

COMPARISON OF THE COULTER COUNTER AND AERODYNAMIC PARTICLE SIZER

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Abstract

Engineers working in air quality and air pollution often need to characterize the size distribution of aerosols. Two of the more commonplace methods for determining particle size distributions are the electrical sensing zone method and the time-of-flight method. The two methods have been compared for regularly shaped particles. Agricultural applications typically involve irregularly shaped particles. This study compared the two methods for two irregularly shaped dusts – Arizona Road Dust with mass mean diameters of 2.5 μm and 10 μm .

Both methods have their advantages, particularly the ability to sample real time with the APS and the ability to analyze large numbers of samples after collection by the Coulter Method. The differences between the sizes reported were insignificant for many applications where the natural variability in the data is much greater than the difference between the instruments. More work needs to be done on developing shape factors to compare the two instruments and possible shape factors to compare to an absolute standard, such as a gravitational settling method.

Introduction

When studying air quality and air pollution engineering it is often necessary to obtain the particle size distribution (PSD) of particulate matter entrained in the air or the gas of interest. This particle size distribution gives us substantial information about how that particulate matter will behave when transported in an aerosol.

There are many aspects of particle size that are of interest to researchers and industry. Some people may be interested in the largest length across a particle while others may be interested in the volume of the particle. For our purposes, we are most interested in the aerodynamic diameter (d_a). The aerodynamic diameter is defined as the diameter of a unit density sphere that has the same settling velocity as that of the particle in question (Hinds, 1999). This diameter is the best description of how a particle will behave in an aerosol. It can be used to predict whether a particle will be captured by an abatement device or filter or how far it can penetrate into the respiratory system. This measure is useful because it is independent of particle shape, material or density.

The primary problem with using aerodynamic diameter is in trying to measure it. By definition, the measurement would need to be made by some sort of sedimentation method in still air. While instruments do exist that do this (Timbrell, 1972), the times involved are generally too long for regular analysis of large numbers of samples. Therefore other methods of determining aerodynamic diameter have been developed that use measurements of other particle properties as surrogates of aerodynamic diameter.

Two of the more commonplace methods are the electrical sensing zone method and the time-of-flight method. The electrical sensing zone (ESZ) method uses a device that measures the impedance caused by a particle passing through an electrical sensing zone. This impedance is related to the particles volume. The volume is then converted into an equivalent spherical diameter by the formula:

$$d_e = (6V)^{1/3} \quad (1)$$

Where V is the particle volume obtained from the ESZ instrument and d_e is the equivalent spherical diameter, which is not the same as the aerodynamic diameter. To convert from d_e to d_a the following formula is used

$$d_a = d_e \left(\frac{\rho_p}{\rho_o} \right)^{1/2} \quad (2)$$

where ρ_p is the particle density and ρ_o is unit density (1 g/cm^3). This method works well for spherical or nearly spherical particles but can perform poorly for nonspherical and irregularly shaped particles (Tomb and Corn, 1973, Chung and

Thompson, 1989). When dealing with agricultural dusts we rarely see spherical shapes. We are often times dealing with soil particles that have very irregular shapes. Because of these irregular shapes, the above formula can yield incorrect aerodynamic diameters. One method of addressing this potential error is the use of a dynamic shape factor, χ . The dynamic shape factor is a ratio of the actual drag force to that of a sphere of the same size (Hinds, 1999) and is determined experimentally. When this factor is used, equation 2 becomes

$$d_a = d_e \left(\frac{\rho_p}{\rho_o \chi} \right)^{1/2} \quad (3)$$

The aerodynamic particle sizer (APS) is another method used to estimate aerodynamic particle size. The APS uses the time-of-flight method. This method operates by pulling a sample from the aerosol of interest and accelerating it through a nozzle. As the air stream passes through the nozzle it crosses two LASER beams. These LASER beams measure the time it takes for a particle to pass between them. This time reflects the velocity of the particle, which is related to the drag force on and density of the particle. The instrument is calibrated such that the velocity for each aerodynamic size is known (Miller and Lines, 1988). This instrument works well for obtaining real-time aerodynamic number size distributions of spherical particles, but can have significant errors for irregularly shaped, which have a higher drag force than spherical particles, or dense particles when compared to sedimentation methods (Marshall and Mitchell, 1990, Marshall, Mitchell and Griffiths, 1990).

