
Contents

Preface	xxv
Chapter 1 Introduction	1
1.1 Introduction	2
Example 1.1: Surge Tank	5
Example 1.2: Taking a Shower	12
1.2 Instrumentation	15
Analog	15
Digital	16
Techniques Used in This Textbook	16
Control Valve Placement	16
1.3 Process Models and Dynamic Behavior	16
Example 1.3: Liquid Surge Vessel Model	18
1.4 Control Textbooks and Journals	20
1.5 A Look Ahead	22
1.6 Summary	23
Student Exercises	24
Chapter 2 Fundamental Models	31
2.1 Background	32
Reasons for Modeling	32
Lumped Parameter System Models	32
2.2 Balance Equations	33
Integral Balances	34
Instantaneous Balances	36
Steady State	36
2.3 Material Balances	36
Example 2.1: Gas Surge Drum	37

Outlet Flow as a Function of Gas Drum Pressure	38
Example 2.2: An Isothermal Chemical Reactor	39
2.4 Constitutive Relationships	44
Gas Law	45
Chemical Reactions	46
Equilibrium Relationships	47
Heat Transfer	47
Flow Through Valves	48
2.5 Material and Energy Balances	48
Review of Thermodynamics	49
Example 2.3: Heated Mixing Tank	50
2.6 Form of Dynamic Models	56
State Variables	57
Input Variables	57
Parameters	57
Output Variables	58
Vector Notation	58
Steady-State Solutions	58
Numerical Integration	58
2.7 Linear Models and Deviation Variables	59
Deviation Variable Formulation	59
Linearization of Nonlinear Models	60
Example 2.4: A Second-Order Reaction	62
Example 2.5: Jacketed Heater	65
2.8 Summary	66
Suggested Reading	68
Student Exercises	68
Appendix 2.1: Solving Algebraic Equations	76
Appendix 2.2: Integrating Ordinary Differential Equations	76
Example 2.2: An Isothermal Chemical Reactor, continued	77
Chapter 3 Dynamic Behavior	79
3.1 Background	80
3.2 Linear State Space Models	80
Stability	82
Example 3.1: Exothermic CSTR	83
MATLAB Eigenvalue Function	84
Generalization	84
3.3 Introduction to Laplace Transforms	85
Exponential Function	85
Derivatives	86
Time Delays (Dead Time)	86

Step Functions	87
Pulse	87
Impulse	88
Other Functions	88
Initial- and Final-Value Theorems	89
Example 3.2: Application of Initial- and Final-Value Theorems	91
General Solution Procedure	91
Example 3.3: Second-Order Differential Equation	93
3.4 Transfer Functions	95
3.5 First-Order Behavior	97
Step Response	97
Impulse Response	98
Example 3.4: Stirred-Tank Heater	99
3.6 Integrating System	101
Step Response	101
Impulse Response	101
Example 3.5: Tank-Height Problem	101
3.7 Second-Order Behavior	103
Pure Second-Order Systems	103
Underdamped Step Response Characteristics	107
Second-Order Systems with Numerator Dynamics	107
Example 3.6: Illustration of Numerator Dynamics	109
3.8 Lead-Lag Behavior	110
3.9 Poles and Zeros	111
Example 3.7: Comparison of Various Transfer Function Forms	111
3.10 Processes with Dead Time	113
3.11 Padé Approximation for Dead Time	114
Example 3.8: Application of the Padé Approximations for Dead Time	115
3.12 Converting State Space Models to Transfer Functions	115
Example 3.9: Isothermal CSTR	117
3.13 MATLAB and SIMULINK	118
conv (Convolution) and roots	118
step	119
SIMULINK	119
3.14 Summary	119
References	120
Student Exercises	120
Chapter 4 Empirical Models	127
4.1 Introduction	128
4.2 First-Order + Dead Time	129
Time for 63.2% Approach to New Steady State	129

