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Influential parameters on particle concentration and size distribution in the mainstream of e-cigarettes

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ABSTRACT

Electronic cigarette-generated mainstream aerosols were characterized in terms of particle number concentrations and size distributions through a Condensation Particle Counter and a Fast Mobility Particle Sizer spectrometer, respectively. A thermodilution system was also used to properly sample and dilute the mainstream aerosol.

Different types of electronic cigarettes, liquid flavors, liquid nicotine contents, as well as different puffing times were tested. Conventional tobacco cigarettes were also investigated.

The total particle number concentration peak (for 2-s puff), averaged across the different electronic cigarette types and liquids, was measured equal to $4.39 \pm 0.42 \times 10^9$ part. cm^{-3}, then comparable to the conventional cigarette one ($3.14 \pm 0.61 \times 10^9$ part. cm^{-3}). Puffing times and nicotine contents were found to influence the particle concentration, whereas no significant differences were recognized in terms of flavors and types of cigarettes used.

Particle number distribution modes of the electronic cigarette-generated aerosol were in the 120–165 nm range, then similar to the conventional cigarette one.

1. Introduction

Aerosol exposure is a major environmental health concern due to the particles' ability to penetrate deeply into the respiratory system and cell membranes (Unfried et al., 2007) and translocate from the airways into the blood circulation (Schins et al., 2004; Weichenthal, 2012). Particles are also able to deposit in secondary organ (Semmler et al., 2004), including brain tissue (Calderon-Garciduenas et al., 2004) and to carry condensed toxic compounds (Brown et al., 2001; Nygaard et al., 2004; Schmid et al., 2009). Concerning the human health, indoor air quality represents the most important issue since people spend most of their time indoors (Klepeis et al., 2001) where particle concentrations are typically high (Buonanno et al., 2013; EPA, 2004). A major indoor particle source is the environmental tobacco smoke, ETS (Nazaroff and Singer, 2004; Repace and Lowrey, 1980; WHO, 2005, 2013) which is a mixture of exhaled mainstream smoke, and sidestream smoke released from the smoldering tobacco products. Tobacco cigarettes contain around 4000 different chemicals, including toxins like arsenic and radioactive polonium-210 (Baker et al., 2004; Fowles and Dybing, 2003; IARC, 2004, 2012; Little et al., 1965; Wynder and Hoffmann, 1967). Moreover, in fresh unaged tobacco cigarette mainstream smokes were measured particle concentrations of about 4×10^9 part. cm^{-3}, with an arithmetic mean diameter of about 0.2 μm (Adam et al., 2009; Alderman and Ingebrethsen, 2011; Borgerding and Klus, 2005).

1.1. E-cigarettes: state-of-art

Nowadays, the use of electronic cigarettes (e-cigarettes) is becoming increasingly popular maybe because smokers consider it a healthier alternative to conventional smoking: anyway, comprehensive studies aimed to characterize the aerosol produced by these devices are still not available.

E-cigarettes are made up of three integrated parts contained in a stainless steel shell: a cartridge, an atomizer, and a battery. The cartridge is the liquid reservoir which also acts as a mouthpiece. When an e-cigarette smoker (named "vaper") inhales through the mouthpiece, an air flow sensor activates the atomizer, which heats up the liquid inside the cartridge producing a smoke-like vapor then orally inhaled (Riker et al., 2012). Liquid mixture consists of propylene glycol and/or vegetable glycerin, water, and flavors.

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Different nicotine concentration levels are commercialized: typically 0–6 mg mL^{-1} (low), 12–16 mg mL^{-1} (medium), and 18–24 mg mL^{-1} (high). Flavors can be both natural and artificial, moreover different flavor tastes are available such as tobacco, fruit, and herb. The e-cigarettes can be single-use (disposable, non-refillable) or reusable (refillable tank or not, welded tank atomizer or not), with either automatic or manual battery. Compared with conventional cigarettes, which last about fifteen puffs, e-cigarettes allow from 150 to 300 puffs (Wollscheid and Kremzner, 2009).

E-cigarette products are not adequately regulated so far (Gornall, 2012): the e-cigarette industry claims that the existing legislation (European Parliament and Council of the European Union, 2001a) and the EU rapid alert system, RAPEX, are adequate in their current form to regulate them as consumer products, while Tobacco Industry pushes to include e-cigarettes in the Tobacco Products Directive (TPD) (Roland Berger Strategy Consultants, 2013). The European Commission proposed to extend the TPD to nicotine containing product (NCP) regulation (it will be adopted in 2014), then including almost all e-cigarettes in the medicines regulation (European Parliament and Council of the European Union, 2001b). Thus, e-cigarettes will be required to obtain a marketing authorization from a health regulator.

