

Contents

Foreword	xvii
Preface to the Fourth Edition	xix
Preface to the Third Edition	xxi
Preface to the Second Edition	xxiii
Preface to the First Edition	xxv
Introduction	xxvii
Acknowledgments.....	xxxix
1 Process Equipment Fundamentals	1
1.1 Frictional Losses	3
1.2 Density Difference Induces Flow	3
1.3 Natural Thermosyphon Circulation	3
1.4 Reducing Hydrocarbon Partial Pressure ...	4
1.5 Corrosion at Home	5
1.6 What I Know	6
1.7 Distillation: The First Application	8
1.8 Origin of Reflux	12
1.9 Glossary	12
2 Basic Terms and Conditions	13
3 How Trays Work: Flooding	23
History of Distillation	23
3.1 Tray Types	24
3.2 Tray Efficiency	25
3.3 Downcomer Backup	28
3.4 Downcomer Clearance	28
3.5 Vapor-Flow Pressure Drop	30
3.6 Jet Flood	32
3.7 Incipient Flood	33
3.8 Tower Pressure Drop and Flooding	36
3.9 Optimizing Feed Tray Location	37
3.10 Catacarb CO ₂ Absorber Flooding	38
4 How Trays Work: Dumping	41
<i>Weeping through Tray Decks</i>	
4.1 Tray Pressure Drop	42
4.2 Other Causes of Tray Inefficiency	45
4.3 Bubble-Cap Trays	47
4.4 New High Capacity Trays	49
4.5 Calculating Tray Efficiency	50

5	Notes on Tray Design Details	53
5.1	Process Design Equipment Details	53
6	Why Control Tower Pressure	65
	<i>Options for Optimizing Tower Operating Pressure</i>	
6.1	Selecting an Optimum Tower Pressure	66
6.2	Raising the Tower Pressure Target	67
6.3	Lowering the Tower Pressure	68
6.4	The Phase Rule in Distillation	72
7	What Drives Distillation Towers	75
	<i>Reboiler Function</i>	
7.1	The Reboiler	75
7.2	Heat-Balance Calculations	77
8	How Reboilers Work	85
	<i>Thermosyphon, Gravity Feed, and Forced</i>	
8.1	Thermosyphon Reboilers	86
8.2	Forced-Circulation Reboilers	92
8.3	Kettle Reboilers	93
8.4	Don't Forget Fouling	95
8.5	Vapor Binding in Steam Reboilers	96
9	Inspecting Tower Internals	97
9.1	Tray Deck Levelness	97
9.2	Loss of Downcomer Seal Due to Leaks	98
9.3	Effect of Missing Caps	99
9.4	Repairing Loose Tray Panels	99
9.5	Improper Downcomer Clearance	99
9.6	Inlet Weirs	100
9.7	Seal Pans	100
9.8	Drain Holes	101
9.9	Vortex Breakers	102
9.10	Chimney Tray Leakage	102
9.11	Shear Clips	102
9.12	Bubble-Cap Trays	103
9.13	Final Inspection	104
9.14	Conclusion	105
	Reference	106
10	How Instruments Work	107
	<i>Levels, Pressures, Flows, and Temperatures</i>	
10.1	Level	107
10.2	Foam Affects Levels	112
10.3	Pressure	115

10.4	Flow	116
10.5	Temperature	120
	Reference	122
11	Packed Towers: Better Than Trays?	123
	<i>Packed-Bed Vapor and Liquid Distribution</i>	
11.1	How Packed Towers Work	123
11.2	Maintaining Functional and Structural Efficiency in Packed Towers	129
11.3	Advantages of Packing vs. Trays	135
	Reference	136
12	Steam and Condensate Systems	137
	<i>Water Hammer and Condensate Backup Steam-Side Reboiler Control</i>	
12.1	Steam Reboilers	137
12.2	Condensing Heat-Transfer Rates	139
12.3	Maintaining System Efficiency	142
12.4	Carbonic Acid Corrosion	145
12.5	Condensate Collection Systems	146
12.6	Deaerators	149
12.7	Surface Condensers	152
13	Vapor Lock and Exchanger Flooding in Steam Systems	157
13.1	Function of the Steam Trap	157
13.2	Non-condensable Venting	158
13.3	Corrosive Steam	159
13.4	Condensate Drum	159
13.5	Condensate Drainage and Vapor Lock	160
13.6	Elevated Condensate Collection Drum	162
13.7	Conclusion	164
14	Bubble Point and Dew Point	165
	<i>Equilibrium Concepts in Vapor-Liquid Mixtures</i>	
14.1	Bubble Point	165
14.2	Dew Point	169
	Reference	172
15	Steam Strippers	173
	<i>Source of Latent Heat of Vaporization</i>	
15.1	Heat of Evaporation	173
15.2	Stripper Efficiency	175
	References	182

