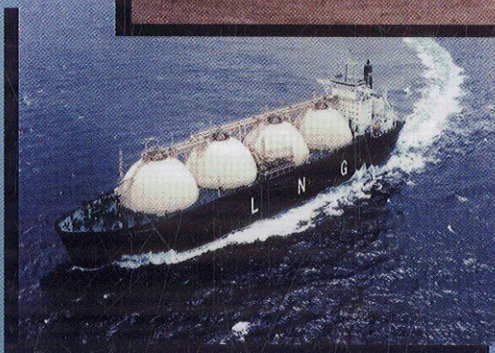


FUNDAMENTALS OF NATURAL GAS PROCESSING

SECOND EDITION



Arthur J. Kidnay
William R. Parrish
Daniel G. McCartney

Contents

Preface.....	xvii
Acknowledgments.....	xix
Authors.....	xxi

Part I

Chapter 1	Processing Principles	3
1.1	Introduction	3
1.2	Units and Conversions	3
1.2.1	Basic Units.....	4
1.2.2	Derived Units	5
1.2.3	Other Important Units in Gas Processing	6
1.2.4	Mathematical Symbols.....	6
1.3	Basic Chemistry Concepts.....	6
1.3.1	Structure and Nomenclature.....	7
1.3.2	Important Chemical Properties	8
1.3.3	Important Physical Properties	10
1.3.4	Mixtures	18
1.4	Specification Test Methods.....	21
1.4.1	Copper Strip Test.....	22
1.4.2	Reid Vapor Pressure	22
1.5	Thermodynamics.....	22
1.5.1	Introduction	22
1.5.2	First Law of Thermodynamics.....	22
1.5.3	Forms of Energy.....	23
1.5.4	State and Path Functions	27
1.5.5	Important Thermodynamic Paths	28
1.5.6	P-H Diagrams.....	29
	Discussion Questions	31
	Exercises.....	31
	References	31
Chapter 2	Pumps.....	33
2.1	Introduction	33
2.2	Pump Fundamentals.....	33
2.2.1	Energy Balance	33
2.2.2	Head	35
2.3	Centrifugal Pumps.....	36
2.3.1	Power, Pump Efficiency, and Temperature Rise	37
2.3.2	Suction Head, Suction Lift, Total Head	39
2.3.3	Net Positive Suction Head and Cavitation.....	40
2.3.4	Characteristic Curves.....	41

2.3.5	System Curves.....	45
2.3.6	Affinity Laws	45
2.3.7	Coordinating Pump and System.....	46
2.4	Reciprocating Pumps.....	47
2.4.1	Pump Fundamentals.....	48
2.5	Rotary Pumps	49
2.6	Pump Comparisons	50
2.6.1	Centrifugal	50
2.6.2	Positive Displacement	50
	Discussion Questions	51
	Exercises.....	51
	References	52

Chapter 3 Heat Transfer 53

3.1	Introduction	53
3.2	Modes of Heat Transfer	53
3.2.1	Conduction	53
3.2.2	Convection.....	56
3.2.3	Radiation	56
3.2.4	Heat Transfer Coefficients.....	57
3.3	Cooling and Heating Sources	61
3.3.1	Cooling Sources	61
3.3.2	Hot Fluids	61
3.4	Heat Exchanger Types	62
3.4.1	Shell and Tube	62
3.4.2	Kettle Exchangers.....	63
3.4.3	Air-Cooled Exchangers	64
3.4.4	Plate Frame Exchangers	65
3.4.5	Plate-Fin Exchangers.....	66
3.4.6	Printed Circuit Heat Exchangers	68
3.4.7	Condensers	68
3.5	Reboilers.....	69
3.5.1	Kettle Reboiler	69
3.5.2	Recirculating Thermosyphon.....	69
3.5.3	Pump-through Reboiler.....	70
3.5.4	Once-through Reboiler.....	71
3.5.5	Internal Reboilers	71
	Discussion Questions	72
	Exercises.....	72
	References	73