The APS 3320 also has documented problems with detecting “large” particles that don’t really exist (Stein, Beck and Gabrio, 2000). The reason for these particles being miss-sized is unknown but the theory is that that either the particles escaped the aerosol flow or that they recirculated in the air stream. The miss-sized particles are known as phantom counts. These particles usually account for a very small percentage of the total number of particles, around 0.07%, but when converted to a mass or volume basis can alter the distribution significantly because of their relatively large volume. One way to determine the existence of these phantom counts, is to collect both time-of-flight and light scattering data simultaneously with the APS unit. Larger particles will scatter more light than smaller particles. By examining the light scattering intensity versus the particle size as determined by time of flight then the miss-sized particles with low light scattering for their particle size can be determined and removed from the distribution. One method of doing this is by using a “mask” that will remove the phantom counts and give a corrected particle size distribution and statistics. This mask is based on the minimum threshold of light scattered for each size particle.

Chung and Thompson (1989) compared the TSI APS with the Coulter Multisizer for several particle shapes. They showed that, for regularly shaped latex spheres and silicon carbide test dust, there was very good correlation between the two methods. They showed that for regularly shaped particles such as fibers and plates, the two methods were not consistent with each other due to inherent inaccuracies for these shapes, such as tumbling of the plates and the orientation of the fiber in the air stream. For roughly spherical hollow particles, the two methods were also not consistent because the Coulter Multisizer is not able to fully detect holes in the particles. This study did not compare the two methods using irregularly shaped particles.

There is little data comparing the electrical sensing zone method and time-of-flight method for irregular shaped particles similar to what would be seen in agricultural air quality research. This project will concentrate on making this comparison.

Material and Methods

This experiment was designed to compare the TSI Aerodynamic Particle Sizer Model 3320 (TSI, Inc., St. Paul, MN), as a typical time-of-flight method, with the electrical sensing zone method using the Coulter Multisizer III (Beckman Coulter, Inc., Miami, FL). A dust chamber was designed to feed a uniform particle size distribution to both the APS and the filters used for the Coulter analysis. This method was also chosen because it is similar to situations where these two methods might be used in other experiments. A description of the dust chamber design, sampling protocol, filter analysis and data analysis follows.

Dust Chamber Design

The dust chamber was designed to provide a uniform concentration of a selected dust to the filters and the APS inlet. A diagram of the chamber is shown in figure 1. Clean air was brought in through a High Efficiency Particulate Air (HEPA) filter. This air entered the mixing chamber where it was mixed with the aerosol containing the dust of interest using small fans. The dust was provided using a turntable dust feeder. The concentration of dust in the chamber was controlled by the speed of the turntable.

From the mixing chamber the air flowed through a flow straightener into the sampling chamber. The flow straightener is made of perforated steel and helped to straighten and even the flow across the profile of the chamber. This helped to ensure the velocities and concentrations across the sampling regions were uniform. The sampling chamber consisted of the sampling chain and a fan, which vents outside the chamber.

The diagram of the sampling chain is shown in figure 2. This chain consisted of three filter assemblies and the APS inlet. The center of each was 13 cm apart and each end of the chain was 30 cm from the wall of the chamber to reduce edge effects on the dust concentrations. Each filter assembly consisted of a 37 mm teflon membrane filter with 2 μm pore size (Teflo W/Ring, Pall Gelman Laboratory) in a 37 mm filter holder. The filter holder was connected to a critical flow venturi, which was connected to a manifold, which connected all of the filters to a vacuum pump. The critical flow venturis were previously calibrated and found to maintain the flow rate through each filter at 19.8 L/min regardless of the pressure drop across the filter.