16	Draw-Off Nozzle Hydraulics	183
	<i>Nozzle Cavitation Due to Lack of Hydrostatic Head</i>	
16.1	Nozzle Exit Loss	183
16.2	Critical Flow	186
16.3	Maintaining Nozzle Efficiency	187
16.4	Overcoming Nozzle Exit Loss Limits	192
	Reference	195
17	Pumparounds and Tower Heat Flows	197
	<i>Closing the Tower Enthalpy Balance</i>	
17.1	The Pumparound	197
17.2	Vapor Flow	201
17.3	Fractionation	205
18	Condensers and Tower Pressure Control	209
	<i>Hot-Vapor Bypass: Flooded Condenser Control</i>	
18.1	Subcooling, Vapor Binding, and Condensation	210
18.2	Pressure Control	218
19	Air Coolers	225
	<i>Fin-Fan Coolers</i>	
19.1	Fin Fouling	225
19.2	Fan Discharge Pressure	227
19.3	Effect of Reduced Air Flow	228
19.4	Adjustments and Corrections to Improve Cooling	229
19.5	Designing for Efficiency	231
20	Thermodynamics	237
	<i>How It Applies to Process Equipment</i>	
20.1	Why Is Thermodynamics Important to the Plant Operator?	237
20.2	The Source of Steam Velocity	238
20.3	Converting Latent Heat to Velocity	241
20.4	Effect of Wet Steam	242
20.5	Steam Ejector Temperature Profile	243
20.6	Roto-Flow Turbo Expander	243
20.7	The Meaning of Entropy	244
21	Deaerators and Steam Systems	247
	<i>Generating Steam in Boilers and BFW Preparation</i>	
21.1	Boiler Feedwater	248
21.2	Boilers	253

21.3	Convective Section Waste-Heat Steam Generation	259
	References	260
22	Steam Generation	261
22.1	Boiler Blowdown Rate	261
22.2	Types of Steam-Generating Equipment	262
22.3	Boiler Feed Water Preparation	266
22.4	Effect of Air Preheat on Boiler Capacity	269
22.5	Deaerator Operation	270
22.6	Boiler Feedwater Preheat	272
22.7	Boiler Thermal Efficiency	273
22.8	Sloped Demister	273
	References	275
23	Vacuum Systems: Steam Jet Ejectors	277
23.1	Theory of Operation	277
23.2	Converging and Diverging Compression	279
23.3	Calculations, Performance Curves, and Other Measurements in Jet Systems	280
23.4	Optimum Vacuum Tower-Top Temperature	295
23.5	Measurement of a Deep Vacuum without Mercury	296
	Reference	297
24	Steam Turbines	299
	<i>Use of Horsepower Valves and Correct Speed Control</i>	
24.1	Principle of Operation and Calculations	299
24.2	Selecting Optimum Turbine Speed	305
25	Surface Condensers	311
	<i>The Condensing Steam Turbine</i>	
25.1	The Second Law of Thermodynamics	312
25.2	Surface Condenser Problems	317
25.3	Surface Condenser Heat-Transfer Coefficients	325
	References	326
26	Shell-and-Tube Heat Exchangers: Heat-Transfer Fouling Resistance	327
26.1	Allowing for Thermal Expansion	327
26.2	Heat-Transfer Efficiency	336
26.3	Exchanger Cleaning	340

26.4	Mechanical Design for Good Heat Transfer . . .	341
26.5	Importance of Shell-Side Cross-Flow	346
	References	348
27	Heat Exchanger Innovations	349
27.1	Smooth High Alloy Tubes	350
27.2	Low-Finned Tubes	350
27.3	Sintered Metal Tubes	350
27.4	Spiral Heat Exchanger	351
27.5	Tube Inserts	352
27.6	Twisted Tubes and Twisted Tube Bundle . . .	355
27.7	Helical Tube Support Baffles	360
	Reference	361
28	Shell-and-Tube Heat Exchangers:	
	Design Details	363
28.1	Selecting the Process Fluid Location	364
28.2	Design the Shell Side for Ease of Cleaning	365
29	Fired Heaters: Fire- and Flue-Gas Side	375
	<i>Draft and Afterburn; Optimizing Excess Air</i>	
29.1	Effect of Reduced Air Flow	377
29.2	Absolute Combustion	378
29.3	Draft	387
29.4	Air Leakage	391
29.5	Efficient Air/Fuel Mixing	393
29.6	Optimizing Excess Air	394
29.7	Air Preheating, Lighting Burners, and Heat Balancing	394
	Reference	401
30	Fired Heaters: Process Side	403
	<i>Coking Furnace Tubes and Tube Failures</i>	
30.1	Process Duty versus Heat Liberation	403
30.2	Heater Tube Failures	409
30.3	Flow in Heater Tubes	415
30.4	Low-NOx Burners	416
30.5	Tube Fire-Side Heaters	417
31	Refrigeration Systems	419
	<i>An Introduction to Centrifugal Compressors</i>	
31.1	Refrigerant Receiver	421
31.2	Evaporator Temperature Control	422
31.3	Compressor and Condenser Operation	423
31.4	Refrigerant Composition	426