Very few studies investigated health effects due to the e-cigarette use (Bullen et al., 2010; Dawkins et al., 2012; Flouris et al., 2013, 2012; Vansickel et al., 2010). A review of 16 studies (Cahn and Siegel, 2011) found e-cigarettes comparable in toxicity to nicotine replacement therapies (NRT) but less harmful than tobacco cigarettes. Nonetheless, there are still some questions about the safety of the chemicals in e-cigarette liquids, and the current lack of regulation means there is no way of verifying what actually is in them, especially with so many different brands suddenly entered the market and the variation in performance properties within brands detected by Williams and Talbot (2011).

The products of the e-cigarettes may contain ingredients that are known to be toxic to humans. As example, the propylene glycol, released in the vapor, is known to be responsible of upper airway irritations (Wieslander et al., 2001). Vardavas et al. (2012) reported adverse physiologic effects after short-term use of e-cigarette similar to some effects recognized in tobacco smoking. Gennimata et al. (2012) also showed that e-cigarette use causes potential harmful short-term effects on lung function.

A further issue to be controlled and regulated, is the real nicotine content in the liquid (Britton and McNeill, 2013; Grana, 2013). As example, the US Food and Drug Administration detected nicotine trace and others dangerous substances even in e-cigarettes classified as nicotine-free (FDA, 2009). This is not a trivial aspect, since nicotine can be toxic in high doses and can lead people to nicotine addiction then inducing them to use other tobacco products such as conventional cigarettes (Bell and Keane, 2012). No information on long-term health effects of e-cigarette use is still available.

1.2. Aims of the work

The present study is focused on the total particle number concentration and size distribution measurement of the mainstream aerosol generated by e-cigarettes. Data were analyzed and compared to those from a conventional tobacco cigarette. In order to propose an exhaustive characterization of the e-cigarette emission, different influence parameters such as type of the e-cigarette, flavor, nicotine content and puffing time were investigated. Measurements of particle number concentrations and size distributions were performed with a one-second-time resolution in order to identify the impact of the particles inhaled by e-cigarette vaper on human health and to put a new insight for assessing of respiratory dosimetry.

2. Materials and methods

2.1. Experimental campaign

Different types of e-cigarettes were tested: two rechargeable models (e-cigarettes A and B) and one disposable model (e-cigarette C). Their characteristics are summarized in Table 1. E-cigarettes were filled with different liquids in terms of flavor and nicotine content. Rechargeable models were cleaned with deionized water after each test in order to avoid possible liquid contamination. Two tobacco flavors, (Liquid 1) and (Liquid 4), an e-juice flavor, (Liquid 2), and a herb flavor (Liquid 3) were used. Three nicotine levels were tested: zero (0 mg mL^{-1}), medium (8–9 mg mL^{-1}), and high (12–18 mg mL^{-1}) concentrations. Details of the liquid characteristics are reported in Table 2. E-cigarettes were recently purchased and unused prior to testing. Batteries of the rechargeable models (e-cigarettes A and B) were fully charged before each experiment. Conventional tobacco cigarettes were also tested. In particular, cigarettes with a nicotine concentration equal to 0.8 mg per cigarette were considered (Table 2).

Measurements were performed in the European Accredited (EA) Laboratory of Industrial Measurements (LAMI) at the University of Cassino and Southern Lazio, Italy, where thermo-hygrometric conditions were continuously monitored, in order to guarantee temperature and relative humidity values equal to 20 ± 1 °C and 50 ± 10%, respectively.

