Tandem Configurations of Different Aerosol Classifiers with the Aerodynamic Aerosol Classifier (AAC)

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BACKGROUND

The Aerodynamic Aerosol Classifier (AAC) is a novel aerosol instrument that classifies particles based on their aerodynamic diameter (d_a, i.e. centrifugal-to-drag force ratio). It selects particles independent of their charge-state and has a transmission efficiency 2.6 to 5.1 times higher than current electrostatic classifiers, while producing a monodispersed aerosol with no multiple-charging artifacts (Johnson et al., 2018).

These characteristics allow the AAC to be utilized for a wide range of applications, including different configurations with other aerosol classifiers, such as the Differential Mobility Analyzer (DMA) and Centrifugal Particle Mass Analyzer (CPMA). The DMA and CPMA classify particles based on their mobility diameter (d_m, i.e. electrostatic-to-drag force ratio) and mass-to-charge (m_p/q, i.e. centrifugal-to-electrostatic force ratio), respectively.

While tandem DMAs and DMA-CPMA configurations have been previously studied, limited research has investigated AAC-DMA or AAC-CPMA systems. We present here an investigation into the relationships between these different particle properties for spherical morphologies.

AAC

The AAC selects particles of a particular aerodynamic diameter by generating a control sheath flow and passing it between two rotating concentric cylinders as shown in Figure 1. This rotation induces a known centrifugal force on each individual particle. Particles with larger aerodynamic diameters impact the outer surface of the classifier, while particles with aerodynamic diameters smaller than the AAC setpoint remain entrained in the sheath flow. Therefore, only particles with the correct aerodynamic diameter pass through the AAC classifier.

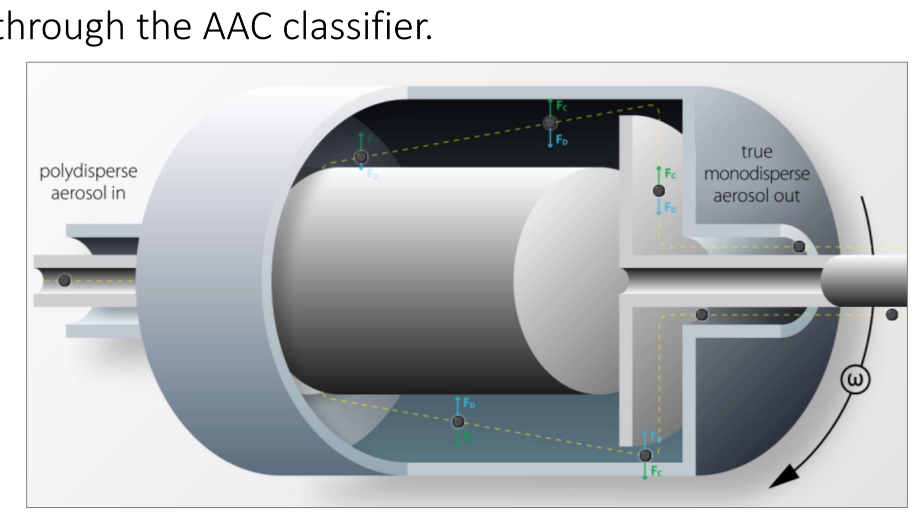


Figure 1: AAC operating principle (https://www.cambustion.com/products/aac/animation)

