A Comparative Study of ENDS Particle Size Analysis with Electrical and Gravimetric Measurements of Diluted and Un-Diluted Aerosols

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Introduction

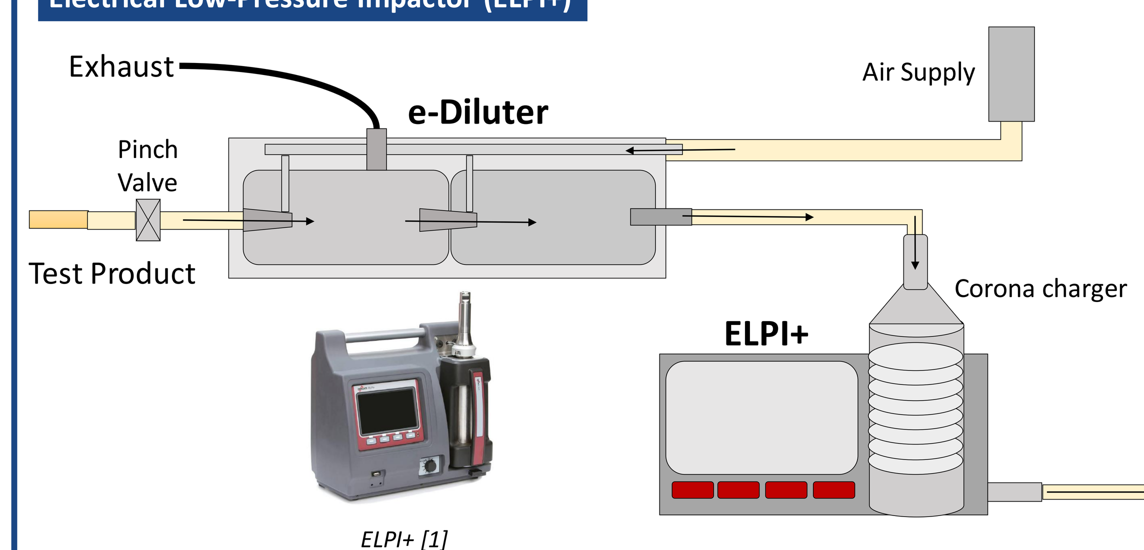
Particle size analysis of emissions has emerged as an important property for the health and safety evaluation of electronic nicotine delivery systems (ENDS). Particle size measurement has been conducted with gravimetric cascade impactor instruments, where particles are sorted by size using their aerodynamic properties, for decades. As an evolution of this principle, the more recently developed electrical low-pressure impactor (ELPI+) charges incoming aerosol particles to enable live electrical readouts of particle flux between filter stages, providing more sensitive and timely data collection. In fact, the high sensitivity of these modern measurement techniques requires volumetric dilution of ENDS aerosols for optimal performance. This contrasts with the capabilities of gravimetric cascade impactors which can capture and measure undiluted aerosols.

To investigate the equivalency of experimental aerosol properties between different puff generation and measurement techniques, a comparative study was conducted using electronic cigarettes (e-Cig) and heated tobacco product (HTP) types. Puff profiles were generated using either a programmable syringe pump engine or a 2-stage flow dilution apparatus ("e-Diluter") and analyzed by either a traditional gravimetric cascade impactor or ELPI+ instrument, respectively, with differing numbers of impactor stages and stage cut sizes.

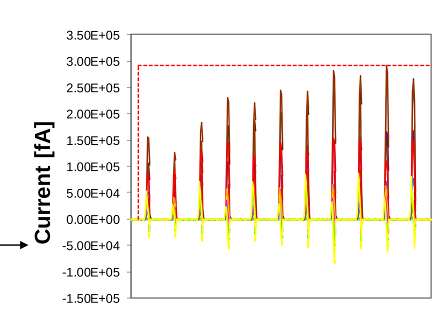
Electronic cigarette (e-Cig)	Heated Tobacco Product (HTP)
Product A	Product B
▪ 55 mL puff volume ▪ 3 second puff duration ▪ 30 second puff period ▪ Square puff shape ▪ Horizontal position ▪ ELPI+ = 50 puffs, MOUDI = 5 puffs	▪ 55 mL puff volume ▪ 2 second puff duration ▪ 30 second puff period ▪ Bell puff shape ▪ Horizontal position ▪ ELPI+ = 12 puffs, MOUDI = 5 puffs

Instrumental Techniques

Electrical Low-Pressure Impactor (ELPI+)

