AEROSOL SCIENCE AND TECHNOLOGY

SECOND EDITION

Parker C. Reist

Aerosol Science and Technology

Parker C. Reist
Professor of Air and Industrial Hygiene Engineering
Department of Environmental Sciences and Engineering
University of North Carolina
Chapel Hill, North Carolina

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Preface

This book has had a strange history. It was originally started in 1969 based on lecture notes from an aerosol course I was teaching at the Harvard School of Public Health. In 1972 I moved to the University of North Carolina and brought the course and my work on the book along with me. The new setting and new responsibilities did their part to delay things, and it was not until 1984 that the book was finally published by Macmillan. It was well received. However, in the intervening years there has been a great spurt in the growth of the field of aerosol science: There are a number of universities offering courses in aerosol science, and at one English university it is possible to receive a master's degree in aerosol science; a whole new field has grown up around the concept of using controlled aerosol-producing reactions to create exotic new materials; aerosols are being seen as an effective method for administration of some drugs and may someday replace many intravenous procedures; the ultimate answers to the greenhouse effect appear to be intimately associated with the property of aerosols to absorb some radiation wavelengths better than others; and finally the relative importance of aerosols to the microelectronics industry has been widely recognized, in both a positive and a negative sense.

Accordingly I felt that an update of the 1984 book was in order. New developments in sampling equipment design, refinements in fundamental background information for aerosols, the emergence of fractal geometry as an aerosol tool, and my recognition that several important areas were completely ignored in the first edition all made compelling reasons for this revision. New chapters have been added covering thermophoresis, viable aerosols, and dust explosions; several other chapters have been substantially rewritten.

Finally, at the request of many of my former students, more information on units has been added, many of the worked examples have been clarified, and a number of the figures have been replaced with better illustrations.

In the meantime, much of what was good about the earlier book has been retained, including the original introduction, which still, I think, says it all.

Parker C. Reist
Chapel Hill
March 5, 1992

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Chapter

1

Introduction and Definitions

Aerosols are ubiquitous in our environment. Haze particles are formed over vegetation; dust clouds are blown up by the wind; volcanoes erupt, spewing dense smoke into the atmosphere; and, of course, in their many activities people mark their way by the particles they discharge into the air. This book is about aerosol particles, their physical properties, and the scientific basis that has been developed for predicting their behavior.

Units

Aerosol sizes are usually referred to in terms of the micrometer (μm) (previously called the micron μ). One micrometer is equal to 10^{-4} centimeters (cm), 10^{-6} meters (m), or 10^4 angstrom units, abbreviated Å. In working problems it is necessary to use a consistent set of units. Since most physical constants are available either in cgs or mks units (English units are too cumbersome to use), aerosol sizes given in micrometers very often must be converted to either centimeters or meters for computations (depending on the system of units chosen). When you are working problems involving ratios of particle size, this conversion is not necessary.

Example 1.1 A basketball is 12 in in diameter. Express its diameter in micrometers.

$$1 \text{ in} = 2.54 \text{ cm}$$

$$1 \text{ cm} = 10^4 \ \mu\text{m}$$

$$\text{Diameter} = 12 \text{ in} \times 2.54 \text{ cm/in} \times 10^4 \ \mu\text{m/cm}$$

$$= 3.05 \times 10^5 \ \mu\text{m}$$

Definitions

To begin the systematic study of particles, it is first necessary to consider several commonly used definitions of various types of aerosols.

Aerosol A suspension of solid or liquid particles in a gas, usually air; a colloid. Included in this definition would be:

Dust Solids formed by disintegration processes such as crushing, grinding, blasting, and drilling. The particles are small replicas of the parent material, and the particle sizes can range from submicroscopic to microscopic. Very often sizes are specified by screen mesh size. For example, the percentage passing or retained on a given mesh is indicative of size.

