



PERGAMON

Aerosol Science 34 (2003) 627–634

Journal of
Aerosol Science

www.elsevier.com/locate/jaerosci

Concentration measurement and counting efficiency of the aerodynamic particle sizer 3321

Thomas M. Peters, David Leith*

*Department of Environmental Sciences and Engineering, University of North Carolina,
CB#7431, Rosenau 104, Chapel Hill, NC 27599, USA*

Received 6 September 2002; received in revised form 30 January 2003; accepted 31 January 2003

Abstract

The aerodynamic particle sizer (APS) model 3321 (TSI, Inc., St. Paul, MN) aims to resolve issues identified with an earlier APS, model 3320. These issues include discrepancies between concentrations measured in summing and in correlated modes, and the creation of “anomalous”, large particles caused by recirculation within the detection region. In the present work, the number concentration of a laboratory aerosol was measured with the APS 3321 to be statistically the same in summing mode and in correlated mode for all particles except those in bin 1, $< 0.523 \mu\text{m}$. Further, anomalous large particles were not measured with the APS 3321. The counting efficiency of the APS 3321 was lower than that for the APS 3320 and ranged from 40% to 60% for particles from 0.8 to 4 μm , respectively. Thus, concentrations reported by the APS 3321 were lower than those measured by the impactor. However, because counting efficiencies were roughly constant with particle size and anomalous particles were absent, the shape of the size distribution was similar to that obtained using the impactor.

© 2003 Elsevier Science Ltd. All rights reserved.

Keywords: Aerodynamics size; Particle sizer; Size distribution

1. Introduction

The aerodynamic particle sizer (APS, TSI Inc., St. Paul, MN) measures particle size distributions from 0.5 to 20 μm by determining the time-of-flight of individual particles in an accelerating flow field. A complete particle size distribution may be determined in a matter of seconds or minutes, making the APS the instrument of choice for a broad range of applications, including evaluation of particle samplers (Gorner et al., 2001; Kenny & Gussman, 2000), characterization of ambient

* Corresponding author. Tel: +1-919-966-3851; fax: +1-919-966-7911.

E-mail address: david.leith@unc.edu (D. Leith).

aerosols (Shen, Jaques, Zhu, Geller, & Sioutas, 2002; Shi, Harrison, & Evans, 2001; Yanosky, Williams, & Macintosh, 2002), investigation occupational exposures (Spanne, Olsson, Gudmundsson, & Bohgard, 1996), and evaluation of pharmaceutical delivery devices (Mitchell & Nagel, 1999; Stein, 1999). Successful application of the APS in many of these studies requires accurate measurement of particle size and concentration.

To provide accurate size distributions, the APS must measure both particle size and particle concentration correctly. Size accuracy has not been an issue with this instrument; however, concentration accuracy has been problematic. Early APS instruments, models 33, 3300, and 3310, sometimes create “phantom” large particles when several small particles are simultaneously coincident in the detection region of the instrument (Heitbrink & Baron, 1991, 1992). As particle concentration increases, error due to coincidence becomes larger and limits the useful range of early models to below 100 cm^{-3} . TSI, Inc. substantially redesigned the optics and particle processing circuitry in the APS model 3320 to address coincidence problems, thereby extending the useful range of the instrument to 1000 cm^{-3} (Caldow, Quant, Holm, & Hairston, 1997; Holm, Caldow, Hairston, Quant, & Sem, 1997; TSI Inc., 1997). In addition to time-of-flight data, the APS 3320 provides light scattering intensity information for particles from 0.3 to 20 μm . Two modes of operation are offered: (1) summing mode, in which light-scattering and aerodynamic diameter data are measured independently, and (2) correlated mode, in which the two data are measured simultaneously.

Armendariz and Leith (2002) showed that the particle counts reported by the APS 3320 are lower in correlated mode than in summing mode. Further, artificial counts of large particles at concentrations well below 1000 cm^{-3} seriously bias particle mass distribution measurement (Armendariz & Leith, 2002; Stein et al., 2002). Stein and coworkers termed these particles “anomalous” to distinguish them from coincident “phantom” particles and demonstrated that they are created when particles not properly exiting the APS circulate back into the detection region. Stein et al. offered a method to correct data using the correlated light-scattering intensity information, which, unfortunately, depends on the refractive index of the measured particles and necessitates a unique calibration of the APS 3320 for each aerosol type. The latest version of the APS, model 3321, aims to resolve both these issues with redesigned particle processing circuitry and a redesigned outlet nozzle. The APS 3321 may be purchased new or as an upgrade to the older APS 3320.