The filter holders were positioned facing upwards, perpendicular to the airflow through the chamber. The APS inlet was also facing upwards and at the same height as the filter holders. This setup, of the inlets facing perpendicular to the airflow, is allowable in conditions of low air velocity present in the dust chamber and with the given face velocities of the filters and APS inlet extension (Hinds 1999).

Preliminary tests were run on the chamber and showed the mass on the three filters were consistent. This means that the concentration in the sampling region was consistent and therefore the particle size distribution was also likely to be consistent.

Dust Entrainment and Sampling Procedures

The dust used for these tests was Arizona Test Dust (Powder Technology Inc., Burnsville, MN). This dust was chosen because it could be purchased in the size range of interest, it had an irregular shape that was desirable for this comparison and it could be analyzed in the Coulter electrolyte solution without any problems. Two size ranges were chosen, one with a mass mean diameter of around 2.5 μm and another of around 10 μm . These two sizes were chosen because they coincided with the U.S. Environmental Protection Agency's National Ambient Air Quality Standards (NAAQS) for particulate matter. The two methods being compared, are often used when dealing with samplers and sampling to determine compliance with NAAQS. Therefore these size ranges were chosen to determine the differences between the two methods in this range of interest. Three tests for each dust were run.

Before each new dust was sampled the chamber was cleaned to remove deposited dust. The filter holder assemblies were placed in position and the chamber was sealed. The ventilation fan was started along with the mixing fans and the APS. Several minutes were allowed to pass to purge the chamber of ambient particles.

The dust feeder was then started and the concentration in the chamber was monitored to ensure that it was within the desired limits. The maximum limit was determined by the maximum concentration the APS can accurately handle, around 1000 particles per cubic cm. On the low end, the concentration must be high enough to obtain a sufficient number of particles on the filters in a reasonable amount of time. This time was around one to two hours with a mass of 5 mg or more.

After the dust concentration within the chamber stabilized at an acceptable level the pump for the filters was turned on and the APS began collecting data. The APS collects data every five minutes for 1 minute at a time. Each test was run between one and two hours depending on the type of dust.

At the end of each test the APS stopped collecting data and the filter pump was turned off. The dust feeder was then shut down and the ventilation fan was allowed to run for another minute to remove excess dust from the chamber. The chamber was then opened and the filter covers were reattached. The filter holders were removed from their assemblies and taken for conditioning before being weighed.

Filter Handling and Analysis

The filters used were Pall Gelman Laboratory 37 mm Teflo, PTFE Membrane filters with support rings. These filters were chosen because they have a low background count when analyzed with the Coulter Multisizer III and they worked well with the 37 mm filter holder assemblies.

The filters were removed from their packaging and immediately placed into their filter holders, which included a removable cover. The filters remained in these holders until analysis with the Coulter Counter was begun. During handling and transportation the filter covers remained in place to minimize contamination.

Before samples were collected the filters were conditioned and pre weighed. After the tests, the filters were again conditioned and a post weight was collected. This data was used only for determining the consistency of the dust concentrations within the chamber and was not used in determining the particle size distribution.

After weighing, the filters were analyzed using the Texas A&M University Coulter Counter Method. This method consisted of removing the filter from the filter holder and immersing it in electrolyte. The electrolyte was the liquid used by the Coulter Multisizer III and consists of a solution of lithium chloride salt dissolved in methanol. The submerged filter was subjected to an ultrasonic bath to remove the particles from the filter and to break up agglomerates. The filter was removed from the solution and rinsed with more electrolyte to remove any clinging particles.

The basic procedures for the Coulter were followed as described in the Operator's Manual. A background count was obtained on the clean electrolyte to ensure that the solution was relatively free of particles before adding a sample. The Coulter analysis is run until 25,000 particles were counted to ensure sufficient statistical accuracy. Three analyses were run for each filter and averaged using the Coulter Multisizer III software. This single filter average was used in the comparison between filters later on. This process was completed for each filter using clean electrolyte each time.

Data Analysis

In order to compare the particle size distributions determined by the two methods, we considered just the geometric mean diameter and the geometric standard deviation, both on a number and mass basis.

