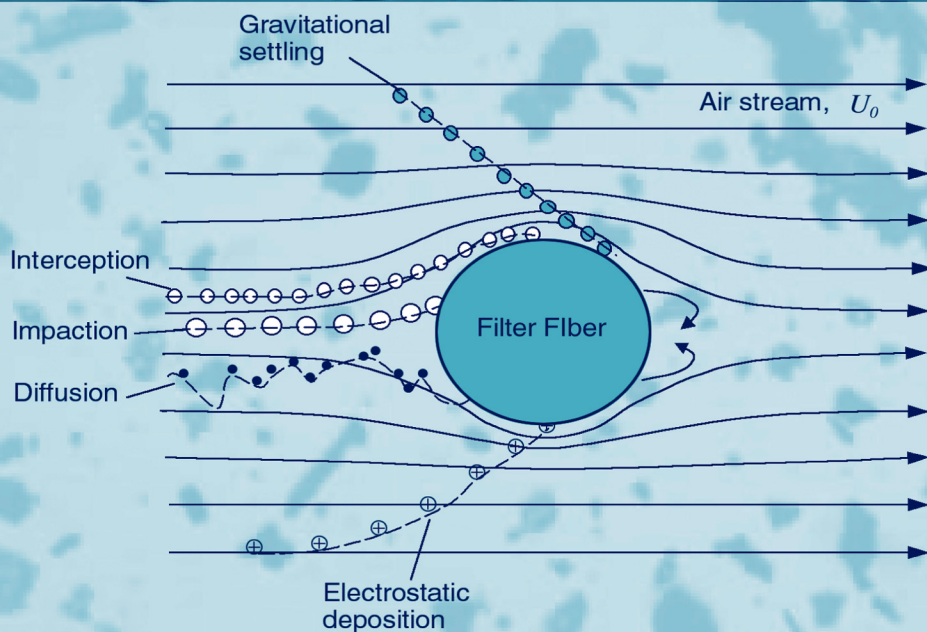


INDOOR AIR QUALITY ENGINEERING



Yuanhui Zhang



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Preface

Airborne pollutants are present all the time and everywhere in the form of gases, odors, and particulate matter. These pollutants have an increasing influence on our daily life. In developed countries, an average working person spends over 90% of his or her lifetime indoors. Growing concerns about indoor air quality (IAQ) and apparently increasing incidences of IAQ-related illness in people has inspired many efforts in this area from industry, academia, the general public, and government agencies.

During my 10 years of teaching about indoor air pollutant measurement and control for a senior and graduate-level engineering class, one of the difficulties that I encountered was finding a suitable textbook. Although there is a considerable amount of literature on the topic and several books cover related topics (such as aerosol science and technology, industrial ventilation, and pollutant measurement instrumentation), there has been a need for a comprehensive textbook to cover the principles and applications of indoor air quality engineering. This book is intended to fill that need. Although this book is primarily written for engineering students and professionals, its principles and approach can be useful to individuals in industrial hygiene, environmental sciences, and public health who are engaged in the measurement and abatement of indoor air quality problems.

This book is an accumulation of my lecture notes. Its aim is to explain the principles in a direct way so that a reader can study them independently. An instructor using this book as a textbook may tailor the contents according to the designated credit hours. The 15 chapters can be divided into three modules:

- Airborne pollutant properties and behavior
- Measurement and sampling efficiency
- Air-cleaning engineering

The first module includes Chapter 1 through Chapter 6 and discusses the properties and mechanics of airborne pollutants, including gases and particulate matter. Properties include physical, chemical, and biological aspects of particulate and gaseous pollutants. Behavior includes particle mechanics, gas kinetics, diffusion, and transportation of pollutants. This module provides the science and is fundamental to identifying and analyzing problems of indoor air quality.

The second module, on measurement and sampling efficiency, includes Chapter 7 through Chapter 9. This module discusses airborne pollutant measurements, including particle impaction, gravitational settling, collection of pollutants by means of diffusion, particle sampling efficiency, and particle production rate in a ventilated airspace. It provides the tools for readers to collect air quality data, analyze a problem, and get ready for engineering solutions.

The third module consists of Chapter 10 through Chapter 15, which discuss IAQ control technologies. Air-cleaning technologies covered in this module include filtration, aerodynamic air cleaning, electrostatic precipitation, wet scrubbing, adsorption, and ventilation effectiveness. This module provides typical methods and technologies to solve IAQ problems.

For those who may choose this book as a textbook, I would like to share my own experience in using this material in my class. On average, one week's course load (typically 3 lecture hours and a 1- to 2-hour laboratory exercise) corresponds to one chapter. Homework is given on a weekly basis. Depending on the availability of equipment, laboratory exercises can be based on chapters or can be arranged according to modules. Four laboratory topics and reports are required in my class:

- Airborne pollutant size distribution and particle statistics
- Concentration measurement and particle mechanics
- Sampling efficiency
- Air-cleaning technologies

In addition, the class is divided into several teams to work on different class projects. Many students have brought their own real-world projects into the class. For example, one team evaluated several types of commercial air cleaners from superstores and made suggestions for improvement.

Although many people have contributed to this book, I am particularly eager to acknowledge the following individuals. Professor Ernest M. Barber, my mentor and friend, inspired me to get into air-quality research and encouraged me to continue. I am especially thankful to Dr. Zhongchao Tan for his tireless efforts on the solutions for this book. He solved and edited all working problems while he was a graduate teaching assistant for this class at the University of Illinois. Dr. Yigang Sun contributed two sections and provided invaluable comments. I am grateful to my former graduate TAs (now professors) Xinlei Wang, Brian He, and Joshua W. McClure, and to the students in my classes over the years, for their comments, critiques, and editorials on the manuscript. There are still inevitable errors, and I am sure that this debugging process will continue after publication. I thank Megan Teague, Malia Appleford and Simon Appleford for their comments and editorial assistance. Finally, I completed this book without spending a sabbatical leave, but the writing occupied many family hours. Thus, I am indebted to my wife, Yanhui Mao, who is a mechanical engineer — enjoying her own work and understanding mine — and to our four-year old son, Matthew, who visited my office so often that he eventually referred to my office as his office and to my office building as “the coolest building in the world.” It was nice that I did not really consider this project as work, because I enjoyed it so much. It was a wonderful learning experience.

And I hope that you will enjoy reading it.

Yuanhui Zhang

The Author

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Nomenclature

Symbol	Description	Dimension
A	Area	m^2
A_c	Collision area of particles	m^2
A_w	Wetted area	m^2
B	Mechanical mobility	$m \cdot N^{-1} s^{-1}$
B_E	Electrical mobility	$m^2 \cdot V^{-1} s^{-1}$
B_{Ei}	Electrical mobility of ions; for air ions, $B_{Ei} = 1.5 \times 10^{-4} m^2/V \cdot s$	$m^2 \cdot V^{-1} s^{-1}$
B_f	Solidity factor	
B_h	Hydrodynamic factor for particle diffusion	
B_i	Particle interception factor	
C	Concentration	
C_c	Slip correction factor for particles	
C_{ca}	Slip correction factor for aerodynamic diameter	
C_{ce}	Slip correction factor for equivalent volume diameter	
C_D	Drag coefficient	
C_e	Equilibrium concentration on the surface of the solid phase	$mg \cdot m^{-3}$
C_{gm}	Concentration of gas in mass	ppmm, $mg \cdot kg^{-1}$
C_{gn}	Concentration of gas in molecules per unit volume	$molecule \cdot m^{-3}$
C_{gn0}	Initial concentration of gas at the diffusion interface	$molecule \cdot m^{-3}$
C_{gv}	Concentration of gas in volume	ppmv, $ml \cdot m^{-3}$
C_i	Concentration of ions	$ion \cdot m^{-3}$
C_{i0}	Undisturbed ion concentration	$ion \cdot m^{-3}$
C_{NC}	Normalized air contaminant concentration	
C_p	Concentration of particles	
C_{pm}	Concentration of particles in mass	$mg \cdot m^{-3}$
C_{pn}	Concentration of particles in number	$particles \cdot m^{-3}$
C_{pn0}	Initial concentration of particles in number	$particles \cdot m^{-3}$
C_r	Pollutant concentration at the exit of a regeneration bed	
C_t	Total concentration of particles and droplets	$particles \cdot m^{-3}$
C_x	Solid-phase pollutant concentration	$g \cdot g^{-1}$
C_{xs}	Saturated solid-phase pollutant concentration, adsorption capacity	$g \cdot g^{-1}$
CMD	Count median diameter	m
c	Specific heat	$kJ \cdot kg^{-1} \cdot K^{-1}$
c_a	Discharge coefficient	
D	Diffusion coefficient; diameter	$m^2 \cdot s^{-1}$; m
D_e	Equivalent diameter	m
D_h	Hydraulic diameter	m
D_p	Diffusion coefficient of particles	$m^2 \cdot s^{-1}$
D_{si}	i^{th} sampling point on a duct diameter in duct sampling	m
D_s	Diameter of sampling head	m
D_{smax}	Maximum diameter of sampling head	m
D_{smin}	Minimum diameter of sampling head	m
D_t	Diameter of tube	m
D_w	Diameter of wire	m
d	Diameter of particles	m
d_{100}	Diameter at which impaction/collection efficiency is 100%	m
d_{50}	Cutsize, diameter at which collection efficiency is 50%	m

Symbol	Description	Dimension
d_c	Colliding diameter	m
d_{cm}	Count mean diameter	m
d_d	Diameter of droplet (solid or liquid)	m
d_e	Equivalent volume diameter in cm	m
d_f	Diameter of a filter fiber	m
d_g	Geometric mean diameter, count median diameter	m
d_i	Midpoint diameter of i^{th} group	m
$d_{\bar{m}}$	Diameter of average mass	m
d_{mm}	Mass mean diameter	m
d_p	Diameter of particles	m
d_{pc}	Critical particle diameter that can be deposited on a ceiling surface	m
d_t	Diameter of tubing	m
$d_{\bar{s}}$	Diameter of average surface	m
d_{sm}	Surface mean diameter	m
d_x	A type of average diameter of particles	m
E	Energy	J
	Electrostatic field intensity, activation energy	$N \cdot C^{-1}(V \cdot m^{-1})$
E_g	Kinetic energy of gases	$N \cdot m, kg \cdot m^2 \cdot s^{-2}$
E_p	Kinetic energy of airborne particles	$N \cdot m, kg \cdot m^2 \cdot s^{-2}$
E_v	Effectiveness coefficient of mixing	
e	Charge of an electron	C
F	Force	N
F_{ah}	Adhesion force of particles	N
F_D	Drag force	N
F_i	Force attributed to inertia	N
F_j	Frequency of particles falling in j^{th} size group	N
F_r	Force attributed to shear or friction	N
F_E	Electrostatic force	N
F_e	External force	N
F_c	Centrifugal force	N
F_{om}	Force caused by osmotic pressure	N
F_{omi}	Force caused by osmotic pressure on one (or i^{th}) particle	N
f	Fractional function	
f_i	Fraction of concentration for i^{th} size group	
f_{im}	Mass fraction of i^{th} size group	
f_j	Fraction of concentration for j^{th} size group	
G	Gravitational constant Gas flow rate	$m^3 \cdot s \cdot kg;$ $kg \cdot s^{-1}, mol \cdot s^{-1}$
G'	Flow rate of stagnant carrying gas	$kg \cdot s^{-1}, mol \cdot s^{-1}$
G_f	Factor of filtration efficiency due to gravitational settling	
g	Gravitational acceleration	$m \cdot s^{-2}$
H	Height	m
	Henry's law constant	
H_a	Annular gap of cyclones	m
H_e	Distance of exhaust air outlet (center line) to floor	m
H_f	Thickness of a filter	m
H_s	Distance of supply air inlet (center line) to floor	m
H_v	Number of velocity heads	
h	Enthalpy	$kJ \cdot kg^{-1}$
	Convective heat transfer coefficient	$kJ \cdot m^{-2} \cdot C \cdot s^{-1}$
h_s	Enthalpy of supply air	$kJ \cdot kg^{-1}$
h_e	Enthalpy of exhaust air	$kJ \cdot kg^{-1}$

Symbol	Description	Dimension
I	Current	A
	Current of ion toward a particle	ion·s ⁻¹
i	i^{th} group of particles, or i th in a group of n variables	
J	Diffusion flux of gases	molecules·m ⁻² ·s ⁻¹
J_E	Ion flux	ions·m ⁻² ·s ⁻¹
J_p	Diffusion flux of particles	particles·m ⁻² ·s ⁻¹
j	j^{th} group of particles	
K	Corrected coagulation coefficient for all particle sizes	
K_0	Coagulation coefficient for $d_p > 0.4 \mu\text{m}$	
K_{1-2}	Coagulation coefficient for two particle sizes	
K_c	Particle capture efficiency of droplet in kinematic coagulation	
K_n	Average coagulation coefficient for particles with n sizes	
Ku	Kuwabara hydrodynamic factor	
K_x	Mass transfer coefficient between gaseous and solid states	s ⁻¹
k	Boltzmann's constant, $R/N_a = 1.38 \times 10^{-23}$ (N·m·K ⁻¹)	N·m·K ⁻¹
	Reaction rate constant	s ⁻¹
	Turbulence kinetic energy	J
k_{rp}	Particle reentrainment factor at collecting surface	
L	Length, characteristic length	m
	Liquid flow rate	kg·s ⁻¹ , mol·s ⁻¹
L'	Flow rate of stagnant absorbing fluid	kg·s ⁻¹ , mol·s ⁻¹
L_t	Length of flow trajectory	m
LMD	Length median diameter	m
L_w	Length of wetted perimeter	m
l	Liter	10 ⁻³ m ³
M	Mass per mole of gases	kg·mol ⁻¹
	Molar weight	g
MMD	Mass median diameter	m
M_g	Mass of gases	kg
M_{di}	Deposited mass for i^{th} particle size range	kg
$\dot{M}_{di}$	Mass deposition rate for i^{th} particle size range	kg·s ⁻¹
$\dot{M}_p$	Total mass of particles	kg
$\dot{M}_p$	Mass production rate of particles	kg·s ⁻¹
$\dot{M}_{pn}$	Net mass production rate of particles	kg·s ⁻¹
$\dot{M}_c$	Mass of contaminants	kg
M_{xs}	Adsorption capacity, in g of adsorbate per 100 g of adsorbent	
$\dot{m}_c$	Mass production rate of contaminant	kg·s ⁻¹
$\dot{m}$	Mass flow rate	kg·s ⁻¹
$\dot{m}_p$	Mass production rate of particle mass	kg·s ⁻¹
$\dot{m}_d$	Mass deposition rate of particle mass	kg·s ⁻¹
m	Mass of a particle or a molecule	kg
$\bar{m}$	Average mass of a particle population	kg·m ⁻³
m_g	Mass of a gas molecule	kg
m_i	Midsized mass of i^{th} group particles	kg
m_p	Mass of a particle	kg
N	Total number of particles or molecules, or ions	
N_a	Avogadro's number, number of molecules per mole	
N_e	Number of complete turns in a cyclone	
N_p	Total number of particles	
N_{pi}	Total number of particles in i^{th} size range	
N_{pd}	Particle number deposited on unit surface area	particles·m ⁻²
n	Number of particle size groups, number of moles, number of ions	
$\bar{n}$	Average number of particle charges	ion·particle ⁻¹