The objectives of this research were: (1) to compare size distributions reported by the APS 3321 in summing and correlated modes when sampling the same aerosol, (2) to investigate creation of anomalous particles in the APS 3321, and (3) to investigate the counting efficiency of the APS 3321.

2. Methods

Fig. 1 shows the experimental setup used to evaluate the APS 3321. A pneumatic nebulizer (Re-order 5207, Professional Medical Products, Inc., Greenwood, SC 29646) created an aerosol composed of high-vacuum oil (Inland 99, IVAX Industries, Inc., Churchville, NY). This aerosol then passed through a Kr-85 charge neutralizer (Model 3054, TSI, Inc., St. Paul, MN), was diluted with clean dry air, and entered a 100 l mixing chamber. Nebulizer pressure and dilution airflow were adjusted to control aerosol concentration.

For summing and correlated mode comparison, an APS 3321 equipped with a diluter (Model 3302A, TSI, Inc. St. Paul, MN) sampled aerosol exiting the mixing chamber at 5 lpm. Four tests

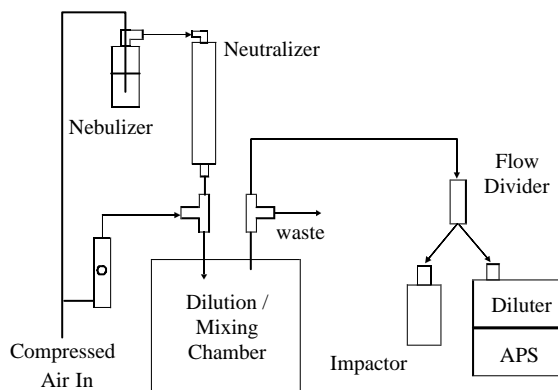


Fig. 1. Experimental setup used to evaluate an APS 3321.

were performed with aerosol concentrations that ranged from 50 to 1100 cm⁻³ as measured by the APS in summing mode after 100:1 dilution. Each test consisted of three 30-s samples collected in summing mode, alternating with three 30-s samples collected in correlated mode. After each test, two mean aerodynamic size distributions were constructed with the data—one from the three summing mode samples and one from the correlated mode samples. Percent counts lost, defined as the percent difference between the mean summing and correlated mode particle counts for the entire distribution, was calculated for each of the four tests. Data from bin 1 for particles < 0.523 μm were excluded from the calculation of percent count lost.

To investigate creation of “anomalous” particles and to determine counting efficiency, the APS/diluter combination and an eight-stage Sierra Ambient Cascade Impactor (Series 210, Graseby-Andersen, Atlanta, GA) sampled the aerosol exiting the mixing chamber at 10 lpm with a flow splitter, which divided the flow equally and isokinetically. Three tests were conducted at an aerosol concentration of 90 cm⁻³ as measured by the APS in summing mode after 100:1 dilution. Each test consisted of two 30-min APS measurements collected in summing mode and a single 1-h impactor measurement. The stainless steel substrates, glass fiber filter, and blanks from the impactor were weighed on a Mettler MT-5 microbalance (Mettler-Toledo, Greifensee, Switzerland). Number distributions from the APS were corrected using the 100:1 diluter efficiency file supplied by TSI, Inc. and converted to mass distributions for comparison with data from the cascade impactor. The impactor analysis combined stages 7 and 8 with cutpoints of 0.87 and 0.52 μm, respectively. To accommodate counting efficiency calculations, mass concentration data from the APS were grouped into intervals that corresponded to the impactor stages. Counting efficiency of the APS 3321 as a function of particle size was then calculated by dividing the APS mass concentration by that measured with the impactor for particles in the same size ranges.

The APS (S/N 1075) evaluated here was the same instrument evaluated by [Armendariz and Leith \(2002\)](#), after upgrading from model 3320 to model 3321 by the manufacturer (TSI, Inc.). The firmware version on board the APS 3321 was 1.12, dated 1 December 2001. The instrument was cleaned and recalibrated when upgraded. Prior to testing, the manufacturer’s calibration was verified using 0.65 and 1.96 μm PSL microspheres (Duke Scientific Corp., Palo Alto, CA 94303). The number mode diameter reported by the APS was within 0.02 μm of that reported by the PSL manufacturer.