Chapter 4 Separation Processes 75

4.1	Introduction	75
4.2	Distillation	75
4.2.1	Basic Concepts	76
4.2.2	Types of Columns.....	83
4.3	Absorption	84
4.3.1	Basic Concepts	84
4.3.2	Physical Absorption.....	84

4.3.3	Chemical Absorption	85
4.3.4	Solvent Selection	85
4.3.5	Regenerative Absorption Process.....	86
4.4	Column Internals	88
4.5	Adsorption	90
4.5.1	Basic Concepts	90
4.5.2	Adsorption Process.....	93
4.6	Membranes	96
4.6.1	Basic Concepts	96
4.6.2	Membrane Process	98
4.7	Summary	101
	Discussion Questions	103
	Exercises.....	103
	References	104

Chapter 5	Phase Separation Equipment.....	105
5.1	Gas–Liquid Separators	105
5.1.1	Primary Separation	106
5.1.2	Gas Gravity Separation	106
5.1.3	Mist Extraction.....	107
5.1.4	Liquid Gravity Separation.....	110
5.2	Filter Separators and Coalescing Filters.....	110
5.3	Cyclone Separators	112
5.4	Liquid–Liquid Separators.....	112
5.5	Residence Time for Various Separator Applications	112
5.6	Filters	114
	Discussion Questions	116
	References	116

Part II

Chapter 6	Overview of the Natural Gas Industry.....	121
6.1	Introduction	121
6.1.1	World Natural Gas.....	122
6.1.2	U.S. Natural Gas.....	123
6.2	Sources of Natural Gas.....	125
6.2.1	Geological Background.....	125
6.2.2	Resource	127
6.2.3	Conventional.....	128
6.2.4	Unconventional.....	129
6.3	Composition of Natural Gas	132
6.3.1	Typical Gas Compositions.....	132
6.3.2	Coal Bed Methane (CBM)	133
6.3.3	Shale Gas.....	134
6.3.4	Impurities	134
6.4	Classification	135
6.4.1	Liquids Content.....	135
6.4.2	Sulfur Content	136

6.5	Principal Products and Markets	136
6.5.1	Methane.....	137
6.5.2	Ethane.....	137
6.5.3	Propane.....	137
6.5.4	Ethane–Propane Mix (E–P Mix).....	138
6.5.5	Isobutane	138
6.5.6	<i>n</i> -Butane	138
6.5.7	Natural Gas Liquids	138
6.5.8	Natural Gasoline	138
6.5.9	Sulfur.....	138
6.6	Product Specifications	139
6.6.1	Natural Gas	139
6.6.2	Liquid Products	140
6.7	Combustion Characteristics.....	140
6.7.1	Heating Value.....	140
6.7.2	Wobbe Number.....	143
	Discussion Questions	144
	Exercises.....	145
	References	145
	Web Sites.....	147
Chapter 7	Overview of Gas Plant Processing	149
7.1	Roles of Gas Plants.....	149
7.2	Plant Processes	149
7.2.1	Field Operations and Inlet Receiving.....	150
7.2.2	Inlet Compression.....	151
7.2.3	Gas Treating	151
7.2.4	Dehydration	151
7.2.5	Hydrocarbon Recovery.....	151
7.2.6	Nitrogen Rejection.....	151
7.2.7	Trace Components.....	151
7.2.8	Outlet Compression	152
7.2.9	Liquids Processing	152
7.2.10	Sulfur Recovery	152
7.2.11	Storage and Transportation	152
7.2.12	Liquefaction.....	152
7.3	Important Support Components	152
7.3.1	Utilities	153
7.3.2	Process Control	154
7.3.3	Safety Systems	155
7.4	Contractual Agreements and Economics	155
7.4.1	Fee-Based Contracts.....	155
7.4.2	Percentage of Proceeds Contracts	156
7.4.3	Wellhead Purchase Contracts.....	156
7.4.4	Fixed Efficiency Contracts	156
7.4.5	Keep Whole Contracts	156
7.4.6	Capital Expenditures	157
7.5	Operational Measures.....	157
7.5.1	Shrinkage	157
7.5.2	Energy Efficiency	158
7.5.3	Processing Margin (Frac Spread).....	158

