

SECOND EDITION

# AEROSOL MEASUREMENT

PRINCIPLES, TECHNIQUES,  
AND APPLICATIONS

EDITED BY

PAUL A. BARON

KLAUS WILLEKE

# CONTENTS

<b>Preface</b>	xv
<b>List of Principal Symbols</b>	xvii
<b>Contributors</b>	xxi
<b>I PRINCIPLES</b>	<b>1</b>
<b>1 Historical Aspects of Aerosol Measurements</b>	<b>3</b>
<i>Kvetoslav R. Spurny</i>	
Introduction	3
The Early Days	3
Preclassical Period of Aerosol Measurement	3
Classical Period of Aerosol Measurement	7
Measurement of Fibrous Aerosols	22
Concluding Remarks	24
<b>2 Bridging Science and Application in Aerosol Measurement:     Assessing Available Tools</b>	<b>31</b>
<i>Paul A. Baron and Klaus Willeke</i>	
Introduction	31
Associated Fields	32
Computer Technology	32
Languages	33
Aerosol Calculator	34
<b>3 Aerosol Fundamentals</b>	<b>45</b>
<i>Paul A. Baron and Klaus Willeke</i>	
Introduction	45
Desirable versus Undesirable Aerosols	46
Units and Use of Equations	46
Common Technical and Descriptive Terms	48
Particle Size and Shape	49
Particle Suspensions	53
Instrument Considerations	54
Particle Shape Measurement	55
Particle Forces	57

<b>4 Gas and Particle Motion</b>	<b>61</b>
<i>Paul A. Baron and Klaus Willeke</i>	
Introduction	61
Bulk Gas Motion	61
Transition and Gas Molecular Flow	64
Gas and Particle Diffusion	67
Aerodynamic Drag on Particles	69
Particle Motion Due to Gravity	71
Particle Parameters	74
Particle Motion in an Electric Field	77
Particle Motion in Other Force Fields	79
<b>5 Physical and Chemical Changes in the Particulate Phase</b>	<b>83</b>
<i>William C. Hinds</i>	
Introduction	83
Condensation	86
Nucleation	88
Evaporation	89
Coagulation	91
Reactions	96
<b>6 Size Distribution Characteristics of Aerosols</b>	<b>99</b>
<i>Walter John</i>	
Basic Concepts of Particle Size and Size Distributions	99
Ambient Aerosols	102
Indoor Aerosols	112
Industrial Aerosols	113
<b>7 An Approach to Performing Aerosol Measurements</b>	<b>117</b>
<i>Paul A. Baron and William A. Heitbrink</i>	
Introduction	117
Quality Assurance: Planning a Measurement	117
Measurement Accuracy	118
Size Range	119
Collection and Analysis Measurements	120
Direct-Reading Measurement of Aerosols	122
Aerosol Measurement Errors	124
<b>II TECHNIQUES</b>	<b>141</b>
<b>8 Sampling and Transport of Aerosols</b>	<b>143</b>
<i>John E. Brockmann</i>	
Introduction	143
Sample Extraction	148
Sample Transport	170

