EPJ Web of Conferences **143**, 02006 (2017) DOI: 10.1051/epjconf/201714302006
EFM 2016

Measurement of an electronic cigarette aerosol size distribution during a puff

Miloslav Belka[1,*], *Frantisek* Lizal[1], *Jan* Jedelsky[1], *Miroslav* Jicha[1], and *Jiri* Pospisil[2]

[1]Dept. of Thermodynamics and Environmental Sciences, Energy Institute, Faculty of Mechanical Engineering, Brno University of Technology, 616 69 Brno, Czech Republic
[2]Dept. of Power Engineering, Energy Institute, Faculty of Mechanical Engineering, Brno University of Technology, 616 69 Brno, the Czech Republic

Abstract. Electronic cigarettes (e-cigarettes) have become very popular recently because they are marketed as a healthier alternative to tobacco smoking and as a useful tool to smoking cessation. E-cigarettes use a heating element to create an aerosol from a solution usually consisting of propylene glycol, glycerol, and nicotine. Despite the wide spread of e-cigarettes, information about aerosol size distributions is rather sparse. This can be caused by the relative newness of e-cigarettes and by the difficulty of the measurements, in which one has to deal with high concentration aerosol containing volatile compounds. Therefore, we assembled an experimental setup for size measurements of e-cigarette aerosol in conjunction with a piston based machine in order to simulate a typical puff. A TSI scanning mobility particle sizer 3936 was employed to provide information about particle concentrations and sizes. An e-cigarette commercially available on the Czech Republic market was tested and the results were compared with a conventional tobacco cigarette. The particles emitted from the e-cigarette were smaller than those of the conventional cigarette having a CMD of 150 and 200 nm. However, the total concentration of particles from e-cigarette was higher.

1 Introduction

Roughly 6 million deaths around the world are attributable to tobacco smoking annually. More than 5 million of those deaths are outcomes of direct tobacco smoking while more than 0.6 million are caused by exposure to secondhand smoke [1]. Secondhand smoke or sometimes referred as “environmental tobacco smoke” is a combination of exhaled mainstream smoke (released from the cigarette end during a puff) and sidestream smoke (released from the cigarette between puffs). A chemical composition of both mainstream and secondhand smoke is almost identical. However, the total particle concentrations vary greatly [2]. Cigarette smoke contains around 4000 constituents including many carcinogens, such as polynuclear aromatic hydrocarbons (PAHs) or aldehydes [2,3].

Because of many adverse effects of smoking tobacco on human health, there are various tobacco control policies being implemented to reduce the tobacco use. The most effective policy is raising tobacco taxes, other can be the introduction of mandatory smoke-free bars and restaurants [4]. However, this is a long-time process and for example, smoke-free bars are not mandatory in the Czech Republic yet. Another mentioned way to avoid using tobacco products can be a use of alternatives, such as electronic cigarettes.

E-cigarettes are advertised as a healthier alternative to conventional cigarettes and they are categorized as nicotine delivery devices. They usually consist of three parts: a battery, an atomizer and a cartridge. The battery provides power to the heating element/atomizer, which atomizes a liquid solution inside the cartridge and thus produces vapors that are inhaled by a user [5]. Major compounds of the liquid solution are propylene glycol, glycerol, various amounts of nicotine and flavors.

An e-cigarette smoke is an aerosol comprised of fine particles (smaller than 1 μm). Knowledge of the particle size distribution and chemical composition is essential because it mainly determines deposition hot-spots and the subsequent impact on human health. A chemical analysis of an e-cigarette smoke has been carried out in several studies [3,6-8] and the results were compared with conventional cigarettes concerning the presence of carcinogens and other harmful constituents. The results showed that although the levels of harmful constituents varied considerably among different brands of e-cigarettes, they were around 1 to 2 orders lower than in conventional cigarette aerosol. On the other hand, a study from Wieslander et al. [9] concludes, that inhalation of highly concentrated propylene glycol can cause irritation of upper respiratory airways in non-asthmatic subjects and some subjects can react with lower airway obstruction or cough. Moreover, since e-cigarette popularity spread only recently, there are no

* Corresponding author: Belka@fme.vutbr.cz

direct studies engaged in the long-term use of e-cigarettes and its biological effects on human health [5].

