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REPORT

Characterization of Aerosol Emissions from Electronic Nicotine Delivery Systems (ENDS)

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1.0 Introduction

Chemical Insights Research Institute (CIRI) has been collaborating with the Georgia State University (GSU) School of Public Health on a research initiative characterizing aerosols released from electronic nicotine delivery systems (ENDS). The study is motivated by the increased usage of ENDS over the last decade, especially among adolescents and young adults, which raises a public health concern. An ENDS device typically contains a mouthpiece, a fluid reservoir, an atomizer, and an energy source, which delivers nicotine by heating and vaporizing an e-liquid that usually contains propylene glycol (PG), vegetable glycerin (VG), nicotine, and flavoring ingredients. As various ENDS devices have gained popularity in the market, aerosol emissions from ENDS have not been well characterized, nor the exposure health impacts. Although ENDS have been claimed as less hazardous than traditional tobacco cigarettes, they are found to generate high levels of particulate matter (PM) and volatile organic compounds. Particularly, exposure to airborne PM is associated with respiratory and cardiovascular diseases.

In this study, we utilized different chamber setups and a custom-made automated device to characterize aerosols emitted from using ENDS devices. The studied devices included three types that are commonly found in the local market, in addition to different e-liquid flavorings and atomizer setups. This report presents CIRI's findings on characterization of aerosol concentrations and size distributions from various vaping conditions.

2.0 Methods and Materials

2.1 CHAMBER SETUPS AND ENDS AEROSOL GENERATION SYSTEM

Three types of chamber setups were used in this study. Initial characterizations were conducted using a specialized glass chamber (**Figure 1**, left) with an air supply at 9 air exchanges per hour (ACH), see Report 280 for details. The air supplied into the chamber was treated to obtain minimal particle and chemical background concentrations and maintained at 23°C and relative humidity of 40-50%. In order to simulate a person using an ENDS device and repeatedly generate aerosols, an automated ENDS aerosol generation system (EAGS) was designed, built, and validated.[1] EAGS is compatible with various ENDS device types and capable of adjusting atomizer settings. To optimize aerosol concentration measurements, an exposure chamber was used for additional dilution. The exposure chamber was a 6 m^3 stainless steel chamber designed and validated according to ASTM D6670-13.[2] The exposure chamber was run with two setups to simulate different environmental conditions. One was an environment without ventilation, i.e., static chamber setup. The outstream from EAGS was delivered into the exposure chamber that ran with the supply air only compensating for the instruments operation; a fan was used to ensure mixing inside the chamber. The other setup was a ventilated environment, i.e., dynamic chamber setup, with 3 ACH. Under this condition, puff numbers could reach above 100 in a short period of time without saturating the measurement instruments. In addition, the EAGS outstream was split for two purposes; 1) toxicity analysis that was connected with condensation lines[3] and 2) aerosol characterization of the air in the exposure chamber. Detailed settings of the exposure chamber, EAGS and sampling can be found in Report 280, Zhang et al.[1] and Jeon et al.[3] See **Figure 1** right for EAGS inside the 6 m^3 exposure chamber.

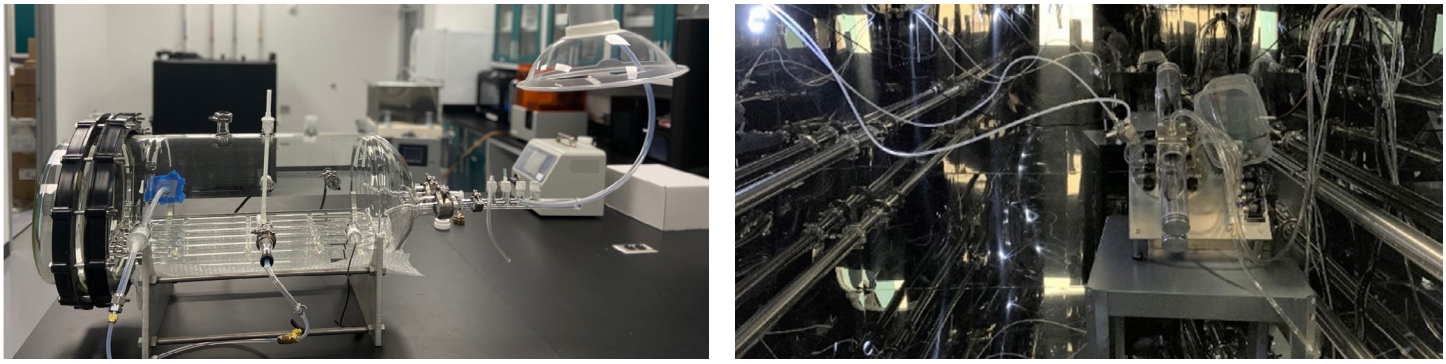


Figure 1: Glass chamber set up (left) and EAGS inside the exposure chamber (right).

