Comparative Evaluation of Commercially Available Liquid Aerosol Generators for Implementation in the Ambient Air Test Facility (AATF)

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Abstract

Accurate and stable aerosol generation is essential for evaluating chemical sensor performance. This requires controlled laboratory conditions that replicate operational environments. This study presents a comparative assessment of four commercially available liquid aerosol generators—the Collison nebulizer, Blaustein Atomizing Module (BLAM), Aeroneb Lab module, and P&S T45 vibrating mesh nebulizer—for their ability to generate well-characterized aerosols for eventual integration into the U.S. Naval Research Laboratory's Ambient Air Test Facility (AATF). The objective was to identify systems capable of producing stable, tunable aerosol output under laboratory conditions with particle size and concentration characteristics relevant to high-flow test environments. Aerosols of sodium chloride (NaCl) and glycerol at concentrations ranging from 0.1–2.5% mass were generated and analyzed using a TSI Aerodynamic Particle Sizer (APS 3321). Performance metrics included particle number concentration (#/cm³), mass concentration (μg/m³), number median diameter (NMD), mass median diameter (MMD), and geometric standard deviation (GSD). The P&S T45 vibrating mesh nebulizer produced the highest particle concentrations with controllable aerosol concentration via duty cycle and flow rate adjustments, while atomizers such as the Collison and BLAM exhibited narrower size distributions (GSD ~1.25) but were more sensitive to solution viscosity and clogging at concentrations > 0.5 wt%. Operating windows were established for each generator by defining thresholds for stable aerosol output. Comparison of number versus mass-weighted size distributions underscores the need to evaluate additional metrics for accurate dose characterization. This study provides quantitative guidance for selecting aerosol generators and establishes a reproducible framework for evaluating generator performance under conditions relevant to future AATF integration.

Keywords: Aerosol generator; Vibrating mesh; Atomizer; NaCl; APS; Particle size distribution

Introduction

Aerosols, micron to submicron-sized particles suspended in air play critical roles in atmospheric chemistry, environmental monitoring, public health, and sensor development. They originate from diverse natural sources, such as volcanic emissions, sea spray, and wildfires, as well as anthropogenic activities, including fossil fuel combustion, industrial processes, and biomass burning (Seinfeld and Pandis, 2016; Pöschl, 2005). Fine particulate matter, particularly particles with aerodynamic diameters less than 2.5 µm ($PM_{2.5}$), has been strongly associated with adverse health outcomes, including asthma exacerbation, cardiovascular disease, and premature mortality (Brook et al., 2010; Pope and Dockery, 2006). In climate systems, aerosols influence radiative forcing, cloud condensation nuclei activity, and atmospheric energy balance, thereby affecting both weather patterns and long-term climate dynamics (Andreae and Rosenfeld, 2008). Controlled laboratory facilities provide essential platforms for studying aerosol behavior, calibrating chemical sensors, and evaluating particle transformation processes under reproducible conditions. Among these, the U.S. Naval Research Laboratory's Ambient Air Test Facility (AATF) offers a unique high-flow wind-tunnel environment capable of delivering either ambient or particle-free air with controlled test aerosol injection and mixing.

Integration of well-characterized liquid aerosol generators into this facility will enable simulation of realistic atmospheric particle conditions for sensor development, calibration, and performance verification. Numerous aerosol generators are commercially available, varying widely in design, operating principle, and output characteristics. Jet atomizers, such as the Collison nebulizer and BLAM, rely on compressed air to shear liquids into droplets, producing high aerosol mass output but requiring careful control of solution viscosity and gas–liquid flow parameters (Olfert and Checkel, 2000; Kim et al., 2001). These systems can experience performance degradation at high solute concentrations due to salt deposition and nozzle clogging. In contrast, vibrating mesh nebulizers, including the Aeroneb Lab and P&S T45, employ piezoelectric elements to drive liquid through micro-perforated membranes, generating aerosols with narrower size distributions and reduced mechanical stress on the liquid (Kuehl et al., 2014; Golshahi et al., 2013). While vibrating mesh devices are widely used in medical applications for drug delivery due to their ability to produce respirable aerosols with minimal residual volume, their performance in environmental testing platforms remains underexplored. Prior studies have primarily focused on medical aerosol delivery systems or indoor air purification technologies (Haughney et al., 2010; Golshahi et al., 2014). Few studies have systematically compared atomizers and vibrating mesh devices under controlled laboratory conditions designed to mimic aspects of sensor testing environments. In particular, there is limited literature evaluating drying completeness, defining stable operating windows, and contrasting number- versus mass-weighted aerosol metrics—all of which are essential for accurate dose characterization and sensor response calibration.

This study addresses these gaps by conducting a side-by-side evaluation of four aerosol generators—two jet atomizers (Collison, BLAM) and two vibrating mesh nebulizers (Aeroneb Lab, P&S T45)—under laboratory conditions. The next phase involves installing the down-selected generators from this study at the AATF and performing long-term trends and repeatability statistics. Aerosols of sodium chloride (NaCl) and glycerol across a range of concentrations (0.1–2.5 wt%) were generated and characterized using a TSI Aerodynamic Particle Sizer (APS 3321) for this laboratory comparison study. Key objectives include: establishing operating parameters for each of the generators, quantifying particle number concentration, mass concentration, and size distributions as a function of solution concentrations; comparing atomizer- versus mesh-based performance across solute types and operating conditions; operating windows for stable, fully dried aerosol output and evaluating the implications of number- versus mass-weighted metrics for sensor testing applications. By defining performance limits, stability criteria, and particle size–mass relationships, this work provides a reproducible framework for selecting and implementing aerosol generators in controlled laboratory test facilities such as the AATF. While absolute aerosol concentrations and drying dynamics will inevitably not scale when transitioning from bench-scale studies to high-flow environments, the relative particle size distributions and its dependence on chemical specific solution concentrations are expected to remain consistent. Thus, the findings presented here not only characterize generator performance under laboratory conditions, but also establish transferable metrics that inform downstream integration and sensor evaluation in the AATF.

Methods

Experimental Setup

Four commercially available liquid aerosol generators were evaluated under controlled laboratory conditions to assess their suitability for producing stable, reproducible aerosols representative of those intended for future implementation at the AATF. The study also focused on selecting devices that are readily available and compatible with typical research and calibration applications. Two compressed-air atomizers—the Collison 3-jet nebulizer (CH Technologies, 1973) and the BLAM (CH Technologies, 2016)—and two vibrating-mesh nebulizers—the P&S T45 (Tekceleo, 2015) and the Aeroneb Lab Module (Kent Scientific, 2015)—were tested.

A schematic diagram of the laboratory setup is shown in **Figure 1**. Each generator was connected individually to a vertical drying column, where aerosolized droplets were mixed with a stream of dry air to ensure complete evaporation prior to measurement. The outlet of the drying column was connected to a TSI APS 3321 for particle size analysis. For the Collison and BLAM atomizers, nebulizer airflows were set between 2–6 L min^{-1} according to manufacturer recommendations for the 3-jet configuration, with a 2.5 µm nominal mass median diameter droplet size and 1.8 geometric standard deviation (GSD) for the Collison nebulizer (Kuehl et al., 2014). The P&S T45 was operated using variable duty cycles (1–100 %) under a constant liquid flow of 0.8–35 mL min^{-1}, depending on the pore size (5 µm or 8 µm). The Aeroneb Lab Module employed an integrated electronic controller to set the duty cycle and flow rate. Both devices were tested at two pore sizes to evaluate the influence of orifice geometry on aerosol characteristics. A HEPA filter was installed downstream of the APS outlet to prevent particle release into the laboratory environment. All tubing was ¼″ inner diameter, with component spacing between 15 and 30 inches to provide representative residence time and minimize particle loss. Flow rates were regulated using a mass flow controller (Omega Engineering) and continuously monitored with a flowmeter to ensure stable operation throughout testing.