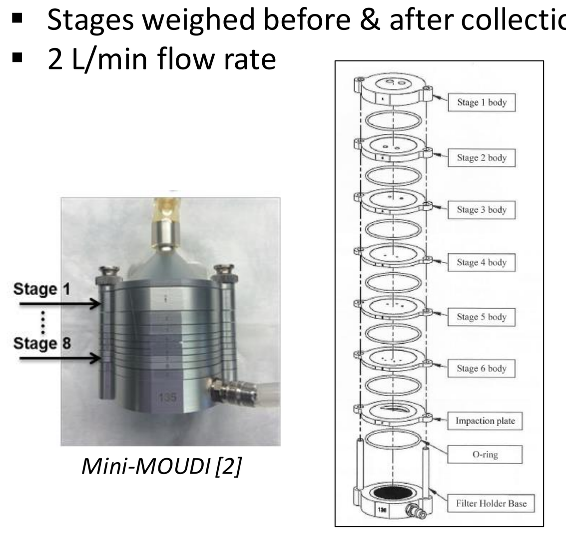


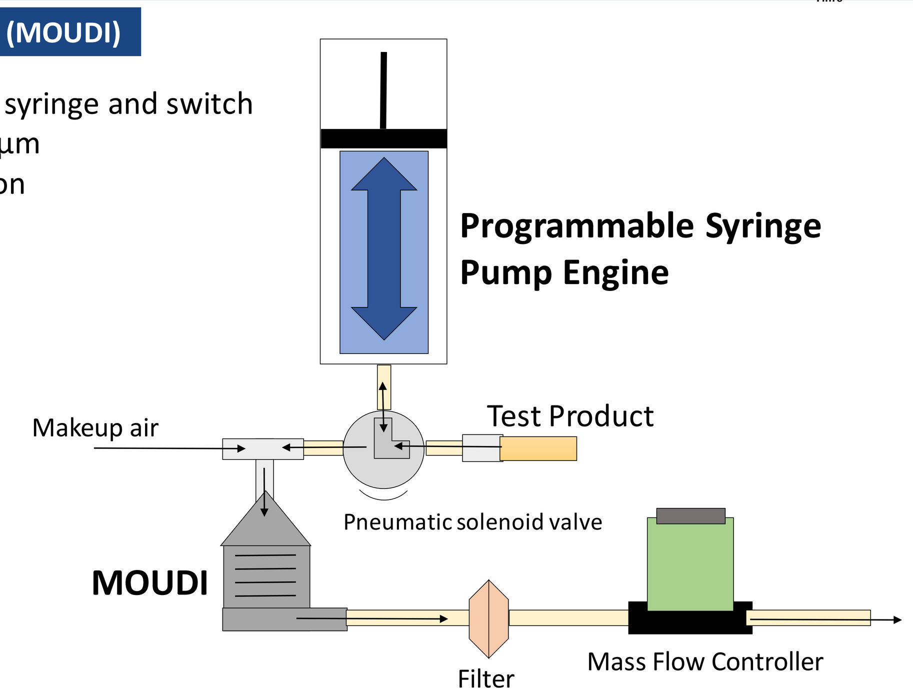
- Emissions are diluted
- Incoming particles charged
- Measures electrical currents
- 14 collection stages spanning 0.016 – 10 µm
- 10 L/min flow rate



Multi-Orifice Uniform Deposition Impactor (MOUDI)