Particle concentration and size distribution measurements encompass many obstacles and complications because one has to deal with high concentration aerosol containing volatile compounds. Ingebrethsen et al. [10] employed spectral transmission procedure to analyze particle concentration and sizes of undiluted e-cigarette aerosol. Fuoco et al. [11] compared several e-cigarettes and conventional tobacco products using Fast Mobility Particle Sizer. Results from both studies showed that e-cigarette aerosol is highly concentrated (order of 10^9 particles/cm^3) with particle diameters around 200 nm. Manigrasso et al. [12] used similar experimental setup and the results implemented in a model for prediction of particle deposition in human respiratory airways. Schripp et al. [13] studied indoor air quality in conjunction with e-cigarette smoking by placing a volunteering smoker into 8 m^3 chamber.

E-cigarettes are becoming more and more popular nowadays. Therefore, it is very important to study their properties and evaluate their potential health threats. In this paper we carried out concentration and size measurements of particles emitted by e-cigarette commonly available on the Czech Republic market. Moreover, the results were compared with conventional tobacco cigarettes.

2 Methods

The aim of the experiments was to measure total particle concentration and sizes of mainstream cigarette and e-cigarette smoke. An experimental setup is depicted in Fig. 1. The smoke was analyzed for a 4 s square puff of total volume 60 cm^3, which was similar to that reported by Ingebrethsen et al [10]. The puff was performed by a "puffing machine", which was a piston placed in a cylinder and driven by an electromotor. The motions of the motor were set via laptop. After the puff was drawn into a sampling chamber, a control valve at the e-cigarette was closed and the one connecting the sampling chamber to a Scanning Mobility Particle Sizer 3936 (TSI, Shoreview, MN, USA) was opened.

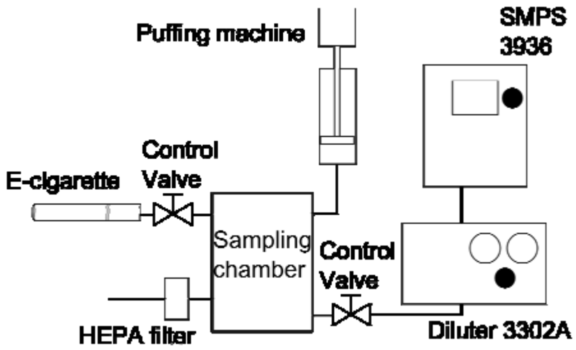

Fig. 1. Experimental setup for particle concentration and size measurement during a cigarette puff

In the SMPS system, the particles were neutralized using X-Ray neutralizer 3087 and then classified according to their electrical mobility inside a Differential Mobility Analyzer 3081. The classification is executed by changing voltage of an electrode. The classified particles continued to a Condensational Particle Counter 3775, where they grew via condensation of butyl alcohol and were counted afterwards. The SMPS requires some time to "scan" a chosen size distribution and the more time, the better accuracy. On the other hand, e-cigarette smoke is high concentration aerosol with volatile compounds. Therefore, fast measurement is required. The interval of 90 s was set as a compromise between sufficient sampling accuracy and requirement of the shortest possible duration of measurement. The flow rate of the SMPS was set to 0.3 LPM.

Because the particle concentration was expected to exceed the limit of the SMPS system, two-step dilution was applied. The first step took place in a 2.5 liters big sampling chamber and the second step was Aerosol Diluter 3302A (TSI, Shoreview, MN, USA). A dilution factor of the aerosol diluter was set to 100 and together with the sampling chamber, the total dilution factor was roughly around 4000. In order to preserve constant pressure inside the sampling chamber during the SMPS measurement, ambient air filtered through HEPA filter was supplied.

An e-cigarette by Joyetech was tested during the measurements and it was filled with two different liquids with nicotine content of 0 and 16 mg/ml. The e-cigarette was fully charged and its reservoir was filled up to three–quarters before the measurements. The e-cigarette has variable wattage output, which changes power output from the battery. The wattage output was adjusted to a maximum value, 9.6 W, and thus delivering the largest amount of vapor. The results were compared with Light Marlboro cigarette, which has a nicotine content of 0.6 mg. Four puffs were measured for every sample while the first puff was not included into averaged results as being considered a "warm up" puff. After every puff, a filtered air was drawn into the sampling chamber by a vacuum pump in order to remove any remaining aerosol.

