CONTENTS

Preface xv Prologue xix

CHAPTER **1**

Chemical Engineering Plant Design 1 General Overall Design Considerations 2 Process Design Development 2 Flowsheet Development 5 Computer-Aided Design 6 Cost Estimation 6 Profitability Analysis of Investments 7 Optimum Design 8 Practical Considerations in Design 11 The Design Approach 12 Engineering Ethics in Design 13

CHAPTER 2

General Design Considerations 15

Health and Safety Hazards 15
Sources of Exposure 16
Exposure Evaluation 18
Control of Exposure Hazards 20
Fire and Explosion Hazards 22
Personnel Safety 27
Safety Regulations 27
Loss Prevention 29
HAZOP Study 29
Fault-tree Analysis 35
Failure Mode and Effect Analysis 36
Safety Audits 36
Environmental Protection 40
Environmental Regulations 41

Development of a Pollution Control System 42 Air Pollution Abatement 42 Water Pollution Abatement 47 Solid Waste Disposal 50 Thermal Pollution Control 51 Noise Control 52 Plant Location 52 Factors Involved 53 Selection of the Plant Site 56 Plant Layout 56 Preparation of the Layout 57 Plant Operation and Control 57 Instrumentation 57 Maintenance 58 Utilities 59 Structural Design 60 Storage 60 Materials Handling 61 Patent Considerations 62 Problems 62

CHAPTER **3** Process Design Development 67

Development of Design Database 67 Literature Survey 68 Patent Search 69
Process Creation 69 Batch Versus Continuous Operation 70 Raw Materials and Product Specifications 70 Process Synthesis Steps 71
Process Design 72 Types of Process Designs 74
Process Flow Diagrams 77
Piping and Instrumentation Diagrams 79

Contents

Vessel and Piping Layout Isometrics 80 Equipment Design and Specifications 81 Scale-up of Equipment in Design 81 Safety Factors 81 Equipment Specifications 84 Materials of Construction 86 The Preliminary Design—A Specific Example 87 Problem Statement 87 Literature Survey 87 Process Creation 88 Development of Conventional Base-Case Design 90 Economic Assessment of Base-Case Design 110 Assessment of Proposed Base-Case Design Modification 113 Summary 120 Problems 121

CHAPTER 4

Flowsheet Synthesis and Development 125

Flowsheet Synthesis and Development 126 General Procedure 126 Process Information 130 **Background Information** 130 Molecular Path Synthesis 131 Selecting a Process Pathway 132 Production Mode 132 Recording Decisions 133 Input/Output Structure 135 Functions Diagram 137 Preprocessing 138 Reactions 139 Recycle 139 By-products, Intermediates, and Wastes 139 Separations 140 **Operations Diagram** 143 Preprocessing 143 Reactors 143 Separations Methods 144 Heating and Cooling 145 145 Minimization of Processing

Process Flowsheet 149 Reactors 149 Mass and Energy Balances 149 Separation Trains 149 Heat Exchange 150 Algorithmic Flowsheet Generation 158 Fundamentals of Algorithmic Process-Network Synthesis 159 Application of Algorithmic Process-Network Synthesis 165 Comparison of Hierarchical and Algorithmic Results 189 Genetic Algorithms 189 Future Approaches to Flowsheet Synthesis and Development 190 Software Use in Flowsheet Synthesis 190 Analysis and Evaluation of Flowsheets 190 Criteria for Evaluating Designs 190 Summary 192 Nomenclature 192 Greek Symbol 193 Problems 193

CHAPTER 5

Software Use in Process Design 196

Software Structure 198 Chemical Property Estimation 198 Process Equipment Models 201 Process Equipment Cost Estimation 202 Process Economic Evaluation 203 Heat Integration 203 Process Control 203 Process Optimization 204 Software Capabilities 204 General-Type Software 205 Software for Process Design 208 Molecular Reaction Databases and Simulators 208 Chemical Cost Databases 209 Flowsheeting Software 209 Unit Operations Simulators 211

viii

Contents

Piping System Design214Plant Layout214Economic Evaluation215Software Selection216Software Use216Physical Property Estimation Guidelines217Process Simulation Guidelines217Avoiding Pitfalls in Software Use220Graphic Interface and Ease of Use221Thermodynamic Property Packages222Simulation Realism222Evaluation of Software Results224

