1

Aerosol Fundamentals

1.1 Introduction

Aerosol dynamics is the science of the formation/emission, movement, sedimentation, and interaction of aerosol particles, and their removal from the airborne transmission route. The aerodynamic behaviors of particles are subject to their basic physicochemical properties. In this chapter, the fundamentals of aerosols, including their definition, origin, basic physical and chemical properties, as well as size distribution, are addressed. Additionally, bioaerosols, which are closely related to airborne diseases and allergic symptoms, are briefly introduced.

1.2 Definitions of Aerosols

Aerosols are tiny solid or liquid particles or their hybrid suspended in a gaseous or air medium, and the size of these particles is larger than 0.001 μm but smaller than 100 μm. Particles dispersed in the air are difficult to classify in a scientifically rigorous way. They are usually described in terms of their physical form or source. Table 1.1 provides some common descriptions of aerosols.

1.3 Sources of Aerosols

The sources of atmospheric aerosols encompass the natural and the anthropogenic origins. Among the global emissions of atmospheric aerosols, the contribution of the natural sources is approximately 6.8 times that from the anthropogenic sources, as shown in Table 1.2. However, the anthropogenic aerosols are mainly emitted in the dense urban areas, resulting in higher local concentrations and thus posing greater risks to human health.

Table 1.1 Common descriptions of aerosols.

	Definition	Size range
Aerosol	An assembly of liquid or solid particles or their hybrid suspended in a gaseous medium consisting of particles and the suspending gas	0.001–100 μm
Particle	Small discrete object	0.001–100 μm
Dust	Solid particles formed by crushing or other mechanical breakage of parent materials	Sub-micrometer to more than 100 μm
Fog and mist	Liquid aerosol formed by condensation or atomization	Sub-micrometer to about 100 μm
Fume	Particles from vapor condensation and the possibly subsequent agglomeration	Less than 0.05 μm
Smog	Solid and liquid aerosols from photochemical reactions or vapor condensation	Less than 1 or 2 μm
Smoke	Solid or liquid aerosols from incomplete combustion or condensation of supersaturated vapor	Less than 1 μm

1.3.1 Natural Aerosol Sources

Natural emissions of aerosols are associated with various physical and chemical processes. The main natural sources of atmospheric aerosols are soil/desert dust and sea salt, as shown in Table 1.2. When seawater waves break, tiny droplets of water are released into the air. As these droplets evaporate, salt particles are formed. The gas-to-particle conversion and the photochemical reactions contribute a significant amount of secondary aerosols. More details on the secondary aerosols are addressed in Section 1.3.3. Additional aerosol contributors include botanical debris and volcanic eruptions. The volcanic eruptions release quantities of ash, dust, and sulfate aerosols into the atmosphere. Forest fires also contribute to aerosol emissions, especially severe wildfires.

1.3.2 Anthropogenic Aerosol Sources

Anthropogenic sources of aerosols contribute substantially to air pollution. As shown in Table 1.2, the majority of the anthropogenic aerosols come from the gas-to-particle conversion and the direct emissions by various human activities. Industrial processes, including manufacturing and construction, can generate aerosols in the form of dust, smog, mist, etc., due to grinding, disturbance, combustion, or the release of chemical pollutants. Transportation is also a major source, as fuel-powered vehicles like cars, trucks, and buses release fine

Table 1.2 Relative contributions of natural and anthropogenic sources to the global emissions of atmospheric aerosols.

Source	Contribution to global emissions in mass percentage (%)
Natural	
Soil/desert dust	41.67
Sea salt	36.11
Gas-to-particle conversion$^{a)}$	5.00
Photochemical reactions$^{b)}$	1.67
Botanical debris	1.39
Volcanic eruption	0.83
Forest fires	0.56
Total of the natural sources	87.23
Anthropogenic	
Gas-to-particle conversion$^{c)}$	9.17
Direct emissions (e.g., soot or mechanical friction)	3.33
Photochemical reactions$^{d)}$	0.28
Total of the anthropogenic sources	12.78

a) Including sulfates from SO_2 and H_2S, nitrate from NO_x, ammonium salts from NH_3.
b) Photochemical particle formation primarily from isoprene and monoterpenes vapors from trees.
c) Including sulfates from SO_2 and nitrates from NO_x.
d) Photochemical particle formation primarily from anthropogenic volatile organic compounds.

