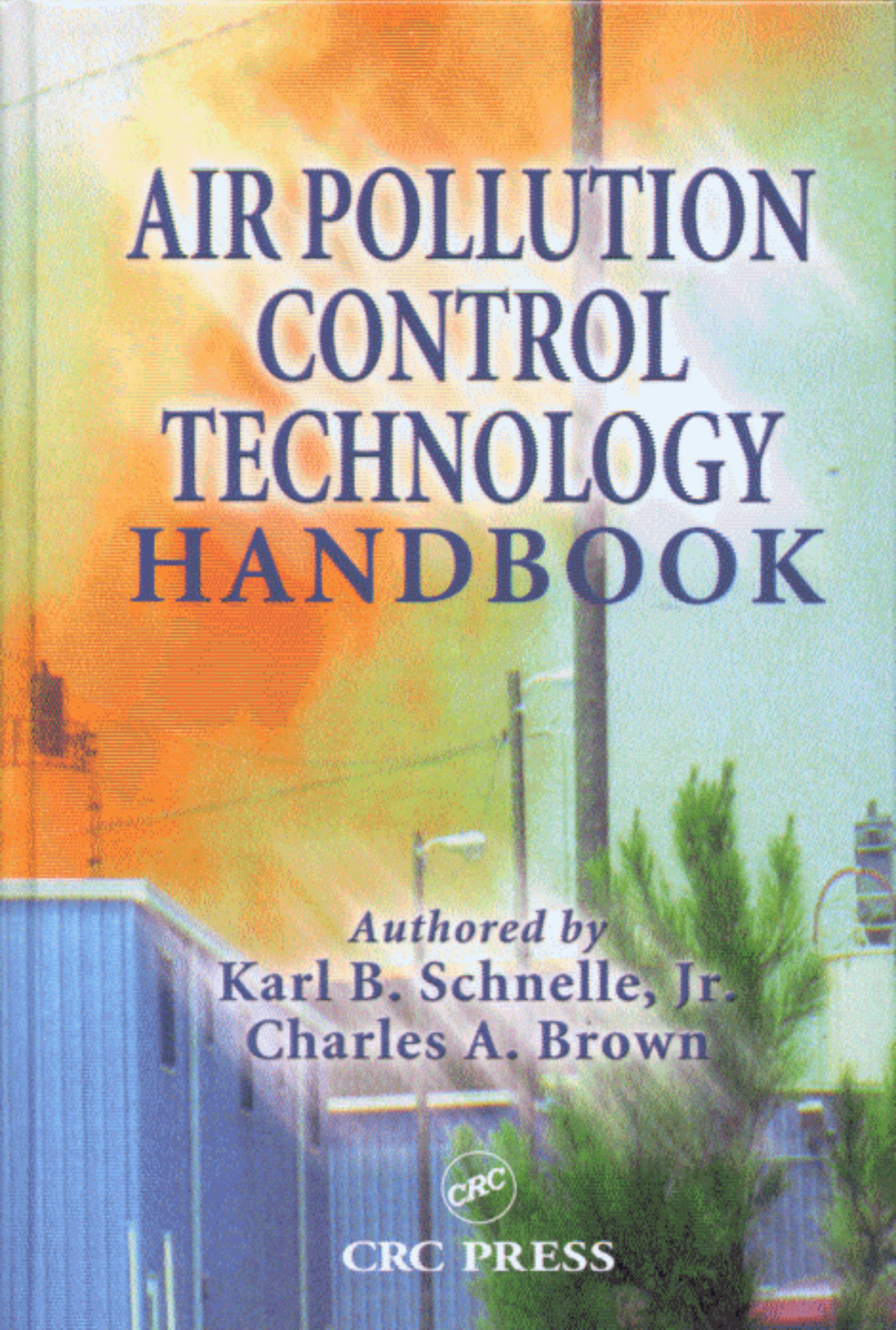




AIR POLLUTION CONTROL TECHNOLOGY HANDBOOK

Authored by
Karl B. Schnelle, Jr.
Charles A. Brown



CRC PRESS

Contents

Chapter 1	A Historical Overview of the Development of Clean Air Regulations.....	1
1.1	A Brief History of the Air Pollution Problem	1
1.2	Federal Involvement in Air Pollution Control.....	3
1.3	Characterizing the Atmosphere.....	5
1.4	Recipe for an Air Pollution Problem.....	6
1.4.1	Sources of Air Pollution	8
1.4.2	Meteorological Parameters Affecting Transport of Pollutants.....	8
1.4.3	The Effects of Air Pollution — A Comparison of London Fog and Los Angeles Smog	10
	References.....	12
Chapter 2	Clean Air Act	13
2.1	History of the Clean Air Act	13
2.1.1	1970 Clean Air Act Amendments.....	13
2.1.1.1	National Ambient Air Quality Standards	14
2.1.1.2	New Source Performance Standards	14
2.1.1.3	Hazardous Air Pollutants.....	14
2.1.1.4	Citizen Suits.....	15
2.1.2	1977 Clean Air Act Amendments.....	15
2.1.2.1	Prevention of Significant Deterioration.....	16
2.1.2.2	Offsets in Non-Attainment Areas	16
2.2	1990 Clean Air Act Amendments.....	17
2.2.1	Title I: Provisions for Attainment and Maintenance of National Ambient Air Quality Standards	18
2.2.1.1	NAAQS Revisions	18
2.2.2	Title II: Mobile Sources.....	20
2.2.3	Title III: Hazardous Air Pollutant Program.....	21
2.2.3.1	Source Categories	21
2.2.3.2	Establishing MACT Standards	22
2.2.3.3	Risk Management Plans	28
2.2.4	Title IV: Acid Deposition Control	29
2.2.5	Title V: Operating Permits	30
2.2.6	Title VI: Stratospheric Ozone Protection	31
2.2.7	Title VII: Enforcement.....	31
2.2.8	Title VIII: Miscellaneous Provisions	32
2.2.9	Title IX: Research.....	32

2.2.10 Title X: Disadvantaged Business	32
2.2.11 Title XI: Employment Transition Assistance	32
References	32

Chapter 3 Air Permits for New Source33