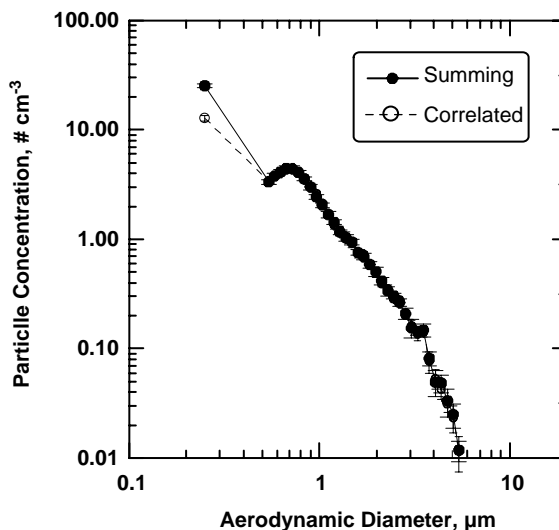


Fig. 2. Comparison of summing and correlated mode analysis for the reported aerodynamic particle size distribution. Error bars represent one standard deviation.

3. Results and discussion

The APS 3321 measured the aerosol particle concentration to be statistically the same in summing and in correlated modes for all size bins, except bin 1 (see Fig. 2). Particle concentration measured in bin 1 in correlated mode averaged $51.2\% \pm 1.2\%$ (one standard deviation) of that measured in summing mode for concentrations ranging from 71 to 1140 cm^{-3} . This result contrasts with the findings of [Armendariz and Leith \(2002\)](#), who found that the APS 3320 counted significantly fewer particles in correlated mode for nearly every bin. With the APS 3321, particle counts lost, shown in Fig. 3, were within $\pm 5\%$ for all concentrations. Prior to the upgrade of the APS 3320, [Armendariz and Leith \(2002\)](#) observed that particle counts lost were 40% at a concentration of 60 cm^{-3} and decreased to 18% at a concentration of 300 cm^{-3} .

The agreement between concentrations measured in summing and correlated modes with the APS 3321 may be due to the new firmware, the revised processing circuit board, or a combination of the two. If the revised firmware solves this issue, then perhaps the summing and correlated mode differences can be resolved in the APS 3320 by simply changing the firmware chip. On the other hand, a full upgrade to the APS 3321 will be necessary if the new processing board is involved in rectifying the concentration measurement issue.

Fig. 4 shows the particle size distribution measured with the cascade impactor and the APS 3321. Particle number concentration measured with the APS was relatively constant throughout the three tests, ranging from 80 to 95 cm^{-3} . The APS measured the shape of the particle size distribution well. However, the average mass concentration measured by the APS (4.8 mg m^{-3}) was significantly lower than that measured by the impactor (12.4 mg m^{-3}). The underestimate of particle mass appears for all particle sizes.

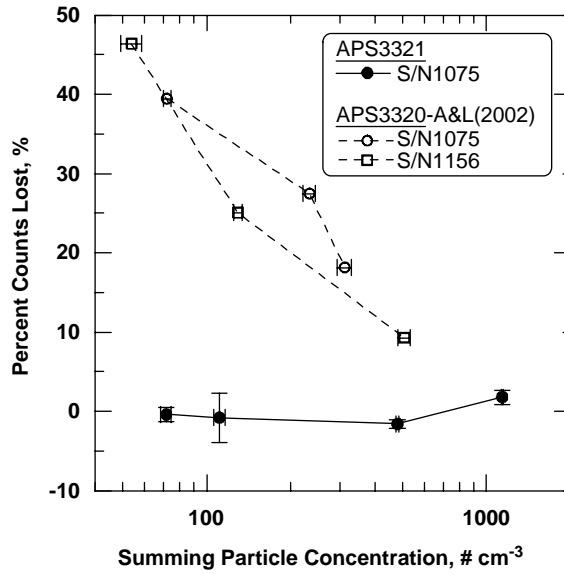


Fig. 3. Percent counts lost in correlated mode versus particle concentration. Error bars represent one standard deviation.