Example 4.1: Numerical Application of 63.2% Method	129
Maximum Slope Method	131
Example 4.2: Maximum Slope Method	131
Two-Point Method for Estimating Time Constant	132
Limitation to FODT Models	132
4.3 Integrator + Dead Time	133
4.4 Discrete-Time Autoregressive Models	136
Introduction to Autoregressive Models	136
Z-Transforms	137
Poles/Zeros of Discrete Models	137
Example 4.3: Discrete Poles and Stability	138
Final and Initial Values Theorems for Discrete Systems	139
4.5 Parameter Estimation	140
Example 4.4: Process Identification	141
4.6 Discrete Step and Impulse Response Models	144
Step Response Models	144
Impulse Response Models	145
4.7 Summary	147
References	147
Student Exercises	147
Appendix 4.1: Files Used to Generate Example 4.4	152
Appendix 4.2	153
Chapter 5 Introduction to Feedback Control	155
5.1 Motivation	156
On-Off Control	156
Proportional Control	157
Valve Gains	159
5.2 Development of Control Block Diagrams	159
Controller Transfer Function	160
Valve Transfer Function	160
Process Transfer Function	160
Disturbance Transfer Function	162
Measurement (Sensor) Transfer Function	162
Control Block Diagram	162
5.3 Response to Setpoint Changes	163
Possible Problems with <i>Offset</i> Using Proportional Controllers	165
Example 5.1: Offset with Proportional (P) Control of a First-Order Process	166
5.4 PID Controller Algorithms	168
PI Control	169
Example 5.2: First-Order Process with a PI Controller	169
PID Control	172

Proportional Band	173
5.5 Routh Stability Criterion	173
Example 5.3: Third-Order Process with a P-Only Controller	174
5.6 Effect of Tuning Parameters	176
Effect of Controller Gain	177
Integral Time	178
Derivative Time	178
5.7 Response to Disturbances	178
Example 5.4: First-Order Process and Load Transfer Functions with P-Only Control	179
5.8 Open-Loop Unstable Systems	180
Example 5.5: First-Order Open-Loop Unstable Process with P-Only Control	180
5.9 SIMULINK Block Diagrams	181
5.10 Summary	182
References	185
Student Exercises	185

Chapter 6 PID Controller Tuning 195

6.1 Introduction	195
PID Controller Forms	196
6.2 Closed-Loop Oscillation-Based Tuning	198
Ziegler-Nichols Closed-Loop Method	198
Example 6.1: Third-Order Process	199
6.3 Tuning Rules for First-Order + Dead Time Processes	201
Ziegler-Nichols Open-Loop Method	201
Cohen-Coon Parameters	202
6.4 Direct Synthesis	203
Direct Synthesis for Minimum-Phase Processes	204
Example 6.2: Direct Synthesis For a First-Order Process	204
Direct Synthesis for Nonminimum-Phase Processes	206
Example 6.3: First-Order + Dead Time Example	206
Example 6.4: Process with a RHP Zero	207
Reformulation of the Desired Response	208
6.5 Summary	209
References	210
Student Exercises	210

