

Contents

Preface	xxvii
Acknowledgements.....	xxix
How to use this book.....	xxxix

CHAPTER 1 Introduction to Design.....	1
1.1 Introduction	1
1.2 Nature of design	1
1.2.1 The design objective (the need).....	4
1.2.2 Setting the design basis.....	4
1.2.3 Generation of possible design concepts.....	5
1.2.4 Fitness testing	6
1.2.5 Economic evaluation, optimization and selection	6
1.2.6 Detailed design and equipment selection	7
1.2.7 Procurement, construction and operation	7
1.3 The anatomy of a chemical manufacturing process.....	7
1.3.1 Continuous and batch processes	9
1.4 The organization of a chemical engineering project.....	10
1.5 Project documentation.....	13
1.6 Codes and standards	15
1.7 Design factors (Design margins).....	17
1.8 Systems of units	17
1.9 Optimization	19
1.9.1 The design objective	20
1.9.2 Constraints and degrees of freedom.....	21
1.9.3 Trade-offs	24
1.9.4 Problem decomposition	25
1.9.5 Optimization of a single decision variable	26
1.9.6 Search methods.....	27
1.9.7 Optimization of two or more decision variables	29
1.9.8 Linear programming	32
1.9.9 Non-linear programming	34
1.9.10 Mixed integer programming	35
1.9.11 Optimization in industrial practice	37
1.10 References	41
1.11 Nomenclature.....	42
1.12 Problems	43

CHAPTER 2	Fundamentals of Material Balances	47
2.1	Introduction	48
2.2	The equivalence of mass and energy	48
2.3	Conservation of mass	48
2.4	Units used to express compositions	49
2.5	Stoichiometry	50
2.6	Choice of system boundary	51
2.7	Choice of basis for calculations	54
2.8	Number of independent components	54
2.9	Constraints on flows and compositions	55
2.10	General algebraic method	56
2.11	Tie components	58
2.12	Excess reagent	59
2.13	Conversion, selectivity and yield	60
2.14	Recycle processes	64
2.15	Purge	66
2.16	By-pass	67
2.17	Unsteady-state calculations	68
2.18	General procedure for material-balance problems	69
2.19	References	70
2.20	Nomenclature	71
2.21	Problems	71
CHAPTER 3	Fundamentals of Energy Balances and Energy Utilization	75
3.1	Introduction	76
3.2	Conservation of energy	76
3.3	Forms of energy (per unit mass of material)	76
3.3.1	Potential energy	76
3.3.2	Kinetic energy	77
3.3.3	Internal energy	77
3.3.4	Work	77
3.3.5	Heat	78
3.3.6	Electrical energy	78
3.4	The energy balance	78
3.5	Calculation of specific enthalpy	82
3.6	Mean heat capacities	83
3.7	The effect of pressure on heat capacity	85
3.8	Enthalpy of mixtures	87
3.8.1	Integral heats of solution	87
3.9	Enthalpy-concentration diagrams	88
3.10	Heats of reaction	90

3.10.1 Effect of pressure on heats of reaction	92
3.11 Standard heats of formation	94
3.12 Heats of combustion.....	95
3.13 Compression and expansion of gases	96
3.13.1 Mollier diagrams	97
3.13.2 Polytropic compression and expansion.....	99
3.13.3 Multistage compressors.....	102
3.13.4 Electrical drives.....	103
3.14 Energy balance calculations.....	103
3.15 Unsteady state energy balances	105
3.16 Energy recovery	106
3.16.1 Heat exchange	106
3.16.2 Waste-heat boilers	107
3.16.3 High-temperature reactors.....	109
3.16.4 Low-grade fuels.....	109
3.16.5 High-pressure process streams.....	111
3.16.6 Heat pumps.....	113
3.17 Heat exchanger networks	114
3.17.1 Pinch technology	115
3.17.2 The problem table method	120
3.17.3 Heat exchanger network design	123
3.17.4 Minimum number of exchangers	126
3.17.5 Threshold problems.....	128
3.17.6 Process integration: integration of other process operations.....	129
3.17.7 Computer tools for heat exchanger network design.....	129
3.18 References	133
3.19 Nomenclature.....	134
3.20 Problems	137
CHAPTER 4 Flow-sheeting.....	141
4.1 Introduction	141
4.2 Flow-sheet presentation.....	142
4.2.1 Block diagrams.....	142
4.2.2 Pictorial representation.....	143
4.2.3 Presentation of stream flow rates.....	143
4.2.4 Information to be included.....	143
4.2.5 Layout	144
4.2.6 Precision of data.....	148
4.2.7 Basis of the calculation	149
4.2.8 Batch processes	149
4.2.9 Utilities	149