CHAPTER 6 Analysis of Cost Estimation 226

Cash Flow for Industrial Operations 226 Cash Flow 226 Cumulative Cash Position 228 Factors Affecting Investment and Production Costs 230 Sources of Equipment 230 Price Fluctuations 230 Company Policies 230 **Operating Time and Rate of Production** 231 Government Policies 232 Capital Investment 232 Fixed-Capital Investment 233 Working Capital 233 Estimation of Capital Investment 233 Types of Capital Cost Estimates 235 Cost Indexes 236 Cost Components in Capital Investment 239 Purchased Equipment 241 Estimating Equipment Costs by Scaling 242 Purchased-Equipment Delivery 244 Purchased-Equipment Installation 244 Instrumentation and Controls 245 Piping 245 Electrical Systems 246 Buildings 246

Yard Improvements 246 Service Facilities 246 Health, Safety, and Environmental Functions 247 Land 248 Engineering and Supervision 248 Legal Expenses 248 Construction Expenses 248 Contractor's Fee 249 Contingencies 249 Methods for Estimating Capital Investment 249 Estimation of Revenue 258 Estimation of Total Product Cost 259 Manufacturing Costs 262 Variable Production Costs 262 Plant Overhead Costs 270 General Expenses 270 Gross Profit, Net Profit, and Cash Flow 271 Contingencies 272 Summary 272 Nomenclature 274 Greek Symbol 275 Problems 275

CHAPTER 7 Interest, Time Value of Money, Taxes, and Fixed Charges 279

Interest 279 Simple Interest 280 Compound Interest 280 Nominal and Effective Interest Rates 281 Continuous Interest 283 Cost of Capital 285 Income Tax Effects 286 Loan Payments 287 Time Value of Money 290 Cash Flow Patterns 292 Discrete Cash Flows 292 Continuous Cash Flows 294 Compounding and Discounting Factors 297 Income Taxes 303 Federal Income Taxes 304 Taxable Income 304 Capital Gains Tax 305 Losses 306 Other Federal Taxes 306 State Taxes 306 Nonincome Taxes 306 Fixed Charges 307 Depreciation 307 Depreciation and Income Tax 308 Depreciable Investments 309 Current Value 309 Salvage Value 309 Recovery Period 309 Methods for Calculating Depreciation 310 Insurance 313 Self-insurance 314 Nomenclature 315 Greek Symbol 316 Problems 316

CHAPTER 8

Profitability, Alternative Investments, and Replacements 319

Profitability Standards 320 Cost of Capital 320 Minimum Acceptable Rate of Return 321 Methods for Calculating Profitability 322 Methods That Do Not Consider the Time Value of Money 322 Methods That Consider the Time Value of Money 327 Selecting a Profitability Method 330 Effect of Inflation on Profitability Analysis 335 Start-up Costs 340 Spreadsheet for Economic Evaluation Calculations 340 Alternative Investments 340 Alternatives When an Investment Must Be Made 342 Analysis with Small Investment Increments 346 Replacements 348 Methods of Profitability Evaluation for Replacements 349 Typical Example of Replacement Policy 349 Book Values and Unamortized Values 350 Investment on Which the Replacement Comparison Is Based 350 Practical Factors in Alternative-Investment and Replacement Analysis 352 Nomenclature 352 Greek Symbol 353 Problems 353

CHAPTER 9 Optimum Design and Design Strategy 358

Defining the Optimization Problem 359 Selecting an Objective Function 361 Structural Optimization 361 Parametric Optimization 362 Variable Screening and Selection 363 Suboptimization 363 Practical and Intangible Considerations 364 Programming Optimization Problems 364 Linear Programming 367 Generalization of Strategy for Linear Programming 370 Simultaneous Equations 372 Nonlinear Programming 373 Dynamic Programming 377 Optimization Solution Methodologies 379 Procedure with One Variable 380 Procedure with Two or More Variables 381 Breakeven Chart for Optimum Analysis of Production 384 Experimental Design and Analysis of Process Simulations 384 Algorithm Solutions to Optimization Problems 386 **Optimization Applications** - 390 **Optimization Application: Optimum Production** Rates in Plant Operation 390 Optimization Application: Cyclic Operations 394