Discussion Questions	159
References	159
Chapter 8 Field Operations and Inlet Receiving.....	161
8.1 Introduction	162
8.2 Field Operations	162
8.2.1 Wellhead Operations	162
8.2.2 Gathering Systems	164
8.2.3 Compressor Stations.....	164
8.2.4 Pipeline Fieldwork.....	166
8.2.5 Pigging	166
8.2.6 Gas Metering.....	170
8.3 Gas Hydrates	170
8.3.1 Properties	170
8.3.2 Hydrate Formation Prediction.....	172
8.3.3 Hydrate Inhibition	174
8.4 Inlet Receiving.....	179
8.4.1 Manifolder Piping.....	180
8.4.2 Inlet Vessels.....	181
8.4.3 Comparison of Slug Catcher Configurations	182
8.5 Safety and Environmental Considerations	182
Discussion Questions	183
Exercises.....	183
References	184
Web Sites.....	184
Chapter 9 Compression.....	185
9.1 Introduction	185
9.2 Fundamentals	186
9.2.1 Thermodynamics of Compression	186
9.2.2 Multistaging	190
9.2.3 Compressor Efficiencies.....	191
9.3 Drivers	193
9.4 Compressor Types	193
9.4.1 Positive Displacement Compressors.....	195
9.4.2 Dynamic Compressors	198
9.5 Capacity and Power Calculations.....	202
9.5.1 Capacity.....	202
9.5.2 Power Requirements.....	206
9.6 Comparison of Reciprocating and Centrifugal Compressors	208
9.7 Safety and Environmental Considerations	209
Discussion Questions	209
Exercises.....	209
References	210
Chapter 10 Gas Treating.....	211
10.1 Introduction	211
10.1.1 The Problem	212
10.1.2 Acid Gas Concentrations in Natural Gas	212

10.1.3	Purification Levels.....	213
10.1.4	Acid Gas Disposal.....	213
10.1.5	Purification Processes	213
10.2	Solvent Absorption Processes	215
10.2.1	Amines	215
10.2.2	Alkali Salts.....	225
10.3	Physical Absorption.....	226
10.3.1	Solvent Properties.....	227
10.3.2	Representative Process Conditions	229
10.3.3	Hybrid Processes	230
10.4	Adsorption	230
10.5	Cryogenic Fractionation	232
10.6	Membranes	234
10.6.1	Carbon Dioxide Removal from Natural Gas.....	234
10.6.2	Operating Considerations.....	234
10.6.3	Advantages and Disadvantages of Membrane Systems	236
10.7	Nonregenerable Hydrogen Sulfide Scavengers.....	237
10.8	Biological Processes	238
10.9	Safety and Environmental Considerations	238
10.9.1	Amines	238
10.9.2	Adsorbents and Solid Scavengers.....	238
10.9.3	Membranes.....	238
	Discussion Questions	239
	Exercises.....	239
	References	240

Chapter 11 Gas Dehydration..... 243

11.1	Introduction	244
11.2	Water Content of Hydrocarbons	244
11.3	Gas Dehydration Processes	248
11.3.1	Absorption Processes	248
11.3.2	Adsorption Processes	255
11.3.3	Non-Regenerable Desiccant Processes.....	267
11.3.4	Membrane Processes.....	267
11.3.5	Other Processes	267
11.3.6	Comparison of Dehydration Processes	267
11.4	Safety and Environmental Considerations	268
	Discussion Questions	268
	Exercises.....	269
	References	270

Chapter 12 Hydrocarbon Recovery..... 273

12.1	Introduction	273
12.1.1	Retrograde Condensation	274
12.2	Process Components.....	275
12.2.1	Refrigeration System.....	275
12.2.2	Turboexpansion	281
12.2.3	Heat Exchange.....	285
12.2.4	Gas–Liquid Separators.....	285
12.2.5	Fractionation.....	285

