

Contents

Preface — V

Symbols and abbreviations — XIII

Part I: Basics

1 Do we need off-gas purification? — 3

- 1.1 Pollutants — 3
- 1.2 Effects of air pollutants — 3
- 1.3 How can we get it done? — 5
- 1.4 Our job — 6

2 The basics (for successful design work) — 8

- 2.1 Volume — 8
 - 2.1.1 Standard volume, dry (in $\text{m}^3_{\text{STP,dry}}$) — 8
 - 2.1.2 Standard volume, humid (in $\text{m}^3_{\text{STP,humid}}$) — 8
 - 2.1.3 Actual volume (in am^3) — 9
- 2.2 Concentration units — 10
 - 2.2.1 Volume fraction — 10
 - 2.2.2 ppm — 10
- 2.3 Conversion from ppm into $\text{mg m}^{-3}_{\text{STP}}$ — 10
- 2.4 Reference oxygen value (ROV) — 11
- 2.5 Gas velocity — 13
- 2.6 Dew point, cooling limit, adiabatic cooling limit and sulfuric acid dew point — 16
 - 2.6.1 Definition — 16
 - 2.6.2 Vapor pressure of water (Antoine equation) — 17
 - 2.6.3 The specific water load and the partial pressure of water vapor — 18
 - 2.6.4 The adiabatic cooling limit — 20
 - 2.6.5 The cooling limit (or “the correct engineer” approach) — 24
 - 2.6.6 Estimation of the sulfuric acid dew point of SO_2 -laden off-gas — 26

3 Specification of solid/gas and liquid/gas dispersions: properties — 36

- 3.1 Optical properties of dispersions — 37
- 3.2 Particle size distribution (PSD) — 38
- 3.3 Particle size distribution (PSD) equations — 42

4 Legislative framework and dispersion modeling — 46

- 4.1 Meteorology — 50
- 4.2 Pollutant dispersion modeling — 56
- 4.3 Smog: photochemical smog — 66
- 4.4 Particulate matter: dispersion and deposition — 71
- 4.5 Pollutant accumulation — 75
- 4.6 Odor and odor dispersion — 81

5 Summary — 89

Part II: Technologies

6 Particulate matter precipitation — 95

- 6.1 Performance of particle separation devices — 95
- 6.2 Outlook — 97
- 6.3 Equipment — 98
 - 6.3.1 Gravity settler — 98
 - 6.3.1.1 Summary — 102
 - 6.3.2 Cyclone separators — 102
 - 6.3.2.1 Applications — 104
 - 6.3.2.2 Flow pattern and mode of action — 107
 - 6.3.2.3 Pressure drop — 109
 - 6.3.2.4 Apparatus design and prediction of the separation efficiency — 110
 - 6.3.2.5 Summary — 121
 - 6.3.3 Electrostatic precipitators — 122
 - 6.3.3.1 Electrical properties of gases and specification of corona discharge — 122
 - 6.3.3.2 Industrial ESPs and requirements for successful particle precipitation — 125
 - 6.3.3.3 Corona discharge and design basics — 127
 - 6.3.3.4 Separation efficiency — 131
 - 6.3.3.5 Theoretical energy consumption — 132
 - 6.3.3.6 Summary — 140
 - 6.3.4 Scrubbers — 141
 - 6.3.4.1 Mechanism of dust precipitation by scrubbing — 141
 - 6.3.4.1.1 Inertial impaction — 142
 - 6.3.4.1.2 Direct interception — 143
 - 6.3.4.1.3 Diffusion — 143
 - 6.3.4.1.4 Other mechanisms: diffusiophoresis, thermophoresis and condensation — 143
 - 6.3.4.2 Separation efficiency of scrubbers — 144

6.3.4.2.1	Semrau model —	144
6.3.4.2.2	Barth model —	144
6.3.4.2.3	Calvert model —	147
6.3.4.2.4	Pressure drop —	149
6.3.4.3	Industrial scrubbers —	150
6.3.4.3.1	Scrubbing tower —	150
6.3.4.3.2	Ejector spray scrubbers (jet scrubber) —	151
6.3.4.3.3	Self-induced spray scrubbers (orifice scrubbers) —	153
6.3.4.3.4	Rotary scrubber —	154
6.3.4.3.5	Venturi scrubbers —	154
6.3.4.4	Scrubber design —	156
6.3.4.5	Summary —	161
6.3.5	Dust precipitation by filtration —	164
6.3.5.1	Deep bed filters —	164
6.3.5.1.1	Pressure drop of fiber layer —	168
6.3.5.2	Cleanable filters (fabric filters) —	169
6.3.5.2.1	Precipitation characteristics and separation efficiency —	171
6.3.5.2.2	Pressure drop —	171
6.3.5.2.3	Cleaning mechanism and filter designs —	172
6.3.5.2.4	Design of cleanable filters —	174
6.3.5.2.5	Filter material and standards —	177
6.3.5.2.6	Fiber materials —	179
6.3.5.3	Granular bed filters —	180
6.3.5.4	Summary —	185
6.4	Conclusion —	185
7	Thermal and catalytic off-gas purification —	186
7.1	Introduction to thermal and catalytic off-gas purification —	186
7.2	Chemical reaction engineering fundamentals —	190
7.2.1	Chemical thermodynamics —	190
7.2.1.1	Enthalpy of reaction —	190
7.2.1.2	Gibbs free enthalpy of reaction —	194
7.2.1.3	Principle of Le Chatelier —	196
7.2.2	Reaction kinetics —	198
7.2.2.1	Rate laws —	198
7.2.2.2	Temperature dependence —	203
7.2.2.3	Summary —	205
7.2.3	Types of reaction —	206
7.2.3.1	Homogeneous gas-phase reactions —	206
7.2.3.2	Heterogeneous catalytic gas-phase reactions —	206
7.2.4	Heterogeneous catalysis —	211
7.2.4.1	Selectivity and yield of a chemical reaction —	212