Example 1.2 How many spherical particles just passing through a 200-mesh screen are required to equal the mass of a single spherical particle that just passes through a 50-mesh screen? Assume that the diameter of the particle passing through the mesh equals the mesh opening and a particle density of 2.65 g/cm^3.

$$\text{Mass of particle passing 50-mesh screen} = \frac{\pi}{6}d^3\rho = \frac{3.14}{6}(0.0297)^3(2.65)$$

$$= 3.64 \times 10^{-5}\ \text{g}$$

$$\text{Mass of particle passing 200-mesh screen} = \frac{\pi}{6}d^3\rho = \frac{3.14}{6}(0.0074)^3(2.65)$$

$$= 5.62 \times 10^{-7}\ \text{g}$$

$$\text{No. particles required} = \frac{3.64 \times 10^{-5}}{5.62 \times 10^{-7}} = 64.7\text{, say 65 particles}$$

Fumes Solids produced by physicochemical reactions such as combustion, sublimation, or distillation. Typical fumes are the metallurgical fumes of PbO, Fe_2O_3, or ZnO. Particles making up fumes are quite small, below 1 μm in size, and thus cannot be sized on screens. The particles appear to flocculate readily.

Smoke A cloud of particles produced by some sort of oxidation process such as burning. The optical density is presupposed. Generally, smokes are considered to have an organic origin and typically come from coal, oil, wood, or other carbonaceous fuels. Smoke particles are in the same size range as fume particles.

TABLE 1.1 Openings of Some Typically Small Mesh Sizes*

Mesh	Opening, mm
50	0.297
100	0.150
200	0.074
400	0.038

*From *Handbook Chem. Phys.*, 54th ed., CRC Press, Cleveland, 1973, p. F147.

Mists and fog Aerosols produced by the disintegration of liquid or the condensation of vapor. Because liquid droplets are implied, the particles are spherical. They are small enough to appear to float in moderate air currents. When these droplets coalesce to form larger drops of about 100 μm or so, they can then appear as rain.

Haze Particles with some water vapor incorporated into them or around them, as observed in the atmosphere.

Smog A combination of smoke and fog, usually containing photochemical reaction products combined with water vapor to produce an irritating aerosol. Smog particle sizes are usually quite small, being somewhat less than 1 μm in diameter.

These definitions have arisen from popular usage, so there is little wonder that they overlap. What one person might call smog someone else could call haze, and both would be correct. Therefore we should generally use the more precise, if less colorful, definition of aerosol and then fill in the details on a more qualitative basis.

Since an aerosol is a collection of particles, it is often desirable to indicate whether the particles are all alike or are dissimilar. Thus there are several other descriptions of aerosols that must also be taken into account.

Monodisperse All particles exactly the same size. A *monodisperse aerosol* contains particles of only a single size. As might be expected, this condition is extremely rare in nature.

Polydisperse Containing particles of more than one size.

Homogeneous Chemical similarity. A *homogeneous aerosol* is one in which all particles are chemically identical. In an *inhomogeneous aerosol* different particles have different chemical compositions.

Morphological Properties of Aerosols

Shape

It is convenient to think of all aerosol particles as spheres for calculation, and this also helps visualize the processes taking place. But, with the exception of liquid droplets, which are always spherical, many shapes are possible. These shapes can be divided into three general classes.

1. *Isometric particles* are those for which all three dimensions are roughly the same. Spherical, regular polyhedral, or particles approximating these shapes belong in this class. Most knowledge regarding aerosol behavior pertains mainly to isometric particles.

2. *Platelets* are particles that have two long dimensions and a small third dimension. Leaves or leaf fragments, scales, and disks fall into this class. Very little is known about platelet behavior in air, and care must be exercised in applying knowledge derived from studying isometric particles to platelets.

3. *Fibers* are particles with great length in one dimension compared to much smaller lengths in the other two dimensions. Examples are prisms, needles, and threads or mineral fibers such as asbestos. Recent concern over the health hazard posed by inhalation of asbestos fibers has prompted study of fiber properties in air. There is still not as much known about fibers as isometric particles.