2.2. Instrumentation and quality assurance

In order to measure total particle number concentrations and size distributions the following instruments were used:

- a TSI model 3775 Condensation Particle Counter (CPC) able to measure total particle number concentration down to 4 nm in diameter with a one-second time resolution;
- a TSI model 3091 Fast Mobility Particle Sizer (FMPS) spectrometer able to measure particles size distribution and total concentration in the range 5.6–560 nm through an electrical mobility technique involving multiple electrometers getting simultaneously signals from all particle sizes with a one-second-time resolution;
- a thermodilution system (two-step dilution) made up of a Rotating Disk Thermodiluter, RDTD (model 379020; Matter Engineering AG) (Hüglin et al., 1997) and a Thermal Conditioner Air Supply (model 379030; Matter Engineering AG) (Burtscher, 2005) allowing to ensure a proper sample conditioning during cigarette-generated particle number distribution and total concentration measurements. Temperature control is also allowed in the thermodilution section by a built-in heater with selectable temperatures;
- a TSI model 3080 Electrostatic Classifier (EC) able to select airborne particles of uniform size from a polydisperse source, resulting in a highly monodisperse aerosol. It is also used along with a CPC 3775 for particle size distribution measurements in Scanning Mobility Particle Sizer (SMPS) spectrometer configuration;
- a TSI model 4410 Flow meter to check flow rates in the tubing connecting the cigarette to the measuring devices.

The CPC was calibrated in the European Accredited Laboratory at the University of Cassino and Southern Lazio by comparison with a TSI 3068B Aerosol Electrometer using NaCl particles generated through a Submicrometer Aerosol Generator (TSI 3940) (Stabile et al., 2013).

2.3. Methodology description

The experimental campaigns were carried out during February–June 2013. Measurements of total particle number concentrations and particle size distributions were performed considering different types of cigarettes and liquids as hereinafter detailed.

Three puff profiles were considered for each test. Each puff profile was performed considering four consecutive puffs (puffing time of 2, 3, or 4 s) with a 30-s inter puff interval. The first puff was considered a "warm up" puff as it could lead to possible measurement errors when e-cigarettes were tested, as also reported in Ingebrethsen et al. (2012). The conventional tobacco cigarette were tested using the same procedure of e-cigarettes. The puffs for both electronic and conventional cigarettes were performed connecting the aerosol sampling line to the cigarette

Table 1
Characteristics of the e-cigarettes tested.

Sample	Delivery system
E-cigarette A	Tank system
E-cigarette B	Atomizer phantom
E-cigarette C	Cartom
Conventional tobacco cigarette	–

Table 2
Characteristics of the liquids.

Sample	Flavoring	Nicotine content
Liquid 1	Selene	0, 9, and 14 mg mL^{-1}
Liquid 2	Strawberry	0, 8, and 12 mg mL^{-1}
Liquid 3	Menthol	0, and 18 mg mL^{-1}
Liquid 4	Camel	0, and 18 mg mL^{-1}
Conventional tobacco cigarette	Marlboro	0.8 mg $cigarette^{-1}$

itself. In particular, a time-controlled switch valve was used to generate a puff (and a inter puff interval) of a selected length: when it was closed the room air was sampled, whereas it was opened (for 2, 3, or 4 s) to perform the puff.

Particle number concentrations and size distributions were measured through the CPC 3775 and the FMPS 3091, respectively. Anyway, because of the high particle number concentration expected, the testing aerosol was diluted through the two-step thermodilution system (RDTD + Thermal Conditioner Air Supply) before entering the CPC or FMPS (particle number concentration and distribution measurements were not performed simultaneously). In particular, the thermodilution system drew the mainstream aerosol from the cigarette's mouthpiece at a fixed flow rate of 1 L min^{-1}, then testing a total volume of 33.3 cm^3 when the 2-s puff tests were performed. Flow rates were checked through the Flow meter TSI 4410. The thermodilution system temperature was set at 37 °C in order to simulate the respiratory apparatus. After the dilution process, the aerosol was drawn from the thermodiluter to the CPC (aerosol flow rate of 1.5 L min^{-1}) or the FMPS (aerosol flow rate of 10 L min^{-1}) depending on whether particle number concentrations or size distributions were measured.

The authors point out that cigarette-generated mainstream aerosols are highly concentrated, and made up of volatile gaseous compounds that tend to condense, leading to either the possible formation of stable nuclei (nucleation) or the growth of existing particles (condensation). Therefore, it was necessary to properly dilute the aerosol through the thermodilution system; if not, particle size distributions and total concentrations could have quickly undergone significant changes in the few seconds lasting between the aerosol sampling and its measurement (Buonanno et al., 2012; Burtscher, 2005; Holmes, 2007; Hüglin et al., 1997).

Moreover, since the path experienced by the aerosol before entering the measurement devices was long, a diffusion loss correction was applied to estimate the particle losses onto the inner surface of the tubing. These corrections were calculated applying the method proposed in Gormley and Kennedy (1949); further details about diffusion loss correction evaluation are reported in Buonanno et al. (2011b).

