Aerosol and Air Quality Research, x: 1–13, xxxx

ISSN: 1680-8584 print / 2071-1409 online
doi: 10.4209/aaqr.201

Ultrafine Aerosol Particles from Laser Printing Process: Response Relationship between Operating Parameters and Emission Characteristics

Bingtao Zhao*

School of Energy and Power Engineering, University of Shanghai for Science and Technology, Shanghai 200093, China

ABSTRACT

Ultrafine aerosol particles (UFAP, diameter < 100 nm) emitted from laser printers have been considered as toxic aerosol. To address the response relationship between the operating parameters and real-time ultrafine emissions, three commercial printers were used to experimentally investigate their emission characteristics under different operating parameters including: the ready process, the number of pages printed, the page coverage and the print mode. The results showed that ultrafine particle emissions varied with the printer model. No causal correlation existed between the ultrafine particle number concentration and the $PM_{2.5}$ mass concentration of a specific printer. Ultrafine particle emission characteristics were highly associated with operating parameters other than printer/cartridge toner model. Not all of the tested printers displayed ultrafine particle emissions in the ready process. Ultrafine particle emissions increased with increasing number of printed pages and page coverage with a nonlinear relationship. Compared with continuous printing, intermittent printing has a so-called "peak-shaving" or "peak-shift" effect. The results may help to provide a simple and effective way to control and reduce ultrafine particle emissions from laser printers by means of improvement of operating conditions.

Keywords: Ultrafine particles; Laser printer; Operating parameter; Emission characteristics; Response relationship.

INTRODUCTION

Emissions of hazardous pollutants from office equipment such as printers and photocopiers have become an important environmental issue related to indoor air quality (Tuomi *et al.*, 2000; He *et al*., 2004; Destaillats *et al*., 2008; Morawska *et al*., 2013). Fine particulate matter (FP) is one of the most important hazardous pollutants (Lee *et al*., 2001; McGarry *et al*., 2011; Mullins *et al*., 2013; Stephens *et al*., 2013) as it is highly associated with public health concerns as toxic aerosol due to persistent lung damage (Matson, 2005; Gehin *et al*., 2008). Previous research has indicated that particles less than 0.5 μm in diameter might contribute the most to the adverse health effects of particulate air pollution and the risk of adverse health effects might increase with decreasing particle size (Meng *et al*., 2013). In recent years, with the increasing quantity of laser printers used in offices and the increasing application of engineered nanoparticles in toner cartridge manufacturing, the emission of ultrafine particles (UFP, also called nanoparticles which are less than 100 nm in diameter) have received great attention as an issue of indoor air pollution (Kagi *et al*, 2007; Tang *et al.*, 2012).

Ultrafine aerosol particle emissions from laser printers have been investigated with emphasis on estimation of the particle emission rate (Wang *et al.*, 2012), the particle elemental composition (Morawska *et al*., 2009; Barthel *et al*., 2011) and the particle surficial characteristics (Jiang and Lu, 2010) in the last decade. It has been demonstrated that a close relationship exists between ultrafine particle emission characteristics and printer model, cartridge type, cartridge age, and paper type. Overall, most of the research has focused on exploring the effects of printer hardware on ultrafine particle emissions.

Basically, ultrafine particle emissions in the printing process are complexly affected by multiple factors. In addition to contributions from differences in hardware configuration, ultrafine particle emissions are also associated with operating or process conditions including: starting process, printing job characteristics, printing mode, and even environmental parameters. Researchers have investigated the effects of printing conditions such as cartridge age and toner coverage on the particle emission rate (He *et al.*, 2007; Wensing *et al.*, 2008; He *et al*., 2010), as well as the effects of page quantity on the maximum particle concentration and particle loss rate (Schripp *et al.*, 2008). More recently, printers with the same manufacturer were investigated to evaluate the individual effects of printing speed on particle emission characteristics (Byeon and Kim, 2012). However, it actually may also be attributed to the difference in the printer models. So far, rare reports have comprehensively

* Corresponding author.
Tel.: +86 21 55271751; Fax: +86 21 55272376.
E-mail address: zhaobingtao@usst.edu.cn

investigated the effects of operating conditions on transit emission characteristics of ultrafine particles from laser printers. Understanding the response relationship between ultrafine particle emission characteristics and operating parameters may contribute to a reduction of particle emissions from laser printers, and also provide an assessment on indoor environmental impact and public health considerations.