12.3	Liquids Removal Processes	286
12.3.1	Dew Point Control and Fuel Conditioning	287
12.3.2	Low Ethane Recovery	291
12.3.3	High Ethane Recovery	294
12.4	Safety and Environmental Considerations	297
	Discussion Questions	298
	Exercises	298
	References	299
Chapter 13	Nitrogen Rejection	301
13.1	Introduction	301
13.2	Nitrogen Rejection for Gas Upgrading	302
13.2.1	Cryogenic Distillation	303
13.2.2	Pressure Swing Adsorption	304
13.2.3	Membranes	304
13.3	Nitrogen Rejection for Enhanced Oil Recovery Using Cryogenic Distillation	305
13.4	Safety and Environmental Considerations	307
	Discussion Questions	307
	Exercises	307
	References	308
Chapter 14	Trace Component Recovery or Removal	311
14.1	Introduction	311
14.1.1	Hydrogen	312
14.1.2	Oxygen	312
14.1.3	NORM	312
14.1.4	Arsenic	315
14.2	Helium	315
14.2.1	Introduction	315
14.2.2	Recovery Methods	316
14.3	Mercury	319
14.3.1	Environmental Considerations	319
14.3.2	Mercury Corrosion	320
14.3.3	Removal Processes	320
14.4	Benzene, Toluene, Ethylbenzene, and Xylenes	321
	Discussion Questions	323
	Exercises	323
	References	324
	Web Sites	325
Chapter 15	Liquids Processing	327
15.1	Introduction	327
15.2	Condensate Processing	328
15.2.1	Sweetening	329
15.2.2	Dehydration	329
15.3	NGL Processing	329
15.3.1	Sweetening	330

15.3.2	Dehydration	333
15.3.3	Fractionation.....	336
15.4	Safety and Environmental Considerations	336
	Discussion Questions	336
	Exercises.....	337
	References	337

Chapter 16 Acid Gas Processing and Disposal..... 339

16.1	Introduction	339
16.1.1	Carbon Dioxide	340
16.1.2	Hydrogen Sulfide.....	340
16.2	Properties of Sulfur	340
16.2.1	Solid State.....	341
16.2.2	Liquid State	341
16.2.3	Vapor State	342
16.3	Sulfur Recovery Processes	342
16.3.1	Claus Process	343
16.3.2	Small-to-Medium Scale Recovery Processes	351
16.4	Sulfur Storage.....	354
16.5	Acid Gas Disposal	354
16.5.1	Enhanced Oil Recovery	355
16.5.2	Disposal Wells.....	355
16.6	Safety and Environmental Considerations	356
	Discussion Questions	357
	Exercises.....	357
	References	358

Chapter 17 Transportation and Storage 361

17.1	Introduction	361
17.2	Gas.....	361
17.2.1	Transportation	361
17.2.2	Market Centers	367
17.2.3	Gas Storage Facilities.....	369
17.3	Liquids.....	373
17.3.1	Transportation	373
17.3.2	Storage.....	375
	Discussion Questions	375
	Exercises.....	376
	References	377

Chapter 18 Liquefied Natural Gas 379

18.1	Introduction	379
18.1.1	Peak Shaving Plants and Satellite Facilities.....	380
18.1.2	Baseload Plants and Stranded Reserves	381
18.2	Gas Treating before Liquefaction.....	385
18.3	Liquefaction Cycles	387
18.3.1	Joule–Thomson Cycles.....	387
18.3.2	Expander Cycles.....	391
18.3.3	Cascade Cycles.....	394

