	356
8.2.3.2	Heat Exchanger	357
8.2.3.3	Large Expander	357
8.2.3.4	Impact of Heat Exchanger Design on Process Design	357
8.2.3.5	Impact of Expander Power on Process Design	359

8.2.4	Process Design for Nitrogen Liquefaction	359
8.2.4.1	Guidelines/Principles of Process Design for Nitrogen Liquefaction	360
8.2.4.2	Core Process for Nitrogen Liquefaction	361
8.2.4.3	Process Extension for Pressureless LIN As Product	364
8.2.4.4	Process Extension for Pressureless Nitrogen as Feed	366
8.2.4.5	Example of a Dual-Expander Claude Process for Nitrogen Liquefaction	366
8.2.5	Example of an Industrial Plant	369
8.2.5.1	Process Design	370
8.2.5.2	Mechanical Design	372
8.2.5.3	Brief Assessment of This Process	372
8.2.6	Operation of Nitrogen Liquefier in Combination with ASU	373
8.2.6.1	Liquid Nitrogen as Cold Carrier for Other Liquid Products	373
8.2.6.2	Flexible Operation for Optimization of Power Bill	373
8.2.7	Status Quo Nitrogen Liquefaction	374
8.3	Helium Liquefaction	374
8.3.1	Overall Helium Liquefier Setup, Feed Gas, and Product	376
8.3.2	Performance Considerations	378
8.3.2.1	Power Requirements	378
8.3.2.2	Definition of Liquefaction Capacity for Helium Liquefiers	380
8.3.2.3	Performance Comparison	380
8.3.3	Main Elements and Impact on Process Design	381
8.3.3.1	Heat Exchanger	381
8.3.3.2	Compressor	382
8.3.3.3	Helium Expander	383
8.3.3.4	Impact of Expander Power on Process Design	383
8.3.4	Process Design	385
8.3.4.1	Typical Features of Helium Liquefaction Process	385
8.3.4.2	Core Process for Helium Liquefaction	386
8.3.4.3	Process Extension, Helium Purification System	392
8.3.4.4	Example of a Claude Process For Helium Liquefaction	393
8.3.5	Example of a Commercial Helium Liquefier	395
8.3.5.1	Process Design	395
8.3.5.2	Compressor System	396
8.3.5.3	Cold Box, Mechanical Design	397
8.3.5.4	Cold Box, Thermal Insulation	397
8.3.6	Status Quo, Helium Liquefaction	398
8.4	Natural Gas Liquefaction	400
8.4.1	Natural Gas Composition	401
8.4.2	LNG Infrastructure and Process Chain	402
8.4.2.1	Infrastructure Process Chain	403
8.4.2.2	Feed Gas and Product	404
8.4.3	Power Requirements	404
8.4.4	Key Hardware Components	406
8.4.5	Process Design for Natural Gas Liquefaction	406

8.4.5.1	Basic Mixed-Fluid Joule–Thomson Process	408
8.4.5.2	Impact of Maldistribution on Design of a Mixed-Fluid-Based Process	418
8.4.5.3	Mixed-Fluid Joule–Thomson Process with Single Phase-Separator	421
8.4.5.4	Mixed-Fluid Joule–Thomson Process with Two-/Multiple-Phase Separators	427
8.4.5.5	Mixed-Fluid Joule–Thomson Process with External Pre-Cooling Stage	427
8.4.6	Examples of Industrial Process for Natural Gas Liquefaction	432
8.4.6.1	Process Example with Propane PreCooling	432
8.4.6.2	Process Example with Aluminum Plate-Fin Heat Exchanger	435
8.4.7	Outlook, Natural Gas Liquefaction	437
	References	438
9	Supplements	439
9.1	Supplements for Cryogenic Refrigeration	439
9.1.1	Example of Techno-economic Optimization	439
9.1.2	Process Design Approaches for Improvement of Joule–Thomson Process	441
9.1.2.1	Relocate the Process to a Higher Pressure Level	441
9.1.2.2	Implementation of a Precooling Stage	444
9.1.2.3	A Combination of These Approaches	445
9.1.2.4	Approaches for Improvement of Joule–Thomson Process, Summary	445
9.2	Supplements for Liquefaction	445
9.2.1	Original Claude Process	445
9.2.2	Kapitsa Process	447
9.2.3	Example of a Nitrogen Liquefaction Process	452
9.2.3.1	Task Definition	452
9.2.3.2	Process and Hardware Concept	452
9.2.3.3	Process Design Calculation, Cold Part of Process	454
9.2.3.4	Heat Exchanger	457
9.2.3.5	Compressor	458
9.2.3.6	Expander-booster Units	459
9.2.3.7	Overall Process	461
9.2.3.8	Losses	461
9.2.3.9	Evaluation	462
9.2.4	Helium Liquefaction Process with Integrated Liquid Nitrogen Precooling	462
9.2.4.1	Procedure for “Process-to-Hardware” Design”	462
9.2.4.2	Formal Task Definition	463
9.2.4.3	Compressor	465
9.2.4.4	Expanders	467
9.2.4.5	Expansion Valve	469
9.2.4.6	Liquid Nitrogen	469

9.2.4.7	Overall Performance and Losses	469
9.2.5	Basic Mixed-Fluid Joule–Thomson Process for Natural Gas Liquefaction	470
9.2.5.1	Task Definition	471
9.2.5.2	Process and Hardware Concept	472
9.2.5.3	Thermodynamic Properties	474
9.2.5.4	Simulation Results	474
9.2.5.5	Heat Exchanger	475
9.2.5.6	Compressor	478
9.2.5.7	Overall Performance and Losses	478
9.2.6	Mixed Fluid Joule–Thomson Process with Single-phase Separator	479
9.2.6.1	Task Definition	479
9.2.6.2	Simulation Results	479
9.2.6.3	Heat Exchanger	479
9.2.6.4	Compressor	483
9.2.6.5	Overall Performance and Losses	483
9.2.7	Mixed Fluid Joule–Thomson Process with Two or More Phase Separators	483
9.2.7.1	Primary Concept	484
9.2.7.2	Mixed-fluid Composition	486
9.2.7.3	Process Variations	486
9.2.7.4	Brief Assessment	486
	References	487
	Index	489