

Aerosol Technology: A Comprehensive Technical Guide to Properties, Behavior, and Measurement of Airborne Particles

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Aerosol science represents a critical intersection of physics, chemistry, and engineering. From the microscopic droplets exhaled during human speech to the vast plumes of volcanic ash circling the globe, aerosols—defined as solid or liquid particles suspended in a gaseous medium—govern a significant portion of our environmental and industrial reality. This article provides an exhaustive technical exploration of aerosol technology, drawing upon the foundational principles established in seminal works like those by **William C. Hinds**. We will examine the physical properties, dynamic behaviors, and the sophisticated measurement techniques used to quantify airborne particles in research and industrial applications.

1. Fundamentals of Aerosol Physics and Particle Characterization

To understand aerosol behavior, one must first define the parameters that characterize individual particles and their collective behavior in a population. Unlike bulk materials, aerosols are characterized by their extreme surface-area-to-volume ratios and their susceptibility to various force fields (gravitational, electrical, and thermal).

Particle Size and Morphology

Particle size is arguably the most influential parameter in aerosol technology. It determines how long a particle remains airborne, where it deposits in the human respiratory system, and how it interacts with light. Aerosol particles typically range from **0.001 micrometers** (10^{-6} m) over **100 micrometers** (10^{-4} m). Particles smaller than 0.1 μm are referred to as the **nanoparticle** or nuclei mode, while those between 0.1 and 2.5 μm are the accumulation mode, and those larger than 2.5 μm are the **coarse** mode.

However, particles are rarely perfect spheres. To handle irregular shapes, aerosol scientists utilize **equivalent diameters**. The most common is the **Aerodynamic Diameter** (d_{ae}), defined as the diameter of a unit-density sphere ($\rho = 1000 \text{ kg/m}^3$) that has the same settling velocity as the particle in question. This allows for a standardized comparison of particles with varying densities and shapes.

Concentration Metrics

Aerosol concentration is expressed in two primary ways:

- **Mass Concentration:** The mass of particulate matter per unit volume of air (e.g., mg/m^3 or $\mu\text{g}/\text{m}^3$).
- **Number Concentration:** The total number of particles per unit volume of air (e.g., $\text{particles}/\text{cm}^3$).

In many technical applications, particularly in cleanroom monitoring or virus transmission studies, number concentration is more relevant than mass concentration, as a few large particles can dominate the mass while millions of small particles dominate the count.

2. Fluid Mechanics and the Motion of Particles

The movement of a particle through a gas is governed by the balance of forces, primarily the drag force exerted by the gas and external forces like gravity. At the microscopic scale, the discrete nature of gas molecules becomes

significant.

Stokes Law and the Drag Force

For small particles moving at low velocities, the drag force (F_d), is described by **Stokes Law**:

$$F_d = 3\pi \eta V r$$

Where: η is the dynamic viscosity of the gas. V is the relative velocity between the particle and the gas. r is the particle radius.

Stokes Law assumes a continuum—that the gas is a continuous fluid. However, when the particle size approaches the **mean free path** of gas molecules ($\approx 0.1 \mu\text{m}$ at STP), the gas no longer behaves as a continuum. The particle "slips" between molecules. To account for this, the **Cunningham Slip Correction Factor (C)** is applied:

$$C = 1 + Kn [1.257 + 0.40 \exp(-1.10/Kn)]$$

Where Kn is the Knudsen number ($Kn = \lambda / r$). This correction is vital for accurately calculating the behavior of sub-micron particles.

Terminal Settling Velocity

When a particle falls under gravity, it eventually reaches a constant **terminal settling velocity** (V_{ts}) where the gravitational force equals the drag force:

$$V_{ts} = \frac{2}{9} \frac{r^2 (\rho_p - \rho_g) g}{\eta C}$$

This equation is the bedrock of aerosol science, used to design everything from sedimentation chambers to industrial air filters.

3. Comparison of Particle Diameter Definitions

Understanding which "diameter" to use is critical for technical accuracy. The following table summarizes the different diameter definitions used in aerosol measurement.

Diameter Type	Symbol	Physical Basis	Primary Application
Geometric Diameter	dg	Physical dimensions measured by microscopy.	Morphology and shape factor analysis.
Aerodynamic Diameter	da	Settling velocity and inertial behavior.	Respiratory deposition, filtration, and impaction.
Stokes Diameter	dst	Drag force in a fluid.	Sedimentation and fluid dynamics studies.
Electrical Mobility Diameter	dm	Velocity in an electric field.	Sizing nanoparticles (SMPS systems).
Optical Diameter	dp,opt	Light scattering intensity.	Optical Particle Counters (OPC) and LIDAR.

4. Particle Size Statistics and Distributions

Aerosols are rarely monodisperse (all one size). They are usually **polydisperse**, requiring statistical distributions to describe them. The most frequently used model is the **Log-Normal Distribution**. This is preferred over the normal distribution because aerosol sizes span several orders of magnitude and cannot be negative.

Key Statistical Parameters

- Count Median Diameter (CMD): The size at which half the particles by count are smaller and half are larger.
- Mass Median Aerodynamic Diameter (MMAD): The size at which half the total mass of the aerosol is contained in particles smaller than this diameter. This is the standard metric in pharmaceutical aerosol delivery (e.g., inhalers).
- Geometric Standard Deviation (GSD or σ_g): A measure of the polydispersity. A GSD of 1.0 indicates a perfectly monodisperse aerosol, while values above 1.25 typically indicate a polydisperse aerosol.