Symbol	Description	Dimension
n_c	Number of collisions among molecules or particles	
n_f	Number of filters	
n_s	Number of collisions between molecules and a surface, number of saturation charges	
n_t	Total number of charges on a particle	
P	Pressure	Pa, N·m ⁻²
P_0	Atmospheric pressure	Pa, N·m ⁻²
P_A	Partial pressure of pollutant	Pa, N·m ⁻²
P_c	Critical pressure	Pa, N·m ⁻²
Pe	Peclet number for particle diffusion	
P_e	Pressure loss due to equipment fittings such as elbows and nozzles	Pa, N·m ⁻²
P_f	Friction pressure losses	Pa, N·m ⁻²
P_n	Penetration rate, penetration for denuders	
P_{om}	Osmotic pressure	Pa, N·m ⁻²
P_v	Dynamic pressure losses	Pa, N·m ⁻²
P_w	Wetted perimeter	m
P_t	Pressure at throat	Pa, N·m ⁻²
pCi	Picocuries, 1 pCi = 0.037 disintegration per second for a radioactive material	s ⁻¹
Q	Volumetric airflow rate	m ³ ·s ⁻¹
Q_{cp}	Volumetric rate of pollutant production	m ³ ·s ⁻¹
Q_e	Volumetric ventilation rate for exhaust air	m ³ ·s ⁻¹
Q_g	Flow rate of gas	m ³ ·s ⁻¹
Q_j	Flow rate of an air jet	m ³ ·s ⁻¹
Q_l	Flow rate of liquid	m ³ ·s ⁻¹
Q_{oc}	Inspiration rate of occupants	m ³ ·s ⁻¹
Q_r	Airflow rate passing an air cleaning device or a regeneration bed	m ³ ·s ⁻¹
Q_s	Sampling rate; volumetric ventilation rate for supply air	m ³ ·s ⁻¹
q	Electric charge in coulombs	C
q_c	Particle collector (e.g., cyclone) quality	
q_f	Filter quality	
q_t	Total heat transfer rate	W
R	Radius	m
	Gas constant $R = 8.31 \text{ J·K}^{-1}\cdot\text{mol}$ for P in Pa and V in m ³	J·K ⁻¹ ·mol
Re	Reynolds number for fluids	
Re_p	Reynolds number for particles	
Re_{p0}	Reynolds number for particles at initial velocity	
RH	Relative humidity	
R_L	Center-to-center distance between two particles	m
r	Radius	m
r_c	Reaction rate of reactants	mole·m ⁻³ ·s ⁻¹
r_{sp}	Radius of a cyclone at which particles are separated	m
S	Stopping distance	m
	Absorption factor	
SMD	Surface median diameter	m
Stk	Stokes's number	
Stk_c	Stokes's number for particle capture efficiency	
Stk_i	Stokes's number for particle impactors	
T	Absolute temperature, temperature	K, °C
THP	Total heat production of occupants	kJ·s ⁻¹
t	Time	s
t_d	A constant unit time (1 s) for particle deposition	s

Symbol	Description	Dimension
t_{min}	Minimum time required	s
t_x	Breakthrough time for an adsorption bed	s
U	Velocity of air or other carrying fluids	m·s ⁻¹
$\vec{U}$	Velocity vector of fluid	m·s ⁻¹
U_0	Initial air velocity, free flow velocity, face flow velocity	m·s ⁻¹
$\vec{U}_d$	Velocity vector of a particle	m·s ⁻¹
U_c	Critical velocity of bulk air for particle detachment	m·s ⁻¹
U_s	Sampling velocity at the face of a sampler	m·s ⁻¹
U_x	Mean air velocity of an air jet at distance x	m·s ⁻¹
u	Molecular speed	m·s ⁻¹
$\bar{u}_i$	Arithmetic mean speed of ions	m·s ⁻¹
$\bar{u}$	Arithmetic mean speed of molecules	m·s ⁻¹
$\hat{u}$	Most probable molecular speed	m·s ⁻¹
$\bar{u}_{p,p}$	Arithmetic mean thermal velocity of particles	m·s ⁻¹
u_p	Most probable thermal velocity of particles	m·s ⁻¹
u_c	Colliding speed of molecules	m·s ⁻¹
u_{rms}	Root-mean-square speed of molecules	m·s ⁻¹
u_{rmsp}	Root-mean-square thermal velocity of particles	m·s ⁻¹
u_t	Gas velocity at the throat	m·s ⁻¹
V	Volume	m ³
	Velocity of particles	m·s ⁻¹
V_0	Initial velocity of particles	m·s ⁻¹
V_{az}	Velocity of adsorption zone	m·s ⁻¹
V_c	Colliding volume swept by a colliding molecule	m ³
V_d	Particle deposition velocity	m·s ⁻¹
V_{dd}	Particle deposition velocity due to diffusion	m·s ⁻¹
V_{di}	Deposition velocity for particles in i^{th} size range	
V_M	Molar volume	m ³ ·mol
V_p	Velocity of particles	m·s ⁻¹
V_r	Relative velocity of a particle to its carrying fluid	m·s ⁻¹
V_{rz}	Velocity of desorption (regeneration) zone	m·s ⁻¹
V_t	Total velocity of a fluid element	m·s ⁻¹
V_{TE}	Terminal velocity of particle in an electrical field	m·s ⁻¹
$\bar{V}_{TE}$	Average terminal velocity of particle in an electrical field	m·s ⁻¹
V_{TS}	Terminal settling velocity of particles	m·s ⁻¹
V_{TSi}	Terminal settling velocity of i^{th} size particles	m·s ⁻¹
V_{TF}	Terminal velocity with constant external force	m·s ⁻¹
ν	Molecular kinematic viscosity	m ² ·s ⁻¹
	Specific volume	m ³ ·kg ⁻¹
ν_e	Specific volume of exhaust air	m ³ ·kg ⁻¹
ν_s	Specific volume of supply air	m ³ ·kg ⁻¹
$\dot{W}_p$	Moisture production rate	kg·s ⁻¹
w_s	Moisture content of the supply air	
w_e	Moisture content of the exhaust air	
X_A	Mass ratio of pollutant A in liquid phase	
x, y, z	Cardinal coordinate	m
x_A	Mass fraction (or mole fraction) of pollutant A in liquid phase	
Y_A	Mass ratio of pollutant A in gas phase	
y_A	Mass fraction (or mole fraction) of pollutant A in gas phase	
α	Angle between the sampler axis and flow direction	degree
α_j	Divergent angle of an air jet	degree
α_s	Solidity, solid volume fraction of a screen or a filter	
β	Coagulation coefficient correction factor	

Symbol	Description	Dimension
β_d	Angle between a settling velocity and the deposition surface	degree
β_s	Solubility of the gas to the scrubbing liquid	
γ	Surface tension; for water, $\gamma = 0.073$ N/m Specific heat ratio	$\text{N}\cdot\text{m}^{-1}$
ΔP	Pressure drop	Pa
ΔW	Potential difference	V
δ	Thickness; thickness of a sampler wall	m
ε	Error in percentage, surface absolute roughness Fluid flow dissipation rate	
ε_0	Permittivity (dielectric constant) of a vacuum $= 8.85 \times 10^{-12} \text{ C}^2\cdot\text{N}^{-1}\cdot\text{m}^{-2}$	$\text{C}^2\cdot\text{N}^{-1}\cdot\text{m}^{-2}$
ε_f	Permittivity (dielectric constant) of filter fiber	$\text{C}^2\cdot\text{N}^{-1}\cdot\text{m}^{-2}$
ε_p	Permittivity (dielectric constant) of particles	$\text{C}^2\cdot\text{N}^{-1}\cdot\text{m}^{-2}$
Γ_k	Effective diffusivity of k ; k is the kinetic energy	$\text{m}^2\cdot\text{s}^{-1}$
Γ_ω	Effective diffusivity of ω ; ω is the specific dissipation rate	$\text{m}^2\cdot\text{s}^{-1}$
κ	Concentration factor in the Freundlich equation (Equation 13.4) for adsorption	$\text{kg}\cdot\text{m}^{-3}$
κ_r	Concentration factor for regeneration	$\text{kg}\cdot\text{m}^{-3}$
ϕ	Angular variable in spherical coordinate	degree
η	Viscosity of fluid	$\text{Pa}\cdot\text{s}$
λ	Mean free path of gases	m
ξ	Sampling efficiency, collection efficiency	
ξ_c	Particle collection efficiency by kinematic coagulation	
ξ_d	Particle removal efficiency by deposition	
ξ_f	Overall filtration efficiency of a filter	
ξ_{fp}	Filtration efficiency of a filter due to interception	
ξ_{fi}	Filtration efficiency of a filter due to inertial impaction	
ξ_{fd}	Filtration efficiency of a filter due to diffusion	
ξ_{fs}	Filtration efficiency of a filter due to gravitational settling	
ξ_{fe}	Filtration efficiency of a filter due to electrostatic deposition	
ξ_k	Particle capture efficiency by coagulation	
ξ_r	Efficiency of room air cleaning resulting from an indoor air-cleaning system	
ξ_{oc}	Air-cleaning efficiency of occupants	
ξ_x	Collection efficiency for any given particle size	
θ	Angular variable in spherical coordinate	degree
ρ	Density	$\text{kg}\cdot\text{m}^{-3}$
ρ_a	Density of air	$\text{kg}\cdot\text{m}^{-3}$
ρ_0	Standard (aerodynamic) density of particles = 1000 kg/m ³	$\text{kg}\cdot\text{m}^{-3}$
ρ_g	Density of gas	$\text{kg}\cdot\text{m}^{-3}$
ρ_p	Density of particles	$\text{kg}\cdot\text{m}^{-3}$
σ	Standard deviation	
σ_g	Geometric standard deviation (also <i>GSD</i>)	
τ	Relaxation time, time constant Average residence time of air in the room	s s
τ_c	Time constant for particle concentration in a ventilated airspace	s
τ_E	Time constant for particle charging	s
τ_i	Initial age of air in the room	s
τ_r	Residual lifetime of air in the room	s
$\bar{\tau}$	Time period that ventilation rate varies	s
$\bar{\tau}_j$	Local mean air age at an arbitrary point in the room	s
$\bar{\tau}_e$	Mean air age of the room or at the exhaust	s

Symbol	Description	Dimension
ζ	A pure number in the Freundlich equation (Equation13.4) for adsorption	
ζ_r	A pure number in for regeneration of an adsorption bed	
ω	Specific dissipation rate	
χ	Shape factor	

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List of Acronyms

Acronym	Description
ACGIH	American Conference of Governmental Industrial Hygienists
ACH	Air change per hour
APS	Aerodynamic particle sizer
ARI	Air-Conditioning and Refrigeration Institute
ASHRAE	American Society of Heating, Refrigeration and Air-conditioning Engineers
ASAE	American Society of Agricultural Engineers
ASME	American Society of Mechanical Engineers
BMRC	British Medical Research Council
BRI	Building-related illness
CAA	Clean Air Act
CAAA	Clean Air Act Amendments
CCD	Charged coupled device
CFD	Computational fluid dynamics
CHSes	Collimated honeycomb structures
CMD	Count median diameter
CNC	Condensation nucleus counter
DOE	Department of Energy (United States)
DOP	Diocetyl phthalate or bio (2-ethylhexyl) phthalate
EPA	Environmental Protection Agency (United States)
ESP	Electrostatic precipitation
FEV	Fetal exposure value
HEPA	High-efficiency particle attenuation
ISO	International Organization for Standardization
LDV	Laser Doppler velocimetry
LES	Large eddy simulation
LSV	Laser speckle velocimetry
MMD	Mass median diameter
MP	Moisture production
MPPS	Most penetrating particle size
NIOSH	National Institute of Occupational Safety and Health
NRC	National Research Council (United States)
OSHA	Occupational Safety and Health Agency (United States)
PEL	Permissible exposure limit
PIV	Particle image velocimetry
PM	Particulate matter
PSM	Particle streak mode
PTV	Particle tracking velocimetry
RNG	Renormalization group
RSM	Reynolds stress model
SBS	Sick building syndrome
SMD	Surface median diameter
SHP	Sensible heat production
SPIV	Stereoscopic particle image velocimetry
STEL	Short-term exposure limit
THP	Total heat production
TLV	Threshold limit values
TSP	Total suspended particulate matter
TWA	Time weighted average

Acronym	Description
UL	Underwriters Laboratories
ULPA	Ultralow-penetration air
VEF	Ventilation effectiveness factor
VEM	Ventilation effectiveness map
VOC	Volatile organic compound

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CHAPTER 1

Air Quality and You

Air is a critical element to many living things. People, for example, may survive for two weeks without food and for two days without water. But without air, a person may only survive for two minutes. In daily life, an average person consumes approximately 1 kg of food, 2 kg of water, and 20 kg of air. Further, in developed countries, an average working person spends over 90% of his or her lifetime indoors.

1.1 BACKGROUND

In order to define air quality, a definition of *clean air* or *standard air* should first be established. Typically, clean air is the dry atmosphere air found in rural areas or over the ocean far from air pollution sources. The chemical composition of such clean, dry atmospheric air is listed in Table 1.1. The atmospheric air also contains from 0.1 to 3% water vapor by volume, depending on temperature. The clean air defined in Table 1.1 is typical because, in many instances, traces of other components are also found in the atmosphere that are considered clean. These other trace components include ammonia, sulfur dioxide, formaldehyde, carbon monoxide, iodine, sodium chloride, and particulate matter such as dust and pollen.

Based on the definition of clean air, *air quality* refers to the degree of pollution of the clean air. In general, the lower the concentration of airborne pollutants, the better the air quality. *Airborne pollutant* is defined as any substance in the air that can harm the health and comfort of humans and animals, reduce performance and production of plants, or accelerate the damage of equipment. Airborne pollutants can be in the forms of solid (e.g., particulate matter), liquid (e.g., mists), and gaseous substances. Excessively high concentrations or depletion of substances listed in Table 1.1 can impose serious air quality problems. For example, excessive emission of carbon dioxide and methane is suspected to be responsible for the greenhouse effect and global warming.

Table 1.1 Chemical Composition and Volumetric Content of Typical Dry Atmospheric Air

Substance	Content (% ^a)	Concentration (ppm ^a)
Nitrogen	78.084 ± 0.004	780,840
Oxygen	20.946 ± 0.002	209,460
Argon	0.934 ± 0.001	9,340
Carbon dioxide	0.033 ± 0.001	330
Neon		18
Helium		5.2
Methane		1.2
Krypton		0.5
Hydrogen		0.5
Xenon		0.08
Nitrogen dioxide		0.02
Ozone		0.01–0.04

^a In volume.

Source: *The Handbook of Air Pollution*, PHS Publication, 1968.

1.1.1 Outdoor Air Quality

Although food and water quality was a far more prevalent human concern in the past, air quality concerns can be traced back more than 700 years. In 1272, King Edward I of England banned the use of “sea coal” in an attempt to clean the smoky sky in London.¹ One of the first recorded publications trying to control smoke in the air is a pamphlet published in 1661 by the royal command of Charles II.² Yet outdoor air pollution became a serious concern, and many pollution episodes were recorded, only since the late 19th century. The very first air pollutant was referred to as “smog,” a combination of smoke and fog, creating a dense haze and foglike condition. In 1873, 268 deaths were reported as the result of a heavy smog in London. In 1930, 60 people died and hundreds became ill during a three-day smog in Meuse Valley, Belgium, a heavily industrialized area. During a nine-day smog in January, 1931, 592 people died in the Manchester, England, area. In 1948, a 4-day smog in Donora, Pennsylvania, caused 20 people to die and nearly 7,000 residents to become ill. Many of these residents eventually died at an earlier age than the average of the townspeople. The most tragic episode of air pollution in human history is the London smog of December, 1952, during which more than 4,000 human lives were claimed and many more residents suffered illness. Public and political reactions resulted in the Clean Air Act of 1956 in the U.K., which is viewed as a turning point in urban pollution legislation. Many notable changes have been made, including how homes are heated and industries are operated, focusing on the reduction of burning soft coal. The United States passed the Clean Air Act (CAA) in 1972, which marked another milestone in air quality control. Since then, there has been no similar smog episode reported, and the atmospheric air quality has improved considerably.

