

# Contents

<b>1</b>	<b>Air Emissions</b> . . . . .	1
1.1	Air . . . . .	1
1.2	Air Pollution and Greenhouse Gases . . . . .	1
1.2.1	Air Pollution . . . . .	2
1.2.2	Greenhouse Gases . . . . .	4
1.3	Effects of Air Pollution and GHGs . . . . .	5
1.3.1	Health Effects of Air Pollution . . . . .	5
1.3.2	Environmental Impact. . . . .	7
1.3.3	Greenhouse Gas Effects . . . . .	8
1.4	Roots of Air Pollution and GHGs . . . . .	9
1.4.1	Anthropogenic Air Emissions . . . . .	9
1.4.2	Growing Population and Energy Consumption. . . . .	10
1.4.3	International Energy Outlook. . . . .	11
1.4.4	Global Air Emissions . . . . .	12
1.5	General Approaches to Air Emission Control . . . . .	14
1.5.1	Air Emission and Air Quality Standards . . . . .	14
1.5.2	General Engineering Approaches to Air Emission Control . . . . .	17
1.6	Scope and Structure of This Book. . . . .	19
1.7	Units and Dimensions . . . . .	20
1.8	Practice Problems . . . . .	21
1.8.1	Multiple Choice Problems. . . . .	21
1.8.2	Calculations . . . . .	22
	References and Further Readings . . . . .	23

## Part I Basic Concepts

<b>2</b>	<b>Basic Properties of Gases</b> . . . . .	27
2.1	Gas Kinetics. . . . .	27
2.1.1	Speeds of Gas Molecules . . . . .	28

2.1.2	Avogadro Constant and Molar Weight . . . . .	30
2.1.3	Gas Pressure . . . . .	30
2.1.4	Density and Specific Volume of a Gas . . . . .	33
2.1.5	Ideal Gas Law and Dalton's Law . . . . .	33
2.1.6	Kinetic Energy of Gas Molecules . . . . .	37
2.1.7	Gas Mean Free Path . . . . .	38
2.1.8	Number of Collisions with Wall/Surface . . . . .	40
2.1.9	Diffusivity of Gases . . . . .	42
2.1.10	Viscosity of a Gas . . . . .	43
2.2	Gas Fluid Dynamics . . . . .	45
2.2.1	Reynolds Number . . . . .	45
2.2.2	Bernoulli's Equation . . . . .	45
2.2.3	Boundary Layer and Drag . . . . .	46
2.3	Gas-Liquid Interfacial Behavior . . . . .	48
2.3.1	Solubility and Henry's Law . . . . .	48
2.3.2	Raoult's Law for Ideal Solution . . . . .	51
2.3.3	A Real Gas-Liquid System . . . . .	53
2.3.4	Interfacial Mass Transfer . . . . .	53
2.4	Practice Problems . . . . .	56
	References and Further Readings . . . . .	58
<b>3</b>	<b>Basics of Gas Combustion . . . . .</b>	<b>59</b>
3.1	Air-Fuel Ratio . . . . .	59
3.2	Combustion Stoichiometry . . . . .	61
3.2.1	Stoichiometric Combustion with Dry Air at Low Temperature . . . . .	62
3.2.2	Fuel Lean Combustion . . . . .	64
3.2.3	Fuel Rich Combustion with Dry Air at Low Temperatures . . . . .	66
3.2.4	Complex Fossil Fuel Combustion Stoichiometry . . . . .	67
3.3	Chemical Kinetics and Chemical Equilibrium . . . . .	68
3.3.1	Chemical Kinetics . . . . .	68
3.3.2	Chemical Equilibrium . . . . .	71
3.3.3	Chemical Equilibrium in Gaseous Combustion Products . . . . .	75
3.3.4	The Pseudo-Steady-State Approximation . . . . .	78
3.4	Thermodynamics of Combustion System . . . . .	79
3.4.1	First Law of Thermodynamics . . . . .	79
3.4.2	Enthalpy Scale for Reacting System . . . . .	81
3.4.3	Heating Values . . . . .	82