Future Plan- Ambient Air Test Facility (AATF)

Although no experiments were performed directly at the AATF in this phase, laboratory testing replicated aerosol generator operating conditions, solution concentrations, and injection geometries planned for future integration. The AATF is a modular 13 m wind-tunnel system that is 30 cm in diameter. Adjustable airflow velocities from 0.5–17 m/s allow simulation of diverse environmental conditions. Two inlet options supply either ambient air or high efficiency particulate air (HEPA) and carbon-filtered air for particle-free testing as shown on left side of Fig. 2. The right side of Fig. 2 shows the inside view of the AATF where the aerosol generators and referee and testing instruments are outfitted. At typical flow rates of 2 m/s, air is well mixed before reaching downstream sampling sections, ensuring homogeneous test conditions. Future work will introduce laboratory-characterized aerosols from aerosol generators down-selected from this study and implemented into the AATF via injection ports located immediately downstream of the inlet switching manifold.

Test Solutions

Aerosols were generated from aqueous solutions of sodium chloride (NaCl, Fisher Scientific) and glycerol (Sigma Aldrich) at concentrations ranging from 0.1% to 2.5% w/w. All solutions were prepared fresh in deionized water (Millipore) and filtered through 0.2 μm membranes to prevent clogging of jets or mesh pores. NaCl was selected as a model inorganic salt for calibration and drying studies, while glycerol was chosen for its hygroscopic properties relevant to atmospheric simulants.

Instrumentation and Calibration

Particle size distributions were measured using a TSI Aerodynamic Particle Sizer (APS 3321; TSI Inc., 2001), which measures aerodynamic diameters from 0.5 to 20 μm across 52 size channels. The APS operated at a total flow rate of 5 L min^{-1}, consisting of 1 L min^{-1} sample flow and 4 L min^{-1} sheath flow, with data collected at 10 s intervals. Prior to this study, the instrument underwent factory calibration at TSI, and the calibration was subsequently verified in our laboratory using monodisperse polystyrene latex (PSL) spheres (1 μm, 2 μm, and 4 μm; Thermo Fisher Scientific. (2012). As shown in Figure 3, the measured aerodynamic diameters closely matched the nominal PSL bead sizes, confirming the accuracy of the APS. The peak diameters deviated by less than ±3.5% from the nominal values. The geometric standard deviations (GSD) were 1.18, 1.09, and 1.12 for 1 μm, 2 μm, and 4 μm PSLs, respectively, consistent with expected APS resolution limits at smaller diameters (Wang and John, 1988; TSI Inc., 2001). The corresponding full widths at half maximum (FWHM) were 27 %, 10 %, and 15 %, indicating excellent size resolution and minimal broadening. These results verified that the APS 3321 was properly calibrated and performing within specification, ensuring confidence in all subsequent aerosol size distribution measurements conducted in this study.

Experimental Protocol

We established the operating conditions for the Collison nebulizer by varying both nebulizer and drying air flow rates to identify stable aerosol generation and complete drying behavior. The three-jet Collison nebulizer was operated within the manufacturer's recommended range of 2–6 L min^{-1} and 20–100 psig air pressure. We tested across this range of airflow to evaluate performance using a 0.5 % NaCl solution. **Figure 4** shows the normalized particle size distribution as a function of nebulizer flow rate. As shown in **Figure 4** (left), operation below 3 L min^{-1} resulted in unstable aerosol generation, whereas increasing the nebulizer airflow above 4 L min^{-1} produced aerosol concentrations exceeding the APS saturation limit of 1000 particles cm^{-3}. Based on these results, a nebulizer airflow of 3.5 L min^{-1} was selected for subsequent experiments.

Once the nebulizer flow rate was fixed, the drying airflow was varied from 8 to 22 L min^{-1} to determine drying completeness. As shown in **Figure 4** (right), the mode diameter decreased with increasing drying air until reaching a stable region between 13 and 19 L min^{-1}, identified as the full drying window. Within this region, mode diameters of the measured size distributions remained uniform, indicating complete solvent evaporation. At lower drying airflows, particles were not fully dried, while at higher flows above 19 L min^{-1}, excessive air shortened residence time in the drying column, leading to incomplete evaporation and resulting in larger mode diameters. The 13–19 L min^{-1} range was therefore selected as the optimal drying condition to ensure consistent, fully dried aerosol output, and this same approach was applied when determining operating windows for the other three aerosol generators examined in this study.

Data Analysis

Size distributions were reported as dN/dlogDp or N/cm^3 versus aerodynamic diameter (Dp). Number median diameter (NMD) and geometric standard deviation (GSD) were obtained from lognormal fits to number distributions, while mass median diameter (MMD) and total mass concentration were derived assuming spherical particles with densities of 2.17 g/cm^3 (NaCl) and 1.26 g/cm^3 (glycerol).

Results and Discussion

Comparison of Collison and BLAM Nebulizers

The performance of the Collison nebulizer and the BLAM was evaluated under identical conditions to assess reproducibility and concentration-dependent aerosol behavior. **Figure 5** shows the measured number size distributions for NaCl solutions ranging from 0.05% to 2.5% at a fixed carrier gas flow of 3.5 L min^{-1} and drying flow of 16 L min^{-1}. Both generators produced highly similar aerosol size distributions, confirming consistent atomization characteristics. Increasing solute concentration resulted in a clear increasing shift in the mode diameter—from approximately 0.7 µm at 0.05% NaCl to 1.0 µm at 2.5%—and a corresponding increase in total number concentration.

The statistical parameters derived from these distributions are summarized in **Table 1**, which lists number and mass median diameters (NMD, MMD), geometric standard deviations (GSD), and total particle concentrations. The NMD increased from 0.7 µm to 0.9–1.0 µm with concentration, while the MMD increased from 0.8 µm to 1.7–1.8 µm. The GSD remained near-monodisperse (1.2) at low solute concentrations but broadened to about 1.5 at higher concentrations, reflecting greater variability in droplet formation and evaporation as solute loading increased.

Overall, these findings demonstrate that both compressed-air atomizers produce stable, reproducible NaCl aerosols, with particle size and concentration scaling predictably. For general aerosol generation, characterization and calibration applications, either generator performs adequately; however, the BLAM offers advantages for generating bioaerosols and biological suspensions because its design minimizes mechanical shear and impingement forces, thereby reducing potential damage to fragile microorganisms and biomolecules (Mainelis et al., 2005; May et al., 2013; McCluskey et al., 2020). This makes BLAM particularly suitable for applications requiring gentle aerosolization such as biological materials or certain sensitive pharmaceuticals.

Table 1. Aerosol size and concentration metrics for Collison and BLAM nebulizers across NaCl solutions.