Comparisons between particle number concentrations obtained varying the main operating parameters (nicotine content, puffing time, type of cigarette, flavor) were performed through Student's *t* test and analysis of variance (ANOVA) according to the number of variables tested: a p value < 0.01 was regarded as statistically significant.

Nicotine content influence was evaluated considering the e-cigarette A and a fixed 2-s puffing time for all the liquid under investigation. Comparisons were performed liquid by liquid through the Student's *t* test.

The effect of the puffing time was measured performing tests with a puff length of 2, 3 and 4 s using the e-cigarette A and the Liquid 1 for the three nicotine concentration levels (zero, medium, high). Comparisons were tested for each nicotine content with the ANOVA test.

The influence of the type of e-cigarette was assessed comparing data obtained using the devices A, B, and C filled with Liquid 1 at high nicotine content and considering a 2-s puff length. ANOVA test was used to statistically evaluate the results.

Flavor effect was investigated considering the e-cigarette A and 2-s puff time. Liquid 1–4 at the same nicotine content (0 mg mL^{-1}) were tested. Intra-liquid comparisons were evaluated through the ANOVA test.

Particle number distributions produced by different cigarettes, and e-cigarettes' liquids (different flavor and nicotine content) were measured using the e-cigarette A and a 2-s puffing time. Conventional tobacco cigarettes were also analyzed. Puff generation procedure and number of tests were similar to those used during the abovementioned particle number concentration measurements.

The volatile fraction of the e-cigarette-generated mainstream aerosol was also measured. Particle volatility information is important both to estimate the particles' composition and to analyze aerosol potential health impacts: in fact, volatility may influence the behavior of the particles after deposition in the respiratory tract and the related potential health effects. To these purposes, the scientific community performed particle volatility analyses for different indoor and outdoor sources including diesel (Sakurai et al., 2003) and cooking (Buonanno et al., 2011a). The volatility analysis of e-cigarette-generated mainstream aerosol was measured through the particle number distribution at different thermodilution temperatures. Measurements were performed considering different types of cigarettes (conventional vs. electronic cigarettes) and e-cigarette liquids (Liquid 1 at high nicotine content, Liquid 2 at zero nicotine content). Temperature levels equal to 37 °C, 100 °C and 150 °C were considered.

Particle number concentration and distribution data discussed in the Results represent the average of the peaks (maximum concentrations) measured during the three puffs (the first puff was excluded as discussed above) for the three puff profiles. Moreover, the particle size distributions data measured by the FMPS were normalized to the total particle number concentrations data measured through the CPC.

In Table 3 details of the experimental apparatus and the corresponding setting parameters used during particle number concentration and distribution measurements were summarized.

Concerning particle number distribution data, a study based on the size distribution measurements of the e-cigarette aerosol reported an artificial small particle mode maybe due to the particle evaporation during high aerosol dilutions in the electrical mobility measurements (Ingebrethsen et al., 2012). Kulkarni and Wang (2006) addressed this artifact to the width of the probability density function in the electrical mobility measurements which is the widest at the smallest electrical mobility. This resulted in an over-estimation of the particle concentration in the first bins of the distribution if not corrected as reported in the following study of Olfert et al. (2008). Therefore, in order to take into account this possible measurement artifact, beside the particle size distribution measurements of the liquids through FMPS, we also measured the particle size distribution of the diluted mainstream aerosol connecting the CPC to the Electrostatic Classifier 3080 as previous used by Stabile et al. (2012). The experiment was performed using the e-cigarette A with the Liquid 1 (high nicotine content) and 2-s puff length. The e-cigarette was connected to the inlet of the thermodilution section (RDTD + Thermal Conditioner Air Supply). The diluted aerosol was channeled into the EC 3080 and immediately flown to the CPC. In particular, the dilution rate was set to the minimum vale (1:16) in order to minimize the dilution effects; the EC 3080 was used to classify dimensionally monodisperse particles and the CPC to measure particle number concentration of such selected diameter. Diameter logarithmically equally spaced were considered to build the particle size distribution through EC + CPC in the range 5.83–583 nm with a resolution of 14 channels. To this purpose, an aerosol-sheath flow rate ratio equal to 1:10 was considered, moreover, in order to cover the selected range, aerosol/sheath flows (0.3/3 or 1.5/15 l min^{-1}) and impactor diameter nozzles (0.0457 or 0.071 cm) were properly used. Finally, particle number concentration values of every channel were corrected by charging and selecting efficiencies characteristics of the EC 3080 (Buonanno et al., 2009; Stabile et al., 2012).