Source: Hinds and Zhu (2022) / with permission of John Wiley & Sons.

particles and gases into the atmosphere. Additionally, agricultural activities such as tilling and plowing generate dust aerosols. Household activities like heating, cooking, and cleaning can also produce aerosol particles. The burning of solid fuels, such as wood or coal, releases smoke, soot, and combustion byproducts. Physiological activities such as breathing, speaking, coughing, or sneezing can release droplets and aerosols into the surrounding environment, though the amounts are quite limited.

1.3.3 Secondary Aerosols

The atmospheric aerosols of both natural and anthropogenic origins involve secondary aerosols produced by the gas-to-particle conversion and the photochemical reactions. Secondary aerosols are particles formed through chemical reactions from precursor gases such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), volatile organic compounds (VOCs), and ammonia (NH_3). These reactions result in the formation of new particles or the growth of existing particles. The particle size of secondary aerosols is generally in the range of 0.001–2.5 μm (Kavouras and Stephanou 2002), and they are the main source of fine particulate matter ($PM_{2.5}$) in the atmosphere.

1.4 Physical Properties of Aerosol Particles

The physical properties of aerosol particles, including particle size, density, shape, surface area, concentration, and charge, can significantly affect the aerodynamic behavior of the particles. Understanding these fundamental properties and appropriately characterizing them are crucial for indoor aerosol control.

1.4.1 Particle Size

The size of aerosol particles plays an essential role in their behavior, as nearly all dynamic characteristics of aerosols are influenced by particle size. For example, the duration of aerosol particles' suspension in the air and the penetration ratio of inhaled aerosol particles into the lungs are both strongly dependent on the particle size. Aerosol particles exhibit a wide size range, and the sizes of the smallest and largest particles can differ by a factor of up to 100 or even more. This wide range highlights the importance of using appropriate methods to precisely characterize the particle size distribution, as will be discussed in detail in Section 1.7.

Particle size is typically measured in micrometers (μm), and 1 μm is equal to one-millionth of a meter. A particle with a diameter of 1 μm is extremely small, approximately 1/70 the diameter of a human hair. Although some very tiny particles are measured in nanometers (nm), which are even smaller, micrometers are more commonly used when discussing particle size. Aerosol particles are generally classified into three main categories based on size, namely, ultrafine, fine, and coarse particles.

Ultrafine particles (UFPs) are aerosol particles with a diameter less than 0.1 μm (100 nm). Owing to their extremely small size, they exhibit unique dynamic behavior compared to larger particles. For instance, UFPs can stay suspended in the air for long periods and are capable of traveling long distances. Additionally, UFPs pose the greatest threat to human health due to their ability to penetrate epithelial cells and enter the bloodstream. Fine particles are aerosol particles with diameters ranging from 0.1 to 2.5 μm, and they constitute the largest mass ratio of $PM_{2.5}$ (aerosol particles equal to or less than 2.5 μm in diameter). Because of their small size, fine particles can remain airborne for prolonged periods and be transported over long distances by the wind. These particles can be inhaled into

Table 1.3 Size ranges of common indoor aerosol particles.

Category	Emission source	Size range (μm)	References
Combustion	Candle	0.02–1	Afshari et al. (2005)
	Cigarette		
Cooking	Cooking on a gas stove	0.05–0.1	Dennekamp et al. (2001)
	Cooking on an electric stove		
	Frying meat	0.02–1	Afshari et al. (2005)
Household use	Flat iron with steam	0.02–1	Afshari et al. (2005)
	Motor of a vacuum cleaner		
Office equipment	3D printer	0.001–0.1	EPA (2024)
	Laser printer	0.005–0.3	Gu et al. (2020)

the lungs, leading to significant health consequences. Coarse particles, meanwhile, are aerosol particles with a diameter ranging from 2.5 to 10 μm. Due to their larger size, coarse particles tend to settle out of the air under the action of gravity.

Table 1.3 summarizes the size ranges of common indoor aerosol particles generated by different sources. As displayed in the table, the sizes of indoor aerosol particles are generally less than 1 μm. Among them, the particles produced by 3D printing are the smallest, and all are UFPs. The size range of particles produced by laser printing spans from 0.005 to 0.3 μm.

1.4.2 Particle Density

Particle density refers to the mass of particles per unit volume and is typically expressed in kilograms per cubic meter (kg/m^3) or grams per cubic centimeter (g/cm^3). It should be noted that particle density refers specifically to the density of the particles themselves, rather than the overall aerosol density that includes the volume of the suspending air. The density of particles plays a crucial role in their motion in the air. For instance, gravity acts as an external force on particles and is proportional to their density. Particles with a higher density correspond to a stronger inertial force during motion.

