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Concentration measurement and counting efficiency for the aerodynamic particle sizer 3320

Alfredo J. Armendariz*, David Leith

Department of Environmental Sciences and Engineering, University of North Carolina, CB#7400, Rosenau 104, Chapel Hill, NC 27599-7400, USA

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Abstract

The aerodynamic particle sizer (APS, Model 3320, TSI Inc., St. Paul, MN) is an instrument that counts and sizes particles by time-of-flight, an aerodynamic property, and/or by light-scattering intensity, an optical property. If the counting efficiency of the APS 3320, defined as the number of particles counted divided by the number sampled is not 1.0 for particles of all sizes, then the reported size distributions and particle concentrations will be biased.

A laboratory aerosol was sampled with two APS 3320s alternating between collecting only time-of-flight data in summing mode and collecting simultaneous time-of-flight and light-scattering intensity data in correlated mode. Collecting data in correlated mode resulted in errors in the reported aerodynamic size distributions and concentrations. The magnitude of the concentration error was an inverse function of concentration, ranging from approximately 10% at 500 particles/cm^3 to 45% at 50 particles/cm^3.

Experiments were also conducted to determine the counting efficiency of the APS 3320 in summing mode by comparing size distributions obtained with the analyzer to those obtained with a cascade impactor. Counting efficiency increased from 30% for 0.5 μm particles to 100% for 0.9 μm particles, then decreased to 60% for 5 μm particles. For particles larger than about 5 μm, the size distribution reported by the APS 3320 was distorted by artificial particle counts. To determine accurate particle size distributions and concentrations, the values reported by this instrument must be adjusted for counting efficiency.

Keywords: Aerodynamic particle sizer; APS 3320; Counting efficiency

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* Corresponding author. Tel.: +1-919-966-7337; fax: +1-919-966-7911.
E-mail address: aarmenda@email.unc.edu (A.J. Armendariz).

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Nomenclature

η	counting efficiency
N_{counted}	number of particles counted
N_{sampled}	number of particles sampled
η_{inlet}	inlet efficiency
$\eta_{\mathrm{transport}}$	transport efficiency
$\eta_{\mathrm{detection}}$	detection efficiency
We	Weber number
$\mathrm{We}_{\mathrm{critical}}$	critical Weber number
ρ_g	gas density
V_{R}	relative velocity
d	particle diameter
σ	surface tension
C_{D}	coefficient of drag
Re	Reynolds number
C_{n}	number concentration
PCL	percent counts lost

1. Introduction

1.1. APS 3320—principles of operation

The aerodynamic particle sizer (APS, Model 3320, TSI Inc., St. Paul, MN) is used to determine the concentration and size distribution of particles from 0.3 to 20 μm in diameter at concentrations up to 1000 particles/cm^3 (Caldow, Quant, Holm, & Hairston, 1997; TSI, Inc., 1998). This instrument sizes particles aerodynamically by time-of-flight and/or optically by light-scattering intensity. The time-of-flight capability is based on previous APS designs with improvements to the optics and electronics. The 3320 is the first APS model that measures light-scattering intensity. Thus, two simultaneous indications of size can be measured for each particle.

The APS operates in either correlated or summing mode. Correlated mode refers to the simultaneous measurement of aerodynamic diameter and light-scattering intensity for each particle. This process allows for the analysis of the quantity of light scattered by particles of a given aerodynamic size. In summing mode, aerodynamic sizes, light-scattering sizes, or both are measured. However, when both sizes are selected, the instrument provides two separate distributions, one for aerodynamic diameter and one for light-scattering intensity, and the instrument does not delineate the amount of light scattered by particles of a given aerodynamic diameter.

The APS operates at 5 l/min, with 1 l/min entering a nozzle (85 mm long, 3 mm diameter) and 4 l/min directed to a filter. In the nozzle, the aerosol accelerates through an 813 μm orifice before recombining with the filtered air flow. The combined flow accelerates through a 1041 μm orifice in a second nozzle and enters the detection area (Chen, Cheng, & Yeh, 1985). Here, the time for each particle to pass between a pair of overlapping laser beams is detected and converted to aerodynamic particle size using a pre-programmed calibration. In addition, the light-scattering intensity is determined by analysis of the magnitudes of the pulses of scattered light from the lasers (Holm, Caldow, Hairston, Quant, & Sem, 1997).