Other Sampling Issues	188
Summary and Conclusions	190
<b>9 Filter Collection</b>	<b>197</b>
<i>K. W. Lee and R. Mukund</i>	
Introduction	197
General Principles of Filter Sampling	198
Aerosol Measurement Filters	201
Filtration Theory	205
Filter Selection	220
<b>10 Inertial, Gravitational, Centrifugal, and Thermal Collection Techniques</b>	<b>229</b>
<i>Virgil A. Marple, Bernard A. Olson, and Kenneth L. Rubow</i>	
Introduction	229
Inertial Classifiers	230
Settling Devices and Centrifuges	254
Thermal Precipitators	256
<b>11 Chemical Analysis Methods for Atmospheric Aerosol Components</b>	<b>261</b>
<i>Paul A. Solomon, Gary Norris, Matthew Landis, and Michael Tolocka</i>	
Introduction	261
Scope and Objectives	263
Mass Measurements	266
Water-Extractable Anion and Cation Analysis Methods	268
Particulate Carbon	272
Elemental Analysis by Nondestructive Techniques	276
Elemental Analysis by Destructive Techniques	279
Continuous Methods	281
Summary	284
<b>12 Analysis of Individual Collected Particles</b>	<b>295</b>
<i>R. A. Fletcher, J. A. Small, and J. H. J. Scott</i>	
Introduction	295
Light Microscopy	298
Electron Beam Analysis of Particles	303
Laser Microprobe Mass Spectrometry	334
Secondary Ion Mass Spectrometry	340
Raman Microprobe	345
Infrared Microscopy	348
Scanning Probe Microscopy	349
Complementary Capabilities of Microanalytical Instrumentation	353
<b>13 Real-Time Single-Particle Analysis</b>	<b>365</b>
<i>Anthony S. Wexler and Murray V. Johnston</i>	
Introduction	365
Particle Detection	371
Particle Sizing	372

	Particle Vaporization and Ionization	373
	Mass Analysis	377
	Data Handling and Interpretation	379
	Putting It All Together—Selected Instruments	380
<b>14</b>	<b>Dynamic Mass and Surface Area Measurements</b>	<b>387</b>
	<i>Urs Baltensperger, Ernest Weingartner, Heinz Burtscher, and Jorma Keskinen</i>	
	Introduction	387
	Mass Measurement	387
	Piezoelectric Crystal Measurement Method	387
	Beta Gauge Method	389
	Tapered-Element Oscillating Microbalance Method	395
	Electrical Low-Pressure Impactor	399
	Surface Area Measurement	404
	Epiphaniometer	406
	Diffusion Charger	408
	Photoelectric Aerosol Sensor	412
<b>15</b>	<b>Optical Direct-Reading Techniques: Light Intensity Systems</b>	<b>419</b>
	<i>Josef Gebhart</i>	
	Introduction	419
	Light Scattering and Extinction by a Single Sphere	420
	Light Scattering and Extinction by an Assembly of Particles	427
	Single-Particle Optical Counters	433
	Multiple-Particle Optical Techniques	446
	Light Scattering by Irregular Particles	449
<b>16</b>	<b>Optical Direct-Reading Techniques: In Situ Sensing</b>	<b>455</b>
	<i>Daniel J. Rader and Timothy J. O'Hern</i>	
	Introduction	455
	Overview	456
	Light Scattering	461
	Single-Particle Counters: Intensity Based	465
	Single-Particle Counters: LDV Visibility Based	469
	Single-Particle Counters: Phase Based	470
	Single-Particle Counters: Imaging	473
	Ensemble Techniques: Particle Field Imaging	475
	Ensemble Techniques: Fraunhofer Diffraction	477
	Ensemble Techniques: Dynamic Light Scattering	481
	Performance Verification	482
	Conclusions	487
<b>17</b>	<b>Direct-Reading Techniques Using Particle Motion and Optical Detection</b>	<b>495</b>
	<i>Paul A. Baron, Malay K. Mazumder, and Yung-Sung Cheng</i>	
	Introduction	495
	Electric-Single Particle Aerodynamic Relaxation Time Analyzer	496
	Aerodynamic Particle Sizer	508
	Aerosizer	520
	Fibrous Aerosol Monitor	527