Different types of particles exhibit varying densities. For solid or liquid particles, their densities are equivalent to those of their parent materials. However, particles such as smoke or fog may have lower densities than the substances that form them. This is because there may be numerous tiny air pockets inside these particles.

Table 1.4 lists the densities of some common indoor aerosol particles. It is evident that the densities of all particles are generally around 1,000 kg/m^3. Kitchen smoke particles are primarily composed of lipids, combustion byproducts

Table 1.4 Densities of common indoor aerosol particles.

Particle source	Particle name	Density (kg/m^3)	References
Combustion	Candle smoke	910	Pagelsa et al. (2009)
	Cigarette smoke	1,180	Johnson et al. (2014)
Test particles	DEHS particles[a)]	912	Nothhelfer et al. (2025)
	DOP particles[a)]	986	Chen et al. (1990)
Cooking	Cooking fumes	910–1,030	Pikmann et al. (2024)
Material/process emission	3D printing particles	1,105	Matsumura et al. (2023)

a) DEHS and DOP particles refer to aerosol particles generated using diethylhexyl sebacate and dioctyl phthalate, respectively.

(such as carbonaceous particles), moisture, and other organic materials, and the density of these particles depends on the content of each component. In this book, unless otherwise specified, the particle density is assumed to be 1,000 kg/m^3, which is the standard density.

1.4.3 Particle Shape

Liquid aerosol particles tend to be round or spherical because of surface tension. Meanwhile, the shapes of solid aerosol particles can be highly irregular and more complex, for example, with jagged edges or elongated forms, as shown in Figure 1.1. For the sake of convenience in discussing aerosol properties, irregularly shaped particles are often assumed to be spherical, even if they are not. This is mainly because many of the equations and theories describing aerosol dynamic behavior are more straightforward for spherical particles. For non-spherical particles, the corresponding "equivalent diameter" can be used,

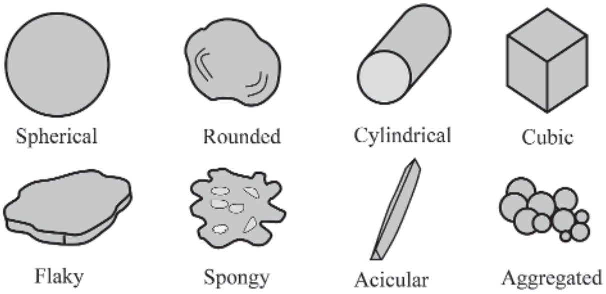

Figure 1.1 Typical shapes of aerosol particles.

Table 1.5 Common equivalent diameters used in aerosol aerodynamics.[a]

Equivalent diameter	Definition	Mathematical expression
Average diameter	The average diameter of particles measured in n given directions	$d = \frac{1}{n}\sum_{i=1}^{n} d_i$
Surface area diameter	The diameter of a sphere with the same surface area as the studied particle	$d = \sqrt{\frac{A_\mathrm{s}}{\pi}}$
Volume diameter	The diameter of a sphere with the same volume as the studied particle	$d = \sqrt[3]{\frac{6V_\mathrm{p}}{\pi}}$
Mass diameter	The diameter of a sphere with the same mass and density as the studied particle	$d = \sqrt[3]{\frac{6m}{\pi\rho_\mathrm{p}}}$
Aerodynamic diameter	The diameter of a sphere with a density of 1,000 kg/m^3, having the same terminal settling velocity as the studied particle	$d = \sqrt{\frac{18V_\mathrm{TS}\eta}{1,000g}}$
Stokes diameter	The diameter of a sphere having the same density and settling velocity as the studied particle	$d = \sqrt{\frac{18V_\mathrm{TS}\eta}{\rho_\mathrm{p}g}}$

a) In this table, A_s is the surface of a particle, V_p is the particle volume, m is the particle mass, ρ_p denotes particle density, V_TS is the terminal settling velocity of a particle, η is the dynamic viscosity of air, and g is the gravitational acceleration.

which is the diameter of a spherical particle that has the same physical properties, like volume or surface area, as the irregularly shaped particle. Table 1.5 defines some common equivalent diameters used in aerosol aerodynamic studies. The aerodynamic and Stokes diameters mentioned in Table 1.5 are described in detail in Chapter 2.

The use of equivalent diameter aids in the analysis of the dynamic properties of particles without greatly impairing accuracy. In most cases, ignoring the exact shape of a particle does not significantly affect the outcome (Hinds and Zhu 2022). However, for particles with very unusual shapes, like long, thin fibers or highly branched structures found in some types of smoke, the impact of shape becomes more evident. In such situations, these particles can be characterized by their fractal dimension.