Parameters	**0.05% NaCl**	**0.1% NaCl**	**0.5% NaCl**	**2.5% NaCl**
NMD (µm) – Collison	0.7	0.8	0.9	1.0
NMD (µm) – BLAM	0.7	0.7	0.9	1.0

Parameters	0.05% NaCl	0.1% NaCl	0.5% NaCl	2.5% NaCl
GSD, number – Collison	1.2	1.2	1.4	1.5
GSD, number– BLAM	1.2	1.2	1.4	1.5
Total concentration (#/cm³) – Collison	348	454	754	928
Total concentration (#/cm³) – BLAM	338	620	765	940
MMD (µm) – Collison	0.8	0.91	1.3	1.7
MMD (µm) – BLAM	0.8	0.9	1.4	1.8
GSD, mass – Collison	1.2	1.3	1.4	1.5
GSD, mass – BLAM	1.3	1.4	1.4	1.5
Total concentration (mg/m³) – Collison	0.05	0.09	0.4	0.9
Total concentration (mg/m³) – BLAM	0.04	0.1	0.4	0.9

Number vs. Mass Size Distributions

Aerosol size distribution can be analyzed in terms of number, surface area, volume, or mass, depending on the intended application. In this study, both number and mass distributions were evaluated to provide a more complete characterization of the generated aerosols. **Figure 6** compares the number- and mass-weighted aerodynamic size distributions of aerosols produced from a 0.5 % NaCl solution using the Collison nebulizer and BLAM. Because aerosol mass scales with the cube of particle diameter (D^3), the mass distribution is inherently shifted toward larger particle sizes relative to the number distribution. In Fig. 6, we demonstrated this effect by calculating the contribution to total number and mass concentrations from particles smaller and larger than 1.5 μm. Only about 3 % of the total particle number generated by the Collison is larger than 1.5 μm, yet this small fraction accounted for roughly 52 % of the total aerosol mass. Similarly, the BLAM exhibited a slightly broader size distribution, with approximately 6 % of the total particle number exceeding 1.5 μm and contributing to about 58 % of the total mass. This variation highlights the fundamental difference between number- and mass-weighted aerosol representations and emphasizes the importance of evaluating both metrics when characterizing aerosol generation performance, particularly when assessing dose delivery, deposition behavior, or sampling efficiency.

Aerosol Characterization of Vibrating Mesh Devices: P&S T45 and Aeroneb

Vibrating mesh–based aerosol generators represent a major advancement in liquid aerosol production, offering precise droplet control with minimal noise and mechanical stress. The P&S T45 employs a micro-perforated mesh that vibrates at a fixed frequency to produce uniform droplets through thousands of precision-formed apertures. The central mesh, approximately 5 mm in diameter, contains ~1000 conical holes of same hole size ranging from 0.5 μm to 50 μm in diameter depending on configuration, and operates at 128 kHz to generate droplets within the same size range (0.5–50 μm). The device functions without compressed air, utilizing an amplified piezoelectric effect that minimizes heat generation and preserves liquid composition during atomization. The P&S T45 used in this study incorporated a built-in 10 mL liquid reservoir and operated on a 12 V DC power supply. It features a pulse-width-modulated (PWM) interface (3.3 V) allowing linear control of aerosol output by varying the duty cycle from 0 to 100%. Flow rates ranged from 0.8 to 35 mL min^{-1}, depending on pore size and duty cycle, and the system's touchscreen display enabled direct adjustment of flow and operation parameters. Only low-viscosity liquids (< 3 mPa·s) were suitable for aerosolization due to the fine pore geometry.

The Aeroneb Lab Module operates on a similar vibrating-mesh principle, using piezoelectrically driven perforated membranes to generate aerosols with minimal shear or impaction—an advantage for applications requiring gentle aerosolization. However, unlike the P&S T45, the Aeroneb Lab offers only two fixed pore-size configurations, limiting flexibility in tailoring particle size distributions. Both devices share the fundamental advantage of producing highly reproducible, low-velocity aerosols with minimal evaporation losses but differ in their configurability and operational control interfaces.

Figure 7 shows the aerodynamic particle size distributions of NaCl aerosols generated using vibrating mesh nebulizers with 5 µm pores. The left panel shows the influence of NaCl concentration on aerosols produced with the P&S T45 device. As the concentration of the salt solution increased from 0.05% to 2.5%, the mode diameter shifted from approximately 0.8 µm to 1.7 µm. Additionally, the distributions became progressively widened with increasing solute concentration. This broadening is reflected by an increase in the GSD from 1.25 at 0.05% to approximately 1.6 at 2.5%, suggesting polydispersity at higher solute concentrations. The right panel compares aerosols generated from 0.5% NaCl using P&S T45 and Aeroneb devices, both operated with 5 µm pore sizes. While both systems produced unimodal distributions centered near 1 µm, the Aeroneb exhibited a narrower distribution (GSD ≈ 1.25) compared to the P&S T45 (GSD ≈ 1.5).

For the P&S T45, both duty cycle and flow rate could be independently adjusted, allowing fine control of output aerosol concentration, which is of interest for the current program. To illustrate the versatility, **Figure 8** shows the aerosol concentration as a function of duty cycle for varying concentrations of NaCl solutions. The concentration response is shown to be linear as a function of duty cycle. The Aeroneb device regulates these parameters internally and does not provide control to the user which limits the range of operation flexibility. Despite this limitation, both devices demonstrated consistent droplet formation and stable operating behavior under identical test conditions.

Liquid aerosol: Glycerol

In this experiment, we used the P&S T45 vibrating mesh nebulizer to compare aerosol formation from NaCl and glycerol solutions under identical operating and drying conditions. The left side of Figure 9 shows that the 0.1% glycerol aerosol produced slightly larger aerodynamic diameters compared to 0.1% NaCl. This shift is attributed to glycerol's higher viscosity and lower volatility, which slow evaporation and result in larger residual droplet sizes even after complete drying. The right side compares 0.1% and 0.5% glycerol aerosols generated with the same device. Increasing glycerol concentration caused a noticeable broadening of the size distribution and a modest increase in mode diameter, reflecting less efficient solvent evaporation and minor droplet coalescence at higher solute content. This observation confirms that for viscous or low-volatility liquids, even small changes in concentration significantly affect the final aerosol size distribution. All measurements were performed using the same flow and drying conditions as in earlier tests, ensuring that differences observed are solely due to fluid properties rather than drying rate.

Distributions by Generator

Particle size distributions for 2.5% NaCl aerosols at the same operating conditions, nebulizer, and drying conditions (19 L min^{-1}) revealed clear distinctions in performance among the four aerosol generators (**Figure 10** and **Table 2**). The Collison nebulizer and BLAM both produced unimodal, submicron aerosols with median diameters of 0.75 µm and 0.77 µm, respectively. The BLAM exhibited a higher GSD = 1.45 compared to the Collison (GSD = 1.25), indicating a wider size distribution. Their total particle number concentrations were 155 and 277 #/cm³, respectively, confirming stable and efficient aerosolization under identical operating conditions.

The Aeroneb generated aerosols with a median diameter of 0.96 µm and a GSD of 1.25, similar to Collison nebulizer but an extended tail toward larger diameters. Its higher total number concentration (500 #/cm³) reflects efficient droplet production despite limited user-controlled parameters. The P&S T45, operated at a 10% duty cycle, produced distinctly larger particles with a median diameter of 1.75 µm and the broadest size distribution (GSD = 1.54). The elevated total concentration (771 #/cm³) demonstrates higher aerosol output but with reduced uniformity, likely due to coalescence A comparison based on mass concentration further highlights these differences.

The P&S T45 generated the largest MMD (2.87 µm) and highest total mass concentration (2.9 mg/m³), while the Aeroneb produced moderately large particles (1.62 µm) with a total concentration of 0.31 mg/m³. In contrast, the Collison and BLAM produced smaller MMDs (0.91 µm and 1.79 µm, respectively) and lower total mass concentrations (<0.3 mg/m³), consistent with their finer and more monodisperse output. Collectively, these results confirm that jet-based atomizers (Collison and BLAM) provide tighter control over droplet breakup and drying, generating smaller, more uniform aerosols, whereas vibrating mesh systems (Aeroneb and P&S T45) yield larger, more polydisperse distributions due to their distinct droplet formation and evaporation mechanisms. However, vibrating mesh systems enable generation of varying size droplets based on the pore size and P&S T45 offers control of aerosol concentration.