3. Results and discussion

3.1. Average total particle number concentration

The total particle number concentration in the mainstream aerosol emitted by e-cigarettes, averaged across all the liquids (in terms of nicotine content and flavor as listed in Table 2) and types of e-cigarettes for 2-s puffs, was equal to $4.39 \pm 0.42 \times 10^9$ part. cm^{-3}. Similar concentrations in the 10^9 part. cm^{-3} range were measured in previous studies by Ingebrethsen et al. (2012) and Schripp et al. (2013) through spectral transmission and electrical mobility technique measurements. The authors point out that, in the present study, for the very first time were presented particle concentration data concerning e-cigarettes measured with 1-s time resolution through a condensation particle counter.

Table 3
Details of the apparatus and setting parameter used during the experimental analysis.

Measurement	Experimental apparatus	Cigarettes tested
Particle number concentration	CPC 3775 (aerosol flow 1.5 L min^{-1}) RDTD + Thermal Conditioner Air Supply - dilution ratio 1:1000 - termodilution temperature 37 °C	e-cigarettes: - Liquid 1 - Liquid 2 - Liquid 3
Particle number distribution	FMPS 3091 (aerosol flow 10 L min^{-1}) RDTD + Thermal Conditioner Air Supply - dilution ratio 1:880 - termodilution temperature 37 °C	- Liquid 4 Conventional cigarette
Volatility analysis	FMPS 3091 (aerosol flow 10 L min^{-1}) RDTD + Thermal Conditioner Air Supply - dilution ratio 1:880 - termodilution temperatures 37, 100, and 150 °C	e-cigarettes: - Liquid 1 - Liquid 2 Conventional cigarette

Average particle number concentrations in the mainstream aerosol produced by conventional tobacco cigarettes were equal to $3.14 \pm 0.61 \times 10^9$ part. cm^{-3}, therefore e-cigarettes were found to produce mainstream aerosols with particle concentrations similar or even higher than conventional ones.

3.2. Nicotine level

In Table 4 the total particle number concentrations for each liquid analyzed at zero and high nicotine content were displayed. Measurements were performed through the e-cigarette A considering a 2-s puff. Nicotine-free liquids shown particle concentrations ranging between 3.26×10^9 and 4.09×10^9 part. cm^{-3}, whereas e-cigarettes with high nicotine content generated mainstream aerosol particle concentrations in the range 5.08×10^9 and 5.29×10^9 part. cm^{-3}. Then, particle number concentrations measured using liquids with high nicotine content were statistically greater (with a 99% confidence level) than those obtained testing the corresponding liquids with zero nicotine content. Therefore, the nicotine level can be considered a major parameter affecting the particle emission from e-cigarettes.

3.3. Puffing time

Fig. 1 shows particle number concentrations from e-cigarette A filled with Liquid 1 with three nicotine concentration levels (zero, medium, high) at different puffing time: 2 s, 3 s and 4 s. Particle number concentrations increased with the puffing time, similar trends were showed for zero, medium and high nicotine content as well. As also showed in the previous section, e-cigarettes at high nicotine contents emitted the highest particle number concentration.

Particle number concentrations measured for 2-s (3.41×10^9, 3.43×10^9, 4.20×109 part. cm^{-3} for zero, medium and high nicotine content, respectively), 3-s (3.60×10^9, 3.95×10^9, 5.03×10^9 part. cm^{-3}) and 4-s puff lengths (3.82×10^9, 4.18×10^9, 5.52×10^9 part. cm^{-3}) were found statistically different (with a p value less than 0.01). In particular, the longer the puffing times the higher the particle number concentration measured in the mainstream aerosol. Similar results were found by Ingebrethsen et al. (2012) through spectral transmission measurements. The puffing time effect could depend on the performance of the battery and heating system, which are able to provide more heat to evaporate the liquid for longer puffs.