3.1 Elements of a Permit Application.....	33
3.1.1 Applicability	34
3.1.1.1 Potential to Emit	34
3.1.1.2 Fugitive Emissions	34
3.1.1.3 Secondary Emissions	34
3.1.2 Significant Emission Rates	35
3.1.3 Modification	36
3.1.4 Emissions Netting	37
3.1.4.1 Netting Example	37
3.2 Best Available Control Technology	38
3.2.1 Step 1: Identify Control Technologies.....	39
3.2.2 Step 2: Eliminate Technically Infeasible Options.....	40
3.2.3 Step 3: Rank Remaining Options by Control Effectiveness.....	40
3.2.4 Step 4: Evaluate Control Technologies in Order of Control Effectiveness.....	41
3.2.4.1 Energy Impacts	41
3.2.4.2 Environmental Impacts	41
3.2.4.3 Economic Impacts and Cost Effectiveness	42
3.2.5 Step 5: Select BACT.....	42
3.3 Air Quality Analysis	43
3.3.1 Preliminary Analysis	43
3.3.2 Full Analysis	44
3.4 NSR Reform.....	44
References.....	44

Chapter 4 Atmospheric Diffusion Modeling for PSD Permit Regulations45

4.1 Introduction — Meteorological Background	45
4.1.1 Inversions	45
4.1.1.1 Surface or Radiation Inversions	45
4.1.1.2 Evaporation Inversion	45
4.1.1.3 Advection Inversion.....	46
4.1.1.4 Subsidence Inversion	46
4.1.2 The Diurnal Cycle.....	46
4.1.3 Principal Smoke-Plume Models	47
4.2 The Tall Stack	48
4.3 Classifying Sources by Method of Emission	48
4.3.1 A Definition of Tall Stacks	48
4.3.2 Process Stacks	51

4.4	Atmospheric-Diffusion Models	51
4.4.1	Other Uses of Atmospheric-Diffusion Models	52
4.5	EPA Computer Programs for Regulation of Industry	52
4.5.1	The Industrial Source Complex Model	54
4.5.2	Screening Models	54
4.5.3	The New Models	54
4.6	The Source-Transport-Receptor Problem	55
4.6.1	The Source	55
4.6.2	Transport	56
4.6.2.1	The Effective Emission Height	56
4.6.2.2	Bulk Transport of the Pollutants	56
4.6.2.3	Dispersion of the Pollutants	57
4.6.3	The Receptor	57
	References	57