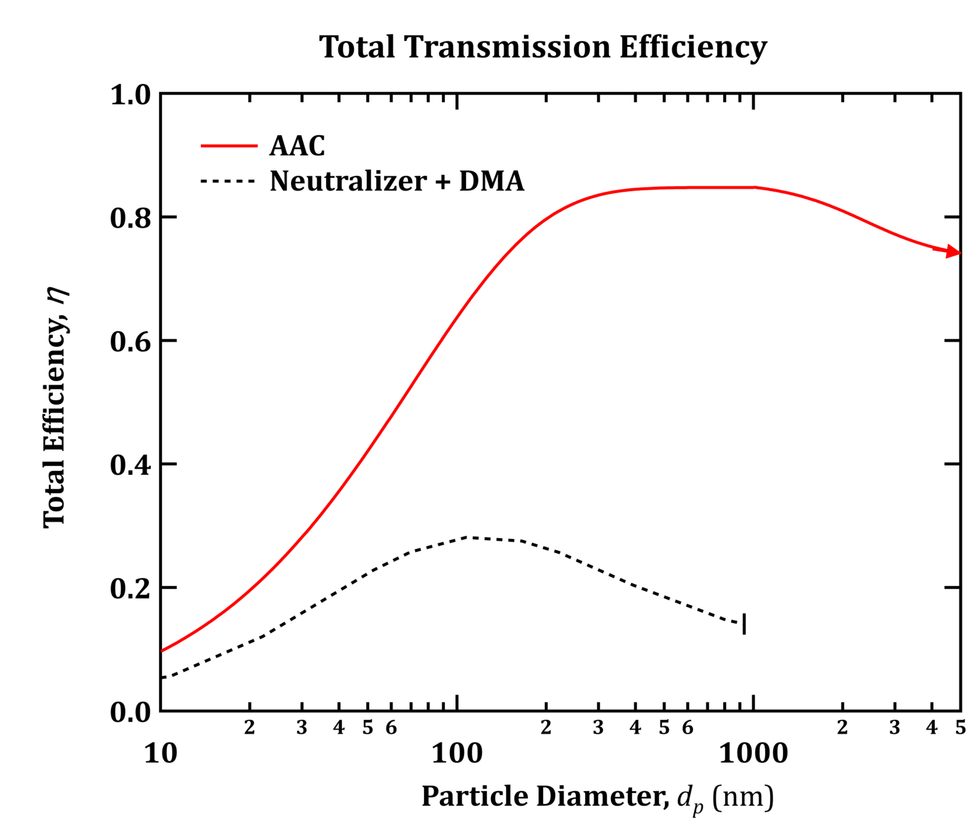
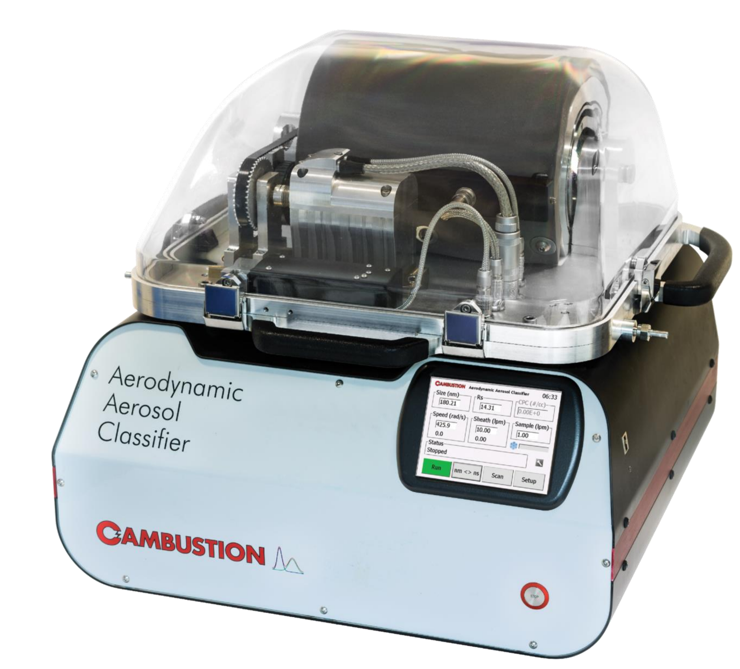


Figure 2: Transmission efficiency of the AAC



Photograph of the AAC

METHODOLOGY

This study used an AAC to select particles based on their aerodynamic diameter from a polydispersed DOS (Bis-2-ethylhexyl sebacate) aerosol generated using a BGI Collison nebulizer. The particle mobility and mass of the AAC classified aerosol was determined by diluting, charging and dividing the sample between a stepping DMA and stepping CPMA in parallel as shown in Figure 3. The particle number concentration of each twice classified aerosol (N_2) was measured using a Condensation Particle Counter (CPC) and recorded as a function of the downstream classifier (i.e. DMA or CPMA) setpoint.

