Aerosol Technology

Properties, Behavior, and Measurement of Airborne Particles

William C. Hinds

Second Edition
Aerosol Technology
CONTENTS

Preface to the First Edition xi
Preface to the Second Edition xiii
List of Principal Symbols xv

1 Introduction 1

1.1 Definitions / 3
1.2 Particle Size, Shape, and Density / 8
1.3 Aerosol Concentration / 10
Problems / 12
References / 13

2 Properties of Gases 15

2.1 Kinetic Theory of Gases / 15
2.2 Molecular Velocity / 18
2.3 Mean Free Path / 21
2.4 Other Properties / 23
2.5 Reynolds Number / 27
2.6 Measurement of Velocity, Flow Rate, and Pressure / 31
Problems / 39
References / 41

3 Uniform Particle Motion 42

3.1 Newton’s Resistance Law / 42
3.2 Stokes’s Law / 44
3.3 Settling Velocity and Mechanical Mobility / 46
3.4 Slip Correction Factor / 48
3.5 Nonspherical Particles / 51
3.6 Aerodynamic Diameter / 53
3.7 Settling at High Reynolds Numbers / 55
3.8 Stirred Settling / 62
CONTENTS

7 Brownian Motion and Diffusion 150
  7.1 Diffusion Coefficient / 150
  7.2 Particle Mean Free Path / 154
  7.3 Brownian Displacement / 156
  7.4 Deposition by Diffusion / 160
  7.5 Diffusion Batteries / 165
Problems / 168
References / 169

8 Thermal and Radiometric Forces 171
  8.1 Thermophoresis / 171
  8.2 Thermal Precipitators / 176
  8.3 Radiometric and Concentration Gradient Forces / 178
Problems / 180
References / 180

9 Filtration 182
  9.1 Macroscopic Properties of Filters / 182
  9.2 Single-Fiber Efficiency / 190
  9.3 Deposition Mechanisms / 191
  9.4 Filter Efficiency / 196
  9.5 Pressure Drop / 200
  9.6 Membrane Filters / 202
Problems / 204
References / 204

10 Sampling and Measurement of Concentration 206
  10.1 Isokinetic Sampling / 206
  10.2 Sampling from Still Air / 213
  10.3 Transport Losses / 216
  10.4 Measurement of Mass Concentration / 217
  10.5 Direct-Reading Instruments / 222
  10.6 Measurement of Number Concentration / 225
  10.7 Sampling Pumps / 228
Problems / 230
References / 231
CONTENTS

11 Respiratory Deposition 233
   11.1 The Respiratory System / 233
   11.2 Deposition / 235
   11.3 Deposition Models / 242
   11.4 Inhalability of Particles / 245
   11.5 Respirable and Other Size-Selective Sampling / 249
Problems / 257
References / 258

12 Coagulation 260
   12.1 Simple Monodisperse Coagulation / 260
   12.2 Polydisperse Coagulation / 268
   12.3 Kinematic Coagulation / 272
Problems / 276
References / 277

13 Condensation and Evaporation 278
   13.1 Definitions / 278
   13.2 Kelvin Effect / 281
   13.3 Homogeneous Nucleation / 283
   13.4 Growth by Condensation / 285
   13.5 Nucleated Condensation / 288
   13.6 Condensation Nuclei Counters / 292
   13.7 Evaporation / 294
Problems / 301
References / 302

14 Atmospheric Aerosols 304
   14.1 Natural Background Aerosol / 304
   14.2 Urban Aerosol / 307
   14.3 Global Effects / 312
Problems / 314
References / 315

15 Electrical Properties 316
   15.1 Units / 316
   15.2 Electric Fields / 318
   15.3 Electrical Mobility / 320
   15.4 Charging Mechanisms / 323
   15.5 Corona Discharge / 331
21 Production of Test Aerosols 428

21.1 Atomization of Liquids / 428
21.2 Atomization of Monodisperse Particles in Liquid Suspensions / 434
21.3 Dispersion of Powders / 438
21.4 Condensation Methods / 443
Problems / 445
References / 446

Appendices 447

A1. Useful Constants and Conversions Factors / 447
A2. Some Basic Physical Laws / 449
A5. Properties of Gases and Vapors at 293 K [20°C] and 101 kPa [1 atm] / 452
A6. Viscosity and Density of Air versus Temperature / 452
A7. Pressure, Temperature, Density, and Mean Free Path of Air versus Altitude / 453
A8. Properties of Water Vapor / 455
A9. Properties of Water / 455
A11. Properties of Airborne Particles at Standard Conditions / 458
A12. Slip Correction Factor for Standard and Nonstandard Conditions / 460
A13. Properties of Selected Low-Vapor-Pressure Liquids / 461
A14. Reference Values for Atmospheric Properties at Sea Level and 293 K [20°C] / 462
A15. Greek Symbols Used in This Book / 464
A16. SI Prefixes / 464

Index 465
Airborne particles are present throughout our environment. They come in many different forms, such as dust, fume, mist, smoke, smog, or fog. These aerosols affect visibility, climate, and our health and quality of life. This book covers the properties, behavior, and measurement of aerosols.