Chapter 7 Frequency-Response Analysis 215

7.1 Motivation	216
7.2 Bode and Nyquist Plots	219
Example 7.1: First-Order System	219

Complex Transfer Functions	223
Example 7.2: First-Order + Time Delay	223
7.3 Effect of Process Parameters on Bode and Nyquist Plots	224
Effect of Process Order	224
Concepts of “All-Pass” and “Nonminimum Phase”	225
Frequency Response Introductory Summary	227
7.4 Closed-Loop Stability Concepts	228
7.5 Bode and Nyquist Stability	230
Bode Stability Criterion	230
Nyquist Stability Criterion	231
Gain Margin	231
Phase Margin	232
Example 7.3: Nonminimum-Phase Process	232
7.6 Robustness	235
7.7 MATLAB Control Toolbox: Bode and Nyquist Functions	236
7.8 Summary	238
Reference	238
Student Exercises	238
Chapter 8 Internal Model Control	245
8.1 Introduction to Model-Based Control	246
Static Control Law	247
Dynamic Control Law	248
8.2 Practical Open-Loop Controller Design	249
Response of Manipulated and Output Variables to Step Setpoint Changes	250
Issues in Dynamic Controller Design	251
Example 8.1: Inverse Response System	252
Example 8.2: Numerical Example of an Inverse Response System	253
8.3 Generalization of the Open-Loop Control Design Procedure	255
Controller Factorization	256
Example 8.3: Factorization Techniques	256
Comparison of Output Responses for Different Controller Factorizations	257
8.4 Model Uncertainty and Disturbances	259
Example 8.4: First-Order Process with Model Uncertainty	259
8.5 Development of the IMC Structure	260
8.6 IMC Background	262
8.7 The IMC Structure	263
Perfect Model, No Disturbances	264
Perfect Model, Disturbance Effect	265
Model Uncertainty, No Disturbances	265
8.8 The IMC Design Procedure	265

Example 8.5: First-Order + Dead Time Process	267
Example 8.6: Second-Order with an RHP Zero	269
8.9 Effect of Model Uncertainty and Disturbances	270
The Effect of Model Uncertainty on Setpoint Response	270
Disturbance Rejection	271
Example 8.7: First-Order Process	271
8.10 Improved Disturbance Rejection Design	273
Example 8.8: First-Order Process, Improved Disturbance Rejection Design	274
8.11 Manipulated Variable Saturation	275
8.12 Summary	276
Terms	277
Summary of Internal Model Control System Design Procedure	278
References	279
Student Exercises	279
Appendix 8.1: Derivation of Closed-Loop Relationships for IMC	283
Chapter 9 The IMC-Based PID Procedure	285
9.1 Background	286
9.2 The Equivalent Feedback Form to IMC	286
The IMC-Based PID Control Design Procedure	289
9.3 IMC-Based Feedback Design for Delay-Free Processes	290
Focus on Setpoint Tracking	290
Example 9.1: IMC-Based PID Design for a First-Order Process	290
Example 9.2: IMC-Based PID Design for a Second-Order Process	291
Focus on Disturbance Rejection	292
Integrating Processes	293
Summary for Delay-Free Processes	294
9.4 IMC-Based Feedback Design for Processes with a Time Delay	294
First-Order + Dead Time	294
Example 9.3: IMC-Based PID Design for a First-Order + Dead Time Process	294
Integrator + Dead Time	296
Gain + Dead Time	297
9.5 Summary of IMC-Based PID Controller Design for Stable Processes	298
9.6 IMC-Based PID Controller Design for Unstable Processes	301
Example 9.4: IMC-Based PID Design for a First-Order Unstable Process	302
Summary of IMC-Based PID Controller Design for Unstable Processes	304
9.7 Summary	304
IMC-Based PID Procedure Summary	305
References	306
Student Exercises	307

Chapter 10	Cascade and Feed-Forward Control	313
10.1	Background	314
10.2	Introduction to Cascade Control	314
	Cascade to Flow Control	315
	Reactor Temperature Cascade Control	318
10.3	Cascade-Control Analysis	320
10.4	Cascade-Control Design	321
	Rules of Thumb for Cascade Control	322
10.5	Cascade IMC	323
10.6	Feed-Forward Control	324
10.7	Feed-Forward Controller Design	326
	Example 10.1: First-Order Process and Disturbance Transfer Functions	327
	Numerical Example	327
	Example 10.2: First-Order + Dead Time Process and Disturbance Transfer Functions	328
	Example 10.3: Process Higher Order than Disturbance Transfer Function	329
	Numerical Simulation	329
	Example 10.4: Process Has Inverse Response, Disturbance Does Not	329
	Static Feed-Forward Control	330
10.8	Feed-Forward Control in the IMC Structure	331
10.9	Summary of Feed-Forward Control	331
10.10	Combined Feed-Forward and Cascade	332
10.11	Summary	332
	References	333
	Student Exercises—Cascade Control	334
	Student Exercises—Feed-Forward Control	340
	Student Exercises—Feed-Forward and Cascade	341
Chapter 11	PID Enhancements	345
11.1	Background	345
11.2	Antireset Windup	346
	Reset (Integral) Windup	346
	Example 11.1: Illustration of Reset Windup	347
	Antireset Windup (ARW) Techniques	348
	Example 11.2: Illustration of Reset Windup Compensation (ARW)	349
	Example 11.3: Cascade Control of a CSTR	350
11.3	Autotuning Techniques	354
	Control Block Diagram	355
	Relay Deadband (Hysteresis)	357
	Controller Tuning	358
11.4	Nonlinear PID Control	359
11.5	Controller Parameter (Gain) Scheduling	361
11.6	Measurement/Actuator Selection	363

