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Publication Date

2016-06-01

DOI
10.1016/j.atmosenv.2016.03.027

Atmospheric Environment 134 (2016) 61–69

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Effects of design parameters and puff topography on heating coil temperature and mainstream aerosols in electronic cigarettes

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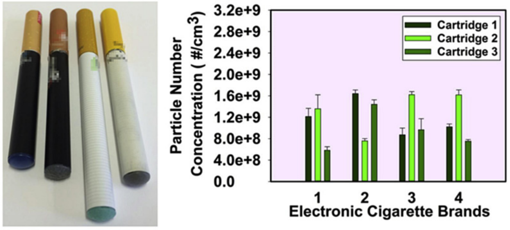
HIGHLIGHTS

- A wide range of heating coil temperature and aerosol concentration is observed.
- Heating coil temperature increases with longer puff and lower puff flow rate.
- Particle number concentration increases with longer puff and higher flow rate.
- Mainstream aerosol CMD increases with longer puff and lower puff flow rate.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 5 November 2015
Received in revised form
8 March 2016
Accepted 10 March 2016
Available online 16 March 2016

Keywords:
Electronic cigarette
Ultrafine particles
Heating coil temperature
Particle number concentration
Particle size

ABSTRACT

Emissions from electronic cigarettes (ECs) may contribute to both indoor and outdoor air pollution and the number of users is increasing rapidly. ECs operate based on the evaporation of e-liquid by a high-temperature heating coil. Both puff topography and design parameters can affect this evaporation process. In this study, both mainstream aerosols and heating coil temperature were measured concurrently to study the effects of design parameters and puff topography. The heating coil temperatures and mainstream aerosols varied over a wide range across different brands and within same brand. The peak heating coil temperature and the count median diameter (CMD) of EC aerosols increased with a longer puff duration and a lower puff flow rate. The particle number concentration was positively associated with the puff duration and puff flow rate. These results provide a better understanding of how EC emissions are affected by design parameters and puff topography and emphasize the urgent need to better regulate EC products.

1. Introduction

Exposure to airborne particles have been linked to cardiovascular and pulmonary diseases in human beings (Brook et al., 2010; Ghio et al., 2000; Pope III and Dockery, 2006; Wallace, 1996; Wichmann and Peters, 2000). Considering that people spend more than 80% of time indoors, it is important to assess the indoor particle exposures (Klepeis et al., 2001; Morawska et al., 2013; Wallace, 1996). Tobacco smoke has been the main source of indoor particles (Miller and Nazaroff, 2001; Weschler, 2009) that can increase the indoor $PM_{2.5}$ (particulate matter with aerodynamic diameter equal to or less than 2.5 μm) level by 12–46 μg/m^3 when compared with non-smoke indoor environments (Wallace, 1996). Recently, electronic cigarette (EC), as the alternative of tobacco cigarette, is increasingly popular all over the world (Ayers et al.,

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http://dx.doi.org/10.1016/j.atmosenv.2016.03.027
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2011; Dawkins et al., 2013). ECs are advertised as ‘healthy replacements’ to tobacco cigarettes which attracts a large population of tobacco cigarette users to switch to ECs. In addition, the wide variety of appealing flavor choices (Farsalinos et al., 2013a) and big advertising investment (Richardson et al., 2014) also attract a large number of consumers including adolescents (Control and Prevention, 2013). In United States, the EC adolescent users from high school tripled from 4.5% in 2013 to 13.4% in 2014, approximately from 660,000 to 2 million students; while the middle school users rose from 1.1% (120,000 students) in 2013 to 3.9% (450,000 students) in 2014 (CDC, 2015).

Emissions from this increasing EC usage are likely contributing to both indoor and outdoor air pollution since toxic and carcinogenic compounds have been found in mainstream EC aerosols (Fromme and Schober, 2015; Kosmider et al., 2014; McAuley et al., 2012; Trtchounian et al., 2010). For example, Aldehydes, which could be a product of the thermal dehydration of glycerin or glycols, have been detected in EC mainstream (Goniewicz et al., 2014; McAuley et al., 2012; Uchiyama et al., 2013). Heavy metals, presumably produced by the oxidation of the heating coil, have also been found in EC emissions (Lerner et al., 2015; Pellegrino et al., 2012; Williams et al., 2013).

A few studies have been conducted on the physical characteristics (i.e., particle number concentration and size distribution) of EC mainstream aerosols (Fuoco et al., 2014; Ingebrethsen et al., 2012; Laugesen, 2009; Schripp et al., 2013). These studies observed particle number concentrations ranging from 1.8×10^9 cm^{-3} to 8.38×10^9 cm^{-3} and count median diameters (CMDs) from 14 nm to 458 nm (see Supplemental Information Table S1). However, it is still largely unknown how the particle number concentration and CMD are affected by EC design parameters and puff topography.

Unlike other nicotine addiction cessation devices (i.e., patches and gums), there are no FDA standards for EC products to unify the requirements on the product design, e-liquid, nicotine content, and manufacturing quality control (Williams and Talbot, 2011). Trehy et al. (2011) and Goniewicz et al. (2012) both noted that the performance of nicotine delivery efficiency is not consistent between ECs of different brands due to the lack of manufacturing standards. The concentration of mainstream aerosols was different across various brands and within same brand (Williams and Talbot, 2011). Given these circumstances, it is of great importance to explore the relationships between the design parameters and the resulting mainstream aerosol characteristics. A better understanding of these relationships can provide a foundation for future EC regulations.

Puff topography is also considered as an influential factor on the mainstream particles. Behar et al. (2015) found that the average puff duration for experienced smokers is 2.65 ± 0.98 s, with an average flow rate of 1.2 ± 0.36 L/min (peak flow of 1.62 L/min). Farsalinos et al. (2013b) also studied the puff protocol by dividing participants into two groups: experienced EC smokers and tobacco smokers who switched to using ECs. For EC users, their average puff duration was 4.2 ± 0.7 s. While for tobacco smokers who switched to ECs, it was 2.4 ± 0.5 s. Regarding the puff flow rate, one study indicated that 0.42 L/min is the minimum puff flow rate of most tested brands (Williams et al., 2013). Fuoco et al. (2014) reported that longer puff duration led to higher particle number concentration. However, the effects of puff duration and puff flow rate on the size distribution of EC mainstream particles, which is a crucial parameter in determining the particle deposition in various parts of the human respiratory system, have not been evaluated.