32	Cooling Water Systems	429
32.1	Locating Exchanger Tube Leaks	430
32.2	Tube-Side Fouling	430
32.3	Changing Tube-Side Passes	431
32.4	Cooling Tower pH Control	432
32.5	Wooden Cooling Towers	432
32.6	Back-Flushing and Air Rumbling	433
32.7	Acid Cleaning	433
32.8	Increasing Water Flow	434
32.9	Piping Pressure Losses	435
32.10	Cooling Tower Efficiency	435
32.11	Wet Bulb Temperature	435
	Reference	438
33	Catalytic Effects: Equilibrium and Kinetics	439
33.1	Kinetics vs. Equilibrium	439
33.2	Temperature vs. Time	440
33.3	Purpose of a Catalyst	441
33.4	Lessons from Lithuania	442
33.5	Zero Order Reactions	444
33.6	Runaway Reaction	444
33.7	Common Chemical Plant and Refinery Catalytic Processes	445
34	Centrifugal Pumps: Fundamentals of Operation	447
	<i>Head, Flow, and Pressure</i>	
34.1	Head	447
34.2	Starting NPSH Requirement	452
34.3	Pressure	453
34.4	Pump Impeller	461
34.5	Effect of Temperature on Pump Capacity	463
35	Centrifugal Pumps: Driver Limits	465
	<i>Electric Motors and Steam Turbines</i>	
35.1	Electric Motors	465
35.2	Steam Turbines	470
35.3	Gears	472
	Reference	472
36	Centrifugal Pumps: Suction Pressure Limits	473
	<i>Cavitation and Net Positive Suction Head</i>	
36.1	Cavitation and Net Positive Suction Head	473
36.2	Sub-atmospheric Suction Pressure	484

37	Centrifugal Pumps: Reducing Seal and Bearing Failures	489
37.1	A Packed Pump	489
37.2	Mechanical Seal	490
37.3	Purpose of Seal Flush	491
37.4	Seal Leaks	493
37.5	Wasting External Seal Flush Oil	494
37.6	Double Mechanical Seal	495
37.7	Dry Seals	496
37.8	Application of Nitrogen Barrier Seals Using Double Mechanical Seals	497
37.9	Steam Use in Seal Chamber	498
37.10	Pressure Balancing Holes	498
37.11	Bearing Failures	499
37.12	Starting a Centrifugal Pump	502
	References	505
38	Control Valves	507
38.1	Pumps and Control Valves	509
38.2	Operating on the Bad Part of the Curve	510
38.3	Control Valve Position	511
38.4	Valve Position Dials	512
38.5	Air-to-Open Valves	513
38.6	Saving Energy in Existing Hydraulic Systems	513
38.7	Control Valve Bypasses	514
38.8	Plugged Control Valves	515
39	Separators: Vapor-Hydrocarbon-Water	517
	<i>Liquid Settling Rates</i>	
39.1	Gravity Settling	517
39.2	Demisters	520
39.3	Entrainment Due to Foam	521
39.4	Water-Hydrocarbon Separations	523
39.5	Electrically Accelerated Water Coalescing	525
39.6	Static Coalescers	526
40	Gas Compression: The Basic Idea	529
	<i>The Second Law of Thermodynamics Made Easy</i>	
40.1	Relationship between Heat and Work	529
40.2	Compression Work ($C_p - C_v$)	532
	Reference	534

