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An Analysis of Acceptable Particle Losses in Tubing

Transportation of particles in tubing between a sample inlet and the optics of particle counters has at many times been at the forefront of discussion regarding the truth of readings. When the validation implications of losses due to various forces are reviewed, the certainty of the result is always in question. So what are these forces, what are the losses, and what are acceptable results? This paper hopes to address these issues and to allow for a better understanding of the problem.

External Influences

Forces acting on particles

Cleanroom certification and monitoring activities can be seen as tests performed to quantify the dynamics of the body of air within a confined space. This space may be either the air in the general cleanroom or in a transport duct or a laminar flow zone. The following describes the mechanisms of how particles behave and will assist in the understanding of sampling difficulties and in improving the efficiency of sampling.

- The **Stokes number** is the ratio of a particle's radius to the dimension of an obstacle to fluid flow. This is an important factor in determining when a particle in motion will be collected by an obstacle or will pass around it. An obstacle could be a filter fiber or the sample inlet.
- The **drag coefficient** is the ratio of the force of gravity to the inertial force on a particle in fluid. It indicates how a particle will resist any force that could cause a change in the particle velocity. Smaller particles have smaller drag coefficients owing to their lesser mass.
- The **Relaxation time** is the time for a particle initially in equilibrium with a moving fluid to match a change in fluid velocity. Large particles have a long relaxation time. Therefore, when an air stream moves through tubing that contains small-radius bends or elbows, the large particles will deposit on a tube wall because they cannot adapt easily to sudden velocity changes owing to tube curvature, but will continue in their original direction until they impact on the tube wall. A related term is **stopping distance**, which is defined as the distance for a particle initially moving within a gas stream to come to a stop when the gas flow is halted, as by an obstacle.
- The **Deposition velocity** or **sedimentation velocity** is the ratio of particle flux, distance per unit time for sedimentation to occur relative to the ambient particle concentration.

Particle Size (μm)	Settling Velocity (cms^{-1})
0.00037	
0.01	6.95×10^{-6}
0.1	8.65×10^{-5}
1.0	3.50×10^{-3}
10	3.06×10^{-1}
100	2.62×10^{1}

Table 1. Settling velocities of particles

There are also additional forces in effect on particles; these forces on the particles and their subsequent response to those forces control the particles migration through the air:

- **Viscous forces**, the fluid dynamic force from a moving fluid stream, the viscous nature of an air stream will pull particles along that flow path. If this flow is laminar then other forces act upon the larger particles encouraging settling and deposition, smaller particles remain buoyant on a laminar flow. In turbulent flow streams the larger particles are re-entrained back into the airflow should they deposit, smaller particles are now more prone to additional forces acting upon them.
- **Brownian motion**, as the particles migrate through a body of air, random impacts from individual molecules will cause them to veer from course.

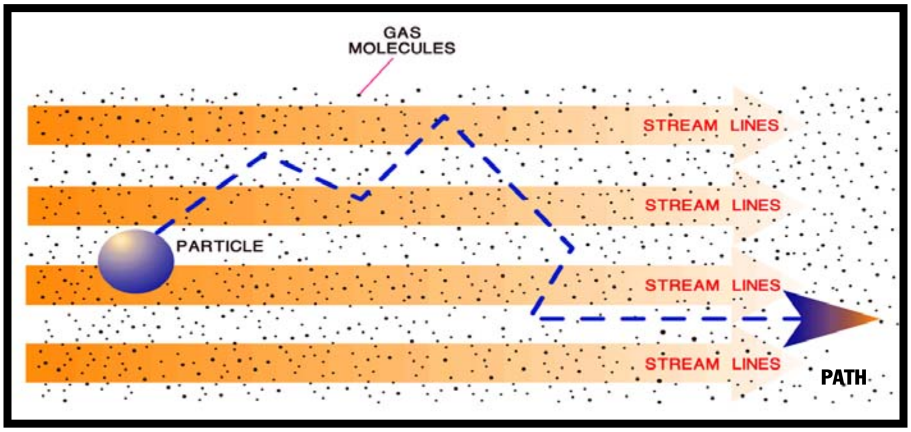

Figure 1. Migration of a particle along a mean free path, due to Brownian motion.

- **Gravitational force**, this force on a particle varies with particle mass and the difference between particle and air density, the larger the particle the greater the interaction.
- **Electrostatic forces**, this force on a particle varies with the particle's electrical charge (surface area controlled) and the strength of the electrical field in which the particle is located. Electrostatic charge can develop as a particle slips through the air stream. It is important to minimize these interactions to ensure all particles reach the final destination.
- **Diffusion forces**, this force on a particle varies inversely with particle's radius. Therefore, smaller particles are more prone to interactions due to diffusion.
- **Thermophoretic forces**, these forces (effective mainly for small particles) vary with the particle's surface area and temperature gradient.