For each test run, an average particle size distribution from each method was determined. For the Coulter Method, the statistics for each of the three filters used during the test were averaged to get the average result for the test. For the APS results the number of particles in each size range were added for each sample taken during the test. These totals were used as the 'average' distribution. Comparisons of each test and averages for each dust (found in a similar manner) are presented.

The results were also compared on a mass basis by converting the number data to mass. The same basic parameters, geometric mass mean diameter and geometric standard deviation, were used for the comparison. All of this was done with and without the phantom count correction.

Results and Discussion

A total of three tests for each of the two dusts were conducted as described previously. For each test three filters collected dust continuously for Coulter analysis. These filters and their analysis results are labeled with the test number that they were used for and an 'a' through 'c' label that denotes their position in the sampling train, from left to right (i.e., 1a). During each of the tests APS samples were collected for one minute every five minutes. A summary of the test duration and the number of APS samples collected is shown in table 1.

The TSI 3320 APS had a reported reliable sizing range of 0.8 to 19.8 μm , aerodynamic diameter, whereas the Coulter Multisizer III with a 30 μm aperture tube had a reported size range of 0.8 to 18 μm equivalent spherical diameter. The Coulter size range corresponds to an aerodynamic size range of 1.3 to 29.2 μm based on a density of 2.65 g/cm^3 as reported by the manufacturer, using equation 2 to convert into aerodynamic diameter. In order to compare the data on the same basis, the APS data that was below the range of the Coulter Multisizer II (i.e. less than 1.333 μm , because that is the closest size range) and the Coulter data that was above 19.776 μm aerodynamic diameter, or 12.19 μm equivalent spherical diameter, were ignored. This means that the number of particles in those size ranges was not reported in the distributions shown or used in any of the calculations.

APS Results

The APS unit was not able to collect data continuously for the entire sampling period due to lack of memory. Therefore, one-minute samples were taken every five minutes. For each test, these one-minute APS samples were combined by summing the number of particles in each size range for all of the samples. This yields a composite sample that is similar to the filter samples.

As discussed previously, the APS has a problem of miss-sizing a small percentage of the particles. These particles show up as relatively large particles and therefore show disproportionately large volumes. To remedy this problem, TSI provided us with a mask that effectively removes some of these miss-sized particles from the data. This mask works by comparing the time-of-flight size with the amount of light scattered for that particle. If the amount of light scattered is not as high as what would be expected for a carbon particle, which scatters the least amount of light of any particle, then that particle is removed from the distribution. The mask makes little difference in the number distribution because it only removes a very small percentage of the particles, around 0.07% according to TSI, but on the mass distribution the tail has been somewhat reduced, but not

eliminated. A more aggressive mask would probably reduce this tail even further, but determining what the basis of that mask should be is not the objective of this study. Later comparisons with the Coulter data will be made with both the original and masked data.

The two parameters of primary interest in this study are the geometric mean diameter and the geometric standard deviation. These parameters, for the first three tests, are shown in table 2 for both the number and mass distributions, with and without the carbon mask. The effects of the disproportionately large volume of larger particles is evident in the significantly higher geometric mass mean diameter compared to the geometric number mean diameter. The distribution is also more compact, as evident by the much smaller geometric standard deviation of the mass distribution. The mask plays a much more significant role with the mass distribution than on the count. The geometric mean diameter is significantly lower than without the mask due to removal of those few large volume particles and the geometric standard deviation is slightly less.

The statistics for test four through six are shown in table 3. Once again the mask made little difference in the number distribution's statistics, but made a significant difference in the mass statistics. This is due to the same principle discussed previously.

Coulter Method Results

The count and mass size distributions for the 4-8 μm , as measured by the Coulter Multisizer III showed a bimodal character. Unlike the APS data, though, the Coulter results showed more variability. The mass data does not show this same amount of variability, primarily because of the domination of the volume of the larger particles compared to the smaller particles.