The aim of this work is to present a detailed investigation of the effects of operating parameters including: ready process (RP), number of pages (NP), page coverage (PC) and print mode (PM) on particle emissions for different laser printers. On this basis, the response relationship between ultrafine particle emissions and operating parameters are analyzed and discussed to reveal the effect mechanism.

EXPERIMENT SYSTEM AND METHODS

Experimental Setup

A laboratory-scale experimental system used in this study is illustrated in Fig. 1. It consisted of a commercial printer placed at the central bottom of a chamber, an aeration/exhausting system, and a monitoring system. The chamber with a volume of 0.53 m^3 was used to test the particle emission characteristics. The air cleaned by a high efficiency particulate air (HEPA) filter was aerated into the top of the chamber with a diffuser and exhausted from the side of the chamber. Particle emission characteristics were sampled and monitored from the opposite side of the chamber.

In this work, three widely-used commercial laser printers made by different producers or, by same producer but varied model: Brother HL-2240 (coded as Printer A), HP LaserJet 1606dn (coded as Printer B) and HP LaserJet P2015dn (coded as Printer C) were tested for ultrafine particle emission characteristics under varying operating parameters, as described in Table 1.

The real-time ultrafine particle number concentration was monitored using a water-based condensation particle counter with 5 nm to > 3 μm particle size range and 0 to > 2×10^4 particle concentration (WCPC Model 3785, TSI Inc.). The ultrafine particle size distribution was measured using a scanning mobility particle sizer with 2-1000 nm measurement range (SMPS Model 3080, TSI Inc.). The $PM_{2.5}$ mass concentration was measured using a DustTrak with 0.001–100 mg m^{-3} measurement range (Model 8520 TSI Inc.) over the test period. In addition, a temperature/humidity meter was used to measure the temperature/humidity in the chamber.

Experimental Design

All measurements were performed in the following phases: (1) Cleaning process: background particle concentration was monitored until the ultrafine particle concentration was very low with less than 200 # cm^{-3} in the chamber, and then stable for 5 minutes. (2) Ready process (optional): ultrafine particle concentration measurements were taken immediately after power initiation until ready status was reached. (3) Printing process: the measurement was taken during the printing job from beginning to end. (4) Decay process: the measurement was taken after the print job had finished. The printing and decay processes lasted for 30 minutes in total.

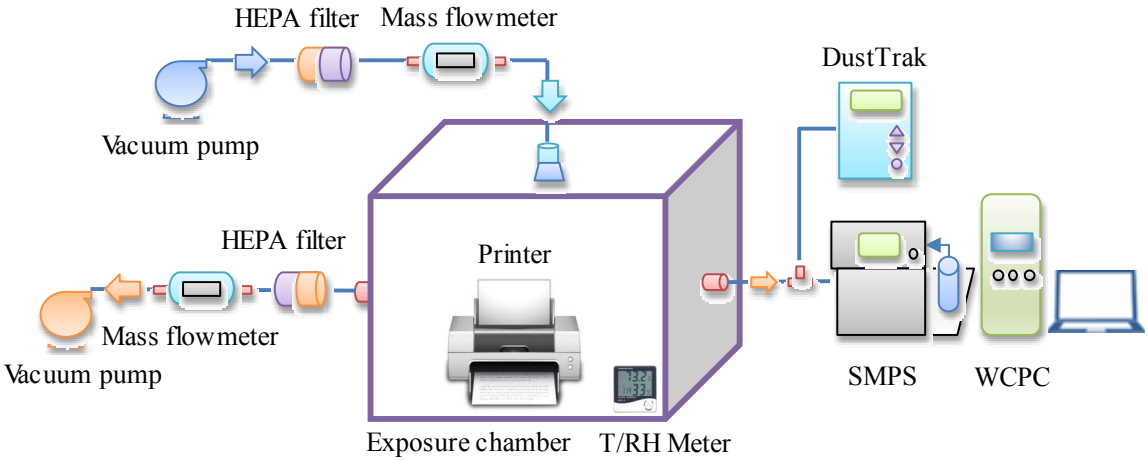


Fig. 1. Schematic diagram of experimental system.