3 Results

The particle number concentrations and size distributions of e-cigarettes can be seen in Fig. 2. and Fig. 3. Particle number concentrations were in the order of 10^9 part/cm^3, which is comparable to results by Fuoco et al [11]. Size

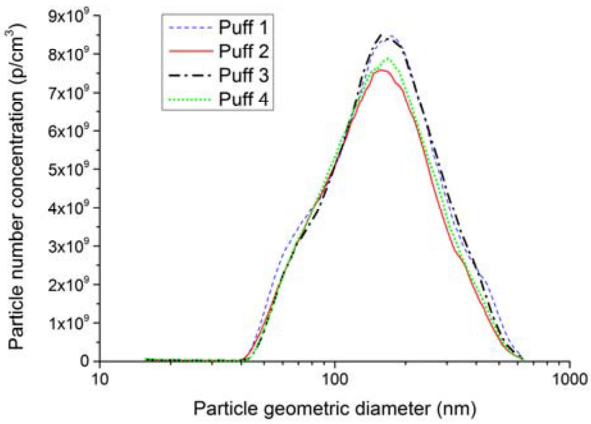

Fig. 2. Size distribution of the e-cigarette with high nicotine content

distributions of single puffs are rather identical and there is no noticeable difference for the first "warm up" puff, which was expected considering the e-cigarette working principle. The main modes for the e-cigarette with high nicotine content were 156–174 nm, for the e-cigarette with zero nicotine content they were in the range of 145–168 nm, which indicated that there was no significant dependence of particle sizes on nicotine content.

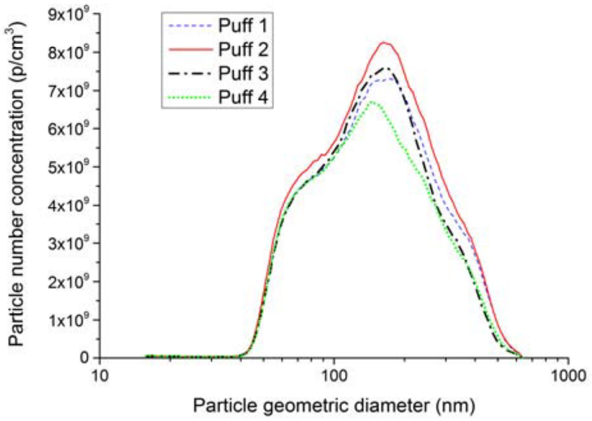

Fig. 3. Size distribution of the e-cigarette with zero nicotine content

The particle number concentration and size distribution of conventional cigarette is depicted in Fig. 4. The particle number concentrations varied greatly between individual puffs. The particle number concentration increased with increasing puff number. This phenomenon was observed in other studies as well [14,15] and it is probably caused by the actual length of the remaining smoldering cigarette. On the other hand, the size distributions were comparable between the puffs except for the first puff. The main mode for the first puff was 156 nm while for the rest of the puffs the main modes covered the range of 187–201 nm.

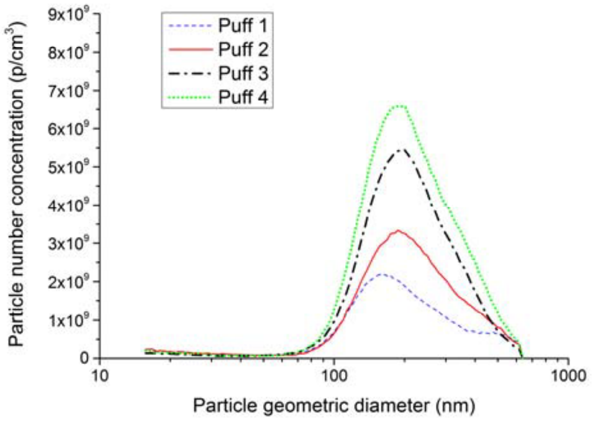

Fig. 4. Size distribution of the conventional cigarette

A comparison of size distributions of the e-cigarette and the conventional cigarette can be seen in Fig. 5. Size distribution for every type was calculated as the mean average of puffs 2 to 4. The averaged total number concentrations and count median diameters (CMDs) are listed in Table 1. All the distributions were log-normal with positive skewness. Comparing two liquids for the e-cigarette, there is a minor change in particle number concentration, in particular higher nicotine content resulted in higher particle number concentration for the main mode. However, as can be seen in Table 1, the total number concentration is higher for the zero nicotine content liquid. It is worth noting that there is a small deviation at 70 nm diameter for zero nicotine content e-cigarette, which increases the total number concentration and decreases a CMD.