Looking at the particle statistics for each individual filter and the averages for each dust in table 4 we can see that this variability is significant. We can see that the average CGMD increased for each test, which coincides with the increasing relative number of large particles. This same increasing trend is present across the filters (A to C) for each test. It is not clear if this is an actual trend in the data due to the experimental design or the methods used, or if it is random error that appears as a trend.

The mass distribution statistics are shown in table 4. While the same increasing trend throughout the test is shown, its variability is not as significant as in the count distribution. Once again, the reason for this is the relatively large mass of the particles at the larger end of the size spectrum. The trend across the filters is not as evident for the mass distribution. The trend is definitely present in test 1 and seems to be present in test 3, although is not necessarily significant. Test 2 shows no trend. The mass distribution seems to confuse the issue of whether or not the apparent trend is really part of the experiment or just random error.

One possible cause of the trend across the filters could be incomplete mixing of larger particles across the profile of the box. Filter and dust masses were also measured during this experiment to confirm proper mixing. If the larger particles were improperly mixed then the dust masses should follow the same trend as the mass geometric mean diameter, and to a lesser extent to the count geometric mean diameter. The dust masses are shown in table 5. As can be seen there does not appear to be any trend across the profile, although there is some variability, especially during test 2. There does not appear to be any correlation between the dust mass collected and the geometric mean diameters of either the count or mass distribution.

A possible explanation for the increasing trend throughout the three tests is the increasing efficiency of the HEPA filter used to filter the incoming laboratory air. Filters generally become more efficient as a dust layer builds up on the filter, especially for smaller particles. This phenomenon should not be significant in this situation because the HEPA filter is nearly 100% efficient in the size range of interest. Background data collected by the APS while the test box was sealed with no dust being fed and the unfiltered room air (not shown here) indicated there were few particles in the room air or the filtered air, and that most of these particles were concentrated around 2 μm and did not show the same shaped distribution as the left tail of the count distribution measured by the Coulter Multisizer III. The APS data collected simultaneously with the filter samples did not show the increasing trend, which would be expected if there were a systematic problem in the experimental setup. After examining all of this, it was concluded that the apparent trend was random experimental and/or measurement error since the same trend was not experienced during sampling of the second dust.

APS and Coulter Comparison

A combination of methods was used to compare the results of the two instruments. The primary variables of concern were the geometric mean diameter and the geometric standard deviation for both the count and mass distributions. A statistical analysis was performed using the SAS program to determine statistically significant differences between the average of the Coulter Multisizer filters, APS runs, and APS with carbon mask results for each set of three tests for each dust. An Analysis of Variance (ANOVA) was performed to determine if any significant difference existed and Fisher's Least Significant Difference (LSD) Method ($\alpha = 0.05$) was used to determine which of the means were different. Non-orthogonal linear

contrasts were used to verify the LSD results since they control the experiment-wise error rate better. All of the ANOVA indicated statistically significant differences and the LSD and linear contrast methods gave the same results throughout.

If we examine the count distributions for the three methods shown, the primary differences come in the variability of the Coulter data as discussed previously. The standard deviations of the Coulter geometric mean diameters are much larger than those of either APS method, indicating much greater variability.

Looking at the count statistics, table 6, we see that the count geometric mean diameter is much lower for the Coulter than the APS methods. This difference of about 0.8 μm is statistically but unlikely to be of practical significance depending on the application.

The mass statistics show the mass geometric mean diameters are 9.60, 8.78, and 8.62 μm for the Coulter, APS, and APS(mask) respectively. The differences between the Coulter MGMD and the APS methods' MGMDs are statistically significant and practically significant for situations requiring high accuracy. The difference between the APS methods is not statistically different. This difference, of course, is due to the carbon mask, which removes some of the phantom larger particles. If a more aggressive mask were applied this difference would be even greater.

Examination of the geometric standard deviations for both the count and mass distributions shows that there is much less variability between both the tests and the methods than was present in the mean diameters. The 2.21 CGSD for the Coulter is statistically significantly different than that of the 2.07 CGSD of the APS methods. It is also important to note that the variability between tests for the GSD is nearly identical for all of the methods, indicating that it is not as sensitive of a parameter as is the geometric mean diameter.