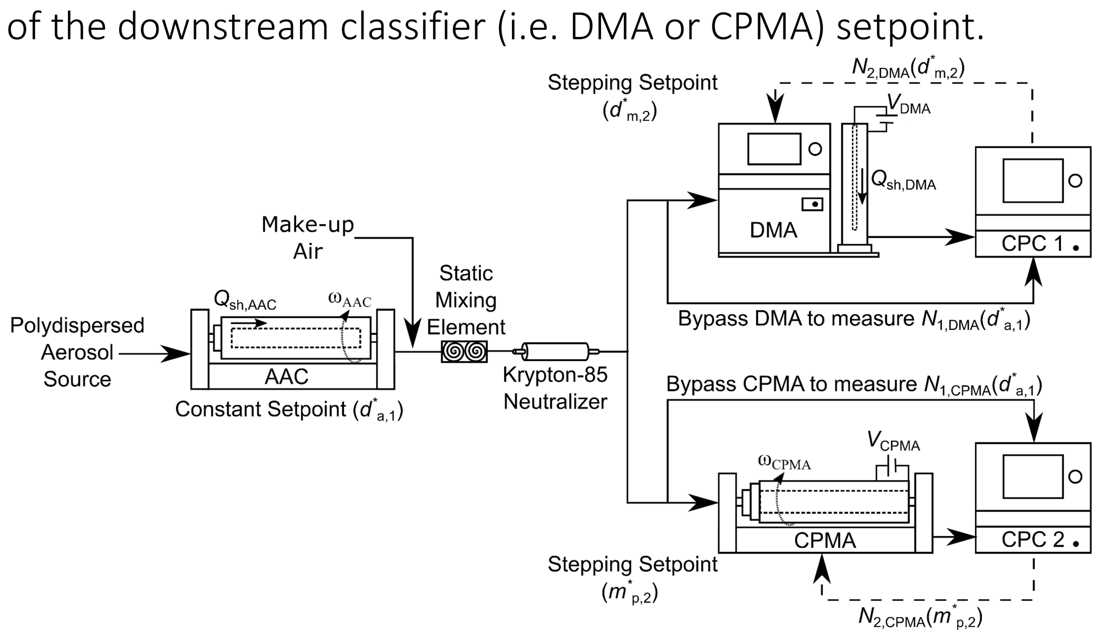


Figure 3: Experimental setup

TANDEM INVERSION

The charge-states of the monodispersed aerosol produced by the AAC appeared as distinct peaks in the DMA or CPMA scans as shown in Figure 4. The area under the AAC-DMA peaks relative to the AAC classified particle number concentration (N_1) was used to determine the particle charging fractions (f_n), while the position of the peaks in the mobility ($d^*_{m,2}$) or mass ($m^*_{p,2}$) domain relative to the AAC aerodynamic diameter setpoint ($d^*_{a,1}$) was used to determine the effective particle density. These measurements were calculated by fitting the theoretical tandem transfer function for particle charge states n_{min} to n_{max} to the data from each tandem configuration using chi-squared minimization as follows:

$$\frac{N_2}{N_1} = \frac{\lambda_{\Omega,\mathrm{DS}} \sum_{n=n_{\min}}^{n_{\max}} f_n \int \Omega_{\mathrm{AAC}} \cdot \Omega_{\mathrm{DS},n} \cdot dx}{\int \Omega_{\mathrm{AAC}} \cdot d d_a} \qquad \text{(Eq1)}$$

Where Ω_{AAC} is the AAC transfer function, while $\lambda_{\Omega,\mathrm{DS}}$, $\Omega_{\mathrm{DS},n}$ and x are the transmission efficiency, transfer function and measurand of the downstream (DS) electrostatic classifier (i.e. DMA or CPMA), respectively. Based on previous studies (Birmili et al., 1997; Johnson et al., 2018; Reavell et al., 2011), each of the three classifiers' transfer function was approximated as a triangle. The dashed line shown in each inversion example subplot is the inversion initial guess based on theory. The theoretical charge fractions were estimated based on Wiedensohler (1988) and Gunn & Woessner (1956), while the effective particle density was known (914 kg/m³).