Example 1.3 An asbestos fiber is 10 μm in length with a circular cross-section of 0.5-μm diameter. Find the diameter of a sphere that has the same volume as the fiber.

$$\text{Volume of fiber} = \frac{\pi}{4}(0.5)^2(10)$$

$$= 1.96\ \mu\text{m}^3$$

$$\text{Volume of sphere} = \frac{\pi}{6}d^3$$

$$d^3 = 1.96\frac{6}{\pi} = 3.75$$

$$d = 1.55\ \mu\text{m}$$

Particle shape can vary with the formation method and the nature of the parent material. Particles formed by the condensation of vapor molecules are generally spherical, especially if they go through a liquid phase during condensation. Particles formed by breaking or grinding larger particles, termed *attrition,* are seldom spherical, except in the case where liquid droplets are broken up to form smaller liquid droplets.

Size

A particle is generally imagined to be spherical or nearly spherical. Either particle radius or particle diameter can be used to describe particle size. In theoretical discussions of particle properties, the radius is most commonly used, whereas in more practical applications the diameter is the descriptor of choice. Thus one should carefully ascertain which definition is being used when the term *particle size* is used. In this text particle diameter is used throughout.

Once a choice of diameter or radius is made, there are a number of ways that this diameter or radius can be defined which reflect particle properties other than physical size. For a monodisperse aerosol, a single measure describes the diameters of all the particles. But with polydisperse aerosols a single diameter is not sufficient to describe all particle diameters, and certain presumptions must be made as to the distribution of sizes. Other parameters besides diameter alone must be used. This is discussed in more detail in Chap. 2.

Two commonly encountered definitions of particle size are Feret's diameter and Martin's diameter. These refer to estimates of approximate particle size when determined from viewing the projected images of a number of irregularly shaped particles. *Feret's diameter* is the maximum distance from edge to edge of each particle, and *Martin's diameter* is the length of the line that separates each particle into two equal portions. Since these measures could vary depending on the orientation of the particle, they are valid only if averaged over a number of particles and if all measurements are made parallel to one another. Then, by assuming random orientation of the particles, an average diameter is measured.

This measurement problem can be simplified somewhat by using the *projected area diameter* instead of Feret's or Martin's diameter. This is defined as the diameter of a circle having the same projected area as the particle in question. Figure 1.1 illustrates these three definitions. In general, Feret's diameter will be larger than the projected area diameter which will be larger than Martin's diameter.

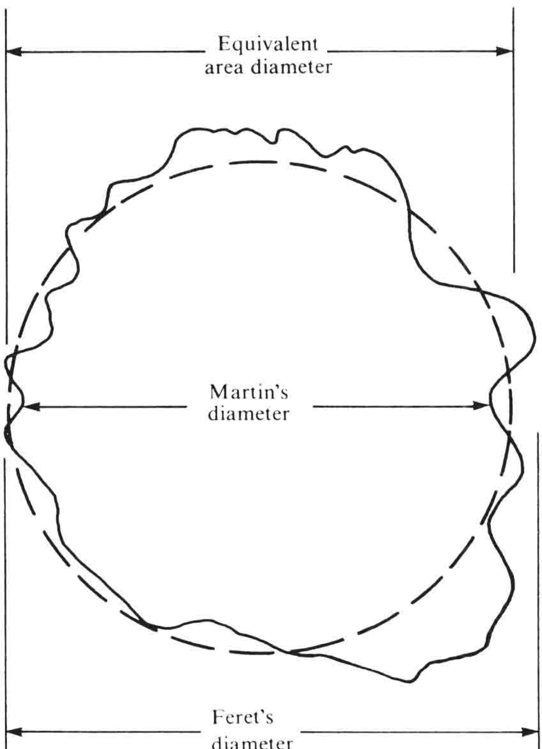

Figure 1.1 Illustration of three common definitions of particle diameter. In general, Martin's diameter is less than the equivalent area diameter, which in turn is less than Feret's diameter.

Example 1.4 Figure 1.2 shows a collection of five irregularly shaped particles. By measuring along lines parallel to the scale line, determine Martin's, Feret's, and the projected area diameter for this collection of particles.

The measured values are

Feret's diameter = 15 scale units

Martin's diameter = 10 scale units

Projected area diameter = 13 scale units

Sometimes a diameter is defined in terms of particle settling velocity. All particles having similar settling velocities are considered to be the same size, regardless of their actual size, composition, or shape. Two such definitions which are most common are

Aerodynamic diameter Diameter of a unit density sphere (density = 1 g/cm^3) having the same aerodynamic properties as the particle in question. This means that particles of any shape or density will have the same aerodynamic diameter if their settling velocity is the same.

