CleanAir Engineering
500 W. Wood Street
Palatine, IL 60067-4975
800-627-0033
www.cleanair.com

What Defines or Characterizes a "Particle" and What Limitations Can These Definitions Impose on Particle Size Distributions?

Molecular structure, homogeneity, morphology (shape, texture and phase) and suspension medium associated with the particles can cause different size measurement devices to respond differently to the same particle. When comparing the results from two different types of sizing instruments, one should know if any characteristic of the particle other than size, or any characteristic of the sample presentation could affect the reported values. Errors can be associated with non-ideal or even inappropriate application of the measuring instruments.

Is There a Single, Standard Definition for "Particle Size" That Can Be Applied to Any Particle?

There are many definitions, but none has been universally adopted as a comprehensive standard. Of the in-situ testing methods in the air pollution industry, Aerodynamic Diameters are used. These methods include:

- CARB Method 501[i] – Determination of Size Distribution of Particulate Matter from Stationary Sources;
- OTM-027 – Determination of PM_{10} and $PM_{2.5}$ Emissions From Stationary Sources (Constant Sampling Rate Procedure);
- CTM-039 - Measurement of $PM_{2.5}$ and PM_{10} Emissions by Dilution Sampling (Constant Sampling Rate Procedures);
- Method 201 – Determination of PM_{10} Emissions (Exhaust Gas Recycle Procedure); and
- Method 201A – Determination of PM_{10} Emissions (Constant Sampling Rate Procedure).

Some techniques will use the projected cross-sectional diameter. Of course, the projected cross-sectional diameter remains constant regardless of the angle of view for a sphere; therefore a sphere is isotropic in a geometrical sense. No other regular or irregular shape projects the same cross-section at all angles of view.

The fact that an irregular particle can present a different cross-section depending on orientation is only one of the measurement problems. Another is that an irregularly shaped cross-section has different "diameters" depending on where the chord is drawn.

What Do Particle Sizing Instruments Actually Measure?

As previously discussed for in-situ devices, the aerodynamic particle size is determined. Many laboratory techniques will determine particle size indirectly from direct measurements of some parameter other than the complete geometry. These parameters are associated with a physical phenomenon in which the particle is involved. The direct measurement may be of some characteristic of the reaction of the particle to an action, or it may be of the reaction of something that has interacted with the particle.

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An example of the former is the particle's sedimentation velocity in a fluid. An example of the latter is the pattern of light scattered by the particle. The parameter being directly measured is related to particle geometry by some law, theory or model describing the physical phenomenon.

The previously discussed in-situ methods use sedimentation velocity and assume particles of unit density.

How Does Particle Density Affect Measurement of Particle Size?

Particle density affects the motion of a particle through a fluid and is taken into account in the following generalized equation:

$$d_{pa} = d_{ps} \sqrt{\rho_p}$$

Where:

d_{pa} = Aerodynamic particle diameter, (μm)

d_{ps} = Stokes diameter, (μm)

ρ_p = Particle density, (g/cm^3)

The Stokes diameter for a particle is the diameter of a sphere that has the same density and settling velocity as the particle under question. It is based on the drag force caused by the difference in velocity of the particle and the surrounding fluid. Particles that appear to have different physical sizes and shapes along with different Stokes diameters can have the same aerodynamic diameter. This is illustrated in Table 1, below.

If the particle density is known, Stokes diameters can be determined. But, it should be realized that the above equation is extremely simplified for ideal particles. Particles approximately in the range covered by the Cunningham corrected Stokes Equation should be corrected using the equation below. This size range is basically between one and fifteen micro-meters.

Conversion between aerodynamic and Cunningham corrected Stokes diameters can be solved by trial and error using the following equations:

$$d_{ps} = d_{pa} \sqrt{\frac{C_a}{C\rho_p}}$$

Where:
d_{ps} = Stokesian particle diameter, (μm)
d_{pa} = Aerodynamic particle diameter, (μm)
C = Cunningham Correction Factor applied using d_{ps} (dimensionless)
C_a = Cunningham Correction Factor applied using D_{pa} (dimensionless)
ρ_p = Particle Density, (g/cm^3)

$$C = 1 + \left[1.257 + 0.400\, e^{\left[\frac{-1.10 d_{pa}}{2\lambda_g}\right]} \right] \left[\frac{2\lambda_g}{d_{pa}} \right]$$

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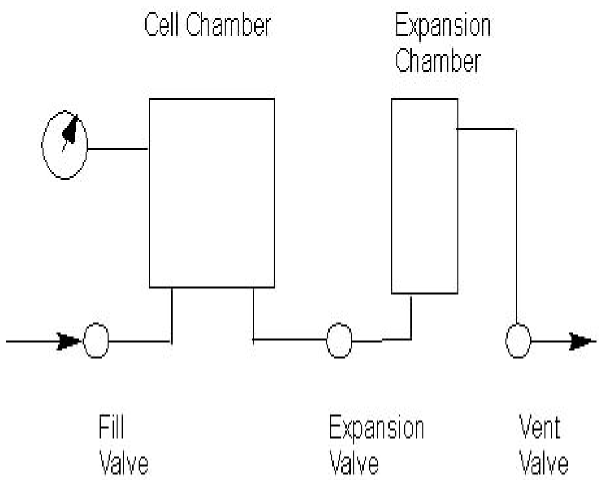