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2.2 STUDIED ENDS DEVICES AND PUFFING CONDITIONS

Three types of ENDS devices were studied including vape pen, pod-type, and mod-type devices. The pod-type device came with a plastic container pre-loaded with an e-liquid, while the vape pen and mod-type, also called tank, device came with a plastic or glass tank that can be re-filled with e-liquids. In addition, the atomizer of the mod-type device can also be replaced. Different atomizers can have different coil resistances and run with different voltages, which determine the power of atomizers. In this study, we examined various ENDS devices using different e-liquid flavorings and atomizer setups (see **Table 1** for details). The vape pen was studied in the glass chamber; the pod- and mod-type devices were studied with EAGS and the exposure chamber. The puff topography applied to EAGS was based on average adult cigarette smokers as described by Cooperation Center for Scientific Research Relative to Tobacco (CORESTA).[4] The flow rate during the puffing was 1.1 L/min and the puff duration was 3 seconds.

Table 1: Experimental parameters for ENDS aerosol characterizations.

Chamber setup	ENDS device	E-liquid flavor (nicotine strength)	Coil resistance and power	Puff rate
Glass	Vape pen	Clove	Unknown	1/5 min
Static	Pod	Tobacco 1 (5%)	2 Ω, 7 W	20/4 hours
	Mod	Tobacco 3 (0.3%)	0.2 Ω, 45 W	1/hour
Dynamic	Pod	Tobacco 1 (5%) Tobacco 1 (3%) Tobacco 2 (5%)	2 Ω, 7 W 2 Ω, 7 W 2 Ω, 7 W	0.5-4/min 2/min 2/min
	Mod	Tobacco 3 (0.3%) Tobacco 3 (0.3%) Tobacco 3 (0.3%) Tobacco 4 (0.3%)	0.15 Ω, 51 W 0.2 Ω, 45-63 W 0.6 Ω, 22-29 W 0.15 Ω, 51 W	2/min 0.3/min 0.3-2/min 2/min

Note: Tobacco 1 and 2 had 70VG/30PG and Tobacco 3 had 65VG/35PG, ingredients for Clove and Tobacco 4 were unknown.

2.3 AEROSOL CHARACTERIZATION AND DATA ANALYSIS

Aerosol concentrations and size distributions were monitored online using a scanning mobility particle sizer (SMPS) and an optical particle sizer (OPS). The instruments covered a wide range of particle sizes from 8 nm to 10 µm. Total emitted particles were calculated using particle concentration of all sizes as a function of time, based on the method in ANSI/CAN/UL 2904.[5] Emission factor was defined as the total particles emitted from vaping divided by the number of puffs (in unit of #/puff). Particle mass concentrations were estimated from number concentrations assuming spherical particles and mass emission factors were calculated accordingly in unit of µg/puff.

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3. Results

3.1 GLASS CHAMBER RESULTS

In the glass chamber, spikes of particle concentrations were observed when puffs were generated. From particle number distribution (**Figure 2** top), emitted particles were in small sizes (~ 10 nm) in the beginning of puffing; and as the vape dispersed, particles rapidly grew into larger sizes (mode ~ 120 nm). Interestingly, a separate mode at size range of 300-500 nm was observed by OPS, thus for particle mass distribution, the particles contributed to the total mass were mainly larger than 300 nm (**Figure 2** bottom).