1.4.4 Particle Surface Area

Surface area is defined as the total area of the particle's outer surface. In general, the surface area of fine particles with equal mass is greater than that of coarse particles. For instance, a cube with a side length of 1 cm has a surface area of 6×1^2 cm^2, while a smaller cube with a side length of $1/n$ cm has a surface area of $6 \times (1/n)^2$ cm^2. In a cube with a side length of 1 cm, there are n^3 such smaller cubes, resulting in a total surface area of $6n$ cm^2, which indicates that the surface area has increased by a factor of n. The surface area of particles influences not only their settling velocity but also the health effects of aerosols that deposit in the alveolar region because the contact area of the aerosols with the tissue cells is a critical parameter affecting particle toxicity (Ruzer and Harley 2012).

In addition to the particle surface area, the concept of the specific surface area is widely used in aerosol studies, and it is defined as the total surface area per unit mass of particles. Considering a spherical particle, the relationship between the specific surface area S_w (m^2/kg) and particle diameter is given by:

$$S_\mathrm{w} = \frac{\pi d_\mathrm{p}^2}{\frac{1}{6}\pi d_\mathrm{p}^3 \rho_\mathrm{p}} = \frac{6}{d_\mathrm{p}\rho_\mathrm{p}} \tag{1.1}$$

where ρ_p is the particle density (kg/m^3) and d_p is the particle diameter (m).

In Eq. (1.1), it can be seen that the specific surface area of particles is inversely proportional to their size, with smaller particles having larger specific surface areas. For particles with identical density, the specific surface area of a particle with a size of 0.1 μm is 100 times that of a particle with a size of 10 μm. Additionally, the specific surface area is influenced by factors such as particle porosity, pore size distribution, shape, and surface roughness. As the specific surface area of particles increases, their surface energy also rises, which enhances the surface reactivity. Furthermore, this parameter is crucial for understanding the coagulation, adhesion, and adsorption behavior of aerosol particles.

1.4.5 Particle Concentration

Aerosol particle concentration indicates the amount of particulate matter present in the air. The particle concentration can be expressed in terms of mass concentration or number concentration. Mass concentration refers to the total mass of particles present in a specific volume of air and is typically expressed in units such as grams per cubic meter (g/m^3), milligrams per cubic meter (mg/m^3), or micrograms per cubic meter (μg/m^3). The particle mass concentration serves as a key indicator of air pollution levels and potential health risks. For instance, the World Health Organization (WHO), the US Environmental Protection Agency (EPA), and the Chinese national standard (GB/T 18883-2022) have established exposure limits of $\mathrm{PM}_{2.5}$ and PM_{10} based on the particle mass concentration, as shown in Table 1.6.

The particle number concentration indicates the number of particles present in a given volume of air, typically expressed in units like particles per cubic centimeter

Table 1.6 $PM_{2.5}$ and PM_{10} concentration limits.

Organization/entity	$PM_{2.5}$ (μg/m^3)	PM_{10} (μg/m^3)	Comment
WHO[a]	15	45	24-hour average
EPA	35	150	
Chinese national standard	50	100	

a) Only the air quality guideline (AQG) levels by the WHO are presented.

Table 1.7 Comparison of particle concentration when expressed in different units.

Item	Mass concentration (μg/m^3)	Parts per million (volume/volume) (ppm)	Parts per million (mass/mass) (ppm)
Indoor $PM_{2.5}$ concentration limit specified by the WHO	15	1.5×10^{-5}	0.01
Indoor PM_{10} concentration limit specified by the WHO	45	4.5×10^{-5}	0.04

(particles/cm^3) or particles per cubic meter (particles/m^3). This metric is especially useful for quantifying specific types of particles, such as biological aerosols or fibers, where the particle count is more significant than the total particle mass.

The volume ratio or mass ratio in parts per million (ppm), i.e., the ratio of the particle volume or mass to the suspending gas medium's volume or mass, is not employed for aerosol concentration because the use of this unit generally yields very small values, especially for the volume ratio. Table 1.7 compares the quantities expressed in various units. It is evident that when volume ratios are employed, the particle concentration values are six orders of magnitude lower than the mass concentration of the particles.

1.4.6 Electrical Properties of Aerosol Particles

The electrical properties of aerosol particles are mainly reflected in the magnitude and polarity of their charges. Almost all particles, whether generated naturally or anthropogenically, carry some charges. For most particles, the magnitudes of positive and negative charges are approximately equal, leading to the overall electrical neutrality of particles suspended in the air.