This is a basic textbook for people engaged in industrial hygiene, air pollution control, radiation protection, or environmental science who must, in the practice of their profession, measure, evaluate, or control airborne particles. It is written at a level suitable for professionals, graduate students, or advanced undergraduates. It assumes that the student has a good background in chemistry and physics and understands the concepts of calculus. Although not written for aerosol scientists, it will be useful to them in their experimental work and will serve as an introduction to the field for students starting such careers. Decisions on what topics to include were based on their relevance to the practical application of aerosol science, which includes an understanding of the physical and chemical principles that underlie the behavior of aerosols and the instruments used to measure them.

Although this book emphasizes physical rather than mathematical analysis, an important aspect of aerosol technology is the quantitative description of aerosol behavior. To this end I have included 150 problems, grouped at the end of each chapter. They are an important tool for learning how to apply the information presented in the book. Because of the practical orientation of the book and the intrinsic variability of aerosol properties and measurements, correction factors and errors of less than 5 percent have generally been ignored and only two or three significant figures presented in the tables.

Aerosol scientists have long been aware of the need for a better basic understanding of the properties and behavior of aerosols among applied professionals. In writing this book, I have attempted to fill this need, as well as the long-standing need for a suitable text for students in these disciplines. The book evolved from class notes prepared during nine years of teaching a required one-semester course on aerosol technology for graduate students in the Department of Environmental Health Sciences at Harvard University School of Public Health.

Chapters are arranged in the order in which they are covered in class, starting with simple mechanics and progressing to more complicated subjects. Particle statistics is delayed until the student has a preliminary understanding of aerosol properties and can appreciate the need for the involved statistical characterization. Applications are discussed in each chapter after the principles have been presented. The more complicated applications, such as filtration and respiratory deposition, are
introduced as soon as the underlying principles have been covered. The operating principles of different types of aerosol measuring instruments are given in general terms so that one may correctly interpret data from them and explain the frequent differences in results between instruments. Discussion of specific instruments is limited because they change rapidly and are covered well in *Air Sampling Instruments*, 5th edition, ACGIH, Cincinnati, OH (1978). The latter (or any future edition) makes an excellent companion to this text. Several general references are given at the end of each chapter. Tables and graphs are provided in the appendix for general reference and for help in dealing with the problems at the end of each chapter.

While many people have contributed to this book, I would like to acknowledge particularly Klaus Willeke of the University of Cincinnati, who reviewed the manuscript and made many helpful suggestions; Kenneth Martin, who provided the SEM photos; and Laurie Cassel, who helped prepare and type the manuscript.

William C. Hinds

Boston, Massachusetts
February 1982
PREFACE TO THE SECOND EDITION

More than 16 years have passed since the first edition of *Aerosol Technology* was published in 1982. During this time the field of aerosol science and technology has expanded greatly, both in technology and in the number of scientists involved. When the first edition was published there were two national aerosol research associations, now there are 11 with regular national and international meetings. Growth areas include the use of aerosols in high-technology material processing and the administration of therapeutic drugs, and there is an increased awareness of bioaerosols, aerosol contamination in microelectronic manufacturing, and the effect of aerosols on global climate. While the first edition proved to be popular and useful, and became a standard textbook in the field, changes in technology and growth of the field have created the need to update and expand the book.