Table 2. Aerosol number- and mass-based metrics for four nebulizers operated with a 2.5% NaCl solution at 19 L min^{-1}, including median diameters, geometric standard deviations, and total particle concentrations.

Parameter	Collison Nebulizer	BLAM	Aeroneb	P&S T45
Number Statistics				
Median Diameter (µm)	0.75	0.77	0.96	1.75
GSD	1.25	1.45	1.25	1.54
Total Concentration ($\#/cm^3$)	155	277	500	771
Mass Statistics				
Median Diameter (µm)	0.91	1.79	1.62	2.87
GSD	1.32	1.49	1.39	1.64
Total Concentration (mg/m^3)	0.19	0.26	0.31	2.90

Conclusion

This study provides a comprehensive performance evaluation of four commercially available liquid aerosol generators—Collison nebulizer, BLAM, Aeroneb Lab module, and P&S T45—under laboratory conditions to down select generators for the U.S. Naval Research Laboratory's Ambient Air Test Facility (AATF). Key findings include: APS calibration validation with 1–4 µm PSL spheres confirmed measurement accuracy within ±3.5%, ensuring reliable size distribution characterization. Drying completeness was quantitatively defined by the slope of mode diameter versus drying air flow or duty cycle ($\Delta mode/\Delta x \approx 0$), ensuring fully evaporated particles for all reported measurements. Stable operating windows in nebulizer air flows were identified for generating stable aerosol distributions for Collison and BLAM. Vibrating mesh nebulizers (Aeroneb, P&S T45) exhibited monotonic increases in particle concentration with duty cycle. All the generators exhibited larger size distributions with increased solute concentrations, with atomizers mostly still exhibiting monodispersed distributions (GSD < 1.3) and vibrating mesh-based devices shifting to larger size particles and becoming more polydispersed. While submicron particles dominated number distributions (>95%) for atomizers, particles >1.5 µm contributed >50% of total aerosol mass, emphasizing the need to report both metrics for accurate assessment of aerosol delivery and deposition profiles. Hygroscopic growth effects were more pronounced for glycerol than NaCl due to its higher water retention and viscosity, shifting mode diameters toward larger sizes under identical drying conditions. Overall, this work establishes standardized methods for defining complete drying, operating windows, and number–mass distribution relationships across generator types and solutes. These identified generator parameters for stable operation, solution concentration dependent size distributions and generator parameter dependent aerosol concentration are directly transferable to aerosol generation at AATF.

Acknowledgements

None

Competing Interest Declaration –

The authors declare no competing interests.

Ethics, Consent to Participate, and Consent to Publish declaration

Ethics, Consent to Participate, and Consent to Publish declarations: not applicable.

Oyedoyin Aduroja, Vasanthi Sivaprakasam: review and editing (equal). Vasanthi Sivaprakasam: Conceptualization (lead); review and editing (lead). Oyedoyin Aduroja: writing – original draft (lead); formal analysis (lead); writing Vasanthi Sivaprakasam: Methodology (lead); writing – review and editing (equal). Cathy Scotto: Conceptualization (supporting); Writing – original draft (supporting); Writing – review and editing (equal).

Data availability statement

Available upon request and the organization's authorization

Funding

This research is based upon work supported by the Office of the Director of National Intelligence (ODNI), Intelligence Advanced Research Projects Activity (IARPA), via NELO funding doc# N4175624WR00700-Basic. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the ODNI, IARPA, or the U.S. Government.

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Figure Caption

Figure 1. Schematic of the experimental setup showing aerosol generation, drying column, and measurement configuration using the APS 3321.

Figure 2. Photographs of the Ambient Air Test Facility (AATF): (a) exterior view showing the ambient and filtered-air inlets, and (b) interior view of the wind tunnel and instrumentation setup for aerosol generation and testing.

Figure 3. APS 3321 calibration using monodisperse polystyrene latex (PSL) spheres 1 µm, 2 µm, and 4 µm in diameters.

Figure 4. Optimization of nebulizer and drying air flow rates for the Collison nebulizer using 0.5% NaCl. The left panel shows normalized particle size distributions at varying nebulizer flow rates, and the right panel identifies the full drying window (13–19 L min^{-1}) based on mode diameter stability.

Figure 5. Comparison of aerosol number size distributions generated using the Collison nebulizer (dashed lines) and BLAM (solid lines) across NaCl concentrations of 0.05%, 0.1%, 0.5%, and 2.5%. Increasing solute concentration shifts the mode diameter toward larger sizes and increases total particle concentration for both generators.

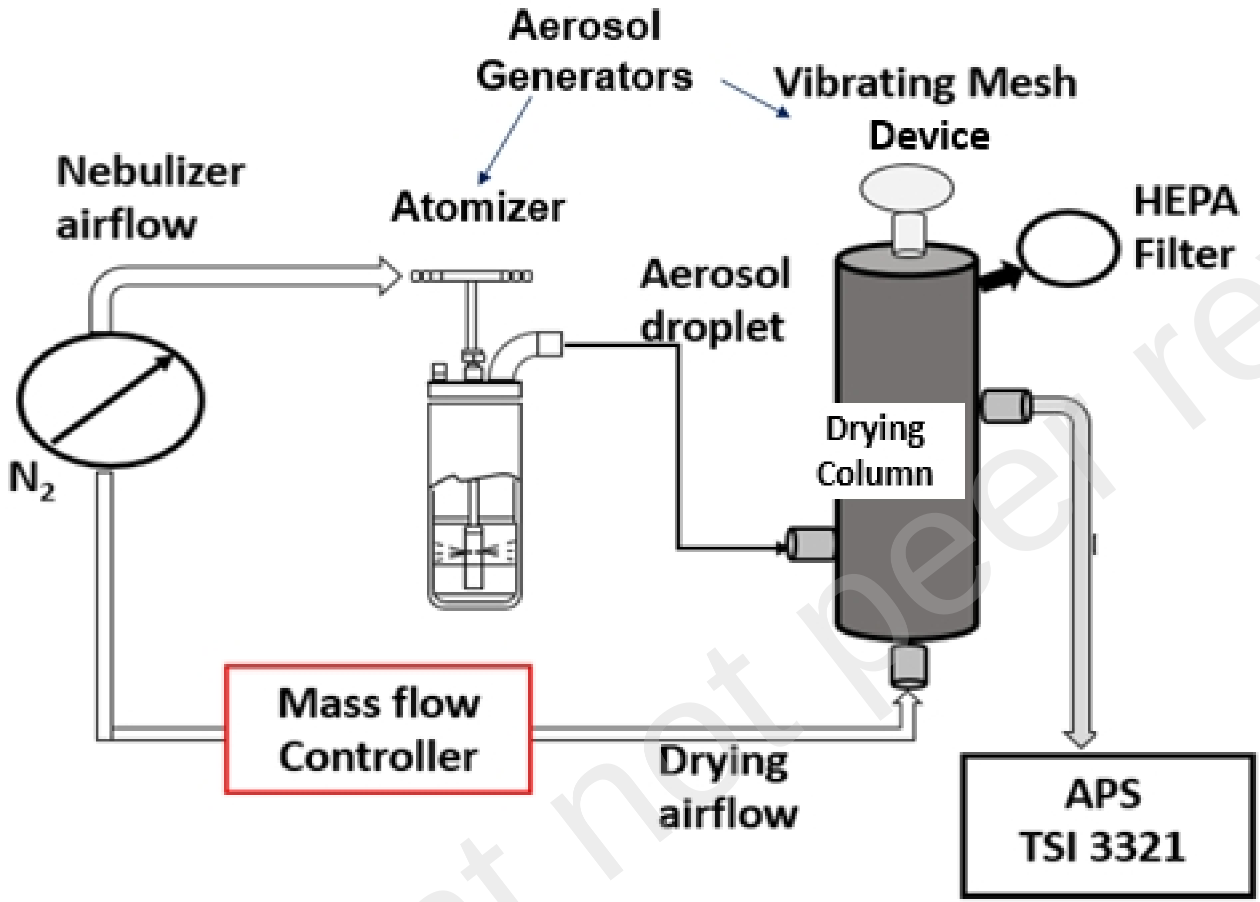
Figure 6. Number and mass size distributions of 0.5% NaCl aerosols from the Collison nebulizer and BLAM, highlighting the greater mass contribution of larger particles, demonstrated here by summing the contributions of particles smaller and larger than 1.5 µm.