3.4. Type of cigarette

Particle number concentrations in the mainstream aerosol emitted by the e-cigarette A, B and C were measured using the Liquid 1 at high nicotine content and considering a 2-s puffing time. ANOVA test applied to the resulting concentrations indicated no statistically differences between the type of e-cigarettes tested: $4.46 \pm 0.53 \times 10^9$, $3.93 \pm 0.62 \times 10^9$, $5.14 \pm 0.63 \times 10^9$ part. cm^{-3} were found for A, B and C e-cigarettes, respectively. Therefore, particle number concentration of the mainstream aerosol was not affected by e-cigarette type or brand.

Table 4
Total particle number concentration measured in the mainstream aerosol of e-cigarette A as function of the nicotine content and liquid flavoring: 2-s puffs were considered.

	Average total particle number concentration at zero nicotine content (part. cm^{-3})	Average total particle number concentration at high nicotine content (part. cm^{-3})
Liquid 1	$4.09 \pm 0.54 \times 10^9$	$5.28 \pm 0.29 \times 10^9$
Liquid 2	$3.73 \pm 0.37 \times 10^9$	$5.24 \pm 0.91 \times 10^9$
Liquid 3	$3.26 \pm 0.46 \times 10^9$	$5.29 \pm 0.24 \times 10^9$
Liquid 4	$3.45 \pm 0.40 \times 10^9$	$5.08 \pm 0.07 \times 10^9$

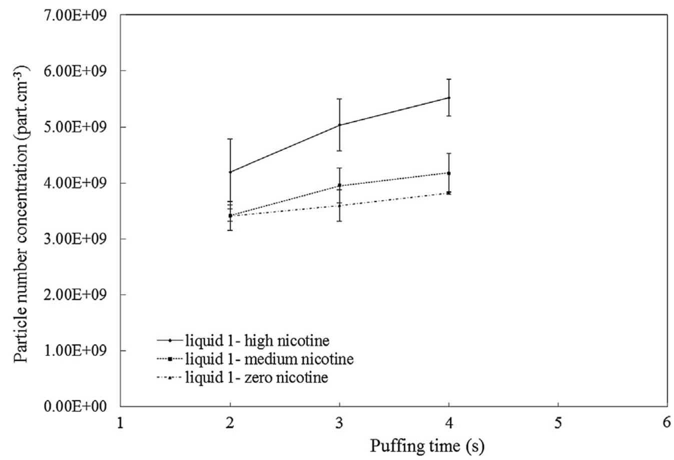

Fig. 1. Particle number concentrations from e-cigarette A filled with Liquid 1 at different puffing time: 2 s, 3 s and 4 s.

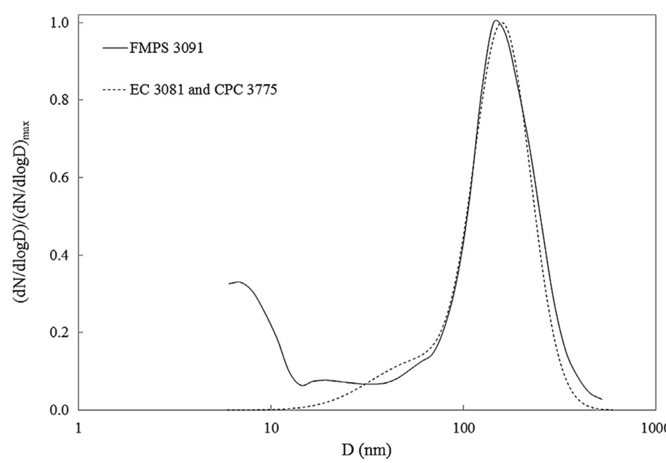

Fig. 2. Particle size distribution of the thermodiluted mainstream aerosol measured in two different methods: connecting the CPC to the Electrostatic Classifier 3080 (dashed line) and through the FMPS (solid line). E-cigarette A filled with Liquid 1 at high nicotine content was used for this experiment.

3.5. Flavors

Particle number concentrations from the e-cigarette A filled with all the liquids at fixed nicotine content (0 mg ml^{-1}) and puffing time (2 s) were found statistically (ANOVA, $p < 0.01$) not different. In particular, $4.09 \pm 0.54 \times 10^9$, $3.73 \pm 0.37 \times 10^9$, $3.26 \pm 0.46 \times 10^9$, and $3.45 \pm 0.40 \times 10^9$ part. cm^{-3} were measured for Liquid 1, Liquid 2, Liquid 3, and Liquid 4, respectively. Consequently, e-cigarette liquid flavors cannot be considered a major influence parameter in particle concentration emission of such devices.