The heating coil is a critical component that can reach high temperatures to vaporize the e-liquid, which subsequently condenses into particles. The schematic diagram and working theory of ECs is shown and explained in the Supplemental Information Fig. S1. The temperature of the heating coil is not only related to particle generation and nicotine delivery but also to the formation of toxic compounds. One study showed that a higher input voltage, which means more output power to the heating coil, resulted in higher carbonyl yields (Ohta et al., 2011). Brown et al. (2011) also noted that the coil temperature needs to be studied because it may alter the aerosol size distribution. However, the heating coil temperature and its variability are largely unknown. Recently, Talih et al. (2015) developed a mathematical model to predict the heating coil temperature and investigate its effects on nicotine delivery efficiency, but no temperature measurements were conducted.

To fill these knowledge gaps, we first compared the heating coil temperatures and mainstream particle characteristics from randomly selected cartridges within the same and across different EC brands. We then studied the effects of puff topography (i.e., puff duration and puff flow rate) on the heating coil temperature and mainstream particle characteristics. To the authors' best knowledge, this is the first elucidation of the effects of EC heating coil temperature on the characteristics of mainstream particles. Results from this study may be used in studying the pyrolysis and oxidation of compounds in the e-liquid (Farsalinos et al., 2013a, 2013b; Trtchounian et al., 2010). In addition, it is the first study focusing on the effects of variable puff topography on the physical characteristics of EC particles, which can provide insights for EC exposure assessment (Lerner et al., 2015; Manigrasso et al., 2015a, 2015b).

2. Methods and materials

2.1. Experimental design

Rechargeable ECs with a tobacco flavor and zero nicotine level from four manufacturers, labeled as EC1, EC2, EC3, and EC4, were used in this study. To test the variability within the same brand, three cartridges were randomly selected from each package for all four brands. Before each experiment, the battery was fully charged to ensure that the battery voltage remained constant. Each cartridge was puffed less than 100 times to ensure there was sufficient e-liquid inside.

The study has two aims: (I) test the variability of the heating coil temperature and mainstream particle characteristics of the cartridges within the same and across different EC brands and (II) study the effects of puff topography (i.e., puff duration and puff flow rate) on the heating coil temperature and mainstream particle characteristics. The ECs and puff topography used for the two aims are listed in the Supplemental Information Table S2.

For Aim I, a typical EC puff topography, namely 3-s puff duration and 1 L/min puff flow rate, was used to test three randomly selected cartridges from each brand. For Aim II, based on published puff topography data, we first fixed the puff flow rate at 1 L/min and studied puff duration at 2, 3, 4 and 5 s. We then fixed the puff duration at 3 s and changed the puff flow rate from 0.5, 1, 1.5–2 L/min. Aim II measurements were conducted on EC2. All measurements were conducted at a puff interval of 30 s to mimic real puffing habits (Behar et al., 2015).

2.2. Temperature measurement

The temperature of the heating coil was measured by a thermocouple thermometer (OM70, Omega Inc.) equipped with a fine thermocouple K-type probe. The measurement accuracy, measurement resolution, and measurement range of this combination of thermometer and thermocouple are ±0.5 °C, 0.1 °C and 250 °C–1300 °C, respectively. The measured temperature was recorded every second by a data logger.

The diameter of the thermocouple probe (0.5 mm) is less than one-third of the diameter of the end-holes and the fiberglass cylinder of all brands so that it can be inserted into the cartridge from the end-hole to touch the heating coil (and/or wick) (as shown and explained in the Supplement Information, Fig. S2). For each measurement, the probe was completely inserted 8 times to ensure that the final results reflected the average and representative temperature of the heating coil.

2.3. Mainstream particle measurement

A 320 L stainless-steel chamber (as shown in the Supplemental Information, Fig. S3) with a mixing fan inside was set up to dilute the mainstream EC aerosols. The chamber was tightly closed to avoid air exchange with ambient air. During the experimental period, the relative humidity and temperature inside the chamber were controlled at 30 ± 10% and 24 ± 1 °C, respectively.

A homemade puffing machine composed of a compressed air source, a solenoid valve, and a Raspberry Pi (Raspberry Pi Foundation, UK), which serves as a timer and solenoid valve controller, was used to puff the ECs by pushing clean air through the EC from the front air slits. A piece of Python code running on the Raspberry Pi, which can be adjusted by changing the code, accurately controlled the puff duration and puff interval. The flow rate of the inlet air was calibrated by a flow meter DC-Lite (Drycal, Bios Inc., US). For a given puff duration and puff flow rate, the corresponding dilution ratio was derived by dividing the chamber volume by the puff volume (i.e. puff duration × puff flow rate) and is listed in Table S3 of the Supplemental Information.

The particle number concentration and size distribution were measured by a Scanning Mobility Particle Sizer (SMPS 3080, TSI Inc., Shoreview, MN). The sampling flow rate of the SMPS is 0.6 L/min and the measurement range is 7–289 nm (100 s up scan, 20 s down scan). The SMPS starts to work right after each puff. All particle measurements were repeated five times for each puff protocol. After each measurement, the chamber was flushed by clean air until the total particle number concentration in the chamber was less than 1000 particles cm^{-3}.

3. Results and discussion

3.1. Effects of design parameters

3.1.1. Heating coil temperature difference

To study the heating coil temperature difference of the cartridges, the puff topography was fixed at 3-s puff duration, 30-s puff interval, and a puff flow rate of 1 L/min. The heating coil temperatures measured on three different cartridges of each EC brand are shown in Fig. 1. For each brand, the cartridges were labeled as Cartridge 1, Cartridge 2, and Cartridge 3, in the order of the peak heating coil temperature. As shown in Fig. 1, the heating coil temperature increased dramatically and peaked at the end of each puff; it then decreased gradually during the puff interval. Although this temperature trend is typical, the peak heating coil temperature varies for different EC products. The measured peak temperatures covered a wide range from 138.6 °C (EC4, Cartridge 3) to 231.0 °C (EC1, Cartridge 1 and EC3, Cartridge 1), which indicates that the heating process was not consistent from brand to brand. On average, EC3 had the highest peak temperature of 215.8 °C, while EC4 had the lowest peak temperature of 152.3 °C.

EC1, EC3, and EC4 showed considerable within brand discrepancies. For EC1, the peak temperatures were 231.0, 211.9, and 180.0 °C, while the temperatures of EC3 fluctuated from 195.7 to 231.0 °C. EC4 had lower temperature than others as a whole and also revealed a large variance in peak temperatures of 198.1, 161.7 and 138.6 °C. Only EC2 showed a relatively low variance in peak temperature when compared with the other brands. The average peak temperature of the three EC 2 cartridges was 182.2 ± 1.2 °C.