4.2.10 Equipment identification	149
4.2.11 Computer aided drafting	150
4.3 Process simulation programs.....	150
4.4 Specification of components and physical property models.....	153
4.4.1 Pure components	153
4.4.2 Pseudocomponents	154
4.4.3 Solids and salts	155
4.4.4 User components	156
4.5 Simulation of unit operations.....	156
4.5.1 Reactors	158
4.5.2 Distillation	167
4.5.3 Other separations	179
4.5.4 Heat exchange	181
4.5.5 Hydraulics.....	187
4.5.6 Solids handling	187
4.6 User models	188
4.6.1 Spreadsheet models	188
4.6.2 User subroutines	188
4.7 Flow-sheets with recycle.....	191
4.7.1 Tearing the flow-sheet.....	191
4.7.2 Convergence methods	193
4.7.3 Manual calculations.....	194
4.7.4 Convergence problems	196
4.8 Flow-sheet optimization.....	203
4.8.1 Use of controllers	203
4.8.2 Optimization using process simulation software	204
4.9 Dynamic simulation	205
4.10 References	205
British Standards	206
American and International Standards.....	206
4.11 Nomenclature.....	206
4.12 Problems	207
 CHAPTER 5 Piping and Instrumentation	 215
5.1 Introduction	215
5.2 The P and I diagram.....	216
5.2.1 Symbols and layout.....	216
5.2.2 Basic symbols.....	217
5.3 Valve selection	221
5.4 Pumps and compressors	223
5.4.1 Pump selection	223

5.4.2 Pressure drop in pipelines	226
5.4.3 Power requirements for pumping liquids.....	230
5.4.4 Characteristic curves for centrifugal pumps	233
5.4.5 System curve (operating line)	233
5.4.6 Net positive suction head (NPSH)	237
5.4.7 Pump and other shaft seals.....	238
5.4.8 Gas Compressors	241
5.5 Mechanical design of piping systems	241
5.5.1 Piping System Design Codes	241
5.5.2 Wall thickness: pipe schedule	242
5.5.3 Pipe supports	243
5.5.4 Pipe fittings.....	243
5.5.5 Pipe stressing	243
5.5.6 Layout and design	244
5.6 Pipe size selection	244
5.7 Control and instrumentation.....	253
5.7.1 Instruments	253
5.7.2 Instrumentation and control objectives.....	253
5.7.3 Automatic control schemes	254
5.8 Typical control systems.....	255
5.8.1 Level control.....	255
5.8.2 Pressure control	255
5.8.3 Flow control.....	255
5.8.4 Heat exchangers	257
5.8.5 Cascade control	259
5.8.6 Ratio control	259
5.8.7 Distillation column control	260
5.8.8 Reactor control	263
5.9 Alarms, safety trips and interlocks	264
5.9.1 Interlocks	265
5.10 Computers in process control.....	265
5.11 References	268
British and European Standards.....	269
American and International Standards.....	270
5.12 Nomenclature.....	270
5.13 Problems	272
CHAPTER 6 Costing and Project Evaluation	275
6.1 Introduction	275
6.2 Costs, revenues and profits	276
6.2.1 Fixed capital investment	276

