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COUNTING EFFICIENCY AND RESOLUTION IN OPTICAL PARTICLE COUNTERS

This paper answers some questions that arise during the selection and use of Optical Particle Counters (OPCs or particle counters):

1) What is counting efficiency and why should it be 50% at the most sensitive sizing threshold?
2) What is the meaning of OPC resolution and why is it important?
3) How will counting efficiency affect data for actual particle distributions in cleanrooms as compared to data from monodispersed calibration particles?

Most OPCs use a light source to illuminate a sample volume, an optical system to collect the particle's scattered light pulse, a process to convert the scattered light into an electrical signal, and electronics to correlate particle size with the scattered light pulse. While the specific design varies greatly between manufacturers (and while the instruments vary with different sensitivity and flow rates), the fundamental principles of OPC operation are quite similar across the industry.

Counting Efficiency

Counting efficiency is the probability that an OPC will sense and accurately count a particle passing through the OPCs sample volume. This probability describes the percentage of particles counted at—or above—a specified particle size. In *Figure 1*, three plots illustrate counting efficiency versus particle size. *Curve A* (the vertical line) shows a counting-efficiency curve for a hypothetical OPC with *perfect* sizing resolution. *Curve B* shows the curve for a real-world OPC with *good* resolution. *Curve C* shows the curve for an OPC with *poor* resolution[1]. While the signal produced by the particles is symmetrically distributed around the nominal most sensitive threshold, the exponential relationship between particle size and signal causes the counting efficiency curve to be asymmetrical. The discussion of 50% counting efficiency is deferred until after the section on Sensor Resolution because it relies upon an understanding of OPC resolution.

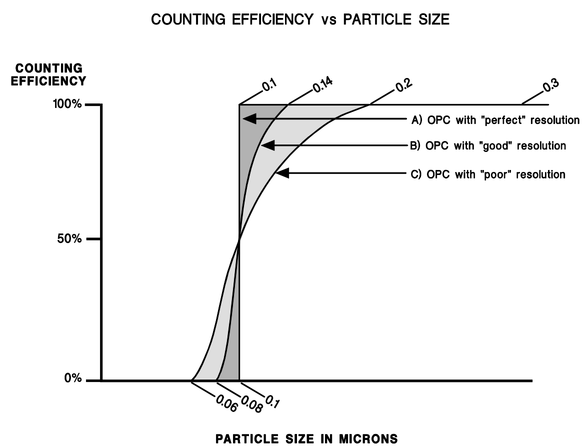

Figure 1: Counting Efficiency vs. Particle Size

Sensor Resolution

An OPC's *resolution* is the ability to resolve small differences in particle size. A number of factors combine to make an OPC's resolution less than perfect. These factors include the illumination uniformity within the sampling volume, the quality of the optical system, the quality of the electronics in the Pulse Height Analyzer module, and the noise due to photon statistics[2].

If it were possible to introduce the exact same -sized particles to a real-world OPC, the factors above would produce a familiar *bell curve* (normal or Gaussian) distribution. *Figure 2* illustrates the distributions that result when sampling particles (of the exact same size) to OPCs with *perfect*, *good*, and *poor* resolution.

With perfect resolution, the OPC will always place each particle in the same size channel regardless of the size channel's width.

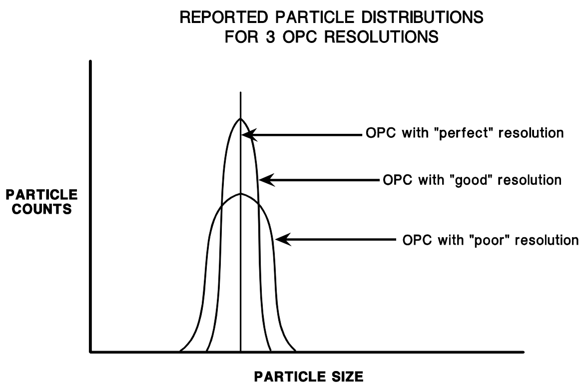

Figure 2: Particle Distributions

The resolution described up to this point could be called *fundamental* resolution because it is the best resolution of which the instrument is capable.

The minimum possible width of the OPC size channels are determined by the fundamental resolution. Therefore, an OPC with good resolution can have more size channels than an OPC with poor resolution.

The term *instrument resolution* describes the number of particle size channels, integrated by the manufacturer, to span the instrument's entire size range. The minimum possible channel size width is limited by the fundamental resolution. The instrument resolution selected for Particle Measuring Systems' particle counters is much broader than the fundamental resolution. This is done to simplify instrument operation, minimize costs, and applications seldom require high particle resolution.

However, Particle Measuring Systems manufactures a high-resolution OPC, called a spectrometer, and a spectrometers' resolution can meet the accuracy mandated by fundamental resolution. The *LAS-X II* spectrometer has 100 particle size channels ranging from 0.09 to 7.5 microns. Another spectrometer, the *HSLAS II,* also includes 100 particle size channels but detects much smaller particles ranging from 0.06 to 1.0 micron.