3.5	Adiabatic Flame Temperature . . . . .	84
3.5.1	Constant Pressure Adiabatic Flame Temperature . . .	85
3.5.2	Constant Volume Adiabatic Flame Temperature. . .	87
3.6	Practice Problems . . . . .	87
	References and Further Readings . . . . .	90
<b>4</b>	<b>Properties of Aerosol Particles. . . . .</b>	<b>91</b>
4.1	Particle Motion . . . . .	91
4.1.1	Particle Reynolds Number. . . . .	91
4.1.2	Stokes' Law . . . . .	92
4.1.3	Dynamic Shape Factor . . . . .	93
4.1.4	The Knudsen Number and Cunningham Correction Factor . . . . .	94
4.2	Rectilinear Particle Motion . . . . .	95
4.2.1	Particle Acceleration. . . . .	96
4.2.2	Settling at High Reynolds Numbers . . . . .	99
4.2.3	Aerodynamic Diameter . . . . .	100
4.2.4	Curvilinear Motion of Aerosol Particles . . . . .	101
4.2.5	Diffusion of Aerosol Particles . . . . .	102
4.2.6	Particle Deposition on Surface by Diffusion . . . . .	104
4.3	Particle-Surface Interaction . . . . .	105
4.4	Particle Coagulation . . . . .	106
4.4.1	Monodisperse Aerosol Coagulation . . . . .	107
4.4.2	Polydisperse Coagulation . . . . .	108
4.5	Aerosol Particle Size Distribution . . . . .	110
4.6	Practice Problems . . . . .	113
	References and Further Readings . . . . .	115
<b>5</b>	<b>Principles for Gas Separation . . . . .</b>	<b>117</b>
5.1	Adsorption . . . . .	117
5.1.1	General Consideration . . . . .	117
5.1.2	Adsorption Affinity . . . . .	119
5.1.3	Adsorption Isotherm. . . . .	120
5.1.4	Adsorption Wave. . . . .	127
5.1.5	Breakthrough Time . . . . .	129
5.1.6	Regeneration of the Adsorbent. . . . .	131
5.2	Absorption . . . . .	132
5.2.1	Counter Flow Absorption Tower . . . . .	132
5.2.2	Absorption Equilibrium Line and Operating Line. . .	135
5.2.3	Height of the Packed Absorption Tower . . . . .	141
5.2.4	Chemical Absorption . . . . .	145
5.3	Practice Problems . . . . .	147
	References and Further Readings . . . . .	149

<b>6</b>	<b>Separation of Particles from a Gas</b> . . . . .	151
6.1	General Consideration . . . . .	151
6.1.1	Particle Separation Efficiency . . . . .	151
6.1.2	Particle Separation Efficiency of Multiple Devices . . . . .	153
6.2	Gravity Settling Chambers . . . . .	154
6.2.1	Laminar Flow Model . . . . .	154
6.2.2	Turbulent Flow Model . . . . .	155
6.3	Electrostatic Precipitation . . . . .	158
6.3.1	The Electric Field Intensity . . . . .	158
6.3.2	Particle Charging . . . . .	159
6.4	Cyclone . . . . .	163
6.4.1	Cyclone Fractional Efficiency . . . . .	164
6.4.2	Pressure Drop of Cyclone . . . . .	171
6.4.3	Other Cyclone Models . . . . .	171
6.5	Filtration . . . . .	172
6.5.1	Single Fiber Filtration Efficiency . . . . .	174
6.5.2	Overall Fibrous Filtration Efficiency. . . . .	180
6.5.3	Fibrous Filter Pressure Drop . . . . .	183
6.5.4	Particle Accumulation. . . . .	185
6.5.5	Granular Filtration . . . . .	186
6.6	Practice Problems . . . . .	189
	References and Further Readings . . . . .	191