11.7	Implementing PID Enhancements in SIMULINK	363
	Constrained vs. Unconstrained	363
	ARW	363
	Autotuning	366
11.8	Summary	366
	References	367
	Student Exercises	367
 Chapter 12 Ratio, Selective, and Split-Range Control		371
12.1	Motivation	371
12.2	Ratio Control	372
12.3	Selective and Override Control	373
12.4	Split-Range Control	374
	Example 12.1: 1000 Liter Stirred-Tank Heater	376
12.5	SIMULINK Functions	377
12.6	Summary	379
	References	379
	Student Exercises	379
 Chapter 13 Control-Loop Interaction		381
13.1	Introduction	382
13.2	Motivation	382
	Example 13.1: Whiskey Blending	384
13.3	The General Pairing Problem	385
	Two Input–Two Output Processes	387
	Input 1–Output 1 Dynamic Behavior	388
	Example 13.1, continued	390
	Steady-State Effective Gain	391
13.4	The Relative Gain Array	392
	Two-Inputs and Two-Outputs	393
	Definition of the Relative Gain	393
	Relative Gain Between Input 1 and Output 1 for a Two Input–Two Output System	393
	The RGA	394
13.5	Properties and Application of the RGA	395
	Sum of Rows and Columns Property of the RGA	395
	Use of RGA to Determine Variable Pairing	395
	Example 13.2: RGA for Variable Pairing	396
	Two Input–Two Output Systems	396
	Implications for the Sign of a Relative Gain	396
	Midchapter Summarizing Remarks	397
13.6	Return to the Motivating Example	398
	Total Material Balance	398

Component Material Balance on Ethanol	398
13.7 RGA and Sensitivity	399
Failure Sensitivity	400
Sensitivity to Model Uncertainty	402
Example 13.3: Model Uncertainty and the RGA	402
13.8 Using the RGA to Determine Variable Pairings	403
Example 13.1, continued	403
Example 13.4: A Three Input–Three Output System	405
Example 13.5: A Four Input–Four Output Distillation Column (Alatiqi and Luyben, 1986)	407
13.9 MATLAB RGA Function File	407
13.10 Summary	408
References	409
Student Exercises	409
Appendix 13.1: Derivation of the Relative Gain for an n -Input– n -Output System	415
Appendix 13.2: m-File to Calculate the RGA	416
 Chapter 14 Multivariable Control	 419
14.1 Background	420
14.2 Zeros and Performance Limitations	420
SISO Zeros	420
Multivariable Transmission Zeros	421
Example 14.1: Calculation of Transmission Zeros	421
Example 14.2: Quadruple Tank Problem (Johansson, 2000)	423
14.3 Scaling Considerations	424
Example 14.3: Mixing Tank	425
14.4 Directional Sensitivity and Operability	428
SVD	429
Example 14.3, continued	430
Operating Window	433
Example 14.3, continued	433
14.5 Block-Diagram Analysis	434
14.6 Decoupling	435
Ideal Decoupling	436
Simplified Decoupling	437
Static Decoupling	439
14.7 IMC	440
Example 14.1, continued	440
14.8 MATLAB <code>tzero</code> , <code>svd</code> , and LTI Functions	444
Transmission Zero Calculation	444
Example 4.2, continued	444
SVD	446