3.6. Particle size distribution

Fig. 2 shows the particle size distribution of the thermodiluted mainstream aerosol obtained using the e-cigarette A with the Liquid 1 at high nicotine content (2-s puff length), measured

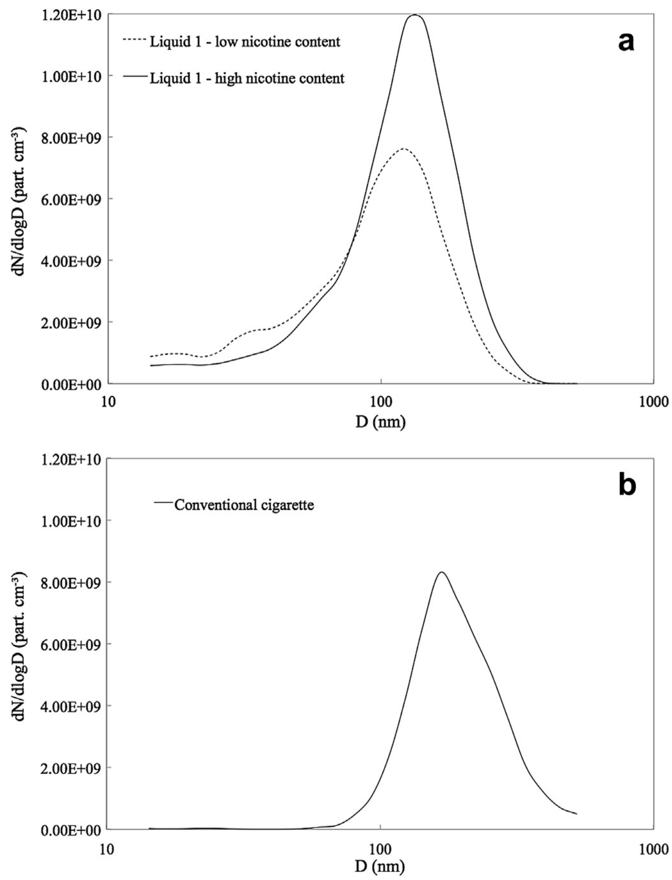

Fig. 3. Particle number distribution measured through the FMPS 3091 (after thermodilution at 37 °C) of the mainstream aerosol from the Liquid 1 (a) and from the conventional tobacco cigarette (b).

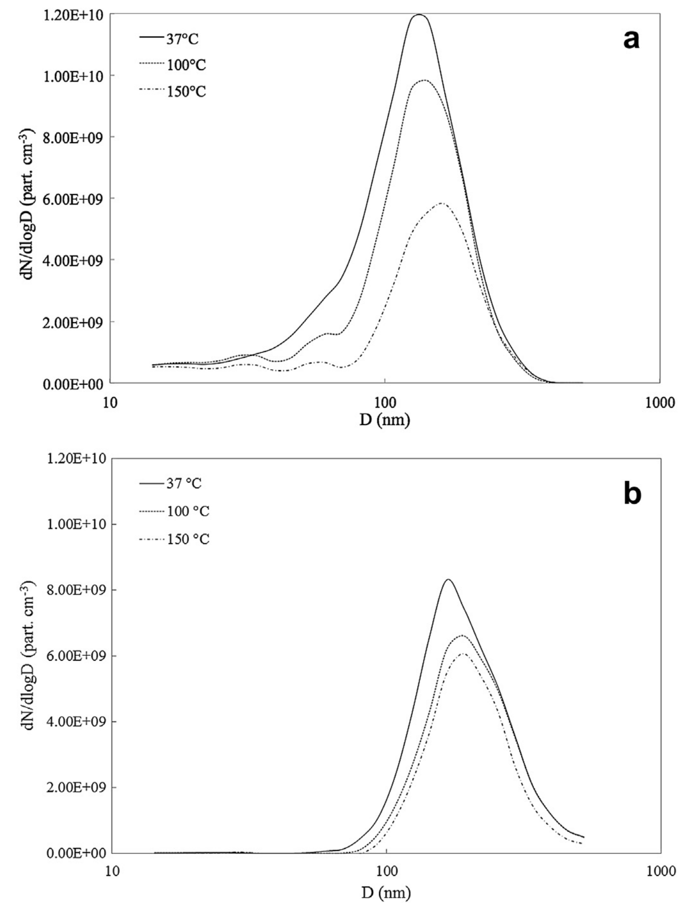

Fig. 4. Volatility analysis at three temperature levels (37 °C, 100 °C, and 150 °C) of mainstream aerosol generated by: (a) e-cigarette A using Liquid 1 at high nicotine content; (b) conventional tobacco cigarette.