## Part II Engineering Applications

<b>7</b>	<b>Combustion Process and Air Emission Formation</b> . . . . .	195
7.1	Gaseous Fuel Flame . . . . .	195
7.2	Liquid Fuel Combustion . . . . .	196
7.2.1	Droplet Vaporization . . . . .	197
7.2.2	Vapor Combustion . . . . .	199
7.3	Solid Fuel Combustion . . . . .	200
7.3.1	Solid Fuels . . . . .	200
7.3.2	Solid Fuel Combustion . . . . .	203
7.4	Formation of VOCs and PAHs . . . . .	205
7.5	Formation of CO and CO <sub>2</sub> . . . . .	205
7.5.1	Volatile Oxidation . . . . .	205
7.5.2	Char Oxidation . . . . .	206
7.6	Formation of SO <sub>2</sub> and SO <sub>3</sub> . . . . .	207
7.7	NO <sub>x</sub> . . . . .	210
7.7.1	Nitric Oxide . . . . .	211
7.7.2	Nitrogen Dioxide . . . . .	217

7.8	Formation of Particulate Matter. . . . .	218
7.8.1	Ash-Forming Elements in Fuels. . . . .	219
7.8.2	Soot Particles . . . . .	220
7.9	Fate of Trace Elements . . . . .	221
7.9.1	Trace Elements in Fuels . . . . .	221
7.9.2	Trace Elements in Flue Gases . . . . .	222
7.9.3	Mercury . . . . .	223
7.10	Greenhouse Gases . . . . .	223
	References and Further Readings . . . . .	224
<b>8</b>	<b>Pre-combustion Air Emission Control . . . . .</b>	<b>227</b>
8.1	Fuel Cleaning. . . . .	227
8.1.1	Coal Cleaning . . . . .	227
8.1.2	Oil and Gas Refinery . . . . .	229
8.2	Fuel Substitution. . . . .	232
8.3	Thermochemical Conversion of Fuels . . . . .	233
8.3.1	Pyrolysis. . . . .	233
8.3.2	Gasification and Syngas Cleaning . . . . .	234
8.3.3	Combined Cycle Technologies. . . . .	239
8.4	Biofuels. . . . .	240
8.4.1	Solid Biofuels . . . . .	240
8.4.2	Biodiesel . . . . .	243
8.4.3	Bioethanol . . . . .	245
8.4.4	Hydrothermal Conversion of Biomass to Biofuels . . . . .	248
8.4.5	Biogas . . . . .	252
	References and Further Readings . . . . .	253
<b>9</b>	<b>In-combustion Air Emission Control . . . . .</b>	<b>257</b>
9.1	Stationary Combustion Devices. . . . .	257
9.1.1	Pulverized Coal/Biomass Combustion. . . . .	257
9.1.2	Fluidized Bed Combustion . . . . .	258
9.2	Internal Combustion Engines . . . . .	261
9.2.1	Spark Ignition Engines . . . . .	261
9.2.2	Diesel Engines. . . . .	263
9.3	SO <sub>2</sub> Capture by Furnace Sorbent Injection . . . . .	264
9.3.1	SO <sub>2</sub> Capture by FSI in Pulverized Coal Combustion. . . . .	264
9.3.2	SO <sub>2</sub> Capture in Fluidized Bed Combustion . . . . .	267
9.4	In-combustion NO <sub>x</sub> Control . . . . .	268
9.4.1	Air Staging . . . . .	268
9.4.2	Fuel Staging . . . . .	270
9.4.3	Flue Gas Recirculation . . . . .	271
9.4.4	Combined Low-NO <sub>x</sub> Technologies. . . . .	272