Example 14.3, continued	446
LTI Objects in SIMULINK Block Diagrams	447
Example 14.1, continued	447
14.9 Summary	447
References	448
Student Exercises	449
Appendix 14.1	451

Chapter 15 Plantwide Control 453

15.1 Background	454
15.2 Steady-State and Dynamic Effects of Recycle	455
Steady-State Effects of Recycle	455
Example 15.1: A Simple Recycle Problem	456
Dynamic Effects of Recycle	459
Example 15.2: Dynamic Effect of Recycle	461
15.3 Unit Operations Not Previously Covered	462
Supply-Side vs. Demand-Side Control of Production	462
Compressor Control	463
Heat Exchangers	464
Adiabatic Plug Flow Reactors	465
15.4 The Control and Optimization Hierarchy	466
Operating Levels	466
Petroleum Refining Example	468
Discussion	468
15.5 Further Plantwide Control Examples	469
Example 15.3: MPN Process and Instrumentation Diagram	470
Example 15.4: HDA Process	473
The Art of Process Engineering	476
Example 15.5: HDA “Back of the Envelope” Material Balance	477
15.6 Simulations	478
Example 15.6: A Simple Recycle System	479
15.7 Summary	480
References	482
Student Exercises	482

Chapter 16 Model Predictive Control 487

16.1 Motivation	488
Basic Description	488
16.2 Optimization Problem	488
Objective Functions	490
Models	491

16.3	Dynamic Matrix Control	493
	Example 16.1: First-Order Process	498
	Example 16.2: Van de Vusse Reactor	501
16.4	Constraints and Multivariable Systems	503
	Quadratic DMC (QDMC)	504
	Multivariable Systems	506
16.5	Other MPC Methods	507
	MPC with Industrial Applications	507
	MPC Research	507
16.6	MATLAB	509
16.7	Summary	509
	References and Relevant Literature	510
	Student Exercises	512
	Appendix 16.1: Derivation of the Step Response Formulation	513
	Appendix 16.2: Derivation of the Least Squares Solution for Control Moves	514
	Appendix 16.3	515
	Chapter 17 Summary	521
17.1	Overview of Topics Covered in This Textbook	521
	Chapters	522
	Modules	526
17.2	Process Engineering in Practice	526
	Topics Not Covered	527
	Art and Philosophy of Process Engineering	527
	Rules of Process Operations	529
17.3	Suggested Further Reading	529
17.4	Notation	530
	Student Exercises	533
	Module 1 Introduction to MATLAB	539
M1.1	Background	540
M1.2	Matrix Operations	541
	Matrix Notation Review	541
	MATLAB Matrix Operations	542
M1.3	The MATLAB Workspace	545
M1.4	Complex Variables	546
M1.5	Plotting	547
M1.6	More Matrix Stuff	550
M1.7	For Loops	552
M1.8	m-Files	552
	Script Files	553

Contents	xix
Function Routines	554
Commonly Used MATLAB Functions	554
M1.9 Summary of Commonly Used Commands	556
M1.10 Frequently Used MATLAB Functions	556
Additional Exercises	557
Module 2 Introduction to SIMULINK	559
M2.1 Background	559
M2.2 Open-Loop Simulations	561
M2.3 Feedback-Control Simulations	563
Other Commonly Used Icons	569
M2.4 Developing Alternative Controller Icons	570
M2.5 Summary	571
Additional Exercises	572
Module 3 Ordinary Differential Equations	573
M3.1 MATLAB ode—Basic	574
Example M3.1: Van de Vusse Reaction	575
M3.2 MATLAB ode—Options	577
M3.3 SIMULINK sfun (.mdl Files)	578
Example M3.2: Van de Vusse Reaction	579
M3.4 SIMULINK sfun (.mdl Files)—Advanced	581
Example M3.3: Van de Vusse Reactor Extended	582
M3.5 Summary	584
Module 4 MATLAB LTI Models	585
M4.1 Forming Continuous-Time Models	585
State Space	586
Transfer Function	587
Zero-Pole Gain	588
Converting Between Model Types	589
Converting from Transfer Function to State Space Form	590
Multiple Inputs and/or Outputs	591
Input Time Delays	592
M4.2 Forming Discrete-Time Models	593
Discrete State Space Models	594
Discrete Transfer Function	596
Discrete Filter Form	596
Converting Between Discrete Model Types	597
M4.3 Converting Continuous Models to Discrete	598
M4.4 Converting Discrete Models to Continuous	599