The mass GSD shows similar between test variability, but demonstrates the opposite trend between instruments. The Coulter MGSD of 1.34 is statistically different from the APS and masked APS values of 1.40 and 1.38. This difference is not likely to be practically significant though. It should be noted that with the mask applied, the MGSDs of the APS and Coulter come closer together due to less influence of the phantom particles. It is likely that a more aggressive mask could make them very close, indicating that the distributions are shaped the same, but one is shifted relative to the other. This would allow for a simple shape factor as discussed in the Introduction to scale the data for comparison between methods or to a reference method.

Coulter results for Dust B were much less variable than for Dust A, giving standard deviation comparable to those of the APS methods, as can be seen in table 7. The count distributions for all of the methods reveal that the GSD for the Coulter was slightly larger than that of the APS methods, resulting in a geometric mean diameter that was statistically different, and at this size range of some practical significance. None of the count statistics for the different methods seem to differ by much, although they are statistically different. The GSD of the masked APS data should be noted because it is smaller than the original APS data, which is expected, but both are smaller than the Coulter GSD. This indicated that if a more aggressive mask were applied, the differences between the methods would be even greater.

For the mass distributions the APS data shows a much higher MGMD and MGSD than either the Coulter or the masked APS data due to the phantom counts on the high end of the distribution. Once removed through the use of the carbon mask, the MGMD of 2.56 μm comes to within 0.1 μm of the Coulter distributions 2.64 μm , which is neither of statistical or likely practical significant difference. The MGSD, on the other hand, is still significantly different between the Coulter (1.36) and the masked APS data (1.75), but much closer than was the original APS data (2.58). Once again, it might be possible to further reduce the MGSD of the APS data by applying a stronger mask, thus bringing it closer to that of the Coulter, but this would further increase the difference between the means of the two methods.

Conclusions

The Coulter Method gave consistently higher sizes than did the APS, at least once the mask was applied. One exception existed -- the count distribution for the 4-8 μm dust. It is not clear why the Coulter Multisizer III gave such varying results for this dust, but it is clear that the variability seemed to play a key role in the fact that the count mean diameter was lower than that of the APS.

The fact that the Coulter Method gave consistently higher diameters than the APS method, but similar shapes, indicates that there is a need for a way to scale the distributions so that they give comparable results. A shape factor similar to the ones discussed in the Introduction could be used to scale and compare data collected by these two different instruments. This dataset is not sufficient to develop a shape factor for this dust because of its variability. Attempts to do so gave significantly varying results for the shape factor. More tests need to be conducted and a stronger mask developed by the manufacturer

before accurate shape factors can be developed. Time and instrument availability did not allow for further tests to be conducted.

Even if a shape factor is developed that can scale the Coulter data to the APS data, or visa versa, it is unclear which is more accurate for obtaining the true aerodynamic size. This was not the point of this study, but a few observations can be made. Both instruments are accurate for spherical particles, the problem comes about when we test irregular particles, which are much more common in real worlds scenarios, are analyzed. The Coulter Method does not account for the shape of the particles, only the volumes and the densities, this makes it more likely to give higher diameters than actually exist since it cannot account for increased drag due to shape irregularities. On the other hand it has not been shown that the APS performs well for extremely irregular shaped particles and the APS does have an obvious problem with miscounting and miss-sizing some particles, which can make a difference, especially, on a mass basis. The APS has a tendency to undersize irregular shaped particles, which could also account for some of the difference between the methods.

Overall it seems both methods have their advantages, particularly the ability to sample real time with the APS and the ability to analyze large numbers of samples after collection by the Coulter Method. The differences between the sizes reported could be insignificant in many applications where the natural variability in the data is much greater than the difference between the instruments. More work needs to be done on developing shape factors to compare the two instruments and possible shape factors to compare to an absolute standard, such as a gravitational settling method.

References

Chung, K. Y. K. and J. Thompson. 1989. Coulter vs. APS – A Comparitive Study. *J. of Aerosol Science* 20(8): 1517-1520.