The charging of particles is primarily attributed to collisions between particles, natural radiation, attachment of external particles or electrons, etc. The magnitude of the particle charge varies with the particle size, mass, humidity, temperature, etc. In general, larger particles can carry more charges than smaller particles due to the greater surface area of the former, which provides more opportunities to acquire and retain charges from surrounding ions. Higher humidity, for example, can lead to the dissipation of charges through the condensation of water vapor.

The charges carried by particles significantly affect their dynamic behavior. Charged particles are subjected to electrostatic forces when exposed to an electric field, which alters their trajectories. This principle is widely utilized in electrostatic precipitators. Additionally, the polarity of the charges on aerosol particles plays a crucial role in their agglomeration and coagulation behavior. Particles with opposite charges attract each other, promoting the agglomeration and formation of larger particles, which settle more quickly in the air. In contrast, particles with the same charges repel each other, inhibiting agglomeration and prolonging their suspension time in the air. Furthermore, the electrostatic attraction between charged particles and approaching surfaces influences deposition behavior. When charged particles pass through a surface with an opposite charge, they are strongly attracted, leading to an increased deposition velocity and deposition rate. For instance, the charging of particles with diameters of 0.5, 1.0, and 2.0 μm was claimed to increase their deposition velocity by up to 72% in indoor space (Din et al. 2020).

1.5 Chemical Properties

Aerosol particles may be composed of various chemical substances, including organic compounds, inorganic salts, metals, and biological materials. Aerosols can be acidic, neutral, or alkaline, depending on their chemical compositions. Furthermore, aerosols can be divided into soluble aerosols and insoluble aerosols, depending on whether they can dissolve in water or other solutions. Soluble aerosols, such as salts, can dissolve in the moisture present in the air, leading to probable chemical reactions or changes in the aerosols' size and dynamic behavior. Insoluble aerosols, such as certain types of dust, are generally unaffected by humidity, which well maintains their original shape and size. In indoor environments, the formation of certain aerosols is even attributed to chemical reactions. For instance, secondary organic aerosols (SOA) may arise from chemical reactions between ozone and VOCs emitted by cleaning agents, paints, and building materials. These reactions contribute to an increase in particle concentrations indoors.

1.6 Bioaerosol

When we discuss aerosols, our minds often go immediately to dust or smoke. However, there are also large numbers of bioaerosols in the air. The definition and sources of bioaerosols are briefly introduced in the following sections.

1.6.1 Definition

Bioaerosols are diverse particles derived from living organisms, including pollens, fragments of fungal mycelium or spores, bacteria and spores, viruses, protozoa, excrement or fragments of insects, and hair or dander from mammals, along with other residues or byproducts from these organisms. Bioaerosols are widely distributed in both indoor and outdoor air. Among particles larger than 0.2 μm, approximately 5–50% originate from biological particles (Ruzer and Harley 2012). The commonly used units for characterizing the concentration of bioaerosols are particles/m^3 and CFU/m^3, where CFU/m^3 represents the number of viable bacteria or fungi in the air that can form colonies after being cultured.

The size range of bioaerosols is very wide. Viruses are the smallest live bioaerosols, with sizes ranging from 0.02 to 0.3 μm. The size range of bacteria is typically between 0.25 and 10 μm, the size range of fungi is between 1 and 60 μm, while the diameters of pollen range from a few micrometers to around 100 μm. The size ranges and sources of common bioaerosols are presented in Table 1.8.

Although most bioaerosols in the air are harmless, some bioaerosol particles may be infectious or allergenic or carry toxic components or metabolites. Living organisms may reproduce, but this is not a prerequisite for allergenic or toxic effects. Dead cells or cell remnants may also have an impact on human health.

Table 1.8 A summary of common bioaerosols in terms of size ranges and sources.

