

James H. Vincent

Aerosol Sampling

Science, Standards, Instrumentation and Applications

 WILEY

Contents

<i>Preface</i>	xvii
A SCIENTIFIC FRAMEWORK FOR AEROSOL SAMPLING	1
1 Introduction	3
1.1 Aerosols	3
1.2 Particle size	4
1.3 Elementary particle size statistics	5
1.4 Aerosol measurement	8
1.5 Sampler performance characteristics	9
References	12
2 Fluid and aerosol mechanical background	13
2.1 Fluid mechanical background	13
2.1.1 Introduction	13
2.1.2 Equations of fluid motion	13
2.1.3 Streamlines and streamsurfaces	15
2.1.4 Boundary layers	16
2.1.5 Stagnation	18
2.1.6 Potential flow	20
2.1.7 Turbulence	20
2.2 Aerosol mechanics	22
2.2.1 Particle drag force and mobility	22
2.2.2 Drag coefficient	22
2.2.3 Slip	23
2.2.4 General equation of motion under the influence of an external force	24
2.2.5 Particle motion without external forces	25
2.2.6 Particle aerodynamic diameter	27
2.2.7 Impaction	28
2.2.8 Molecular diffusion	30
2.2.9 Turbulent diffusion	32
References	33
3 Experimental methods in aerosol sampler studies	35
3.1 Introduction	35
3.2 Methodology for assessing sampler performance	35
3.2.1 The direct (trajectory) method	35
3.2.2 The indirect (comparison) method	36
3.2.3 Critique of the alternative methods	37

3.3	Scaling relationships for aerosol samplers	38
3.4	Test facilities	39
3.4.1	Moving air	40
3.4.2	Calm air	45
3.4.3	Slowly moving air	48
3.5	Test aerosol generation	50
3.5.1	Idealised test aerosols	50
3.5.2	Dry-dispersed dusts	52
3.5.3	Aerosol materials	57
3.5.4	Electric charge effects	59
3.6	Reference methods	60
3.7	Assessment of collected aerosol	60
3.8	Aerosol sampler test protocols and procedures	61
	References	68
4	The nature of air flow near aerosol samplers	71
4.1	Introduction	71
4.2	Line and point sink samplers	71
4.3	Thin-walled slot and tube entries	73
4.3.1	Facing the freestream	73
4.3.2	Other orientations	74
4.4	Thick-walled tubes	75
4.5	Simple blunt samplers facing the wind	76
4.5.1	Two-dimensional blunt sampling systems	76
4.5.2	Axially symmetric blunt sampling systems	80
4.6	Blunt samplers with orientations other than facing the wind	82
4.6.1	A cylindrical blunt sampler	82
4.6.2	Flow stability	84
4.6.3	A spherical blunt sampler	86
4.7	More complex sampling systems	89
4.8	Effects of freestream turbulence	90
	References	90
5	Aerosol aspiration in moving air	93
5.1	Introduction	93
5.2	Thin-walled tube samplers	94
5.2.1	Qualitative picture of aerosol transport	94
5.2.2	Impaction model for a thin-walled tube facing the freestream	96
5.2.3	Physical definition of impaction efficiency for aerosol sampling	98
5.2.4	Experimental studies for thin-walled tubes facing the freestream	98
5.2.5	Experimental studies for thin-walled tubes at other orientations	104
5.2.6	Impaction model for other orientations	105
5.2.7	Mathematical models	109
5.2.8	Conditions for ‘acceptable’ isokinetic sampling	114
5.3	Blunt samplers	116
5.3.1	Impaction model for a blunt sampler facing the freestream	116