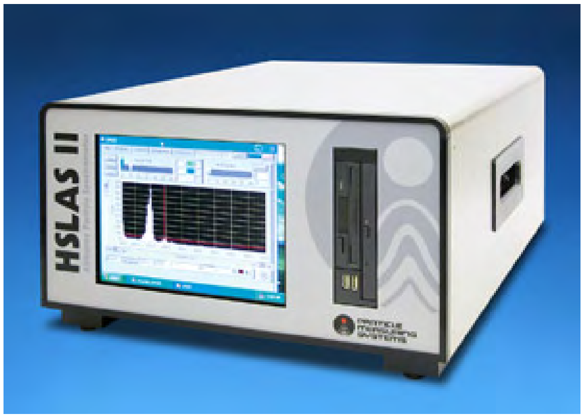

Figure 3: HSLAS II Spectrometer

Particle Measuring Systems uses spectrometers to calibrate and verify other, less-sensitive particle counters called *in-house standards.* These *standard* particle counters are then used to verify calibration on newly-manufactured OPCs. Commercially available particles, called polystyrene latex spheres (PSLs), are particles that have monodispersed distributions and are used by spectrometers and OPCs to exhibit a narrow distribution. The OPC's particle distribution is a function of the OPC's resolution (or lack thereof) and the standard particles used to calibrate or check the OPC. Consequently, imperfect resolution can broaden—or flatten—the particle distribution.

Sensor resolution may be quantified by introducing standard particles to the spectrometer. If the variance of the standard particles distribution is *VarStd*, the variance of the distribution reported by the spectrometer is *VarRpt*, and the mean particle diameter is *D*, then:

$$\%\ resolution = \left(\frac{100}{D}\right)\sqrt{VarRpt - VarStd}$$

While *% resolution* is a term used in some specifications, you may be more familiar with the synonymous terms *Coefficient of Variation* and *Relative Standard Deviation.*

A useful indication of resolution is provided when specifying the point where particle counting efficiency reaches 100%. Since an OPC's first-channel sensitivity defines the particle size at 50% counting efficiency, one can calculate the approximate resolution using the particle size that corresponds to 100% counting efficiency.

Figure 4: Lasair II 100 Particle Counter

Example: The Lasair®-II-110 has 100% counting efficiency starting at 0.14 microns and the instrument's first-channel sensitivity is 0.1 micron. Using the formula for percent resolution, we find a resolution of about 10%[3].

The particle sizes corresponding to 0% and 100% counting efficiency is annotated on Curves A, B, and C of Figure 1.

There are two factors that affect the apparent sensitivity and resolution of an OPC, but these factors are beyond the control of the designer due to *Mie scattering*. Light scattered from a particle follows Mie theory and is a function of the particle's size and shape, as well as, the ratio of the particle's refractive index to the transport media's refractive index. Most OPCs are calibrated using PSLs carried in a transport media of air, water, or gas. A real-world distribution of particle refractive indices will produce a degradation of resolution, while a change in the transport media's refractive index will produce a change in sensitivity. Although special calibrations are available for certain combinations of particle and media refractive indices, it is generally impractical to calibrate each OPC for a specific combination.

50% Counting Efficiency

Having established that real-world OPCs do not have perfect resolution, it may be instructive to examine counting efficiency Curve B in Figure 1 from a different perspective. Since the curve is not vertical, it is necessary to specify the point on the curve corresponding to nominal sensitivity. The point selected by most other manufacturers is the 50% level of counting efficiency.

Before discussing the underlying reasoning behind setting the most sensitive threshold at the 50% level of counting efficiency, it is important to understand what is referred to as *half-count calibration*. An industry standard procedure requires selecting standard particles, with a narrow distribution, and mean size that closely match a channel sizing threshold; this procedure facilitates OPC calibrations. If a sizing threshold is positioned at the mean size, and the calibration sample is mostly free of background counts, the counts will be split evenly between the adjacent size classes and share the sizing threshold as a common boundary. This procedure is referred to as half-count calibration. When under test, a relatively small shift in the sizing threshold produces an easily detectable difference in the counts in the adjacent size channels.

Specifying an OPC's most sensitive threshold requires selecting the 50% level of counting efficiency, which produces sizing results consistent with the results acquired at the other thresholds. *Figure 3* illustrates counting efficiency using a tri-modal distribution of standard particles, with the size corresponding to each mode equal to an OPC particle sizing threshold. In each of the three thresholds shown, 50% of the standard particles are below the threshold and 50% are above the threshold. Any thresholds above the most sensitive threshold should count 100% of the particle distributions, with 50% of each population below the respective threshold and 50% above. The only difference at the most sensitive threshold is that 50% of the populations below the threshold are not counted[4].