considering two different methods: connecting the CPC to the Electrostatic Classifier 3080 (dashed line) and through the FMPS (solid line). The particle size distribution measured through the FMPS showed a main mode at around 150 nm and a smaller mode at around 10 nm. Similar results were also found by Schripp et al. (2013) who observed a bimodal distribution of diluted e-cigarette aerosol: a mode in the in the 30 nm diameter range, and second one at about 100 nm. On the contrary, the size distribution measured channel by channel with the EC and CPC showed only the main mode at 150 nm, then suggesting that the smaller particle diameter mode of the diluted mainstream aerosol measured through the FMPS was an artifact as also reported by Ingebrethsen et al. (2012) and Olfert et al. (2008).

Measurements of particle number distributions of the mainstream aerosol emitted by e-cigarettes, performed through the FMPS 3091, resulted similar in terms of shape and mode for all the liquid tested. The measurement range of the distribution was cut off down to 14 nm since the 10-nm fake mode detected for all the liquids tested. When two nicotine levels (zero and high) at a fixed liquid flavor were compared, no significant effects on the particle distribution mode were detected: a main mode at 120–140 nm, 165 nm, 125 nm, and 120–140 nm was measured for nicotine-free Liquid 1, 2,3, and 4, respectively; while modes equal to 124, 165, 124, and 143 nm were measured for Liquid 1–4 with nicotine, respectively. As example, the particle size distribution of the mainstream aerosol generated by the Liquid 1 was showed in Fig. 3a. The particle size distribution of the conventional cigarette provided a similar mode at 165 nm (Fig. 3b).

3.7. Volatility analysis

The volatility analysis results were reported in terms of particle size distribution and corresponding total concentration measured through the FMPS 3091 at the three different thermodilution temperature levels: 37 °C, 100 °C and 150 °C.

At 100 °C and 150 °C the total particle number concentration of e-cigarette filled with Liquid 1 at high nicotine content, e-cigarette filled with Liquid 2 at zero nicotine content, and conventional tobacco cigarette decreased to 79% and 47%, 92% and 53%, and 82% and 68%, respectively, with respect to the corresponding total concentrations measured at 37 °C. These differences clearly show that a different amount of volatiles evaporated when different liquids (in terms of flavoring and nicotine content) and cigarettes (electronic or conventional) were considered.

Nonetheless the volatile and semivolatile compounds evaporated quite homogenously all over the size distribution since no important shift in the mode were detected at different temperatures. As example, the volatility analysis of the mainstream aerosol generated by Liquid 1 at high nicotine content and conventional tobacco cigarette was shown in Fig. 4: the mode shifted to about 190 nm at 100 °C for both the cigarettes tested.

4. Conclusions

The study focuses on the physical characterization of the mainstream aerosol generated by e-cigarettes in terms of total particle number concentrations and size distributions. Conventional tobacco cigarettes were also tested for comparison. An experimental campaign aimed to evaluate the influence parameters affecting the e-cigarette-generated particles from a dimensional point of view was performed: type of cigarette, liquid flavor, nicotine content and puffing time were considered.

The particle number concentration of the mainstream aerosol generated by e-cigarettes, averaged across the all liquids and type of e-cigarette tested, resulted equal to $4.39 \pm 0.42 \times 10^9$ part. cm^{-3}, which is similar to that of conventional tobacco cigarette.

Major influence parameters were the liquid nicotine content and the puffing time. In particular, greater particle number concentrations were measured for higher nicotine content liquids, with respect to nicotine-free ones, and longer puffs, otherwise liquid flavors and e-cigarette type did not affect the particle emission.

Particle size distribution measured in e-cigarette-generated mainstream aerosol showed a mode higher than 100 nm (120–165 nm) and similar to conventional tobacco cigarette one. No effects of the nicotine content as well as liquid flavor were found in particle size distribution data.

The authors believe that findings of the present paper can be propaedeutic for future studies involving the particle dose evaluations and related toxicological health effects as the e-cigarettes were found to be a major particle source, which can lead to significantly high deposition in vapers. Moreover, the results here presented can be worthwhile for regulatory authorities aimed to rule the e-cigarette use.

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