5. Mechanics of Aerosol Deposition and Behavior

How particles leave the air and deposit on surfaces is governed by five primary mechanisms. Understanding these is essential for designing effective filtration and personal protective equipment (PPE).

Inertial Impaction

This occurs when a gas stream turns sharply, but a particle's inertia causes it to continue on its path and collide with a surface. This is the dominant mechanism for particles larger than $2\text{ }\mu\text{m}$. The **Stokes Number (Stk)** characterizes this behavior; a high Stk indicates a high probability of impaction.

Interception

Interception occurs when a particle follows a gas streamline but its physical size (radius) is large enough that it touches a fiber or surface. This mechanism is independent of particle velocity.

Diffusion (Brownian Motion)

For very small particles (typically $< 0.1\text{ }\mu\text{m}$), the random bombardment by gas molecules causes the particle to wander across streamlines and contact surfaces. This is known as Brownian diffusion and is more effective at low flow velocities.

Gravitational Settling

Large particles are removed from the air simply by falling out due to gravity. This is most relevant in horizontal ducts or the upper respiratory tract.

Electrostatic Attraction

If the particle and the surface carry opposite charges, electrostatic forces can significantly enhance deposition. This principle is utilized in **Electrostatic Precipitators (ESPs)** used in power plants to remove fly ash.

6. Measurement Technologies and Instrumentation

Quantifying aerosols requires specialized instruments capable of counting and sizing particles in real-time or via laboratory analysis.

Inertial Impactors

These devices, such as the **Cascade Impactor**, use a series of nozzles and collection plates. As the air moves through the device, each stage removes particles of a specific aerodynamic size range. The mass collected on each stage is weighed to determine the MMAD.

Optical Particle Counters (OPC)

OPCs pass a stream of particles through a laser beam. Each particle scatters light, and the intensity of the scattered light is related to the particle size. This method is fast and non-destructive but depends on the **refractive index** of the material.

Condensation Particle Counters (CPC)

For particles too small to scatter light effectively ($< 0.1 \mu\text{m}$) a CPC is used. The particles pass through a saturated vapor (usually alcohol or water), which condenses onto the particles, "growing" them into droplets large enough to be counted optically.

7. Technical Comparison: Real-Time vs. Filter-Based Sampling

Feature	Filter-Based Sampling	Real-Time Instrumentation
Primary Output	Total mass or chemical composition.	Number/Size distribution over time.
Temporal Resolution	Low (hours to days).	High (seconds to minutes).
Accuracy	High for mass (gravimetric).	Variable (requires calibration).
Portability	High (passive samplers).	Moderate to Low.
Cost	Low per sample.	High initial investment.

8. Field Guide: Practical Implementation of Aerosol Sampling

When conducting aerosol measurements in the field or in a laboratory setting, several technical considerations must be addressed to ensure data validity.

Isokinetic Sampling

When sampling from a moving gas stream (e.g., a smokestack), the velocity of the air entering the sample probe must exactly match the velocity of the surrounding gas stream. This is called **isokinetic sampling**.

- Super-isokinetic: Probe velocity is higher than stream velocity. Large particles are under-sampled due to inertia.
- Sub-isokinetic: Probe velocity is lower than stream velocity. Large particles are over-sampled.

Transport Losses

Particles can be lost in the tubing between the sampling point and the instrument due to settling in horizontal sections, impaction in bends, or diffusion to the walls. Sampling lines should be kept as short and straight as possible, using conductive materials to prevent electrostatic losses.

9. Case Studies and Troubleshooting

Case Study: N95 Respirator Efficiency

The N95 designation means the filter removes 95% of particles at the **Most Penetrating Particle Size (MPPS)**. Technical analysis shows that the MPPS is typically around 0.3 µm. Why? Because particles smaller than this are easily caught by **diffusion**, and larger particles are easily caught by **impaction** and **interception**. The 0.3 µm range is where all mechanisms are at their weakest. Troubleshooting filter failure often involves identifying leaks in the seal rather than the material itself, as the filter media's efficiency usually exceeds its rating for non-MPPS sizes.

Common Troubleshooting: Data Noise in OPCs

If an Optical Particle Counter shows erratic readings, the first step is to check for **coincidence errors**. This occurs when the aerosol concentration is so high that two particles are in the sensing volume at the same time, leading the instrument to count them as one larger particle. The solution is to use an **aerosol diluter** before the sample enters the OPC.

10. Technical Summary and Synthesis

Aerosol technology is a discipline defined by the delicate balance of fluid dynamics and particle physics. Mastery of

this field requires a deep understanding of how particle size dictates behavior across various force fields. As we have explored, the transition from continuum mechanics to molecular slip (the Knudsen regime) is critical for nanoparticles, while inertial effects dominate the coarse mode. The use of equivalent aerodynamic diameters remains the most robust method for predicting deposition and transport, providing a bridge between theoretical models and practical measurement.

The future of aerosol technology lies in the refinement of real-time chemical characterization (such as Aerosol Mass Spectrometry) and the development of low-cost sensor networks for urban air quality monitoring. By applying the rigorous mathematical frameworks established by Hinds and his successors, engineers and scientists can continue to solve complex problems in public health, climate modeling, and high-tech manufacturing. Whether the goal is to optimize drug delivery to the deep lungs or to scrub pollutants from industrial exhaust, the principles of aerosol properties, behavior, and measurement remain the essential foundation for innovation.

Tags: #Aerosol Science #Particle Physics #Fluid Dynamics #William C. Hinds #Airborne Particles #Technical Writing