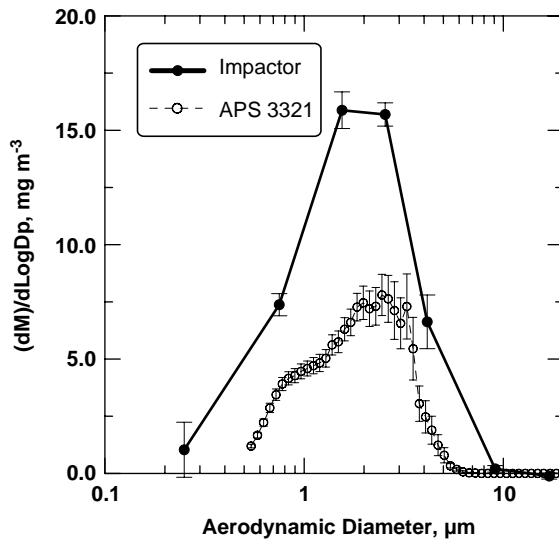


Fig. 4. Average aerodynamic particle size distributions from three tests with an APS 3321 and a cascade impactor. Error bars represent one standard deviation.

A normalized mass distribution plot (Fig. 5) shows the ability of the APS 3321 to resolve the problem of anomalous counts due to recirculating particles. The apparent mass of particles above 5 μm reported by Armendariz and Leith (2002) using the APS 3320 creates an apparent tail of large particles that can be attributed to particle recirculation (Stein et al., 2002). The mass distribution

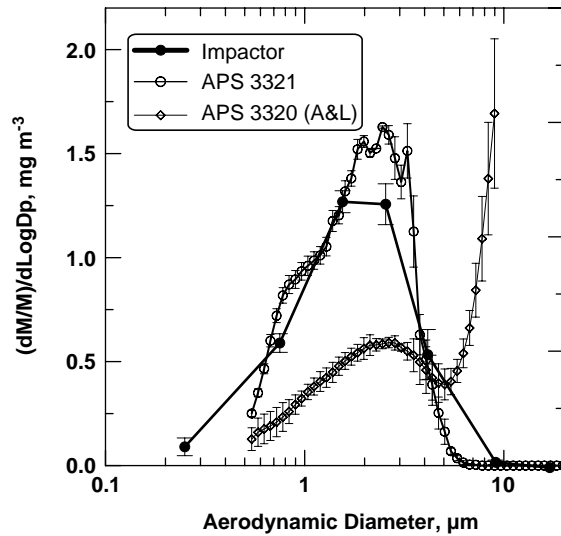


Fig. 5. Normalized aerodynamic particle size distributions from an APS 3321, an APS 3320, and a cascade impactor. Error bars represent one standard deviation.

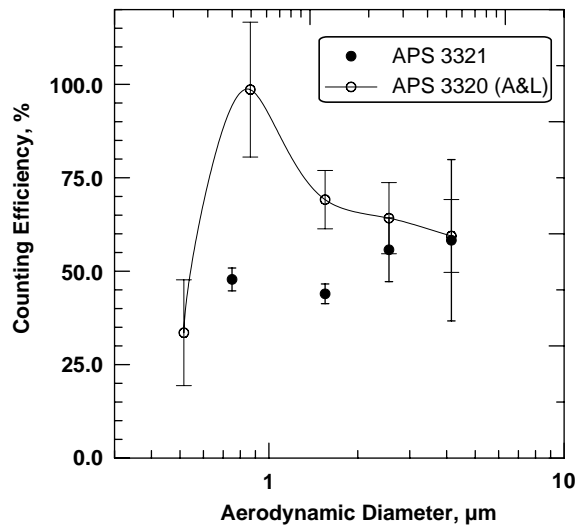


Fig. 6. Counting efficiency of the APS 3321. Error bars represent one standard deviation.

obtained with the APS 3321 shows no such tail. The improved performance with the APS 3321 is likely due to the redesigned outlet nozzle; however, the new processing circuitry may also play a role.

Fig. 6 shows the counting efficiency of the APS 3321 contrasted with that for the APS 3320 as measured by [Armendariz and Leith \(2002\)](#). The counting efficiency for the APS 3321 between 1 and 3 μm (45%) was lower than that reported previously for the APS 3320 (65%) but increased to 60%

for 4 μm particles. Because the APS evaluated in this work was upgraded from the same instrument tested previously by Armendariz and Leith, system optics were the same so cannot account for the difference in counting efficiency between models. Perhaps the lower counting efficiency of the APS 3321 is due to the new data processing circuitry. Because its counting efficiencies were lower than unity, the APS 3321 measured a lower average mass concentration than the impactor. Further, because counting efficiencies were roughly constant with particle size and anomalous particles were not present, the shape of the size distribution measured with the APS 3321 matched that measured with the impactor fairly well.

One limitation of this work is that only a single APS 3321 was tested. Yanosky et al. (2002) observed variability between instruments for APS model 3320 but were unable to attribute the difference to flow sensor calibration, size calibration, or optics sensitivity.