Figure 7. Aerodynamic particle size distributions of NaCl aerosols generated using vibrating mesh nebulizers with 5 µm pore sizes. Left: Effect of NaCl concentration on aerosol size distribution for the P&S T45. Right: Comparison between P&S T45 and Aeroneb devices operated with 0.5% NaCl solution.

Figure 8. Aerosol number concentration as a function of nebulizer duty cycle for NaCl solutions ranging from 0.05% to 2.5% showing linearlity.

Figure 9. Comparison of aerosol size distributions generated using the Tekceleo P&S T45 vibrating mesh nebulizer with (left) 0.1% NaCl vs. 0.1% glycerol and (right) 0.1% vs. 0.5% glycerol solutions.

Figure 10. Normalized aerodynamic particle size distributions of 2.5% NaCl aerosols generated using four aerosol generators.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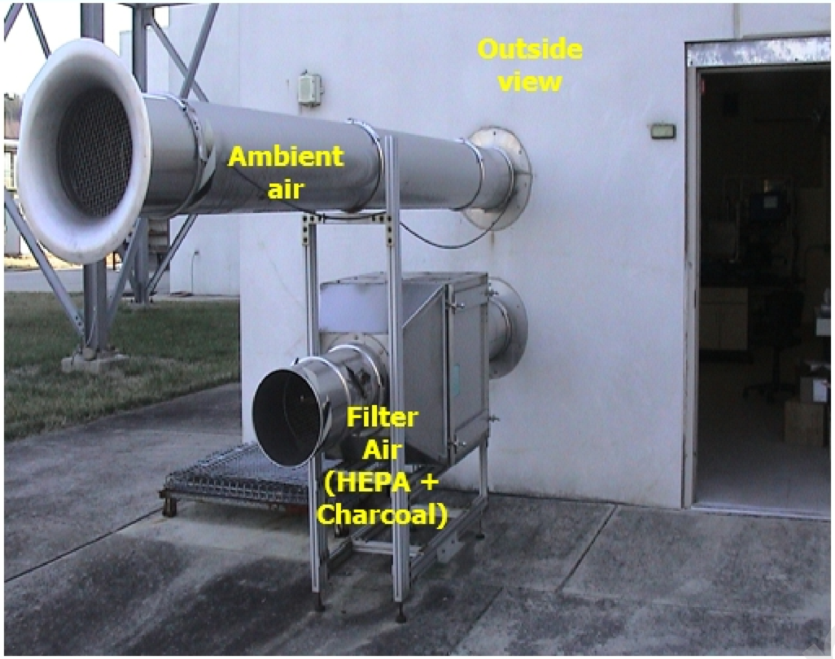
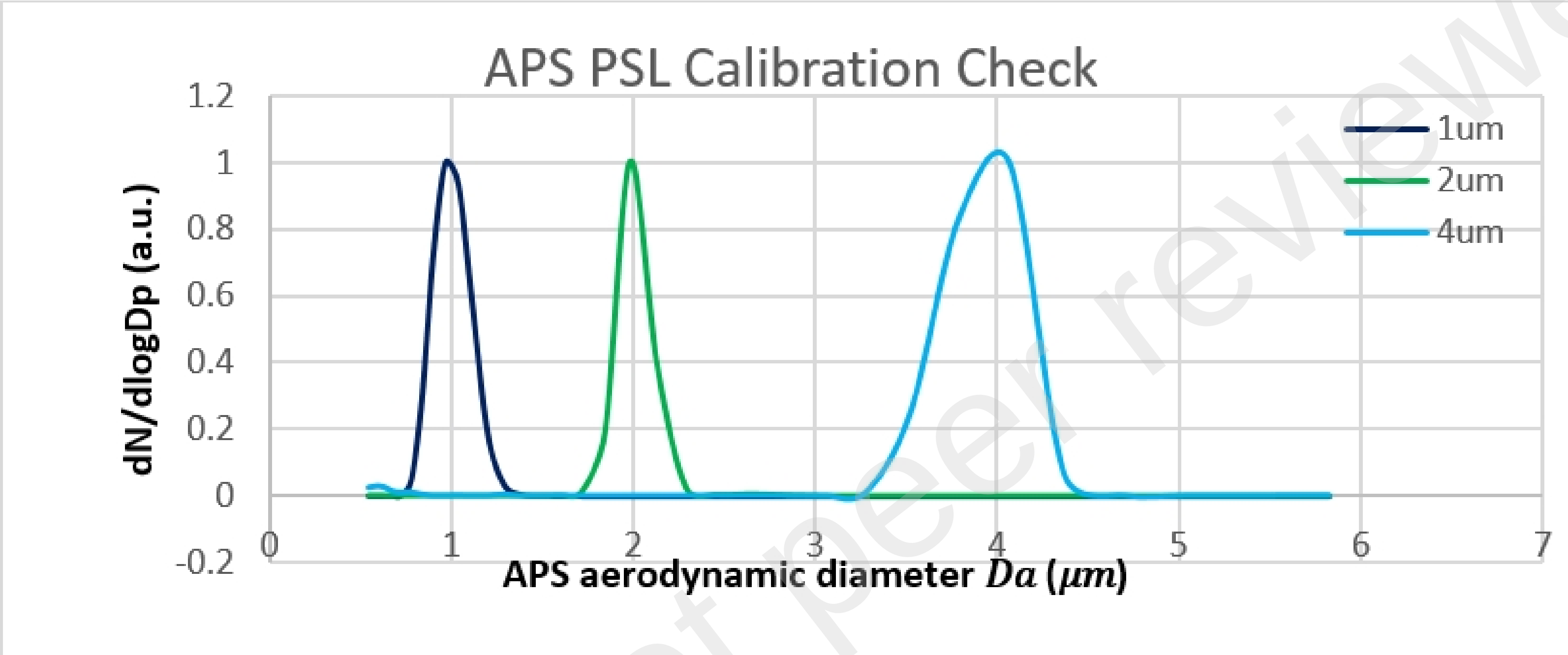
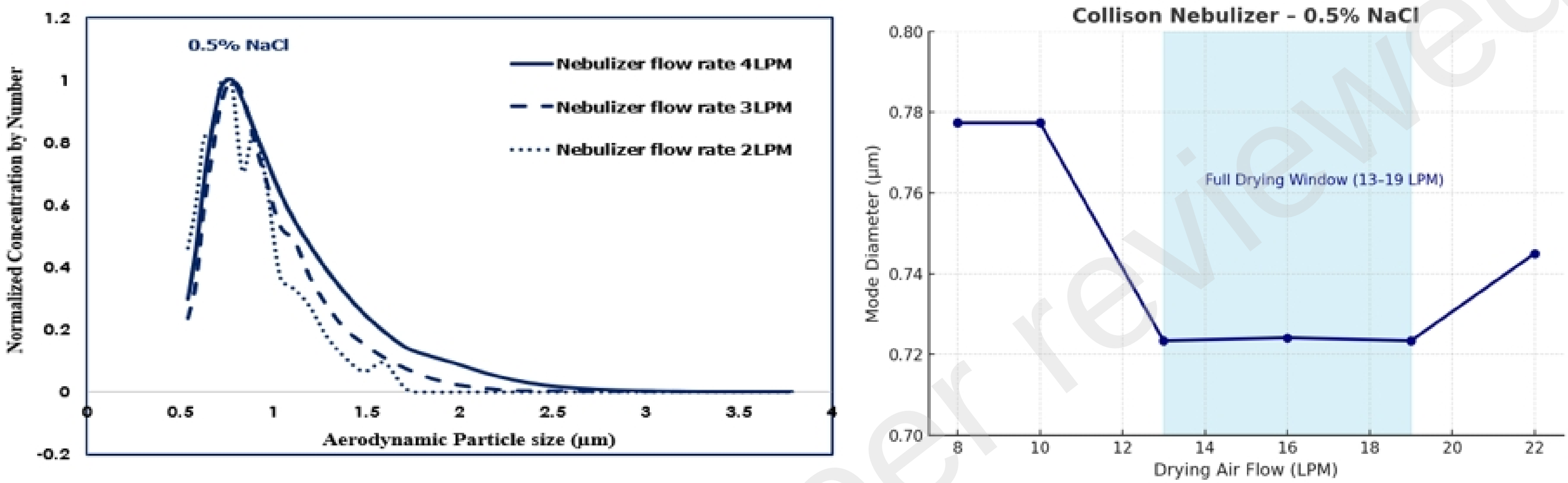
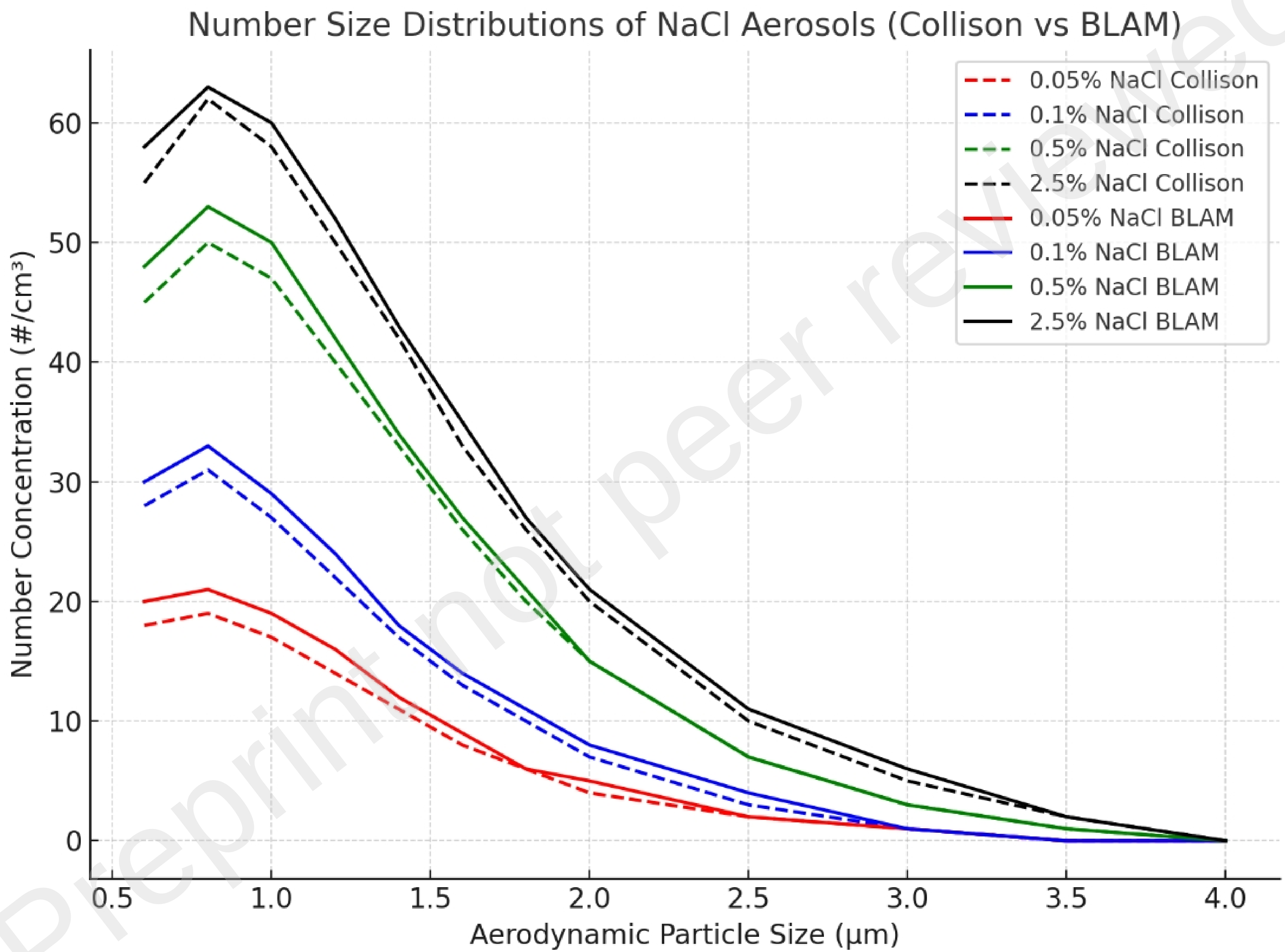
APS
TSI 3321


Outside view
Ambient air
Filter Air (HEPA + Charcoal)

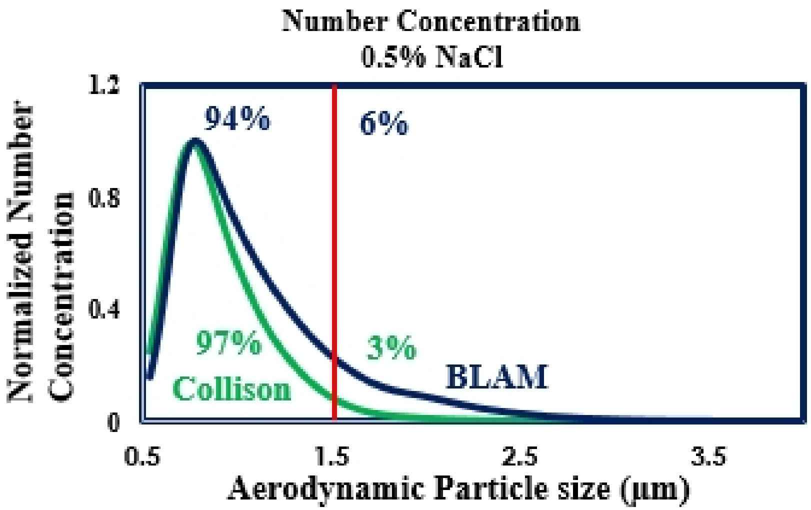
Ambient Air Test Chamber
Aerosol Generators