6.2.2 Working capital	279
6.2.3 Variable costs of production	279
6.2.4 Fixed costs of production	280
6.2.5 Revenues, margins and profits	281
6.2.6 Cash flows at the end of the project	282
6.3 Estimating capital costs.....	283
6.3.1 Accuracy and purpose of capital cost estimates	283
6.3.2 Rapid cost estimates.....	284
6.3.3 The factorial method of cost estimation	290
6.3.4 Estimating Purchased Equipment Costs	294
6.3.5 Cost Escalation	301
6.3.6 Location factors	303
6.3.7 Offsite costs	305
6.3.8 Computer tools for cost estimation	305
6.3.9 Validity of cost estimates	314
6.4 Estimating production costs and revenues.....	314
6.4.1 Sources of price data	314
6.4.2 Forecasting prices	316
6.4.3 Transfer pricing	319
6.4.4 Utility costs.....	319
6.4.5 Consumables costs.....	325
6.4.6 Waste disposal costs.....	326
6.4.7 Labour costs.....	327
6.4.8 By-product revenues.....	328
6.4.9 Summarizing production costs and revenues	329
6.5 Taxes and depreciation.....	329
6.5.1 Taxes.....	330
6.5.2 Investment incentives	331
6.5.3 Depreciation charges	331
6.6 Project financing.....	335
6.6.1 Basics of corporate accounting and finance	335
6.6.2 Debt financing and repayment	338
6.6.3 Equity financing	338
6.6.4 Cost of capital	339
6.7 Economic evaluation of projects.....	340
6.7.1 Cash flow and cash flow diagrams	340
6.7.2 Simple methods for economic analysis	341
6.7.3 Time value of money	342
6.7.4 Net present value.....	342
6.7.5 Discounted cash-flow rate of return (DCFRROR).....	343

6.7.6 Annualized cost methods	345
6.7.7 Summary	347
6.8 Sensitivity analysis	354
6.8.1 Simple sensitivity analysis	354
6.8.2 Parameters to study	355
6.8.3 Statistical methods for risk analysis	355
6.8.4 Contingency costs	357
6.9 Project portfolio selection	358
6.9.1 Types of projects	358
6.9.2 Limits on the project portfolio	359
6.9.3 Decision criteria	360
6.10 References	362
American Laws and Standards	363
6.11 Nomenclature	363
6.12 Problems	365
 CHAPTER 7 Materials of Construction	 371
7.1 Introduction	371
7.2 Material properties	372
7.3 Mechanical properties	372
7.3.1 Tensile strength	374
7.3.2 Stiffness	374
7.3.3 Toughness	374
7.3.4 Hardness	374
7.3.5 Fatigue	374
7.3.6 Creep	375
7.3.7 Effect of temperature on the mechanical properties	375
7.4 Corrosion resistance	375
7.4.1 Uniform corrosion	376
7.4.2 Galvanic corrosion	377
7.4.3 Pitting	378
7.4.4 Intergranular corrosion	379
7.4.5 Effect of stress	379
7.4.6 Erosion-corrosion	380
7.4.7 High-temperature oxidation and sulphidation	380
7.4.8 Hydrogen embrittlement	380
7.5 Selection for corrosion resistance	381
7.6 Material costs	381
7.7 Contamination	383
7.7.1 Surface finish	384
7.8 Commonly used materials of construction	384

7.8.1 Iron and steel	384
7.8.2 Stainless steel	385
7.8.3 Nickel.....	387
7.8.4 Monel.....	387
7.8.5 Inconel and Incoloy	388
7.8.6 The Hastelloys	388
7.8.7 Copper and copper alloys.....	388
7.8.8 Aluminium and its alloys	388
7.8.9 Lead	389
7.8.10 Titanium.....	389
7.8.11 Tantalum.....	389
7.8.12 Zirconium	389
7.8.13 Silver.....	389
7.8.14 Gold	390
7.8.15 Platinum.....	390
7.9 Plastics as materials of construction for chemical plant	390
7.9.1 Poly-vinyl chloride (PVC)	391
7.9.2 Polyolefins	391
7.9.3 Polytetrafluoroethylene (PTFE)	391
7.9.4 Polyvinylidene fluoride (PVDF).....	391
7.9.5 Glass-fibre reinforced plastics (GRP)	392
7.9.6 Rubber.....	392
7.10 Ceramic materials (silicate materials)	392
7.10.1 Glass	393
7.10.2 Stoneware	393
7.10.3 Acid-resistant bricks and tiles.....	393
7.10.4 Refractory materials (refractories).....	393
7.11 Carbon.....	394
7.12 Protective coatings	394
7.13 Design for corrosion resistance.....	394
7.14 References	395
British and European Standards.....	396
American and International Standards.....	396
Bibliography	396
7.15 Nomenclature.....	397
7.16 Problems	397
CHAPTER 8 Design Information and Data.....	399
8.1 Introduction	399
8.2 Sources of information on manufacturing processes.....	400
8.3 General sources of physical properties	402
8.4 Accuracy required of engineering data.....	403