The counting efficiency of the APS 3320, η, is defined as the number of particles of a given size counted divided by the number sampled

$$\eta = \frac{N_{\text{counted}}}{N_{\text{sampled}}}. \tag{1}$$

Counting efficiency incorporates inlet efficiency and transport efficiency, as defined in Brockmann (1993), plus the particle detection efficiency, defined as the number of particles that is counted divided by the number that enters the detection area,

$$\eta = \eta_{\text{inlet}} \eta_{\text{transport}} \eta_{\text{detection}}. \tag{2}$$

To prevent bias of the size distributions when sampling a polydisperse aerosol, the counting efficiency of the APS must be constant as a function of particle size. Furthermore, a counting efficiency less than unity causes underestimated particle concentrations.

1.2. *Background*

The APS has been used to investigate exposure to occupational aerosols (O'Brien, Baron, & Willeke, 1987; Chen, Barber, & Zhang, 1998), to evaluate or design other aerosol samplers (Smith, Baron, & Murdock, 1987; Sreenath, Vincent, & Ramachandran, 1999; Chen, Huang, Lin, Shih, & Jeng, 1999; Page, Volkwein, Baron, & Deye, 2000), to evaluate air filtration systems (Wake, 1989), and to examine the performance of metered dose drug inhalers (Stein, Beck, & Gabrio, 2000). The APS 3320 is also being used to characterize ambient particulate matter in EPA's PM Supersites program (Pandis, Davidson, & Robinson, 2000). For all these applications, accuracy in particle size distribution and particle concentration measurements is important.

Time-of-flight instruments, including the APS series, have been susceptible to a variety of errors. Inaccurate sizing of liquid particles can result from particle deformation in the accelerating inlet gas stream. Griffiths, Iles, and Vaughan (1986) examined the mis-sizing of liquid droplets in an APS 3300 comparing the droplet sizes created with a vibrating orifice monodisperse aerosol generator (VOMAG) to sizes reported by the APS. For 15 μm droplets, droplets near the upper size limit of the APS, the error between the APS and VOMAG varied from 7% to 20% depending on the liquid used to generate the droplets. However, they found little or no difference between the instruments for droplets 5 μm and smaller. Similar conclusions were reached by Baron (1986), who sized VOMAG-generated oleic acid particles using an APS 3300 and a settling chamber. For 15 μm particles, the error in the APS was approximately 20%. For particles smaller than 7 μm, the error was less than 10%. Brockmann, Yamano, and Lucero, (1988) compared oleic acid droplets and PSL spheres in an APS 3310 and noted that oleic acid droplets smaller than 7 μm were accurately sized, while droplets larger than 7 μm had increasing error with particle size. Similarly, Chen, Cheng, and Yeh (1990) used dioctyl phthalate particles generated with a VOMAG to study deformation in an APS. Droplet deformation was not significant for DOP droplets smaller than 5 μm.

Earlier APS models were also subject to coincidence errors (Baron, 1986; Heitbrink, Baron, & Willeke, 1991; Heitbrink & Baron, 1992; Peters, Chein, Lundgren, & Keady, 1993), but the manufacturer has designed new optics and electronics into the APS 3320 to address this problem (Holm et al., 1997; TSI, Inc., 1998). These modifications are intended to “virtually eliminate” coincidence errors (Caldow et al., 1997).

Stein et al. (2000) measured the particle size distributions of metered dose inhaler plumes with an APS 3320 and a cascade impactor. The APS 3320 data were collected in correlated mode and the light-scattering intensity characteristics of the particles were examined. According to Stein et al., the aerodynamic size distribution data showed a substantial number of artificial large particles that distorted the distribution and produced false mass median aerodynamic diameters. With a data mask, these artificial particle counts were removed, improving the comparison of the APS and the impactor for particles smaller than 4.8 μm. Nevertheless, poor agreement existed between the instruments for particles greater than 4.8 μm. They also found that the APS systematically underestimated the mass fraction of particles smaller than 4.8 μm by 8%.

Our interest in this instrument arises from its use to sample jet fuel mist generated during the start-up of US Air Force jet engines in extremely cold weather. For each engine start, the particle concentration determined with the APS 3320 was lower than the concentration determined with collocated electrostatic particle samplers (Armendariz, Leith, Boundy, & Goodman, 2000). In addition, the aerodynamic size distributions reported by the APS 3320 in summing mode differed from the distributions reported in correlated mode. These discrepancies motivated the research discussed in this paper.

The objectives of this research were: (1) to compare the size distributions reported by the APS 3320 in summing and correlated modes when sampling the same aerosol; and (2) to investigate the counting efficiency of the APS 3320.