Chapter 5 Source Testing 59

5.1	Introduction	59
5.2	Code of Federal Regulations	59
5.3	Representative Sampling Techniques	59
5.3.1	Gaseous Pollutants	59
5.3.2	Velocity and Particulate Traverses	62
5.3.3	Isokinetic Sampling	63
	References	65

Chapter 6 Ambient Air Quality and Continuous Emissions Monitoring 67

6.1	Ambient Air Quality Sampling Program	67
6.2	Objectives of a Sampling Program	67
6.3	Monitoring Systems	67
6.3.1	Fixed vs. Mobile Sampling	68
6.3.2	Continuous vs. Integrated Sampling	68
6.3.3	Selection of Instrumentation and Methods	69
6.4	Federal Reference Methods and Continuous Monitoring	69
6.5	The "Complete" Environmental Surveillance and Control System	71
6.6	Typical Air Sampling Train	73
6.7	Integrated Sampling Devices for Suspended Particulate Matter	73
6.8	Continuous Air Quality Monitors	74
6.8.1	Electroconductivity Analyzer for SO ₂	75
6.8.2	Coulometric Analyzer for SO ₂	77
6.8.3	Nondispersive Infrared Method for CO	78
6.8.4	Flame Photometric Detection of Total Sulfur and SO ₂	80
6.8.5	Hydrocarbons by Flame Ionization	80
6.8.6	Fluorescent SO ₂ Monitor	80

6.8.7	Chemiluminescence for Detection of Ozone and Nitrogen Oxides.....	80
6.8.8	Calibration of Continuous Monitors.....	82
6.8.8.1	Specifications for Continuous Air-Quality Monitors.....	82
6.8.8.2	Steady-State Calibrations.....	83
	References.....	84

Chapter 7 Cost Estimating..... 85

7.1	Time Value of Money.....	85
7.1.1	Annualized Capital Cost.....	85
7.1.2	Escalation Factors.....	86
7.2	Types of Cost Estimates.....	86
7.3	Air Pollution Control Equipment Cost.....	88
7.3.1	OAQPS Control Cost Manual.....	88
7.3.2	Other Cost-Estimating Resources.....	88
	References.....	88

Chapter 8 Process Design and the Strategy of Process Design..... 91

8.1	Introduction to Process Design.....	91
8.2	The Strategy of Process Design.....	91
8.2.1	Process Flowsheets.....	93
8.3	Mass and Energy Balances.....	94
8.3.1	A Mass-Balance Example.....	96
8.3.2	An Energy-Balance Example.....	97
	References.....	99

Chapter 9 Profitability and Engineering Economics..... 101

9.1	Introduction — Profit Goal.....	101
9.2	Profitability Analysis.....	101
9.2.1	Mathematical Methods for Profitability Evaluation.....	101
9.2.2	Incremental Rate of Return on Investments as a Measure of Profitability.....	102
9.2.2.1	An Example.....	103
9.3	The Effect of Depreciation.....	104
9.3.1	An Example.....	105
9.4	Capital Investment and Total Product Cost.....	106
9.4.1	Design Development.....	107
	References.....	107

Chapter 10	Introduction to Control of Gaseous Pollutants.....	109
10.1	Absorption and Adsorption	110
10.1.1	Fluid Mechanics Terminology	113
10.1.2	Removal of HAP and VOC by Absorption and Adsorption	114
Reference		115
Chapter 11	Absorption for HAP and VOC Control.....	117
11.1	Introduction	117
11.2	Aqueous Systems	117
11.3	Nonaqueous Systems.....	118
11.4	Types and Arrangements of Absorption Equipment.....	119
11.5	Design Techniques for Countercurrent Absorption Columns	119
11.5.1	Equilibrium Relationships	122
11.5.2	Ideal Solutions — Henry's Law	125
11.5.3	Countercurrent Absorption Tower Design Equations	128
11.5.4	Origin of Volume-Based Mass-Transfer Coefficients.....	130
11.5.4.1	Steady-State Molecular Diffusion.....	130
11.5.5	The Whitman Two-Film Theory	131
11.5.6	Overall Mass-Transfer Coefficients	133
11.5.7	Volume-Based Mass-Transfer Coefficients.....	134
11.5.8	Determining Height of Packing in the Tower: the HTU Method.....	135
11.5.9	Dilute Solution Case	137
11.6	Countercurrent Flow Packed Absorption Tower Design.....	138
11.6.1	General Considerations	138
11.6.2	Operations of Packed Towers.....	138
11.6.3	Choosing a Tower Packing.....	140
11.6.3.1	Dumped Packings.....	140
11.6.4	Packed Tower Internals	141
11.6.5	Choosing a Liquid–Gas Flow Ratio	142
11.6.6	Determining Tower Diameter — Random Dumped Packing.....	143
11.6.7	Determining Tower Diameter — Structured Packing	145
11.6.8	Controlling Film Concept	146
11.6.9	A Correlation for the Effect of L/G Ratio on the Packing Height	147
11.6.10	Henry's Law Constants and Mass-Transfer Information	149
11.6.11	Using Henry's Law for Multicomponent Solutions	151
11.7	Sample Design Calculation.....	152
11.7.1	Flooding.....	157
11.7.2	Structured Packing	157
References		158