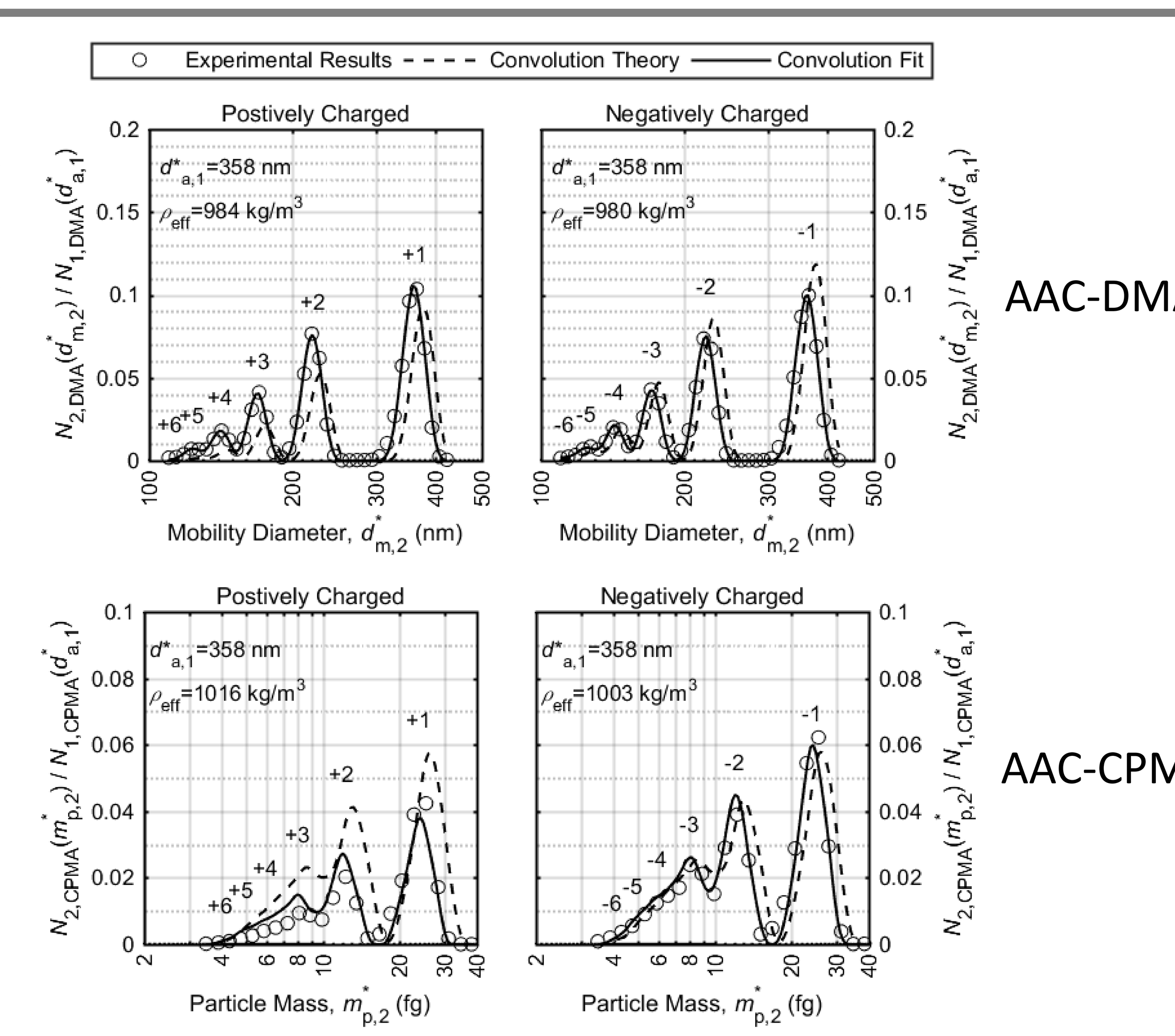


Figure 4: Example tandem AAC- electrostatic classifier scans with a 358 nm aerodynamic diameter AAC setpoint

RESULTS

A minimum of four parallel AAC-DMA and AAC-CPMA scans were completed at each AAC setpoint. Two scans with positive electrostatic classifier voltages and the other two with negative. Due to the low concentration at small particle sizes of the aerosol source, as well as the lower transmission efficiency of the CPMA compared to the DMA, the 40 nm AAC-CPMA N_2 measurements were too low to reliably process. The average effective densities measured by both tandem systems is shown in Figure 5, while the charge fractions measured by the AAC-DMA system is shown in Figure 6.

The average effective particle densities measured by the AAC-DMA and AAC-CPMA agreed within 7.3% and 12.9% of predicted (914 kg/m³), respectively. These maximums are equivalent to 2.57% or 2.03% setpoint uncertainty in the AAC and DMA or AAC and CPMA, respectively, assuming the uncertainty between the classifiers in each tandem arrangement is equal. Both tandem systems measured larger effective densities as the particle aerodynamic diameter increased. An approximately linear trend was also identified by Johnson et al. (2018) for classification agreement between tandem AACs.