2. Methods

2.1. Comparison of summing and correlated modes

A high-vacuum oil aerosol (Inland 99, IVAX Industries, Inc., Churchville, NY) was generated with a HEART nebulizer (Westmed, Inc., Tucson, AZ) in a 1.0 m^3 aerosol chamber (see Fig. 1). The outlet of the nebulizer was connected to a Kr-85 charge neutralizer (TSI Inc., St. Paul, MN) after which the aerosol was directed to a dilution cylinder. A DustTrak light-scattering photometer (TSI Inc., St. Paul, MN) was used to establish that particle concentration in the chamber remained constant over time. Particle concentration was controlled with a pair of variable speed blowers arranged to remove aerosol from the chamber continuously, and re-supply the chamber with clean air. Aerosol was sampled through a port in the side of the chamber to an APS 3320 equipped with a Model 3302A diluter (TSI Inc., St. Paul, MN) and connected to a computer. The nebulizer and its stand were grounded to prevent the buildup of static charge on their surfaces.

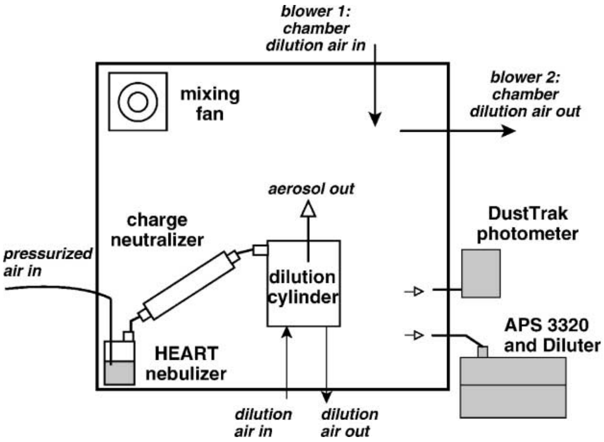

Fig. 1. Aerosol chamber used for comparison of summing and correlated mode sampling.

Samples were taken from the aerosol chamber with either of two APS 3320 instruments (unit #1: S/N 1075, manufactured August 1998; unit #2: S/N 1156, manufactured May 2000), both equipped with firmware version 1.78. The manufacturer's calibration was used for both units since each had operated less than 10% of the 5000 h recommended by the manufacturer before recalibration. Six tests were performed, three with each instrument. Each test consisted of three 30-s samples collected in summing mode, alternating with three 30-s samples collected in correlated mode (i.e. summing-correlated-summing-correlated-summing-correlated). The chamber aerosol concentration and diluter operation were adjusted so that the six tests covered a concentration range of 50–500 particles/cm^3 into the APS.

After every test, mean aerodynamic size distributions were constructed with the data from each of size bins 2 through 52. One mean size distribution was constructed with the three summing mode samples and another was constructed with the three correlated mode samples. Data from bin 1, representing particles less than 0.523 μm that produced a signal in the instrument, were excluded from the analysis.

Statistical tests were performed with SAS-STAT to analyze the significance of the differences between the mean summing and correlated mode size distributions. Statistical tests also were performed to analyze the significance of the differences in the number of counts reported in each size bin between the two modes. Tests included paired t-tests for the mean size distribution comparisons and t-tests for the bin-by-bin comparisons, both at the $\alpha = 0.05$ significance level. In addition, the percent counts lost (PCL), defined as the percent difference between the mean summing and correlated mode particle counts for the entire distribution, was calculated for each of the six tests. A least-squares regression analysis was performed to examine the trend in PCL with particle concentration.

2.2. Counting efficiency

The experimental conditions for the counting efficiency tests are given in Table 1. For each test, an aerosol of oleic acid was generated with a HEART nebulizer in a 1.0 m^3 chamber

Table 1
Experimental conditions for counting efficiency tests

Parameter	Value
Test durations	150–180 min
Number of tests	3
Total sample flow	10 l/min
APS and impactor flows	5 l/min, each
chamber particle concentrations	25–40 mg/m^3
APS diluter capillary	100 : 1
Nebulizer pressure	10–15 psi

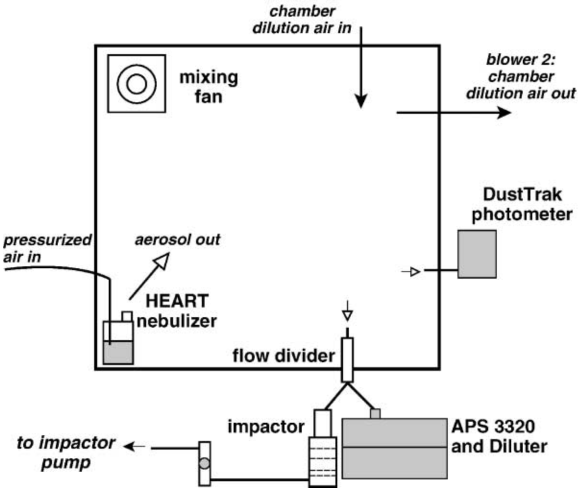

Fig. 2. Aerosol chamber used for counting efficiency tests.