During the study, we observed that the 30-s puff interval was not long enough for the temperature of the heating coil to drop back to its initial temperature, making the starting temperature of the next puff 3–5 °C higher than the previous one. To investigate whether this small increase of starting temperature will lead to a higher peak temperature, experiments with three different puff intervals (i.e., 30, 20, and 10 s puff intervals) were conducted. The results, as shown in the Supplemental Information Fig. S4, demonstrate that, although the starting temperature increased gradually puff by puff, especially for the shorter puff interval, there was no significant increase in the peak temperature. The peak heating coil temperature is a characteristic of an EC for a given puff topography and has little to do with the starting temperature.

Currently, there are no specific requirements or well-accepted ranges for heating coil temperature. The working temperature of ECs under normal conditions has been described on an EC discussion forum as 60–70 °C (Terminology, 2013), which has been cited by researchers and in several online materials about ECs. There are no measurement descriptions or results on that popular EC forum to support this conclusion. These values are very different from our experiment results. In our experiments, when the thermocouple probe was accidentally placed 1 mm away from the heating coil, the measured temperature fell to 60–70 °C, which indicates a huge temperature gradient around the heating coil. This supports the idea that the e-liquid evaporates when in contact with the heating coil and then rapidly cools and quickly condenses into liquid particles around the heating coil. Schripp et al. (2013) reported a heating coil temperature of more than 350 °C without the e-liquid. Similar temperatures were also observed in this study when the e-liquid was almost exhausted. This high temperature measured without e-liquid has been cited as the heating coil temperature by some researchers (Kim and Shin, 2013; Kosmider et al., 2014), but our results show that normal working temperatures of EC heating coil are less than 250 °C. It is important to clearly define the working EC temperature to facilitate related research activities in the future.

3.1.2. EC mainstream aerosol difference

The mainstream aerosols from different cartridges within and across the four EC brands were also measured. The results of particle number concentration from all cartridges are shown in Fig. 2. All concentrations have been corrected by the dilution ratio. The particle number concentrations ranged from 0.58×10^9 cm^{-3} (EC1, Cartridge 3) to 1.64×10^9 cm^{-3} (EC2, Cartridge 1). For each brand, the particle number concentration varied greatly, especially for EC2, which had the largest variance among the cartridges from the same package. These measured particle concentrations are consistent with the range of ~$10^9/cm^3$ in the literature (Fuoco et al., 2014; Ingebrethsen et al., 2012; Laugesen, 2009; Schripp et al., 2013), but on the lower end. This is likely because more evaporation may have happened inside the experimental chamber that was operated at a higher dilution ratio than other studies.

Fig. 3 presents particle size distribution data measured from each of the cartridge of all four brands. The horizontal axis represents particle size on a logarithmic scale, while the vertical axis represents normalized particle number concentration. In general, unimodal log-normal distribution was observed for all particle size distributions. The CMD showed some differences within and across brands and ranged from 18 nm (EC2, Cartridge 2) to 29 nm (EC3, Cartridge 2). EC1 had the largest variance of CMD, while EC4 had the least. The results of CMD are comparable with Ingebrethsen et al.'s (2012) results where the dilution ratios in the two studies were similar (as shown in Supplemental Information Table S1 and

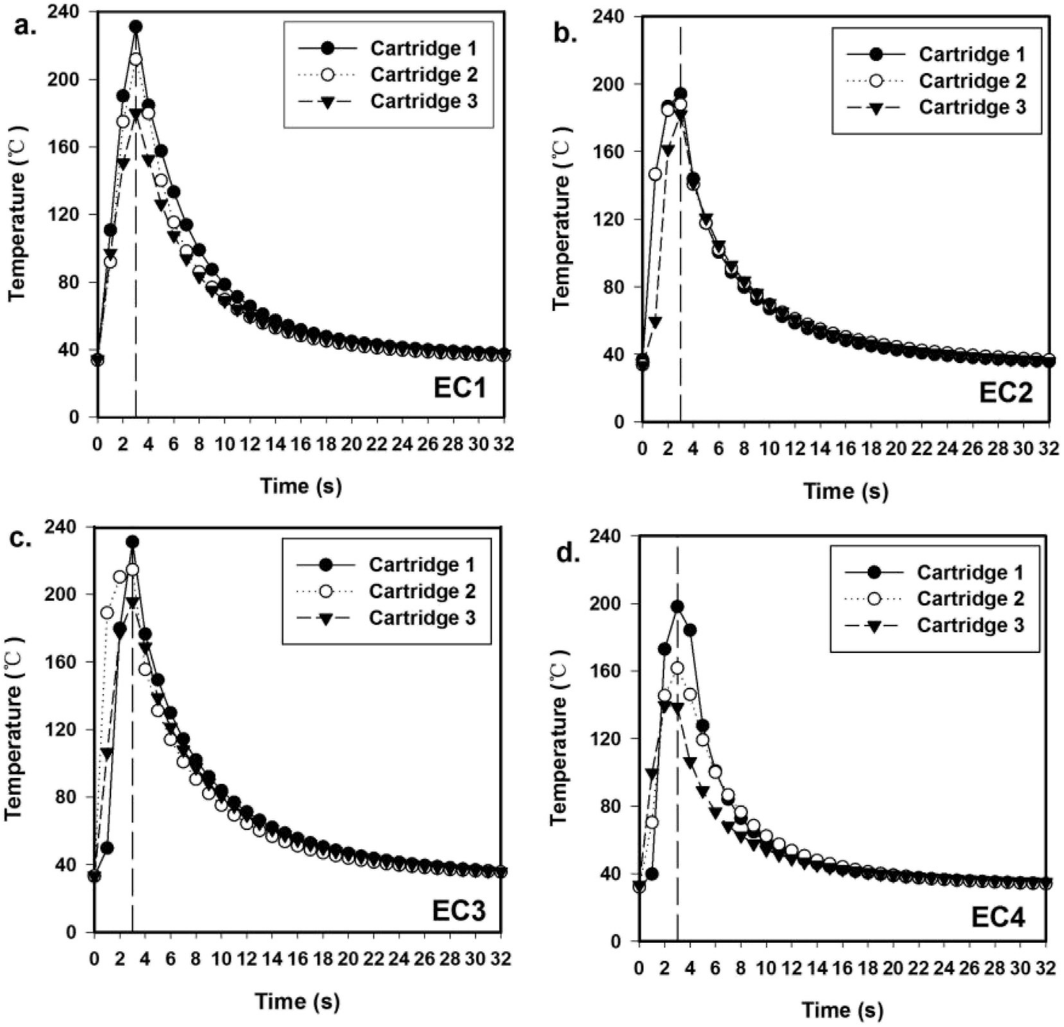

Fig. 1. The heating-coil temperature profiles of all 12 cartridges from four brands at 3-s puff duration and 30-s puff interval. The vertical dash line divided the 3-s puff duration and the 30-s puff interval.