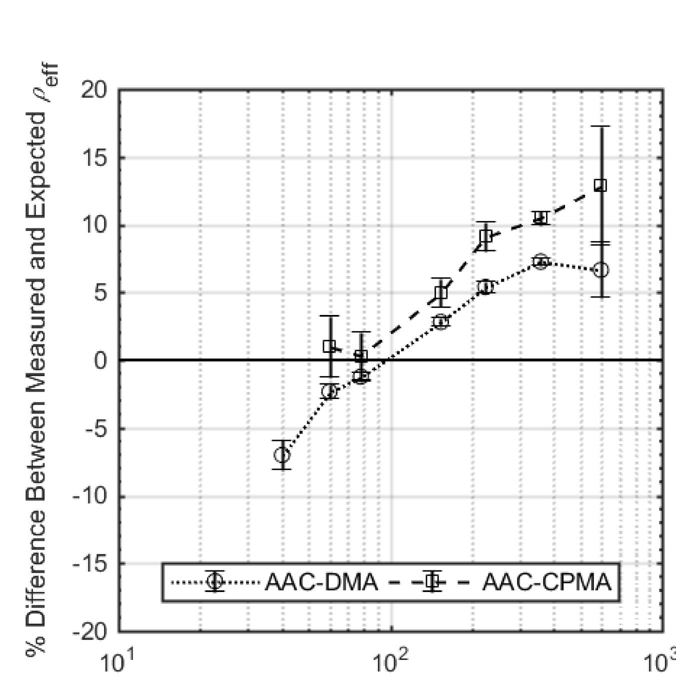


Figure 5: Agreement between known and measured effective densities

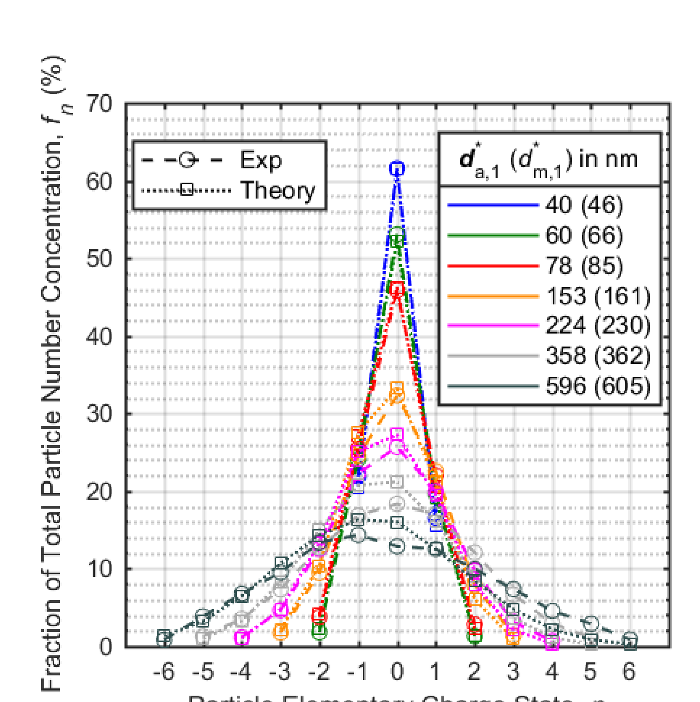


Figure 6: Agreement between charge fractions measured by the AAC-DMA and theory

The agreement of the charge fractions measured by the tandem AAC-DMA with theory (Wiedensohler, 1988; Gunn & Woessner, 1956) is shown in Figure 6. The average absolute difference between the measured and predicted values was 1.08%; however, this average difference isn't uniform. As particle size increases, theory predicts higher negative one charge and neutral charge fractions, and lower positive two to five charge fractions than the measured values. These results also demonstrate the capability of the AAC-DMA system to resolve up to 13 charge states (6 positive, 6 negative and the neutral) at one particle size.

SUMMARY

The average effective particle densities measured by the AAC-DMA and AAC-CPMA agreed within 7.3% and 12.9% of predicted (914 kg/m³), respectively.

The average absolute difference between the charge fractions measured by the AAC-DMA system and theory was 1.08%. These results also demonstrate the capability of the AAC-DMA system to resolve up to 13 charge states.

The high agreement between the measured and predicted values for both the charge fractions and effective density validate these novel tandem aerosol classifier configurations and supporting inversions.

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