The particle's response to these forces is controlled by the particle's size, mass, shape, and electrical charge. For essentially all of these forces, the major particle parameter is size, because the magnitude of the several forces varies with particle size squared or cubed.

Practical considerations

There are several ways in which one can design a system to minimize these forces and their impact on sampling errors.

Isokinetic sampling

In laminar flow environments, or in ducts leading to a filter, the air is considered to be moving unidirectionally. The sampling of this air flow must neither be over or under sample the distribution of particles within that flow. This requirement is satisfied when isokinetic sampling is performed. Isokinetic sampling means that the air velocity in the supply air is the same as the air velocity in the particle counters sample-tubing inlet.

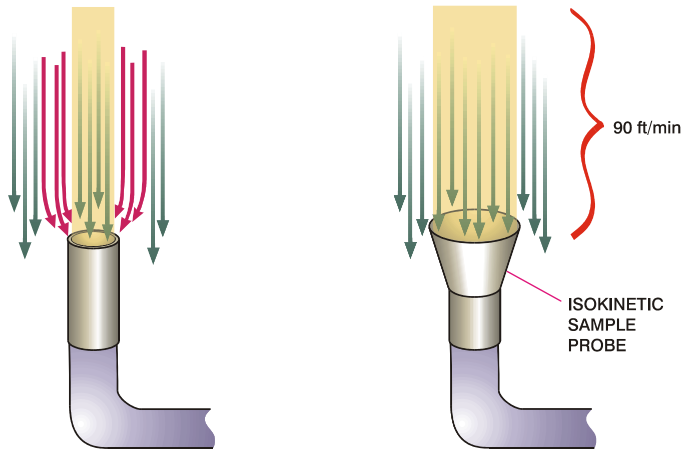

Figure 2. Isokinetic sampling.

If the velocities differ, then either a positive or negative sample collection error occurs. An isokinetic sample error increases with particle size, but is not of great concern for particles smaller than 1–2 µm. Federal Standard FS209E (Airborne Particulate Cleanliness Classes in Cleanrooms and Clean Zones, Federal Standard No. 209E. Washington, DC: General Services Administration, 1992) shows that isokinetic sampling errors greater than 5% are not expected for particles smaller than a few micrometers when using a sample probe with inlet diameter of 2 mm or larger, even when sampling and sampled air velocities differ by an order of magnitude. However, when macro particles ≥5 µm are to be measured, then isokinetic sampling is required. Particle Measuring Systems has a calculator that accurately assesses the dimensions of the isokinetic probe and the associated errors should a non-standard sample probe be used.

Particle loss in transport tubing

When a sample is taken for either certification or routine monitoring operations, it is not uncommon for the isokinetic sample probe (ISP) to be in a remote location from the particle counter optics. The sample is drawn through tubing to the particle counter. When the sample is to be transported any significant distance in the tube; from the point of sampling to the point of measurement, then some particle losses will occur in the transport tubing, the losses are dependant on tubing type, velocity, diameter and distance. Large particles are lost by a combination of gravitational settling to the bottom of the duct and inertial deposition on the walls of the tubing when directional changes occur. Small particles are lost to the duct walls by Brownian motion and diffusion effects.

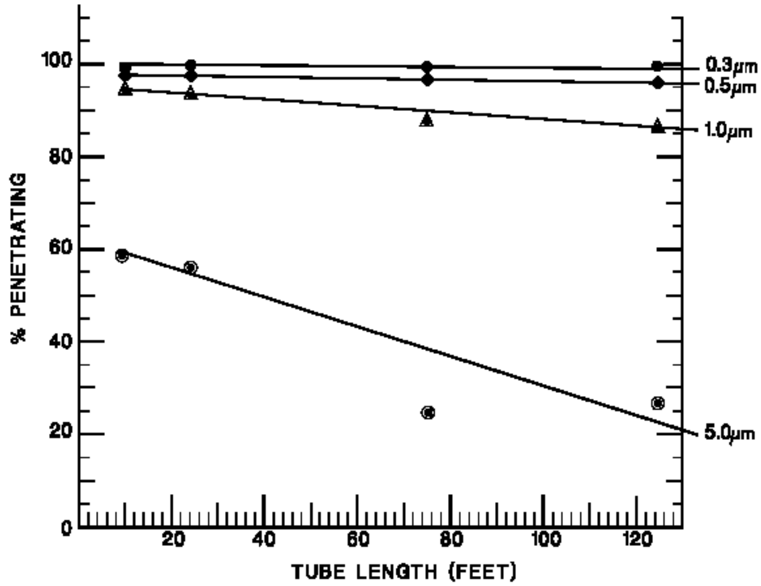

Figure 3. Particle loss in manifold sample tubing (1/2" tubing at 100litre/minute flow rate)

Figure 3 illustrates the percentage penetration of different sized particles sampled through a manifold system over distances up to 125 feet. Particles <1.0 µm in diameter show no significant losses, and the differences are essentially experimental error, but larger particles show a significant level of loss even over very short distances.