Another air pollutant is acid deposition. Acid deposition is not a recent phenomenon. In the 17th century, scientists noted the ill effects that industry and acidic pollution were having on vegetation and people. However, the term *acid rain* was not coined until two centuries later, when Angus Smith published a book called *Acid*

Rain in 1872. In the 1960s, the problems associated with acid deposition became an international issue when fishermen noticed declines in fish numbers and diversity in many lakes throughout North America and Europe.

Acidic pollutants can be deposited from the atmosphere to the earth's surface in dry (sulfur dioxide, SO_2 , and nitrogen oxide, NO_x) and wet forms (nitric acid, HNO_3 , sulfuric acid, H_2SO_4 , and ammonium, NH_4). The term *acid precipitation* is used specifically to describe wet forms of acid pollution that can be found in rain, sleet, snow, fog, and cloud vapor. An acid can be defined as any substance that, when dissolved in water, dissociates to yield corrosive hydrogen ions. The acidity of substances dissolved in water is commonly measured in terms of pH (defined as the negative logarithm of the concentration of hydrogen ions). According to this measurement scale, solutions with a pH of less than 7.0 are described as being acidic, while a pH greater than 7.0 is considered alkaline. Precipitation normally has a pH between 5.0 and 5.6, because of natural atmospheric reactions involving carbon dioxide. Precipitation is considered acidic when its pH falls below 5.6 (which is 25 times more acidic than pure water).

Acid rain has caused the death of thousands of acres of forest and water pollution in the northeastern United States and Canada. Some sites in eastern North America have precipitation with pHs as low as 2.3 — about 1000 times more acidic than is natural. As a result, the United States and Canada entered an Air Quality Agreement in 1991 to address transboundary air pollution.³ Under this agreement, the first effort was focused on acid rain issues. The two governments have made significant reductions in emissions of the two major acid rain pollutants — sulfur dioxide and nitrogen oxide. Caps for total permanent national emission of sulfur dioxide were established.³ Canadian commitment was to achieve a permanent national cap for SO_2 emissions of 3.2 tones by 2000. U.S. commitment is to achieve a permanent national cap for SO_2 emissions of 8.95 tones by 2010. By 1998, the total national SO_2 emissions of both countries were substantially reduced. The U.S. was 30% and Canada was 18% below the national allowance for SO_2 emissions. Nitrogen oxide, on the other hand, is more difficult than sulfur dioxide to control because the emissions involve both stationary and mobile sources. Canadian commitments included reducing NO_x stationary source emissions 100,000 tones below the forecast level of 970,000 tones by 2000, and implementing a NO_x control program for mobile sources. Because the largest NO_x contributor in Canada is the transportation sector, which accounts for 60% of all emissions, major improvements are expected by 2010, with an expected decline in NO_x emissions of 10% from 1990 levels, primarily as a result of improved standards for on-road vehicles. The United States continues to address NO_x emissions from stationary and mobile sources under the 1990 Clean Air Act Amendments (CAAA), which mandated a 2-million ton reduction in NO_x emissions by the year 2000,⁴ and a further reduction of 90% in the subsequent 10 years (Tier 4). The Acid Rain Program and the motor vehicle source control program together are expected to achieve this goal, and further annual national emission reduction requirements are under development.

While the worldwide efforts of reducing acid rain have been focused on the stationary (factories) and mobile (on-road vehicles) sources, another acid rain source — animal agriculture — has been receiving attention. In the Netherlands, for example, approximately two-thirds of the acid rain has been attributed to the gas (ammonia

and sulfuric gases) emissions from livestock production. The Dutch government called for a 70% reduction of 1993's ammonia emission by the year 2000⁵ but had not achieved that goal by the year 2003. Taiwan has already started to phase out pork production on the island. In the United States and Canada, where land bases are large, environmental regulations on the livestock industry are becoming more and more stringent.⁶

The continued awareness of air quality and efforts to protect the natural environment lead to other concerns regarding air pollutants, including greenhouse gases (carbon dioxide and methane), ozone depletion in the stratosphere, synthetic chemical gases emitted from manufacturing and other processes, ground-level ozone, and particulate matter (PM) concentrations.

1.1.2 Indoor Air Quality

Most people are aware that outdoor air pollution can damage the environment and their health, but they may not know that indoor air pollution can also have significant effects. Until the late 1960s, attention to air quality was primarily focused on the outdoors because, by that time, outdoor air pollution was considered responsible for many adverse health effects. In the early 1970s, scientists started to investigate the cause of complaints in indoor working environments. U.S. Environmental Protection Agency (EPA) studies of human exposure to air pollutants indicated that indoor air levels of many pollutants may be two to five times — and occasionally, more than 100 times — higher than outdoor levels.⁷ Over the past several decades, our exposure to indoor air pollutants is believed to have increased due to a variety of factors, including the construction of more airtight buildings, reduced ventilation rates to conserve energy, the use of synthetic building materials and furnishings, and the use of chemically formulated personal care products, pesticides, printing inks, and household cleaners. In recent years, comparative risk studies performed by the EPA and its Science Advisory Board (SAB) have consistently ranked indoor air pollution among the top five environmental risks to public health. As a result of these studies, people began to realize that the indoor air quality is important to their comfort and health. Additionally, improvement in the quality of outdoor air since the 1972 Clean Air Act enhances the relative importance of indoor air quality.

The importance of indoor air quality is also due to the sheer amount of time that people spend indoors. Traditionally, people spent more time outdoors than indoors. Today, people in industrialized countries spend more than 90% of their lifetimes indoors.⁸ In the United States, for example, every day an average working person spends 22 hours and 15 minutes indoors and one hour in cars or in other modes of transportation — another type of indoor environment.⁹ Thus, the total time staying indoors for an average working person is 23 hours and 15 minutes per day, or 97.7% of his or her lifetime! Other people, such as young children and seniors, may spend more time indoors than employed people. Clearly, the quality of indoor air should be as high as possible.

Increasing attention to indoor air quality has contributed to the awareness of poor health associated with a poor indoor environment. Two types of illnesses related to poor indoor air quality have been identified: sick building syndrome (SBS) and

building-related illness (BRI). While the definition of SBS varies slightly in the literature, SBS can be defined as the discomfort or sickness associated with poor indoor environments with no clear identification of the source substances.^{10, 11} Symptoms of SBS include irritation of sensory organs (eyes, nose, throat, ears, and skin), fatigue, headache, respiratory disorders, and nausea.

Building-related illness (BRI) is defined as a specific, recognized disease entity caused by some known agents that can be identified clinically. Symptoms of BRI include hypersensitivity pneumonitis, humidifier fever, asthma, and legionella. The distinction between SBS and BRI is whether the causes of the sickness can be diagnosed clinically. Once the cause of an SBS symptom is identified, the SBS becomes a BRI. On many occasions, people do not distinguish between the two, and sick building syndrome refers to all illnesses associated with poor indoor environments, which are often referred to as *sick buildings*.

Indoor air quality and associated SBS have a profound impact on our quality of life and economy. Approximately 1 million buildings in the United States are sick buildings, within which 70 million people reside or work.¹² These sick buildings do not include agricultural buildings such as animal facilities and grain elevators. Most of these agricultural structures have unique, often more serious, air quality concerns.

The National Institute for Occupational Safety and Health (NIOSH) ranked the top 10 occupational diseases and injuries in 1982 in the following descending order of importance:

1. Occupational lung dysfunctions, including lung cancer, pneumoconioses, and occupational asthma
2. Musculoskeletal injuries, including back injury, carpal tunnel syndrome, arthritis, and vibration white finger disease
3. Occupational cancers other than lung cancer
4. Traumatic death, amputations, fractures, and eye losses
5. Cardiovascular diseases, including myocardial infarction, stroke, and hypertension
6. Reproductive problems
7. Neurotoxic illness
8. Noise-induced hearing loss
9. Dermatologic problems, including dermatoses, burns, contusions, and lacerations
10. Psychological disorders

The top occupational disease — lung dysfunctions — is undoubtedly related to the air quality to which people are exposed.

A large number of studies have identified confinement animal facilities as particularly hazardous workplaces.^{13–18} Particulate matter (dust, endotoxins, living or dead microorganisms and fungi) and gases (ammonia, hydrogen sulfide, and carbon dioxide) in animal buildings^{16, 19} have been implicated as contributors to the increased incidence of respiratory disorders among livestock workers compared to grain farmers and nonfarm workers.^{13, 20} Young farmers may be at particular risk of developing chronic bronchitis, coughing, wheezing, toxic organic dust syndrome, and/or occupational chronic pulmonary disease.¹⁷

Particulate matter (PM) in animal buildings is different from other types of building dust in at least three aspects:

First, animal building dust is biologically active in that it contains a variety of bacteria, microorganisms, and fungi.^{21, 22}

Second, its concentration is high, typically more than 10 or even 100 times higher than in office and residential buildings.

Third, it is an odor carrier.²³

Some odorous compounds as low as at one part per trillion may still have a nuisance effect on the building occupants and the neighborhood. Some bacteria carried by PM in animal buildings, such as *Listeria monocytogenes* and *Streptococcus suis*, are zoonotic agents that have caused fatal diseases in people.^{24, 25} In Europe, 33% of pork producers suffer chronic respiratory symptoms related to poor indoor air quality.²⁶ In the Netherlands, 10% of swine producers had to change jobs due to severe respiratory problems caused by poor air quality.²⁷ In cold climates, such as in the midwestern United States and Canada, the problems appear to be more serious because of (1) larger building size and longer working hours and (2) lower air exchange rates due to cold climates and energy conservation concerns. A study in Saskatchewan, Canada, indicated that nearly 90% of swine producers suffer one or more acute respiratory symptoms such as coughing, wheezing, nasal and throat irritation, and chest tightness, and 50% suffer chronic lung dysfunction, allegedly due to the poor indoor air quality.²⁸

Because intensive confinement in animal housing has only become common practice since the late 1960s and early 1970s, the full effect of air quality in animal buildings on human health has not yet been fully revealed. Improving the work environment for livestock producers has become an increasingly important issue for health care officials, governments, and, especially, producers and animal facility designers. Air in animal facilities must be the best possible quality; technically effective and economically affordable air quality control technologies must be developed. It has been proved that improving air quality or reducing dust inhalation resulted in improved human respiratory responses.^{18, 19} Thus, intervention for contaminant control has great potential in research, product development, and management practices. Researchers are constantly striving to improve existing air quality control technologies and probing into new areas. Current design of animal facilities focuses on thermal comfort and animal performance. New generations of animal facilities must be designed to be more environmentally friendly, safer for humans and animals, and acceptable to the local communities. To meet these requirements, air quality control in livestock buildings plays a pivotal role. Significant progress has been made in reducing contaminant concentrations and improving the indoor environment.

1.2 TERMINOLOGY AND DEFINITIONS

Rather than using chemical composition to characterize air contaminants, this book defines the following terminologies commonly used in the literature to categorize airborne contaminants.

Acid deposition — Acidic pollutants deposited from the atmosphere to the earth's surface in wet and dry forms. Typical acidic pollutants include sulfur dioxide (SO₂), nitrogen oxide (NO_x), and ammonium (NH₄).

Acid rain — Wet forms of acidic pollutants found in rain, snow, fog, or cloud vapor. Most acid rain forms when nitrogen oxide (NO_x) and sulfur dioxide (SO_2) are converted to nitric acid (HNO_3) and sulfuric acid (H_2SO_4) through oxidation and dissolution, and when ammonia gas (NH_3) from natural sources is converted into ammonium (NH_4).

Aerosol — A general term for airborne particles, in either solid or liquid state, that are usually stable in a gas for at least a few seconds. Some aerosols can be suspended in the air for hours, or even years, depending on the particle size and fluid conditions. Aerosol particle size can range from 0.001 to larger than 100 μm in diameter.

Bioaerosols — A special category of aerosols of biological origin. Bioaerosols include living organisms, such as bacteria and fungi, and parts of products of organisms, such as fungal spores, pollen, and allergens from animals and insects.

Dust — Solid particles formed by mechanical disintegration of a material, such as grinding and crushing, or other decomposition processes, such as decaying.

Fume — Solid particles formed by condensation of vapors or gaseous combustion products. Fume usually consists of a cluster of primary particles, such as smoke particles. Fume particle sizes can be from submicrons to a few microns.

Smog — A combination of smoke and fog and other airborne pollutants that forms a dense haze or foglike atmosphere. The word *smog* is derived from the combination of the words *smoke* and *fog*.

Smoke — A visible aerosol usually generated from incomplete combustion. Smoke particle size is usually smaller than 1 μm .

Mist and fog — Liquid particles formed by condensation or atomization. Mist particles are spheres with a size range from submicrons to 200 μm .

Particulate matter (PM) — The scientific definition of PM is the same as for aerosol. The word *aerosol* is often used in atmospheric science, while the term *particulate matter* is more common in indoor air quality and occupational health science and applications. However, in this text PM primarily refers to solid, airborne particles, as many PM measurement methods involve drying and gravimetric processes. PM is also interchangeable with the terms *particulate contaminant*, *particle*, and *dust* in this text.

Volatile organic compound (VOC) — An organic compound, generally containing carbon and/or hydrogen, that evaporates easily. VOCs are found in everything from paints and coatings to underarm deodorants and cleaning fluids, from fecal synthetic processes to the decomposition of organic waste materials. VOCs have been found to be a major contributing factor to ground-level ozone, a common air pollutant and proven public health hazard.

1.3 UNITS

Throughout the text, the SI (International Systems) units meter, kilogram and second (m-kg-s) will be used as the primary dimension system. However, due to the nature of particle size, which is usually in the range of microns or submicrons, centimeter, gram, and second (c-g-s) are used as a secondary dimension system. Liters and milliliters are also used in very small volumes or low flow rates. Those secondary units are easily derived from the m-kg-s system. Readers are advised to pay special attention to the consistency of units before applying an equation. Related unit conversions and coefficients are listed in Appendix 1.

DISCUSSION TOPICS

1. What constitutes an air contaminant?
2. Discuss the definition of air quality. "Too much of a good thing can be a bad thing": List examples of this statement in the context of air quality.
3. What are the differences between smoke and fume?
4. Why does particulate matter usually refer to solid particles only, whereas aerosols may include liquid particles?
5. How do you estimate the total ammonia emission from an animal facility? Is such estimation feasible?
6. What are the key factors that make indoor air quality an increasing concern of scientific communities, governments, and the general public?
7. Why may the PM in animal facilities be a more serious concern than in other types of indoor environments?
8. Human history contains fewer episodes of indoor air quality problems than outdoor air pollution tragedies. Does this suggest that indoor air quality is a much lesser concern? Explain.
9. How is dry and wet acid deposition formed? What are the potential sources of acid rain, and how can you reduce these sources?
10. How does outdoor air pollution affect indoor air quality?
11. Do you prefer that outdoor air be filtered before entering your home, or that outdoor air be let directly into your home? Discuss the pros and cons of each option.
12. Name some major adverse effects of outdoor air pollution and of poor indoor air quality. Discuss the differences between these two environmental problems.
13. Visit Web sites to keep up with recent indoor air quality issues. Such Web sites may include the U.S. EPA, Environmental Canada, the National Institute of Occupational Safety and Health (NIOSH), and the Occupational Safety and Health Agency (OSHA).