8.5	Prediction of physical properties	404
8.6	Density	405
8.6.1	Liquids	405
8.6.2	Gas and vapour density (specific volume)	406
8.7	Viscosity	407
8.7.1	Liquids	407
8.7.2	Gases	411
8.8	Thermal conductivity	412
8.8.1	Solids	412
8.8.2	Liquids	412
8.8.3	Gases	412
8.8.4	Mixtures	413
8.9	Specific heat capacity	413
8.9.1	Solids and liquids	413
8.9.2	Gases	416
8.10	Enthalpy of vaporization (latent heat)	420
8.10.1	Mixtures	421
8.11	Vapour pressure	422
8.12	Diffusion coefficients (diffusivities)	423
8.12.1	Gases	423
8.12.2	Liquids	424
8.13	Surface tension	426
8.13.1	Mixtures	427
8.14	Critical constants	428
8.15	Enthalpy of reaction and enthalpy of formation	431
8.16	Phase equilibrium data	431
8.16.1	Experimental data	431
8.16.2	Phase equilibrium	431
8.16.3	Equations of state	433
8.16.4	Correlations for liquid phase activity coefficients	434
8.16.5	Prediction of vapour-liquid equilibrium	435
8.16.6	K-values for hydrocarbons	437
8.16.7	Sour-water systems	437
8.16.8	Vapour-liquid equilibrium at high pressures	437
8.16.9	Liquid-liquid equilibrium	437
8.16.10	Choice of phase equilibrium model for design calculations	440
8.16.11	Gas solubility	441
8.16.12	Use of equations of state to estimate specific enthalpy and density	442
8.17	References	442
	Bibliography: General sources of physical properties	445
8.18	Nomenclature	446

8.19 Problems	448
CHAPTER 9 Safety and Loss Prevention.....	451
9.1 Introduction	451
9.1.1 Safety legislation	452
9.1.2 Layers of plant safety	455
9.1.3 Intrinsic and extrinsic safety	457
9.2 Materials hazards	457
9.2.1 Toxicity	458
9.2.2 Flammability	459
9.2.3 Materials incompatibility	460
9.2.4 Ionizing radiation	462
9.2.5 Materials safety data sheets	462
9.2.6 Design for materials hazards	463
9.3 Process hazards	464
9.3.1 Pressure	464
9.3.2 Temperature deviations	465
9.3.3 Noise	466
9.3.4 Loss of containment	466
9.3.5 Fires and ignition sources	467
9.3.6 Explosions	469
9.3.7 Human error	471
9.4 Analysis of product and process safety	472
9.4.1 Safety checklists	473
9.5 Failure-mode effect analysis	475
9.5.1 FMEA procedure	476
9.5.2 FMEA rating scales	477
9.5.3 Interpretation of FMEA scores	477
9.5.4 Tools for FMEA	478
9.6 Safety indices	478
9.6.1 Calculation of the Dow F & EI	479
9.6.2 Potential loss	483
9.6.3 Basic preventative and protective measures	483
9.6.4 Mond fire, explosion, and toxicity index	485
9.6.5 Summary	486
9.7 Hazard and operability studies	489
9.7.1 Basic principles	489
9.7.2 Explanation of guide words	491
9.7.3 Procedure	491
9.8 Quantitative hazard analysis	496
9.8.1 Fault trees	498

9.8.2 Equipment reliability	499
9.8.3 Tolerable risk and safety priorities	500
9.8.4 Computer software for quantitative risk analysis	501
9.9 Pressure relief	503
9.9.1 Pressure relief scenarios	504
9.9.2 Pressure relief loads	506
9.9.3 Design of pressure relief valves	508
9.9.4 Design of non-reclosing pressure relief devices	513
9.9.5 Design of pressure relief discharge systems	514
9.9.6 Protection from under-pressure (vacuum)	515
9.10 References	517
Bibliography	519
British and European Standards	519
American and International Standards	520
9.11 Nomenclature	522
9.12 Problems	523
CHAPTER 10 Equipment Selection, Specification and Design	525
10.1 Introduction	525
10.2 Gas-Gas separations	528
10.2.1 Adsorption	528
10.2.2 Membrane separation	535
10.2.3 Cryogenic distillation	540
10.2.4 Absorption and stripping	540
10.2.5 Condensation	540
10.3 Solid-Solid separations	541
10.3.1 Screening (sieving)	542
10.3.2 Liquid-solid cyclones	543
10.3.3 Hydroseparators and sizers (classifiers)	544
10.3.4 Hydraulic jigs	544
10.3.5 Tables	544
10.3.6 Classifying centrifuges	545
10.3.7 Dense-medium separators (sink and float processes)	545
10.3.8 Flotation separators (froth-flotation)	546
10.3.9 Magnetic separators	546
10.3.10 Electrostatic separators	546
10.4 Liquid-Solid (Solid-Liquid) Separators	547
10.4.1 Thickeners and clarifiers	548
10.4.2 Filtration	549
10.4.3 Centrifuges	555
10.4.4 Hydrocyclones (liquid-cyclones)	562