Where:
C = Cunningham Correction Factor applied using D (dimensionless)
d_{ps} = Particle diameter, (cm)
λ_g = Mean free path of gas molecules, (cm)

For particles generally larger than 15 µm, C can be simplified to 1.0. For the iterative solution that should be used on smaller particles, everything on the right side of the former equation is known except C. As a first approximation, C = C_a could be assumed. When the first value of d_{ps} for this C is obtained, a new C can be determined and used to produce the corrected d_{ps}. A third iteration (or more) is usually required depending on the accuracy desired.

In the converse, particles that appear to be visually similar can have different aerodynamic diameters. This is from the nature of the mathematical size descriptions.

Measuring Particle Density

Density is measured from a bulk sample using an AccuPyc 1330 Pycnometer manufactured by Micromeritics. This instrument determines density from the volume of a sample by measuring the pressure change of helium in a calibrate volume cell. The sample mass is measured separately.

[1] FGD Chemistry and Analytical Methods Handbook, Volume 2: Chemical and Physical Test Methods, Revision 1. CS-3612, Volume 2, Revision 1. Research Project: 1031-4. Electric Power Research Corporation, Final Report, November 1988.

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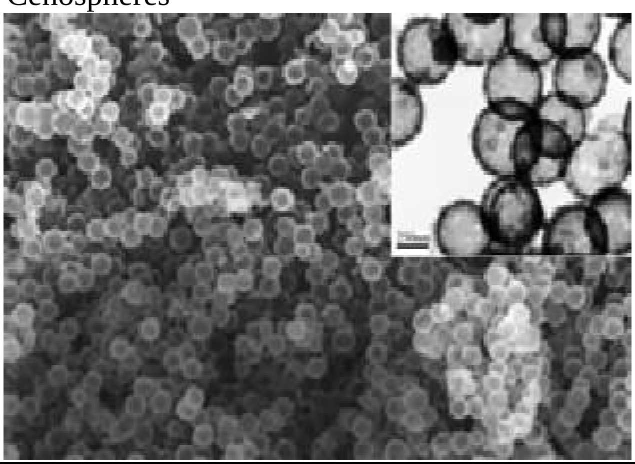
[i] CARB 501 – Determination of Size Distribution of Particulate Matter from Stationary Sources: California Air Resources Board, Amended: September 12, 1990.

Table 1: Stokes Diameters Compared with Aerodynamic Diameters of Differently Shaped Particles with Different Density Values

Solid Sphere 	r_p = 2.0 g/cc d_{ps} = 1.4 um	d_{pa} = 2.0 um
Cenospheres 	r_p = 0.5 g/cc d_{ps} = 2.8 um	d_{pa} = 2.0 um

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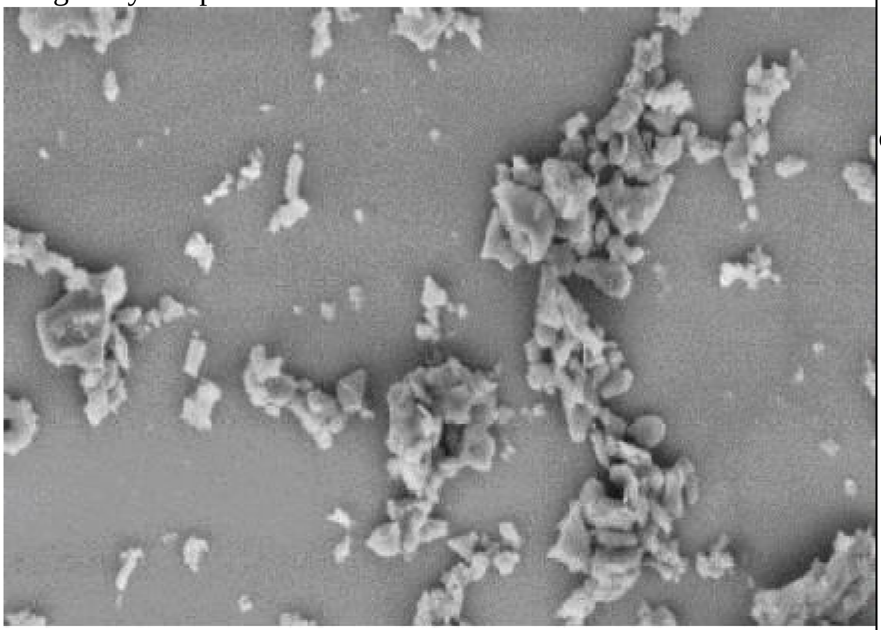
Irregularly Shaped Particles 	r_p = 2.4 g/cc d_{ps} = 1.3 um	d_{pa} = 2.0 um