Contents

Preface *page* xiii
Acknowledgments xx
Nomenclature xxi

1 Low-Carbon Energy, Why? 1

1.1 Introduction 1
1.2 Consumption 2
1.3 Global Warming 6
1.4 CO_2 Emission by Fuel and Sector 13
1.5 International Agreements 16
1.6 CO_2 Emissions Mitigation 17
1.7 Conversion 32
References 33

2 Thermodynamics 34

2.1 Introduction 34
2.2 The First Law of Thermodynamics 35
2.3 The Second Law of Thermodynamics 43
2.4 The Combined Statement and Availability 47
2.5 Thermodynamic Efficiency 61
2.6 Equilibrium 73
2.7 The Fundamental Equation 76
2.8 Describing the State 78
2.9 Mass Transfer Equilibrium 86
2.10 Gas Separation 97
2.11 Liquefaction and Its Application 102
2.12 Summary 107
Problems 108
References 121

3 Chemical Thermodynamics and Thermochemical Calculations 122

3.1 Introduction 122
3.2 Stoichiometry and Mass Conservation 124

3.3 Reaction Energetics 132
3.4 Combustion and Combustion Engine Efficiency 150
3.5 Absolute Entropy and the Third Law of Thermodynamics 151
3.6 Equilibrium 154
3.7 Hydrocarbon Combustion Reactions 166
3.8 Maximum Work in a Chemical Reaction 170
3.9 Fuel Reforming Efficiency 176
3.10 Indirect Conversion, Combustion Engines 197
3.11 About Fuels and Their Production 201
3.12 Summary 203
Problems 204
References 215

4 Electrochemical Thermodynamics 217

4.1 Introduction 217
4.2 Electrochemical Reactions 218
4.3 Thermodynamics of Fuel Cells 227
4.4 Nernst Equation 232
4.5 Fuel Cell Efficiencies 242
4.6 Open-Circuit Potential and Thermodynamic Equilibrium 245
4.7 Half-Cell Potential 248
4.8 The Electrochemical Potential 250
4.9 Thermodynamics of Hybrid Systems 252
4.10 Summary 258
Problems 259
References 266

5 Thermomechanical Conversion: Gas Turbine Cycles 268

5.1 Introduction 268
5.2 Heat Engines 269
5.3 Gas Turbines 274
5.4 Regenerative/Recuperative Cycles 288
5.5 Reheating and Intercooling 292
5.6 Impact of Working Fluid Properties 297
5.7 Bottoming Cycles 302
5.8 Cogeneration 303
5.9 Gas Turbines Operating at High Temperature 303
5.10 Gas Turbines in Power Generation 305
5.11 Performance Criteria 307
5.12 Compressed Air Energy Storage System 308
5.13 Summary 308

Problems 310
References 314

6 Thermomechanical Conversion: Two-Phase Cycles 315

6.1 Introduction 315
6.2 Two-Phase Power Cycles 316
6.3 The Rankine Cycle 316
6.4 Superheat 322
6.5 Reheat 323
6.6 Regeneration 327
6.7 Supercritical Two-Phase Rankine Cycles 337
6.8 Hypercritical Cycles 340
6.9 Binary Two-Phase Cycles 350
6.10 Organic Rankine Cycles 351
6.11 Cooling 356
6.12 Modeling Software 360
6.13 Summary 361
Problems 362
References 367

7 Fuel Cells at Finite Current 369

7.1 Introduction 369
7.2 Fuel Cell Components 370
7.3 Fuel Cell Types and Materials 371
7.4 Polarization Curves 372
7.5 Kinetics of Electrochemical Processes at Surfaces 374
7.6 Transport of Uncharged Species 387
7.7 Fuel Utilization and Gas Consumption Losses 399
7.8 Fuel Crossover/Internal Currents 400
7.9 Overall MEA Model 402
7.10 Fuel Cell Types 406
7.11 Summary 418
Problems 418
References 422

8 Combined, Oxy-Combustion, and Hybrid Cycles 423

8.1 Introduction 423
8.2 Humid Air Cycles 424
8.3 Thermochemical Recuperation 429
8.4 Combined Cycles 431
8.5 Oxy-Combustion Cycles 441

8.6 Hybrid Fuel Cell–Gas Turbine/CC Cycles 453
8.7 Summary 474
Problems 475
References 483

9 Geothermal, Solar Thermal, and Integration 484

9.1 Introduction 484
9.2 Working with Lower-Temperature Sources 485
9.3 Geothermal Energy Applications 486
9.4 Solar Thermal Energy Applications 494
9.5 Integrating Solar and Fuel Energy 511
9.6 Fair Allocation Method 520
9.7 Summary 520
Problems 521
References 523

10 Gas Separation Processes and Application to Carbon Capture Plants 524

10.1 Introduction 524
10.2 Separation Energy Penalty 526
10.3 Gas Separation Processes 528
10.4 Absorption 532
10.5 Adsorption 556
10.6 Cryogenic Distillation 565
10.7 Membrane Separation 570
10.8 Dense Metallic Membranes 586
Problems 602
References 605

11 Low-to-Zero CO_2 Cycles: Natural Gas 608

11.1 Introduction 608
11.2 CO_2 Capture Requirements 609
11.3 Low CO_2 Emission Power Cycle Layout 610
11.4 Post-Combustion Capture 612
11.5 Oxy-Combustion 618
11.6 Chemical Looping 628
11.7 Membrane-Based Oxy-Combustion Cycles 645
11.8 Pre-Combustion Capture 646
11.9 Comparison 654
Problems 656
References 658

12 Coal, Power Cycles, Gasification, and Synfuels 659

12.1 Introduction 659
12.2 Resources and Consumption 659
12.3 Plant Efficiency 661
12.4 Coal Ranks 662
12.5 Coal Burning in Boilers 664
12.6 Gasification-Based Combined Cycles 669
12.7 Gasification 684
12.8 Fuel Synthesis Using Syngas 699
Problems 710
References 716

13 Carbon Capture Cycles: Coal 717

13.1 Introduction 717
13.2 Cycles for CO_2 Capture 717
13.3 Post-Combustion Capture 718
13.4 Oxy-Combustion 722
13.5 Pre-Combustion Capture 733
13.6 Chemical-Looping Combustion 745
References 750

14 Biomass, Bio-energy, and Biofuels 753

14.1 Introduction 753
14.2 Complex Hydrocarbons 754
14.3 Photosynthesis and Biomass Composition 758
14.4 Conversion 766
14.5 Bioconversion 767
14.6 Thermochemical Conversion 773
14.7 Modeling Gasification and Combustion 793
14.8 Gasification for Power and Fuel Production 801
Problems 803
References 804

Index 806