The objective of the book has remained the same: to provide a clear, understandable, and useful introduction to the science and technology of aerosols for environmental professionals, graduate students, and advanced undergraduates. In keeping with changes in the field, this edition uses dual units, with SI units as the primary...
### LIST OF PRINCIPAL SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>acceleration, particle radius</td>
</tr>
<tr>
<td>(a_c)</td>
<td>centrifugal acceleration, Eq. 3.15</td>
</tr>
<tr>
<td>(A)</td>
<td>area, cross-sectional area</td>
</tr>
<tr>
<td>(A_p)</td>
<td>cross-sectional area of a particle</td>
</tr>
<tr>
<td>(A_s)</td>
<td>surface area</td>
</tr>
<tr>
<td>(b)</td>
<td>coefficient for Hatch–Choate equation, Eq. 4.47</td>
</tr>
<tr>
<td>(B)</td>
<td>particle mobility, Eq. 3.16</td>
</tr>
<tr>
<td>(B_0)</td>
<td>luminance of an object, Eq. 16.26</td>
</tr>
<tr>
<td>(B')</td>
<td>luminance of background, Eq. 16.26</td>
</tr>
<tr>
<td>(c)</td>
<td>molecular velocity; velocity of light</td>
</tr>
<tr>
<td>(\bar{c})</td>
<td>mean molecular velocity, Eq. 2.22; mean thermal velocity of a particle, Eq. 7.10</td>
</tr>
<tr>
<td>(c_{\text{rms}})</td>
<td>root mean square molecular velocity, Eq. 2.18; root mean square thermal velocity of a particle, Eq. 7.9</td>
</tr>
<tr>
<td>(c_x, c_y, c_z)</td>
<td>velocity in the (x, y, z) directions</td>
</tr>
<tr>
<td>(C)</td>
<td>particle concentration in sampling probe</td>
</tr>
<tr>
<td>(C_i)</td>
<td>Cunningham correction factor, Eq. 3.19; slip correction factor, Eq. 3.20</td>
</tr>
<tr>
<td>(C_D)</td>
<td>drag coefficient, Eq. 3.4</td>
</tr>
<tr>
<td>(C_m)</td>
<td>mass concentration, mass of particles per unit volume of aerosol</td>
</tr>
<tr>
<td>CMD</td>
<td>count median diameter</td>
</tr>
<tr>
<td>(C_N)</td>
<td>number concentration, number of particles per unit volume of aerosol</td>
</tr>
<tr>
<td>(C_R)</td>
<td>apparent contrast, reduced contrast, Eqs. 16.27 and 16.33</td>
</tr>
<tr>
<td>(C_0)</td>
<td>true concentration, inherent contrast, Eq. 16.26</td>
</tr>
<tr>
<td>(C_{E_R})</td>
<td>collection efficiency for respirable precollector, Eq. 11.14</td>
</tr>
<tr>
<td>(C_{E_T})</td>
<td>collection efficiency for thoracic precollector, Eq. 11.18</td>
</tr>
<tr>
<td>(d)</td>
<td>particle diameter; derivative</td>
</tr>
<tr>
<td>(\bar{d})</td>
<td>arithmetic mean diameter, Eq. 4.11</td>
</tr>
<tr>
<td>(d^*)</td>
<td>Kelvin diameter, Eq. 13.5</td>
</tr>
<tr>
<td>(d_a)</td>
<td>aerodynamic diameter, Eq. 3.26</td>
</tr>
<tr>
<td>(d_A)</td>
<td>specified average diameter, Eq. 4.47</td>
</tr>
<tr>
<td>(d_c)</td>
<td>diameter of cylinder</td>
</tr>
<tr>
<td>(d_d)</td>
<td>droplet diameter</td>
</tr>
<tr>
<td>(d_e)</td>
<td>equivalent volume diameter, Eqs. 3.23 and 19.3</td>
</tr>
<tr>
<td>(d_f)</td>
<td>fiber diameter</td>
</tr>
<tr>
<td>(d_F)</td>
<td>Feret’s diameter, Fig. 20.1</td>
</tr>
<tr>
<td>(d_g)</td>
<td>geometric mean diameter, Eq. 4.14</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>$d_i$</td>
<td>midpoint diameter of the $i$th group</td>
</tr>
<tr>
<td>$d_m$</td>
<td>diameter of a gas molecule</td>
</tr>
<tr>
<td>$d_{\text{mm}}$</td>
<td>mass mean diameter, Eq. 4.26</td>
</tr>
<tr>
<td>$d_M$</td>
<td>Martin’s diameter, Fig. 20.1</td>
</tr>
<tr>
<td>$d_p$</td>
<td>particle diameter</td>
</tr>
<tr>
<td>$d_{\text{pp}}$</td>
<td>diameter of average property proportional to $d_p$, Eq. 4.22</td>
</tr>
<tr>
<td>$d_{PA}$</td>
<td>projected-area diameter, Fig. 20.1</td>
</tr>
<tr>
<td>$(d_{qm})_{\beta}$</td>
<td>$p$ moment average of the $q$th moment distribution, Eq. 4.36</td>
</tr>
<tr>
<td>$d_s$</td>
<td>Stokes diameter, Eq. 3.26</td>
</tr>
<tr>
<td>$d_t$</td>
<td>diameter average surface, Eq. 4.22</td>
</tr>
<tr>
<td>$d_{sm}$</td>
<td>surface mean diameter, Eqs. 4.27 and 4.31</td>
</tr>
<tr>
<td>$d_w$</td>
<td>tube diameter</td>
</tr>
<tr>
<td>$d_{50}$</td>
<td>particle diameter for 50% collection efficiency, Eqs. 5.28 and 19.1</td>
</tr>
<tr>
<td>$D$</td>
<td>particle diffusion coefficient, Eqs. 7.1 and 7.7</td>
</tr>
<tr>
<td>$D_{ba}$</td>
<td>diffusion coefficient of gas $b$ in air, Eq. 2.35</td>
</tr>
<tr>
<td>$D_F$</td>
<td>fractal dimension, Eq. 20.5</td>
</tr>
<tr>
<td>$D_j$</td>
<td>impactor jet diameter</td>
</tr>
<tr>
<td>$D_s$</td>
<td>sampling probe diameter</td>
</tr>
<tr>
<td>$D_v$</td>
<td>diffusion coefficient of vapor in air</td>
</tr>
<tr>
<td>$D_0$</td>
<td>duct diameter</td>
</tr>
<tr>
<td>$DF$</td>
<td>deposition fraction, total, Eq. 11.5</td>
</tr>
<tr>
<td>$DF_{\text{AL}}$</td>
<td>deposition fraction, alveolar, Eq. 11.4</td>
</tr>
<tr>
<td>$DF_{\text{HA}}$</td>
<td>deposition fraction, head airways, Eq. 11.1</td>
</tr>
<tr>
<td>$DF_{\text{TB}}$</td>
<td>deposition fraction, tracheobronchial, Eq. 11.3</td>
</tr>
<tr>
<td>$e$</td>
<td>charge of an electron; coefficient of restitution, Eq. 6.6; base for natural logarithms</td>
</tr>
<tr>
<td>$E$</td>
<td>efficiency; electrical field strength, Eqs. 15.6 and 15.10</td>
</tr>
<tr>
<td>$E_D$</td>
<td>overall filter efficiency, Eqs. 9.1 and 9.2</td>
</tr>
<tr>
<td>$E_{DF}$</td>
<td>single-fiber efficiency for diffusion, Eq. 9.27</td>
</tr>
<tr>
<td>$E_{DR}$</td>
<td>single-fiber efficiency for diffusion-interception interaction, Eq. 9.28</td>
</tr>
<tr>
<td>$E_G$</td>
<td>single-fiber efficiency for settling, Eq. 9.30</td>
</tr>
<tr>
<td>$E_I$</td>
<td>impacter efficiency, Eq. 5.27; single-fiber efficiency for impaction, Eq. 9.24</td>
</tr>
<tr>
<td>$E_L$</td>
<td>surface field limit, Eq. 15.28</td>
</tr>
<tr>
<td>$E_q$</td>
<td>single-fiber efficiency for electrostatic attraction, Eq. 9.32</td>
</tr>
<tr>
<td>$E_R$</td>
<td>single-fiber efficiency for interception, Eq. 9.21</td>
</tr>
<tr>
<td>$E_{\Sigma}$</td>
<td>total single-fiber efficiency, Eqs. 9.14 and 9.33</td>
</tr>
<tr>
<td>$f$</td>
<td>fraction; frequency; frequency of light, fraction of sites with colonies, Eq. 19.3</td>
</tr>
<tr>
<td>$f_{ab}$</td>
<td>fraction between sizes $a$ and $b$</td>
</tr>
<tr>
<td>$f(d_p)$</td>
<td>frequency function of particle size distribution, Eq. 4.4</td>
</tr>
<tr>
<td>$f_n$</td>
<td>fraction of particles having $n$ charges, Eqs. 15.30 and 15.31</td>
</tr>
</tbody>
</table>
LIST OF PRINCIPAL SYMBOLS