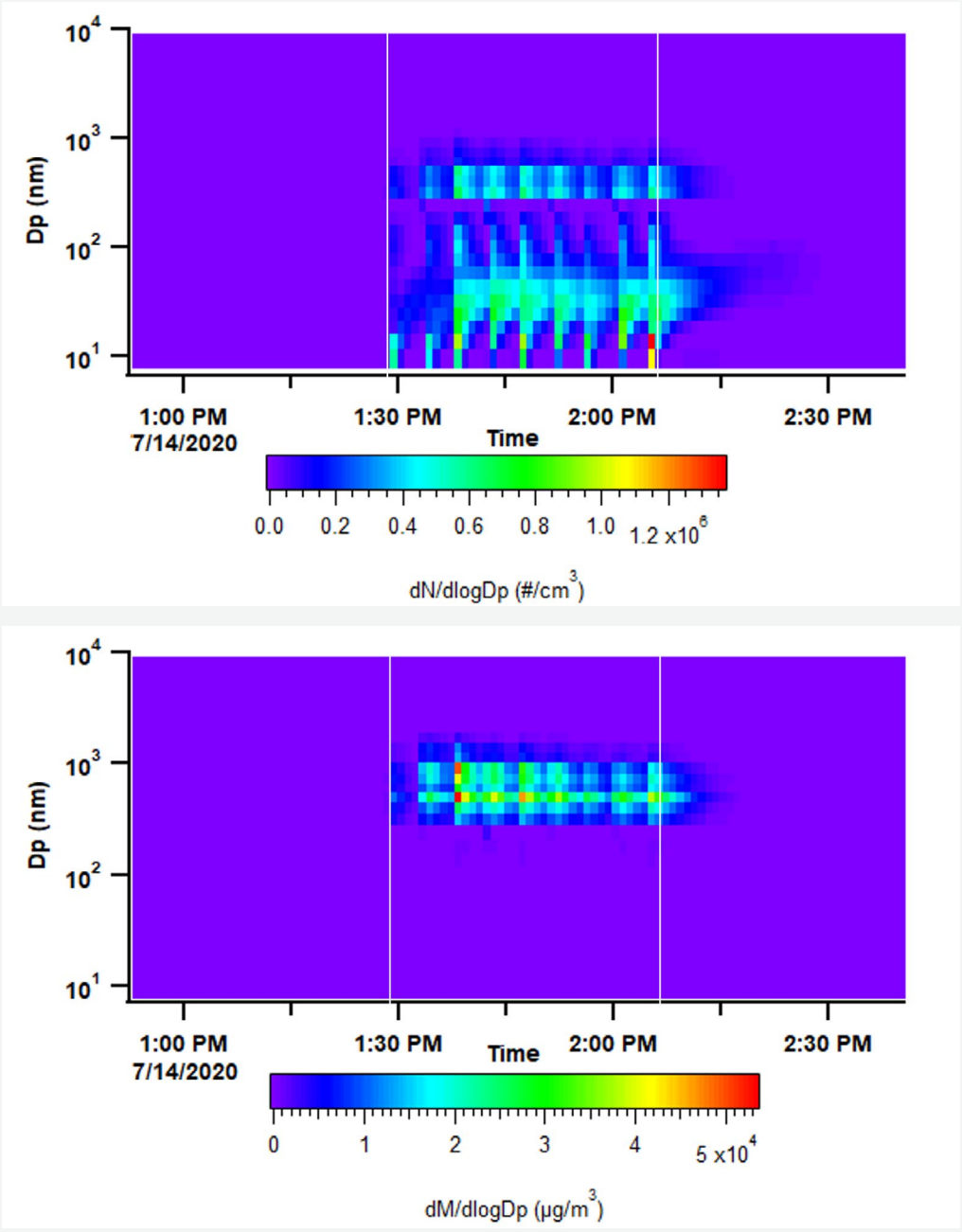


Figure 2: Particle size distributions (top=number, bottom=mass) for glass chamber experiment with vape pen and Clove flavor e-liquid. Vertical lines indicate puffing period.

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3.2 STATIC CHAMBER RESULTS

The static chamber setup simulated a person vaping in an unventilated room. The pod-type device was run for up to 20 puffs and the mod-type device for 4 puffs due to the instrument limitation. **Figure 3** shows particles emitted from vaping accumulated with the increase of puff numbers when minimal ventilation was applied. In this setup, the pod-type device emitted mostly particles smaller than 300 nm with the mode diameter of ~ 100 nm (**Figure 3** top), while the pod-type device emitted bi-modal distributed particles with mode diameters of ~ 60 and 800 nm (**Figure 3** bottom). Therefore, the mod-type device tended to emit higher particle mass.

The differences of the particle characterizations could be a result of the different device type, e-liquid ingredients and atomizer parameters. Specifically, the e-liquid used in the pod-type device contained protonated nicotine, which more readily evaporates and forms secondary aerosols. This could result in the observed higher concentrations of small particles from the pod-type device.

