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Particulate Emissions from Commercial Handheld Sparklers: Evaluation of Physical Characteristics and Emission Rates

Raghu Betha, Rajasekhar Balasubramanian*

Department of Civil and Environmental Engineering, Faculty of Engineering, National University of Singapore, 1 Engineering Drive 2, E1A-07-03, 117576 Singapore

ABSTRACT

Ground level fireworks, such as sparklers, are commonly used by children during festive occasions and celebrations. Airborne particulate matter (PM) emissions from these fireworks are of serious health concern. However, to date no information is available on the PM emission characteristics from sparklers and their emission rates. In this study, three commonly used sparklers, namely, low smoke sparklers (LSS), colored sparklers (CS) and whistling sparklers (WS), were investigated for their PM emissions and emission rates. It was observed that WS (4.45×10^{11} s^{-1} or 3.24×10^{10} g^{-1}) had higher emission rates compared to CS (2.9×10^{11} s^{-1} or 1.64×10^{10} g^{-1}) and LSS (7×10^{10} s^{-1} or 1.68×10^{9} g^{-1}). A relatively large number of nanoparticles (NPs) were emitted from their burning. About 83% of PM emitted by WS and CS were in the nano size range (aerodynamic diameter (AED) < 50 nm) whereas LSS had 62% of total particles in the nano size range. In addition, particle deposition fractions into the lung were also estimated. It was found that CS and WS had higher deposition efficiency compared to that of LSS.

***Keywords*:** Sparkler emissions; Particle number concentration; Emission rates; Deposition fraction.

INTRODUCTION

Fireworks are an integral part of major festive occasions and celebrations all over the world. A wide variety of pyrotechnics are used to produce various visual, light, sound, gas and smoke effects. The emissions from these fireworks have been reported to elevate levels of PM in ambient air during festive celebrations (Kulshrestha *et al.*, 2004; Drewnick *et al.*, 2005; Moreno *et al.*, 2007; Wang *et al.*, 2007; Steinhauser *et al.*, 2008; Vecchi *et al.*, 2008). The metallic nature of airborne particles emitted from the fireworks is of great health concern (Smith and Vu, 1975; Murty, 2000; Ravindra *et al.*, 2003). Air pollutants, emitted from pyrotechnic displays at a high altitude, can be dispersed in a large volume of air and therefore may not pose a significant health hazard, (Dutcher *et al.*, 1999; Perry, 1999). However, the ground level pyrotechnic displays such as sparklers are in the immediate vicinity to people. Therefore, exposure to emissions from sparklers can lead to adverse health effects because of the presence of ultrafine particles (UFPs; PM with aerodynamic diameter (AED) ≤ 100 nm) (Kulshrestha *et al.*, 2004; Oberdorster *et al.*, 2005).

Sparklers mainly consist of a metal rod, or thin tube coated with an explosive mixture to burn, producing a shower of colorful sparks. Sparklers may be designed to be non-handheld or handheld (i.e., fixed to a support) (Russell, 2000). Their chemical composition can be described by four main components (McManus, 1975; Helmenstine, 2012): (1) A metallic component (e.g., aluminum, iron, titanium, zinc, magnesium powder or flakes), which is responsible for producing sparks; (2) An oxidizing component (e.g., potassium, barium or strontium nitrates, potassium chlorate, ammonium perchlorate); (3) A combustible binder, which holds the mixture together (e.g., dextrin, nitrocellulose, shellac, gum Arabic, or other sugars and resins); and (4) A fuel component (e.g., charcoal). Fine particulate matter, or $PM_{2.5}$ (PM with AED < 2.5 μm), UFPs, and nanoparticles (NPs, PM with AED < 50 nm), emitted from sparklers, are mainly metallic in nature (Kulshrestha *et al.*, 2004) and pose a threat to human health due to the abilities of UFP and NPs to deposit in all regions of the respiratory tract. The deposited particles can be taken up by cells, and translocate to sensitive organs of exposed individuals via the blood or lymph (Oberdorster *et al.*, 2005). PM generated from the combustion of sparklers is likely to fall in the nanoscale size range initially. Then, atmospheric processes could lead to growth of the particles into the accumulation mode (AED > 100 nm), whose atmospheric fate, environmental impacts and toxicity to people are determined by their physical and chemical characteristics. The persistence of particles in the