\[ F \] force

\[ F(a) \] cumulative frequency at \( a \), Eq. 4.8

\[ F(x) \] cumulative fraction at \( x \), Eq. 11.12

\[ F_{\text{adh}} \] force of adhesion, Eqs. 6.1-6.4

\[ F_D \] drag force, Eqs. 3.4 and 3.8

\[ F_E \] electrical force, Eq. 15.8

\[ F_f \] frictional force on a fluid element, Eq. 2.36

\[ F_G \] force of gravity, Eq. 3.11

\[ F_I \] inertial force on a fluid element, Eq. 2.39

\[ F_n \] form component of Stokes drag, Eq. 3.6

\[ F_{\text{th}} \] thermal force, Eqs. 8.1 and 8.4

\[ F_v \] volume fraction of spheres in liquid, Eq. 21.6

\[ F_t \] frictional component of Stokes drag, Eq. 3.7

\[ g \] acceleration of gravity

\[ G \] gravitational settling parameter, Eq. 9.29; ratio of cloud velocity to particle velocity, Eqs. 17.6 and 17.7

\[ \text{GSD} \] geometric standard deviation, \( \sigma_g \), Eq. 4.40

\[ h \] height; velocity head, Eq. 2.43

\[ H \] height of chamber; thermophoretic coefficient, Eq. 8.5; latent heat of evaporation of a liquid

\[ i_1 \] Mie intensity parameter for perpendicular component of scattered light, Eqs. 16.23 and 16.24

\[ i_2 \] Mie intensity parameter for parallel component of scattered light, Eqs. 16.23 and 16.25

\[ I \] number of intervals for grouped size data, Eq. 4.14; light intensity, Eq. 16.7

\[ I_0 \] incident light intensity, Eq. 16.7

\[ I_1(\theta) \] intensity of scattered light at angle \( \theta \), perpendicular polarization, Eq. 16.24

\[ I_2(\theta) \] intensity of scattered light at angle \( \theta \), parallel polarization, Eq. 16.25

\[ \text{IF} \] inhalable fraction, Eq. 11.7, 11.8

\[ \text{IF}_N \] inhalable fraction for nose breathing, Eq. 11.9

\[ J \] diffusion flux, Eqs. 2.30 and 7.1

\[ k \] Boltzmann’s constant

\[ k_v \] thermal conductivity of a gas or vapor

\[ K \] a constant; corrected coagulation coefficient, Eq. 12.13

\[ K_0 \] uncorrected coagulation coefficient, Eq. 12.9

\[ \bar{K} \] effective coagulation coefficient for polydisperse aerosols, Eq. 12.17

\[ K_E \] electrostatic constant of proportionality (SI units), Eq. 15.1 and Table 15.1

\[ \text{KE} \] kinetic energy

\[ \text{Kn} \] Knudsen number = \( 2\lambda/d_p \)