<b>18</b>	<b>Electrical Techniques</b>	<b>537</b>
	<i>Richard C. Flagan</i>	
	Introduction	537
	Behavior of Charged Particles	538
	Relationship Between Migration and Diffusion	540
	Aerosol Charge Conditioning	540
	Particle Sampling	551
	Particle Size Distribution Measurement	551
<b>19</b>	<b>Condensation Detection and Diffusion Size Separation Techniques</b>	<b>569</b>
	<i>Yung-Sung Cheng</i>	
	Introduction	569
	Condensation Theory	570
	Condensation Nuclei Counters	573
	Theories of the Diffusion Measurement Technique	579
	Diffusion Denuders	582
	Diffusion Batteries	587
	Conclusions	596
<b>20</b>	<b>Electrodynamic Levitation of Particles</b>	<b>603</b>
	<i>E. James Davis</i>	
	Introduction	603
	Levitation Principles	605
	Particle Sizing	608
	Force Measurement	613
	Mass and Charge Measurement	615
	Evaporation/Condensation	618
	Chemical Reactions	620
	Concluding Remarks	622
<b>21</b>	<b>Instrument Calibration</b>	<b>627</b>
	<i>Bean T. Chen and Walter John</i>	
	Introduction	627
	Measurement Methods and Calibration Standards	628
	General Considerations	629
	Calibration Apparatus and Procedures	632
	Test Aerosol Generation	635
	Calibration of Flow, Pressure, and Velocity	650
	Instrument Calibration	656
	Summary of Calibration Procedures	660
<b>22</b>	<b>Methods of Size Distribution Data Analysis and Presentation</b>	<b>667</b>
	<i>Douglas W. Cooper</i>	
	Introduction	667
	Particle Size Distributions	668
	Concentration Distributions	673
	Summarizing Data with a Few Parameters	675

Summarizing Size Distributions Graphically	679
Confidence Intervals and Error Analysis	682
Testing Hypotheses with Size Distribution Data	684
Coincidence Errors	689
Choosing Size Interval Demarcations	690
Data Inversion	690
<b>III APPLICATIONS</b>	<b>703</b>
<b>23 Nonspherical Particle Measurements: Shape Factors, Fractals, and Fibers</b>	<b>705</b>
<i>Paul A. Baron, Christopher M. Sorensen, and John E. Brockmann</i>	
Introduction	705
Shape Factor	705
Fractal Particles	707
Fibers	725
<b>24 Biological Particle Sampling</b>	<b>751</b>
<i>Tiina Reponen, Klaus Willeke, Sergey Grinshpun, and Aino Nevalainen</i>	
Introduction	751
Bioaerosol Types	752
Sources of Bioaerosols	756
General Sampling Considerations	757
Principles of Bioaerosol Collection	760
Collection Time	764
Selection of Sampler	769
Calibration	771
Contamination	771
Sample Analysis	772
<b>25 Aerosol Measurement in the Workplace</b>	<b>779</b>
<i>Andrew D. Maynard and Paul A. Jensen</i>	
Introduction	779
Aerosol Exposure Measurement in the Workplace	780
Sampling Against Exposure Conventions	784
Measurement of Size Distribution	791
Use of Direct-Reading Instruments	792
Future Trends	794
<b>26 Mine Aerosol Measurement</b>	<b>801</b>
<i>Bruce K. Cantrell and Jon C. Volkwein</i>	
Introduction	801
Mine Aerosol Sources	802
Physical Characteristics of Mine Aerosol	803
Measurement Technology	806

<b>27</b>	<b>Ambient Air Sampling</b>	<b>821</b>
	<i>John G. Watson and Judith C. Chow</i>	
	Introduction	821
	Sampling System Components	822
	Sampling Systems	833
	Selecting a Sampling System	838
	Conclusions	839
<b>28</b>	<b>Fugitive Dust Emissions</b>	<b>845</b>
	<i>Chatten Cowherd, Jr.</i>	
	Introduction	845
	Factors Affecting Dust Emissions	845
	Emission Calculation Procedure	848
	Emission Quantification Techniques	850
	Emission Models	854
	Emission Control Options	855
<b>29</b>	<b>Indoor Aerosols and Exposure Assessment</b>	<b>859</b>
	<i>Charles E. Rodes and Russell W. Wiener</i>	
	Introduction	859
	Concentrations Versus Exposures	860
	Measurement Strategies	862
	Sampling and Analysis Methods	866
	Indoor Air Assessments	872
	Exposure Studies	876
	Modeling	879
<b>30</b>	<b>Measurement of Aerosol from Aircraft</b>	<b>887</b>
	<i>James Charles Wilson and W. Russell Seebaugh</i>	
	Introduction	887
	Research Utilizing Aerosol Measurement from Aircraft	887
	Objectives to be Achieved in Airborne Aerosol Sampling and Measurement	888
	Airborne Aerosol Measurement Techniques	889
	Effects Complicating Aerosol Sampling from Aircraft	891
	Review of Inlets	894
	Conclusions	898
<b>31</b>	<b>Measurement of High-Concentration and High-Temperature Aerosols</b>	<b>903</b>
	<i>Pratim Biswas</i>	
	Introduction	903
	Dilution Systems	904
	EPA Stack Sampling Methods	911
	High-Temperature Impactors	912
	In Situ Measurements	913
	Characterization of Combustion Aerosols	923