(see Fig. 2). A sample of the aerosol was drawn at 10 l/min through a flow divider (Model 3708, TSI Inc., St. Paul, MN) that divided the flow equally and isokinetically to the APS/diluter and to an eight-stage Sierra Ambient Cascade Impactor (Series 210, Graseby-Andersen, Atlanta, GA). A liquid aerosol was used to minimize errors from particle bounce on the impactor stage substrates. Flow through the APS 3320 was 5 l/min and was controlled electronically by the instrument using three internal flow pressure transducers and two internal pumps. Flow to the impactor was set at 5 l/min with a flow calibrator (Gilibrator 2, Sensidyne, Clearwater, FL) and was monitored with an in-line Dwyer rotameter (Model RMB-51, Dwyer Instruments, Michigan City, IN) that was previously calibrated in-line with the Gilibrator 2. Each counting efficiency test lasted from 150 to 180 min. Three tests were conducted. Prior to each test, the Gilibrator 2 was used to check the flow entering each instrument separately and to verify the total flow entering the flow divider. To prevent the build-up of static charges, the nebulizer, nebulizer stand, flow divider, and impactor were grounded. Additionally, Po^{210} ionizing units (Model 1U400, NRD LLC, Grand Island, NY) were mounted at the exit nozzle of the nebulizer.

Table 2
Average aerodynamic particle diameter collected on each stage of the Sierra series 210 ambient cascade impactor sampling at 5 l/min (Graseby Andersen, 1991)

Impactor stage	Average size (μm)
Inlet and 1	> 21
2	17
3	9.1
4	4.2
5	2.6
6	1.6
7	0.87
8	0.52
Final filter	< 0.25

Number distributions from the APS were converted to mass distributions for comparison with data from the cascade impactor. The conversion was done by multiplying counts in each interval by the mass of the midpoint diameter particle for that interval. For analyses of cascade impactor data, the aerodynamic diameter assigned to the particles on each impactor stage was taken as the arithmetic average of the manufacturer-determined cut sizes for that stage and its preceding stage (Graseby Andersen, 1991). In addition, particle mass that collected on a substrate placed after the inlet was added to the mass from the first stage substrate (Table 2). The stainless steel substrates, glass fiber filter, and blanks were weighed on a Mettler MT-5 microbalance (Mettler-Toledo, Greifensee, Switzerland).

As part of the counting efficiency tests, a data mask provided by the manufacturer and intended to remove artificial particle counts in APS 3320 correlated data files was evaluated. The mask attempts to utilize the light-scattering intensity measurements recorded for each particle to distinguish valid particle counts from artificial ones. The mask is based on the principle that a large particle generally scatters more light than a small particle; hence, a particle sized to be very large aerodynamically but associated with very little light-scattering is probably artificial (Stein et al., 2000).

2.3. Weber number analysis

The Weber number, defined as

$$\mathrm{We} = \rho_{\mathrm{g}} V_{\mathrm{R}}^2 d/\sigma, \tag{3}$$

relates the aerodynamic drag to the surface tension of a liquid particle. For a droplet in motion, the initial condition for droplet deformation occurs when the drag force equals the surface tension force, as shown in Eq. (4) (Lefebvre, 1989):

$$C_{\mathrm{D}} \left(\frac{\pi d^2}{4}\right) (0.5 \rho_{\mathrm{g}} V_{\mathrm{R}}^2) = \pi d \sigma. \tag{4}$$

Rearranging, the critical Weber number is found to be

$$\mathrm{We}_{\mathrm{critical}} = \frac{\rho_{\mathrm{g}} V_{\mathrm{R}}^2 d}{\sigma} = \frac{8}{C_{\mathrm{D}}}. \tag{5}$$

For Weber numbers greater than $8/C_{\mathrm{D}}$, deforming drag forces are larger than conserving surface tension forces and particles may deform.

Particles of different sizes have different relative velocities passing through the nozzles in the APS. Weber numbers were calculated with Eq. (3) for oleic acid particles ($\sigma = 32.8$ dyn/cm) ranging from 0.5 to 20 μm in diameter using relative velocities that were calculated with Eq. (6), derived from Baron (1986)

$$V_{\mathrm{R}} = 3320\,\mathrm{Ln}(d) + 2360. \tag{6}$$

Weber numbers calculated with Eq. (3) were compared to critical Weber numbers calculated with Eq. (5), estimating the drag coefficient with

$$C_{\mathrm{D}} = \left(\frac{24}{\mathrm{Re}}\right)(1 + (\mathrm{Re}^{2/3})/6) \tag{7}$$

for all particle sizes (Hinds, 1982). Ratios of Weber number to critical Weber number for particles from 0.5 to 20 μm in diameter were determined. The density of air in the nozzle inlet (i.e. ambient air pressure) was used in the calculations of Reynolds numbers and drag coefficients. For comparison, ratios of Weber number to critical Weber were also calculated for water, glycerol, and dioctyl phthalate droplets ($\sigma = 73$, 62.5, 33 dyn/cm, respectively).