REFERENCES

1. Stern, A.C., *Air Pollution*, 2nd ed., Academic Press, New York, NY, 1976.
2. Wark, K., Warner, C.F., and Davis, W.T., *Air Pollution — Its Origin and Control*, 3rd ed., Addison-Wesley, Menlo Park, CA, 1998.
3. U.S. EPA, *Air Quality Agreement — 1998 Progress Report*, Acid Rain Division, U.S. Environmental Protection Agency, Washington, DC, 1998.
4. U.S. EPA, *Clean Air Act Amendment*, U.S. Environmental Protection Agency, Washington, DC, 1990.
5. C.A.B. International Information Services, *General News*, Wallingford, Oxon, U.K., 13(4):139, 1992.
6. IDA, *Livestock Management Facilities Act*, State of Illinois Department of Agriculture, Springfield, IL, 1997.
7. U.S. EPA, *Why Is the Environment Indoors Important to Us?* Indoor Environment Division, U.S. Environmental Protection Agency, Washington, DC, 2000.
8. NRC, *Committee on Indoor Air Pollutants: Indoor Pollutants*, National Research Council, National Academy Press, Washington, DC, 1981.
9. Meyer, B., *Indoor Air Quality*, Addison-Wesley, Reading, MA, 1983.

10. Molhave, L., The sick buildings — a sub-population among the problem buildings, in *Indoor Air '87*, Seifert B., Esdorn, H., and Fischer, M., eds., Proceedings of the IV International Conference on Indoor Air Quality and Climate, Vol. 2, Berlin, Institute for Water, Soil, and Air Hygiene, 469–473, 1987.
11. Burge, S., Hedge, A., and Wilson, S., Sick building syndrome: a study of 4373 office workers, *Am. Occup. Hyg.*, 31:493–504, 1987.
12. Cone, J.E. and Hodgson, M.J., Problem buildings: building associated illness and the sick building syndrome, in *State of the Art Reviews — Occupational Medicine*, Hanley & Belfus, Philadelphia, PA., 1989.
13. Donham, J.K. et al., Environmental and health studies of workers in Swedish swine confinement buildings, *Br. J. of Ind. Med.*, 40:31–37, 1989.
14. Barber, E.M., Rhodes, C.S., and Dosman, J.A., A survey of air quality in Saskatchewan pig buildings, Can. Soc. Agr. Eng., Paper No. 91-216, CSAE, Ottawa, ON, Canada, 1991.
15. Atwood, P. et al., A study of the relationship between airborne contaminants and environmental factors in Dutch swine confinement buildings, *Am. Ind. Hygin. Assoc. J.*, 48:745–751, 1987.
16. Zejda, J.E. et al., Respiratory health of swine producers, focus on young workers, *CHEST*, 103:702–709, 1993.
17. Zejda, J.E. et al., Respiratory health status in swine producers relates to endotoxin exposure in the presence of low dust levels, *J. Occup. Med.*, 36(1):49–56, 1994.
18. Zhang, Y. et al., Acute respiratory responses of human subjects to air quality in a swine building, *J. Agr. Eng. Res.*, 70:367–373, 1998.
19. Senthilselvan A. et al., Positive human health effects of dust suppression with canola oil in swine barns, *Am. J. Respir. and Crit. Care Med.*, 156:410–417, 1997.
20. Dosman, J.A. et al., Respiratory symptoms and alterations in pulmonary function tests in swine producers in Saskatchewan: results of a survey of farmers, *J. Occup. Med.*, 30:715–720, 1988.
21. Martin W.T. et al., Bacterial and fungal flora of dust deposits in a swine building, *Br. J. Occup. Env. Med.*, 53:484–487, 1996.
22. Wiegard, B. and Hartung, J. Bacterial contaminant of air and floor surfaces in an animal house of a cattle clinic, *Proc. of 4th Intern. Livestock Environ. Symp.*, ASAE, St. Joseph, MI, 643–649, 1993.
23. Wang, X. et al., Odor carrying characteristics of dust from swine facilities, ASAE Paper 98, ASAE, St. Joseph, MI, 1998.
24. Fachlam, R.R. and Carey, R.B., Streptococci and aerococci, in *Manual of Clinical Microbiology*, Lennette, E.H., ed., Amer. Soc. Microbiology, Washington, DC, 1985.
25. Bortolussi, R., Schlech, W.F., and Albritton, W.L., Listeria, in *Manual of Clinical Microbiology*, Lennette, E.H., ed., Amer. Soc. Microbiology, Washington, DC, 1985.
26. Van't Klooster, C.E. and Voermans, J.A.M., European perspectives — how are they solving their problems? Symposium on Meeting the Environmental Challenge, National Pork Producers Council, November 17–18, 1993, Minneapolis, MN, 1993.
28. Zhou, C. et al., Increased airways responsiveness in swine farmers, *CHEST*, 99:941–944, 1991.
27. Preller, L. et al., *Proc. of 3rd Inter. Symp: Issues in Health, Safety and Agriculture*, Centre for Agr. Medicine, University of Saskatchewan, Saskatoon, SK, Canada, 23–24, 1992.

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CHAPTER 2

Properties of Indoor Air Contaminants

This chapter discusses basic properties of airborne contaminants, including shape, density, size, concentration, source, and microbiological composition. In this book, particulate contaminants primarily refer to solid particles larger than $0.01\text{ }\mu\text{m}$ in diameter, and thus include smoke and fumes. Gaseous molecules, though very small particles, have very different characteristics and behavior from particulate matter. These characteristics will be discussed in more detail in Chapter 5. In the last section of this chapter, threshold limit values (TLVs) for typical indoor air contaminants are discussed. These TLVs will serve as the criteria for many indoor environment qualities and therefore are presented early in this book.

By completing this chapter, the reader will be able to

- Specify particle densities — including actual density, standard density, and density relative to air— and interpret particle shape
- Define particle size using three diameters: equivalent volume diameter, Stokes diameter, and aerodynamic diameter
- Classify particle sizes based on respiratory characteristics or EPA criteria
- Describe and convert pollutant concentrations in different units, such as ppm, ppmv, mg/m^3 , $\text{particle}/\text{m}^3$ (count/m^3 , $\text{molecule}/\text{m}^3$)
- Determine TLVs, including TWA, STEL, and FEV, from existing literature
- Calculate the normalized TLVs for an environment containing more than one type of pollutant

2.1 PARTICLE DENSITY

The *density* of particles refers to the mass per unit volume of the particle. Unlike the density of other commercial materials, the density of airborne particles varies widely because of its complex composition. Particles collected indoors may consist of various materials, including carpet, furniture, dander from the occupants, insects, fecal materials, smoke, cleaning agents, and outdoor pollutants. For exam-

ple, particles from a bedroom may consist of a large amount of cloth fiber, hair, and dander, and the density may be low. Particles from an animal building may consist of a considerable amount of feedstuff, and the density may be close to that of the animal feed. In a welding shop, airborne particles may contain a large amount of sanding powder and metals and thus be considerably heavier than residential building particles.

When the actual density of a particulate contaminant is needed, measurements must be taken for that particulate contaminant sample. In this book, unless specified, we assume the density of particles of concern to be standard; that is, the density of particles is $1,000 \text{ kg/m}^3$ (1 g/cm^3), the same as the density of water under standard conditions. This standard density, combined with aerodynamic diameter, simplifies measurement and analysis of complicated airborne particles.

2.2 PARTICLE SHAPE

Particles in indoor environments are found in all kinds of shapes: sphere, rectangle, flake, fiber, and many other, irregular shapes. The shapes of most solid particles are nonspherical and highly irregular. Gaseous molecules, which are very small particles, are considered spheres in the context of this book. Airborne liquid particles, such as water droplets in a spray, are usually considered spheres. Figure 2.1 shows a microscopic view of a dust sample collected in an animal facility. From a typical indoor environment with occupants, this dust sample contains some fine hair (near the upper-right corner), dander flakes (lower-left corner), feedstuffs, and dead microorganisms (most are very small in Figure 2.1).

Particle shape is an important variable, affecting particle behavior and transportation, air-cleaning technology, and the effect on a respiratory system. For example, fiber-shaped particles may be particularly harmful to the lungs when they are inhaled, because they are more difficult to remove once they are settled in or have clung to

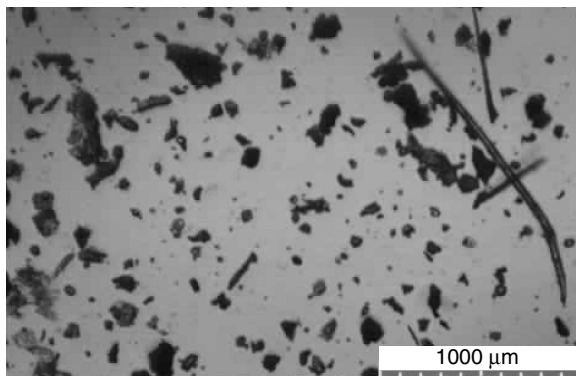


Figure 2.1 A dust sample collected from an animal facility. The particles are found in many different irregular shapes. Particles include feed, serum, dander, and hair from animals and human workers.

airways. On the other hand, the same nature of the fiber shape makes these particles easier to remove from an air stream by filtration. Most importantly, the shape of a particle determines its aerodynamic characteristics, the basis for developing many particle instrumentations. Consider two pieces of identical paper: One is squeezed into a paper ball and the other remains flat, and they are tossed into the air. The paper ball will drop quickly, while the flat piece may float in the air for a long period of time. Detailed particle shape and its effect on the particles will be described in Chapter 4.

2.3 PARTICLE SIZE

Particle size is the most important property of particles because it affects the behavior, transport, and control technologies of the particles. Sizes of particles can range widely. It is common for particle size to vary several 100- or several 1000-fold. The relative size of a large particle and a small particle can be illustrated in the astronomical image (Figure 2.2) of the sun and the earth. The little dot at the upper right corner represents the relative size of the earth to the sun. The relative sizes of the largest to the smallest particles in Figure 2.2 are analogous to the relative sizes of the moon to a space station, a space station to a grain of sand, a grain of sand to a cigarette smoke particle, and a cigarette smoke particle to a gas molecule. The range of particle sizes in Figure 2.2 can be found in the same type of particles. For example, dust in an animal production building may contain particles as large as 100 microns and as small as 0.01 micron. A dust fall following a volcano eruption contains large particles (in the range of millimeters) that can settle down in a few hours, and small particles (in the range of submicrons) that can stay airborne for years.

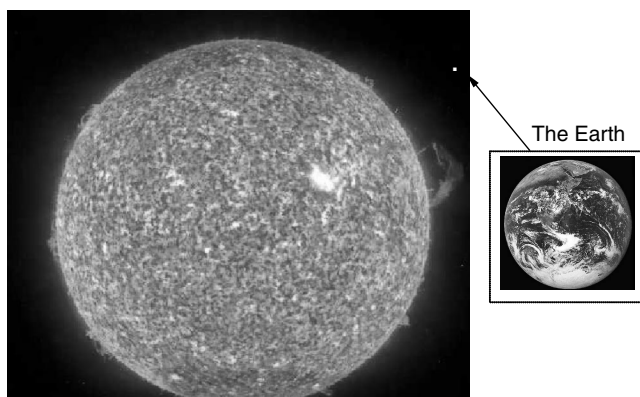


Figure 2.2 Commonly, the sizes of concerned particles vary several 100- or 1000-fold. Relative sizes of a large particle to a small particle are illustrated in this astronomical image of the sun and the earth. (Courtesy of SOHO/EIT consortium, a project of international cooperation between ESA and NASA.)

Table 2.1 Dimensions of Length, Symbols, and Typical Particles at Respective Size Ranges

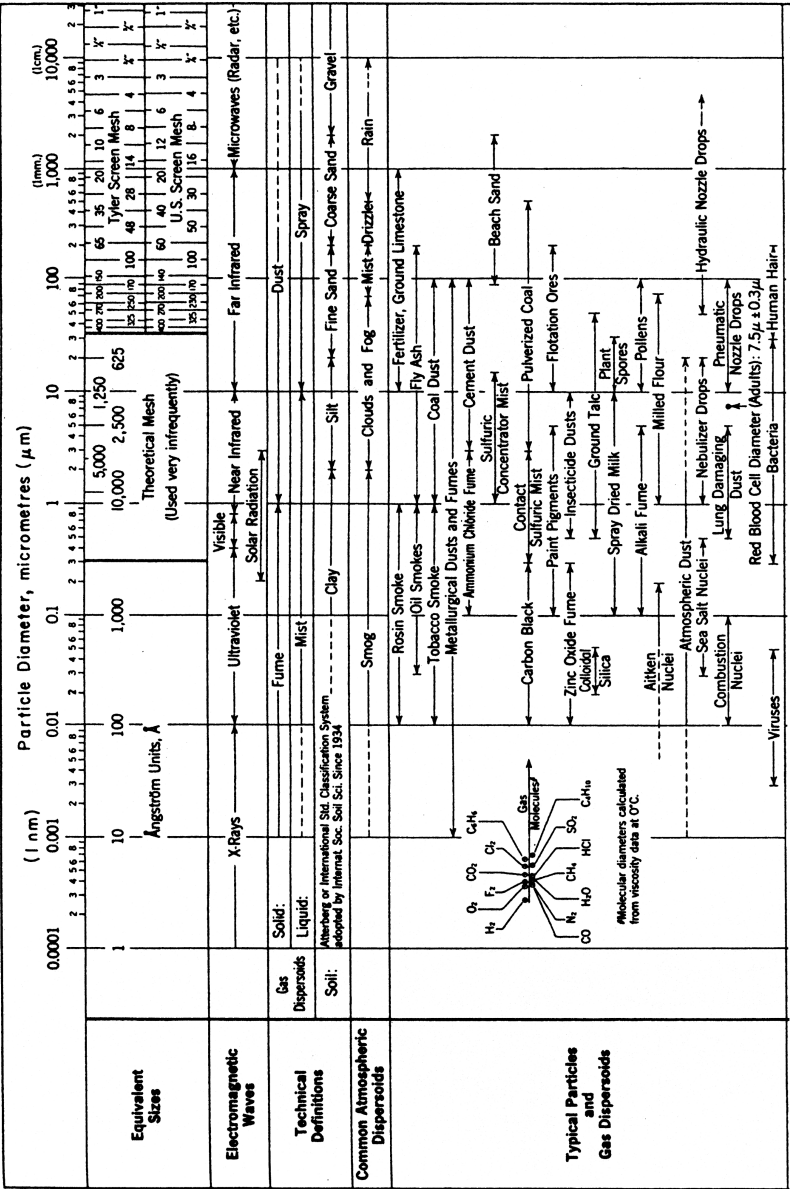
Terminology	Symbol	Dimension (m)	Typical Particles in the Size Range
Kilometer	km	10^3	A small moon
Meter	m	1	A concrete road block
Decimeter	dm	10^{-1}	A soft ball
Centimeter	cm	10^{-2}	A mint candy
Millimeter	mm	10^{-3}	A grain of sand
Micrometer	μm	10^{-6}	A cigarette smoke particle
Nanometer	nm	10^{-9}	A large gas molecule
Angstrom	$\text{\AA}$	10^{-10}	A small gas molecule

An appreciation of particle size ranges is fundamental to understanding particle properties. Particle size not only changes the particle properties but also the laws governing these properties, such as interaction and transportation. For example, gravitational force is the predominant bonding force among the very large particles, such as the sun and the earth. Drag force is the predominant force defining the motion of airborne particles ranging from submicrons to millimeters. Diffusion force, on the other hand, determines the mass transfer of gaseous molecules and the behavior of very small particles (typically smaller than $0.01\ \mu\text{m}$).