Bioaerosol	Particle size range (μm)	Source	References
Virus	0.02–0.3	Infected individuals, body fluids, sewage, etc.	Louten (2016)
Bacterium	0.25–10	Respiratory tracts, skin, soil, feces, wastewater, etc.	Aryal (2022)
Fungus	1–60	Decaying plants, soil, wastewater, and damp environments	Golan and Pringle (2017)
Pollen	5–100	Flowers, trees, and grasses	Ryan (1999)
Protozoa	1–50	Soil, water bodies, and contaminated environments	Baron (1996)
Dust mite debris	0.5–50	Household dust, bedding, and carpets	Ryan (1999)
Hair	70–90	Humans and animals	Loussouarn et al. (2016)
Dander	0.4–100	Human and animal skin shedding	Ryan (1999)

1.6.2 Sources of Bioaerosols

A portion of bioaerosols originate from outdoor sources such as soil, surface water, and plants. Microorganisms in soil can be aerosolized due to mechanical disturbances like farming activities, soil excavation, landfill operations, and dust storms. Bacteria are the most abundant organisms in surface soil, with concentrations exceeding 10^{10} cells/g (Maier et al. 2008). Many natural and artificial water bodies, such as sewage oxidation ponds and cooling water systems, contain large quantities of microorganisms, including Gram-negative bacteria and actinomycetes. These microorganisms can form bioaerosols through bubble bursts when subjected to disturbances. Some plants release pollen in order to reproduce. The fungal spores or bacteria on the surfaces of living and dead plants can also be aerosolized due to high-speed airflow sweeping.

The processing of organic materials in many occupational environments can become a high-intensity source of bioaerosols; these materials include plants, organic fertilizers, wastewater, and contaminated liquids. In both industrial and non-industrial environments, microorganisms growing in a building's HVAC (heating, ventilating, and air conditioning) system or the structure of the building itself can also be specific bioaerosol sources. In general, high humidity is a prerequisite for microbial growth. Building interiors with water leakage or condensation can become sources of fungal and other biological aerosols.

In non-industrial indoor environments such as office and residential buildings, the main source of bioaerosols, especially for bacteria and viruses, is humans. High concentrations of bacteria in indoor air may not necessarily pose a health hazard, but they are a sign of poor ventilation of the interior environment. Culturable bacteria and fungi (above 5,000 and 500 CFU/m^3, respectively) have been recommended as indicators of the presence of abnormal indoor bioaerosol sources or insufficient ventilation (Reponen et al. 1992).

1.7 Size Distribution of Aerosol Particles

Aerosols can be divided into monodisperse aerosols and polydisperse aerosols. Among the monodisperse aerosols, the size of the particles can be described in terms of the particle diameter alone. However, monodisperse aerosols can only be generated in the laboratory. Most aerosols are polydisperse, with particle sizes spanning several orders of magnitude. Given the wide variation in particle size and the strong influence of size on the aerodynamic properties of aerosols, it is essential to use statistical methods to characterize these size distributions.

1.7.1 Overview of Particle Sizes

Particle size is commonly characterized in terms of mean, mode, median, and geometric mean size. The mean, or arithmetic average, is obtained by summing all particle sizes and then dividing by the total number of particles. The algebraic mean diameter can be calculated as:

$$\bar{d}_{\mathrm{p}} = \frac{\sum n_i d_i}{\sum n_i} = \int_0^{\infty} d_{\mathrm{p}} f(d_{\mathrm{p}}) \mathrm{d}d_{\mathrm{p}} \tag{1.2}$$

where n_i is the number of particles in the ith group, d_i is the algebraic mean of the upper and lower limits of the particle size range or the square root of the product of the upper and lower limits of the particle size range, and $f(d_{\mathrm{p}})$ is the frequency function.

The mode is the particle size that appears most frequently. The median represents the midpoint in the distribution, where half of the particles are smaller and half are larger than the median size. The geometric mean d_{g} is calculated as the Nth root of the product of N particles:

$$d_{\mathrm{g}} = (d_1 d_2 d_3 \cdots d_N)^{1/N} \tag{1.3}$$

For size data grouped into M intervals, the geometric mean involves the characteristic diameters and the number of particles in each interval:

$$d_{\mathrm{g}} = \left(d_1^{n_1} d_2^{n_2} d_3^{n_3} \cdots d_M^{n_M}\right)^{1/N} \tag{1.4}$$

where n_1, n_2, n_3, …, n_M are the number of particles in each interval, and d_1, d_2, d_3, …, d_M are the midpoints or characteristic diameters in corresponding intervals.

The geometric mean diameter can also be expressed in terms of $\ln(d)$ by converting Eq. (1.4) to natural logarithms as:

$$\ln d_{\mathrm{g}} = \frac{\sum n_i \ln d_i}{N} \tag{1.5}$$

$$d_{\mathrm{g}} = \exp\left(\frac{\sum n_i \ln d_i}{N}\right) \tag{1.6}$$

1.7.2 Particle Size Distribution Functions

Although the size of aerosol particles can be expressed using the aforementioned characteristic quantities, it is more commonly expressed in functional forms in practical applications. In general, the distributions of particle size are random, but they can be approximated into certain patterns and thus represented by specific distribution functions. Among these, the most widely used is the log-normal distribution function. The log-normal distribution is derived from the normal distribution, which is introduced in the following sections.