M4.5	Step and Impulse Responses	599
M4.6	Summary	602
	Reference	602
	Additional Exercises	602
Module 5 Isothermal Chemical Reactor		605
M5.1	Background	605
M5.2	Model (Chapter 2)	606
M5.3	Steady-State and Dynamic Behavior (Chapter 3)	607
	Steady-State Input-Output Curve	608
	Linear Analysis	608
	Case 1—Operation on the “Left-Hand Side” of the Peak Concentration	610
M5.4	Classical Feedback Control (Chapters 5 and 6)	610
	Closed-Loop Performance Requirements	610
M5.5	Internal Model Control (Chapter 8)	613
	Open-Loop Controller Design and Implementation	613
	Internal Model Controller Implementation	615
	Reference	616
	Additional Exercises	616
Module 6 First-Order + Time-Delay Processes		619
M6.1	Motivation	620
M6.2	Closed-Loop Time-Domain Simulation	620
M6.3	Bode Analysis	621
	Gain Margin	623
	Crossover Frequency/Ultimate Period	623
	Nyquist Diagram	623
M6.4	Ziegler-Nichols Tuning	625
M6.5	IMC-Based PID Control	628
M6.6	Summary	629
	References	629
	Additional Exercises	629
	Appendix M6.1	630
Module 7 Biochemical Reactors		631
M7.1	Background	631
	Model	632
	Scale Up	632
M7.2	Steady-State and Dynamic Behavior	633
	Steady-State Conditions	633
	Linear Model	633

M7.3	Stable Steady-State Operating Point	634
M7.4	Unstable Steady-State Operating Point	635
M7.5	SIMULINK Model File	636
	Reference	638
	Additional Exercises	638

Module 8 CSTR 641

M8.1	Background	642
M8.2	Simplified Modeling Equations	643
	Overall Reactor Material Balance	643
	Balance on Component A	644
	Reactor Energy Balance	644
	State Variable Form of the Equations	644
	Steady-State Solution	645
	Linearization	645
M8.3	Example Chemical Process—Propylene Glycol Production	646
	Parameter Values	647
M8.4	Effect of Reactor Scale	647
	Reactor Scale	647
	Steady-State (Nonlinear) Results	648
	Linear Open-Loop Results	648
	Linear Closed-Loop Results	650
M8.5	For Further Study: Detailed Model	651
	Linear Open-Loop Results	653
	Nonlinear Open-Loop Results	654
	Linear Closed-Loop Results	654
M8.6	Other Considerations	655
	Nonlinear Behavior	655
	Split-Range Control	656
M8.7	Summary	656
	References	657
	Additional Exercises	658
	Appendix M8.1	659

Module 9 Steam Drum Level 661

M9.1	Background	661
M9.2	Process Model	662
M9.3	Feedback Controller Design	663
	IMC-Based PID	664
	Ziegler-Nichols (or Tyreus-Luyben)	665
	Frequency Response	665