Hinds, W. C. 1999. *Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles*. Wiley-Interscience, Inc.

Marshall, I. A. and J. P. Mitchell. 1990. Calibration of a TSI Serodynamic Particle Sizer With Monodisperse Non-Spherical Particles. *J. Aerosol Science* 21(Suppl. 1): S613-S616.

Marshall, I.A., J. P. Mitchell and W. D. Griffiths. (1990) The Behaviour of Regular-Shaped Non-Spherical Particles in a TSI Aerodynamic Particle Sizer. *J. Aerosol Science* 22(1): 73-89.

Miller, B. V. and R. W. Lines. 1988. Recent Advances in Particle Size Measurements: A Critical Review. *CRC Critical Reviews in Analytical Chemistry* 20(2): 75-116.

Timbrell, V. 1972. An Aerosol Spectrometer and Its Applications. In *Assessment of Airborne Particles*, ed. Mercer, T. T., Morrow, P. E. and Stober, W., ch. 15. Charles C. Thomas Publishers, Springfield IL.

Tomb, T. F. and M. Corn. 1973. Comparison of Equivalent Spherical Volume and Aerodynamic Diameters for Irregularly Shaped Particles. *Am. Industrial Hygiene Assoc. J.* 34:13-34.

Table 1. Summary of test information.

Test Number	Dust Used	Duration (min)	Number of APS Samples
1	ATD 4-8 μm	61	12
2	ATD 4-8 μm	61	12
3	ATD 4-8 μm	61	12
4	ATD 0.8-2.5 μm	93	19
5	ATD 0.8-2.5 μm	128	23
6	ATD 0.8-2.5 μm	121	25

Table 2. Summary of the basic particle size statistics for the APS, with and without the carbon mask, for tests 1 through 3 (the count and mass geometric mean diameters are in μm).

Instrument	Test	CGMD	GSD	MGMD	GSD
APS without Mask	1	4.444	2.044	8.799	1.399
	2	4.356	2.079	8.762	1.397
	3	4.379	2.085	8.775	1.399
Mask	Average	4.393	2.069	8.779	1.398
	Std. Dev.	0.045	0.022	0.019	0.001
APS with Mask	1	4.422	2.042	8.633	1.381
	2	4.336	2.078	8.612	1.382
	3	4.360	2.084	8.613	1.381
Mask	Average	4.373	2.068	8.619	1.381
	Std. Dev.	0.044	0.023	0.012	0.000

Table 3. Summary of the basic particle size statistics for the APS, with and without the carbon mask, for tests 4 through 6 (the count and mass geometric mean diameters are in μm).

Instrument	Test	CGMD	GSD	MGMD	GSD
APS without Mask	4	1.841	1.277	3.737	2.591
	5	1.856	1.278	3.608	2.502
	6	1.841	1.277	3.828	2.635
Mask	Average	1.846	1.277	3.724	2.576
	Std. Dev.	0.009	0.000	0.110	0.067
APS with Mask	4	1.834	1.266	2.544	1.736
	5	1.851	1.268	2.610	1.783
	6	1.834	1.265	2.523	1.717
Mask	Average	1.840	1.266	2.559	1.745
	Std. Dev.	0.010	0.002	0.045	0.034

Table 4. Summary of particle size statistics for each filter in tests 1 through 3 found using the Coulter Method (the count and mass geometric mean diameters are in μm).

Filter	CGMD	CGSD	MGMD	MGSD
1a	2.727	2.166	9.115	1.410
1b	3.098	2.195	9.470	1.379
1c	3.605	2.207	9.599	1.335
Average	3.143	2.189	9.394	1.375
Std. Dev.	0.440	0.021	0.250	0.037
2a	3.514	2.277	9.860	1.331
2b	3.667	2.230	9.636	1.320
2c	3.971	2.192	9.691	1.308
Average	3.717	2.233	9.729	1.320
Std. Dev.	0.233	0.043	0.117	0.011
3a	3.850	2.195	9.614	1.313
3b	3.930	2.201	9.686	1.309
3c	4.002	2.201	9.765	1.309
Average	3.927	2.199	9.688	1.310
Std. Dev.	0.076	0.004	0.076	0.002

Table 5. Filer weights for tests 1 through 3.