1.7.2.1 Normal Distribution

The normal distribution, also known as the Gaussian distribution, is a probability distribution used to describe the sizes of particles when they cluster around a central value. In a normal distribution, most particles have sizes close to the mean, with a few particles having sizes that deviate significantly from it. The number distribution function of the normal distribution is given by:

$$\frac{\mathrm{d}N}{\mathrm{d}(d_\mathrm{p})} = \frac{N}{\sqrt{2\pi}\delta_\mathrm{g}} \exp\left[-\frac{(d_\mathrm{p} - \overline{d}_\mathrm{p})^2}{2{\delta_\mathrm{g}}^2}\right] \tag{1.7}$$

where N is the total number of collected particles, d_p(μm) is the particle diameter, and $\overline{d}_\mathrm{p}$ denotes the algebraic mean diameter. Meanwhile, δ_g represents the geometric standard deviation and can be expressed as:

$$\delta_\mathrm{g} = \left(\frac{\sum n_i (d_\mathrm{p} - \overline{d}_\mathrm{p})^2}{N-1}\right)^{1/2} \tag{1.8}$$

The value of δ_g is generally greater than 0, and it is used to describe the degree of divergence of aerosol particle sizes. A larger value of δ_g indicates a greater degree of dispersion among aerosol particles. If $\delta_\mathrm{g} = 0$, the aerosol is classified as a monodisperse system, where all particles possess the same diameter.

The normal distribution function is rarely employed to describe aerosol particle size distributions, as most aerosols display a skewed distribution with a long tail at larger sizes. Notably, the normal distribution is symmetrical and is mainly applicable to monodisperse test aerosols, certain pollens and spores, specifically prepared polystyrene latex spheres, and so on.

1.7.2.2 Lognormal Distribution

As mentioned above, a few particle distributions conform to the normal distribution since particle distribution curves are generally skewed. This skewness can be eliminated by taking the logarithmic operation of the particle size, resulting in a lognormal distribution. The lognormal distribution has become one of the most prevalent statistical distributions in aerosol science. The lognormal distribution of particle sizes can be formulated as:

$$\frac{\mathrm{d}N}{\mathrm{d}(\log(d_\mathrm{p}))} = \frac{N}{\sqrt{2\pi}\log(\delta_\mathrm{g})} \exp\left[-\frac{(\log(d_\mathrm{p}) - \log(\overline{d}_\mathrm{p}))^2}{2(\log(\delta_\mathrm{g}))^2}\right] \tag{1.9}$$

where log is the base 10 or constant e logarithm. The terms $\log(\overline{d}_\mathrm{p})$ and $\log(\delta_\mathrm{g})$ can be formulated as:

$$\log(\overline{d}_\mathrm{p}) = \frac{\sum n_i \log(d_i)}{N} \tag{1.10}$$

$$\log(\delta_\mathrm{g}) = \left(\frac{\sum n_i (\log(d_i) - \log(\overline{d}_\mathrm{p}))^2}{N-1}\right)^{1/2} \tag{1.11}$$

where n_i is the number of particles in size group i, having a midpoint of size d_i, and where $N = \sum n_i$. As compared with the normal distribution, the lognormal distribution replaces $\overline{d}_\mathrm{p}$ with $\log(\overline{d}_\mathrm{p})$ and δ_g with $\log(\delta_\mathrm{g})$.

Example 1.1

The number of laboratory-generated oil mist particles collected in 1 ml of air by an electrostatic low-voltage impactor (ELPI+, Dekati, Finland) is shown in Table 1.9. The ELPI can measure particles between 6 nm and 10 μm, with 14 size intervals. The size of a particle in a specific size interval is equal to or greater than the lower limit and smaller than the upper limit of that interval. Please plot the lognormal distribution curve of the particle sizes.

Solution

To draw a lognormal distribution curve, three key parameters need to be determined, namely, $\log(\overline{d}_\mathrm{p})$, $\log(\delta_\mathrm{g})$, and N in Eq. (1.9). According to Eq. (1.10), $\log(\overline{d}_\mathrm{p})$ can be obtained (base 10 logarithm), with a value of −1.06. Then, according to Eq. (1.11), $\log(\delta_\mathrm{g})$ can be calculated, with a value of 0.54. The value of N is 187,882 from Table 1.9. The logarithmic normal distribution of oil mist particle sizes is illustrated in Figure 1.2.