3. Results

3.1. Comparison of summing and correlated modes

Fig. 3 shows the mean size distributions collected during one test of summing versus correlated mode sampling. Particle concentration and size distribution in the aerosol chamber were essentially constant during the test. For all six tests, concentrations measured in correlated mode were consistently lower than concentrations in summing mode. For particles of certain sizes, this difference was markedly and consistently greater than for other sizes. Further, the figure shows that in both correlated and summing modes, the instrument reported a constant, artificial concentration of particles larger than about 5 μm.

Paired *t*-tests were performed to compare the mean summing mode size distribution to the mean correlated mode size distribution for each test. These paired *t*-tests indicated that the mean size distributions from summing and correlated modes were significantly different ($p < 0.0001$) for each test.

PCL versus summing mode particle concentration is shown in Fig. 4. A least-squares regression analysis indicated that PCL had a strong inverse correlation to the log of particle

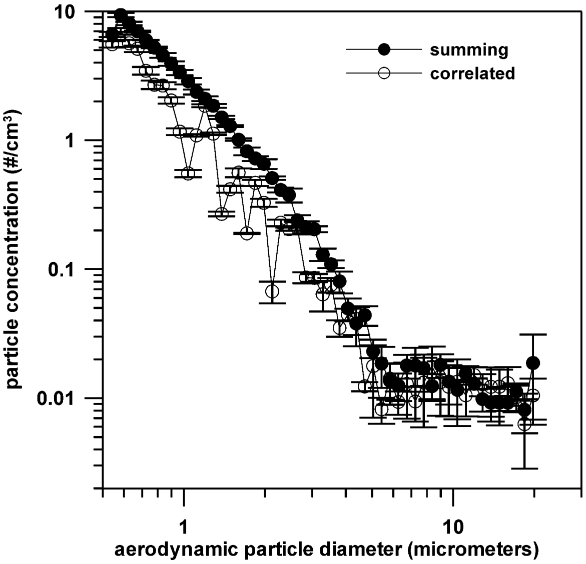

Fig. 3. Effect of summing and correlated mode analysis on the reported aerodynamic particle size distribution. Error bars represent one standard deviation.

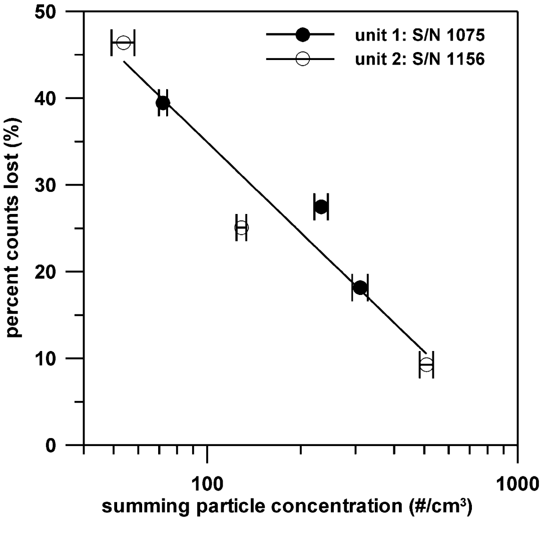

Fig. 4. PCL versus particle concentration. Error bars represent one standard deviation.

concentration

$$\mathrm{PCL} = -15\,\mathrm{Ln}(C_N) + 104, \quad r^2 = 0.92. \tag{8}$$

For all six tests, additional t-tests at an $\alpha = 0.05$ significance level indicated that the differences in particle counts in some size bins were usually significant whereas the differences in other size