Airborne particles are one of the major concerns in indoor environments. Airborne particles are defined as particles that can be suspended in the air for an extended period of time under normal conditions. Thus, the particle size of concern for indoor air quality is no larger than a fine grain of sand (in a range of $100\ \mu\text{m}$ in diameter), because such large particles will quickly settle down to ground surfaces. The smallest particles of concern are usually larger than $0.01\ \mu\text{m}$. Particles smaller than $0.01\ \mu\text{m}$ can be treated as gas. Gas molecules, which are considered spherical particles ranging in size from 1 to $10\ \text{\AA}$, will not be treated in the context of particulate matter.

To determine the size of a particle, it is important to have a yardstick for measurement. A commonly used yardstick is micrometers, or microns (μm). In this book, particle size refers to a particle's diameter d in microns. When particle type must be distinguished to avoid confusion, subscripts are used to refer to specific particles. For example, d_p is used for solid particles, d_l for liquid particles, and d_g for gaseous molecule particles. Table 2.1 lists the dimensions commonly used in daily life and in particle sciences. Examples of typical particles within the size range gives a perspective on the different dimensions.

In bright sunlight, a naked human eye can visualize an airborne particle approximately $50\ \mu\text{m}$ in diameter, which is about the diameter of a human hair. Some typical particles and their size ranges are shown in Figure 2.3. Particles in Figure 2.3 range from $1\ \text{\AA}$ to $3\ \text{cm}$, or from about the size of a gas molecule to that of a golf ball. Particles in Figure 2.3 include solid, liquid, and gaseous particles. Very small particles, such as gaseous molecules, have very different properties and behave differently from particles larger than $1\ \mu\text{m}$. This fact is the primary reason for discussing gaseous contaminants and particulate contaminants separately.



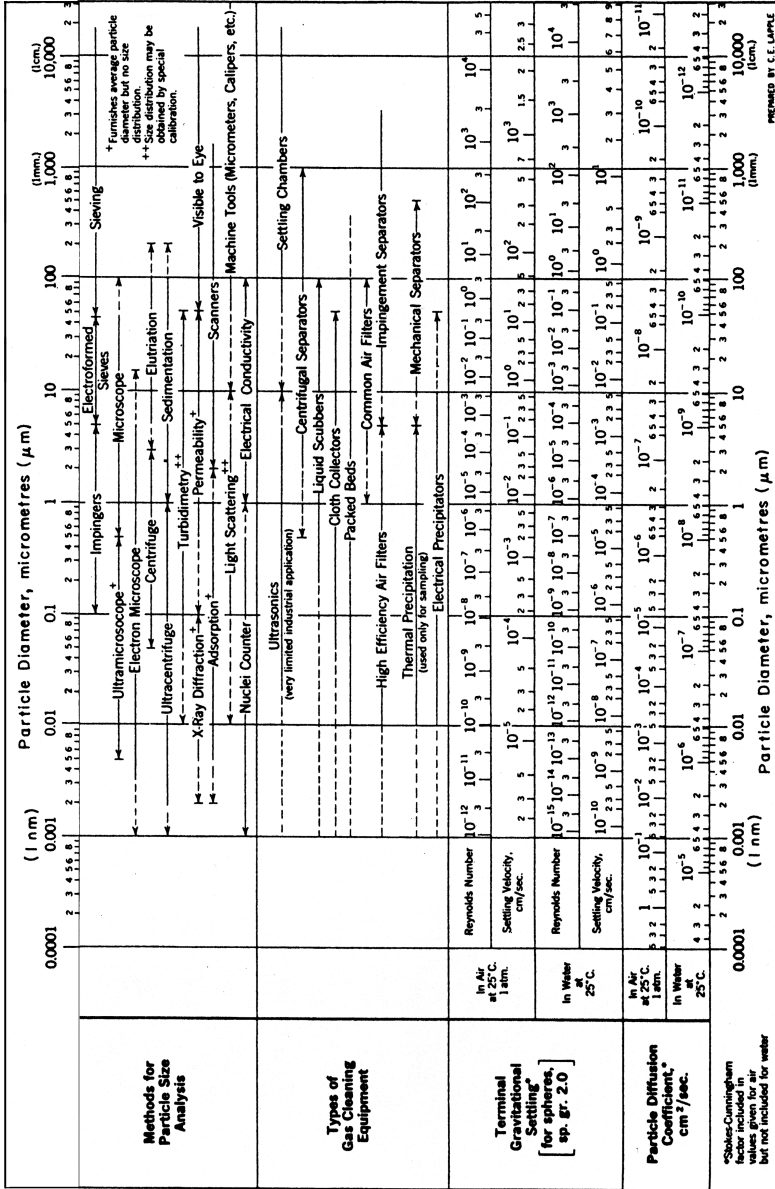


Figure 2.3 Continued.

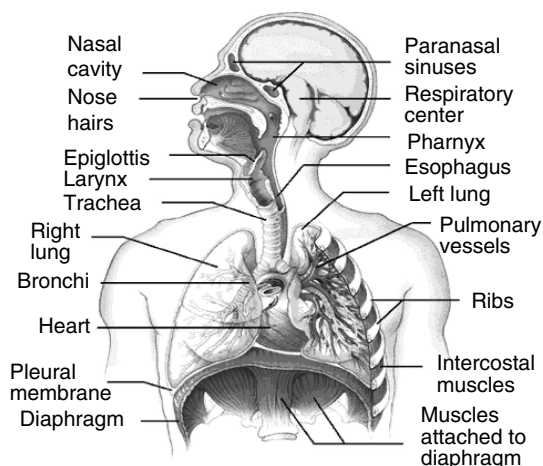


Figure 2.4 An overview of the human respiratory system. (From *The Atlas of the Human Body*, American Medical Association Web site <http://www.ama-assn.org>, 1999. With permission.)

2.3.1 Human Respiratory System

One common characterization of particle size derives from occupational health and safety, in which the primary concern is particle size and deposition in a human respiratory system. Humans have developed effective defense mechanisms to prevent airborne particles from entering the respiratory system, especially some sensitive regions. Figure 2.4 gives an overview of a human respiratory system.

The human respiratory system can be divided into three major regions:

- Head airways region
- Tracheobronchial region
- Pulmonary or alveolar region

The head airways region includes the nasal cavity, pharynx, epiglottis, and larynx. This region is also called the *extrathoracic* or *nasopharyngeal* region. Inhaled air is pretreated (heating and humidification) and large particles are intercepted in this region. The tracheobronchial region, also called *thoracic* or *lung airways* region, includes the airways from trachea to bronchi at both sides of the lung. The pulmonary region includes the pulmonary vessels or alveolar ducts, shown as the inverted tree area in Figure 2.4. This is the working area where gas exchanges take place. For an adult person, the total area of gas exchange is approximately 75 m², and the total length of the pulmonary vessels is about 2,000 km. An adult person breathes about 12 to 20 times per minute and inhales about 10 to 20 liters of air per minute at a moderate workload.

2.3.2 Particle Size Categories

According to the behavior of particles in the human respiratory system, particle size is divided into three major categories: inhalable particles, thoracic particles, and

Table 2.2 Commonly Used Terms and Size Ranges of Particles

Particles	Size Range
Total ^a	All sizes of particles of concern in the air
Inhalable (inspirable) ^a	≤ 100 μm
Thoracic ^b	≤ 10 μm
Respirable ^b	≤ 4 μm
Diminutive ^c	≤ 0.5 μm
PM10 (coarse particles) ^d	≤ 10 μm
PM2.5 (fine particles) ^d	≤ 2.5 μm

^a Source: Vincent, J. H., *Aerosol Sampling — Science and Practice*, John Wiley & Sons, New York, NY, 1989.
^b Source: ACGIH, *Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices*, American Conference of Governmental Industrial Hygienists, Cincinnati, OH, 2000.
^c Source: Zhang et al., *Am. Soc. Heat. Refrig. Air Cond. Eng.* 100(1): 906–912, 1994.
^d Source: EPA, *Terms of Environment*, U.S. Environmental Protection Agency, Washington, DC, 1998.

respirable particles.¹ These three particle size categories correspond to the three regions of the human respiratory system where the particles can deposit: head airways region, tracheobronchial region, and pulmonary or alveolar region. A particle category can more simply (but less accurately) be defined as the particle sizes at which the sampling efficiency is 50% in mass with the respective sampler. The particle size at 50% sampling efficiency is also called *particle cutsize* or *particle cutpoint*. Obviously, such a definition and the median point vary with the type of sampler and its sampling (also called *aspiration*) efficiency. Sampling efficiencies will be discussed in more detail in later chapters. Other particle categories include total particle,² diminutive particle,³ PM2.5, and PM10,⁴ which have different definitions from the sampling efficiency-based definition. The terminologies and size ranges of particles are summarized in Table 2.2.

More accurate definitions and characteristics of particle size categories are given in the following paragraphs and illustrated in Figure 2.5. In a practical respiratory system, the particle mass fraction collected in a region is a gradual curve, rather than a sharp cut, as given in Table 2.2. The cutsize only indicates the particle size at which the mass collection efficiency reaches 50%. It is obvious that, in terms of particle mass concentrations, the total particle is greater than the inhalable, the inhalable is greater than the thoracic, the thoracic is greater than the respirable, and the respirable is greater than the diminutive.

The term *inhalable particle* refers to the particles that can be inhaled by an air sampler during a measurement process. The air sampler could be a sampling instrument or a human respiratory tract. One of the widely used cutsizes for inhalable particle mass is defined as 100 μm.¹ The inhalable particle size may be different from the actual particle size in the air sample, depending on the efficiency of inhalation (or aspiration) of the sampler. Although the definition of inhalable particles includes all sizes, it is based on the study of particles smaller than 100 μm.⁵ One reason for this definition is that particles larger than 100 μm will settle down quickly under normal conditions. Some early studies defined inhalable particles as those

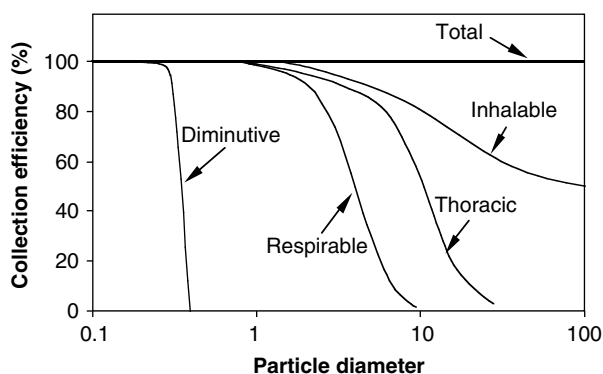


Figure 2.5 Particle categories (in mass fraction) defined by their collection efficiencies. Note that inhalable, thoracic, and respirable particles refer to the particles at which the collection efficiencies are 50%.

particles smaller than $30\text{ }\mu\text{m}$,⁶ because there are rarely particles larger than $30\text{ }\mu\text{m}$ in indoor environments. As a practical matter, larger particles are more difficult to inhale into a sampler. Therefore, some particle measurement instruments have particle upper size limits smaller than $30\text{ }\mu\text{m}$. An alternative term for inhalable particles is *inspirable particles*.⁷ The International Organization for Standardization (ISO) defines inspirability as the orientation-averaged aspiration efficiency for a human head. This definition was largely based on work done by Ogden and Birkett⁶ for particles smaller than $30\text{ }\mu\text{m}$. Sampling/aspiration efficiency for different types of samplers is discussed in later chapters.

Thoracic particles are defined as particles that can be deposited in the lung airways and gas exchange regions of a human respiratory system. The cutsize of thoracic particle mass is $10\text{ }\mu\text{m}$.¹ This definition is the same as that of the ISO.⁷

The term *respirable particles* refers to the particles that can travel to and deposit in the gas exchange region of a human respiratory system. There are differences among the size ranges of respirable particles as defined by different agencies or scientific societies. For example, the American Conference of Governmental and Industrial Hygienists (ACGIH) defines respirable particles as particles smaller than $4\text{ }\mu\text{m}$.¹ This definition is in accord with the ISO⁷ and the European Standardization Committee.⁸ The British Medical Research Council (BMRC) considers respirable particles to be smaller than $7\text{ }\mu\text{m}$.² In occupational health studies regarding working conditions in biological structures such as animal buildings, the respirable particle is suggested to be a particle smaller than $5\text{ }\mu\text{m}$.⁹ In this book, the term *respirable particle* refers to the particles smaller than $4\text{ }\mu\text{m}$.

The concept of total particles was introduced in the early days of environmental and occupational health studies. The total particle refers all airborne particles in an air sample. If an air sampler has a 100% sampling efficiency for all sizes of particles, particles sampled by the sampler would be the *true* total particle in the air. In practice, such an air sampler with a particle sampling efficiency of 100% for all particle sizes at all sampling conditions does not exist. Thus, the total particle was effectively defined entirely by the particular instrumentation under given sampling conditions.

By carefully designing a sampler and choosing sampling conditions, sampling efficiency close to 100% can be achieved; thus, the total particle can be measured, at least for the particles with aerodynamic diameters smaller than 30 μm .

In other practical scenarios, such as evaluation of particle control technologies, some extremely small particles must be excluded, especially when the particle concentration is measured in numbers rather than mass. *Diminutive particles* were introduced for such a purpose. Diminutive particles are defined as particles smaller than 0.5 μm .³ The reason for introducing the diminutive particles into the study was to isolate the effect of background particles contained in the supply air from atmosphere on indoor air particle number concentrations. In many indoor air quality problems, the supply air to the indoor environment is not filtered. The supply air (often the atmospheric air outdoors) contains a large number of small particles, typically smaller than 0.5 μm . When particle count concentration is used instead of particle mass concentration, very small particles may have a predominant majority of particle count; even the mass of these large numbers of small particles is very small compared to the total mass of particles. Diminutive particles are useful in identifying or analyzing the particles generated within a concerned airspace. Some particle statistics exclude particles smaller than 0.3 μm in diameter, because of the optical cut-off phenomenon.¹⁰ Particles smaller than 0.3 μm in diameter cannot be measured using the light scattering principle.

Concerning emissions and outdoor air pollution, the particle size is often characterized using the terms PM2.5 and PM10. PM2.5 refers to particulate matter smaller than 2.5 μm in diameter and is also called *fine particles*. PM10 refers to particulate matter nominally smaller than 10 μm and also is called *coarse particles*.⁴

2.3.3 Particle Diameters

The highly irregular shape of particles, together with variations in density, calls for a term to describe the size of a particle. A particle's size refers to its *diameter*. However, a diameter can have different meanings. Understanding the meaning of different types of diameters is important to the study of particle properties and behavior. The following diameters are relevant to airborne particle behavior and are frequently encountered in the literature:

Equivalent volume diameter (d_e) of an irregularly shaped particle is defined as the diameter of the sphere that would have the same volume and density as the particle. As an example of determining the equivalent diameter, consider a piece of irregularly shaped glass. If the glass piece were melted and filled up a sphere (the sphere must be full) with a diameter d , then the d is the equivalent diameter (d_e) of that piece of glass.

Stokes diameter (d_s) is defined as the diameter of the sphere that would have the same density and settling velocity as the particle. To determine the Stokes diameter, consider the same piece of irregularly shaped glass as an example. If a ball made of the same glass had the same settling velocity as that of the irregularly shaped piece, the diameter of the glass ball would be the Stokes diameter of the irregularly shaped glass piece. Settling velocity can be determined by releasing the glass ball at a sufficient height H and recording the traveling time t . The settling velocity

will be H/t . This method is usually sufficiently accurate for particles smaller than 200 μm .

Aerodynamic diameter (d_a) of an irregularly shaped particle is defined as the diameter of the sphere with a standard density (1,000 kg/m^3) that would have the same settling velocity as the particle. If we use the irregularly shaped piece of glass as an example, the aerodynamic diameter can be determined by comparing the settling velocities of the glass piece with a water droplet (an approximate sphere with a standard density). If the water droplet had the same settling velocity as the glass piece, the diameter of the water droplet would be the aerodynamic diameter of the glass piece.