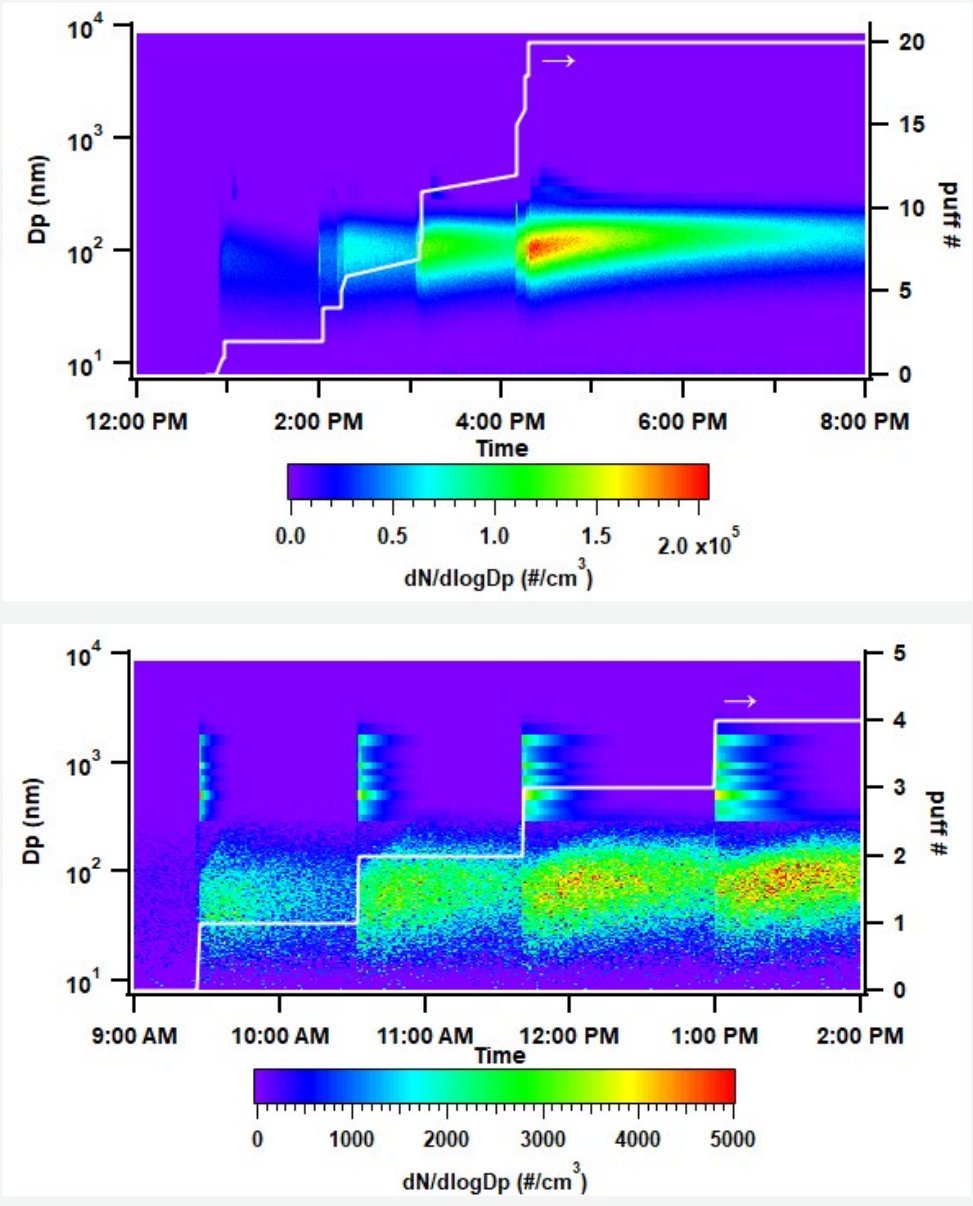


Figure 3: Particle number size distributions corresponding with puff numbers for static chamber experiments with pod-type device (top) and mod-type device (bottom).