Chapter 12	Adsorption for HAP and VOC Control	161
12.1	Introduction to Adsorption Operations	161
12.2	Adsorption Phenomenon	161
12.3	Adsorption Processes	162
12.3.1	Stagewise Process	162
12.3.2	Continuous Contact, Steady-State, Moving-Bed Adsorbers	163
12.3.3	Unsteady-State, Fixed-Bed Adsorbers	163
12.3.4	Newer Technologies	164
12.3.4.1	Rotary Wheel Adsorber	164
12.3.4.2	Chromatographic Adsorption	164
12.3.4.3	Pressure Swing Adsorption	164
12.4	Nature of Adsorbents	164
12.4.1	Adsorption Design with Activated Carbon	166
12.4.1.1	Pore Structure	166
12.4.1.2	Effect of Relative Humidity	166
12.5	The Theories of Adsorption	167
12.6	The Data of Adsorption	168
12.7	Adsorption Isotherms	170
12.7.1	Freundlich's Equation	170
12.7.2	Langmuir's Equation	170
12.7.3	The Brunner, Emmett, Teller, or BET, Isotherm	171
12.7.3.1	Adsorption without Capillary Condensation	171
12.7.3.2	Adsorption with Capillary Condensation	172
12.8	Polanyi Potential Theory	172
12.9	Unsteady-State, Fixed-Bed Adsorbers	173
12.10	Fixed-Bed Adsorber Design Considerations	176
12.10.1	Safety Considerations	176
12.11	Pressure Drop Through Adsorbers	176
12.12	Adsorber Effectiveness and Regeneration	177
12.12.1	Steam Regeneration	177
12.12.2	Hot Air or Gas Regeneration	178
12.13	Breakthrough Model	178
12.13.1	Mass Transfer	184
12.13.2	Breakthrough Curve Example	185
12.14	Regeneration Modeling	188
	References	189

Chapter 13	Thermal Oxidation for VOC Control	191
13.1	Combustion Basics	191
13.2	Flares	192
13.2.1	Elevated, Open Flare	194
13.2.2	Smokeless Flare Assist	196
13.2.3	Flare Height	197

13.2.4	Ground Flare	198
13.2.5	Safety Features.....	198
13.3	Incineration	200
13.3.1	Recuperative Thermal Oxidizer.....	200
13.3.2	Regenerative Thermal Oxidizer.....	200
13.3.3	Recuperative vs. Regenerative Design Selection	204
13.4	Catalytic Oxidation.....	205
	References.....	207

Chapter 14 Control of VOC and HAP by Condensation 209

14.1	Introduction	209
14.2	VOC Condensers	209
14.2.1	Contact Condensers	210
14.2.2	Surface Condensers.....	211
14.2.2.1	An Example — Condensation Temperature.....	212
14.3	Coolant and Heat Exchanger Type	213
14.3.1	An Example — Heat Exchanger Area and Coolant Flow Rate	213
14.4	Mixtures of Organic Vapors	217
14.4.1	An Example — Condensation of a Binary Mixture.....	218
14.5	Air As a Noncondensable	221
	References.....	221
	Appendix A: Derivation of the Area Model for a Mixture Condensing from a Gas	222
	Appendix B: Algorithm for the Area Model for a Mixture Condensing from a Gas	223