* Corresponding author. Tel.: +65-6516-5135;
Fax: +65-6774-4202
E-mail address: ceerbala@nus.edu.sg

air is mainly dependent on their particle number concentration (PNC), and size distribution (PSD) (Seinfeld, 1997; Hinds, 1999). Unlike the emissions from commercial products such as church candles, incense sticks and cigarettes (Fine *et al.*, 1999; See *et al.*, 2008; Gowadia *et al.*, 2009), which are mainly composed of organic compounds, PM emitted from sparklers is metallic in nature and is known to exert toxic effects on humans (Buzea *et al.*, 2007). However, recent studies have shown that the toxic effects of PM are not entirely due to their composition, but also due to their size and concentration in air (Chung *et al.*, 2009; Liden *et al.*, 2009).

Despite the potential health concern, metallic aerosol emissions from sparklers have not been investigated systematically. To the best of our knowledge, there is no database available in literature on the physical and chemical characteristics of sparkler emissions. To fill this knowledge gap, this study on particulate emissions from handheld sparklers was conducted. Physical properties such as PNC and PSD of particles emitted from sparklers were investigated. In addition, emission factors of PM from these sparklers (#/s and #/g of sparkler burnt) were also estimated, followed by the calculation of the deposition fraction of these particles into human lungs. These emission factors can be of great value while developing exposure assessment models to quantify the health risk due to inhalation of metallic particulate emissions from handheld sparklers.

EXPERIMENTAL METHODS

Measurement of Particle Number Concentrations and Size Distributions

An experimental chamber (shown in Fig. 1) with 0.5 m × 0.5 m × 0.5 m dimensions was used to characterize PNC and PSD emitted from sparklers in a controlled environment. Sparklers were placed in the centre of the chamber and ignited to burn. Three most commonly available sparklers were chosen for this study: (1) Whistling sparklers (WS), (2) Low smoke sparklers (LSS) and (3) Colored sparklers (CS). PM emissions were measured using fast mobility particle size spectrometer (FMPS, TSI Incorporated, MN, USA). The aerosol inlet of the FMPS was placed right in the middle of the chamber, and a small fan at the bottom of the chamber stirred air to ensure particle homogeneity within the chamber. FMPS measured sub-micrometer particles (AED < 1 μm) in the sparkler smoke over a particle size range of 5.6–560 nm at a time resolution of 1 sec.

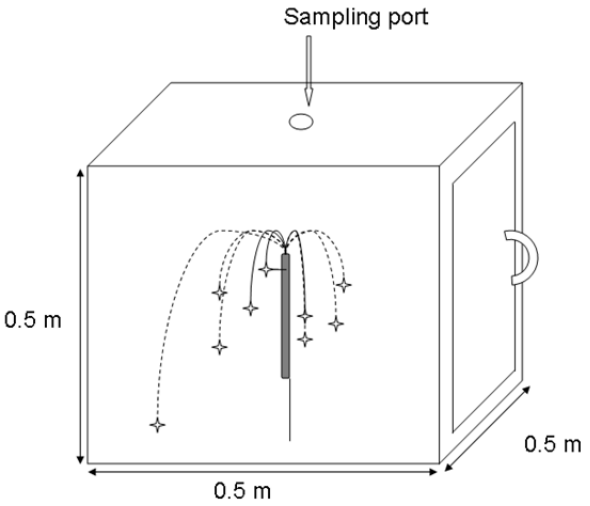

Fig. 1. Experimental chamber.

Prior to measurements, the chamber was purged with laboratory air for about 15 min. Each sampling cycle comprised a 30 min background air monitoring in the chamber, an entire burning cycle, and a 60 min post burning period. One sparkler was lit with propane lighter just outside the chamber door and was brought into the chamber immediately. The door was closed instantaneously to ensure that the loss of particles was minimal. The experiment was repeated 3 times for each type of sparkler.