\[ \text{Ku} \] Kuwabara hydrodynamic factor, Eq. 9.22

\[ K_R \] Kelvin ratio, Eq. 13.5

\[ K_m \] Pressure rise index, Eq. 18.1
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{1,2}$</td>
<td>coagulation coefficient of particle size 1 with size 2, Eq. 12.16</td>
</tr>
<tr>
<td>$L$</td>
<td>length; length of fluid element, length of chamber, duct, or tube; path length of light beam, Eq. 16.7</td>
</tr>
<tr>
<td>$L_R$</td>
<td>limit of resolution, Eq. 20.9</td>
</tr>
<tr>
<td>$L_V$</td>
<td>visual range, Eq. 16.35</td>
</tr>
<tr>
<td>$m$</td>
<td>mass of molecule; mass of particle; index of refraction, Eq. 16.2</td>
</tr>
<tr>
<td>$m_r$</td>
<td>relative index of refraction, Eq. 16.5</td>
</tr>
<tr>
<td>$M$</td>
<td>molecular weight; total mass</td>
</tr>
<tr>
<td>MMD</td>
<td>mass median diameter</td>
</tr>
<tr>
<td>$n$</td>
<td>number of molecules per unit volume; number concentration; number of elementary charges</td>
</tr>
<tr>
<td>$n_A$</td>
<td>number concentration at $A$</td>
</tr>
<tr>
<td>$n_c$</td>
<td>rate of capture, Eq. 12.20; number of organisms collected, Eq. 19.3</td>
</tr>
<tr>
<td>$n_i$</td>
<td>number of particles in the $i$th group</td>
</tr>
<tr>
<td>$n_L$</td>
<td>charge limit, Eqs. 15.28 and 15.29</td>
</tr>
<tr>
<td>$n_m$</td>
<td>number of moles</td>
</tr>
<tr>
<td>$n(t)$</td>
<td>number of charges at time $t$, Eqs. 15.24, 15.25, and 15.33</td>
</tr>
<tr>
<td>$n_c$</td>
<td>rate of molecular collisions, Eq. 2.24</td>
</tr>
<tr>
<td>$n_0$</td>
<td>initial number concentration; initial number of charges</td>
</tr>
<tr>
<td>$N$</td>
<td>number of molecules; total number of particles in sample; particle number concentration</td>
</tr>
<tr>
<td>$N_A$</td>
<td>Avogadro's number</td>
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<tr>
<td>NA</td>
<td>numerical aperture, Eq. 20.8</td>
</tr>
<tr>
<td>$N_i$</td>
<td>ion concentration</td>
</tr>
<tr>
<td>$N(t)$</td>
<td>particle number concentration at time $t$, Eq. 12.12</td>
</tr>
<tr>
<td>$N_0$</td>
<td>particle number concentration at time zero</td>
</tr>
<tr>
<td>$p$</td>
<td>pressure; partial pressure</td>
</tr>
<tr>
<td>$p_A$</td>
<td>partial pressure of component $A$, Eq. 13.1</td>
</tr>
<tr>
<td>$p_d$</td>
<td>partial pressure of vapor at droplet surface, Eq. 13.5</td>
</tr>
<tr>
<td>$p_s$</td>
<td>saturation vapor pressure, Eq. 13.2</td>
</tr>
<tr>
<td>$p_T$</td>
<td>total pressure</td>
</tr>
<tr>
<td>$p_v$</td>
<td>velocity pressure, Eqs. 2.43 and 2.44</td>
</tr>
<tr>
<td>$p_{\infty}$</td>
<td>partial pressure of vapor away from droplet</td>
</tr>
<tr>
<td>$P$</td>
<td>pressure, perimeter</td>
</tr>
<tr>
<td>$P$</td>
<td>penetration, overall filter penetration, Eqs. 9.3 and 9.4</td>
</tr>
<tr>
<td>Pe</td>
<td>Peclet number, Eq. 9.26</td>
</tr>
<tr>
<td>PF</td>
<td>PM-10 fraction, Eq. 11.19</td>
</tr>
<tr>
<td>$P(n)$</td>
<td>probability of $n$ solid spheres in a droplet, Eq. 21.5</td>
</tr>
<tr>
<td>$q$</td>
<td>amount of charge; amount of charge on a particle, Eq. 15.2; weighting parameter for moment distributions</td>
</tr>
<tr>
<td>$q_F$</td>
<td>filter quality, Eq. 9.12</td>
</tr>
<tr>
<td>$q_{MD}$</td>
<td>median of the qth moment distribution, Eq. 4.48</td>
</tr>
<tr>
<td>$Q$</td>
<td>flow rate</td>
</tr>
<tr>
<td>$Q_a$</td>
<td>absorption efficiency, Eq. 16.10</td>
</tr>
<tr>
<td>$Q_e$</td>
<td>extinction efficiency, Eq. 16.8</td>
</tr>
</tbody>
</table>
LIST OF PRINCIPAL SYMBOLS

