

CONTENTS

Nomenclature	xv
Preface	xxiii

PART I Basic Concepts

1	Scope and History of Combustion	3
1.1	The Nature of Combustion	3
1.2	Historical Perspective of Combustion Science	6
1.3	Historical Perspective of Fuels	8
1.4	Historical Perspective of Combustion Technology <i>Lighting / Steam Boilers / Internal-Combustion Engines / Compression-Ignition Engines / Gas Turbines / Rocket Engines</i>	10
1.5	General Reference Sources	22
1.6	Summary	23
	References	24
2	Fuels	25
2.1	Gaseous Fuels <i>Characterization of Gaseous Fuels</i>	27
2.2	Liquid Fuels <i>Molecular Structure / Characterization of Liquid Fuels / Liquid Fuel Types / Gasoline Quality / Gasoline Formulation and Emissions / Diesel Fuel Quality / Diesel Fuel Formulation and Emissions / Turbine Fuel Quality</i>	30
2.3	Solid Fuels <i>Biomass / Peat / Coal / Refuse Solid Fuel / Analysis and Testing of Solid Fuels</i>	47
2.4	Summary	57
	Problems	57
	References	59
3	Thermodynamics of Combustion	61
3.1	Review of First Law Concepts	61
3.2	Properties of Mixtures	64

3.3	Combustion Stoichiometry	66
3.4	Chemical Energy <i>Heat of Reaction \wedge Heat of Formation and Absolute Enthalpy</i>	72
3.5	Chemical Equilibrium <i>Chemical Equilibrium Criterion \wedge Properties of Combustion Products</i>	77
3.6	First Law Combustion Calculations <i>Adiabatic Flame Temperature \wedge Graphical Method for Determination of Flame Temperatures \wedge Combustion in a Closed Volume</i>	88
3.7	Second Law Analysis <i>Steady-Flow Burner \wedge Hydrocarbon Fuel Availability</i>	96
3.8	Summary	100
	Problems	101
	References	105
4	Chemical Kinetics of Combustion	107
4.1	Elementary Reactions	107
4.2	Chain Reactions	112
4.3	Preignition Kinetics	118
4.4	Global Reactions <i>Comments on Applications of Chemical Kinetics to Modeling</i>	120
4.5	Nitrogen Oxide Kinetics <i>Prompt NO and Fuel-Bound NO</i>	125
4.6	Reactions at Solid Surface	133
4.7	Soot Kinetics	135
4.8	Summary	137
	Problems	138
	References	140

P A R T II

Combustion of Gaseous and Vaporized Fuels

5	Flames	145
5.1	Laminar Premixed Flames <i>Effect of Stoichiometry on Laminar Burning Velocity \wedge Effect of Reactant Pressure and Temperature on Laminar Burning Velocity \wedge Stabilization of a Premixed Flame</i>	146

5.2	Laminar Flame Theory	155
	<i>Laminar Burning Velocity Theory \wedge Simplified Laminar Flame Model</i>	
5.3	Turbulent Premixed Flames	164
	<i>Turbulent Length and Time Scales \wedge Weak Turbulent Flames \wedge Wrinkled Reaction Sheets \wedge Distributed Reaction Zones</i>	
5.4	Explosion Limits	171
5.5	Flame Quenching	173
	<i>Experimental Results \wedge Quench Theory</i>	
5.6	Ignition	179
5.7	Diffusion Flames	183
	<i>Free Jet Flames \wedge Concentric Jet Flame \wedge Counterflow Diffusion Flames \wedge Turbulent Diffusion Flame Modeling</i>	
5.8	Summary	193
	Problems	194
	References	195
6	Gas-Fired Furnace Combustion	199
6.1	Energy Balance and Furnace Efficiency	199
	<i>Furnace Efficiency</i>	
6.2	Burner Types	204
	<i>Premixed Burners with Entrained Air \wedge Premixed Burners with Pressurized Air \wedge Nozzle-Mix Burners</i>	
6.3	Pulse Combustion Furnace	211
6.4	Fuel Substitution	213
6.5	Emissions from Gas-Fired Furnaces	214
	<i>Combustion Modification to Control NO_x</i>	
6.6	Summary	221
	Problems	221
	References	223
7	Premixed-Charge Engine Combustion	224
7.1	Introduction to Spark-Ignition Engine Combustion	224
7.2	Charge Preparation	230
7.3	Ignition and Burning Rate Analysis	234
	<i>Burning Rate Analysis \wedge Burning Rate Prediction</i>	
7.4	Flame Structure and Correlations	240
7.5	Computational Fluid Dynamics Modeling	242
	<i>Kernel Growth Phase \wedge Fully Developed Flame Phase \wedge End-Gas Burnup Phase</i>	