M9.4	Feed-Forward Controller Design	666
M9.5	Three-Mode Level Control	666
Appendix M9.1:	SIMULINK Diagram for Feed-Forward/Feedback Control of Steam Drum Level	667
Appendix M9.2:	SIMULINK Diagram for 3-Mode Control of Steam Drum Level	667
Module 10 Surge Vessel Level Control		669
M10.1	Background	669
M10.2	Process Model	670
M10.3	Controller Design	670
	Proportional Gain	671
	Nonlinear Proportional Gain	672
M10.4	Numerical Example	672
	Step Disturbances	673
	Sinusoidal Disturbances	673
	Additional Simulations	675
M10.5	Summary	675
	Reference	676
	Additional Exercises	676
	Appendix M10.1: The SIMULINK Block Diagram	677
Module 11 Batch Reactor		679
M11.1	Background	679
M11.2	Batch Model 1: Jacket Temperature Manipulated	681
	Effect of Scale (Size)	683
	Quasi-Steady-State Behavior	683
	IMC-Based Design	684
M11.3	Batch Model 2: Jacket Inlet Temperature Manipulated	685
	IMC-Based PID Tuning Parameters	687
M11.4	Batch Model 3: Cascade Control	688
M11.5	Summary	689
	Reference	690
	Additional Exercises	690
Module 12 Biomedical Systems		691
M12.1	Overview	691
M12.2	Pharmacokinetic Models	692
	Modeling Equations	693
M12.3	Intravenous Delivery of Anesthetic Drugs	694
M12.4	Blood Glucose Control in Diabetic Patients	694
	Nonlinear Model	695

Linear Model	695
Example Set of Parameters	696
Desired Control Performance	697
M12.5 Blood Pressure Control in Post-Operative Patients	698
M12.6 Critical Care Patients	698
M12.7 Summary	700
References	700
Additional Exercises	701

Module 13 Distillation Control 703

M13.1 Description of Distillation Control	704
Simplified Model	705
M13.2 Open-Loop Behavior	706
Response to Reflux Change	706
Response to Vapor Boil-Up Change	706
Response to Simultaneous Changes in Reflux and Vapor Boil-Up	707
M13.3 SISO Control	708
M13.4 RGA Analysis	709
M13.5 Multiple SISO Controllers	710
Setpoint Changes	710
Disturbance Rejection	711
M13.6 Singular Value Analysis	712
MATLAB SVD Analysis	712
M13.7 Nonlinear Effects	714
M13.8 Other Issues in Distillation Column Control	714
M13.9 Summary	716
References	716
Additional Exercises	717
Appendix M13.1	718

Module 14 Case Study Problems 721

M14.1 Background	721
M14.2 Reactive Ion Etcher	723
M14.3 Rotary Lime Kiln Temperature Control	724
M14.4 Fluidized Catalytic Cracking Unit	725
M14.5 Anaerobic Sludge Digester	725
M14.6 Drug Infusion System	727
M14.7 Suggested Case Study Schedule	728
M14.8 Summary	730
Additional Exercises	731

Module 15	Flow Control	733
M15.1	Motivating Example	733
	Flowmeter	735
	DP Cell	735
	Pressure to Current Transducer	736
	Controller—Concept of Proportional Band	736
	Current-to-Pressure Transducer	737
	Control Valve	738
M15.2	Flowmeters	738
	Square Root Extractor	740
M15.3	Control Valves	741
M15.4	Pumping and Piping Systems	743
M15.5	Summary	747
	References	747
	Additional Exercises	747
Module 16	Digital Control	749
M16.1	Background	750
M16.2	PID Controllers	750
	Z-Transform Representation of PID Control	752
M16.3	Stability Analysis for Digital Control Systems	753
	Example M16.1: Stability of a Discrete Control System	753
M16.4	Performance of Digital Control Systems	754
	Example M16.2: Effect of Sample Time on PI Control Performance	755
M16.5	Discrete IMC	756
	Example M16.3	757
M16.6	Summary	759
	References	760
	Additional Exercises	760
	Appendix M16.1: SIMULINK .mdl File for Example M16.2	762
	Appendix M16.2: SIMULINK .m and .mdl Files for Example M16.3	762
Index		765
About the Author		770