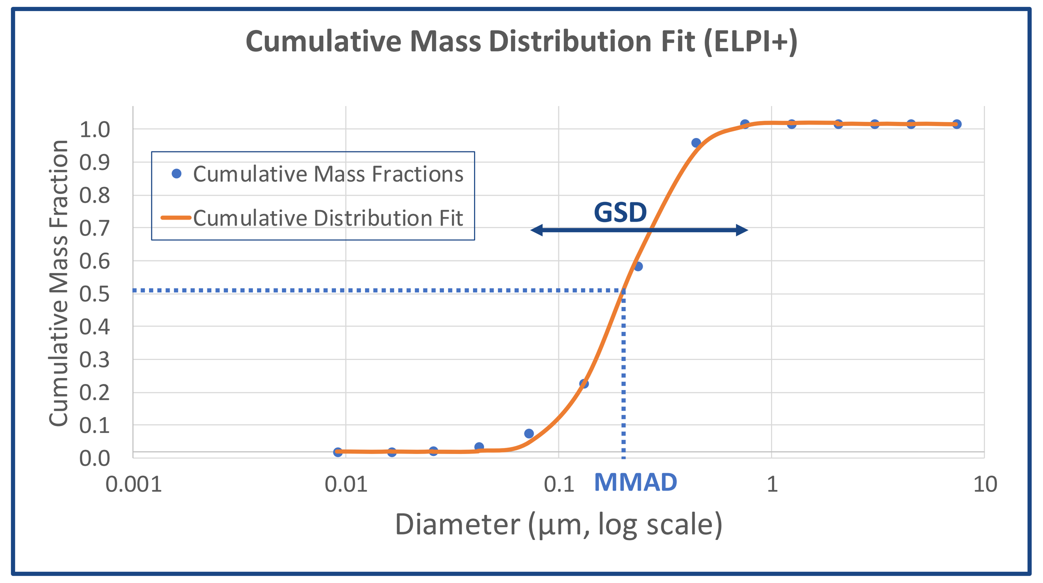
- Emissions are pulled / pushed through syringe and switch
- 8 collection stages spanning 0.18 – 10 µm
- Stages weighed before & after collection
- 2 L/min flow rate





Results and Discussion

Particle size distributions (PSDs) were modeled following the standard assumption of a lognormal distribution pattern. Results were compared based on mass median aerodynamic diameter (MMAD) and geometric standard deviation (GSD), found by fitting the cumulative mass fractions from each collection stage to a cumulative distribution curve using a least-squares regression algorithm [3]. For ELPI+ data, the measured electrical currents are mathematically transformed into particle counts as well as accumulated particle mass on each collection stage. With particle count data, it was also possible to calculate CMAD and an alternative value for MMAD [4]. Together, these count-derived statistics were used to generate an alternative GSD value. Thus, in addition to ELPI+ vs. MOUDI and e-Cig vs. HTP, curve-fitting parameter results are compared with count-derived values in the plots below.



$$Fit = \frac{1}{2}\left[1 + erf\left(\frac{(\ln(x) - \mu)}{\sigma\sqrt{2}}\right)\right]$$

MMAD = e^{μ}
GSD = e^{σ}

- An alternative approach to calculating MMAD is possible for ELPI+ data utilizing particle counts (n) and their corresponding diameters (d)

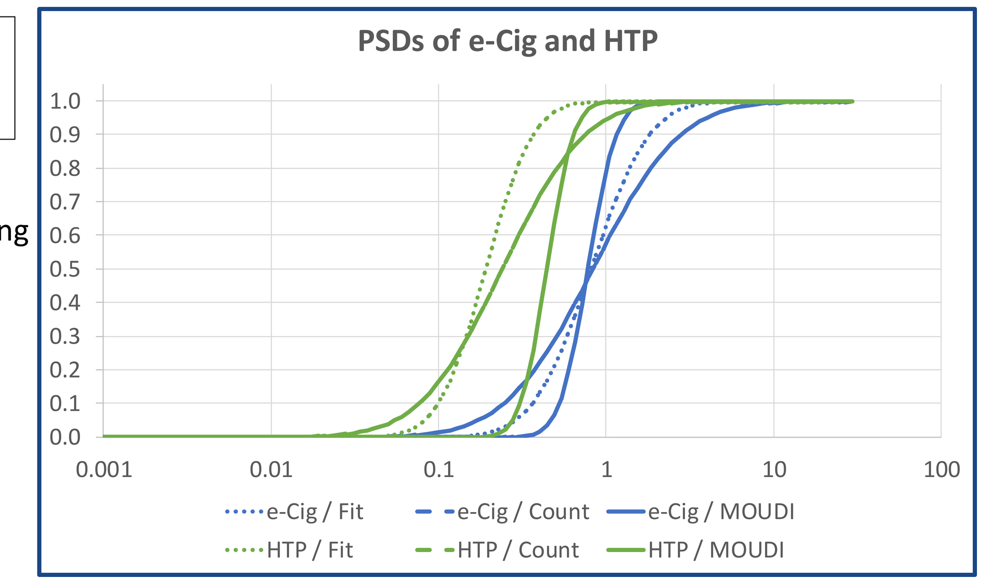
$$MMAD = e^{\left[\frac{\sum nd^3 \ln d}{\sum nd^3}\right]}$$