X

Optimization Application: Economic Pipe Diameter 401 Optimization Application: Cooling Water Flow Rate 406 Optimization Application: Distillation Reflux Ratio 409 Optimization Application: Pinch Technology Analysis 414 Nomenclature 433 Greek Symbols 435 Problems 435

CHAPTER 10 Materials and Fabrication Selection 440

Factors Contributing to Corrosion 440 Combating Corrosion 443 Properties of Materials 444 Ferrous Metals and Alloys 444 Nonferrous Metals and Alloys 450 Inorganic Nonmetals 451 Organic Nonmetals 452 Low- and High-Temperature Materials 455 Gasket Materials 457 Tabulated Data for Selecting Materials of Construction 457 Selection of Materials 457 Economics Involved in Selection 464 Fabrication of Equipment 465 Methods of Fabrication 466 Problems 467

CHAPTER 11 Written and Oral Design Reports 469

Written Reports 47()
Organization of a Written Report 470
Preparing the Report 473
Presenting the Results 474
Comments on Common Errors 480
Checklist for the Final Report 481

Oral Reports 481 Organization and Presentation of an Oral Design Report 482 Problems 484

CHAPTER 12 Materials-Handling Equipment— Design and Costs 485

Basic Concepts of Fluid Transport 485 Newtonian Fluids 486 Non-Newtonian and Bingham Fluids 488 Vacuum Flow 489 Frictional Losses Encountered in Pipelines 491 Power Requirements for Transport of Liquids and Gases 492 Piping in Fluid Transport Processes 497 Selection of Piping Materials 497 Design of Piping Systems 499 Costs for Piping and Piping System Auxiliaries 502 Pumping of Fluids 508 Selection of Pumps 508 Design Procedures for Pumps 515 Costs for Pumps and Motors 516 Compression and Expansion of Fluids 520 Selection of Compressors 520 Selection of Fans and Blowers 523 Selection of Vacuum System Equipment 524 Selection of Turbines, Expanders, and Other Drivers 525 Design Procedures for Compressors 527 Design Procedures for Turbines and Expanders 529 Costs for Compressors, Fans, Blowers, and Expanders 531 Agitation and Mixing of Fluids 536 Selection of Agitators and Mixers 536 Design Procedures for Agitators and Mixers 539 Costs for Agitators and Mixers 544 Flow Measurement of Fluids 549

Storage and Containment of Fluids 552
Design Procedures for Pressure Vessels 553
Costs for Tanks, Pressure Vessels, and Storage Equipment 553
Transport of Solids 560
Selection of Solids Transport Equipment 561
General Design Procedures for Solids Transport Equipment 565
Costs for Solids Transport Equipment 572
Handling of Solids 572
Selection of Solids-Handling Equipment 577
General Design Procedures for Solids-Handling Equipment 580
Costs for Solids-Handling Equipment 582
Nomenclature 587
Greek Symbols 589
Problems 589

CHAPTER 13 Reactor Equipment—Design and Costs 592

Reactor Principles 594 Reactor Types 596 Space Velocity and Space Time 597 Batch Reactors 597 Tubular Plug-Flow Reactors 598 Back-Mix Reactors 599 Nonideality of Reactors 599 Accounting for Reactor Nonideality 600 Residence Time Distribution 600 Nonideal Reactor Emulation Using Ideal Reactor Combinations 601 Recycle Reactors 602 **Development of Chemical Reaction Rate** Expressions 605 Types of Reactions 606 Reaction and Reactor Performance 613 Parallel Reactions 613 Series Reactions 614 Systems of Identical Multiple Reactors 614