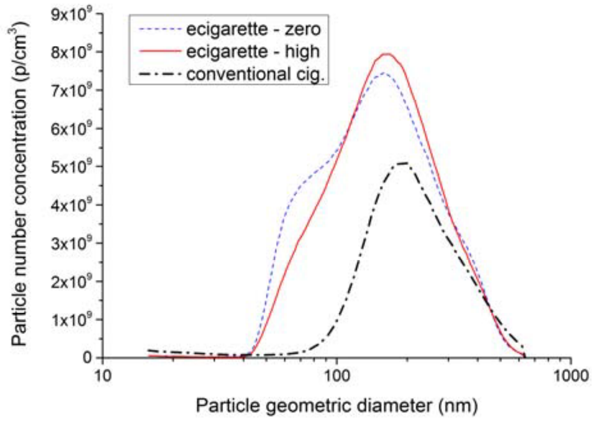

Fig. 5. Comparison of size distributions between e-cigarette and conventional cigarette; two e-cigarette cartridges were tested (high and zero nicotine content)

The total particle concentrations of e-cigarette were roughly two times higher than that of a conventional cigarette. This indicates that although e-cigarette smoke contains less harmful constituents than conventional cigarette smoke, the particle numbers for e-cigarettes are higher and human respiratory airways can be exposed to high doses of compounds such as propylene glycol. The median size of the particles was a little bit smaller for the e-cigarettes and ranged around 150 nm. This means that as well as for conventional cigarettes, e-cigarette smoke particles are in fine or ultrafine range and thus can easily penetrate deep into human lungs and deposit there mostly by diffusion and sedimentation.

Table 1. Comparison of total particle concentrations and CMDs (count median diameters); Value±Geometric Standard Deviation

	Averaged total number concentration (p/cm^3)·10^9	Averaged CMD (nm)
E-cigarette zero nicotine	4.81±0.1	147.1±4,5
E-cigarette high nicotine	4.63±0.05	157.6±3,8
Conventional Cigarette	2.41±0.15	201.6±0.3

Discussion

In this paper we carried out measurements of particle number concentrations and size distributions of e-cigarettes using the SMPS 3936 system. The measured cigarette mainstream smoke was sampled into the chamber and analyzed within 90 s. The total concentration and size distributions were found to be in acceptable agreement with other studies [11,14].

However, there are some uncertainties in the measurement. Since the SMPS system divides a size distribution into channels and then scans the concentration in every channel step by step, it requires constant size distribution in analyzed sample during scan time. However, an e-cigarette smoke is high concentration aerosol with volatile compounds. That means high probability of coagulation, which is a collision between particles and subsequent adherence. The coagulation rate is time-dependent, therefore it is convenient to measure the particle sizes very fast, but measurement of the size distribution within few seconds is not possible with the SMPS 3936 system.

Coagulation can be prevented by proper dilution, such as sampling of particles into a chamber. On the other hand, Ingebrethsen et al. [10] stated that high dilution can cause evaporation of large particles and biases in the results. Moreover, dilution of e-cigarette smoke can result in condensation of volatile gaseous compounds and occurrence of small diameter (less than 50 nm) mode in size distribution. This bimodal distribution was observed for example by Schripp et al. [13]. Small diameter mode was not found in our measurements, but there was a slight deviation around 70 nm for zero nicotine content e-cigarette.

Another issue is the sedimentation and deposition of particles on the chamber walls, which can alter the size distribution during measurement.

To summarize the facts above, the concentration and size distribution of e-cigarette was measured with sufficient accuracy. However, more measurements will be needed to quantify the influence of various aerosol phenomena.

Conclusions

The total concentrations and size distributions of e-cigarette mainstream smoke were measured by the SMPS system. The e-cigarettes emitted smoke with concentrations in the order of 10^9 particles/cm^3. The main mode was approximately 170 nm and the count median diameter was approximately 150 nm. There was only a minor change in concentrations and sizes between different liquids used in the e-cigarette.

Comparing the e-cigarette smoke with that of a conventional cigarette, the number concentration was two times higher for the e-cigarette and the count median diameter was smaller than that of the conventional cigarette, 150 against 200 nm. This indicates that some e-cigarettes can deliver considerably more particles into a human respiratory system than conventional cigarettes, even though the e-cigarette smoke contains less harmful constituents. All the particles of the e-cigarette smoke are smaller than 1 μm and some of them are in ultrafine particle range (smaller than 0.1 μm), thus able to penetrate deep into a human respiratory system, deposit there and potentially get into the bloodstream. However, these measurements are only a first step in evaluation of possible health outcomes. It is necessary to evaluate a long-term health effects of e-cigarettes

Acknowledgement

This work was supported by the Czech Science Foundation under the grant GA16-23675S and by the project FSI-S-14-2355.

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