Table 1.9 Number of oil mist particles collected in 1 ml of air in the lab.

Size range (μm)	Particle count	Midpoint of size range (μm)
0.006–0.016	102,302	0.011
0.016–0.027	31,704	0.0215
0.027–0.054	13,781	0.0405
0.054–0.093	10,528	0.0735
0.093–0.154	6,821	0.1235
0.154–0.26	6,275	0.207
0.26–0.379	5,390	0.3195
0.379–0.609	5,000	0.494
0.609–0.942	4,307	0.7755
0.942–1.59	1,024	1.266
1.59–2.38	500	1.985
2.38–3.97	124	3.175
3.97–6.64	88	5.305
6.64–10	38	8.32
0.006–10 (Total)	187,882	N/A

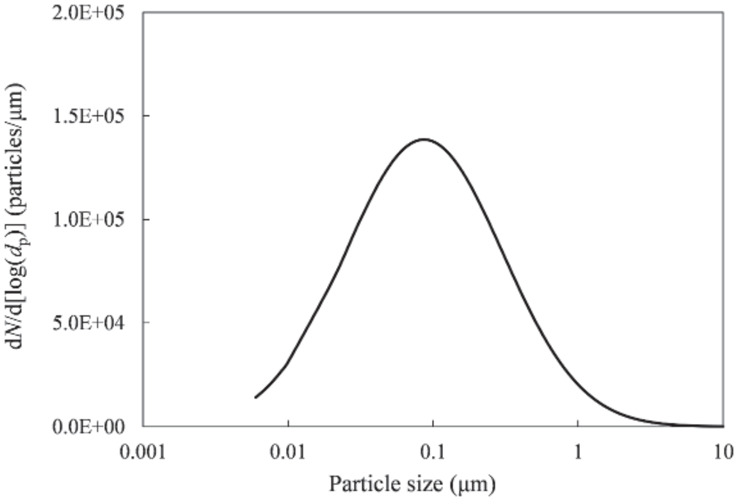

Figure 1.2 Logarithmic normal distribution of oil mist particle sizes.

1.8 Summary

This chapter mainly introduces the definition and sources of aerosols, the physical properties of aerosol particles (including particle size, shape, density, surface area, electrical charges, and aerosol concentration), and chemical properties, as well as the definition and sources of bioaerosols, and methods for charactering the size distribution of polydisperse aerosol particles. The preceding content is the basis for studying indoor aerosol dynamics and will be used often in subsequent chapters.

The particle size of aerosol particles is typically measured in micrometers. The particle size of indoor aerosols is commonly around 1 μm, and their density is generally more or less 1,000 kg/m^3. Due to the irregular shapes of particles, especially solid particles, equivalent particle size is often used as a characteristic parameter. The surface area of particles is a key factor in evaluating inhalation exposure, and fine particles of equal mass have a larger surface area than do coarse particles. Additionally, the specific surface area is frequently used to characterize particle surface activity, which affects particle aggregation and coagulation significantly. Aerosol concentration can be expressed in terms of mass concentration and number concentration. The former is mainly used to evaluate indoor air pollution, while the latter is mostly used to quantify biological aerosol particles or fiber particles. As for the size distributions of aerosol particles, they are often polydisperse and are typically described by a lognormal distribution function.

Problems

1.1 Calculate the aerodynamic diameter of an irregular particle with a terminal settling velocity of 0.001 m/s. Assume the air dynamic viscosity is 1.8×10^{-5} Pa · s.
[Answer: 5.8 μm]

1.2 The size distribution of aerosol particles is as follows. Please calculate the geometric mean diameter.

Size range (μm)	Particle count
0.1–0.3	50
0.3–0.5	30
0.5–1.0	20

[Answer: 0.3 μm]

1.3 An irregularly shaped particle has a volume of 2×10^{-18} m^3. Please calculate its volume-equivalent diameter.
[Answer: 1.6 μm]

1.4 A spherical aerosol particle has a diameter of 0.5 μm and a density of 1,200 kg/m^3. Please calculate its specific surface area.
[Answer: 10,000 m^2/kg]

1.5 Explain the possible mechanism to generate secondary organic aerosols (SOA) in indoor environments and discuss their impact on the indoor air quality.

1.6 Explain why the lognormal distribution is more commonly used than the normal distribution to describe the particle size distribution, and discuss the physical meaning of the geometric standard deviation in the lognormal distribution.

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