9.5	In-combustion Soot Control . . . . .	272
9.6	Engine Exhaust Gas Recirculation. . . . .	273
9.7	Practice Problems . . . . .	274
	References and Further Readings . . . . .	275
<b>10</b>	<b>Post-combustion Air Emission Control. . . . .</b>	<b>277</b>
10.1	Introduction . . . . .	277
10.2	Control of Particulate Matter Emissions . . . . .	277
	10.2.1 Electrostatic Precipitator Designs . . . . .	278
	10.2.2 Filtration System Designs . . . . .	280
	10.2.3 Wet Scrubbing. . . . .	285
10.3	Flue Gas Desulfurization . . . . .	288
	10.3.1 Wet FGD . . . . .	288
	10.3.2 Steam Reactivation of Calcium Based Sorbents . . . . .	291
	10.3.3 Dry FGD . . . . .	294
	10.3.4 Semi-Dry FGD . . . . .	294
10.4	NO <sub>x</sub> Reduction Using SCR and SNCR . . . . .	295
	10.4.1 Selective Catalytic Reduction . . . . .	295
	10.4.2 SNCR . . . . .	296
	10.4.3 Reagents. . . . .	297
10.5	Simultaneous Removal of SO <sub>x</sub> and NO <sub>x</sub> . . . . .	297
10.6	Control of Volatile Organic Compounds . . . . .	298
	10.6.1 Volatile Organic Compounds Adsorption . . . . .	299
	10.6.2 Oxidation of VOCs . . . . .	299
	10.6.3 Flaring . . . . .	300
	10.6.4 Thermal Oxidizers . . . . .	300
	10.6.5 Catalytic Oxidation . . . . .	303
	10.6.6 Other Approaches to Volatile Organic Compounds Control . . . . .	304
10.7	Control of Soot Particles . . . . .	305
10.8	Control of Trace Metals. . . . .	305
	10.8.1 Mercury in Particulate Control and FGD Devices. . . . .	306
	10.8.2 Mercury Adsorption by Activated Carbon. . . . .	307
	10.8.3 Mercury Captured by Metal Oxides, Silicates, and Fly Ashes . . . . .	308
10.9	Proper Layout for Post-combustion Air Pollution Control Devices . . . . .	308
10.10	Practice Problems . . . . .	309
	References and Further Readings . . . . .	311
<b>11</b>	<b>Air Dispersion . . . . .</b>	<b>315</b>
11.1	Box Model. . . . .	315
11.2	General Gaussian Dispersion Model . . . . .	318

- 11.2.1 Atmosphere . . . . . 318
- 11.2.2 Atmospheric Motion and Properties . . . . . 320
- 11.2.3 Air Parcel . . . . . 320
- 11.2.4 Adiabatic Lapse Rate of Temperature . . . . . 321
- 11.2.5 Atmospheric Stability . . . . . 322
- 11.2.6 Wind Speed . . . . . 324
- 11.3 Gaussian-Plume Dispersion Models . . . . . 329
  - 11.3.1 General Gaussian Dispersion Model . . . . . 330
  - 11.3.2 Plume Rise . . . . . 335
  - 11.3.3 Plume Downwash . . . . . 338
  - 11.3.4 Ground Surface Reflection . . . . . 340
  - 11.3.5 Mixing Height Reflection . . . . . 341
- 11.4 Gaussian Puff Models . . . . . 343
- 11.5 Practice Problems . . . . . 344
- References and Further Readings . . . . . 345

**Part III Special Topics**

- 12 Carbon Capture and Storage . . . . . 349**
  - 12.1 Background Information . . . . . 349
  - 12.2 CO<sub>2</sub> Generation in Combustion. . . . . 351
  - 12.3 General Approaches to Reducing GHG Emissions. . . . . 354
  - 12.4 Carbon Capture Processes . . . . . 355
    - 12.4.1 Pre-combustion Carbon Capture. . . . . 355
    - 12.4.2 In-combustion Carbon Capture . . . . . 358
    - 12.4.3 Post-combustion Carbon Capture . . . . . 362
  - 12.5 CO<sub>2</sub> Separation by Adsorption . . . . . 363
    - 12.5.1 Physical Adsorption . . . . . 363
    - 12.5.2 Chemical Adsorbents . . . . . 364
  - 12.6 CO<sub>2</sub> Separation by Absorption . . . . . 366
    - 12.6.1 Physical Absorption . . . . . 366
    - 12.6.2 Amine-Based Chemical Absorption . . . . . 367
    - 12.6.3 Non-amine-Based Chemical Absorption . . . . . 373
    - 12.6.4 Ionic Liquids as CO<sub>2</sub> Solvents. . . . . 375
  - 12.7 CO<sub>2</sub> Transportation . . . . . 378
    - 12.7.1 Pipeline Transportation . . . . . 379
    - 12.7.2 Ship Transportation . . . . . 381
  - 12.8 CO<sub>2</sub> Storage . . . . . 381
    - 12.8.1 Enhanced Oil Recovery and Enhanced Gas Recovery . . . . . 382
    - 12.8.2 Coal Bed Methane Recovery . . . . . 383
    - 12.8.3 Saline Aquifer Storage . . . . . 384