10.4.5 Pressing (expression).....	565
10.4.6 Solids drying.....	566
10.5 Separation of dissolved solids.....	574
10.5.1 Evaporators.....	574
10.5.2 Crystallization.....	577
10.5.3 Precipitation.....	580
10.5.4 Membrane separations.....	581
10.5.5 Ion exchange.....	585
10.5.6 Adsorption.....	585
10.6 Liquid-Liquid separation.....	586
10.6.1 Decanters (settlers).....	586
10.6.2 Plate separators.....	591
10.6.3 Coalescers.....	591
10.6.4 Centrifugal separators.....	591
10.7 Separation of dissolved liquids.....	592
10.7.1 Solvent extraction and leaching.....	592
10.7.2 Chromatography.....	593
10.8 Gas-Solids separations (Gas cleaning).....	598
10.8.1 Gravity settlers (settling chambers).....	598
10.8.2 Impingement separators.....	598
10.8.3 Centrifugal separators (cyclones).....	600
10.8.4 Filters.....	607
10.8.5 Wet scrubbers (washing).....	608
10.8.6 Electrostatic precipitators.....	609
10.9 Gas – Liquid separators.....	609
10.9.1 Settling velocity.....	610
10.9.2 Vertical separators.....	611
10.9.3 Horizontal separators.....	612
10.10 Size reduction and size enlargement.....	614
10.10.1 Crushing and grinding (comminution) equipment.....	614
10.10.2 Size enlargement (agglomeration) equipment.....	615
10.11 Mixing equipment.....	619
10.11.1 Gas mixing.....	619
10.11.2 Liquid mixing.....	619
10.11.3 Solids and pastes.....	626
10.12 Transport and storage of materials.....	627
10.12.1 Gases.....	627
10.12.2 Liquids.....	630
10.12.3 Solids.....	632
10.13 References.....	634
British and European Standards.....	639
American and International Standards.....	639

10.14	Nomenclature.....	640
10.15	Problems	642
CHAPTER 11	Separation Columns (Distillation, Absorption and Extraction)	645
11.1	Introduction	646
11.2	Continuous distillation: Process description.....	647
11.2.1	Reflux considerations.....	648
11.2.2	Feed-point location.....	649
11.2.3	Selection of column pressure	649
11.3	Continuous Distillation: Basic Principles	649
11.3.1	Stage equations.....	649
11.3.2	Dew point and bubble point.....	651
11.3.3	Equilibrium flash calculations	651
11.4	Design variables in distillation.....	654
11.5	Design methods for binary systems	655
11.5.1	Basic equations.....	655
11.5.2	McCabe-Thiele method.....	657
	Procedure	658
11.6	Multicomponent distillation: General considerations.....	662
11.6.1	Key components	663
11.6.2	Product specifications.....	663
11.6.3	Number and sequencing of columns.....	665
11.6.4	Complex columns.....	667
11.6.5	Distillation column sequencing for azeotropic mixtures.....	669
11.7	Multicomponent distillation: short-cut methods for stage and reflux requirements	671
11.7.1	Minimum number of stages (Fenske equation)	672
11.7.2	Minimum reflux ratio.....	674
11.7.3	Feed-point location.....	675
11.8	Multicomponent systems: Rigorous solution procedures (computer methods)....	678
11.8.1	Linear algebra (simultaneous) methods	678
11.8.2	Inside-out algorithms.....	679
11.8.3	Relaxation methods	679
11.9	Other distillation processes	680
11.9.1	Batch distillation.....	680
11.9.2	Vacuum distillation	681
11.9.3	Steam distillation.....	681
11.9.4	Reactive distillation.....	681
11.9.5	Petroleum distillation	682
11.10	Plate efficiency	682
11.10.1	Prediction of plate efficiency	683
11.10.2	O'Connell's correlation.....	685
11.10.3	Van Winkle's correlation	687