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3.3 DYNAMIC CHAMBER RESULTS

The dynamic chamber setup simulated a person vaping in a moderately ventilated room. **Figure 4** shows the particle concentrations inside the exposure chamber reaching a relatively steady state during an extended period of constant puffing (up to 200 puffs). Interestingly, under the ventilated condition, both the pod- and mod-type devices showed high concentrations of larger particles (> 300 nm), with the mod-type device having an average geometric mean diameter (GMD) of ~ 600 nm and the pod-type device of ~ 300 nm (**Figure 4**). The decrease in small particle emissions could be ascribed to the less preferred process of secondary aerosol formation when the precursor vapors were not sufficiently condensed due to ventilation. On the other hand, the increase in large particle emissions could be ascribed to aerosol growth with water vapor, given the main ingredients in e-liquids (PG and VG) are hygroscopic.

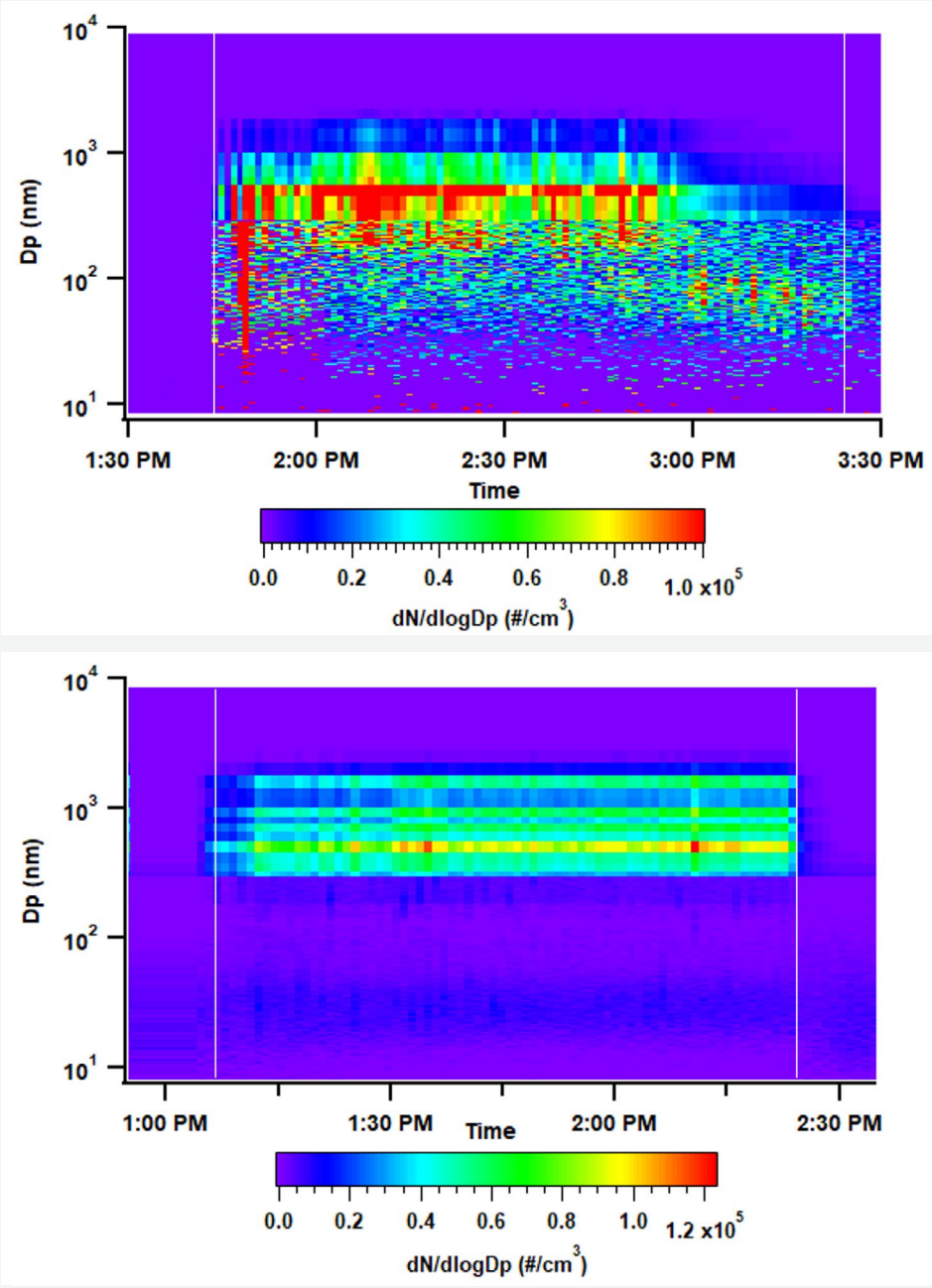


Figure 4: Particle number size distributions for dynamic chamber experiments with pod-type device and Tobacco 1 (3% nicotine) (top) and mod-type device with Tobacco 3 and 0.6 Ω, 22 W atomizer (bottom). Vertical lines indicate puffing period.

