
Contents

Preface.....	xi
Acknowledgments	xv
Authors	xvii
Systems of Units	xix
Conversion Factors.....	xxi
1. Introduction.....	1
Learning Objectives.....	1
1.1 Definitions of Chemical Engineering	2
1.2 Sets of Units and Unit Conversion.....	3
1.2.1 Conversion of Units	3
1.2.2 Temperature Measurement	5
1.2.3 Temperature Conversion	6
1.3 Significant Figures	8
1.3.1 Multiplication, Division, Addition, and Subtraction of Significant Numbers	9
1.4 Dimensional Homogeneity.....	10
1.4.1 Dimensionless Quantities.....	11
1.5 Process and Process Variables.....	13
1.5.1 Process Flow Sheet.....	13
1.5.2 Process Unit	13
1.5.3 Process Streams.....	13
1.5.4 Density, Mass, and Volume	13
1.5.5 Mass and Volumetric Flow Rates	14
1.5.6 Moles and Molecular Weight	16
1.6 Compositions of Streams	17
1.6.1 Mass Fraction and Mole Fraction	17
1.6.2 Concentration	19
1.7 Pressure Measurement.....	22
1.7.1 Types of Pressures	23
1.7.2 Standard Temperature and Pressure	24
1.7.3 Pressure-Sensing Devices.....	25
1.8 Process Classification and Material Balance.....	38
1.8.1 Material and Energy Balances	38
Homework Problems	39
References	42

2. Process Units and Degrees of Freedom Analysis	43
Learning Objectives	43
2.1 Process Units: Basic Functions	44
2.1.1 Divider (Splitter).....	44
2.1.2 Mixer (Blender).....	44
2.1.3 Dryer (Direct Heating).....	44
2.1.4 Filter	45
2.1.5 Distillation Column.....	46
2.1.6 Multieffect Evaporator	46
2.1.7 Dehumidification.....	48
2.1.8 Humidifier	48
2.1.9 Leaching and Extraction.....	49
2.1.10 Absorber (Stripper)	49
2.1.11 Partial Condenser and Flash Separator	50
2.1.12 Flash Separator.....	50
2.1.13 Crystallizer	51
2.1.14 Reactors	51
2.1.15 Batch Reactor	52
2.1.16 PFRs and PBRs	53
2.1.17 CSTR and Fluidized Bed Reactor	53
2.2 Process Flow Diagram.....	53
2.3 Labeling a PFD	54
2.4 Degrees of Freedom Analysis	55
2.4.1 Possible Outcomes of DFA.....	56
2.5 Independent Equations	56
2.6 Multiunit PFD.....	66
2.7 DFA, Multiunit Process	68
Homework Problems	71
References	74
3. Material Balance on Single-Unit Process	75
Learning Objectives	75
3.1 Introduction to Material Balance	75
3.2 Material Balance Fundamentals	77
3.3 Mass Balance on Steady-State Processes	78
3.3.1 Stream Specification	78
3.4 Basis for Calculation	83
3.4.1 Procedure for Solving Material Balance Problems	83
Homework Problems	100
References	102
4. Multiunit Process Calculations	105
Learning Objectives	105
4.1 Multiunit Process	105
4.2 Degrees of Freedom Analysis	106

4.3	Recycle, Bypass, Purge, and Makeup	108
4.3.1	Recycle	108
4.3.2	Bypass	109
4.3.3	Purge	109
4.3.4	Makeup	110
	Homework Problems	132
	References	135
5.	Material Balances on Reactive Systems	137
	Learning Objectives	137
5.1	Stoichiometry Basics	138
5.1.1	Stoichiometric Equation	138
5.1.2	Stoichiometric Coefficients	138
5.1.3	Stoichiometric Ratio	138
5.1.4	Limiting Reactant	139
5.1.5	Excess Reactants	139
5.1.6	Fractional Conversion	143
5.2	General Material Balance	143
5.2.1	Differential Balance	144
5.2.2	Integral Balance	144
5.2.3	Formulation Approaches of Mass Balance	145
5.3	Extent of Reaction Method for a Single Reaction	145
5.4	Element or Atomic Balance Method	147
5.5	Molecular or Component Balance Approach	147
5.6	Extent of Reaction and Multiple Reactions	157
5.7	Molecular Species Approach for Multiple Reactions	162
5.8	Degrees of Freedom Analysis for Reactive Processes	168
5.8.1	Chemical Equilibrium	169
5.9	Combustion Reactions	172
5.9.1	Theoretical and Excess Air	172
	Homework Problems	179
	References	182
6.	Multiple-Unit Systems Involving Reaction, Recycle, and Purge	183
	Learning Objectives	183
6.1	Multiple-Unit Process Flowcharts	183
6.1.1	Flow Sheet for Reaction with Recycle	184
6.1.2	Reaction with Product Splitter and Recycle	184
6.1.3	Reaction with Recycle and Purge	185
6.2	Degrees of Freedom Analysis for Reactive Multiple-Unit Processes	186
6.3	Reaction and Multiple-Unit Steady-State Processes	192
	Homework Problems	208
	References	214