18.4	Storage of LNG.....	401
18.4.1	Cryogenic Aboveground Storage	401
18.4.2	Cryogenic In-Ground Storage	404
18.4.3	Rollover	405
18.5	Transportation	407
18.5.1	Truck Transport.....	407
18.5.2	Pipelines	407
18.5.3	Marine Transport	407
18.6	Regasification and Cold Utilization of LNG	411
18.6.1	Regasification	411
18.6.2	Cold Utilization	412
18.7	Economics	412
18.7.1	Liquefaction Costs.....	413
18.7.2	Shipping Costs.....	414
18.7.3	Regasification Terminal Costs.....	415
18.8	Safety and Environmental Considerations	416
	Discussion Questions	416
	Exercises.....	417
	References	418
	Web Sites	420

Chapter 19 Capital Costs of Gas Processing Facilities..... 421

19.1	Introduction	421
19.2	Basic Premises for All Plant Component Cost Data	421
19.3	Amine Treating.....	421
19.4	Glycol Dehydration.....	422
19.5	NGL Recovery with Straight Refrigeration (Low Ethane Recovery)	423
19.6	NGL Recovery with Cryogenic Processing (High Ethane Recovery) and Nitrogen Rejection.....	423
19.7	Sulfur Recovery and Tail Gas Cleanup.....	425
19.7.1	Sulfur Recovery at High Capacities	425
19.7.2	Sulfur Recovery at Low Capacities.....	425
19.8	NGL Extraction Plant Costs for Larger Facilities	427
19.9	Corrections to Cost Data	429
	Discussion Questions	429
	References	429

Chapter 20 Natural Gas Processing Plants

20.1	Introduction	431
20.2	Plant with Sweet Gas Feed and 98% Ethane Recovery	431
20.2.1	Overview of Plant Feed and Product Slate.....	431
20.2.2	Inlet Compression.....	431
20.2.3	Heat Exchange.....	432
20.2.4	Dehydration	432
20.2.5	Propane Refrigeration	432
20.2.6	Hydrocarbon Recovery.....	432
20.2.7	Amine Treating	434
20.2.8	Deethanizer	434
20.2.9	Outlet Residue Sales Gas Compression.....	434

20.3	Plant with Sour Gas Feed, NGL, and Sulfur Recovery.....	434
20.3.1	Overview of Plant Feed and Product Slate.....	435
20.3.2	Inlet Receiving	435
20.3.3	Inlet Compression.....	435
20.3.4	Gas Treating	435
20.3.5	Sulfur Recovery	436
20.3.6	Dehydration	436
20.3.7	Hydrocarbon Recovery.....	436
20.3.8	Liquids Processing	436
20.4	Plant with Sour Gas Feed, NGL Recovery, and Nitrogen Rejection.....	437
20.4.1	Overview of Plant Feed and Product Slate.....	437
20.4.2	Inlet Receiving	437
20.4.3	Gas Treating	438
20.4.4	Sulfur Recovery	438
20.4.5	Dehydration	438
20.4.6	NRU and Cold Box.....	439
20.4.7	Liquids Processing	439
	Discussion Questions	439
	Exercises.....	439
	References	440
Notation		441
	Greek Symbols	442
	Subscripts	443
	Superscripts	443
Appendix A: Glossary of Gas Process Terminology		445
Appendix B: Physical Constants and Physical Properties		457
B.1	Unit Conversion Factors	460
B.2	Gas Constants and Standard Gas Conditions	461
B.2.1	Universal Gas Constants	461
B.2.2	Standard Gas Conditions.....	461
B.2.3	Useful Conversions Based upon Standard Volumes	462
B.3	Thermodynamic and Physical Property Data	462
B.3.1	Table of Physical Constants of Pure Fluids.....	462
B.3.2	Temperature-Dependent Properties of Pure Fluids.....	469
B.3.3	<i>Physical Properties of Alkanolamines and</i> Alkanolamine–Water Systems	483
B.3.4	Physical Properties of Glycols and Glycol–Water Systems.....	489
B.3.5	Properties of Saturated Steam.....	497
B.3.6	Pressure–Enthalpy Diagrams and Saturation Tables of Pure Hydrocarbons, Nitrogen and Carbon Dioxide.....	501
B.4	Hydrocarbon Compressibility Factors.....	531
	References	533
Author Index		535
Subject Index		541