

CONTENTS

Preface to the Third Edition ix

Acknowledgments xi

1 Introduction 1

Motivation to Study Combustion 1

A Definition of Combustion 8

Combustion Modes and Flame Types 9

Approach to Our Study 10

References 11

2 Combustion and Thermochemistry 12

Overview 12

Review of Property Relations 12

Extensive and Intensive Properties 12

Equation of State 13

Calorific Equations of State 13

Ideal-Gas Mixtures 15

Latent Heat of Vaporization 18

First Law of Thermodynamics 18

First Law—Fixed Mass 18

First Law—Control Volume 20

Reactant and Product Mixtures 21

Stoichiometry 21

Standardized Enthalpy and

Enthalpy of Formation 26

Enthalpy of Combustion and Heating
Values 29

Adiabatic Flame Temperatures 33

Chemical Equilibrium 38

Second-Law Considerations 38

Gibbs Function 40

Complex Systems 46

Equilibrium Products of Combustion 46

Full Equilibrium 46

Water-Gas Equilibrium 49

Pressure Effects 52

Some Applications 53

Recuperation and Regeneration 53

Flue- (or Exhaust-) Gas Recirculation 59

Summary 66

Nomenclature 66

References 68

Review Questions 69

Problems 70

3 Introduction to Mass Transfer 79

Overview 79

Rudiments of Mass Transfer 79

Mass Transfer Rate Laws 80

Species Conservation 86

Some Applications of Mass Transfer 88

The Stefan Problem 88

Liquid–Vapor Interface Boundary Conditions 90

Droplet Evaporation 94

Summary 101

Nomenclature 101

References 103

Review Questions 103

Problems 104

4 Chemical Kinetics 107

Overview 107

Global Versus Elementary Reactions 107

Elementary Reaction Rates 109

Bimolecular Reactions and Collision Theory 109

Other Elementary Reactions 114

Rates of Reaction For Multistep Mechanisms 115

Net Production Rates 115

Compact Notation 116

Relation Between Rate Coefficients and

Equilibrium Constants 118

Steady-State Approximation 120

The Mechanism for Unimolecular Reactions 121

Chain and Chain-Branching Reactions 123

Chemical Time Scales 129

Partial Equilibrium 133

Reduced Mechanisms 135

Catalysis and Heterogeneous Reactions 136

Surface Reactions 136

Complex Mechanisms 138

Summary	139
Nomenclature	140
References	141
Questions and Problems	143
5 Some Important Chemical Mechanisms	149
Overview	149
The $\text{H}_2\text{--O}_2$ System	149
Carbon Monoxide Oxidation	152
Oxidation of Hydrocarbons	153
General Scheme for Alkanes	153
Global and Quasi-Global Mechanisms	156
Real Fuels and Their Surrogates	158
Methane Combustion	159
Complex Mechanism	159
High-Temperature Reaction Pathway Analysis	168
Low-Temperature Reaction Pathway Analysis	170
Oxides of Nitrogen Formation	170
Methane Combustion and Oxides of Nitrogen Formation—A Reduced Mechanism	174
Summary	175
References	176
Questions and Problems	179
6 Coupling Chemical and Thermal Analyses of Reacting Systems	183
Overview	183
Constant-Pressure, Fixed-Mass Reactor	184
Application of Conservation Laws	184
Reactor Model Summary	187
Constant-Volume, Fixed-Mass Reactor	187
Application of Conservation Laws	187
Reactor Model Summary	188
Well-Stirred Reactor	194
Application of Conservation Laws	194
Reactor Model Summary	197
Plug-Flow Reactor	206
Assumptions	206
Application of Conservation Laws	206
Applications to Combustion System Modeling	210
Summary	211

Nomenclature	211
References	212
Problems and Projects	213
Appendix 6A—Some Useful Relationships among Mass Fractions, Mole Fractions, Molar Concentrations, and Mixture Molecular Weights	218
7 Simplified Conservation Equations for Reacting Flows	220
Overview	220
Overall Mass Conservation (Continuity)	221
Species Mass Conservation (Species Continuity)	223
Multicomponent Diffusion	226
General Formulations	226
Calculation of Multicomponent Diffusion Coefficients	228
Simplified Approach	231
Momentum Conservation	233
One-Dimensional Forms	233
Two-Dimensional Forms	235
Energy Conservation	239
General One-Dimensional Form	239
Shvab–Zeldovich Forms	241
Useful Form for Flame Calculations	245
The Concept of a Conserved Scalar	245
Definition of Mixture Fraction	246
Conservation of Mixture Fraction	247
Conserved Scalar Energy Equation	251
Summary	252
Nomenclature	252
References	254
Review Questions	255
Problems	255
8 Laminar Premixed Flames	258
Overview	258
Physical Description	259
Definition	259
Principal Characteristics	259
Typical Laboratory Flames	261
Simplified Analysis	266
Assumptions	266
Conservation Laws	266
Solution	269

Detailed Analysis	273
Governing Equations	274
Boundary Conditions	274
Structure of CH_4 -Air Flame	276
Factors Influencing Flame Velocity and Thickness	279
Temperature	279
Pressure	280
Equivalence Ratio	280
Fuel Type	282
Flame Speed Correlations for Selected Fuels	285
Quenching, Flammability, and Ignition	287
Quenching by a Cold Wall	287
Flammability Limits	293
Ignition	295
Flame Stabilization	300
Summary	303
Nomenclature	304
References	305
Review Questions	307
Problems	308
9 Laminar Diffusion Flames	311
Overview	311
Nonreacting Constant-Density Laminar Jet	312
Physical Description	312
Assumptions	313
Conservation Laws	314
Boundary Conditions	314
Solution	315
Jet Flame Physical Description	320
Simplified Theoretical Descriptions	323
Primary Assumptions	323
Basic Conservation Equations	324
Additional Relations	325
Conserved Scalar Approach	325
Various Solutions	332
Flame Lengths for Circular-Port and Slot Burners	336
Roper's Correlations	336
Flowrate and Geometry Effects	340
Factors Affecting Stoichiometry	341
Soot Formation and Destruction	346
Counterflow Flames	350
Mathematical Description	351
Structure of CH_4 -Air Flame	353