Table S3). A more detailed comparison is presented in Table S1 in the Supplemental Information summarizing results from other studies when much different dilution ratios were used.

3.1.3. *Manufacturing discrepancies*

Considerable differences were observed in heating coil temperature and particle emissions from the tested cartridges across the four brands and even within the same brand. Although the mechanical design of the cartridges from all brands were similar (as shown in the Supplemental Information, Fig. S1), the parameters of individual parts of the ECs were different (Supplemental Information, Fig. S5) across different brands and even within the same brand. Manufacturing parameters of the tested EC cartridges are listed in Table 1, including the flavor description, main ingredients, resistance of the heating coil, description of the air slits, total areas of the air slits, diameters of the end-holes, and the position of the heating coil. These discrepancies are likely to cause the variance in both heat generation (heat coil temperature) and particle emissions.

The temperature of the heating coil depends on the electrical current that goes through the resistance wire to generate heat; meanwhile, the air flow and the evaporation of the e-liquid take away heat. The resistance of the heating coil is a crucial factor that can affect heat generation. The results of the resistances were inconsistent, especially for EC3 and EC4. The air slits are usually set at the front of the EC or between the battery and the cartridge. Although the air flow rate that goes through the cartridge was fixed at 1 L/min, the size and position of the air slits determine the air pressure exerted on the surface of the heating coil and the wick (Williams and Talbot, 2011), which influences the evaporation of the e-liquid.

Comparing Fig. 1 with Fig. 2, there is no direct relationship between the heating coil temperature and particle number concentration. This is because the particle generation process (i.e., particle nucleation and particle condensation) is more complicated than the heat generation in ECs. For example, the position of the heating coil may also affect particle emissions by determining the time that particles need to stay in the cartridge, i.e., the coagulation time for particles inside the cartridge. Particles with a concentration of ~10^9 cm^{-3} can coagulate to double in size in 2–3 s (Hinds, 1999). Another factor is the ingredients in the e-liquid that have variable enthalpies of vaporization. There were no complete ingredient lists on the product packages for tested ECs. The unknown and variable ingredients may lead to the variance of particle emissions and give rise to health concerns.

In conclusion, the aforementioned manufacturing parameters

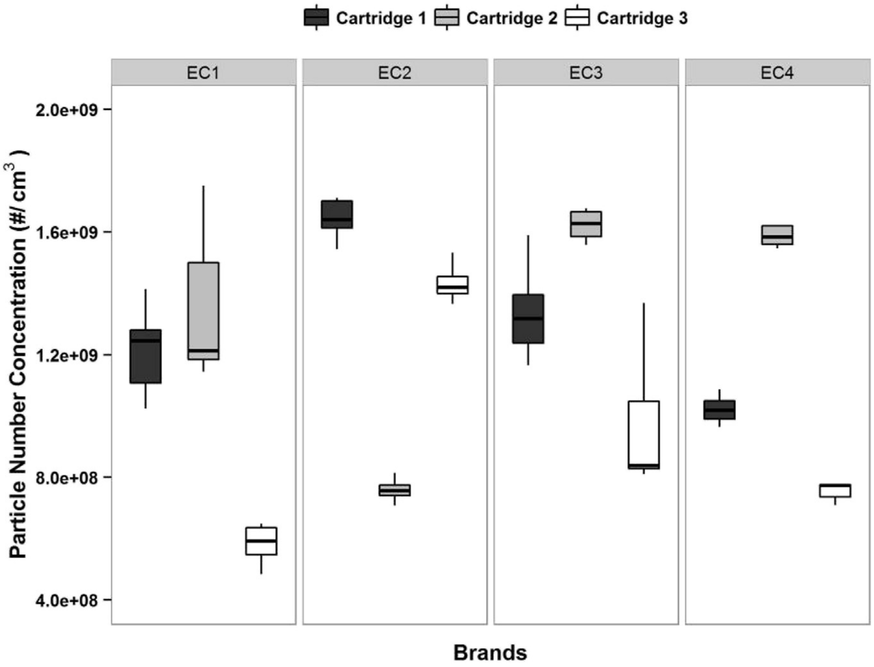

Fig. 2. The particle number concentration of the mainstream particles from different cartridges of four different electronic cigarette brands.