Determination of Emission Rates

The emission rates of PM of different sizes were determined from the PNC and PSD data according to the method based on a single compartment mass balance model assuming that the emission rates and decay rates of the particles remained constant reported by Liu *et al.* (2003). In their model Liu *et al.* (2003) used the mass balance model to estimate emission rates of particles based on mass concentrations. However, the model calculation can also be used to estimate the particle emission rate based on the PNC since particles are assumed to be perfect spheres with a constant density. As the airborne particles can be removed by several pathways, for example, dry deposition on the chamber walls, or infiltration through the sampling hole, with different rates for particles of different sizes, their respective removal rates were evaluated using Eq. (1)

$$C_j = C_{max,j}[e^{-k_j(t-T)}], \quad t \geq T \tag{1}$$

where C_j (#/cm^3) represents the number concentration of particles of size j at the time t (s), the time elapsed from the initiation of sparkler burning, while $C_{max,j}$ (#/cm^3) represents the maximum concentration of particles of size j which corresponds to C_j at time T (s), the time when the concentrations start dropping. The background concentration of particles was subtracted from the concentration readings to compute C_j and $C_{max,j}$. The slope of the linear regression plot of $\ln(C_j/C_{max,j})$ against (T-t) would then be equal to k_j (#/s), the removal rate of particles of size j.

After establishing the removal rate k_j, the emission rate of the particles of size j, P_j (#/s), was subsequently calculated from Eq. (2) (See *et al.*, 2007):

$$C_j = \frac{P_j}{Vk_j}(1-e^{-k_j t}) \tag{2}$$

where V (0.125×10^6 cm^3) is the volume of the chamber and P_j is the slope of the linear regression plot of C_j against $(1-e^{-k_j t})/Vk_j$. The emission rate of particles of size j in

terms of per mass of sparkler burned, E_j (#/g), was then evaluated from the burn rate, B (g/s), from the following equations:

$$B = \frac{m_i - m_f}{T} \quad (3)$$

$$E_j = \frac{P_j}{B} \quad (4)$$

where m_i and m_f are the masses of the sparklers before and after burning, respectively.

Particle Deposition in the Lung

One of the most important parameters in the evaluation of potential health impacts based solely on physical characteristics is the amount of particles that can be deposited in the lung, which is mainly governed by the particle diameter (D_p, nm) (See *et al.*, 2007). For airborne particles of diameter ranging from 5.6 to 560 nm, almost all the particles are expected to be deposited in the alveolar region. The following equations developed by (See *et al.*, 2007), were used for the calculation of the deposition rate of particles for the sparklers:

$$f_i = 0.8850 - \frac{2.991 D_{pj}}{178.1 + D_{pj}} + \frac{3.112 D_{pj}}{525.7 + D_{pj}} \quad (5)$$

$$N = \sum_{j=5.6}^{560} N_j = \sum_{j=5.6}^{560} P_j \times f_j \quad (6)$$

$$f = \frac{N}{P} \quad (7)$$

where f_j and f denote the deposition fraction of particles of size j and that of all particles from 5.6 to 560 nm, respectively. N_j (#/s) and N (#/s) represent the number of particles of size j and that of all particles from 5.6 to 560 nm that are capable of being deposited in the lung, respectively. P_j has the same meaning as explained above, and P (#/s) is the total emission rate of particles in the diameter range of 5.6 to 560 nm. The above equations assume that all particles contained in sparkler emissions are inhaled by exposed individuals and are deposited in the alveolar region of the respiratory tract.

RESULTS AND DISCUSSION

Number Concentrations and Size Distributions of Different Types of Sparklers

Fig. 2 shows the temporal variation of PNC of a typical sampling sequence of a sparkler. It consisted of background measurement ($t < 0$), the burning period ($0 \le t \le T$) and the post-burning period ($t \ge T$). The burning duration is dependent on the sparkler type and $t = 0$ represents the start of the burning process of the sparkler. As soon as the lighted sparkler was brought into the experimental chamber at $t = 0$, the PNC increased rapidly until the sparkler was fully burned out at $t = T$. The maximum PNC, C_{max}, was nearly 40 times (1.60×10^5 #/cm^3) the background concentration and reached its value at time T = 52 s in the case of LSS. CS and WS, on the other hand, have shown that the PNC increased up to 97 and 231 times of the initial concentration when the sparkler was brought into the experimental chamber, respectively. The maximum PNC, C_{max}, (CS: 4.12×10^5 #/cm^3; WS: 9.2×10^5 #/cm^3) was reached at time T = 22 s for CS and T = 13 s for WS. Subsequently, the concentration reached the original background level