\( Q_s \) sample flow rate; scattering efficiency, Eq. 16.10
\( Q_0 \) duct flow rate
\( r \) radial position
\( R \) gas constant, Eq. 2.1; radius; interception parameter, Eq. 9.20;
separation distance of electric charges, Eq. 15.2
\( \text{Re} \) Reynolds number, particle or flow, Eq. 2.41
\( \text{Re}_f \) fiber Reynolds number, Eq. 9.13
\( \text{Re}_0 \) initial Reynolds number, Eq. 5.21
\( \text{RF} \) respirable fraction, Eq. 11.10
\( S \) stopping distance, Eq. 5.19
\( S_R \) saturation ratio, Eq. 13.3
\( \text{SMD} \) surface median diameter
\( \text{Stk} \) Stokes number, Eqs. 5.23 and 5.24
\( \text{Stk}_{50} \) Stokes number for 50% collection efficiency, Eq. 5.28
\( t \) time; thickness of filter
\( T \) temperature
\( T_d \) temperature at droplet surface
\( \text{TF} \) thoracic fraction, Eq. 11.15
\( T_x \) temperature away from droplet
\( U \) velocity; gas velocity; gas velocity inside filter, Eq. 9.6; gas velocity in
sampling probe
\( \bar{U} \) average velocity in duct
\( U_0 \) face velocity of filter; free-stream velocity
\( v \) gas volume
\( v_d \) droplet volume
\( v_p \) particle volume
\( v_m \) volume of a molecule, Eq. 13.9
\( v_1, v_2 \) volume of gas or vapor at state 1 or 2
\( V \) velocity of particle; relative velocity between particle and gas
\( V_c \) critical velocity for bounce, Eq. 6.5; cloud velocity, Eq. 17.4
\( V_{\text{dep}} \) deposition velocity, Eq. 7.27
\( V_f \) final velocity
\( \text{VMD} \) volume median diameter
\( V_r \) gas velocity in the \( r \) direction, Eq. 3.41
\( V(t) \) particle velocity at time \( t \), Eq. 5.15
\( V_{\text{th}} \) thermophoretic velocity, Eqs. 8.2 and 8.6
\( V_T \) tangential velocity, Eq. 3.15
\( V_{\text{TC}} \) terminal centrifugal velocity, Eq. 3.14
\( V_{\text{TE}} \) terminal electrical velocity, Eq. 15.15
\( V_{\text{TF}} \) terminal velocity for constant external force \( F \), Eq. 5.5
\( V_{\text{TS}} \) terminal settling velocity, Eqs. 3.13 and 3.21
\( \bar{V}_r \) average velocity in the \( r \)-direction, Eq. 3.37
\( V_0 \) initial velocity; velocity at time zero
\( V_\infty \) gas velocity far away from particle or fiber
\( V_\theta \) gas velocity in the \( \theta \) direction, Eq. 3.42
\( W \) width of slot; voltage
LIST OF PRINCIPAL SYMBOLS

\(x\) separation distance; distance from wall
\(\bar{x}\) average number of spheres per droplet, Eq. 21.6
\(\bar{x}_{\text{MMD}}\) average number of spheres in an MMD-sized droplet, Eq. 21.7
\(x_{\text{rms}}\) rms displacement of particle, Eq. 7.18;
\(x(t)\) position of particle at time \(t\), Eq. 5.18
\(y\) vertical distance
\(z\) number of molecular collisions per unit area, Eq. 2.15
\(Z\) electrical mobility, Eq. 15.21
\(Z_i\) ion mobility
\(\alpha\) volume fraction of fibers in a filter, solidity, Eq. 9.7; size parameter for light scattering, Eq. 16.6
\(\alpha_v\) volume shape factor, Eq. 20.2
\(\beta\) correction factor for coagulation coefficient, Eq. 12.13
\(\gamma\) surface tension; fraction captured per unit thickness of filter, Eqs. 9.11 and 9.19
\(\Gamma\) velocity gradient
\(\delta\) diffusion boundary-layer thickness, Eq. 7.30
\(\partial\) partial derivative
\(\Delta d\) diameter interval
\(\Delta p\) pressure drop, pressure differential, Eqs. 2.47, 2.52, and 9.36
\(\nabla T\) temperature gradient
\(\varepsilon\) relative permittivity (dielectric constant); threshold of brightness contrast, Eq. 16.34
\(\varepsilon_0\) permittivity of vacuum, Eq. 15.2
\(\eta\) viscosity, Eq. 2.26
\(\Theta\) angle between flow direction and sampling probe
\(\theta\) scattering angle
\(\lambda\) gas mean free path, Eq. 2.25; wavelength of light; step size, Eq. 20.5
\(\lambda_p\) particle mean free path, Eq. 7.11
\(\mu\) deposition parameter for diffusion loss in tubes, Eqs. 7.28 and 7.33
\(\rho\) density of gas; density of particle
\(\rho_b\) density of bulk material
\(\rho_c\) density of cloud, Eq. 17.2
\(\rho_g\) density of gas
\(\rho_L\) density of liquid
\(\rho_p\) density of particle
\(\rho_0\) standard density, 1000 kg/m\(^3\) [1.0 g/cm\(^3\)]
\(\sigma\) standard deviation, Eq. 4.38
\(\sigma_a\) absorption coefficient, Eq. 16.11
\(\sigma_e\) extinction coefficient, Eq. 16.7
\(\sigma_g\) geometric standard deviation, GSD, Eq. 4.40
\(\sigma_s\) scattering coefficient, Eq. 16.11
\(\tau\) relaxation time, Eq. 5.3
\(\phi\) bend angle, Eq. 10.17; Fuchs-effect correction factor, Eq. 13.16
\(\chi\) dynamic shape factor, Eq. 3.23
\(\omega\) angular frequency, rotational velocity
Introduction