5.3.2	Experimental investigations of blunt samplers of simple shape facing the wind	120
5.3.3	Blunt samplers at other orientations	123
5.3.4	Mathematical and numerical approaches to blunt samplers	125
5.3.5	Orientation-averaged conditions	126
	References	127
6	Aspiration in calm and slowly moving air	131
6.1	Introduction	131
6.2	Sampling in perfectly calm air	131
6.2.1	Qualitative description	131
6.2.2	Experimental studies for sampling in perfectly calm air	135
6.2.3	Analytical models for aspiration efficiency in calm air	138
6.2.4	Descriptive modeling of aspiration efficiency	144
6.2.5	Criteria for 'representative sampling' in calm air	147
6.3	Slowly moving air	149
6.3.1	Definition of calm air	150
6.3.2	Intermediate conditions	152
	References	155
7	Interferences to aerosol sampling	157
7.1	Introduction	157
7.2	Interferences during aspiration	157
7.2.1	Effects of turbulence on aspiration	158
7.2.2	Effects of electrostatic forces on aspiration	162
7.2.3	External wall effects	165
7.3	Interferences after aspiration	173
7.3.1	Deposition losses inside a straight sampling tube	173
7.3.2	Deposition losses inside a bent sampling tube	180
7.3.3	Deposition inside a thin-walled tube facing into the wind	181
7.3.4	Deposition inside a thin-walled tube at other orientations	184
7.3.5	Rebound of particles from internal walls	185
7.3.6	More complicated systems	186
7.3.7	Electrostatic effects	186
	References	188
8	Options for aerosol particle size selection after aspiration	193
8.1	Introduction	193
8.2	Elutriation	194
8.2.1	Vertical elutriation	194
8.2.2	Horizontal elutriation	195
8.3	Filtration by porous foam media	197
8.4	Centrifugation	201
8.5	Impaction	205
8.5.1	Conventional impaction	205
8.5.2	Low pressure and micro-orifice impaction	209
8.5.3	Virtual impaction	209

8.6	Diffusion	211
8.6.1	Deposition by diffusion in laminar flow through tubes	211
8.6.2	Deposition by diffusion in flow through screens	212
8.7	Other particle size-selective mechanisms	213
8.7.1	Electrostatic precipitation	213
8.7.2	Thermal precipitation	214
8.7.3	Optical processes	215
	References	215
B	STANDARDS FOR AEROSOLS	219
9	Framework for aerosol sampling in working, living and ambient environments	221
9.1	Introduction	221
9.2	Exposure to aerosols	222
9.2.1	The human respiratory tract	223
9.2.2	Definitions of exposure	225
9.2.3	Variability of exposure	227
9.3	Framework for health-related aerosol sampling	227
9.3.1	Criteria	227
9.3.2	Sampling instrumentation	228
9.3.3	Analytical methods	228
9.3.4	Sampling strategies	229
9.3.5	Exposure limits	232
9.3.6	Overview	233
9.4	Non-health-related aerosol standards	233
	References	235
10	Particle size-selective criteria for coarse aerosol fractions	237
10.1	Introduction	237
10.2	Experimental studies of inhalability	237
10.2.1	Early experimental measurements of inhalability	237
10.2.2	Physical basis of inhalability	241
10.2.3	Inhalability for very large particles	242
10.2.4	Inhalability at very low wind speeds	244
10.3	Particle size-selective criteria for the inhalable fraction	247
10.3.1	Early recommendations	248
10.3.2	Modern criteria for the inhalable fraction	249
10.3.3	Further recommendations	252
10.4	Overview	252
	References	253
11	Particle size-selective criteria for fine aerosol fractions	255
11.1	Introduction	255
11.2	Studies of regional deposition of inhaled aerosols	255
11.2.1	Framework	255
11.2.2	Theories, simulations and models	258

11.2.3	Experiments for studying regional deposition	259
11.2.4	Results for total deposition	260
11.2.5	Results for extrathoracic deposition	261
11.2.6	Results for tracheobronchial deposition	262
11.2.7	Results for deposition in the alveolar region	264
11.2.8	Results for the deposition of fibrous aerosols	265
11.2.9	Results for the deposition of very fine and ultrafine aerosols	266
11.3	Criteria for fine aerosol fractions	268
11.3.1	Historical overview	268
11.3.2	Modern criteria for the thoracic and respirable aerosol fractions	273
11.3.3	Criteria for the extrathoracic aerosol fraction	275
11.3.4	Criteria for the tracheobronchial and alveolar aerosol fractions	276
11.3.5	Criteria for very fine aerosol fractions	278
11.3.6	Criteria for fibrous aerosols	279
11.3.7	Criteria for ultrafine aerosols	280
11.4	Overview	282
11.4.1	Summary	282
11.4.2	Precision and tolerance bands	283
11.4.3	International harmonisation of sampling criteria	284
	References	285
12	Health effects and Limit values	289
12.1	Introduction	289
12.2	Aerosol-related health effects	289
12.2.1	Diseases of the respiratory tract	290
12.2.2	Diseases beyond the respiratory tract	291
12.3	The processes of standards setting	292
12.4	Occupational exposure limits (OELs)	292
12.4.1	Health-based exposure limits	293
12.4.2	Regulatory exposure limits	293
12.4.3	OELs for aerosols	294
12.5	Ambient atmospheric aerosol limits	297
12.5.1	Black smoke and fine particles	297
12.5.2	Establishment of the EPA PM NAAQS limit values	298
12.5.3	Limits for non-health-related aerosols	300
12.6	Special cases	301
12.6.1	Fibrous aerosols	302
12.6.2	Bioaerosols	303
12.6.3	Ultrafine aerosols	304
	References	305
C	AEROSOL SAMPLING INSTRUMENTATION	309
13	Historical milestones in practical aerosol sampling	311
13.1	Introduction	311
13.2	Occupational aerosol sampling	312