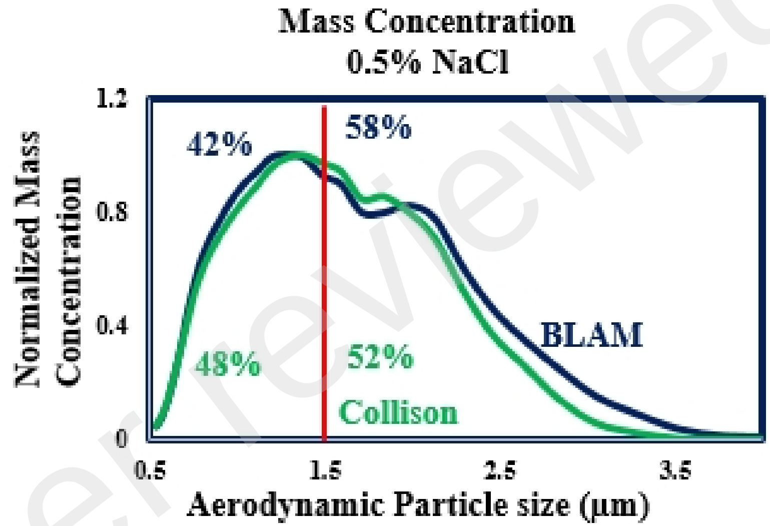

APS PSL Calibration Check
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
dN/dlogDp (a.u.)
0
1
2
3
4
5
6
7
APS aerodynamic diameter Da (μm)
1um
2um
4um

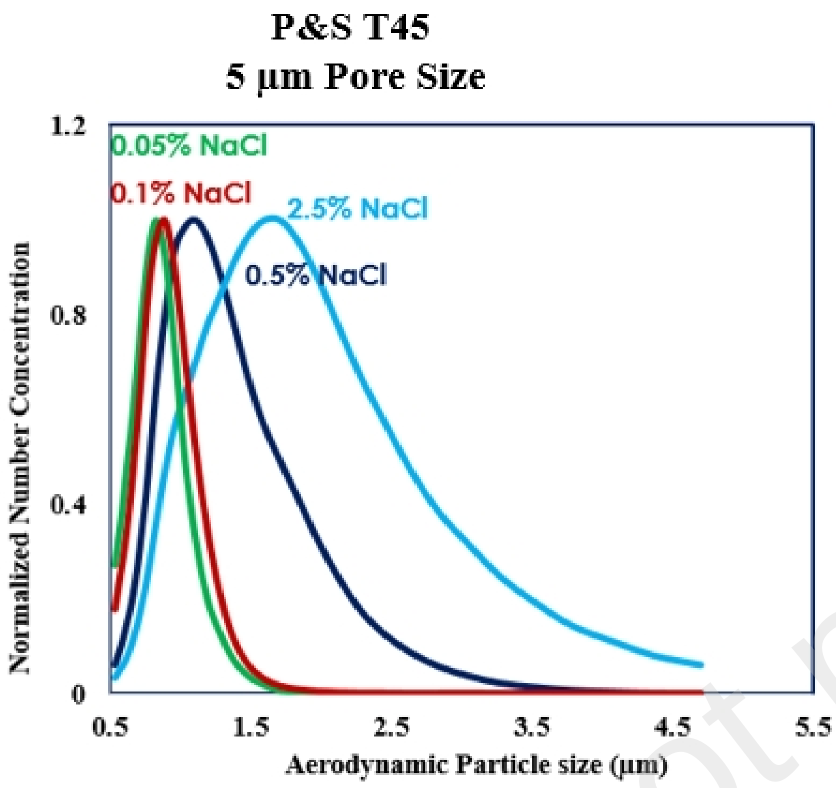

0.5% NaCl
Nebulizer flow rate 4LPM
Nebulizer flow rate 3LPM
Nebulizer flow rate 2LPM
Normalized Concentration by Number
Aerodynamic Particle size (µm)
Collison Nebulizer – 0.5% NaCl
Full Drying Window (13–19 LPM)
Mode Diameter (µm)
Drying Air Flow (LPM)

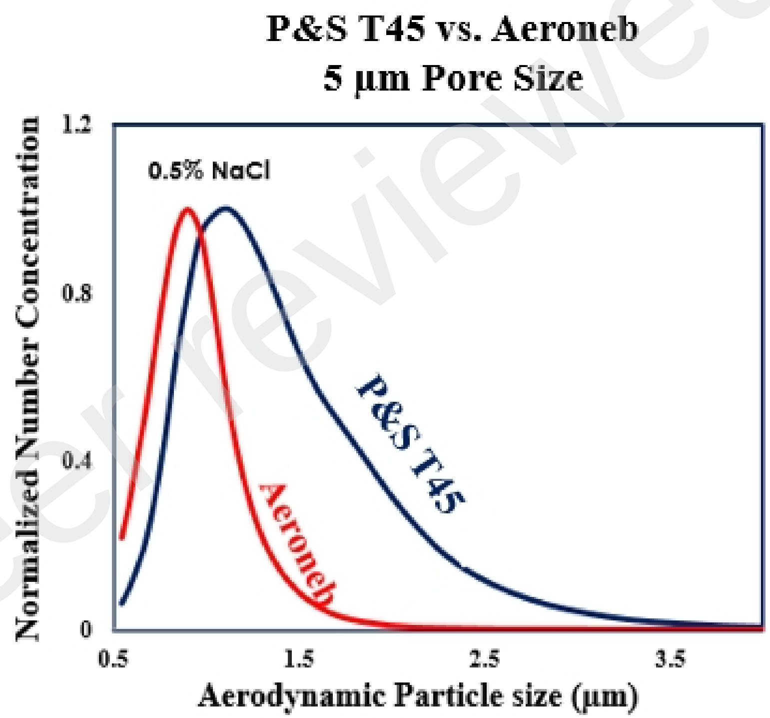


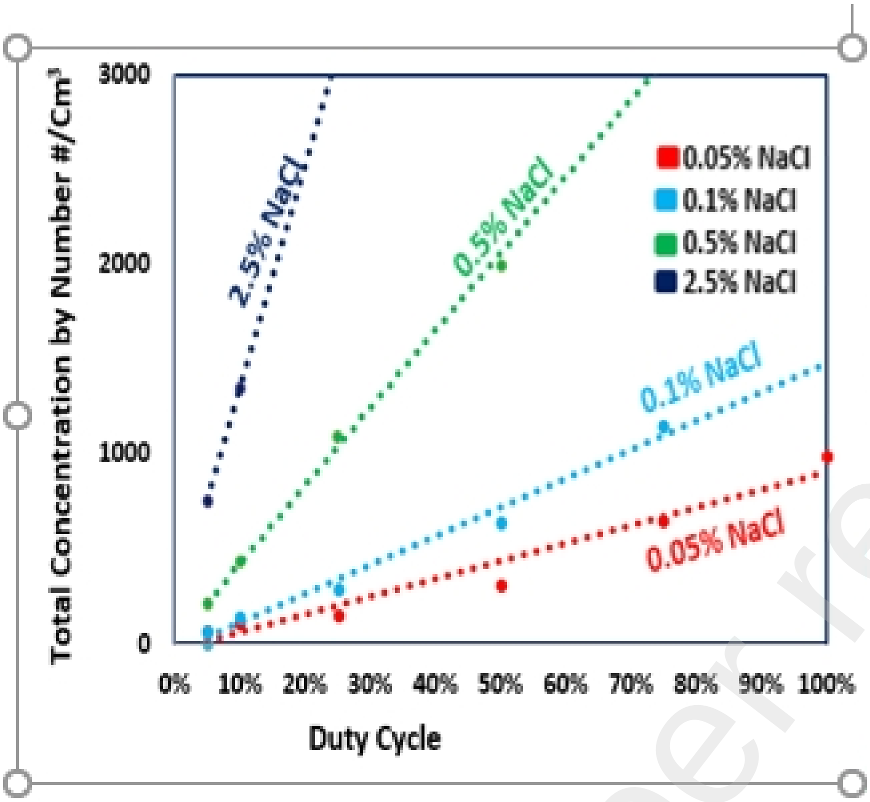
Number Size Distributions of NaCl Aerosols (Collison vs BLAM)
0.05% NaCl Collison
0.1% NaCl Collison
0.5% NaCl Collison
2.5% NaCl Collison
0.05% NaCl BLAM
0.1% NaCl BLAM
0.5% NaCl BLAM
2.5% NaCl BLAM
Number Concentration (#/cm³)
0
10
20
30
40
50
60
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Aerodynamic Particle Size (µm)