<b>32</b>	<b>Manufacturing of Materials by Aerosol Processes</b>	<b>929</b>
	<i>Sotiris E. Pratsinis, Georgios Skillas, and Toivo T. Kodas</i>	
	Materials	929
	Aerosol Processes	931
	Measurement Techniques	939
<b>33</b>	<b>Aerosol Measurements in Cleanrooms</b>	<b>959</b>
	<i>Robert P. Donovan</i>	
	Introduction	959
	International Standards for Classifying, Verifying, and Monitoring Cleanrooms: ISO 14644-1 and -2	962
	Commercially Available Aerosol Particle Counters for Cleanroom Classification and Monitoring	971
	Measuring Particulate Emissions from Cleanroom Equipment	974
	Conclusions	977
<b>34</b>	<b>Radioactive Aerosols</b>	<b>979</b>
	<i>Mark D. Hoover and George J. Newton</i>	
	Introduction	979
	Radiation and Radioactive Decay	980
	Radiation Detection	983
	Safe Handling of Radioactive Aerosols	985
	Objectives for Measuring Radioactive Aerosols	988
	Application of Standard Measuring Techniques	991
	Special Techniques for Radioactive Aerosols	996
	Practical Options for Data Transmission and Networking	1003
	Adequacy of the Existing Aerosol Science Data Base	1003
	Conclusions	1004
<b>35</b>	<b>Radon and Its Short-Lived Decay Product Aerosols</b>	<b>1011</b>
	<i>Beverly S. Cohen</i>	
	Introduction	1011
	Radon in the Environment	1011
	Radiometric Properties of Radon and Daughters	1014
	Aerosol Properties of Radon and Daughters	1016
	Human Exposure Parameters	1017
	Air Sampling for Radon and Its Short-Lived Decay Products	1019
	Calibration	1026
	Protocols for Indoor Measurement	1027
	Conclusions	1027
<b>36</b>	<b>Measurement of Pharmaceutical and Diagnostic Aerosols</b>	<b>1031</b>
	<i>Anthony J. Hickey and David Swift</i>	
	Introduction	1031
	Pharmaceutical Aerosols by Route of Administration	1033
	Diagnostic Aerosols	1039

Characterization of Pharmaceutical and Diagnostic Aerosols	1041
Current Issues in Pharmaceutical and Diagnostic Aerosol Measurement	1050
Conclusions	1050
<b>37 Inhalation Toxicology: Sampling Strategies Related to Control of Exposure Atmospheres</b>	<b>1053</b>
<i>Owen R. Moss</i>	
Introduction	1053
Basic Atmosphere Generation and Control Systems	1054
Properties of Exposure Systems	1056
Basic Sampling Techniques and Strategies	1057
Conclusions	1061
<b>Appendix A Glossary of Terms</b>	1065
<b>Appendix B Conversion Factors</b>	1079
<b>Appendix C Commonly Used Constants</b>	1081
<b>Appendix D Some Properties of Air and Water</b>	1083
<b>Appendix E Major Dimensionless Numbers</b>	1085
<b>Appendix F Properties of Particles</b>	1087
<b>Appendix G Geometric Formulas</b>	1089
<b>Appendix H Bulk Densities of Some Common Aerosol Materials</b>	1091
<b>Appendix I Manufacturers and Suppliers</b>	1093
<b>INDEX</b>	1111