13.2.1	Sampling strategies and philosophies	312
13.2.2	Indices of aerosol exposure	313
13.2.3	Early gravimetric samplers for ‘total’ aerosol	313
13.2.4	Particle count samplers	314
13.2.5	Emergence of gravimetric samplers for the respirable fraction	316
13.2.6	Emergence of gravimetric samplers for ‘total’ and inhalable aerosol	317
13.2.7	Other aerosol fractions	317
13.2.8	Sampling to measure aerosol particle size distribution	317
13.2.9	Direct-reading instruments	318
13.2.10	Overview	319
13.3	Ambient atmospheric aerosol sampling	319
13.3.1	Sampling strategies and philosophies	319
13.3.2	Indices of health-related aerosol exposure	320
13.3.3	Indices for coarse ‘nuisance’ aerosols	322
13.3.4	Direct-reading instruments	322
13.3.5	Overview	322
	References	323
14	Sampling for coarse aerosols in workplaces	327
14.1	Introduction	327
14.2	Static (or area) samplers for coarse aerosol fractions	327
14.2.1	‘Total’ aerosol	327
14.2.2	Inhalable aerosol	328
14.3	Personal samplers for coarse aerosol fractions	333
14.3.1	‘Total’ aerosol	333
14.3.2	Inhalable aerosol	344
14.3.3	Other samplers	351
14.4	Analysis of performance data for inhalable aerosol samplers	352
14.4.1	Statistics	352
14.4.2	Modeling	352
14.5	Passive aerosol samplers	354
	References	356
15	Sampling for fine aerosol fractions in workplaces	359
15.1	Introduction	359
15.2	Samplers for the respirable fraction	359
15.2.1	Early samplers	360
15.2.2	Horizontal elutriators	364
15.2.3	Cyclones	368
15.2.4	Impactors	376
15.2.5	Porous plastic foam filter samplers	378
15.2.6	Other samplers	383
15.2.7	Sampling for ‘respirable’ fibers	385
15.3	Samplers for the thoracic fraction	385
15.3.1	Vertical elutriators	386
15.3.2	Cyclones	386

15.3.3	Impactors	387
15.3.4	Porous plastic foam filter samplers	388
15.4	Samplers for PM _{2.5}	391
15.5	Thoracic particle size selection for fibrous aerosols	393
15.6	Sampling for very fine aerosols	394
15.6.1	Ultrafine aerosols	394
15.6.2	Combustion-related aerosols	394
15.7	Simultaneous sampling for more than one aerosol fraction	395
	References	398
16	Sampling in stacks and ducts	403
16.1	Introduction	403
16.2	Basic considerations	403
16.3	Stack sampling methods	404
16.3.1	United States of America	405
16.3.2	United Kingdom and elsewhere	409
16.4	Sampling probes for stack sampling	410
16.4.1	Standard probes	410
16.4.2	Velocity-sensing probes	411
16.4.3	Null-type probes	411
16.4.4	Self-compensating probes	412
16.4.5	Dilution	413
16.5	Sampling for determining particle size distribution in stacks	414
16.6	Direct-reading stack-monitoring instruments	415
	References	415
17	Sampling for aerosols in the ambient atmosphere	417
17.1	Introduction	417
17.2	Sampling for coarse 'nuisance' aerosols	417
17.3	Sampling for 'black smoke'	423
17.4	Sampling for total suspended particulate in the ambient atmosphere	425
17.4.1	'Total' aerosol	425
17.4.2	Inhalable aerosol	431
17.5	Sampling for fine aerosol fractions in the ambient atmosphere	432
17.5.1	PM ₁₀	432
17.5.2	PM _{2.5}	435
17.5.3	Ultrafine aerosols	439
17.6	Meteorological sampling	440
	References	442
18	Sampling for the determination of particle size distribution	447
18.1	Introduction	447
18.2	Rationale	447
18.3	Aerosol spectrometers	448
18.3.1	Horizontal elutriators	448
18.3.2	Centrifuges	450