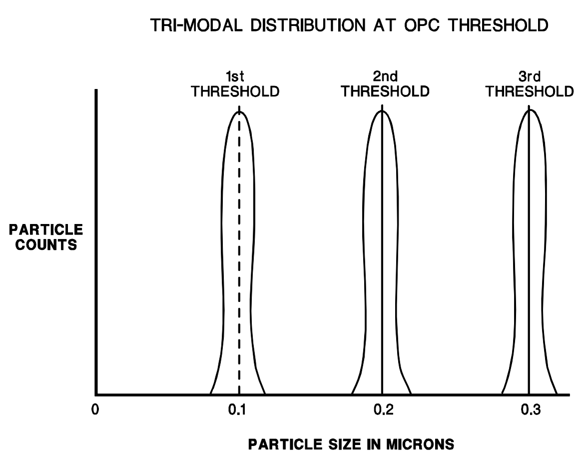

Figure 5: Tri-modal Distribution

Selection of the 50% level of counting minimizes dependence on sensor resolution when selecting the most sensitive threshold. Using the 50% level of counting efficiency, variations in resolution result in a different displacement from the nominal threshold for the 0% and 100% counting efficiency points, but do not result in moving the nominal threshold (Figure 1). A selection other than 50% counting efficiency results in a change in resolution and a change in the nominal threshold. For example, if the 100% level of counting efficiency were selected, the most sensitive nominal threshold would only be valid for the specific OPC selected. Differences in optical, electronic components, and design differences result in movement of the actual most sensitive threshold due to a change in resolution. The same logic would apply to any other threshold setting where one is using a half count determination of that threshold.

In addition, selection of an OPC's particle size that corresponds to 50% counting efficiency is essential for meaningful OPC data comparisons with higher resolution instruments such as the LAS-X II or the HSLAS II. As you can see from Curve B of Figure 1, an OPC with good resolution that counts 100% at 0.14 microns would count about 95% at 0.12, about 50% at 0.10, etc. The range from 0.10 to 0.14 microns, corresponding to a good resolution of an OPC's size difference between 50% and 100% counting efficiency, equates to a sizing error that could span several channels on the HSLAS II. Thus, the selection of an OPC's most sensitive threshold at other than 50% counting efficiency will result in significant counting errors relative to data collected by high resolution instruments.

Actual Particle Distributions

Since the discussion up to this point has focused on sampling monodispersed standard particles, it is reasonable to discuss the effects of counting efficiency on data collected from actual distributions. Most actual distributions are much broader than monodispersed particle distributions, and also much broader than the OPC's particle size ranges spanning counting efficiencies of 0% to 100% (from Figure 1). Since actual distributions respond in that manner, the slope of the distribution becomes important in predicting the effect of an OPC's counting efficiency for a specific distribution.

In Figure 1, each OPC's particle size range corresponds to the most sensitive threshold and is illustrated by the shaded area to the left and right of that threshold. If we move from right to left across the size range, the particle concentration increases at a much faster rate than the decreases in an OPC's counting efficiency. Consequently, all OPCs with imperfect resolution tend to over count populations in a particle distribution where the concentration increases rapidly and the particle size decreases rapidly. Therefore, since a poor resolution OPC counts a larger fraction of the smaller particles in higher concentration area when compared to a good resolution OPC, the poor resolution OPC will over count populations at a significantly higher rate. To calculate the expected total difference in counts between the two OPCs, it would be necessary to integrate the product of the concentration and the counting efficiency across the size range from 0% to 100% counting efficiencies.

To compensate for the effects of imperfect resolution, Particle Measuring Systems performs an OPC's final calibration by comparing the OPC to a standard—or *reference*—OPC while both instruments are sampling diluted ambient air.

Summary

When selecting an OPC's most sensitive threshold, it is important to select the size at which the counting efficiency is 50%. This selection produces results consistent at each threshold and also, with data from higher resolution instruments. Perhaps most important, when monodispersed particles are introduced to an OPC, using the particles' mean size provides accurate selection of the mean-pulse amplitude and defines the accuracy of the particle threshold. This important point is true regardless of an OPC's resolution or a particle's standard deviation.

Notes:

[1] Percent resolutions selected to illustrate good and poor are 10% and 25% respectively.
[2] A low signal-to-noise ratio (S/N) can also produce resolution degradation by allowing artifacts (noise pulses) to be counted as particles. For purposes of this discussion, we will assume that the S/N ratio is adequately sufficient and allow us to ignore this factor.
[3] Response curves in Figure 1 and the distributions in Figure 2 reflect the effect of OPC resolution only (not the resolution of the standard particles). Thus, the term *variance of the standard particles (VarStd)* in the expression for *% resolution* may be set to 0. Then, the term $\sqrt{VarRpt - VarStd}$ may be reduced to $\sqrt{VarRpt}$. This is the standard deviation of the distribution, which would be produced by the OPC if it sampled a group of particles all exactly the same size. This standard deviation may be inferred from the point at which the collection efficiency reaches about 100% in Figure 1. Since

99.994% of the area under a normal distribution contains four standard deviations around the population mean, we can state that a displacement of 0.04 microns from a mean size of 0.1 microns is approximately equal to four standard deviations centered at the mean. Therefore, we can calculate as follows:

$$\%\ resolution = \left(\frac{100}{0.1}\right)\left(\frac{0.04}{4}\right) = 10\%$$

[4] Actually, as discussed in the section on Sensor Resolution, the number is exactly 50% for the hypothetical OPC with perfect resolution.

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