Test 1		Test 2		Test 3	
Filter	Dust (mg)	Filter	Dust (mg)	Filter	Dust (mg)
A	2.4	A	3.4	A	16.5
B	2.6	B	734.0	B	13.7
C	3.3	C	9.6	C	14.3

Table 6. Summary of APS and Coulter data for tests 1 through 3.

Instrument	Test	CGMD	GSD	MGMD	GSD
Coulter	1	3.143	2.189	9.394	1.375
	2	3.717	2.233	9.729	1.320
	3	3.927	2.199	9.688	1.310
	Average	3.596	2.207	9.604	1.335
	Std. Dev.	0.406	0.023	0.182	0.035
APS without Mask	1	4.444	2.044	8.799	1.399
	2	4.356	2.079	8.762	1.397
	3	4.379	2.085	8.775	1.399
	Average	4.393	2.069	8.779	1.398
	Std. Dev.	0.045	0.022	0.019	0.001
APS with Mask	1	4.422	2.042	8.633	1.381
	2	4.336	2.078	8.612	1.382
	3	4.360	2.084	8.613	1.381
	Average	4.373	2.068	8.619	1.381
	Std. Dev.	0.044	0.023	0.012	0.000

Table 7. Summary of APS and Coulter data for tests 4 through 6.

Instrument	Test	CGMD	GSD	MGMD	GSD
Coulter	4	2.086	1.301	2.670	1.375
	5	2.086	1.298	2.638	1.350
	6	2.083	1.291	2.625	1.351
	Average	2.085	1.296	2.644	1.358
	Std. Dev.	0.001	0.005	0.024	0.014
APS without Mask	4	1.841	1.277	3.737	2.591
	5	1.856	1.278	3.608	2.502
	6	1.841	1.277	3.828	2.635
	Average	1.846	1.277	3.724	2.576
	Std. Dev.	0.009	0.000	0.110	0.067
APS with Mask	4	1.834	1.266	2.544	1.736
	5	1.851	1.268	2.610	1.783
	6	1.834	1.265	2.523	1.717
	Average	1.840	1.266	2.559	1.745
	Std. Dev.	0.010	0.002	0.045	0.034

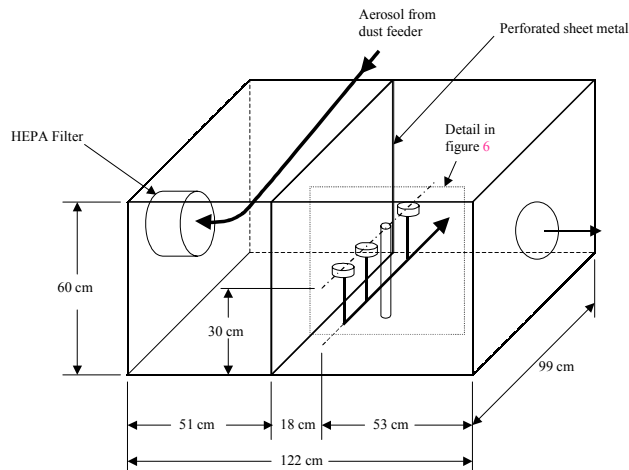


Figure 1. Diagram of the dust chamber used for the experiments.

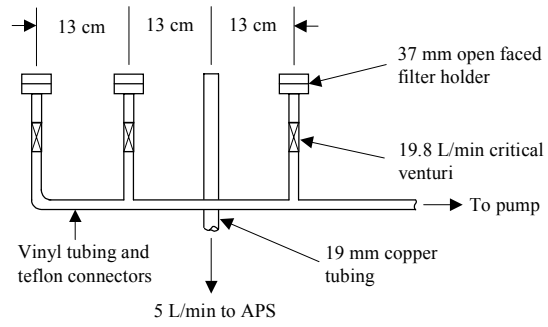


Figure 2. Detail of the sampling train and APS inlet location.