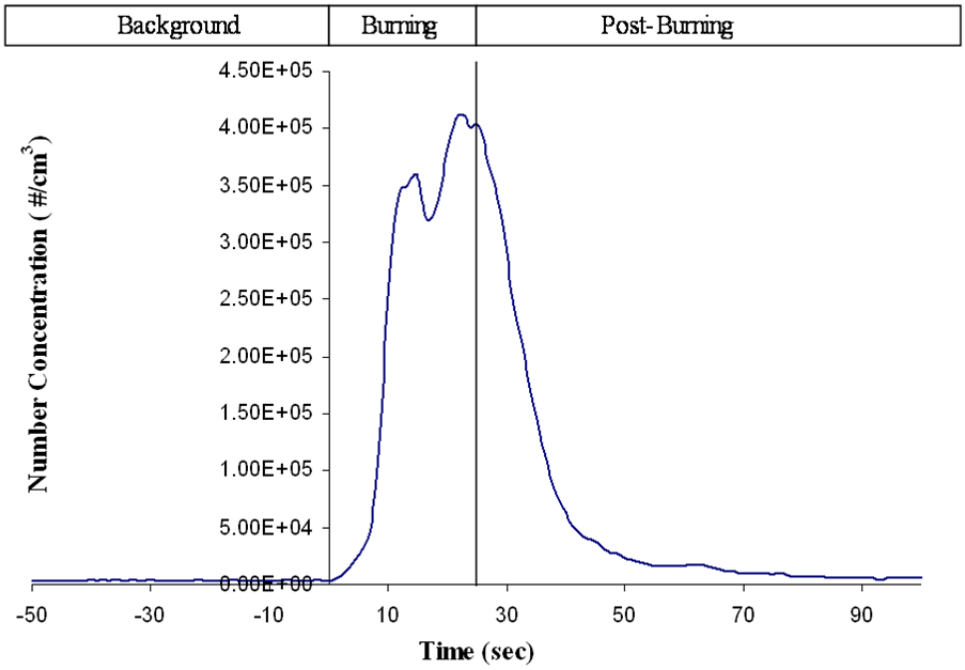

Fig. 2. Temporal variations of number concentrations of a typical sampling cycle of sparkler.

approximately 60 s after t = T for both LSS and CS. However, for WS the particle decay took relatively longer (90 s) because of the highest C_{max} among the three types of sparklers investigated in this study.

Fig. 3 presents the PSD of LSS, CS and WS of at various stages of the burning period which included the start ($0 < t \leq T/3$), middle ($T/3 < t \leq 2T/3$), and end ($2T/3 < t \leq T$) of the burning period. It was observed that the particle peak diameter remained unchanged throughout the burning period. The key reason for the lack of variation in peak diameters during measurements was that the relative humidity in the chamber was maintained at a constant value (40%) during the entire course of experiments. The low humidity levels in the experimental laboratory and the short duration of the burning time reduced the hygroscopic growth of particles. The lowest number of particles was emitted at the start and the PNC increased with the progress of the burning process, eventually reaching the peak towards the end of the burning process. For the LSS (Fig. 3(a)), the highest concentration of particles was in the nanometer size range (0–50 nm) at 62%, followed by the Aitken mode (50–100 nm) at 32%. The lowest number of particles was found in the submicrometer or accumulation mode particle range (100–560 nm) at 6%. The PSD observed at various stages of the burning period for the CS is shown in Fig. 3(b). 85% of the total particles emitted were in the nanometer size range (0–50 nm) while the aitken-mode and accumulation mode particles accounted for 7% and 8%, respectively. WS also showed similar trends to those of CS. Nearly 80% of particles were in the nanometer size range of 0–50 nm while the Aitken and accumulation mode particles accounted for 13% and 7%, respectively. From these results, it is clear that a major fraction of airborne particles emitted from sparklers were nanoparticles in the size range of 0–50nm. The observed fraction of nano particles in the size range of 0–50 nm (80%) emitted from sparklers was comparable to that of diesel engine emissions (Kittelson, 1998). Diesel particulate matter (DPM) comprises nearly 90% of airborne particles in the nucleation mode (Kittelson, 1998). However, unlike diesel engines, the emissions from sparklers were mainly of metallic origin (Kulshrestha *et al.*, 2004). Therefore, the latter particles are of utmost concern from human health viewpoint because redox active metals such as Fe^{2+} induce oxidative stress in cells exposed to the emission upon inhalation leading to various health effects (Halliwell, 1991).