11.10.4	AIChE method	688
11.10.5	Entrainment	692
11.11	Approximate column sizing	692
11.12	Plate contactors.....	693
11.12.1	Selection of plate type.....	697
11.12.2	Plate construction	699
11.13	Plate hydraulic design	703
11.13.1	Plate-design procedure	704
11.13.2	Plate areas	705
11.13.3	Diameter	705
11.13.4	Liquid-flow arrangement.....	707
11.13.5	Entrainment	708
11.13.6	Weep point	709
11.13.7	Weir liquid crest	709
11.13.8	Weir dimensions	710
11.13.9	Perforated area.....	711
11.13.10	Hole size	712
11.13.11	Hole pitch	713
11.13.12	Hydraulic gradient	713
11.13.13	Liquid throw	714
11.13.14	Plate pressure drop	714
11.13.15	Downcomer design [back-up]	716
11.14	Packed columns	725
11.14.1	Types of packing	727
11.14.2	Packed-bed height	731
11.14.3	Prediction of the height of a transfer unit (HTU)	736
11.14.4	Column diameter (capacity).....	742
11.14.5	Column internals	747
11.14.6	Wetting rates.....	753
11.15	Column auxiliaries	755
11.16	Solvent extraction (Liquid–Liquid extraction)	755
11.16.1	Extraction equipment	756
11.16.2	Extractor design.....	756
11.16.3	Extraction columns.....	761
11.16.4	Supercritical fluid extraction.....	761
11.17	References	762
11.18	Nomenclature.....	765
11.19	Problems	770

CHAPTER 12 Heat-transfer Equipment..... 773

12.1	Introduction	774
------	--------------------	-----

12.2	Basic design procedure and theory	775
12.2.1	Heat exchanger analysis: the effectiveness—NTU method	776
12.3	Overall heat-transfer coefficient	776
12.4	Fouling factors (Dirt factors)	780
12.5	Shell and tube exchangers: construction details	781
12.5.1	Heat-exchanger standards and codes	785
12.5.2	Tubes	785
12.5.3	Shells	788
12.5.4	Tube-sheet layout (tube count)	789
12.5.5	Shell types (passes)	791
12.5.6	Shell and tube designation	791
12.5.7	Baffles	791
12.5.8	Support plates and tie rods	793
12.5.9	Tube sheets (plates)	793
12.5.10	Shell and header nozzles (branches)	794
12.5.11	Flow-induced tube vibrations	795
12.6	Mean temperature difference (Temperature driving force)	796
12.7	Shell and tube exchangers: general design considerations	801
12.7.1	Fluid allocation: shell or tubes	801
12.7.2	Shell and tube fluid velocities	802
12.7.3	Stream temperatures	802
12.7.4	Pressure drop	802
12.7.5	Fluid physical properties	803
12.8	Tube-side heat-transfer coefficient and pressure drop (Single phase)	804
12.8.1	Heat transfer	804
12.8.2	Tube-side pressure drop	808
12.9	Shell-Side Heat-Transfer and Pressure Drop (Single phase)	810
12.9.1	Flow pattern	810
12.9.2	Design methods	812
12.9.3	Kern's method	813
12.9.4	Commercial software for heat exchanger design	831
12.10	Condensers	833
12.10.1	Heat-transfer fundamentals	834
12.10.2	Condensation outside horizontal tubes	837
12.10.3	Condensation inside and outside vertical tubes	839
12.10.4	Condensation inside horizontal tubes	843
12.10.5	Condensation of steam	844
12.10.6	Mean temperature difference	844
12.10.7	Desuperheating and sub-cooling	844
12.10.8	Condensation of mixtures	846