Summary	356
Nomenclature	357
Reference	359
Review Questions	362
Problems	363
10 Droplet Evaporation and Burning	366
Overview	366
Some Applications	366
Diesel Engines	367
Gas-Turbine Engines	369
Liquid-Rocket Engines	371
Simple Model of Droplet Evaporation	374
Assumptions	375
Gas-Phase Analysis	376
Droplet Lifetimes	380
Simple Model of Droplet Burning	383
Assumptions	383
Problem Statement	385
Mass Conservation	385
Species Conservation	385
Energy Conservation	388
Summary and Solution	394
Burning Rate Constant and Droplet Lifetimes	395
Extension to Convective Environments	400
Additional Factors	402
One-Dimensional Vaporization-Controlled Combustion	403
Physical Model	404
Assumptions	405
Mathematical Problem Statement	405
Analysis	406
Model Summary	412
Summary	416
Nomenclature	417
References	419
Problems	422
Projects	423
Appendix 10A—Sir Harry R. Ricardo's Description of Combustion in Diesel Engines [51]	425
11 Introduction to Turbulent Flows	427
Overview	427
Definition of Turbulence	428

Length Scales in Turbulent Flows	431
Four Length Scales	431
Turbulence Reynolds Numbers	433
Analyzing Turbulent Flows	437
Reynolds Averaging and Turbulent Stresses	438
The Closure Problem	440
Axisymmetric Turbulent Jet	444
Beyond the Simplest Model	447
Summary	448
Nomenclature	449
References	450
Questions and Problems	452
12 Turbulent Premixed Flames	453
Overview	453
Some Applications	453
Spark-Ignition Engines	453
Gas-Turbine Engines	454
Industrial Gas Burners	455
Definition of Turbulent Flame Speed	457
Structure of Turbulent Premixed Flames	459
Experimental Observations	459
Three Flame Regimes	460
Wrinkled Laminar-Flame Regime	465
Distributed-Reaction Regime	470
Flamelets-in-Eddies Regime	472
Flame Stabilization	474
Bypass Ports	474
Burner Tiles	475
Bluff Bodies	475
Swirl or Jet-Induced Recirculating Flows	477
Summary	478
Nomenclature	479
References	480
Problems	483
13 Turbulent Nonpremixed Flames	486
Overview	486
Jet Flames	489
General Observations	489
Simplified Analysis	494
Flame Length	500
Flame Radiation	506
Lift-off and Blowout	510
Other Configurations	515
Summary	519

Nomenclature	519
References	520
Review Questions	524
Problems	525
14 Burning of Solids	527
Overview	527
Coal-Fired Boilers	527
Heterogeneous Reactions	529
Burning of Carbon	530
Overview	531
One-Film Model	532
Two-Film Model	543
Particle Burning Times	550
Coal Combustion	551
Other Solids	551
Summary	552
Nomenclature	552
References	553
Questions and Problems	554
15 Emissions	556
Overview	556
Effects of Pollutants	557
Quantification of Emissions	559
Emission Indices	559
Corrected Concentrations	561
Various Specific Emission Measures	564
Emissions from Premixed Combustion	565
Oxides of Nitrogen	565
Carbon Monoxide	573
Unburned Hydrocarbons	575
Catalytic Aftertreatment	576
Particulate Matter	576
Emissions from Nonpremixed Combustion	578
Oxides of Nitrogen	579
Unburned Hydrocarbons and Carbon Monoxide	593
Particulate Matter	595
Oxides of Sulfur	597
Greenhouse Gases	598
Summary	601
Nomenclature	602
References	603
Questions and Problems	612

16 Detonations 616

Overview 616

Physical Description 616

Definition 616

Principal Characteristics 617

One-Dimensional Analysis 618

Assumptions 618

Conservation Laws 619

Combined Relations 620

Detonation Velocities 626

Structure of Detonation Waves 630

Summary 635

Nomenclature 635

References 636

Problems 637

17 Fuels 638

Overview 638

Naming Conventions and Molecular Structures 638

Hydrocarbons 638

Alcohols 642

Other Organic Compounds 642

Important Properties of Fuels 644

Ignition Characteristics 644

Volatility 646

Energy Density 647

Conventional Fuels 648

Gasoline 648

Diesel Fuels 654

Heating Oils 654

Aviation Fuels 655

Natural Gas 657

Coal 662

Alternative Fuels 667

Biofuels 667

Fischer-Tropsch Liquid Fuels 677

Hydrogen 678

Summary 679

Nomenclature and Abbreviations 679

References 680

Problems 685

Appendix A Selected Thermodynamic Properties of Gases Comprising C–H–O–N System 686**Appendix B** Fuel Properties 700**Appendix C** Selected Properties of Air, Nitrogen, and Oxygen 704**Appendix D** Binary Diffusion Coefficients and Methodology for their Estimation 707**Appendix E** Generalized Newton's Method for the Solution of Nonlinear Equations 710**Appendix F** Computer Codes for Equilibrium Products of Hydrocarbon–Air Combustion 713

Index 715