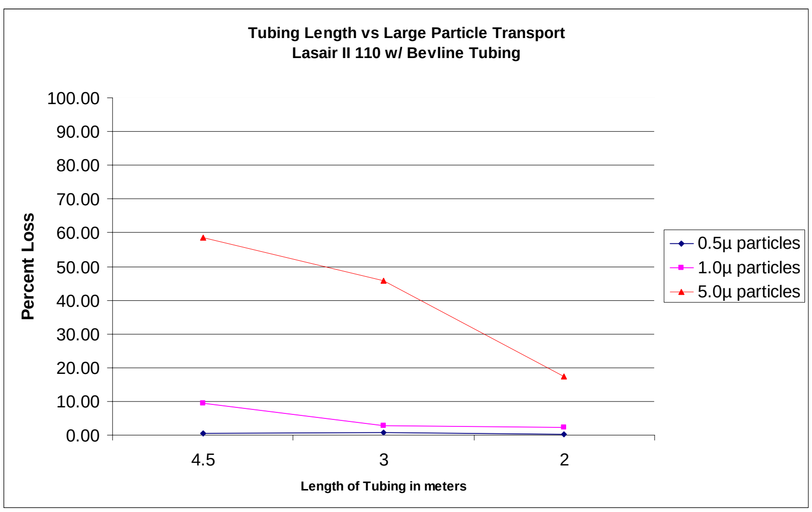

Figure 4. Particle loss in a portable particle counter (3/8" tubing at 28.3 liter/minute flow rate)

When portable particle counters (such as the Lasair II) are used, the flow rate in the tubing is significantly reduced; therefore, the maximum permissible distance is also reduced. Figure 4 shows a similar pattern to that for manifold sampling but over much shorter distances.

Electrostatic forces also account for a proportion of the losses in a sample; therefore to reduce the effect of these additional forces various types of material were tested to establish a suitable standard. The order is based on a combination of particle loss rate, electrical conductivity, and potential for oxide or sulfide formation when the tubing is exposed to urban air.

No.1 – Stainless Steel
No.2 – Bev-a-line
No.3 – Polyester (as polyurethane)
No.4 – Polyester lined vinyl
No.5 – Copper
No.6 – High density polyethylene
No.7 – Glass
No.8 –Teflon

Table 2. Particle transport line material preference

The diameter of the tubing should be selected to ensure the Reynolds number is between 5,000 and 25,000 as required in FS209E (Airborne Particulate Cleanliness Classes in Cleanrooms and Clean Zones, Federal Standard No. 209E. Washington, DC: General Services Administration, 1992). The Reynolds number range is one for which no significant turbulent deposition occurs for particles smaller than 5–10 μm, a residence time in the tubing should be no more than 10-20 seconds ensuring the transmission of particles larger than 0.1 μm before any significant losses occur.

Acceptable losses

This section is the most difficult to define as any loss can be deemed to be unacceptable, however let us look at the uncertainties, the acceptable errors for particle counting. The table below shows a comparison of various standards associated with airborne-particle counting. Although not fully adopted they outline the errors and how error stack-up can very quickly show particle counters to be quite different from each other.

	JIS B9921:1997	ISO-13323-2	ASTM f328-98
Particle Size Accuracy		5%	
Particle CV		5%	
Sizing Accuracy	5%	10%	
Counting Efficiency	20%	20%	10%
Sample Volume	10%	10%	5%
Resolution		10%	10%
Coincidence Level	5%	10%	
Flow Rate Accuracy	5%	5%	10%
Time Accuracy	1%	1%	
Volume Accuracy		5%	
Total Error %	+/- 46%	+/- 81%	+/- 35%

Table 3. Error analysis for various counting standards

From the table above we have a spread of errors from 35% to 81% making an assumed average error of approximately 50%. If we also add to this an acceptable loss of an isokinetic sampling of 5% for counts, then the errors for particle transportation tends to be relatively small.

In qualifying the particle losses of any system, whether it be 28.3 lpm (1 CFM) or a manifold based system, the ability to systematic errors is very easy and biasing of data is dependant on probe orientation, distance apart, air flow patterns, number of particles being sampled, duration of test, base line variables between counters, optical variances, etc. Therefore, defining an absolute allowance is difficult.

Taking a personal rule of thumb of ensuring that any sampling errors are at least 50% of the maximum permitted counting error (50%), then any sample that tests an environment at least 25% efficiency of transportation loss the total error should not be affected significantly.

Therefore, providing our estimated particle counting losses qualification exercise does exceed 25% loss; equivalent to 2.0 m for a 28.3 lpm particle counter (Lasair II, Airnet 510) or approximately 7.0 m for a manifold device (Aerosol Manifold II-16) then acceptable values for 5.0 µm particles can be determined.