7.6	Chamber Design	244
7.7	Emissions Control	250
7.8	Engine Efficiency	256
7.9	Alternative Automobile Engines	258
7.10	Summary	261
	Problems	264
	References	267
8	Detonation of Gaseous Mixtures	269
8.1	Transition to Detonation	269
8.2	Steady-State Detonation	274
8.3	One-Dimensional Model for Propagation Velocity and Pressure and Temperature Rise across a Detonation	276
8.4	Maintained Detonations	281
8.5	Summary	283
	Problems	283
	References	284

P A R T III **Combustion of Liquid Fuels**

9	Spray Formation and Droplet Behavior	289
9.1	Spray Formation	290
9.2	Size Distributions	295
9.3	Fuel Injectors	300
	<i>∧ Nozzles for Intermittent Injectors</i>	
9.4	Spray Dynamics	311
	<i>Diesel Spray Dynamics ∧ Single-Droplet Dynamics</i>	
9.5	Vaporization of Single Droplets	321
	<i>Unsteady Vaporization ∧ Steady-State Vaporization ∧ Some Observations on Droplet Vaporization</i>	
9.6	Spray Models for CFD Programs	332
9.7	Summary	333
	Problems	334
	References	336
10	Oil-Fired Furnace Combustion	339
	10.1 Oil-Fired Systems	339
		343

10.3	Plug Flow Model of Distillate Spray Combustion	349
10.4	Emissions from Oil Furnaces	352
10.5	Summary	356
	Problems	357
	References	357
11	Gas Turbine Spray Combustion	359
11.1	Gas Turbine Operating Parameters	360
11.2	Combustor Design	363
	<i>Ignition \wedge Flame Stabilization \wedge A Specific Combustor Design</i>	
11.3	Combustion Rate	372
11.4	Liner Heat Transfer	376
11.5	Low-Emissions Combustors	379
11.6	Summary	384
	Problems	384
	References	386
12	Direct-Injection Engine Combustion	388
12.1	Introduction to Diesel Engine Combustion	389
12.2	Fuel Injection	392
12.3	Ignition Delay	396
12.4	Combustion Rates	399
	<i>Burning Rate Analysis \wedge Fitting of Burning Rate Curves</i>	
12.5	Chamber Geometry	410
12.6	Emissions	413
	<i>Emission Trends with Operating Parameters</i>	
12.7	Diesel Design Improvements	421
12.8	CFD Modeling of Diesel Combustion	424
	<i>Grids and Grid-Element Equations \wedge Spray Models \wedge Ignition Models \wedge Combustion \wedge Emissions Models</i>	
12.9	Summary	438
	Problems	440
	References	442
13	Detonation of Liquid-Gaseous Mixtures	445
13.1	Detonation of Liquid Fuel Sprays	446
	<i>Droplet Breakup \wedge Spray Detonations</i>	
13.2	Detonation of Liquid Fuel Films	452