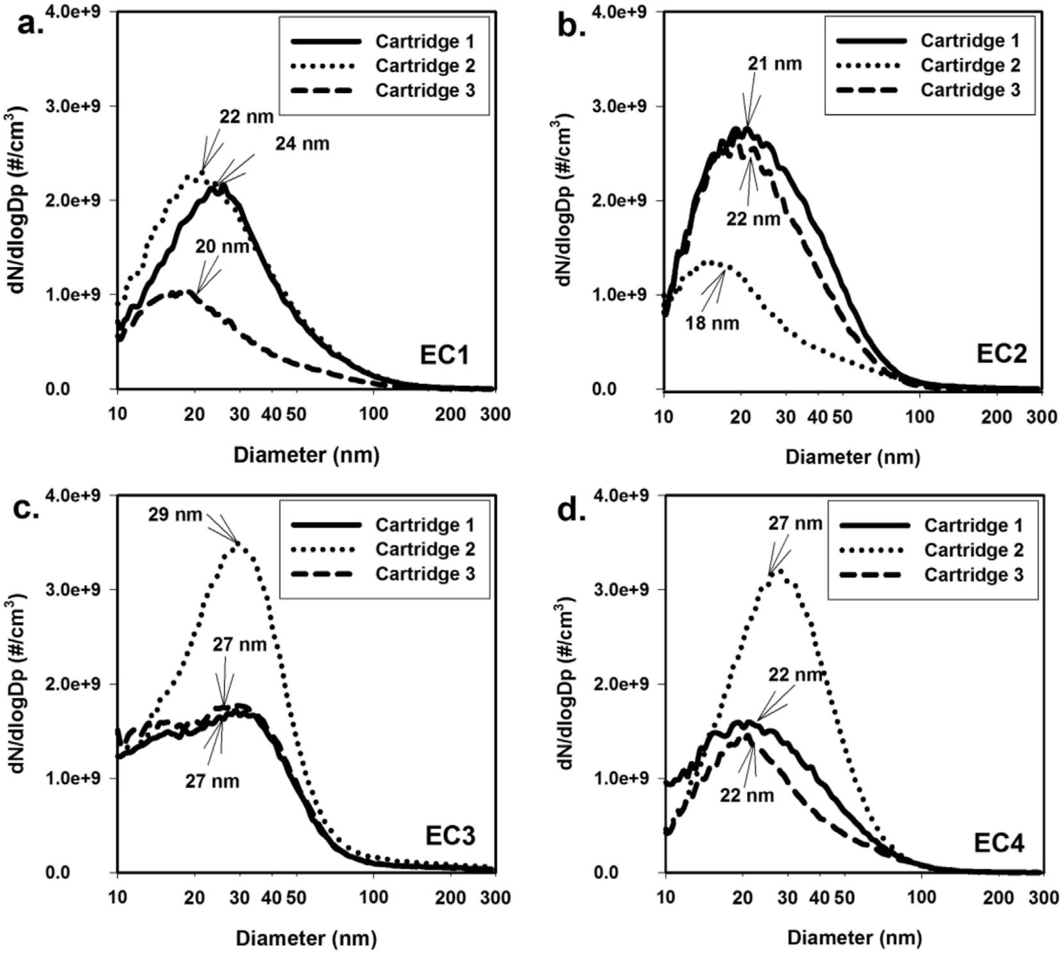

Fig. 3. The size distribution of the mainstream particles from different cartridges of four different electronic cigarette brands.

Table 1
The design parameters of the ECs from all four brands (i.e. EC1, EC2, EC3, EC4).

Brands	Description of flavor	Main ingredients	Cartridge no.	Resistance (Ω)	Length (from heating coil to end-hole) (mm)	Description of the air slit *** Length by width (mm × mm)	Total area of air slit (mm^2)	Diameter of the end-hole (mm)
EC1	Classic Tobacco	PG*, VG**	1	3.0	14.00	Two front slits (2.19 × 0.39);	3.00	1.48
			2	3.1	15.22	Four middle slits (1.29 × 0.25);		
			3	2.9	14.32			
EC2	Tobacco	VG	1	3	26.82	Two front slits (2.12 × 0.61);	3.99	2.12
			2	3.1	25.39	Four middles slits (1.75 × 0.20)		
			3	2.9	25.87			
EC3	Absolute Tobacco	PG, VG	1	4.5	17.55	Two front slits (2.92 × 0.30);	1.75	1.89
			2	3.2	17.61	No middle slits;		
			3	4.4	17.62			
EC4	Classic Tobacco	PG, VG	1	3.2	25.59	Two front slits (2.12 × 0.30);	4.02	2.41
			2	3.1	25.41	Four middle slits (1.72 × 0.40);		
			3	3.9	25.98			

*PG stands for propylene glycol.
**VG stands for vegetable glycerol.
***All of the sizes were measured using a caliper with an accuracy of 0.1 mm.

are potential reasons for the observed performance discrepancy. These findings demonstrate urgent needs to establish manufacturing standards for EC products. The design parameters illustrated in this paper may offer more information and evidence for future EC policy making. For example, a research reference EC, similar to the research reference for tobacco cigarettes, is needed to make the EC research data comparable.

3.2. Effects of puff topography

3.2.1. Effects of puff topography on heating coil temperature

The temperature of the heating coil was measured when the EC was puffed at a fixed air flow rate of 1 L/min for 2, 3, 4, and 5 s, and when the EC was puffed for 3 s at a flow rate of 0.5, 1, 1.5, and 2 L/min. This part of the study used a cartridge from EC2 (tobacco flavor, 0 mg nicotine). As shown in Fig. 4a and b, the peak temperature of the heating coil increased with the puff duration (165.7, 178.5, 187.0 and 194.0 °C, respectively), and decreased with the puff flow rate (191.0, 178.5, 177.6 and 171.3 °C, respectively). Based on the regression results, the peak heating coil temperature increased by 9.3 °C at 1-s puff increments and decreased by 12.0 °C when the air flow rate increased by 0.5 L/min. When the puff duration is longer, more electricity passes through the heating coil, yielding more heat and evaporating more e-liquid. On the other hand, the stronger air flow dissipates more heat. This may be the main reason why the puff duration and flow rate have opposite effects on the heating coil temperature.

The highest peak temperature that has been observed in this study was 218 °C under 5-s puff duration. The high temperature of the heating coil may lead to more potential health risks because it is accompanied by more pyrolysis reactions and more metal oxidation. The corresponding overheating phenomenon has also been observed by Farsalinos et al. (2013b), who showed that smokers reported an unpleasant burning taste caused by the overheating of the e-liquid.

3.2.2. Effects of puff topography on mainstream aerosols

The particle number concentration from EC mainstream increased with a longer puff duration (as shown in Fig. 5a). Based on the regression results, the particle number concentration increased by 2.50 × $10^8/cm^3$ with each 1-s puff increases. There was a good positive linear correlation between the puff duration and particle number concentration (R2 = 0.99) for EC cartridges with zero nicotine, which was consistent with Fuoco et al.'s results (2014). However, particle concentrations measured in our study were lower than those reported by Fuoco and colleagues. This is likely because the dilution ratio used in this study is higher which may result more evaporation of EC particles (see Supplemental