The equivalent volume diameter only standardizes the shape of the particle by its equivalent spherical volume. The Stokes diameter standardizes the settling velocity of the particle but not the density. The aerodynamic diameter standardizes both the settling velocity and the density of the particles; thus the aerodynamic diameter is a convenient variable to use when analyzing particle behavior and design of particle sampling or control equipment. Aerodynamic diameter is a critical property of particles. More analysis of aerodynamic diameter and its applications is found in later chapters. In this book, particle size refers to its aerodynamic diameter unless otherwise specified.

Other statistically averaged diameters, such as median diameter and mean diameters for mass, volume, surface, length, and count, will be discussed in Chapter 3.

2.4 CONCENTRATION OF GASES AND PARTICLES

A concentration of an airborne contaminant is a quantitative measurement of pollution. The concentration can be expressed in terms of mass, volume, or particle number of the concerned contaminant per unit volume of air.

Particle mass concentration C_{pm} is the mass of the particles per unit volume of air in which the particles are airborne, usually in mg/m^3 (milligram of particles per cubic meter of air). Particle number concentration C_{pn} is the number of particles per unit volume of air in which the particles are airborne, in particles/m^3 or count/m^3 . In practice, often the C_{pn} is in particles/cm^3 (number of particles per milliliter) for convenience, because the C_{pn} usually exceeds 10^4 in particles/m^3 . Particle mass and number concentration can be converted back and forth if the density and size of the particles or the size distribution of the particles is known.

Assume that the particles in an air sample are composed of n sizes, each with an equivalent volume diameter d_{ei} , a density ρ_{pi} , and a fractional mass concentration, C_{pmi} . The mass of a particle at i^{th} size, m_{pi} , is

$$m_{pi} = \frac{\pi d_{ei}^3 \rho_{pi}}{6} \quad (2.1)$$

The particle number concentration at i^{th} size can be calculated as

$$C_{pmi} = \frac{C_{pmi}}{m_{pi}} = \frac{6 C_{pmi}}{\pi d_{ei}^3 \rho_{pi}} \quad (2.2)$$

The total particle number concentration C_{pn} can be obtained by adding particle number concentrations over the n size ranges:

$$C_{pn} = \sum_{i=1}^n \frac{C_{pmi}}{m_{pi}} = \frac{6}{\pi} \sum_{i=1}^n \frac{C_{pmi}}{d_{ei}^3 \rho_{pi}} \quad (2.3)$$

where C_{pn} is in particles/m³, C_{pmi} is in kg/m³, d_e is the equivalent volume diameter in m, and ρ_p is the density of the particles in kg/m³. Care should be exercised in applying consistent units in Equation 2.1 through Equation 2.3. Often, conversions are needed before values can be substituted into the equations.

Assuming that the sampling rate is Q_s in m³/s and the sampling time is t in seconds, the total mass m_s or total number of particles N_s for a given size of particles can be calculated as follows:

$$m_s = Q_s C_{pm} t \quad (2.4)$$

$$N_s = Q_s C_{pn} t \quad (2.5)$$

Example 2.1: An employee works in a building for eight hours per day. Total dust particle concentration in that building is measured at 1.2 mg/m³, of which approximately 10% consists of thoracic particles (< 10 μm). An average person's breathing rate is approximately 20 L/min. Assume the thoracic particles have an average equivalent volume diameter of 1.5 μm, other particles have an average equivalent volume diameter of 12 μm; the density for all particles is 2,000 kg/m³. Assume only thoracic particles can be inhaled. Find the following:

- The total particle number concentration of the building air (in particles/ml)
- How many milligrams of particles the worker inhales during a 2-hour work period
- How many particles the worker inhales during the 2-hour work period

Solution:

- Because the particles are divided into two size ranges with average equivalent volume diameters of 1.5 μm and 12 μm

$$C_{pm1} = 1.2 \text{ mg/m}^3 \times 10\% = 0.12 \text{ mg/m}^3 = 1.2 \times 10^{-7} \text{ kg/m}^3$$

$$C_{pm2} = 1.2 \text{ mg/m}^3 \times 90\% = 1.08 \text{ mg/m}^3 = 1.08 \times 10^{-6} \text{ kg/m}^3$$

Substituting the preceding values into Equation 2.3 gives the total particle number concentration:

$$C_{pn} = \frac{6}{\pi} \sum_{i=1}^n \frac{C_{pmi}}{d_{ei}^3 \rho_{pi}}$$

$$= \frac{6}{\pi} \left(\frac{1.2 \times 10^{-7} (kg / m^3)}{(1.5 \times 10^{-6} m)^3 \times 2000 (kg / m^3)} + \frac{1.08 \times 10^{-6} (kg / m^3)}{(12 \times 10^{-6} m)^3 \times 2000 (kg / m^3)} \right)$$

$$= 3.51 \times 10^7 (particle / m^3)$$

- b. Because $Q_s = 20 \text{ l/min} = 1.2 \times m^3/h$ and $t = 2 \text{ h}$, using Equation 2.4 gives

$$m_s = Q_s C_{pm1} t = 1.2 \left(\frac{m^3}{h} \right) \times 1.2 \times 10^{-7} \left(\frac{kg}{m^3} \right) \times 2 (h)$$

$$= 2.88 \times 10^{-7} (kg) = 0.288 (mg)$$

$$= 2.88 \times 10^{-4} (g) = 0.288 (mg)$$

- c. Using the mass concentration, $C_{pm1} = 0.12 \text{ mg/cm}^3$, and the average diameter $1.5 \mu m$ for thoracic particle, yields

$$N_s = Q_s C_{pm1} t = 1.2 \left(\frac{m^3}{h} \right) \times \frac{6 \times 1.2 \times 10^{-7} (kg / m^3)}{\pi (1.5 \times 10^{-6} m)^3 \times 2000 (kg / m^3)} \times 2 (h)$$

$$= 8.15 \times 10^7 (particles)$$

Concentration of gaseous contaminant C_g is usually expressed in terms of part of gas of concern per million parts of air (ppm):

$$1 \text{ ppm} = 10^{-6} \frac{\text{amount of gas of concern}}{\text{amount of carrying fluid}} \quad (2.6)$$

The ppm could be in either mass concentration C_{gm} or volume concentration C_{gv} . To distinguish the difference between mass and volume, ppmm refers to the gas concentration in mass, and ppmv refers to the gas concentration in volume. Unless specified, ppm is in volumetric concentration in this book. When a gas is expressed

in mass concentration, the value of ppmm is in mg/kg (milligram of gas of concern per kilogram of air). For example, 300 ppmm is equal to 300 mg of gas per kg of air, or 0.0003 kg of gas per kg of air. When a gas is expressed in volume concentration, the value of the ppm is in ml/m³ (milliliter of gas of concern per cubic meter of air). For example, 100 ppm is equal to 100 ml of gas of concern per m³ of air, or 0.0001 m³ of gas per m³ of air. The mass and volume concentration of a gas can be converted back and forth if the densities of the gas and the air are known at the given conditions (temperature and pressure). Unless specified, the temperature and atmospheric pressure in this book are assumed to be at standard conditions, 20°C and 101.315 kPa, respectively.

$$C_{gv} = C_{gm} \frac{\rho_a}{\rho_g} \quad (2.7)$$

where C_{gv} is in ppmv, C_{gm} is in ppmm, ρ_a and ρ_g are densities of air and gas, in kg/m³, respectively.

In some instances, the concentration of a gaseous contaminant is expressed in mg of the contaminant per cubic meter of air: mg/m³. To convert the concentration of gases or vapor between mg/m³ and ppmv, the following equation can be used:

$$C \left(\text{in } \frac{\text{mg}}{\text{m}^3 \text{ air}} \right) = C_{gv} (\text{in ppmv}) \times \rho_g \quad (2.8)$$

When the molar weight of the gas is known, an alternative conversion can be expressed as

$$C \left(\text{in } \frac{\text{mg}}{\text{m}^3 \text{ air}} \right) = \frac{C_{gv} (\text{in ppmv}) \times M}{24.5} \quad (2.9)$$

where M is the molar weight of the gas, and 24.5 is the molar volume of air, in liter per mole, under standard atmospheric conditions (20°C and 101.325 kPa). It should be noted that Equation 2.7 and Equation 2.8 are the same except for the units.

Example 2.2: The carbon dioxide concentration in the ground-level atmosphere is 350 ppmv. The densities of air and carbon dioxide are 1.2 and 1.82 kg/m³, respectively. What is the carbon dioxide concentration in ppmm and in mg/m³ of air?

Solution: Using Equation 2.7 and Equation 2.8

$$C \left(\text{in } \frac{\text{mg}}{\text{m}^3 \text{ air}} \right) = C_{gv} (\text{in ppmv}) \times 1.82 = 350 \times 1.82 = 637 \text{ (mg / m}^3 \text{)}$$

Table 2.3 Particulate Contaminant Sources in Typical Residential (Including Office and Commercial) and Animal Buildings

Residential Buildings		Animal Buildings	
Contaminant	Source	Contaminant	Source
Asbestos	Insulation, siding shingles, roofing materials, textured paints, adhesives, paper, millboard	Feed particles	Grain dust, antibiotics, growth promotants
Dust and molds	Foodstuff, furniture, household products, office machinery, pollen	Fecal material	Dry feces, dead organisms, endotoxins
Dust mites	Carpet, foodstuff, dander, soil	Animal protein	Urine, dander, serum, hair or feathers, mold, pollen, grain mites, insects
Allergens	Pollen, molds, dust mite feces, organisms, dander and animal hairs, endotoxins, household chemicals	Smoke and fumes	Heating systems, sterilizing fumigation, tattooing
Smoke and fumes	Combustion, cooking, smoking, evaporation	Gases and odor	Fecal material, urine, animal bodies
VOC	Formaldehyde, fragrance products, pesticides, solvents, cleaning agents	Other agents	Mineral ash, gram-negative bacteria, microbial proteases, infectious agents
Radon	Soils, well water, building materials		

2.5 AIR CONTAMINANTS AND SOURCES

Identification of sources of particulate contaminants in an indoor environment is important for implementation of appropriate air quality control strategies. Due to the differences in functions and structures of buildings, it is useful but very difficult to have a complete list of sources of particulate contaminants. Most of the airborne contaminants in residential buildings are also present in animal buildings. Additionally, more contaminants, usually in much higher concentrations, are found in animal buildings. Common indoor airborne contaminants in residential and animal buildings and their sources are listed in Table 2.3. When considering typical airborne contaminants with sources found indoors, some deserve more detailed descriptions. The composition of typical contaminants is listed in Table 2.4.

2.5.1 Asbestos

Asbestos is a generic term for a group of naturally occurring mineral silicates in various forms that have been used extensively for building materials including insulation, siding shingles, roofing materials, textured paints, and adhesives. Asbestos, like many minerals, may be present in fibrous (asbestiform) or crystalline (nonasbestiform) forms. There are two basic types of asbestiform asbestos:

- Serpentine, of which chrysotile $\{\text{Mg}_3[\text{Si}_2\text{O}_5](\text{OH})_4\}$ is the sole member
- The amphiboles, of which there are several types, including anthophyllite $\{\text{Mg}, \text{Fe}^{2+}\}_7[\text{Si}_8\text{O}_{22}](\text{OH}, \text{F})_2\}$, amosite $\{(\text{Fe}^{2+})_4(\text{Fe}^{2+}, \text{Mg})_3[\text{Si}_8\text{O}_{22}](\text{OH})_2\}$, and crocidolite $\{\text{Na}_2\text{Fe}_3^{2+}\text{Fe}_2^{3+}[\text{Si}_8\text{O}_{22}](\text{OH}, \text{F})_2\}$

Asbestos fibers are characterized by their large aspect (or length-to-width) ratio and small diameter. Breathing of high levels of asbestos fibers can lead to an increased risk of lung cancer and asbestosis, in which the lungs become scarred with fibrous tissue. The symptoms of these diseases do not usually appear until about 20 to 30 years after the first exposure to asbestos.

There are thousands of commercial products that use asbestos because of its high tensile strength, flexibility, and resistance to temperature, acids, and alkali. Asbestos fibers have been used widely as a building material for fire prevention, thermal and acoustical insulation, and roofing; as a friction material in brake pads; and as a reinforcing material in cement. Because of the widespread use of asbestos, its fibers are ubiquitous in indoor environments. Although there has been declining production due to bans and voluntary phase-outs, it is still common to find asbestos products in older buildings, where they were often the materials of choice for insulation, tiles, and other building products prior to 1975. In a survey of public buildings, the EPA¹¹ found that friable asbestos-containing materials (ACMs) were present in 16% of the buildings surveyed (511,000 of 3.2 million).

The permissible exposure limit (PEL) for asbestos is 0.1 fiber/cm³ for occupational environments, regardless of the condition of the asbestos. There have been many determinations of asbestos fiber levels in outdoor and indoor air in the U.S. and Europe. The National Research Council¹² summarizes that the range of fibers in urban air is between 0.0002 and 0.00075 fibers per cubic centimeter of air. Indoor air in public buildings has an average concentration of 0.0000770 fiber/cm³ in buildings with intact asbestos levels, which is at least 1000 times below the PEL.

Although asbestos is present in almost every building, it is usually not a serious problem, because the mere presence of asbestos in a building is not considered air pollution or hazardous. The danger is that asbestos materials may become damaged over time. The detached asbestos is then airborne and becomes a health hazard. Burdette et al.¹³ have shown that asbestos removal can lead to the increase of indoor airborne asbestos fiber levels (< 0.0002 to 0.004 fiber/cm³ 18 weeks after removal) that can remain for a year or longer. Thus, caution should be exercised in removing asbestos: Improper removal can be more hazardous than leaving it in place. The EPA¹⁴ recommends the removal of badly damaged friable asbestos, leaving intact, well-maintained asbestos in place.