7.2.4.2	Heterogeneous catalysts in off-gas purification —	213
7.2.4.3	Catalyst requirements —	216
7.2.4.4	Summary —	217
7.2.5	Reactor design —	217
7.2.5.1	Material balance for an ideal reactor —	218
7.2.5.2	Design of ideal tubular reactors (PFR) —	219
7.2.6	Process selection —	221
7.3	Off-gas purification by oxidation in the gas phase: combustion —	222
7.3.1	Combustion fundamentals —	223
7.3.1.1	Complete versus incomplete combustion —	223
7.3.1.2	Specification of combustibles —	225
7.3.1.3	Combustion mechanism and procedure —	228
7.3.1.4	Technical considerations for pollutant combustion —	230
7.3.1.5	Summary —	233
7.3.2	Thermal combustion —	233
7.3.2.1	Combustion in flares —	235
7.3.2.2	Thermal combustion in combustion chambers —	235
7.3.2.3	Design of combustion chambers for thermal combustion —	236
7.3.3	Catalytic combustion —	246
7.3.3.1	Reactor design —	248
7.3.3.2	Summary —	250
7.3.4	Combination of thermal and catalytic combustion —	250
7.4	Off-gas purification by reduction in the gas phase —	251
7.4.1	Nitrogen oxides —	251
7.4.1.1	Formation of nitrogen oxides —	251
7.4.1.2	NO _x emission mitigation measures —	253
7.4.1.2.1	Primary measures – prevention of NO _x formation (emission prevention) —	253
7.4.1.2.2	Secondary measures – off-gas purification through NO _x reduction (emission control) —	255
7.4.1.3	Catalytic reduction of NO _x —	257
7.4.1.3.1	Catalyst specification —	257
7.4.1.3.2	Application —	258
7.4.1.3.3	SCR of NO _x : reactor design —	259
8	Absorptive off-gas purification —	266
8.1	Physiochemical basics —	268
8.1.1	Physiosorption —	268
8.1.2	Chemisorption —	269
8.1.3	Absorbent selection —	271
8.1.4	Gas–liquid partition —	271
8.2	Technologies, processes, their thermodynamics and kinetics —	291

8.2.1	NaOH — 293
8.2.2	MgO — 295
8.2.3	ZnO, NiO and FeO — 295
8.2.4	CaCO ₃ — 295
8.2.5	Ca(OH) ₂ (slaked lime) — 296
8.2.6	Activity: the link between energy and the ability to “offer work” — 298
8.2.7	Double-alkali processes — 301
8.2.8	Oxidation of sulfite and hydrogen sulfite — 301
8.3	Design of absorption processes — 303
8.3.1	Mass balances — 304
8.3.2	Selection of equipment — 309
8.4	Apparatus design for absorption towers with stage-wise phase contact: apparatus diameter and apparatus height — 310
8.4.1	The hydraulics of stage-wise phase contact — 311
8.4.2	The theory of separation stages for determining N_{th} — 315
8.4.3	Overall mass transfer efficiency of staged phase contactors — 319
8.5	Apparatus design for absorption towers with continuous phase contact: apparatus diameter and apparatus height — 320
8.5.1	The film theory — 322
8.5.2	The HTU-NTU concept — 324
8.5.3	Mass transfer — 327
8.5.4	Hydraulic design of packed bed absorption towers — 329
8.5.5	Design of spray scrubbers — 334
8.5.5.1	Summary — 338
9	Adsorption — 340
9.1	Basics — 340
9.2	Adsorbents — 342
9.2.1	Activated carbon — 343
9.2.2	Silica and alumina — 344
9.2.2.1	Silica gel — 344
9.2.2.2	Active alumina — 345
9.2.3	Zeolite — 345
9.2.4	Adsorbent selection — 346
9.2.5	Evaluation of pore-related properties — 347
9.2.5.1	Porosity — 347
9.2.5.2	Pore size distribution and surface area — 347
9.3	Adsorption equilibrium — 347
9.3.1	Isotherm classification — 349
9.3.2	Isotherm equations — 350
9.3.2.1	Langmuir isotherm — 350
9.3.2.2	Henry isotherm — 351

9.3.2.3	Freundlich isotherm —	351
9.3.2.4	Brunauer–Emmet–Teller (BET) isotherm —	352
9.3.2.5	Fowler and Guggenheim isotherm —	352
9.3.3	Micropore adsorption —	354
9.4	Transport and dispersion mechanism —	355
9.4.1	Pore diffusion —	356
9.4.2	Surface diffusion —	357
9.4.3	Film diffusion —	357
9.5	Heat of adsorption —	357
9.6	Multicomponent adsorption —	360
9.7	Mass balances in adsorption towers —	360
9.7.1	Type I isotherm systems —	362
9.7.1.1	Adsorption —	362
9.7.1.2	Desorption —	363
9.7.2	Type III isotherm systems —	364

10 Some final remarks — 372

Bibliography — 375

Index — 389