The microscopic particles that float in the air are of many kinds: resuspended soil particles, smoke from power generation, photochemically formed particles, salt particles formed from ocean spray, and atmospheric clouds of water droplets or ice particles. They vary greatly in their ability to affect not only visibility and climate, but also our health and quality of life. These airborne particles are all examples of aerosols. An aerosol is defined in its simplest form as a collection of solid or liquid particles suspended in a gas. Aerosols are two-phase systems, consisting of the particles and the gas in which they are suspended. They include a wide range of phenomena such as dust, fume, smoke, mist, fog, haze, clouds, and smog. The word aerosol was coined about 1920 as an analog to the term hydrosol, a stable liquid suspension of solid particles. Aerosols are also referred to as suspended particulate matter, aerocolloidal systems, and disperse systems. Although the word aerosol is popularly used to refer to pressurized spray-can products, it is the universally accepted scientific term for particulate suspensions in a gaseous medium and is used in that sense in this book.

Aerosols are but one of the several types of particulate suspensions listed in Table 1.1. All are two-component systems having special properties that depend on size of the particles and their concentration in the suspending medium. All have varying degrees of stability that also depend on particle size and concentration.

An understanding of the properties of aerosols is of great practical importance. It enables us to comprehend the process of cloud formation in the atmosphere, a key link in the hydrological cycle. Aerosol properties influence the production, transport, and ultimate fate of atmospheric particulate pollutants. Measurement and control of particulate pollutants in the occupational and general environments require the application of this knowledge. Aerosol technology has commercial application in the manufacture of spray-dried products, fiber optics, and carbon black; the production of pigments; and the application of pesticides. Because the toxicity of inhaled particles depends on their physical as well as their chemical properties, an understanding of the properties of aerosols is required to evaluate airborne particulate hazards. The same knowledge is used in the administration of therapeutic aerosols for the treatment of respiratory and other diseases.

Aerosol technology is the study of the properties, behavior, and physical principles of aerosols and the application of this knowledge to their measurement and control. The particulate phase of an aerosol represents only a very small fraction of its total mass and volume, less than 0.0001%. Bulk properties of aerosols, such as viscosity and density, differ imperceptibly from those of pure air. Consequently, to study the properties of aerosols, one must adopt a microscopic point of view. This
INTRODUCTION

<table>
<thead>
<tr>
<th>Suspending Medium</th>
<th>Type of Suspended Particles</th>
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<tr>
<td></td>
<td>Gas</td>
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<tr>
<td>Gas</td>
<td></td>
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<tr>
<td>Liquid</td>
<td>Foam</td>
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<tr>
<td>Solid</td>
<td>Sponge</td>
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reduces the problem of understanding the complex properties of aerosols to that of understanding the properties of individual particles. The microscopic approach considers one particle at a time and deals with questions about the forces on that particle, its motion, and its interaction with the suspending gas, with electromagnetic radiation, and with other particles.

At the beginning of the 20th century, the study of aerosols was at the forefront of physical science because aerosols represented the smallest observable division of matter. Aerosol science contributed to the early understanding of Brownian motion and diffusion, Millikan’s measurement of the charge on the electron, and Wilson’s cloud chamber experiments for the study of ionizing radiation. This classical period of aerosol science research continued through the first half of the century, concluding with the publication of The Mechanics of Aerosols by Fuchs in 1955. Following World War II, and particularly during the 1970s and 1980s, aerosol technology grew in importance because of an increased environmental awareness and a concern for the health effects arising from air pollution in community and occupational environments. The field expanded rapidly in the 1980s to include the use of aerosols in high-technology production processes and a concern for aerosol contamination in the semiconductor industry (clean technology). The decade of the 1990s has seen increased research on the properties of ultrafine particles (<0.1 μm) and on the effect of aerosols on global climate. Aerosol technology has become an important tool in understanding the effect we have on our environment and the impact of that environment on us.

Any subject that touches upon such diverse phenomena as sunsets, silicosis, rain, cascade impactors, global climate change, cross pollination, electrostatic precipitation, and rainbows is not a simple one. Aerosol technology draws on physics, chemistry, physical chemistry, and engineering. It uses some tools, concepts, and terminology of powder technology. It is used in the fields of occupational hygiene, air pollution control, inhalation toxicology, atmospheric physics and chemistry, and radiological health.

A dual system of units is used in this book, with the primary system being the International System of Units (SI units, or meter-kilogram-second units). Because of a tradition of using cgs (centimeter-gram-second) units in this field, especially in the United States, cgs units are included in square brackets, and some equations and most examples are presented both ways.