4. Conclusions

The APS 3321 offers improvements over the APS 3320. The APS 3321 measured particle concentrations that were statistically the same in summing and in correlated mode for all size bins, except for bin 1 for particles $< 0.523 \mu\text{m}$. The number concentration reported in bin 1 in correlated mode was consistently about half that reported in summing mode. Further, anomalous particles, which commonly appear as a false, large-particle tail in mass distributions measured with the APS 3320, were absent in the data collected with the APS 3321.

Counting efficiencies measured with the APS 3321 were 45% for 2 μm particles and 60% for 4 μm particles, somewhat lower than values previously reported for the APS 3320. As a result, mass concentration measured with the APS 3321 was lower than that measured with the impactor. However, because counting efficiency was roughly constant over the range of particle sizes investigated and anomalous particles were not present, the shape of the size distribution measured using the APS 3321 was similar to that obtained using a cascade impactor.

References

- Armendariz, A. J., & Leith, D. (2002). Concentration measurement and counting efficiency for the aerodynamic particle sizer 3320. *Journal of Aerosol Science*, 33(1), 133–148.
- Caldow, R., Quant, F. R., Holm, R. L., & Hairston, P. P. (1997). *Paper #12PP9, design of a next-generation aerodynamic particle sizing time-of-flight spectrometer*. Paper presented at the American Association for Aerosol Research 16th Annual Conference, Denver, CO.
- Gorner, P., Wrobel, R., Micka, V., Skoda, V., Denis, J., & Fabries, J. F. (2001). Study of fifteen respirable aerosol samplers used in occupational hygiene. *The Annals of Occupational Hygiene*, 45(1), 43–54.
- Heitbrink, W. A., & Baron, P. A. (1991). Coincidence in time-of-flight aerosol spectrometers: Phantom particle creation. *Aerosol Science and Technology*, 53, 427–431.
- Heitbrink, W. A., & Baron, P. A. (1992). An approach to evaluating and correcting aerodynamic particle sizer instruments for phantom particle count creation. *American Industrial Hygiene Association Journal*, 53, 427–431.
- Holm, R. L., Caldow, R., Hairston, P. P., Quant, F. R., & Sem, G. J. (1997). An enhanced time-of-flight spectrometer that measures aerodynamic size plus light-scattering intensity. *Journal of Aerosol Science*, 28 (Suppl. 1), S11–S12.
- Kenny, L. C., & Gussman, R. A. (2000). A direct approach to the design of cyclones for aerosol-monitoring applications. *Journal of Aerosol Science*, 31(12), 1407–1420.

- Mitchell, J. P., & Nagel, M. W. (1999). Time-of-flight aerodynamic particle size analyzers: Their use and limitations for the evaluation of medical aerosols. *Journal of Aerosol Medicine*, 12(4), 217–240.
- Shen, S., Jaques, P. A., Zhu, Y., Geller, M. D., & Sioutas, C. (2002). Evaluation of the SMPS-APS system as a continuous monitor for measuring PM_{2.5}, PM₁₀ and coarse (PM_{2.5-10}) concentrations. *Atmospheric Environment*, 36(24), 3939–3950.
- Shi, J. P., Harrison, R. M., & Evans, D. (2001). Comparison of ambient particle surface area measurement by epiphaniometer and SMPS/APS. *Atmospheric Environment*, 35(35), 6193–6200.
- Spanne, M., Olsson, B. O., Gudmundsson, A., & Bohgard, M. (1996). Characteristics of particle emissions at paint manufacturing. *Journal of Aerosol Science*, 27(1), S437–S438.
- Stein, S. W. (1999). Size distribution measurements of metered dose inhalers using Andersen Mark II cascade impactors. *International Journal of Pharmaceutics*, 186(1), 43–52.
- Stein, S. W., Gabrio, G. W., Oberreit, D., Hairston, P. P., Myrdal, P. B., & Beck, T. J. (2002). An evaluation of mass-weighted size distribution measurements with the model 3320 aerodynamic particle sizer. *Aerosol Science and Technology*, 36, 845–854.
- TSI Inc. (1997). *Model 3320 aerodynamic particle sizer spectrometer instruction manual*. St. Paul, MN: TSI, Inc.
- Yanosky, J. D., Williams, P. L., & MacIntosh, D. L. (2002). A comparison of two direct-reading aerosol monitors with the federal reference method for PM_{2.5} in indoor air. *Atmospheric Environment*, 36(1), 107–113.