Chapter 15 Control of VOC and HAP by Biofiltration 227

15.1	Introduction	227
15.2	Theory of Biofilter Operation	228
15.3	Design Parameters and Conditions.....	229
15.3.1	Depth and Media of Biofilter Bed.....	229
15.3.2	Microorganisms.....	231
15.3.3	Oxygen Supply	232
15.3.4	Inorganic Nutrient Supply	232
15.3.5	Moisture Content	232
15.3.6	Temperature.....	232
15.3.7	pH of the Biofilter.....	233
15.3.8	Loading and Removal Rates.....	233
15.3.9	Pressure Drop.....	233
15.3.10	Pretreatment of Gas Streams	233
15.4	Biofilter Compared to Other Available Control Technology.....	234
15.5	Successful Case Studies	234
15.6	Further Considerations	234
	References.....	235

Chapter 16	Membrane Separation	237
16.1	Overview	237
16.2	Polymeric Membranes	237
16.3	Performance	237
16.4	Applications	238
	References	238
Chapter 17	NO_x Control	241
17.1	NO _x from Combustion	241
17.1.1	Thermal NO _x	241
17.1.2	Prompt NO _x	244
17.1.3	Fuel NO _x	244
17.2	Control Techniques	244
17.2.1	Combustion Control Techniques	245
17.2.1.1	Low-Excess Air Firing	245
17.2.1.2	Overfire Air	245
17.2.1.3	Flue Gas Recirculation	245
17.2.1.4	Reduce Air Preheat	245
17.2.1.5	Reduce Firing Rate	246
17.2.1.6	Water/Steam Injection	246
17.2.1.7	Burners out of Service (BOOS)	246
17.2.1.8	Reburn	247
17.2.1.9	Low-NO _x Burners	247
17.2.1.10	Ultra Low-NO _x Burners	249
17.2.2	Flue Gas Treatment Techniques	249
17.2.2.1	Selective Noncatalytic Reduction (SNCR)	249
17.2.2.2	Selective Catalytic Reduction (SCR)	250
17.2.2.3	Low-Temperature Oxidation with Absorption	252
17.2.2.4	Catalytic Absorption	253
17.2.2.5	Corona-Induced Plasma	254
	References	254
Chapter 18	Control Of SO_x	257
18.1	H ₂ S Control	257
18.2	SO ₂ (and HCl) Removal	259
18.2.1	Reagents	259
18.2.1.1	Calcium-Based Reactions	259
18.2.1.2	Calcium-Based Reaction Products	261
18.2.1.3	Sodium-Based Reactions	261
18.2.1.4	Sodium-Based Reaction Products	262
18.2.2	Capital vs. Operating Costs	263
18.2.2.1	Operating Costs	263

18.2.3	SO ₂ Removal Processes	264
18.2.3.1	Wet Limestone	264
18.2.3.2	Wet Soda Ash or Caustic Soda.....	265
18.2.3.3	Lime Spray Drying	267
18.2.3.4	Circulating Lime Reactor	269
18.2.3.5	Sodium Bicarbonate/Sodium Sesquicarbonate Injection.....	271
18.2.3.6	Other SO ₂ Removal Processes.....	272
18.2.4	Example Evaluation	272
18.3	SO ₃ and Sulfuric Acid.....	273
18.3.1	SO ₃ and H ₂ SO ₄ Formation.....	273
18.3.2	Toxic Release Inventory	277
	References.....	277

Chapter 19 Fundamentals of Particulate Control 279

19.1	Particle-Size Distribution	279
19.2	Aerodynamic Diameter	284
19.3	Cunningham Slip Correction	284
19.4	Collection Mechanisms.....	286
19.4.1	Basic Mechanisms: Impaction, Interception, Diffusion.....	286
19.4.1.1	Impaction.....	287
19.4.1.2	Interception	287
19.4.1.3	Diffusion.....	287
19.4.2	Other Mechanisms	287
19.4.2.1	Electrostatic Attraction.....	287
19.4.2.2	Gravity.....	288
19.4.2.3	Centrifugal Force	288
19.4.2.4	Thermophoresis.....	288
19.4.2.5	Diffusiophoresis	288
	References.....	288