2.5.2 Formaldehyde

Formaldehyde, a colorless, pungent-smelling gas, is a major allergy agent in indoor environments. It can cause watery eyes, burning sensations in the eyes and throat, nausea, and difficulty breathing in some humans who are exposed at elevated levels (above 0.1 ppm). High concentrations may trigger attacks in people with asthma. There is evidence that some people can develop a sensitivity to

Table 2.4 Chemical and Biological Composition of Typical Airborne Contaminants in Indoor Environments

Residential Buildings	Animal Buildings ^d
<i>Toxic substances:</i> ^a	
Benzene	1,2,4-trimethyl benzene
Dichloromethane	1,2,3-trimethyl benzene
Tetrachloroethylene	Vinyl toluene
Trichloroethylene	Propyl toluene
1,2-dichloroethane	Σ ethyl dimethyl benzenes
	1,1-dimethyl butyl benzene
	1,1-diethylpropyl benzene
	1-propylheptyl benzene
	1-ethyloctyl benzene
	1,1,4,6,6-pentamethyl heptyl benzene
	1,1-dimethyldecyl benzene
	2-methyl 2-phenyl tridecane
	1,1-dimethylnonyl benzene
	Chloride hydrocarbons
	1,1,2-trichloro
	1,2,2-trifluoro ethane
	Ketones
	2-butanone
	Cyclohexanone
	1-phenyl ethanone
	5-Methyl 5-phenyl 2-hexanone
	Alcohols
	1-methoxy 2-propanol
	1-ethoxy 2-ethanol
	1-ethoxy 2-propanol
	2-ethyl hexanol
	2-(butoxyethoxy) ethanol
	Phenol/phenolic derivatives
	2-i-propyl phenol
	3-i-propyl phenol
	2,4-di-i-propyl phenol
	Acids/acid derivatives
	Acetic acid
	2,6-di-i-propyl
	4-methyl phenomethylamide
	2-ethyl hexanoic acid
	2-methyl propanoic acid, 1-(1,1-dimethylethyl)-2-methyl propyl diester
	Others
	Hexanal
	Nonanal
	2-vinyl pyrazine
<i>Molds and fungi:</i> ^b	
Alternaria	<i>Gram positive cocci:</i>
Cladosporium	Staphylococcus species (coagulase negative)
Aureobasidium pullulans	Staphylococcus
Aspergillus	haemolyticus
Ulocladium	Staphylococcus hominis
Epilicium	Staphylococcus simulans
Geotrichum	Staphylococcus sciuri
Aspergillus	Staphylococcus warneri
Versicolor	Micrococcus species
Penicillium species	Aerococcus species
Paecilomuces species	Streptococcus equinus
Helminthosporium	Streptococcus suis (presumptive)
Mucor	Enterococcus durans
Rhizopus	
Verucosum	<i>Gram positive bacilli:</i>
Fusarium poae	Corynebacterium species
Sporotrichioides	Corynebacterium xerosis
Yeasts	Bacillus species
Algae	
	<i>Gram negative bacilli:</i>
	Acinetobacter calcoaceticus
	Nonfermentative Gram negative bacillus
	Enterobacter agglomerans
	Pasteurella species
	Vibrio species
<i>VOCs:</i> ^c	
Alkane	<i>Fungi:</i>
Octane	Alternaria species
Tridecane	Cladosporium species
Trimethyl decane	Penicillium species
Tetradecane	
Pentadecane	
Aromatic hydrocarbons	
Toluene	
m,p-xylene	
Propyl benzene	
2-ethyl toluene	
3-ethyl toluene	
4-ethyl toluene	
Cumene	
1,3,5-trimethyl benzene	

^a Source: Otson, R., Meth, F., and Fellin, F., Identification of important sources of five priority substances in Canadian indoor air, *Indoor Air*, Proc. of 7th Int. Conf. on Indoor Air Quality and Climate, Nagoya, 1:565–573, 1996.

^b Source: Byrd, R.R., Prevalence of microbial growth in cooling coils of commercial air conditioning systems, *Indoor Air*, Proc. of 7th Int. Conf. on Indoor Air Quality and Climate, Nagoya, 3:203–207, 1996.

^c Source: Kichner, S. and Karpe, P., Contribution of volatile organic compounds to the odor of building materials, *Indoor Air*, Proc. of 7th Int. Conf. on Indoor Air Quality and Climate, Nagoya, 2:663–668, 1996.

^d Source: Martin W.T., Zhang, Y., Willson, P.J., Archer, T.P., Kinahan, C., and Barber, E.M., Bacterial and fungal flora of dust deposits, in a Wiegard, B. and J. Hartung, Bacterial contaminant of air and floor surfaces in an animal house of a cattle clinic, Proceedings of 4th Intern. Livestock Environ. Symp, 643–649, 1993. swine building, *Br. J. Occup. and Env. Med.*, 53:484–487, 1996.

formaldehyde. It has also been shown to cause cancer in animals and may cause cancer in humans.

Formaldehyde is an important chemical used widely by industries to manufacture building materials and numerous household products. It is also a by-product of combustion and certain other natural processes. Thus, it may be present in substantial concentrations both indoors and outdoors.¹⁵ Sources of formaldehyde in homes include building materials, smoking, household products, and unvented, fuel-burning appliances such as gas stoves or kerosene space heaters. Formaldehyde, by itself or in combination with other chemicals, serves a number of purposes in manufactured products. For example, it is used to add permanent-press qualities to clothing and draperies, as a component of glues and adhesives, and as a preservative in some paints and coating products. During the 1970s, many homeowners had urea-formaldehyde foam insulation (UFFI) installed in the wall cavities of their homes as an energy conservation measure. However, many of these homes were found to have relatively high indoor concentrations of formaldehyde soon after the UFFI installation. Average concentrations in older buildings (before 1980) without UFFI are generally well below 0.1 (ppm). In homes with significant amounts of new pressed wood products, levels can be greater than 0.3 ppm.¹⁵ Since 1985, the U.S. Department of Housing and Urban Development (HUD) has permitted only the use of plywood and particleboard that conform to specified formaldehyde emission limits in the construction of prefabricated and mobile homes.

In buildings, the most significant sources of formaldehyde are likely to be pressed wood products made using adhesives that contain urea-formaldehyde (UF) resins. Pressed wood products made for indoor use include particleboard (used as subflooring and shelving and in cabinetry and furniture), hardwood plywood paneling (used for decorative wall covering and in cabinets and furniture), and medium-density fiberboard (used for drawer fronts, cabinets, and furniture tops). Medium-density fiberboard contains a higher resin-to-wood ratio than any other UF pressed wood product and is generally recognized as being the pressed wood product that emits the highest levels of formaldehyde. Other pressed wood products, such as soft plywood and flake or oriented strand board, are produced for exterior construction use and contain the dark or red/black phenol-formaldehyde (PF) resin. Although formaldehyde is present in both types of resins, pressed woods that contain PF resin generally emit formaldehyde at considerably lower rates than those containing UF resin.

2.5.3 Molds

Molds are almost ubiquitous in indoor environments and play an important part in life cycles: They are the primary forces in assisting with decomposition of organic materials. Some molds cause illness and some, such as penicillin, cure illness. Certain molds help to develop the flavor of wines and cheeses, whereas others can cause them to spoil. There are thousands of types of molds and yeasts, the two groups of plants in the fungus family. Yeasts are single cells that divide to form clusters. Molds consist of many cells that grow as branching threads called *hyphae*. Although both groups can probably cause allergic reactions, only a few dozen types

of molds are significant allergens. In general, *Alternaria* and *Cladosporium* (*Homodendrum*) are the molds most commonly found both indoors and outdoors. *Aspergillus*, *Penicillium*, *Helminthosporium*, *Epicoccum*, *Fusarium*, *Mucor*, *Rhizopus*, and *Aureobasidium* (*Pullularia*) are also common. The seeds or reproductive particles of fungi are called *spores*. They differ in size, shape, and color among species. Each spore that germinates can give rise to new mold growth, which in turn can produce millions of spores.

Along with pollens from trees, grasses, and weeds, molds are an important cause of seasonal allergic rhinitis. Molds can live for years in a dormant state. To grow, the spores need moisture, warm temperature, low air movement, and a food source. Molds can become airborne when their habitats are disturbed by shaking or sweeping. The airborne molds can travel with air current, land on surfaces, and settle into the tiniest cracks and crevices of carpets, furniture, draperies, insulation, rough textures, and smooth surfaces. Heating and cooling ducts, wet carpets, damp upholstery, and air filters on air conditioners and furnaces become common habituating places for molds. People allergic to molds may have symptoms from spring to late fall. The mold season often peaks from July to late summer. Unlike pollens, molds may persist after the first killing frost. Some can grow at subfreezing temperatures, but most become dormant. Snow cover lowers the outdoor mold count dramatically but does not kill molds. After the spring thaw, molds thrive on the vegetation that has been killed by the winter cold. In temperature-controlled indoor environments, molds can thrive at all times, especially when the relative humidity is above 70%. When relative humidity is below 70%, the growth rate of molds quickly decreases. When the relative humidity is below 30%, the molds are primarily in the dormant stage.

Many airborne molds in indoor environments are responsible for human respiratory allergies. Reactions to molds can result in sneezing, itching, coughing, wheezing, shortness of breath, and chest pain. Molds are measured in spores/m³. Specific threshold limit values for molds have not been established to prevent hypersensitivity, irritant, or toxic responses. Like pollen counts, mold counts may suggest the types and relative quantities of fungi present at a certain time and place. For several reasons, however, these counts probably cannot be used as a constant guide for daily activities. One reason is that the number and types of spores actually present in the mold count may have changed considerably in 24 hours because weather and spore dispersal are directly related. Currently, information relating to molds and other bioaerosols consists largely of case studies and qualitative exposure assessment.¹ One rule of thumb for judgment is that mold concentration below 500 spores/m³ is considered low, 500 to 1500 spores/m³ is moderate, and above 1500 spores/m³ is high.

2.5.4 Dust Mites

Dust mites (*Dermatophagoides Farinae*) are microscopic, spiderlike insects found everywhere. An adult dust mite is approximately 200 μ m long and is usually invisible to the naked human eye (Figure 2.6). Dust mites are in the arachnid family, which includes spiders, scorpions, and ticks. Dust mites feed on dead skin that sloughs from our bodies (and probably on potato chips and cookie crumbs). They live their whole lives in dark-corner dust bunnies: hatching, growing, eating, defe-



Figure 2.6 A microscopic dust mite image. An adult dust mite is approximately 200 μm long and is usually invisible to the naked human eye.

cating, mating, and laying eggs. During warm weather, when the humidity is above 50%, they thrive and produce waste pellets. They live about 30 days, and the female lays approximately one egg each day. In less-than-ideal conditions, they can go into dormancy. When they die, their bodies disintegrate into small fragments, which can be stirred into the air and inhaled by people in the environment.

When they are present in indoor environments and inhaled by sensitive people, dust mites are responsible for many sick building symptoms. It is their “bathroom habits” that make us itch and wheeze. Many people develop severe allergies to dust mite droppings. Lie on a rug where they live and you may find itchy red bumps on your skin. Breathe in dust and you may have more serious symptoms, such as difficulty breathing or even a severe asthma attack. Dust mite allergy is an allergy to a microscopic organism that lives in dust that is found in all dwellings and workplaces. Dust mites are perhaps the most common cause of perennial allergic rhinitis. Dust mite allergy usually produces symptoms similar to pollen allergy and also can produce symptoms of asthma.

2.5.5 Smoke and Fumes

Environmental tobacco smoke (ETS) is a mixture of particles that are emitted from the burning end of a cigarette, pipe, or cigar, and from smoke exhaled by the smoker. Smoke can contain any of more than 4000 compounds, including carbon monoxide and formaldehyde. More than 40 of the compounds are known. Exposure to ETS is often called *passive smoking*. Fumes are a combination of particles and gases that are the result of combustion, high-temperature operations (such as cooking, welding, grinding), and adhesive applications. The chemical composition can be more complicated than ETS because fumes can come from a variety of sources.

ETS has been classified as a Group A carcinogen by the U.S. Environmental Protection Agency (EPA), a rating used only for substances proven to cause cancer in humans. The EPA¹⁶ concluded that each year approximately 3,000 lung cancer deaths in nonsmoking adults are attributable to ETS. Exposure to secondhand smoke also causes eye, nose, and throat irritation. It may affect the cardiovascular system,

and some studies have linked exposure to secondhand smoke with the onset of chest pain. ETS is an even greater health threat to people who already have heart and lung illnesses. Infants and young children whose parents smoke in their presence are at increased risk of lower respiratory tract infections (pneumonia and bronchitis) and are more likely to have symptoms of respiratory irritation, such as coughing, wheezing, and excess phlegm. In children under 18 months of age, passive smoking causes between 150,000 and 300,000 lower respiratory tract infections, resulting in 7,500 to 15,000 hospitalizations each year, according to EPA estimates.¹⁶ These children may also have a buildup of fluid in the middle ear, which can lead to ear infections. Slightly reduced lung function may occur in older children who have been exposed to secondhand smoke. Children with asthma are especially at risk from ETS. The EPA estimates that exposure to ETS increases the number of asthma episodes and the severity of symptoms in 200,000 to 1 million children annually.¹⁶ Secondhand smoke may also cause thousands of nonasthmatic children to develop the disease each year.

2.5.6 Radon (Rn)

Radon is a gaseous radioactive element with the symbol Rn, a molar weight of 222 g, a melting point of -71°C , a boiling point of -62°C , and 18 radioactive isotopes. It is an extremely toxic, colorless, and odorless gas; it can be condensed to a transparent liquid and to an opaque, glowing solid. It is used in cancer treatment, as a tracer in leak detection, and in radiography. Radon is a natural product of most soils and rocks as a result of radioactive decay of radium. An unventilated basement is the most likely place to have high radon concentrations.

Radon concentration indoors is in picocuries per liter of air (pCi/l). One curie (Ci) is 3.7×10^{10} radioactive disintegration per second. Thus, one pCi/l = $10^{-12} \times \text{Ci/l} = 0.037$ radioactive disintegration per second per liter of air. The average radon concentrations for outside and indoor air in the United States are 0.4 and 1.3 pCi/l, respectively.¹⁷

There is no scientific doubt that radon gas is a known human lung carcinogen. Prolonged exposure to high levels of radon gas can cause lung cancer. Millions of homes and buildings contain high levels of radon gas. As a means of prevention, the EPA and the Office of the Surgeon General recommend that all homes below the third floor be tested for radon. Because radon is invisible and odorless, a simple test is the only way to determine whether a home has high radon levels. Most homes do not have a radon problem. If a radon problem does occur, it is relatively easy to fix. Ventilation is the most effective method for diluting the radon concentration in an airspace.

2.5.7 Volatile Organic Compounds (VOCs)

Generally speaking, an organic compound is a compound that contains carbon and hydrogen. Some examples of organic compounds are octane, butane, and sugar. Organic compounds that evaporate easily are called *volatile organic compounds* (VOCs). VOCs in the atmosphere come from all combustible engines, industry, fuel

spills, animal and plant production facilities, etc. Certain other fumes, such as those released from industrial plants and print shops, also can contain significant amounts of VOCs. When released into the atmosphere, VOCs contribute to ozone and smog formation. In an indoor environment, VOCs can have direct adverse effects on human health and comfort. Many VOCs have been classified as toxic and carcinogenic, and it is therefore unsafe to be exposed to these compounds in large quantities or over extended periods of time. Some health effects from overexposure to VOCs are dizziness, headaches, and nausea. Long-term exposure to certain VOCs, such as benzene, has also been shown to cause cancer and, eventually, death.

2.5.8 Airborne Contaminants in Animal Environments

The most important contributor to airborne contamination in animal buildings may be dust. Animal building dust sources include feed grains, fecal material, animal skin and hair, insects, and dead microorganisms (Figure 2.6). Previously, dust in animal buildings was considered to originate primarily from feed,⁹ but a number of studies have shown that animal building dust is very complicated. Feddes et al.¹⁸ characterized dust in a turkey building and showed that most dusts may not be from feed. Fecal material was found to be the main constituent of airborne dust in turkey barns. In animal production buildings, especially when oil is added to the feed, it has been suspected that fecal material and animals are major dust sources. Adding oil to animal feed is one of the methods to control dust sources. In one study,¹⁹ it was proved that adding 2% oil to a swine feed formula reduced inhalable mass concentration by 31% and increased the respirable particle count by 45%, compared with the treatment where oil was not added.

Dust in animal buildings is biologically active and different from ordinary dust, such as field dust. Dust particles from animal buildings may combine components of viable organic compounds, mites, fungi, endotoxins, toxic gases, and other hazardous agents.^{3,20} Although the pathology of dusts in animal facilities remains unclear, there is little argument about their adverse effect on animal and human health. Some of the components, such as *Streptococcus suis*, are considered particularly hazardous to animals; others, such as *Alternaria* species, are suspected to be responsible for allergic symptoms in humans. In many animal production facilities, dusts tend to be accepted as a normal part of the job and may be ignored until permanent damage occurs. Toxic gases cause discomfort (e.g., nuisance odor or more dramatic symptoms), which attracts immediate attention and quick action in solving the problem. Dust control is one of the main tasks that will improve air quality in production animal facilities.