13.3 Summary	455
Problems	455
	456

PA R T I V **Combustion of Solid Fuels**

14 Solid Fuel Combustion Mechanisms	459
14.1 Drying of Solid Fuels	459
14.2 Devolatilization of Solid Fuels	463
14.3 Char Combustion	468
<i>Char Burnout \wedge Char Surface Temperature \wedge Ash Formation</i>	
14.4 Summary	474
Problems	475
References	476
15 Fixed-Bed Combustion	477
15.1 Wood Stoves and Dutch Ovens	478
15.2 Stoker-Fired Boilers	480
<i>Combustion in a Spreader Stoker Boiler \wedge Combustion Efficiency, Furnace Efficiency, and Plant Efficiency</i>	
15.3 Emissions from Spreader Stokers	487
15.4 Modeling Fixed-Bed Combustion	490
15.5 Refuse- and Biomass-Fired Boilers	493
15.6 Downdraft Systems	499
15.7 Summary	502
Problems	502
References	504
16 Suspension Burning	506
16.1 Pulverized Coal-Burning Systems	507
<i>Location of Fuel and Air Nozzles \wedge Furnace Design</i>	
16.2 Pulverized Coal Combustion	514
<i>Isothermal Plug Flow of Pulverized Coal \wedge Nonisothermal Plug Flow of Pulverized Char Suspension</i>	
16.3 Behavior of Ash	519
16.4 Emissions from Pulverized Coal Furnaces	522
16.5 Cyclone Combustors	525
16.6 Pulverized Biomass and Refuse-Fired Boilers	527

116.7	Coal-Water Fuel	528
116.8	Summary	529
	Problems	530
	References	532
17	Fluidized-Bed Combustion	534
117.1	Fluidization Fundamentals	535
	<i>Pressure Drop across the Bed \wedge Minimum Fluidization Velocity \wedge Single-Particle Terminal Velocity \wedge Bubbling Beds \wedge Heat and Mass Transfer</i>	
117.2	Combustion in a Bubbling Bed	542
	<i>Neglect Bubbles and Assume Complete Combustion in Bed \wedge Neglect Bubbles but Include Some Combustion above the Bed \wedge Effect of Bubbles and Some Combustion Above the Bed \wedge Fuel Holdup in the Bed</i>	
117.3	Atmospheric Fluidized-Bed Combustion Systems	550
	<i>Atmospheric Emissions</i>	
117.4	Circulating Fluidized Beds	552
117.5	Pressurized Fluidized-Bed Combustion	555
117.6	Summary	560
	Problems	561
	References	563
	Appendixes	565
A	PROPERTIES OF FUELS	565
A.1	Thermodynamic Properties of Alkane Fuels	566
A.2	Thermodynamic Properties of Some Other Hydrocarbon Fuels	567
A.3	Specific Heats of Selected Fuels	568
A.4	Specific Gravity and Bulk Density of Selected Fuels	568
A.5	Transport Properties of Selected Fuels	569
A.6	Surface Tension of Several Fuels and Water	569
A.7	Latent Heat of Vaporization of Selected Fuels	569
A.8	Properties of Dodecane and Octane	570
A.9	Specifications of Unleaded Gasoline Used in U.S. Emissions Certification	571
A.10	Atomic Weights of Elements and Trace Elements in Fuels	571

B	PROPERTIES OF AIR (at 1 atm)	572
C	THERMODYNAMIC PROPERTIES OF COMBUSTION PRODUCTS	573
D	VISCOSITY AND THERMAL CONDUCTIVITY OF GAS MIXTURES	590
	References	592
E	A BRIEF INTRODUCTION TO MASS TRANSPORT BY DIFFUSION IN GASEOUS SYSTEMS	594
	Basic Definitions	594
	Fick's First Law of Diffusion	595
	Diffusivity Values	596
	Computations for Systems with Diffusion	597
	Examples of Steady-State One-Dimensional Diffusion	597
	Multicomponent Diffusion	599
	Problem	599
	References	600
	Index	601