Aerosol Technology: Properties, Behavior, & Measurement of Airborne Particles 2nd Ed

Aerosol Technology

Properties, Behavior, and Measurement of Airborne Particles

Second Edition

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A WILEY-INTERSCIENCE PUBLICATION
JOHN WILEY & SONS, INC.
NEW YORK / CHICHESTER / WEINHEIM / BRISBANE / SINGAPORE / TORONTO

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Published simultaneously in Canada.

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Library of Congress Cataloging-in-Publication Data

Hinds, William C.
Aerosol technology : properties, behavior, and measurement of airborne particles / William C. Hinds. —2nd ed.
p. cm.
"A Wiley-Interscience publication."
Includes bibliographical references and index.
ISBN 0-471-19410-7 (cloth : alk. paper)
1. Aerosols. 2. Aerosols—Measurement. I. Title.
QC882.42.H56 1998 98-23683
648.5'3—dc21

Printed in the United States of America.
10 9 8 7 6 5 4 3 2 1

Aerosol Technology

PREFACE TO THE FIRST EDITION

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

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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 units and cgs units as secondary units. Besides updating and revising old material, I have added a new chapter on bioaerosols and new sections on resuspension, transport losses, respiratory deposition models, and fractal characterization of particles. The chapter on atmospheric aerosols has been expanded to include sections on background aerosols, urban aerosols, and global effects. There are 26 new examples and 30 new problems. The latest edition of *Air Sampling Instruments* remains an excellent companion book, as does *Aerosol Measurement*, by Willeke and Baron. Both provide greater depth and detail on measurement methods and instruments.

Of the many people who have helped with this edition, I would like to particularly acknowledge Janet Macher, Robert Phelan, and John Valiulis for reviewing specific chapters; Rachel Kim and Vi Huynh for typing manuscript changes; doctoral student Nani Kadrichu for entering the equations; and finally, my wife Lynda for her continued support during this long process.

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LIST OF PRINCIPAL SYMBOLS

a	acceleration, particle radius
a_c	centrifugal acceleration, Eq. 3.15
A	area, cross-sectional area
A_p	cross-sectional area of a particle
A_s	surface area
b	coefficient for Hatch–Choate equation, Eq. 4.47
B	particle mobility, Eq. 3.16
B_0	luminance of an object, Eq. 16.26
B'	luminance of background, Eq. 16.26
c	molecular velocity; velocity of light
$\bar{c}$	mean molecular velocity, Eq. 2.22; mean thermal velocity of a particle, Eq. 7.10
c_{rms}	root mean square molecular velocity, Eq. 2.18; root mean square thermal velocity of a particle, Eq. 7.9
c_x, c_y, c_z	velocity in the x, y, z directions
C	particle concentration in sampling probe
C_c	Cunningham correction factor, Eq. 3.19; slip correction factor, Eq. 3.20
C_D	drag coefficient, Eq. 3.4
C_m	mass concentration, mass of particles per unit volume of aerosol
CMD	count median diameter
C_N	number concentration, number of particles per unit volume of aerosol
C_R	apparent contrast, reduced contrast, Eqs. 16.27 and 16.33
C_0	true concentration, inherent contrast, Eq. 16.26
CE_R	collection efficiency for respirable precollector, Eq. 11.14
CE_T	collection efficiency for thoracic precollector, Eq. 11.18
d	particle diameter; derivative
$\bar{d}$	arithmetic mean diameter, Eq. 4.11
d^*	Kelvin diameter, Eq. 13.5
d_a	aerodynamic diameter, Eq. 3.26
d_A	specified average diameter, Eq. 4.47
d_c	diameter of cylinder
d_d	droplet diameter
d_e	equivalent volume diameter, Eqs. 3.23 and 19.3
d_f	fiber diameter
d_F	Feret's diameter, Fig. 20.1
d_g	geometric mean diameter, Eq. 4.14

d_i	midpoint diameter of the *i*th group
d_m	diameter of a gas molecule
$d_{\bar{m}}$	diameter of average mass, Eq. 4.19
d_{mm}	mass mean diameter, Eq. 4.26
d_M	Martin's diameter, Fig. 20.1
d_p	particle diameter
$d_{\bar{p}}$	diameter of average property proportional to d^p, Eq. 4.22
d_{PA}	projected-area diameter, Fig. 20.1
$(d_{qm})_{\bar{p}}$	p moment average of the qth moment distribution, Eq. 4.36
d_s	Stokes diameter, Eq. 3.26
$d_{\bar{s}}$	diameter average surface, Eq. 4.22
d_{sm}	surface mean diameter, Eqs. 4.27 and 4.31
d_t	tube diameter
$d_{\bar{v}}$	diameter of average volume, Eq. 4.22
d_w	wire diameter
d_{50}	particle diameter for 50% collection efficiency, Eqs. 5.28 and 19.1
D	particle diffusion coefficient, Eqs. 7.1 and 7.7
D_{ba}	diffusion coefficient of gas b in air, Eq. 2.35
D_F	fractal dimension, Eq. 20.5
D_j	impactor jet diameter
D_s	sampling probe diameter
D_v	diffusion coefficient of vapor in air
D_0	duct diameter
DF	deposition fraction, total, Eq. 11.5
DF_{AL}	deposition fraction, alveolar, Eq. 11.4
DF_{HA}	deposition fraction, head airways, Eq. 11.1
DF_{TB}	deposition fraction, tracheobronchial, Eq. 11.3
e	charge of an electron; coefficient of restitution, Eq. 6.6; base for natural logarithms
E	efficiency; electrical field strength, Eqs. 15.6 and 15.10
E	overall filter efficiency, Eqs. 9.1 and 9.2
E_D	single-fiber efficiency for diffusion, Eq. 9.27
E_{DR}	single-fiber efficiency for diffusion-interception interaction, Eq. 9.28
E_G	single-fiber efficiency for settling, Eq. 9.30
E_I	impactor efficiency, Eq. 5.27; single-fiber efficiency for impaction, Eq. 9.24
E_L	surface field limit, Eq. 15.28
E_q	single-fiber efficiency for electrostatic attraction, Eq. 9.32
E_R	single-fiber efficiency for interception, Eq. 9.21
E_Σ	total single-fiber efficiency, Eqs. 9.14 and 9.33
f	fraction; frequency; frequency of light, fraction of sites with colonies, Eq. 19.3
f_{ab}	fraction between sizes a and b
$f(d_p)$	frequency function of particle size distribution, Eq. 4.4
f_n	fraction of particles having n charges, Eqs. 15.30 and 15.31