7. Single- and Multiphase Systems	215
Learning Objectives	215
7.1 Single-Phase Systems	215
7.1.1 Liquid and Solid Densities	216
7.2 Ideal Gas Equation of State	217
7.2.1 Gas Density	219
7.3 Real Gas Relationships	220
7.3.1 Compressibility Factor (z)	221
7.3.2 Virial Equation of State	222
7.3.3 van der Waals Equation of State	222
7.3.4 Soave–Redlich–Kwong Equation of State	223
7.3.5 Kay’s Mixing Rules	225
7.4 Multiphase Systems	228
7.4.1 Phase Diagram	228
7.4.2 Vapor–Liquid Equilibrium Curve	228
7.5 Vapor Pressure Estimation	229
7.5.1 Clapeyron Equation	230
7.5.2 Clausius–Clapeyron Equation	230
7.5.3 Cox Chart	231
7.5.4 Antoine Equation	231
7.6 Partial Pressure	234
7.6.1 Dalton’s Law of Partial Pressures	234
7.6.2 Raoult’s Law for a Single Condensable Species	235
7.7 Gibbs’ Phase Rule	241
7.8 Bubble Point, Dew Point, and Critical Point	242
Homework Problems	244
References	246
8. Energy and Energy Balances	247
Learning Objectives	247
8.1 Energy Balance for Closed and Open Systems	247
8.1.1 Forms of Energy: The First Law of Thermodynamics	248
8.1.2 Energy Balance for a Closed System	248
8.1.2.1 Kinetic Energy	249
8.1.2.2 Potential Energy	251
8.1.3 Energy Balance for an Open System	253
8.1.4 Steam Turbine	257
8.1.5 Heaters and Coolers	259
8.1.6 Compressors	261
8.2 Mechanical Energy Balance	263
8.3 Bernoulli’s Equation	267
8.4 Enthalpy Calculations	268
8.4.1 Enthalpy Change as a Result of Temperature	268
8.4.2 Constant Heat Capacity	271

8.5	Enthalpy Calculations with Phase Changes	274
8.5.1	Energy Balance for Open Systems with Multiple Inputs and Multiple Outputs	276
8.5.2	Enthalpy Change because of Mixing	279
8.5.3	Energy Balance for Bioprocesses	281
8.6	Psychrometric Chart.....	283
8.7	Summary	293
	Homework Problems	293
	References	297
9.	Energy Balance with Reaction	299
	Learning Objectives.....	299
9.1	Heat of Reaction	299
9.2	Heats of Formation and Heat of Combustion.....	300
9.2.1	Extent of Reaction	304
9.2.2	Reactions in Closed Processes	304
9.3	Energy Balance for Reactive Processes	307
9.3.1	Heat of Reaction Method	307
9.3.2	Heat of Formation or Element Balance Method	308
9.4	Simultaneous Material and Energy Balances	309
9.4.1	Unknown Process Exit Temperature	322
9.5	Combustion Processes.....	327
9.6	Energy Balance in Bioprocesses.....	332
9.7	Energy Balance in Membrane Reactors	334
9.8	Summary	338
	Homework Problems	339
	References	342
10.	Simultaneous Material and Energy Balances.....	343
	Learning Objectives.....	343
10.1	Material Balances	343
10.1.1	Conversion	343
10.1.2	Yield	344
10.1.3	Selectivity	344
10.1.4	Extent of Reaction (ξ)	344
10.2	Energy Balances	345
10.2.1	Heat of Reaction Method	345
10.2.2	Heat of Formation Method	345
10.2.3	Concept of Atomic Balances	346
10.2.4	Mathematical Formulation of the Atomic Balance	346
10.2.5	Degrees of Freedom Analysis for the Atomic Balance	346
10.2.6	Implementing Recycle on the Separation Process	349
	Homework Problems	375
	References	381

11. Unsteady-State Material and Energy Balances	383
Learning Objectives	383
11.1 Unsteady-State Material Balance	383
11.2 Unsteady-State Energy Balance	394
Homework Problems	405
References	406
Appendix	407
Index	437