Chapter 20 Hood and Ductwork Design 289

20.1	Introduction	289
20.2	Hood Design.....	290
20.2.1	Flow Relationship for the Various Types of Hoods.....	290
20.2.1.1	Enclosing Hoods	290
20.2.1.2	Rectangular or Round Hoods	290
20.2.1.3	Slot Hoods.....	291
20.2.1.4	Canopy Hoods.....	292
20.3	Duct Design.....	293
20.3.1	Selection of Minimum Duct Velocity.....	293
20.3.2	The Mechanical Energy Balance.....	294

20.3.2.1	Velocity Head.....	295
20.3.2.2	Friction Head	296
20.4	Effect of Entrance into a Hood.....	299
20.5	Total Energy Loss.....	300
20.6	Fan Power.....	300
20.7	Hood-Duct Example.....	301
	References.....	303

Chapter 21 Cyclone Design..... 305

21.1	Collection Efficiency	305
21.1.1	Factors Affecting Collection Efficiency	306
21.1.2	Theoretical Collection Efficiency	308
21.1.3	Lapple's Efficiency Correlation.....	310
21.1.4	Leith and Licht Efficiency Model	311
21.1.5	Comparison of Efficiency Model Results	313
21.2	Pressure Drop	313
21.3	Saltation.....	315
	References.....	315

Chapter 22 Design and Application of Wet Scrubbers 317

22.1	Introduction	317
22.2	Collection Mechanisms and Efficiency.....	318
22.3	Collection Mechanisms and Particle Size.....	318
22.4	Selection and Design of Scrubbers.....	320
22.5	Devices for Wet Scrubbing	320
22.6	The Semrau Principle and Collection Efficiency	321
22.7	A Model for Counter-Current Spray Scrubbers	325
22.7.1	Application to a Spray Tower.....	328
22.8	A Model for Venturi Scrubbers.....	333
22.9	The Calvert Cut Diameter Design Technique.....	334
22.9.1	An Example Calculation.....	338
22.9.2	Second Example Problem.....	338
22.10	The Cut-Power Relationship	340
	References.....	340
	Additional References	340
	Appendix A: Calvert Performance Cut Diameter Data	341

Chapter 23 Filtration and Baghouses 347

23.1	Introduction	347
23.2	Design Issues.....	348

23.3	Cleaning Mechanisms	348
23.3.1	Shake/Deflate	348
23.3.2	Reverse Air.....	349
23.3.3	Pulse Jet (High Pressure).....	350
23.3.4	Pulse Jet (Low Pressure)	352
23.3.5	Sonic Horns.....	352
23.4	Fabric Properties.....	353
23.4.1	Woven Bags	354
23.4.2	Felted Fabric	354
23.4.3	Surface Treatment	354
23.4.4	Weight	354
23.4.5	Membrane Fabrics	355
23.4.6	Catalytic Membranes	355
23.4.7	Pleated Cartridges	355
23.4.8	Ceramic Candles	356
23.5	Baghouse Size	356
23.5.1	Air-to-Cloth Ratio.....	356
23.5.2	Can Velocity.....	357
23.6	Pressure Drop	357
23.7	Bag Life.....	359
23.7.1	Failure Modes	359
23.7.2	Inlet Design.....	360
23.7.3	Startup Seasoning	360
	References.....	360

Chapter 24 Electrostatic Precipitators 361

24.1	Early Development.....	361
24.2	Basic Theory.....	361
24.2.1	Corona Formation	362
24.2.2	Particle Charging	363
24.2.3	Particle Migration	364
24.2.4	Deutsch Equation.....	366
24.2.4.1	Sneakage	367
24.2.4.2	Rapping Re-Entrainment	367
24.2.4.3	Particulate Resistivity	367
24.2.4.4	Gas-Flow Distribution.....	369
24.3	Practical Application of Theory	370
24.3.1	Effective Migration Velocity.....	370
24.3.2	Automatic Voltage Controller	371
24.4	Flue Gas Conditioning	371
24.4.1	Humidification	371
24.4.2	SO ₃	372
24.4.3	Ammonia.....	372
24.4.4	SO ₃ and Ammonia	373

24.4.5	Ammonium Sulfate.....	373
24.4.6	Proprietary Additives	373
24.5	Using V-I Curves for Troubleshooting.....	374
	References.....	375
	Index.....	377