18.3.3 Inertial spectrometers	450
18.4 Cascade impactors	452
18.4.1 Outline	452
18.4.2 Earlier cascade impactors	454
18.4.3 Static cascade impactor-based samplers	454
18.4.4 Personal cascade impactors	459
18.4.5 Cascade impactors for stack sampling	462
18.4.6 Inversion procedures for cascade impactors	463
18.5 Other spectrometers	465
18.5.1 Parallel impactors	465
18.5.2 Cascade cyclones	466
18.5.3 Diffusion batteries	467
18.6 Particle size distribution analysis by microscopy	469
References	470
19 Sampling for bioaerosols	473
19.1 Introduction	473
19.2 Standards for bioaerosols	474
19.3 Technical issues for bioaerosol sampling	474
19.4 Early bioaerosol sampling	476
19.5 Criteria for bioaerosol sampling	477
19.6 Inertial samplers	477
19.6.1 Passive samplers	478
19.6.2 Single-stage impactors	478
19.6.3 Cascade impactors	481
19.6.4 Impingers	482
19.7 Centrifugal samplers	485
19.7.1 Cyclones/wetted cyclones	485
19.7.2 Centrifuges	485
19.8 'Total' and inhalable bioaerosol	486
19.9 Other samplers	486
References	486
20 Direct-reading aerosol sampling instruments	489
20.1 Introduction	489
20.2 Optical aerosol-measuring instruments	490
20.2.1 Physical background	490
20.2.2 Transmission/extinction monitoring	492
20.2.3 Light scattering photometry	494
20.2.4 Optical particle counters	498
20.2.5 Particle size and shape	503
20.3 Electrical particle measurement	503
20.4 Condensation nuclei/particle counters	504
20.5 Mechanical aerosol mass measurement	505
20.6 Nuclear mass detectors	509
20.7 Surface area monitoring	510

20.8 Analytical chemical methods	511
20.9 Bioaerosol monitoring	511
20.9.1 Fluorescence technology	511
20.9.2 Particle size and shape for bioaerosols	512
20.9.3 Hybrid systems	512
References	513
D AEROSOL SAMPLE APPLICATIONS AND FIELD STUDIES	517
21 Pumps and paraphernalia	519
21.1 Introduction	519
21.2 Air moving systems	519
21.2.1 Pumps	520
21.2.2 Personal sampling pumps	522
21.2.3 Pulsation damping	523
21.3 Flow rate	524
21.3.1 Flow control	525
21.3.2 Flow measurement	525
21.4 Collection media	526
21.4.1 Filters	526
21.4.2 Filtration efficiency	527
21.4.3 Mass stability	528
21.4.4 Choices and applications	531
21.4.5 Substrates	532
21.5 Analysis of collected samples	533
21.5.1 Handling and transport of samples	533
21.5.2 Gravimetric methods	534
21.5.3 Chemical analysis	534
References	535
22 Field experience with aerosol samplers in workplaces	537
22.1 Introduction	537
22.2 Personal and static (or area) sampling	538
22.3 Relationship between 'total' and inhalable aerosol	539
22.3.1 Side-by-side comparative studies	540
22.3.2 The practical impact of changes from 'total' to inhalable aerosol measurement	548
22.4 Converting particle counts to particle mass	549
22.4.1 Respirable aerosol exposures in the coal industry	549
22.4.2 Respirable aerosol exposures in hard rock mining	552
22.4.3 Inhalable aerosol exposures in the nickel industry	554
22.5 Field experience with samplers for respirable aerosol	558
22.5.1 Gravimetric mass sampling	558
22.5.2 Workplace comparisons between optical and gravimetric aerosol samplers	559
22.6 Classification of workplace aerosols	562
22.6.1 Particle size distribution	562
22.6.2 Combined particle size measurement and chemical speciation	566

22.7 Diesel particulate matter	568
22.8 The future of workplace aerosol measurement	569
References	570
23 Field experience with aerosol samplers in the ambient atmosphere	575
23.1 Introduction	575
23.2 'Nuisance' dust	576
23.3 Total suspended particulate and black smoke	577
23.4 Black smoke and particle size fractions (PM_{10} and $PM_{2.5}$)	580
23.5 Transition to particle size-selective sampling	582
23.6 PM_{10}	585
23.7 $PM_{2.5}$	589
23.8 Personal exposures to PM_{10} and $PM_{2.5}$	589
23.9 Classification of ambient atmospheric aerosols	593
23.9.1 Particle size distribution	593
23.9.2 Chemical composition	594
23.9.3 Bioaerosols	596
References	596
Index	599