- CMAD can also be calculated directly from particle counts

$$CMAD = e^{\left[\frac{\sum nd \ln d}{\sum nd}\right]}$$

- The Hatch-Choate equation relates MMAD, CMAD and GSD

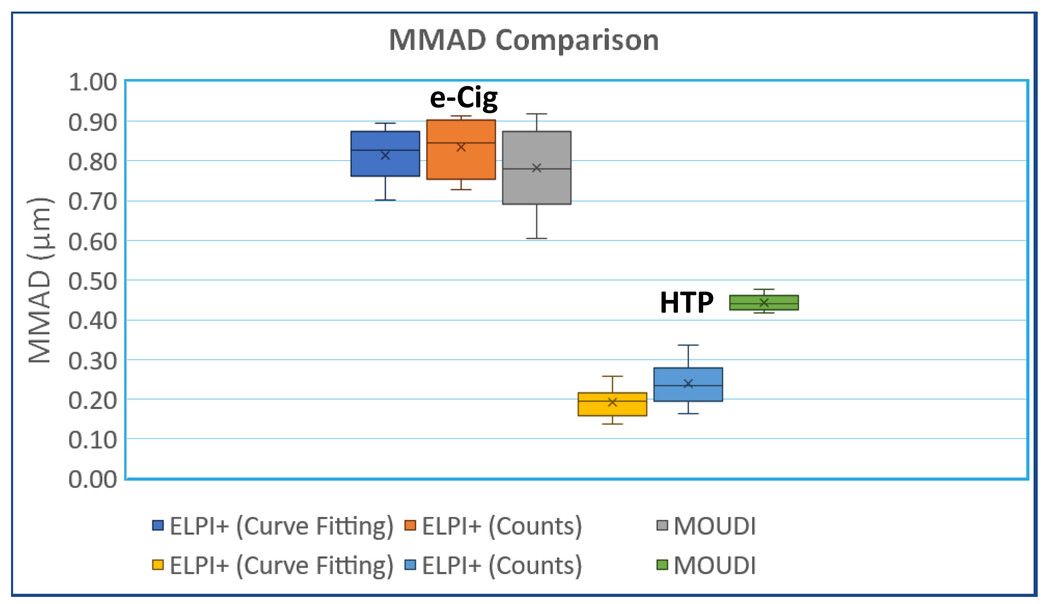
$$\frac{MMAD}{CMAD} = e^{(3\ln^2(GSD))}$$

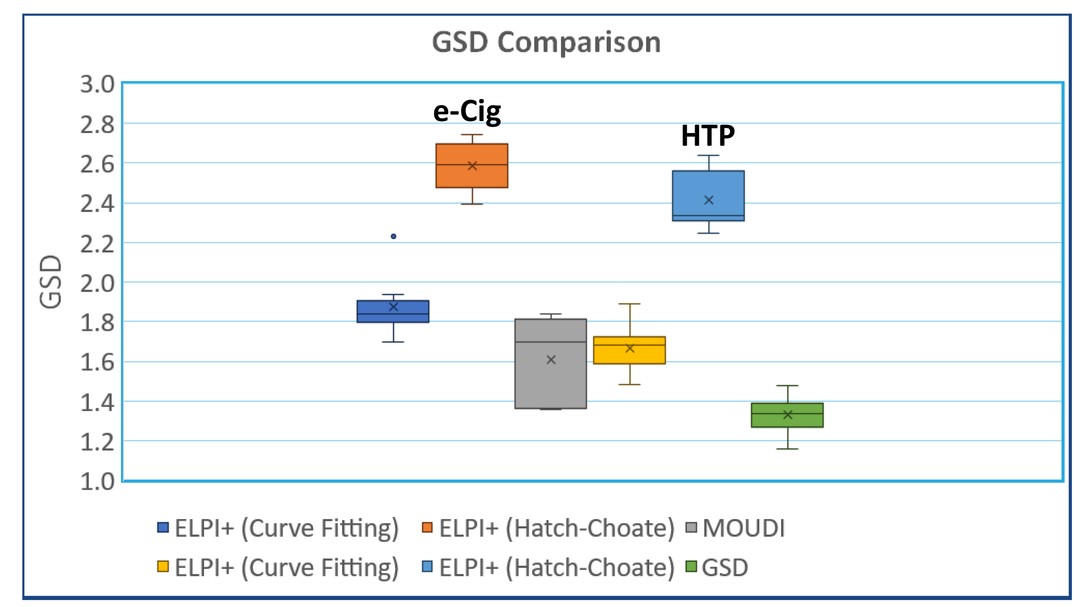


E-Cig PM2.5 Dependence on Method

Method	PM2.5
Curve fitting	96%
Count-derived	88%
MOUDI	99%

Proportion of Particle Mass under 2.5 µm (PM2.5) found by evaluating cumulative mass distribution at x = 2.5