12.10.9 Pressure drop in condensers	850
12.11 Reboilers and vaporizers	855
12.11.1 Boiling heat-transfer fundamentals	857
12.11.2 Pool boiling	859
12.11.3 Convective boiling	861
12.11.4 Design of forced-circulation reboilers	866
12.11.5 Design of thermosyphon reboilers	866
12.11.6 Design of kettle reboilers	875
12.12 Plate heat exchangers	879
12.12.1 Gasketed plate heat exchangers	879
12.12.2 Welded plate	887
12.12.3 Plate-fin	887
12.12.4 Spiral heat exchangers	888
12.13 Direct-Contact heat exchangers	889
12.14 Finned tubes	890
12.15 Double-Pipe heat exchangers	892
12.16 Air-Cooled exchangers	893
12.16.1 Air coolers: construction details	894
12.16.2 Heat transfer in air coolers	895
12.16.3 Air cooler design	896
12.16.4 Air cooler operation and control	897
12.17 Fired heaters (Furnaces and boilers)	901
12.17.1 Basic construction	901
12.17.2 Design	902
12.17.3 Heat transfer	903
12.17.4 Pressure drop	905
12.17.5 Process-side heat-transfer and pressure drop	905
12.17.6 Stack design	905
12.17.7 Thermal efficiency	906
12.17.8 Fired heater emissions	907
12.18 Heat transfer to vessels	907
12.18.1 Jacketed vessels	907
12.18.2 Internal coils	909
12.18.3 Agitated vessels	910
12.19 References	913
British Standards	917
American and International Standards	918
Engineering Sciences Data Unit Reports	918
Bibliography	918
12.20 Nomenclature	919
Problems	924

CHAPTER 13 Mechanical Design of Process Equipment	929
13.1 Introduction	929
13.1.1 Classification of pressure vessels.....	931
13.2 Pressure vessel codes and standards	931
13.3 Fundamental principles and equations.....	934
13.3.1 Principal stresses	934
13.3.2 Theories of failure	935
13.3.3 Elastic stability	936
13.3.4 Membrane stresses in shells of revolution.....	936
13.3.5 Flat plates	942
13.3.6 Dilation of vessels	946
13.3.7 Secondary stresses	947
13.4 General design considerations: pressure vessels	947
13.4.1 Design pressure	947
13.4.2 Design temperature.....	948
13.4.3 Materials	948
13.4.4 Maximum allowable stress (nominal design strength).....	949
13.4.5 Welded joint efficiency and construction categories	951
13.4.6 Corrosion allowance.....	952
13.4.7 Design loads	953
13.4.8 Minimum practical wall thickness.....	953
13.5 The design of thin-walled vessels under internal pressure	954
13.5.1 Cylinders and spherical shells.....	954
13.5.2 Heads and closures.....	955
13.5.3 Design of flat ends	956
13.5.4 Design of domed ends.....	957
13.5.5 Conical sections and end closures	958
13.6 Compensation for openings and branches	961
13.7 Design of vessels subject to external pressure	962
13.7.1 Cylindrical shells.....	962
13.7.2 Vessel heads	965
13.8 Design of vessels subject to combined loading.....	966
13.8.1 Weight loads.....	971
13.8.2 Wind loads (tall vessels)	972
13.8.3 Earthquake loading.....	976
13.8.4 Eccentric loads (tall vessels).....	976
13.8.5 Torque.....	977
13.9 Vessel supports.....	980
13.9.1 Saddle supports.....	981
13.9.2 Skirt supports.....	984
13.9.3 Bracket supports	987

13.10	Bolted flanged joints	989
13.10.1	Types of flange, and selection	990
13.10.2	Gaskets.....	991
13.10.3	Flange faces.....	991
13.10.4	Flange design.....	993
13.10.5	Standard flanges	995
13.11	Heat-exchanger tube-plates	997
13.12	Welded joint design.....	998
13.13	Fatigue assessment of vessels	1001
13.14	Pressure tests	1002
13.15	High-pressure vessels	1002
13.15.1	Compound vessels	1003
13.15.2	Autofrettage	1005
13.16	Liquid storage tanks	1005
13.17	References	1006
	Bibliography	1008
	British and European Standards	1008
	American and International Standards.....	1009
13.18	Nomenclature.....	1009
13.19	Problems	1013
CHAPTER 14	General Site Considerations	1017
14.1	Introduction	1017
14.2	Plant location and site selection.....	1017
14.3	Site layout.....	1020
14.4	Plant layout.....	1021
14.4.1	Techniques used in site and plant layout.....	1023
14.5	Utilities	1025
14.6	Environmental considerations	1027
14.6.1	Environmental legislation	1028
14.6.2	Waste minimization.....	1031
14.6.3	Waste management.....	1033
14.6.4	Noise	1035
14.6.5	Visual impact.....	1035
14.6.6	Environmental auditing	1036
14.7	References	1036
	British and European Standards	1037
	American and International Standards.....	1038
CHAPTER 15	Design of Reactors and Mixers	1039
15.1	Introduction	1040