Emission Rates

The emission rates for different sized particles emitted from LSS, CS and WS were determined using Eqs. (2)–(4) after taking into account the removal rates of particles of different sizes from Eq. (1). Table 1 shows the initial mass of the sparklers before burning, the final mass after the complete burning, the time taken for the burning process and the burning rates of the sparklers along with their standard deviations. From the table, it can be seen that the LSS had the lowest burning rate while the WS had the highest burning rate. The two stacked columns in Figs. 4(a) and 4(b) show the number of NPs (5.6–50 nm), aitken (50–100 nm) and submicrometer or accumulation (100–560 nm) that were emitted per gram of sparkler burnt and per second, respectively. The whistling sparkler (4.45×10^{11} #/s or 3.24×10^{10} #/g) had the highest emission rates in terms of both the time taken to burn and the mass of sparkler burnt for all three size ranges of particles followed by CS (2.9×10^{11} #/s or 1.64×10^{10} #/g) and LSS (7×10^{10} #/s or 1.68×10^{9} #/g). The high emission rates in WS may be contributed by the larger amount of ingredients used in the sparklers. Since whistling sparklers produce both light and noise effects, a larger amount of metallic ingredients may be necessary to produce the effects. The emission rates observed from the sparklers in this study were very high compared to those obtained from other combustion sources such as incense sticks ($0.14–0.4 \times 10^{10}$ #/s) (See *et al.*, 2007), cigarette smoking ($0.32–0.62 \times 10^{10}$ #/s) (He *et al.*, 2004; Afshari *et al.*, 2005).

Deposition of Particles in the Lung

Sparklers are generally used during festive seasons. People, especially children, use these ground level pyrotechnic fireworks holding them in their hands and are therefore exposed to the emissions from sparklers in close proximity. A fair assessment of the potential health impacts due to exposure to different kinds of sparkler emissions will be the actual amount of particles which can be deposited in the respiratory tract of an individual, exposed to sparkler emissions for 1 s, with one sparkler burning at a time. As evaluated from Eqs. (5)–(7), the results of the calculations showed that the CS had the highest deposition fraction 0.57 followed by the whistling sparkler with 0.55. This shows that more than 50% of all the particles emitted from these sparklers are likely to be deposited in the interior part of the human lungs and thus pose harmful health impacts. The LSS was found to have the lowest deposition rate among the three sparklers, with 47% deposition rate. Because of high fraction of NPs, the deposition efficiency of particulate emissions from CS and WS into human lungs was higher compared to that of LSS. Sparkler emissions could be of serious health concern and should be reduced as much as possible.

CONCLUSIONS

In this study, physical characteristics (PNC and PSD) of three different sparklers were investigated. The emission rates of the three varieties of sparklers were determined. Results indicated that the WS had higher particle emission rates and the time of burning, while the LSS had the lowest emission rate. For all the sparklers under study, large fractions of UFPs were emitted. It was found that the NP emissions from LSS constituted 62.5% of the total particulate emissions while whistling (80.6 %) and colored (85%) sparklers showed higher percentage of NP emissions. In addition, the deposition fractions of the particles inside the lungs indicated that both whistling and colored sparklers had higher deposition fractions, 0.55 and 0.57, respectively. For LSS, the deposition fraction was found to be 0.47. Hence, low smoke sparkler poses relatively less harmful