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Due to the differences in chamber size and air change condition, total particle emission factors were compared for emission levels associated with different vaping conditions, see **Table 2**. According to our static chamber results, the pod-type device tended to have higher particle number emission factors than the mod-type device, which was also observed in dynamic chamber experiments. However, pod-type devices also had higher mass emission factors than mod-type devices in the dynamic chamber setup, which was not consistent with the finding from the static chamber setup. This indicated that ventilation conditions could have an impact on particle emission factors, in addition to the aerosol sizes as discussed previously. In general, emission factors obtained from the dynamic chamber setup were lower than those from the static chamber setup, which indicated that ventilation can be used to reduce exposure.

Table 2: Particle emission factors from various vaping and sampling conditions. Average ± standard error is shown for replicate experiments.

ENDS device (e-liquid)	Atomizer setup	Sample #	Number emission factor (#/puff)	Mass emission factor (µg/puff)
Pod (Tobacco 1, 5%)	2 Ω, 7 W	4	(4.92±0.70) × 1010	(2.58±0.60) ×102
Mod (Tobacco 3)	0.2 Ω, 45 W	4	(1.72±0.08) ×1010	(1.50±0.06) ×104
Pod (Tobacco 1, 5%)	2 Ω, 7 W	3	(5.54±2.11) ×109	(1.71±1.00) ×103
Pod (Tobacco 1, 3%)	2 Ω, 7 W	8	(2.92±0.54) ×1010	(5.38±1.47) ×103
Pod (Tobacco 2)	2 Ω, 7 W	4	(7.95±4.93) ×1012	(8.65±4.61) ×103
Mod (Tobacco 3)	0.15 Ω, 51 W	1	5.71×109	2.37×102
Mod (Tobacco 3)	0.2 Ω, 45 W	3	(5.00±1.91) ×109	(1.09±0.64) ×103
Mod (Tobacco 3)	0.2 Ω, 63 W	3	(8.75 ±2.68) ×108	(7.29±2.30) ×102
Mod (Tobacco 3)	0.6 Ω, 22 W	3	(2.97±1.27) ×108	(4.76±3.71) ×101
Mod (Tobacco 3)	0.6 Ω, 29 W	3	(3.05±2.14) ×108	(4.06±3.19) ×101
Mod (Tobacco 4)	0.15 Ω, 51 W	4	(3.13±2.11) ×109	(3.80±2.11) ×103

Note: The first two rows are results of the static chamber experiments and the rest are results of dynamic chamber experiments.

Vaping conditions could also affect particle emission characteristics. Pod-type devices that came with specific e-liquids normally had a higher particle number and mass emission factors than mod-type devices in the dynamic chamber. This could be associated with their e-liquid formula having nicotine in a protonated form. However, the effect of e-liquid flavoring only was not conclusive. For atomizer setups on mod-type devices, atomizers with lower resistance and higher power tended to have elevated particle number and mass emission factors than atomizers with higher resistance and lower power (**Table 2**).

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4.0 Conclusions

Our chamber studies established a methodology on characterizing aerosol emissions from vaping with various ENDS devices. All three chamber setups showed high levels of aerosols emitted during vaping. The mean sizes of the dominant particles emitted can range from ultrafine (below 100 nm) up to 800 nm, which are a major concern regarding exposure health impacts. The aerosol emission characterization was likely determined by ENDS device type, e-liquid ingredients and flavoring, atomizer coil resistance and power, and were also influenced by chamber conditions such as ventilation. In general, the studied pod-type devices had higher particle emission factors than the mod-type devices. For the same mod-type device, atomizers with a smaller resistance had higher emission factors. In addition, secondhand streams could present a risk to children and those susceptible to the adverse health effects when exposed. Our future research will focus on characterizing the emissions from secondhand streams exhaled by ENDS users and assessing the potential health impacts induced by vaping.

5.0 REFERENCES

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