Household pets are a common source of allergic reactions to animals. Many people think that a pet allergy is provoked by the fur of cats and dogs. However, researchers have found that the major allergens are proteins secreted by oil glands in the animals' skin and shed in dander, as well as proteins in the saliva, which sticks to the fur when the animal licks itself. Urine is also a source of allergy-causing proteins. When the substance carrying the proteins dries, the proteins can then become airborne. Cats may be more likely than dogs to cause allergic reactions

because they lick themselves more frequently, may be held more, and spend more time indoors and close to humans. Some rodents, such as guinea pigs and gerbils, have become increasingly popular as household pets. They, too, can cause allergic reactions in some people, as can mice and rats. Urine is the major source of allergens from these animals.

Allergies to animals can take two years or longer to develop and may not subside for six months or more after contact with the animal has ended. Carpets and furniture are a reservoir for pet allergens, and the allergens can remain in them for four to six weeks. In addition, these allergens can stay in household air for months after the animal has been removed. Therefore, it is wise for people with an animal allergy to check with the landlord or previous owner to find out whether furry pets have lived previously on the premises.

2.6 THRESHOLD LIMIT VALUES FOR TYPICAL INDOOR AIR CONTAMINANTS

Threshold limit values (TLVs) refer to concentrations of airborne contaminants and represent conditions under which, it is believed, nearly all workers may be repeatedly exposed day after day without adverse health effects.¹ TLVs are based on available information from industrial experience, from experimental human and animal studies, and, when possible, from a combination of the three. The basis on which the values are established may differ from substance to substance; protection against impairment of health may be a guiding factor for some, whereas reasonable freedom from irritation, narcosis, nuisance, or other forms of stress may form the basis for others. Health impairments considered include those that shorten life expectancy, compromise physiological function, impair the capability for resisting other toxic substances or disease processes, or adversely affect reproductive or developmental processes.

Because of wide variation in individual susceptibility, however, a small percentage of workers may be affected more seriously by aggravation of a preexisting condition or by development of an occupational illness. For example, smoking may act to enhance the biological effects of chemicals encountered in the workplace and may reduce the body's defense mechanisms against toxic substances. Individuals may be hypersusceptible or unusually responsive to some airborne contaminants because of genetic factors, age, personal habits (e.g., smoking, alcohol consumption, or the use of other drugs), medication, or previous exposure. Such workers may not be adequately protected from adverse effects of certain chemicals at concentrations at or below the threshold limits.

There are two categories of TLVs, differentiated by their legal status:

- Mandatory and issued by governmental regulatory agencies, such as the EPA and the Occupational Safety and Health Agency (OSHA) in the United States
- Recommended and published by scientific communities, such as the American Conference of Governmental and Industrial Hygienists (ACGIH) or individual researchers

Mandatory TLVs are enforced by law. Recommended TLVs are intended for use in the practice of industrial hygiene as guidelines or recommendations in the control of potential health hazards in the workplace. These limits are not fine lines between safe and dangerous concentrations; neither are they a relative index of toxicity. In spite of the fact that serious adverse health effects are not believed to occur as a result of exposure to TLVs, the best practice is to maintain concentrations of all atmospheric contaminants as low as is practical.

Three categories of TLVs, according to the exposure, are the following:¹

Time-Weighted Average (TLV-TWA) — The time-weighted average concentration for a conventional eight-hour workday and a 40-hour work week, to which it is believed that nearly all workers may be repeatedly exposed, day after day, without adverse effect

Short-Term Exposure Limit (TLV-STEL) — The concentration to which it is believed that workers can be exposed continuously for a short period of time without suffering from 1) irritation, 2) chronic or irreversible tissue damage, or 3) narcosis of sufficient degree to increase the likelihood of accidental injury, impair self-rescue, or materially reduce work efficiency, provided that the daily TLV-TWA is not exceeded. STEL is not a separate, independent exposure limit; rather, it supplements the TWA limit where there are recognized acute effects from a substance whose toxic effects are primarily of a chronic nature. STELs are recommended only where toxic effects have been reported from high, short-term exposures in either humans or animals. A STEL is defined as a 15-minute TWA exposure that should not be exceeded at any time during a workday, even if the eight-hour TWA is within the TLV-TWA. Exposures above the TLV-TWA up to the STEL should not be longer than 15 minutes and should not occur more than four times per day. There should be at least 60 minutes between successive exposures in this range. An averaging period other than 15 minutes may be recommended when this is warranted by observed biological effects.

Ceiling (TLV-C) — The concentration that should not be exceeded during any part of the working exposure. An alternative term for TLV-C is *fatal exposure value* (FEV).

Not all three categories of TLVs are available for every airborne contaminant. Many airborne contaminants have only one or two of the TLVs. It is important to observe that if any one of these types of TLVs is exceeded, a potential hazard from that contaminant is presumed to exist. Typical indoor air contaminants are listed in Table 2.5. More complete lists of TLVs can be obtained from ACGIH.¹

Whereas the ceiling limit places a definite boundary that concentrations should not be permitted to exceed, the TWA requires an explicit limit to the excursions that are permissible above the TLV-TWAs. TWAs permit excursions above the TLV, provided they are compensated by equivalent excursions below the TLV-TWA during the workday. In some instances, it may be permissible to calculate the average concentration for a work week rather than for a workday. The relationship between the TLV and permissible excursion is a rule of thumb and, in certain cases, may not apply. The amount by which the TLVs may be exceeded for short periods without injury to health depends on a number of factors, such as the nature of the contaminant, whether very high concentrations — even for short periods — produce acute

Table 2.5 Typical Indoor Air Contaminant Threshold Values for Work Places

Contaminant	Symbol	Density (relative to air at room temperature)	Molar Weight (g)	Odor	TWA (in parts per million [ppm] for gases and mg/m ³ for dust)	STEV	FEV
Gaseous (ppmv)							
Ammonia	NH ₃	0.61	17	Sharp, pungent	25	35	300 ^c
Carbon dioxide	CO ₂	1.57	44	None	5,000	30,000	
Carbon monoxide	CO	1.00	28	None	25	400 ^c	
Formaldehyde	HCHO	1.06	30	Pungent		0.3	
Hydrogen sulfide	H ₂ S	1.20	34	Rotten eggs, nauseating	5	50	150
Methane	CH ₄	0.57	16	None	1,000		50,000
Ozone	O ₃	1.70	48	Odorous	0.1		
Radon	Rn	7.84	222	None		4pCi/l ^b	
Particulate matter (mg/m ³)							
Animal building dust, inhalable					2.3 ^a		
Animal building dust, respirable					0.23 ^a		
Asbestos					0.1 fiber/ml		
Coal dust, respirable					0.4		
Flour dust, inhalable					0.5		
Grain dust, inhalable					4.0		
Iron oxide dust and fume, inhalable					5.0		
Metal dust, inhalable					10.0		
Welding fumes					5.0		
Particulates not otherwise classified (PNOC), inhalable					10.0		
Particulates not otherwise classified (PNOC), respirable					3.0		

^a From Canada Plan Service, M-8710, 1985; M-9707, Ottawa, Canada, 1992.
^b EPA, *Radon: Is Your Family at Risk?* Environmental Protection Agency, Washington, DC, 1996.
^c Donham, J.K., Haglund, P., Peterson, Y., Rylander, R., and Belin, L., Environmental and health studies of workers in Swedish swine confinement buildings, *Br. J. Industr. Med.*, 40:31–37, 1989.
Source: If not specified, data are from ACGIH, *Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices*, American Conference of Governmental Industrial Hygienists, Cincinnati, OH, 2000.

poisoning, whether the effects are cumulative, the frequency with which high concentrations occur, and the duration of such periods. All factors must be taken into consideration in arriving at a decision about whether a hazardous condition exists.

For the vast majority of substances with a TLV-TWA, there is not enough toxicological data available to warrant a STEL. Nevertheless, excursions above the TLV-TWA should be controlled even where the eight-hour TLV-TWA is within recommended limits. Although no rigorous rationale was provided for these particular values, the basic concept was intuitive: In a well-controlled process exposure, excursions should be held within some reasonable limits. Unfortunately, neither toxicology nor collective industrial hygiene experience provides a solid basis for quantifying what those limits should be. For those air contaminants that have no TLVs, two simplified STEL criteria, or excursion limit values, are recommended by ACGIH 1:

- Excursions in worker exposure levels may reach three times the TLV-TWA for no more than a total of 30 minutes during a workday.
- Under no circumstances should they exceed five times the TLV-TWA.

This simplification is based on the maximum recommended excursion observed in actual industrial processes. When the toxicological data for a specific substance are available to establish a STEL, this value takes precedence over the excursion limit, regardless of whether it is more or less stringent.

2.6.1 Normalized Air Contaminant Concentration

In many practical indoor air quality problems, several air contaminants exist simultaneously. For example, ammonia and airborne dust are almost always present in an animal facility. The combined effect of these air contaminants on the health and comfort of the occupants is generally considered greater than any one of the existing contaminants in the airspace. When two or more air contaminants that act upon the same organ system are present, their combined effect, rather than that of either individually, should be given primary consideration. The effect on human health of some contaminants may be independent of other contaminants. In this case, TLVs for individual contaminants should be used. In other instances, the effect on health of some contaminants may be compounding and greater than the sum of individual effects.

The synergy of the mixture of air contaminants and their combined effect on human health and comfort is extremely complex. In the absence of information to the contrary, the effects of the different hazards should be considered additive.¹ In order to quantify the combined effect, the concentration of the concerned airborne contaminants is normalized. The normalized air contaminants concentration C_{NC} is defined in Equation 2.10:

$$C_{NC} = \sum \frac{C_i}{TLV_i} \quad (2.10)$$

where C_i and TLV_i are the concentration and threshold limit value, respectively, for the i^{th} concerned air contaminant. When C_{NC} is smaller than unity, the air quality is

acceptable. When C_{NC} is greater than unity, the air quality is not acceptable, and one or several air contaminant concentrations should be reduced. The normalized contaminant concentration is dimensionless and can operate with different contaminants with different concentrations and TLVs.

Example 2.3: In a newly built building, the measured concentrations of formaldehyde and radon are 0.2 ppm and 3 pCi/l, respectively. The recommended TLVs for formaldehyde and radon are 0.4 ppm and 4 pCi/l, respectively. What is the normalized air contaminant concentration?

Solution: For formaldehyde, $C_1 = 0.2$ ppm, $TLV_1 = 0.4$ ppm; for radon, $C_2 = 3$ pCi/l, $TLV_2 = 4$ pCi/l:

$$C_{NC} = \frac{C_1}{TLV_1} + \frac{C_2}{TLV_2} = \frac{0.2 \text{ ppm}}{0.4 \text{ ppm}} + \frac{3 \text{ pCi/l}}{4 \text{ pCi/l}} = 0.5 + 0.75 = 1.25$$

Because the $C_{NC} > 1$, the air quality is not acceptable.

In a practical indoor air quality scenario, the concerned air contaminants should first be identified for a given airspace containing a number of harmful dusts, fumes, vapors, or gases. Frequently, it will only be feasible to attempt to evaluate the hazard by measuring a single contaminant at one time. Then, Equation 2.10 should be applied to establish acceptable TLVs for each contaminant concerned.

DISCUSSION TOPICS

1. Why is the threshold limit value for particulates not otherwise classified (PNOC) 10 mg/m³, whereas for inhalable flour dust it is only 0.5 mg/m³?
2. The size of particles is important because it affects behavior and deposition in airways. What do you think about particle shape? Is the particle shape an important factor? If so, can you think of an example to justify?
3. Why do particles in different size ranges behave very differently? Can a piece of airborne particle cycle around a basketball just as the earth cycles around the sun?
4. What is the rationale for the distinction between total and inhalable particles? Are they the same thing?
5. Why is the diminutive particle a separate particle size range? Are respirable particles good enough for all health and engineering purposes?
6. It seems that the threshold limit value for asbestos (0.1 fiber/ml) is quite low compared with other particulate matter TLVs. Why?

PROBLEMS

1. An employee works in an animal building 8 hours per day. The average ammonia (NH₃) concentration in the building is 10 ppmv. The density of building air is 1.2 kg/m³, and the density of ammonia is 0.72 kg/m³.
 - a. What is the mass concentration of ammonia in ppmm?

- b. What is the ammonia concentration in mg/m^3 of air?
2. Dust mass concentration in a confinement building is measured at $2.8 \text{ mg}/\text{m}^3$ using a filter sampler. Assume the particles are spherical and have an average diameter of $2.5 \mu\text{m}$ with a density of $2,000 \text{ kg}/\text{m}^3$. What is the concentration in $\text{particles}/\text{ft}^3$, $\text{particles}/\text{ml}$, and $\text{particles}/\text{l}$?
3. The dust concentration was measured in a classroom with a laser particle counter. The measured data show that the dust concentration is $32,800 \text{ particles}/\text{ft}^3$. If these particles are standard-density ($1,000 \text{ kg}/\text{m}^3$) spheres with an average diameter of $0.5 \mu\text{m}$, what is the particle concentration in mg/m^3 ?
4. Assume that the material is divided into spheres each having a diameter d and a density of $\rho = 1000 \text{ kg}/\text{m}^3$.
 - a. Derive an expression for the surface area per gram of material as a function of particle size.
 - b. What is the total surface area of 1g of $0.1 \mu\text{m}$ diameter particles?
5. The time-weighted average (TWA) threshold limit for a particular contaminant is the value to or below which a human worker can be exposed 40 hours per week without health problems resulting. One suggested TWA value of respirable particles for biological systems is less than $0.23 \text{ mg}/\text{m}^3$. If the particles are spherical and have an equivalent volume diameter of $1.2 \mu\text{m}$, and if the particle density is $1500 \text{ kg}/\text{m}^3$, what is the TWA value in particle number concentration?
6. One cigarette contains approximately 20 mg of smoking particles. The average diameter of the particles is $0.3 \mu\text{m}$ and density is $1000 \text{ kg}/\text{m}^3$. The smoker consumes 20 cigarettes per day. Assuming that 99.9% of the particles are exhaled during the smoking process, how much mass was deposited in the smoker's lung per day, per year? How many particles were deposited in the lung per day, per year?
7. In question 6, the smoker consumes all 20 cigarettes within 8 hours, and all smoke is inhaled. An employee works 8 hours per day in a building with a respirable dust concentration of $50 \text{ particles}/\text{ml}$. Assume that the average breathing rate of a person is $20 \text{ l}/\text{min}$.
 - a. Compare the total particles inhaled per day by the smoker and by the employee. Who inhales more particles?
 - b. If the average particle diameter is $1 \mu\text{m}$ and density is $1000 \text{ kg}/\text{m}^3$ for the building dust, how much dust was inhaled by the worker?
8. In smoking one pack of cigarettes per day, a smoker inhales 8 L of smoke containing 200 mg of tobacco smoke particles. Assume that these particles are standard density ($1000 \text{ kg}/\text{m}^3$) spheres.
 - a. Find the ratio of the smoke to the TLV of nuisance dusts ($10 \text{ mg}/\text{m}^3$).
 - b. Find the ratio of the smoke to the U.S. national ambient air quality standard for particulate matter ($0.08 \text{ mg}/\text{m}^3$).
9. If airborne particles were considered extremely large gas molecules, what would the molecular weight be of a "gas" of $1.0 \mu\text{m}$ particles having a density of $1000 \text{ kg}/\text{m}^3$? Hint: One mole of any matter has the same number (Avogadro's number) of molecules.
10. In a heated building, concentrations of ammonia, hydrogen sulfide, and carbon dioxide are measured at 18, 0.5, and 2000 ppm, respectively. The TWA threshold limit for ammonia, hydrogen sulfide, and carbon monoxide are 25, 5, and 5000 ppm, respectively. Is the building air quality acceptable, i.e., is the normalized air contaminant concentration smaller than unity?
11. An animal building contains 20 ppmv ammonia and $1.5 \text{ mg}/\text{m}^3$ of inhalable dust in the air. How much dust must be removed from the air to bring the combined