Reactor and Catalyst Equipment 616 Selection of Catalyst 616 Types of Reactors 617 Selection of Reactors 621 Design of Reactor Systems 622 Reactor Design Procedure 626 Software 626 Costs for Reactor Equipment 627 Summary 634 Nomenclature 635 Greek Symbols 636 Problems 637

CHAPTER 14 Heat-Transfer Equipment— Design and Costs 642

Basic Theory of Heat Transfer in Exchangers 643 Steady-State Heat-Transfer Considerations 644 Alternative Approaches to Heat Exchanger Performance 652 Determination of Heat-Transfer Coefficients 656 Film Coefficients for Fluids Flowing Inside of Pipes and Tubes (No Phase Change) 657 Film Coefficients for Fluids Flowing Outside of Pipes and Tubes (No Phase Change) 659 Film Coefficients and Overall Coefficients for Various Heat-Transfer Situations 661 Determination of Pressure Drop in Heat Exchangers 664 Tube-Side Pressure Drop 664 Shell-Side Pressure Drop 665 Selection of Heat Exchanger Type 669 Key Heat Exchanger Types Available 670 Preliminary Selection of Heat Exchanger Types 676 Costs of Heat Exchangers 676 Design of Key Heat Exchanger Types 694 Double-Pipe and Multiple Double-Pipe Exchangers 696 Shell-and-Tube Exchangers 702

Plate Exchangers 724
Compact Exchangers 729
Air-Cooled Exchangers 733
Condensers 734
Evaporators 737
Optimum Design of Heat Exchangers 738
General Case 739
General Methods for Design of Heat
Exchangers 744
Nomenclature 745
Greek Symbols 748
Problems 749

CHAPTER 15

Separation Equipment—Design and Costs 754

Selection of Suitable Separation Processes 755 Guidelines for the Separation Process Selection 757 Equipment Design and Costs for Separating Homogeneous Mixtures 769 Separation by Distillation 769 Distillation Design Procedures for Columns with Sieve Trays 769 Distillation Design Procedures for Columns with Random Packing 783 Distillation Design Procedures for Columns with Structured Packing 787 Rating of Distillation Equipment 788 **Rigorous Design Methods for Multicomponent** Distillation 788 Design Procedures for Other Distillation Processes 789 Equipment Costs for Tray and Packed Columns 792 Separation by Absorption and Stripping 797 Design Procedures for Traved Columns Separating Dilute Solutes 799 Design Procedures for Packed Columns Separating Dilute Solutes 802

Design Procedures for Packed Columns Separating Concentrated Solutes 803 Separation by Extraction 804 Equipment Selection for Liquid/Liquid Extraction 804 Design Procedures for Liquid/Liquid Extraction 806 Equipment Costs for Liquid/Liquid Extraction Equipment 814 Separation Using Membranes 814 Selection of Membrane Types 814 General Design Concepts for Membrane Separation 815 General Design Procedures for Membrane Separation 820 Range of Costs for Several Membrane Systems 824 Separation by Adsorption 824 Selection of Sorbent for Separation by Adsorption 825 Basic Adsorption Cycles 827 Selection of Appropriate Adsorption Cycle 829 General Design Concepts for Separation by Adsorption 830 Costs for Adsorption Equipment 837 Equipment Design and Costs for Separating Heterogeneous Mixtures 837 Separation by Drying 839 Equipment Selection for Drving Solids 839 General Design Procedures for Drving 842 Costs for Typical Dryers 845 Separation by Filtration 851 Selection of Filtration Equipment 851 General Design Procedures for Separation by Filtration 854 Costs for Filtration and Other Solids Separation Equipment 863 Nomenclature 869 Greek Symbols 872 Problems 873

xiii

Contents

APPENDIX A: The International System (SI) of Units 877

APPENDIX **B**:

Auxiliary, Utility, and Instrumentation Cost Data 890 APPENDIX E: Heuristics for Process Equipment Design 966

APPENDIX F: Software Useful for Design 974

Author Index976Subject Index979

Design Problems 899

APPENDIX D:

APPENDIX C:

Tables of Physical Properties andConstants947

xiv