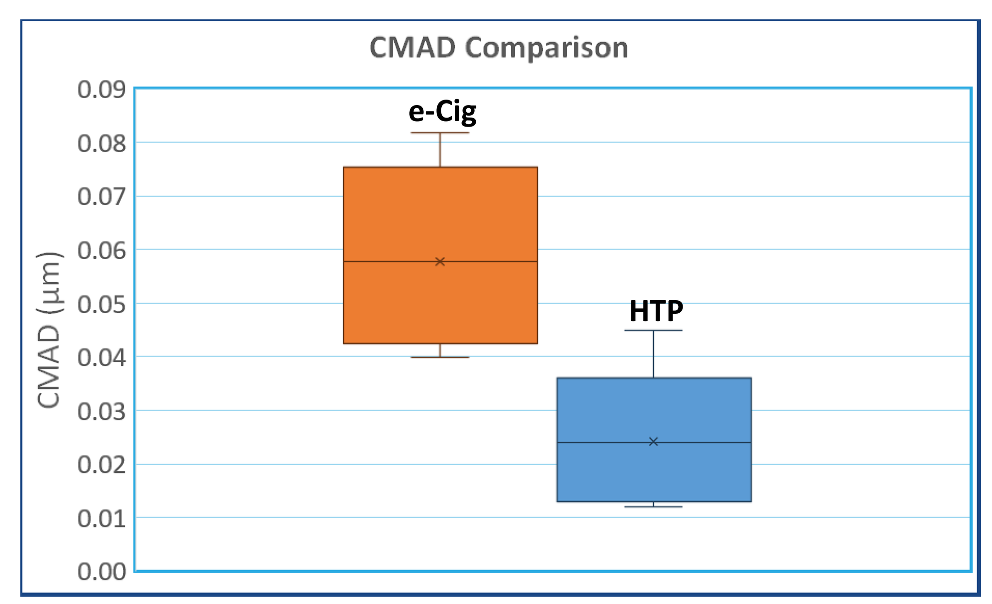




- ➢ e-Cig shows no significant difference between ELPI+ and MOUDI
- ➢ HTP shows significantly greater MMAD for MOUDI measurements, but overall lower MMAD than e-Cig
- ➢ Suggests physical characteristics of product emissions as cause of ELPI+ vs. MOUDI difference, traceable to mechanism of emission generation and/or composition of source material
- ➢ Count-derived MMADs are generally higher by a minor factor

- ➢ Count-derived GSDs are substantially higher than fit-derived values, a result of real data sets deviating from an ideal lognormal distribution
- ➢ MOUDI results indicate lower GSDs overall, potentially an artifact of fewer collection stages vs. ELPI+

- ➢ CMAD follows similar trends to MMAD
- ➢ For HTP, the CMAD approaches the minimum ELPI+ resolution and may lose accuracy in this range



Conclusions and Future Work

It has been shown that the mechanisms of transmission and measurement can have a significant impact on the observed particle size distribution properties of ENDS emissions, most notably for MMAD values of HTPs. Responsible experimentation and reporting requires well-defined parameters and well-controlled conditions. The choice of calculation method is also shown to have a substantial impact on results, such as when determining GSD values.

Future experiments to decouple the influences of aerosol generation/manipulation and the mechanism of measurement would add a valuable piece to this picture. To this end, integration of the MOUDI with the e-Diluter system is planned. Although the ELPI+ system is not capable of measuring undiluted emissions from e-cigs and HTPs, experiments varying the dilution factor within tolerable values are also planned.

Finally, measurement of PSDs of traditional combustible cigarettes should offer even greater insight into the differing behaviours of product emissions.

References

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3. Solver Add-in, Excel
4. Hinds, William C., Yifang Zhu. Aerosol Technology, 3rd Edition. Wiley-Blackwell, 20220420. VitalBook file.
5. Jiang, H.; Gao, X.; Gao, Y.; Liu, Y. Current Knowledge and Challenges of Particle Size Measurements of Mainstream E-Cigarette Aerosols and Their Implication on Respiratory Dosimetry. J. Respir. 2023, 3, 7-28. https://doi.org/10.3390/jor3010003