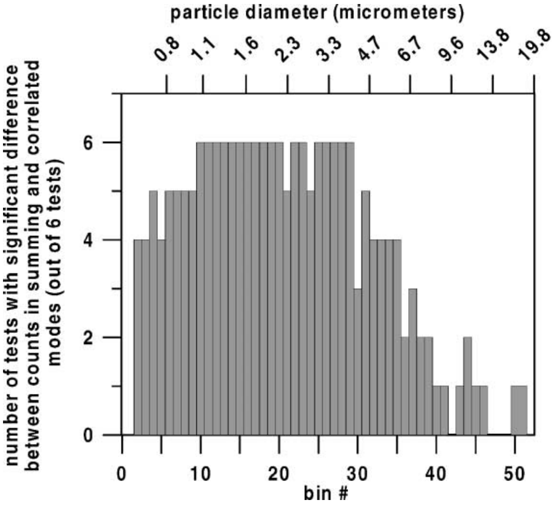

Fig. 5. Bin-by-bin analysis of the significance of the difference between the counts reported in summing mode and correlated mode. Data indicate the number of tests out of six for which a particular bin reported counts in summing mode that were significantly different from counts obtained in correlated mode.

bins were usually insignificant. Fig. 5 shows the number of tests out of the six tests performed for which the counts in a size bin in summing mode were significantly different ($p < 0.05$) than the counts in correlated mode.

3.2. Counting efficiency

Fig. 6 shows a comparison of the mass size distributions of a 180 min sample of oleic acid aerosol measured with the cascade impactor and the APS operating alternately in 30 min summing and correlated modes. Since the APS operated in each mode for half the time, the data from the summing and correlated samples were doubled to represent the full 3 h sample. Fig. 6 also shows the mass size distribution of the data collected in the correlated mode after treatment with the data mask to remove artificial particle counts. The mass reported for particles smaller than about 5 μm in diameter was 30.5 mg by the impactor, 12.9 mg by the APS in summing mode, 7.4 mg by the APS in correlated mode, and 7.3 mg by the APS in correlated mode with the data mask. Above about 5 μm diameter, the APS 3320 reported a constant, artificial concentration as shown in Fig. 3. On a number basis, the artificial particle counts were only a small fraction of the total counts. However, on a mass basis the artificial counts distorted the size distribution. In contrast to the APS 3320, the impactor measured few particles larger than about 9 μm and no particles larger than 17 μm in this test.

Fig. 7 shows the mean size distributions measured by the cascade impactor and the APS operating in summing mode for three tests. The data were analyzed as mass fractions to account for differences in the chamber concentrations between the tests.

The difference in concentration measured by the APS 3320 and the cascade impactor as a function of particle size was used to develop a counting efficiency curve for the APS 3320, as

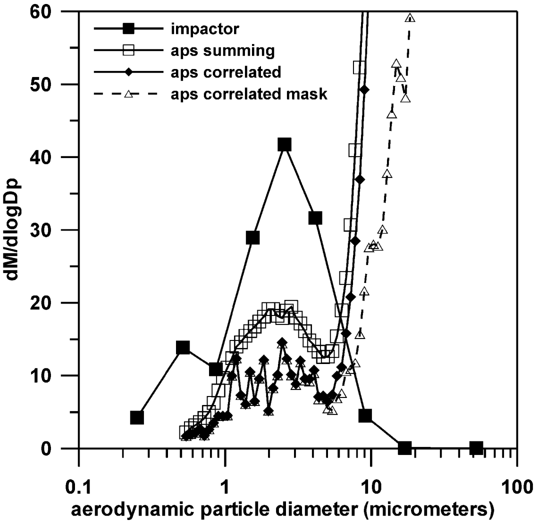

Fig. 6. Aerodynamic particle size distributions measured with an APS 3320 in alternating summing and correlated modes, and with a cascade impactor.

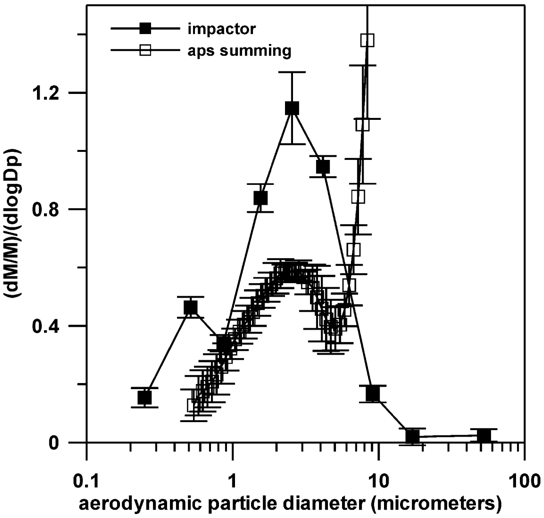

Fig. 7. Average aerodynamic particle size distributions from three tests with an APS 3320 and a cascade impactor.

shown in Fig. 8. This curve was developed using only summing mode and cascade impactor data. Counting efficiency could be determined only for particles less than 5.2 μm because the artificial particle counts created a distortion of the APS size distribution for larger particles. For comparison, data from two additional APS studies, Kinney and Pui (1995) and Blackford, Hanson, Pui, Kinney, & Ananth (1988) are also presented in this figure. Kinney and Pui (1995)