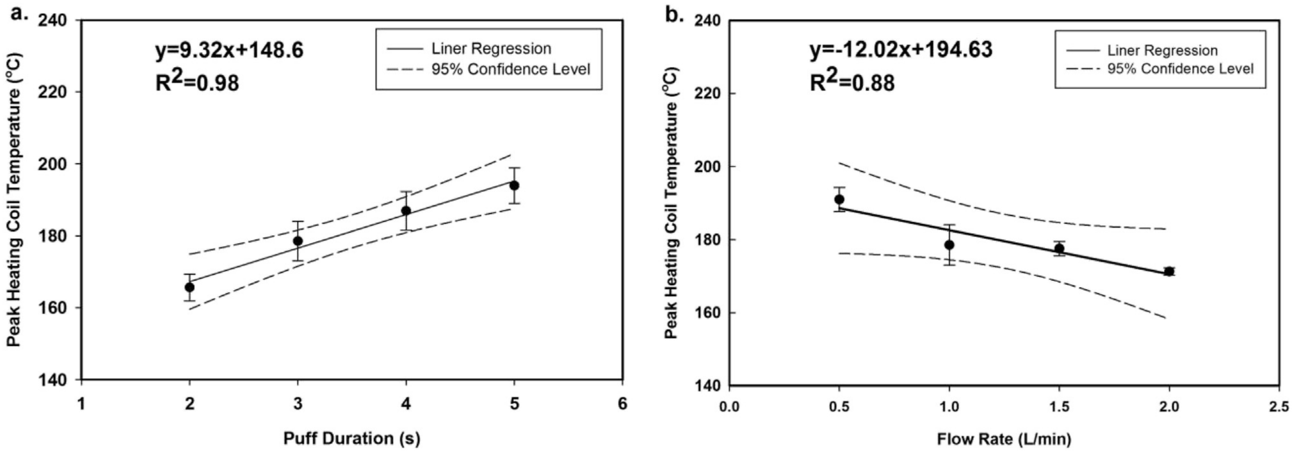

Fig. 4. (a) The peak heating coil temperature with variable puff durations (i.e., 2, 3, 4 and 5 s) and (b) variable puff flow rates (i.e., 0.5, 1, 1.5 and 2 L/min).

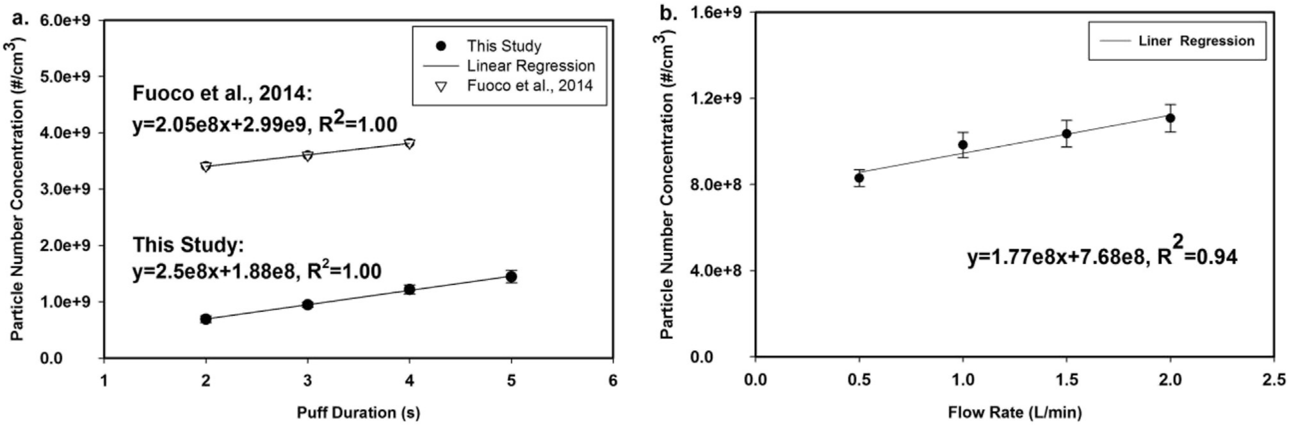

Fig. 5. (a) The particle number concentration with variable puff duration (i.e. 2, 3, 4 and 5 s) and (b) variable puff flow rates (i.e., 0.5, 1, 1.5 and 2 L/min).

Information Table S1). As shown in Fig. 5b, the particle number concentration and flow rate were positively associated. The particle number concentrations increased by 1.77 × 10^8 particles cm^{-3} when the air flow rate increased by 0.5 L/min. This is the first study that elucidates the relationship between flow rate and EC mainstream particles.

The size distributions of mainstream particles emitted from the ECs with variable puff duration and flow rate are shown in Fig. 6a and b. Similar to Fig. 3, unimodal lognormal size distributions were observed. When the puff duration increased from 2 to 5 s at 1-s increments, the CMDs of the EC particles were 17, 20, 23, and 24 nm, respectively. When the flow rate increased from 0.5 to 2 L/min at 0.5 L/min increments, the CMDs were 27, 20, 17, and 15 nm, respectively.

Combining the results discussed in the previous Section 3.2.1, the CMD and peak heating coil temperature have a similar trend with respect to puff duration and flow rate. There was a moderate correlation (r = 0.47) between the peak heating coil temperature and the CMD (as shown in the Supplemental Information, Fig. S6). As discussed before, the coagulation of particles at a concentration magnitude of ~10^9 cm^{-3} was fast, doubling in size in 3–5 s. Longer puff duration generates more particles favoring coagulation resulting in larger CMD (Fig. 6a). On the other hand, increased flow rate means stronger dilution favoring evaporation resulting in smaller CMD (Fig. 6b). This process is similar to the particle generation in tobacco cigarettes. Similar effects of flow rate on the size distribution of mainstream tobacco cigarette particles have been reported in several previous studies (Dickens et al., 2009; Ishizu et al., 1978; Kane et al., 2010).

As discussed above, particle generation from ECs is complicated and determined by many factors. If we treat EC as an aerosol generator, the air flow rate, saturated vapor pressure, and temperature are all crucial parameters that can impact the final characteristics of the emitted particles. In general, the mass consumption of e-liquid per total puff volume for a given puff topography is the main factor. E-liquid mass consumption was defined in this study as the mass difference of the cartridge before and after a certain number of puffs normalized by the total number of puffs. As depicted in the Supplemental Information Fig. S7, the e-liquid consumption was positively correlated with the temperature increase, which clearly demonstrates the influence of temperature on the evaporation of e-liquid.

The average e-liquid consumption was 1.22, 2.59, 3.55 and 5.16 mg for different puff durations (i.e. 2, 3, 4, and 5 s) with 1 L/min puff flow rate, respectively. The average e-liquid consumption was 2.16, 2.59, 2.63 and 2.72 mg for different puff flow rates (i.e. 0.5, 1, 1.5, and 2 L/min) with 3 s puff duration, respectively. These results are within the range reported in Behar et al. (2015), which measured the average e-liquid consumption in a 10-min session containing 13 to 42 puffs.