Stokes' diameter Diameter of a sphere of the same density as the particle in question having the same settling velocity as that particle. Stokes' diameter and aerodynamic diameter differ only in that Stokes' diameter includes the particle density whereas the aerodynamic diameter does not.

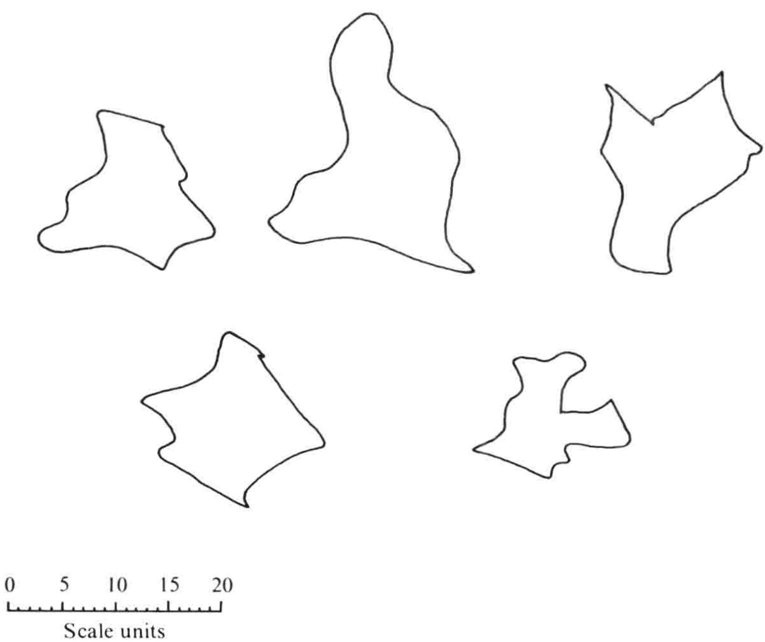

Figure 1.2 Illustration for Example 1.4.

Example 1.5 A sodium chloride cube (density = 2.165 g/cm^3) settles at a rate of 0.3 cm/s. Find the aerodynamic diameter of this cube.

Appendix A gives a corrected sedimentation velocity of 0.306 cm/s for a 10-μm-diameter unit-density sphere. Hence 10 μm is the aerodynamic diameter of this particular salt cube.

Particle diameters of interest in aerosol science cover a range of about four orders of magnitude, from 0.01 μm as a lower limit to approximately 100 μm as the upper limit. The lower limit approximates roughly the point where the transition from molecule to particle takes place. Particles much greater than about 100 μm or so do not normally remain suspended in the air for a sufficient length of time to be of much interest in aerosol science. There are occasions where particles that are either smaller or larger than these limits are important, but usually most particle diameters will fall within the limits of 0.01 to 100 μm.

Particles much greater than 5 to 10 μm in diameter are usually removed by the upper respiratory system, and those smaller than 5 μm can penetrate deep into the alveolar spaces of the lung. Thus 5 to 10 μm is often considered to be the upper diameter for aerosols of physiological interest.

Within the size range of 0.01 to 100 μm lie a number of physical dimensions which have a significant effect on particle properties. For example, the mean free path of an "air" molecule is about 0.07 μm. This means that the air in which a particle is suspended exhibits different properties, depending on particle size. Also the wavelengths of visible light lie in the narrow band of 0.4 to 0.7 μm. Particles smaller than the wavelength of light scatter light in a distinctly different manner than do larger particles.

Particle size is the most important descriptor for predicting aerosol behavior. This is apparent from the above discussion and will become even more apparent in later chapters. Typical particle sizes of selected materials are given in Table 1.2.

TABLE 1.2 Typical Particle Diameters, μm

Tobacco smoke	0.25	Lycopodium	20
Ammonium chloride	0.1	Atmospheric fog	2–50
Sulfuric acid mist	0.3–5	Pollens	15–70
Zinc oxide fume	0.05	"Aerosol" spray products	1–100
Flour dust	15–20	Talc	10
Pigments	1–5	Photochemical aerosols	0.01–1