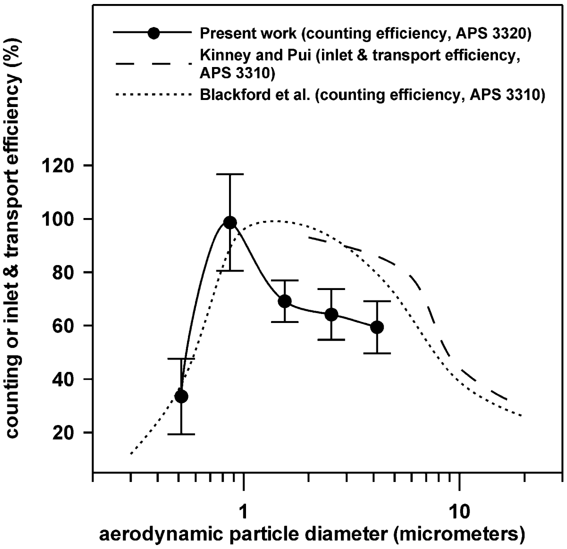

Fig. 8. Counting efficiency of the APS 3320 in summing mode and of the APS 3310. Error bars represent one standard deviation. The Kinney and Pui (1995) and Blackford et al. (1988) curves are approximations derived from those works.

studied the inlet and transmission efficiency of an APS 3310. Blackford et al. (1988) studied APS 3310 counting efficiency, consisting of inlet, transmission, and detection efficiency.

3.3. *Weber number analysis*

Relative velocity in the APS inlet ranges from less than 60 cm/s for 0.5 μm and smaller particles to approximately 12,000 cm/s for 20 μm particles (Baron, 1986). The maximum relative velocity in the APS inlet is 14,800 cm/s, which represents the difference between the inner nozzle gas velocity (150 cm/s) and the outer nozzle orifice velocity (15,000 cm/s).

The ratios of Weber number to critical Weber number for oleic acid, dioctyl phthalate, water, and glycerol particles between 0.5 and 20 μm in diameter are shown in Fig. 9. For oleic acid particles smaller than 8 μm, the Weber numbers are less than 50% of the critical Weber numbers. For particles larger than 8 μm, the Weber numbers are greater than 50% the critical Weber numbers, reaching 120% of the critical values at 20 μm.

4. Discussion

4.1. *Comparison of summing and correlated modes*

The percent counts lost by analyzing particles in correlated mode increased with decreasing particle concentration, reaching 45% at 50 particles/cm^3. At concentrations approaching the upper concentration limit of the device (1000 particles/cm^3), the errors in the particle size distribution introduced by correlated mode analysis were smaller but still statistically significant.

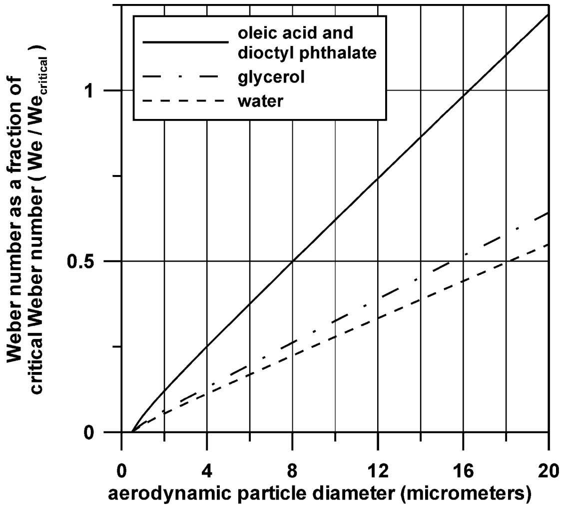

Fig. 9. Fraction of critical Weber number versus aerodynamic diameter for droplets in the APS.

In addition, significant differences between the summing and correlated mode counts occur more often in some size bins than in others, as shown in Fig. 5. This finding suggests that the relationship between PCL and concentration could be specific to aerosol size distribution. If so, the trend of PCL with concentration, presented for these tests as Eq. (8), may change for different aerosols.

The bin-by-bin analysis showed that significant differences between the counts in summing mode and correlated mode occurred more often in bins in the smaller size range of the instrument. However, we cannot necessarily conclude that the larger size bins were less subject to this type of error. The test aerosol contained relatively few large particles so that the lack of a significant difference here may have occurred because few large particles were present.