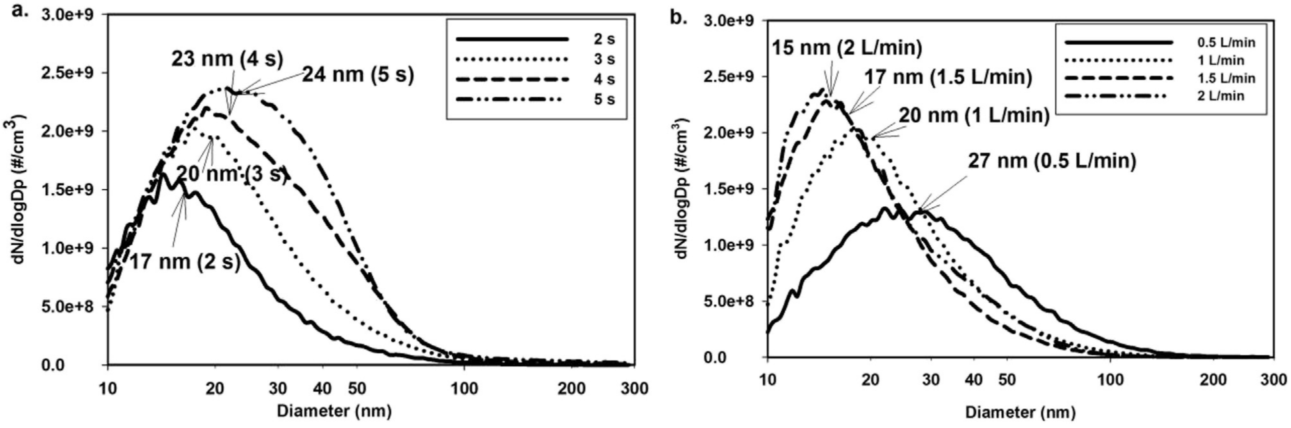

Fig. 6. The size distribution of the mainstream particles with (a) variable puff durations (i.e., 2, 3, 4 and 5 s) and (b) variable puff flow rates (i.e. 0.5, 1, 1.5 and 2 L/min).

4. Conclusions

This study consisted of two parts. First, we measured the heating coil temperature and mainstream aerosols from cartridges within the same brand and among different brands. The peak temperature of heating coil ranged from 138.6 to 231.0 °C. The mainstream particle number concentrations were from 0.58×10^9 to 1.64×10^9 cm^{-3}, while the CMD ranged from 18 to 29 nm. The substantial differences in heating coil temperature and particle emissions reflect the current EC manufacturing status and call for policy-making on quality control for EC products. Second, we showed the effects of different puff topographies on the heating coil temperature and characteristics of mainstream particles. The temperature of the heating coil increased with a longer puff duration and lower puff flow rate. A longer puff duration and lower air flow rate also lead to a larger CMD. Particle number concentration was positively related to the puff duration and puff flow rate, which may result in more particle exposures. A moderate correlation between the peak heating coil temperature and the CMD of mainstream particles was observed. All of these results provide a better understanding of how ECs generate particles and emphasize the urgent need for regulation to appropriately protect public health from EC emissions.

Acknowledgments

This work was supported by the Tobacco-Related Disease Research Program (TRDRP) under the contract number: 23XT-0001. Tongke Zhao would like to thank the China Scholarship Council (No. 201406010038) to support her funding to visit and conduct this research in University of California, Los Angeles.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2016.03.027.

References

Ayers, J.W., Ribisl, K.M., Brownstein, J.S., 2011. Tracking the rise in popularity of electronic nicotine delivery systems (electronic cigarettes) using search query surveillance. Am. J. Prev. Med. 40, 448–453.

Behar, R.Z., Hua, M., Talbot, P., 2015. Puffing topography and nicotine intake of electronic cigarette users. PloS One 10, e0117222.

Brook, R.D., Rajagopalan, S., Pope, C.A., Brook, J.R., Bhatnagar, A., Diez-Roux, A.V., Holguin, F., Hong, Y., Luepker, R.V., Mittleman, M.A., 2010. Particulate matter air pollution and cardiovascular disease an update to the scientific statement from the American heart association. Circulation 121, 2331–2378.

Brown, E., Maharaj, S., James, K., 2011. Necesidad de estrategias de control del tabaco específicas por género hallazgos de la encuesta CAP acerca de la exposición al humo del tabaco ambiental entre mujeres en el grupo de edad reproductiva. West Indian Med. J. 60, 208–213.

CDC, 2015. E-Cigarette Use Triples Among Middle and High School Students in Just One Year. CDC Newsroom Release.

Control, C.f.D., Prevention, 2013. Notes from the field: electronic cigarette use among middle and high school students-United States, 2011–2012. MMWR. Morb. Mortal. Wkly. Rep. 62, 729.

Dawkins, L., Turner, J., Roberts, A., Soar, K., 2013. ‘Vaping’profiles and preferences: an online survey of electronic cigarette users. Addiction 108, 1115–1125.

Dickens, C., McGrath, C., Warren, N., Biggs, P., McAughey, J., 2009. Puffing and inhalation behaviour in cigarette smoking: implications for particle diameter and dose. In: Journal of Physics: Conference Series. IOP Publishing, p. 012019.

Farsalinos, K.E., Romagna, G., Tsiapras, D., Kyrzopoulos, S., Spyrou, A., Voudris, V., 2013a. Impact of flavour variability on electronic cigarette use experience: an internet survey. Int. J. Environ. Res. Public Health 10, 7272–7282.

Farsalinos, K.E., Romagna, G., Tsiapras, D., Kyrzopoulos, S., Voudris, V., 2013b. Evaluation of electronic cigarette use (vaping) topography and estimation of liquid consumption: implications for research protocol standards definition and for public health authorities' regulation. Int. J. Environ. Res. Public Health 10, 2500–2514.

Fromme, H., Schober, W., 2015. Waterpipes and e-cigarettes: impact of alternative smoking techniques on indoor air quality and health. Atmos. Environ. 106, 429–441.

Fuoco, F., Buonanno, G., Stabile, L., Vigo, P., 2014. Influential parameters on particle concentration and size distribution in the mainstream of e-cigarettes. Environ. Pollut. 184, 523–529.

Ghio, A.J., Kim, C., Devlin, R.B., 2000. Concentrated ambient air particles induce mild pulmonary inflammation in healthy human volunteers. Am. J. Respir. Crit. Care Med. 162, 981–988.

Goniewicz, M.L., Knysak, J., Gawron, M., Kosmider, L., Sobczak, A., Kurek, J., Prokopowicz, A., Jablonska-Czapla, M., Rosik-Dulewska, C., Havel, C., 2014. Levels of selected carcinogens and toxicants in vapour from electronic cigarettes. Tob. Control 23, 133–139.

Goniewicz, M.L., Kuma, T., Gawron, M., Knysak, J., Kosmider, L., 2012. Nicotine levels in electronic cigarettes. Nicotine Tob. Res. 158–166.

Hinds, W.C., 1999. Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles. John Wiley & Sons.