Figures 1.1—1.5 show sources of aerosols paired with microscope photographs of the particles produced. They illustrate the range of aerosol-producing activities and the complex nature of the resulting particles.
Aerosols can be subdivided according to the physical form of the particles and their method of generation. There is no strict scientific classification of aerosols. The following definitions correspond roughly to common usage and are precise enough for most scientific description.

**Aerosol** A suspension of solid or liquid particles in a gas. Aerosols are usually stable for at least a few seconds and in some cases may last a year or more. The
term aerosol includes both the particles and the suspending gas, which is usually air. Particle size ranges from about 0.002 to more than 100 μm.

Bioaerosol An aerosol of biological origin. Bioaerosols include viruses, viable organisms, such as bacteria and fungi, and products of organisms, such as fungal spores and pollen.

Cloud A visible aerosol with defined boundaries.

Dust A solid-particle aerosol formed by mechanical disintegration of a parent material, such as by crushing or grinding. Particles range in size from submicrometer to more than 100 μm and are usually irregular.
DEFINITIONS

Fume  A solid-particle aerosol produced by the condensation of vapors or gaseous combustion products. These submicrometer particles are often clusters or chains of primary particles. The latter are usually less than 0.05 μm. Note that this definition differs from the popular use of the term to refer to any noxious contaminant in the atmosphere.

Haze  An atmospheric aerosol that affects visibility.

Mist and Fog  Liquid-particle aerosols formed by condensation or atomization. Particles are spherical with sizes ranging from submicrometer to about 200 μm.

Smog  1. A general term for visible atmospheric pollution in certain areas. The term was originally derived from the words smoke and fog. 2. Photochemical smog is a more precise term referring to an aerosol formed in the atmosphere by the action of sunlight on hydrocarbons and oxides of nitrogen. Particles are generally less than 1 or 2 μm.

FIGURE 1.3  (a) Arc welding. (b) SEM photograph of iron-oxide particles. Magnification 2300x.
Smoke  A visible aerosol resulting from incomplete combustion. Particles may be
solid or liquid, are usually less than 1 μm in diameter, and may be agglomerated like fume particles.

Spray  A droplet aerosol formed by the mechanical breakup of a liquid. Particles
are larger than a few micrometers.

In this book the preceding distinctions are usually not necessary, and the general term *aerosol* is used. Liquid particles are referred to as *droplets*. The term *par-
ticulate matter refers to either solid particles or liquid droplets. A primary aerosol has particles that are introduced directly into the atmosphere, whereas a secondary aerosol has particles that are formed in the atmosphere by chemical reactions of gaseous components (gas-to-particle conversion). A homogenous aerosol is an aerosol in which all particles are chemically identical. Monodisperse aerosols have particles that are all the same size and can be produced in the laboratory for use as test aerosols. Most aerosols are polydisperse, with a wide range of particle sizes, and statistical measures should be used to characterize their particle size.

In this text, standard conditions are defined as a temperature of 293 K [20°C] and an atmospheric pressure of 101 kPa (1Pa = 1N/m²) [760 mm Hg].

1.2 PARTICLE SIZE, SHAPE, AND DENSITY

Particle size is the most important parameter for characterizing the behavior of aerosols. All properties of aerosols depend on particle size, some very strongly. Furthermore, most aerosols cover a wide range of sizes; a hundredfold range between the smallest and largest particles of an aerosol is common. Not only do aerosol properties depend on particle size, but the nature of the laws governing these properties may change with particle size. This emphasizes the need to adopt a microscopic approach and characterize properties on an individual particle basis. Average properties can then be estimated by integrating over the size distribution. An appreciation of how aerosol properties vary with particle size is fundamental to an understanding of their properties.

The “yardstick” for particle size is the micrometer (μm) or its older equivalent, the micron (μ), which is 10^-6 m, 10^-4 cm, or 10^-3 mm. The micron is no longer acceptable as an SI unit. Particle size can refer to particle radius, but in this book it refers to particle diameter. For consistency it is expressed in micrometers for all particle sizes, even though nm is more appropriate for particles less than 0.1 μm. Particle diameter is given the symbol d or, where confusion with other symbols might arise, the symbol dp. It is customary to refer to particle size in micrometers, but calculations require converting micrometers to meters (SI units) by multiplying by 10^-6 or to centimeters (cgs units) by multiplying by 10^-4.

Figure 1.6 shows size ranges for aerosols and other phenomena. A major dividing line is 1 μm, which marks the upper limit of the submicrometer range (less than 1.0 μm) and the lower limit of the micrometer size range (1-10 nm). Figure 1.6 covers a size range of 10^7, from gas molecules to millimeter-sized particles. The particle sizes of the aerosols shown in the figure range from 0.01 to 100 μm, the size range addressed in this book. In general, dusts, ground material, and pollen are in the micrometer range or larger, and fumes and smokes are submicrometer. The smallest aerosol particles approach the size of large gas molecules and have many of their properties. Ultrafine particles cover the range from large gas molecules to about 100 nm (0.001 to 0.1 μm). Particles less than 50 nm are called nanometer particles or nanoparticles. Particles greater than 10 μm have limited stability in the atmosphere, but still can be an important source of occupational exposure because