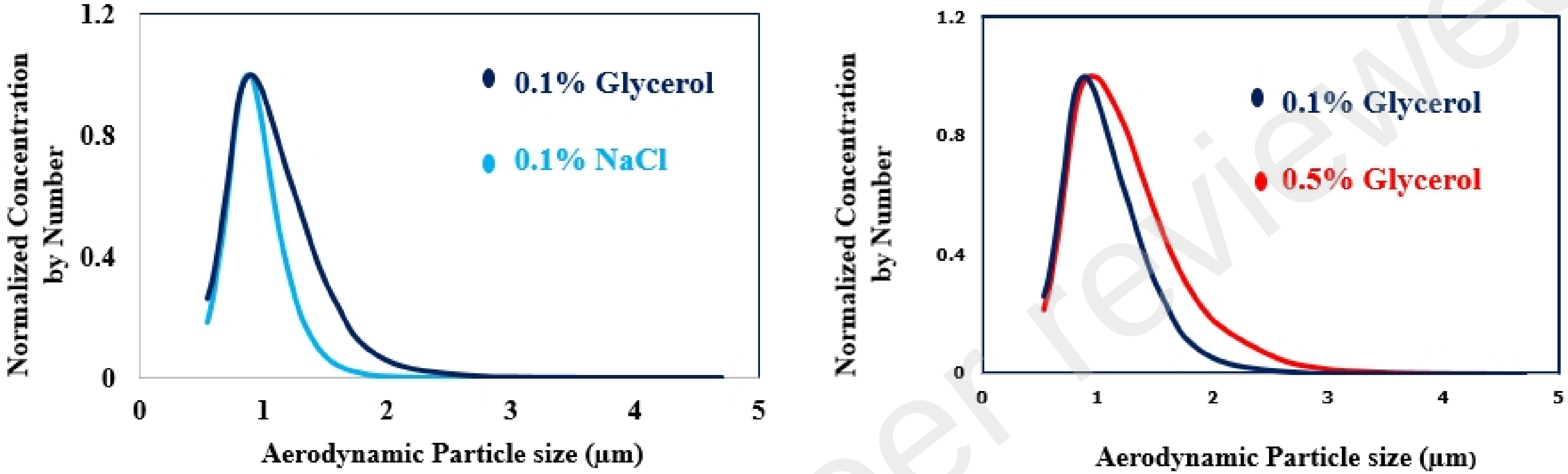

Number Concentration
0.5% NaCl
Normalized Number Concentration
1.2
0.8
0.4
0
94%
6%
97%
3%
Collison
BLAM
0.5
1.5
2.5
3.5
Aerodynamic Particle size (µm)

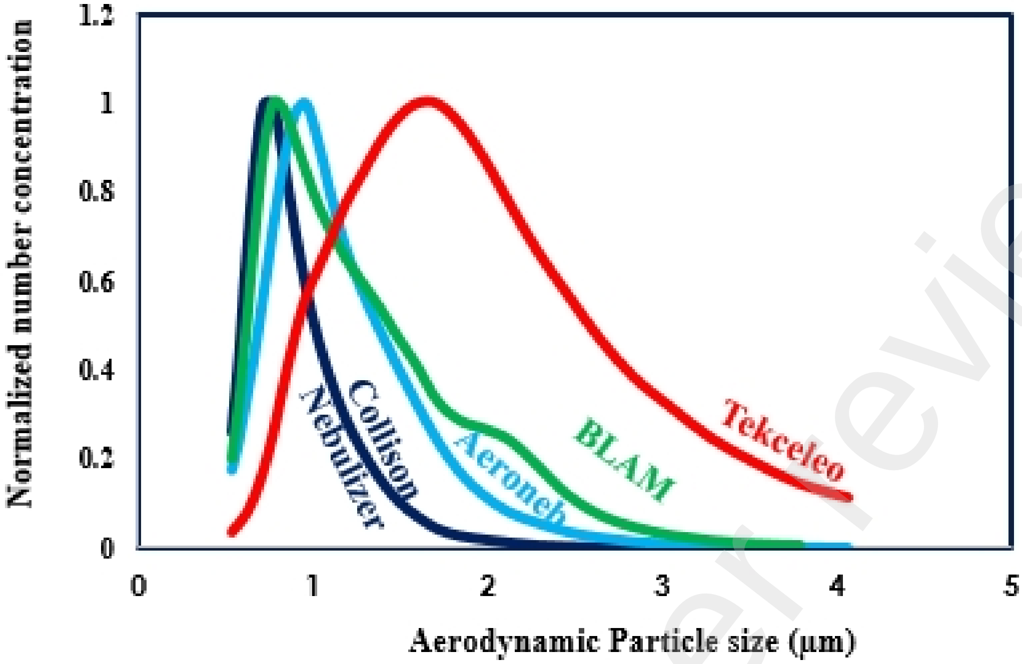

Mass Concentration
0.5% NaCl
Normalized Mass Concentration
1.2
0.8
0.4
0
42%
58%
48%
52%
BLAM
Collison
0.5
1.5
2.5
3.5
Aerodynamic Particle size (µm)


P&S T45
5 µm Pore Size
0.05% NaCl
0.1% NaCl
2.5% NaCl
0.5% NaCl
Normalized Number Concentration
Aerodynamic Particle size (µm)
0
0.4
0.8
1.2
0.5
1.5
2.5
3.5
4.5
5.5


P&S T45 vs. Aeroneb
5 µm Pore Size
0.5% NaCl
P&S T45
Aeroneb
Normalized Number Concentration
Aerodynamic Particle size (µm)
0
0.4
0.8
1.2
0.5
1.5
2.5
3.5


Total Concentration by Number #/Cm³
3000
2000
1000
0
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Duty Cycle
0.05% NaCl
0.1% NaCl
0.5% NaCl
2.5% NaCl
2.5% NaCl
0.5% NaCl
0.1% NaCl
0.05% NaCl


1.2
0.8
0.4
0
0
1
2
3
4
5
Normalized Concentration by Number
Aerodynamic Particle size (μm)
0.1% Glycerol
0.1% NaCl
1.2
0.8
0.4
0
0
1
2
3
4
5
Normalized Concentration by Number
Aerodynamic Particle size (μm)
0.1% Glycerol
0.5% Glycerol


1.2
1
0.8
0.6
0.4
0.2
0
Normalized number concentration
0
1
2
3
4
5
Aerodynamic Particle size (µm)
Collison Nebulizer
Aeroneb
BLAM
Tekceleo