15.2	Reactor design: general procedure.....	1040
15.2.1	General procedure for reactor design	1040
15.2.2	Ideal and real reactors	1046
15.3	Sources of reaction engineering data.....	1049
15.3.1	Enthalpy of reaction	1049
15.3.2	Equilibrium constant and Gibbs free energy	1050
15.3.3	Reaction mechanisms, rate equations and rate constants	1051
15.3.4	Transport properties	1052
15.4	Choice of reaction conditions	1054
15.4.1	Chemical or biochemical reaction	1055
15.4.2	Catalyst	1055
15.4.3	Temperature	1056
15.4.4	Pressure	1057
15.4.5	Reaction phase	1057
15.4.6	Solvent	1058
15.4.7	Concentrations	1058
15.5	Mixing and feed preparation.....	1061
15.5.1	Mixing in stirred tanks	1062
15.5.2	Gas-liquid mixing	1062
15.5.3	Solid-fluid mixing	1062
15.6	Heating and cooling of reacting systems.....	1063
15.6.1	Heating and cooling reactors: basic principles.....	1063
15.6.2	Heating and cooling stirred tank reactors	1065
15.6.3	Heating and cooling catalytic reactors.....	1067
15.6.4	Heat exchange devices as reactors.....	1069
15.7	Multiphase reactors	1072
15.7.1	Vapour-liquid reactors.....	1072
15.7.2	Liquid-liquid reactors	1074
15.7.3	Vapour-solid reactors	1075
15.7.4	Liquid-solid reactors.....	1083
15.7.5	Vapour-liquid-solid reactors.....	1084
15.8	Reactor design for catalytic processes.....	1086
15.8.1	Design for homogeneous catalysis.....	1087
15.8.2	Design for heterogeneous catalysis.....	1087
15.8.3	Design and selection of solid catalysts	1090
15.8.4	Design for catalyst deactivation and regeneration	1092
15.9	Design of bioreactors	1108
15.9.1	Enzyme catalysis	1108
15.9.2	Cell cultivation	1110
15.9.3	Prevention of contamination in biological systems.....	1112
15.9.4	Feed preparation and consumption	1115

15.9.5 Batch fermentation	1117
15.9.6 Continuous fermentation	1120
15.9.7 Bioreactor instrumentation and control	1121
15.9.8 Safety and quality control of bioreactors.....	1122
15.10 Multifunctional batch reactors	1129
15.10.1 Design of batch reactors.....	1129
15.10.2 Multifunctional batch reactors	1130
15.11 Computer simulation of reactors.....	1131
15.11.1 Commercial process simulation models	1131
15.11.2 Network models.....	1132
15.11.3 Hydrodynamic models	1132
15.12 Determining actual reactor performance	1133
15.12.1 Measuring experimental reactor output	1133
15.12.2 Measuring commercial reactor behaviour	1135
15.13 Safety considerations in reactor design	1136
15.13.1 Inherently safer design principles applied to reactors.....	1136
15.13.2 Designing for exothermic reactions	1136
15.13.3 Venting and relief of reactive systems	1139
15.14 Capital cost of reactors.....	1139
15.15 References	1139
Bibliography	1142
International Standards.....	1142
15.16 Nomenclature.....	1143
15.17 Problems	1145
Appendix A Graphical symbols for piping systems and plant.....	1147
Appendix D Conversion factors for Some common SI units.....	1158
Appendix E Design projects I.....	1161
Appendix F Design projects II.....	1181
Appendix G Equipment Specification (Data) Sheets	1209
Index	1225
Appendix B Corrosion Chart.....	e1
Appendix C Physical Property Data Bank.....	e1
Appendix H Typical Shell and Tube Heat-Exchanger Tube-Sheet Layouts	e1
Appendix I Material Safety Data Sheet	e1

Appendices B, C, H and I can be found in the online companion material at (<https://www.elsevier.com/books-and-journals/book-companion/9780081025994>).