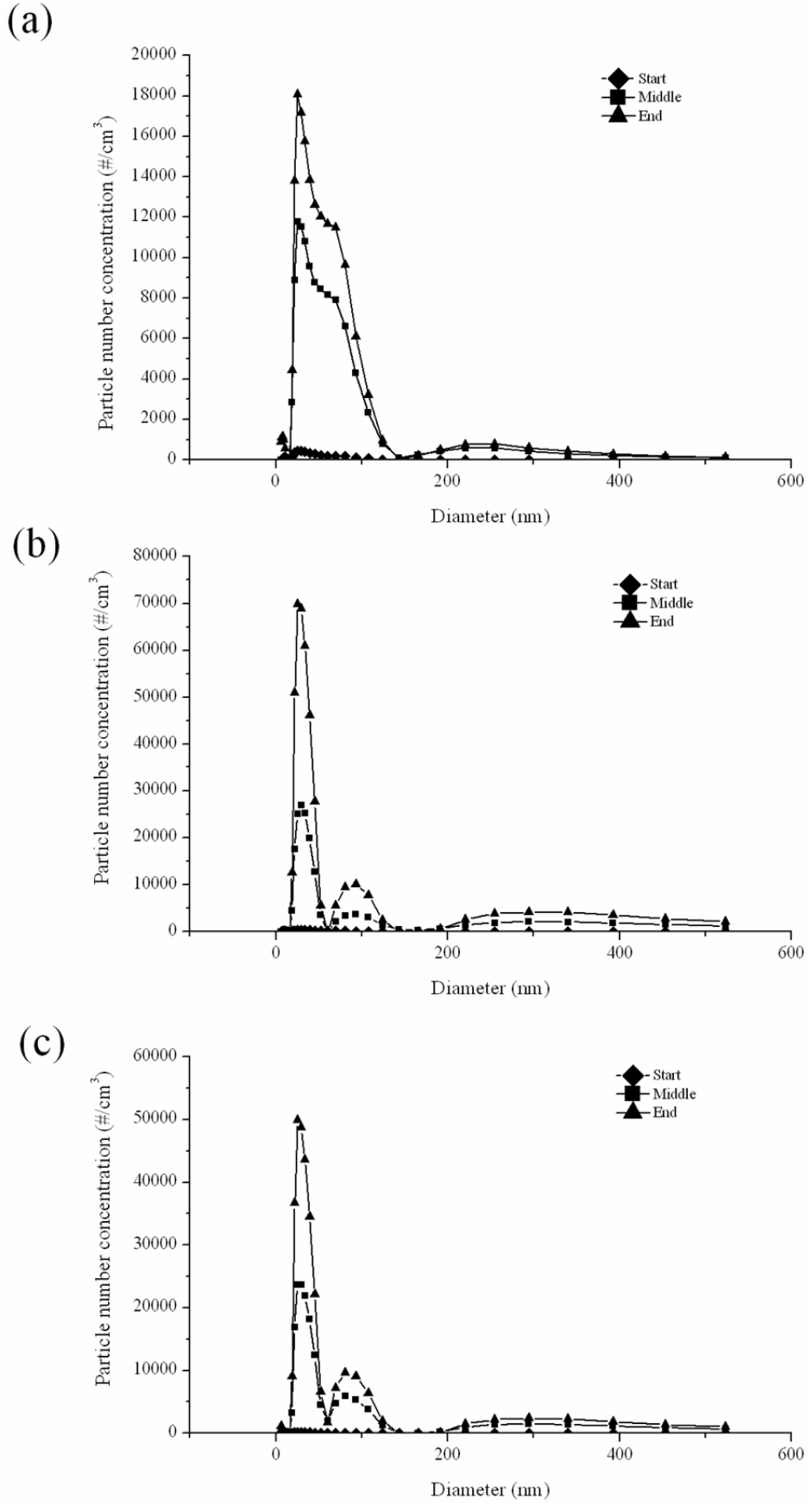

Fig. 3. Particle size distribution at different stages of the burning process (a) low smoke sparklers, (b) colored sparklers, and (c) Whistling sparklers.

Table 1. Characteristics of different sparkler.