Errors introduced by sampling in correlated mode restrict the usefulness of the light-scattering measurement capability of the APS 3320. Using a mask together with the correlated data can help filter out artificial particle counts in the aerodynamic data, as in Stein et al. (2000).

Nevertheless, mask use cannot compensate for errors to the particle size distribution and concentration caused by lost particle counts.

The manufacturer suspects that these correlated mode errors are the result of resolution issues with the current APS 3320 firmware algorithms (Beck, 2000). Even if future firmware helps to solve these problems, those who have used the APS with the firmware originally supplied should be aware that these problems exist.

4.2. *Counting efficiency*

The underestimation of concentration by the APS 3320 for particles between 1 and 5 μm may have occurred because particles deposited within the analyzer. Using fluorometric/washing techniques Kinney and Pui (1995) determined that particles deposit on the inlet nozzles of the APS. They found that the combined inlet and transmission efficiency as a function of particle size varied from greater than 90% for 2 μm particles to 30% for 20 μm particles. They also investigated inlets with different nozzle geometries and found some that produced substantially less particle loss. These nozzles reduced the size resolution capability of the APS and have not been incorporated into the commercial design.

Blackford et al. (1988) obtained a counting efficiency curve similar to the Kinney and Pui (1995) curve for particles larger than 3 μm. The Blackford et al. (1988) curve is slightly lower, perhaps due to the inclusion of detection efficiency effects not incorporated into the Kinney and Pui (1995) study. For particles smaller than 1 μm, the counting efficiency of the APS 3320 tested here was similar to that of the 3310 tested by Blackford et al. (1988). Both instruments had a counting efficiency near 100% for 0.9 μm particles with a decline to approximately 30% for 0.5 μm particles.

For particles larger than 1 μm, the differences in counting efficiency between the APS 3320 and earlier APS models may result from detection efficiency differences among the APS models. The APS 3320 has inlet geometry and flow characteristics similar to earlier APS models, but the optics and electronics in the APS 3320 are substantially different (Caldow et al., 1997).

The summing versus correlated mode comparison was performed with two APS 3320 analyzers. The relationship between lost particle counts and concentration, however, was well characterized with a single line, Eq. (8). In contrast, the counting efficiency experiments were done with a single APS 3320, and counting efficiency for any specific APS 3320 may or may not be described accurately by Fig. 8. Researchers may want to calibrate their own APS 3320s for counting efficiency to account for instrument-to-instrument variability .

The APS 3320 manufacturer suspects that the artificial particle counts in the instrument may be the result of recirculating particles that do not exit the detection region (Beck, 2000). These particles may cross the paths of the lasers multiple times thereby creating extra laser pulses. Modifications to the instrument flows and/or to the design of the detection region might be necessary to correct this problem.

4.3. Weber number analysis

The Weber number analysis indicates that oleic acid droplets less than 8 μm in diameter are not likely to break up or deform before sizing in the APS 3320. The droplets used in this study had Weber numbers below 12–20, the threshold where droplet breakup occurs (Baron, 1986). In addition, droplets smaller than 8 μm had Weber numbers less than 50% of the critical Weber numbers, as shown in Fig. 9. This analysis is consistent with the experimental results and predictions of other researchers, who found that droplet deformation was significant for droplets larger than approximately 5 μm, and not important for smaller droplets. The results of this study and the measurements and predictions of other researchers suggest that oleic acid droplets can be used to characterize the counting efficiency of the APS 3320 up to 5–8 μm in aerodynamic diameter with little or no droplet deformation.

When examining the potential sources of sizing error of the APS 3320, the errors introduced by artificial particle counts, which occur when sampling either liquid or solid particles, are likely to be more important than the errors that result from particle deformation, which occur only when sampling large liquid particles.

5. Conclusions

The APS 3320 can be a useful tool for counting and sizing particles. However, several issues must be considered when using the instrument to size a polydisperse aerosol or to determine concentrations.

1. The collection of *correlated* measurements of light-scattering intensity and aerodynamic particle size introduced substantial, significant error to the reported particle concentrations and aerodynamic size distributions. The magnitude of the particle concentration error varied inversely with particle concentration.
2. Artificial counts of particles greater than 5 μm in diameter biased particle size distribution and concentration measurements in both summing and correlated modes.
3. Using the light-scattering intensity measurement capability of the instrument to distinguish between artificial particle counts and real particle counts requires operating the instrument in correlated mode, which itself introduces significant errors to the reported particle concentrations and size distributions.
4. Counting efficiency for an APS 3320 was 30% for 0.5 μm diameter particles, 100% for 0.9 μm particles, and 60% for 5 μm diameter particles. To determine accurate particle size distributions and concentrations, the data reported by this instrument must be adjusted for counting efficiency.

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