41	Centrifugal Compressors and Surge	535
	<i>Overamping the Motor Driver</i>	
41.1	Centrifugal Compression and Surge	537
41.2	Compressor Efficiency	542
41.3	Frequently Asked Questions about Centrifugal Compressors	551
42	Reciprocating Compressors	553
	<i>The Carnot Cycle; Use of Indicator Card</i>	
42.1	Theory of Reciprocating Compressor Operation	554
42.2	The Carnot Cycle	556
42.3	The Indicator Card	557
42.4	Volumetric Compressor Efficiency	559
42.5	Unloaders	560
42.6	Rod Loading	562
42.7	Variable Molecular Weight	562
43	Compressor Efficiency	565
	<i>Effect on Driver Load</i>	
43.1	Jet Engine	566
43.2	Controlling Vibration and Temperature Rise	566
43.3	Relative Efficiency	568
43.4	Relative Work: External Pressure Losses ...	570
44	Safety Concerns	573
	<i>Relief Valves, Corrosion, and Safety Trips</i>	
44.1	Relief-Valve Plugging	574
44.2	Relieving to Atmosphere	575
44.3	Corrosion Monitoring	576
44.4	Alarms and Trips	578
44.5	Auto-ignition of Hydrocarbons	580
44.6	Paper Gaskets	581
44.7	Calculating Heats of Reaction	582
44.8	Hot Water Explodes Out of Manway	583
45	Relief Valve System Design	585
45.1	Coke Drums	585
45.2	High-Pressure Fixed-Bed Reactors	586
45.3	Trayed Towers and Packed Columns	586
45.4	Liquid-Filled Vessels	586
45.5	Sour Water Strippers	587
45.6	Protecting Relief Valves from Fouling and Corrosion	588

45.7	Dual Relief Valves	588
45.8	Process Design Responsibility for Relief Valve Design	589
45.9	Relief Valve and Pressure-Sensing Connections	589
45.10	Heat Exchanger Safety Reliefs	590
45.11	Relief Valve Effluents	591
45.12	Maintaining Flare Header Positive Pressures	591
45.13	Leaking Relief Valves	592
45.14	Tray Failure Due to Relief Valves	593
45.15	The Piper Alpha Rig Destruction	593
46	Corrosion—Process Units	595
46.1	Closer to Home	595
46.2	Erosive Velocities	596
46.3	Mixed Phase Flow	596
46.4	Carbonate Corrosion	597
46.5	Naphthenic Acid Attack	597
46.6	A Short History of Corrosion	597
46.7	Corrosion—Fired Heaters	605
46.8	Oil-Fired Heaters	608
46.9	Finned-Tube Corrosion	608
46.10	Field Identification of Piping Metallurgy ...	609
47	Waste Water Strippers	611
47.1	Purpose of Sour Water Strippers	611
47.2	Two-Stage Sour Water Stripper	615
47.3	Tray Efficiency	616
47.4	Computer Simulation and Theoretical Tray Efficiency	618
47.5	Use of Caustic to Improve Stripping	619
47.6	Water Stripper Reboiler Corrosion and Fouling	620
47.7	Ballast Water Stripper	621
47.8	Conclusions	621
	Reference	622
48	Fluid Flow in Pipes	623
	<i>Basic Ideas to Evaluate Newtonian and Non-Newtonian Flow</i>	
48.1	Field Engineer's Method for Estimating Pipe Flow	623
48.2	Field Pressure Drop Survey	624
48.3	Line Sizing for Low-Viscosity and Turbulent Flow	627

48.4	Frictional Pressure Loss in Rough and Smooth Pipe	635
48.5	Special Case for Laminar Flow	638
48.6	Smooth Pipes and Turbulent Flow	639
48.7	Very Rough Pipes and Very Turbulent Flow	639
48.8	Non-Newtonian Fluids	639
48.9	Some Types of Flow Behavior	640
48.10	Viscoelastic Fluids	644
48.11	Identifying the Type of Flow Behavior	645
48.12	Apparent and Effective Viscosity of Non-Newtonian Liquids	645
48.13	The Power Law or Ostwald de Waele Model	646
48.14	Generalized Reynolds Numbers	649
	References	651
49	Super-Fractionation Separation Stage	653
49.1	My First Encounter with Super-Fractionation	653
49.2	Kettle Reboiler	658
49.3	Partial Condenser	658
49.4	Side Reboilers and Intercoolers	662
50	Hand Calculations for Distillation Towers	663
	<i>Vapor-Liquid Equilibrium, Absorption, and Stripping Calculations</i>	
50.1	Introduction	663
50.2	Bubble Point and Dew Point Calculations	664
50.3	The Absorption Factor or Stripping Factor Chart	672
50.4	Conclusion	687
	References	687
51	Computer Modeling and Control	689
51.1	Modeling a Propane-Propylene Splitter ...	689
51.2	Computer Control	693
51.3	Material Balance Problems in Computer Modeling	694
51.4	Fourth Edition Update Comments	696
52	Field Troubleshooting Process Problems	697
52.1	De-ethanizer Flooding	697
52.2	The Elements of Troubleshooting	699
52.3	Field Calculations	700

xvi Contents

52.4	Troubleshooting Tools—Your Wrench	701
52.5	Field Measurements	702
52.6	Troubleshooting Methods	706
52.7	Afterword	707
	Glossary	709
	Index	719
	The Norm Lieberman Video Library of Troubleshooting Process Operations	751