Ingebrethsen, B.J., Cole, S.K., Alderman, S.L., 2012. Electronic cigarette aerosol particle size distribution measurements. Inhal. Toxicol. 24, 976–984.

Ishizu, Y., Ohta, K., Okada, T., 1978. Changes in the particle size and the concentration of cigarette smoke through the column of a cigarette. J. Aerosol Sci. 9, 25–29.

Kane, D.B., Asgharian, B., Price, O.T., Rostami, A., Oldham, M.J., 2010. Effect of smoking parameters on the particle size distribution and predicted airway deposition of mainstream cigarette smoke. Inhal. Toxicol. 22, 199–209.

Kim, H.-J., Shin, H.-S., 2013. Determination of tobacco-specific nitrosamines in replacement liquids of electronic cigarettes by liquid chromatography–tandem mass spectrometry. J. Chromatogr. A 1291, 48–55.

Klepeis, N.E., Nelson, W.C., Ott, W.R., Robinson, J.P., Tsang, A.M., Switzer, P., Behar, J.V., Hern, S.C., Engelmann, W.H., 2001. The national human activity pattern survey (NHAPS): a resource for assessing exposure to environmental pollutants. J. Expo. Anal. Environ. Epidemiol. 11, 231–252.

Kosmider, L., Sobczak, A., Fik, M., Knysak, J., Zaciera, M., Kurek, J., Goniewicz, M.L., 2014. Carbonyl compounds in electronic cigarette vapors—effects of nicotine solvent and battery output voltage. Nicotine Tob. Res. 1319–1326.

Laugesen, M., 2009. Ruyan e-cigarette bench-top tests. In: Poster Presented at the Conference of the Society for Research on Nicotine and Tobacco Dublin, April 27–30.

Lerner, C.A., Sundar, I.K., Watson, R.M., Elder, A., Jones, R., Done, D., Kurtzman, R., Ossip, D.J., Robinson, R., McIntosh, S., 2015. Environmental health hazards of e-cigarettes and their components: oxidants and copper in e-cigarette aerosols. Environ. Pollut. 198, 100–107.

Manigrasso, M., Buonanno, G., Fuoco, F.C., Stabile, L., Avino, P., 2015a. Aerosol deposition doses in the human respiratory tree of electronic cigarette smokers. Environ. Pollut. 196, 257–267.

Manigrasso, M., Buonanno, G., Stabile, L., Morawska, L., Avino, P., 2015b. Particle doses in the pulmonary lobes of electronic and conventional cigarette users. Environ. Pollut. 202, 24–31.

McAuley, T.R., Hopke, P., Zhao, J., Babaian, S., 2012. Comparison of the effects of e-cigarette vapor and cigarette smoke on indoor air quality. Inhal. Toxicol. 24, 850–857.

Miller, S., Nazaroff, W., 2001. Environmental tobacco smoke particles in multizone indoor environments. Atmos. Environ. 35, 2053–2067.

Morawska, L., Afshari, A., Bae, G., Buonanno, G., Chao, C., Hänninen, O., Hofmann, W., Isaxon, C., Jayaratne, E., Pasanen, P., 2013. Indoor aerosols: from personal exposure to risk assessment. Indoor air 23, 462–487.

Ohta, K., Uchiyama, S., Inaba, Y., Nakagome, H., Kunugita, N., 2011. Determination of carbonyl compounds generated from the electronic cigarette using coupled silica cartridges impregnated with hydroquinone and 2, 4-dinitrophenylhydrazine. Bunseki Kagaku 60, 791–797.

Pellegrino, R., Tinghino, B., Mangiaracina, G., Marani, A., Vitali, M., Protano, C., Osborn, J., Cattaruzza, M., 2012. Electronic cigarettes: an evaluation of exposure to chemicals and fine particulate matter (PM). Ann. Ig. Med. Prev. Comunita 24, 279–288.

Pope III, C.A., Dockery, D.W., 2006. Health effects of fine particulate air pollution: lines that connect. J. Air Waste Manag. Assoc. 56, 709–742.

Richardson, A., Ganz, O., Vallone, D., 2014. Tobacco on the web: surveillance and characterisation of online tobacco and e-cigarette advertising. Tob. Control 341–347.

Schripp, T., Markewitz, D., Uhde, E., Salthammer, T., 2013. Does e-cigarette consumption cause passive vaping? Indoor Air 23, 25–31.

Talih, S., Balhas, Z., Salman, R., Karaoghlanian, N., Shihadeh, A., 2015. “Direct dripping”: a high-temperature, high-formaldehyde emission electronic cigarette use method. Nicotine Tob. Res. 150–157.

Terminology, V., 2013. Vaping Terms. www.ecigarette-politics.com/vaping-terminology.html.

Trehy, M.L., Ye, W., Hadwiger, M.E., Moore, T.W., Allgire, J.F., Woodruff, J.T., Ahadi, S.S., Black, J.C., Westenberger, B.J., 2011. Analysis of electronic cigarette cartridges, refill solutions, and smoke for nicotine and nicotine related impurities. J. Liq. Chromatogr. Relat. Technol. 34, 1442–1458.

Trtchounian, A., Williams, M., Talbot, P., 2010. Conventional and electronic cigarettes (e-cigarettes) have different smoking characteristics. Nicotine Tob. Res. 12, 905–912.

Uchiyama, S., Ohta, K., Inaba, Y., Kunugita, N., 2013. Determination of carbonyl compounds generated from the E-cigarette using coupled silica cartridges impregnated with hydroquinone and 2, 4-dinitrophenylhydrazine, followed by high-performance liquid chromatography. Anal. Sci. 29, 1219–1222.

Wallace, L., 1996. Indoor particles: a review. J. Air Waste Manag. Assoc. 46, 98–126.

Weschler, C.J., 2009. Changes in indoor pollutants since the 1950s. Atmos. Environ. 43, 153–169.

Wichmann, H.-E., Peters, A., 2000. Epidemiological evidence of the effects of ultrafine particle exposure. Philos. Trans. R. Soc. Lond. A Math. Phys. Eng. Sci. 358, 2751–2769.

Williams, M., Talbot, P., 2011. Variability among electronic cigarettes in the pressure drop, airflow rate, and aerosol production. Nicotine Tob. Res. 13, 1276–1283.

Williams, M., Villarreal, A., Bozhilov, K., Lin, S., Talbot, P., 2013. Metal and silicate particles including nanoparticles are present in electronic cigarette cartomizer fluid and aerosol. PloS One 8 (3), e57987.