F	force
$F(a)$	cumulative frequency at a, Eq. 4.8
$F(x)$	cumulative fraction at x, Eq. 11.12
F_{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_{th}	thermal force, Eqs. 8.1 and 8.4
F_v	volume fraction of spheres in liquid, Eq. 21.6
F_τ	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
GSD	geometric standard deviation, σ_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 θ, perpendicular polarization, Eq. 16.24
$I_2(\theta)$	intensity of scattered light at angle θ, parallel polarization, Eq. 16.25
IF	inhalable fraction, Eq. 11.7, 11.8
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
$\overline{K}$	effective coagulation coefficient for polydisperse aerosols, Eq. 12.17
K_E	electrostatic constant of proportionality (SI units), Eq. 15.1 and Table 15.1
KE	kinetic energy
Kn	Knudsen number = $2\lambda/d_p$
Ku	Kuwabara hydrodynamic factor, Eq. 9.22
K_R	Kelvin ratio, Eq. 13.5
K_{st}	Pressure rise index, Eq. 18.1

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

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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
Re	Reynolds number, particle or flow, Eq. 2.41
Re_f	fiber Reynolds number, Eq. 9.13
Re_0	initial Reynolds number, Eq. 5.21
RF	respirable fraction, Eq. 11.10
S	stopping distance, Eq. 5.19
S_R	saturation ratio, Eq. 13.3
SMD	surface median diameter
Stk	Stokes number, Eqs. 5.23 and 5.24
Stk_{50}	Stokes number for 50% collection efficiency, Eq. 5.28
t	time; thickness of filter
T	temperature
T_d	temperature at droplet surface
TF	thoracic fraction, Eq. 11.15
T_∞	temperature away from droplet
U	velocity; gas velocity; gas velocity inside filter, Eq. 9.6; gas velocity in sampling probe
$\overline{U}$	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_{dep}	deposition velocity, Eq. 7.27
V_f	final velocity
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_{th}	thermophoretic velocity, Eqs. 8.2 and 8.6
V_T	tangential velocity, Eq. 3.15
V_{TC}	terminal centrifugal velocity, Eq. 3.14
V_{TE}	terminal electrical velocity, Eq. 15.15
V_{TF}	terminal velocity for constant external force F, Eq. 5.5
V_{TS}	terminal settling velocity, Eqs. 3.13 and 3.21
$\overline{V}_x$	average velocity in the x-direction, Eq. 3.37
V_0	initial velocity; velocity at time zero
V_∞	gas velocity far away from particle or fiber
V_θ	gas velocity in the θ direction, Eq. 3.42
W	width of slot; voltage

x	separation distance; distance from wall
$\bar{x}$	average number of spheres per droplet, Eq. 21.6
$\bar{x}_{MMD}$	average number of spheres in an MMD-sized droplet, Eq. 21.7
x_{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
α	volume fraction of fibers in a filter, solidity, Eq. 9.7; size parameter for light scattering, Eq. 16.6
α_v	volume shape factor, Eq. 20.2
β	correction factor for coagulation coefficient, Eq. 12.13
γ	surface tension; fraction captured per unit thickness of filter, Eqs. 9.11 and 9.19
Γ	velocity gradient
δ	diffusion boundary-layer thickness, Eq. 7.30
∂	partial derivative
Δd	diameter interval
Δp	pressure drop, pressure differential, Eqs. 2.47, 2.52, and 9.36
∇T	temperature gradient
ε	relative permittivity (dielectric constant); threshold of brightness contrast, Eq. 16.34
ϵ_0	permittivity of vacuum, Eq. 15.2
η	viscosity, Eq. 2.26
Θ	angle between flow direction and sampling probe
θ	scattering angle
λ	gas mean free path, Eq. 2.25; wavelength of light; step size, Eq. 20.5
λ_p	particle mean free path, Eq. 7.11
μ	deposition parameter for diffusion loss in tubes, Eqs. 7.28 and 7.33
ρ	density of gas; density of particle
ρ_b	density of bulk material
ρ_c	density of cloud, Eq. 17.2
ρ_g	density of gas
ρ_L	density of liquid
ρ_p	density of particle
ρ_0	standard density, 1000 kg/m^3 [1.0 g/cm^3]
σ	standard deviation, Eq. 4.38
σ_a	absorption coefficient, Eq. 16.11
σ_e	extinction coefficient, Eq. 16.7
σ_g	geometric standard deviation, GSD, Eq. 4.40
σ_s	scattering coefficient, Eq. 16.11
τ	relaxation time, Eq. 5.3
ϕ	bend angle, Eq. 10.17; Fuchs-effect correction factor, Eq. 13.16
χ	dynamic shape factor, Eq. 3.23
ω	angular frequency, rotational velocity

CONTENTS

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