12.8.4	Deep Ocean Storage . . . . .	385
12.8.5	Ecosystem Storage . . . . .	387
12.9	Environmental Assessment . . . . .	390
	References and Further Readings . . . . .	390
<b>13</b>	<b>Nanoaerosol . . . . .</b>	<b>395</b>
13.1	Sources of Nanoaerosol . . . . .	395
13.2	Exposure to Nanoaerosol . . . . .	396
13.3	Properties of Nanoaerosol . . . . .	399
13.3.1	Number and Size of Nanoaerosol Particles . . . . .	399
13.3.2	Noncontinuum Behavior . . . . .	400
13.3.3	Diffusion of Neutral Nanoaerosol . . . . .	401
13.3.4	Electrical Properties of Nanoaerosol . . . . .	401
13.4	Separation of Nanoaerosol from the Air . . . . .	402
13.4.1	Nanoparticle Transport Efficiency . . . . .	403
13.4.2	Adhesion Efficiency and Nanoaerosol Thermal Rebound . . . . .	406
13.4.3	Critical Thermal Speed . . . . .	408
13.4.4	Adhesion Efficiency . . . . .	408
13.4.5	Adhesion Energy . . . . .	410
13.5	Nanoaerosol Characterization . . . . .	415
13.5.1	Scanning Mobility Particle Sizer . . . . .	415
13.5.2	Particle Classification by Aerodynamic Particle Focusing . . . . .	416
13.5.3	Particle Counting by Current Measurement Electrospray Technique . . . . .	419
13.6	Nanoaerosol Generation . . . . .	420
13.6.1	Evaporation–Condensation Technique . . . . .	420
13.6.2	Electrospray Technique . . . . .	420
13.6.3	Soot Nanoaerosol Particles . . . . .	422
	References and Further Readings . . . . .	423
<b>14</b>	<b>Indoor Air Quality . . . . .</b>	<b>427</b>
14.1	Introduction . . . . .	427
14.2	Threshold Limit Values . . . . .	430
14.2.1	Normalized Air Contaminant Concentration . . . . .	431
14.2.2	Clean Room . . . . .	433
14.3	IAQ Control by Ventilation/Dilution . . . . .	435
14.3.1	Minimum Ventilation Rate . . . . .	435
14.3.2	Psychrometric Chart . . . . .	440
14.4	Indoor Air Cleaning Model . . . . .	441
14.5	Practice Problems . . . . .	444
	References and Further Readings . . . . .	445



- 15 Air Monitoring** . . . . . 447
  - 15.1 Flow Rate and Velocity Measurement . . . . . 447
  - 15.2 Source Sampling . . . . . 448
    - 15.2.1 Isokinetic Sampling . . . . . 449
    - 15.2.2 Effect of Misalignment . . . . . 452
    - 15.2.3 Multiple Sampling Locations . . . . . 454
  - 15.3 Collection of Air Pollutant Samples . . . . . 457
  - 15.4 Data Analysis and Reporting . . . . . 457
  - 15.5 Continuous Emission Monitoring and Opacity Measurement . . . . . 459
  - 15.6 Ambient Air Quality Monitoring . . . . . 460
  - References and Further Readings . . . . . 460
  
- Appendix** . . . . . 463
  
- Index** . . . . . 477