Sparkler type	Initial Mass (m_i, g)	Final Mass (m_f, g)	Burning time (T, s)	Burnt rate (B, g/s)
Whistling sparkler	5.85 ± 0.34	4.66 ± 0.31	14.5 ± 2.1	0.05 ± 0.01
Low smoke sparkler	4.50 ± 0.06	3.76 ± 0.08	41.5 ± 13.4	0.03 ± 0.01
Colored sparklers	2.48 ± 0.05	1.67 ± 0.01	19.0 ± 2.8	0.04 ± 0.01

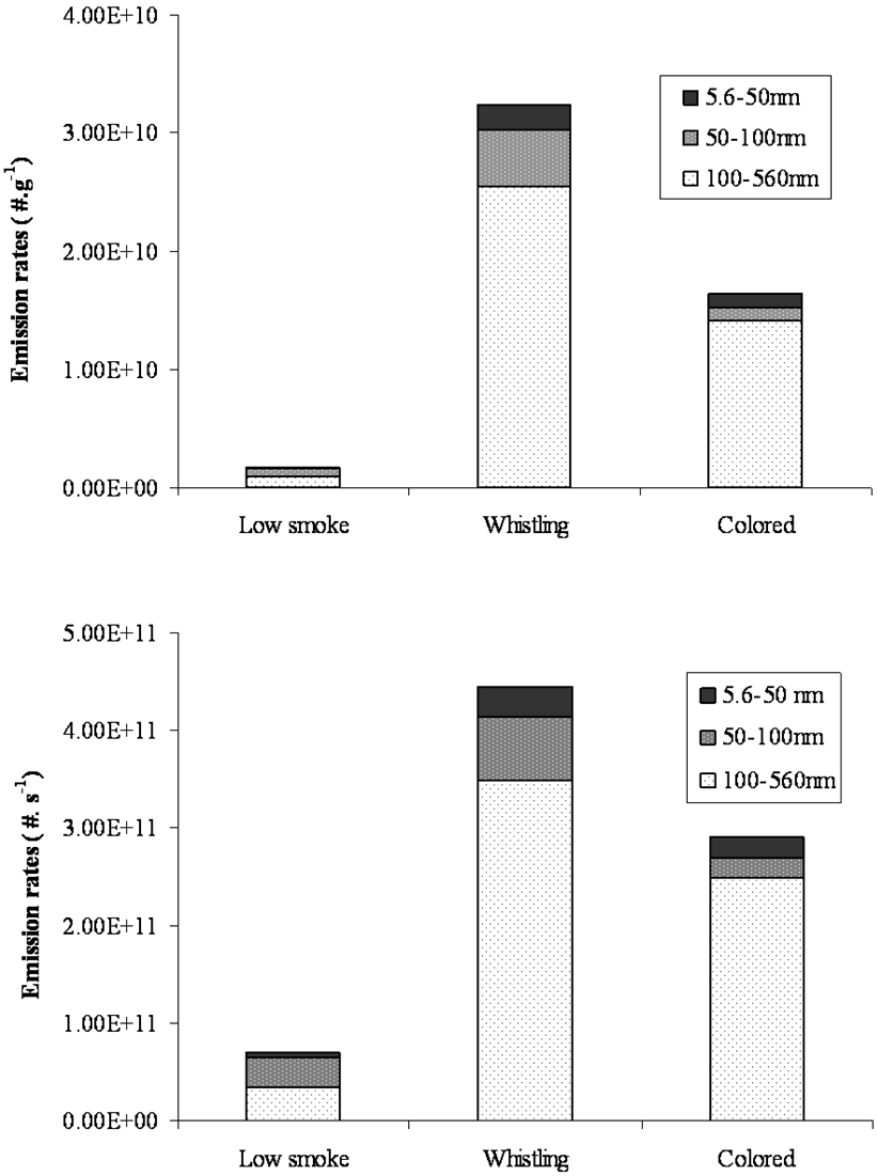

Fig. 4. Emission rates of particle in different size ranges from low smoke, colored and whistling sparklers (a) Emission rates (#/g of sparkler burnt) and (b) Emission rates (#/s).

impacts on human health due to its lower emission rates as well as lower particle deposition rate. Exposure to sparkler emissions can be of serious health concern, especially to children owing to the high particle deposition rates and high amount of NPs generated from sparkler combustion. There might be slight variations in the composition of different type of sparklers across various manufacturers and hence in their emissions. More studies should be conducted to investigate the physical characteristics of UFPs emitted from different brands of the same type of sparklers.

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