Table 1. Printer and toner models used in this work.

Printer used	Printer A	Printer B	Printer C
Model	Brother HL-2240	HP LaserJet 1606dn	HP LaserJet P2015dn
Toner model	TN-420	CE278A	Q7553X
Auto sleep	Yes	Yes	Yes
Print speed[a] (ppm[b])	24	25	13
Manufactured year	2012	2011	2008

[a] Observed value.
[b] ppm: Pages per minute.

The experiment was carried out at 25 ± 1°C temperature, 40 ± 10% relative humidity and 1 h^{-1} air exchange rate. The specific design of the experiment is shown in Table 2.

Evaluation Parameters

Since the aerated air was clean (with very low particle concentration), the printer in the chamber was assumed as the only source of particles during the experiment. According to the law of conservation of mass, the particle concentration transport in the chamber can be modeled using the following governing equation (Ferro *et al*., 2004; Wallace *et al*., 2004; He *et al*., 2007; Schripp *et al*., 2008):

$$dC/dt = S/V - kC \quad (1)$$

where C is the particle concentration, t is time, S is the particle emission rate of printer, V is the volume of the chamber, and k is the particle loss coefficient.

Assuming S and k are constant and independent of C and t, He *et al.* (2007) gave a time-average-based approximate solution to Eq. (1) for evaluation of S in the printing process. However, Eq. (1) actually has the analytic solution. Considering the initial conditions $t = t_0$, $C = C_0$ for printing process, and $t = t_{max}$, $C = C_{max}$ as well as $S = 0$ for decay process, we use the method of separation of variables to obtain the analytic solution as follow:

$$\ln(S/V - kC_t) - \ln(S/V - kC_0) = -k(t - t_0)$$
for printing process (2a)

$$\ln C_t - \ln C_{max} = -k(t - t_{max}) \quad \text{for decay process} \quad (2b)$$

The particle emission rate S and particle loss coefficient k can also be calculated by linear regression based Eq. (2a) and Eq. (2b), respectively. It should be noted that Eq. (2) can be only applied in the situations where the source maintains a constant emission rate. According to Wensing *et al*. (2008) and Schripp *et al*. (2008), the emission rate characteristic from laser printers highly depended on the printer model and the toner cartridge where some presented a constant emission feature but the others had an initial-burst feature. Therefore, we used the average particle emission rate as the characterizing parameter which is defined as $S_{avg} = \int_{t_0}^{t_{max}} S dt / (t_{max} - t_0)$.

Also, to enhance comprehensive and global comparability, we used the area under concentration curve (AUC) based on the experimental data as an evaluation parameter, as proposed by Schripp *et al.* (2008):

$$AUC_t = \int_{t_0}^{t} C(t)\,dt \quad (3)$$

t was set as 30 minutes (from printing start) and the numerical integration method was used to obtain the approximate solution to Eq. (3) in the present work.

We finally selected the following key parameters to evaluate the emission and exposure performances. The peak concentration C_{max} and the peak time t_{max} (from printing start) parameters were used to evaluate the ultrafine particle peak characteristics for the printing process. The ultrafine particle emission rate S_{avg} was used to evaluate the average source emission intensity and, the loss coefficient k was used to evaluate ultrafine particle decay characteristics after cessation of source emissions for the decay process, respectively. The area under time-average concentration curve AUC_{30} (t = 30 min) was used to evaluate the contribution of exposure of overall ultrafine particle emissions. Note Eqs. (1)–(3) can be used for calculation of both number and mass particle concentrations.

RESULTS AND DISCUSSION

Ultrafine Particle Emission Characteristics Varied with Laser Printers

Ultrafine Particle Concentration

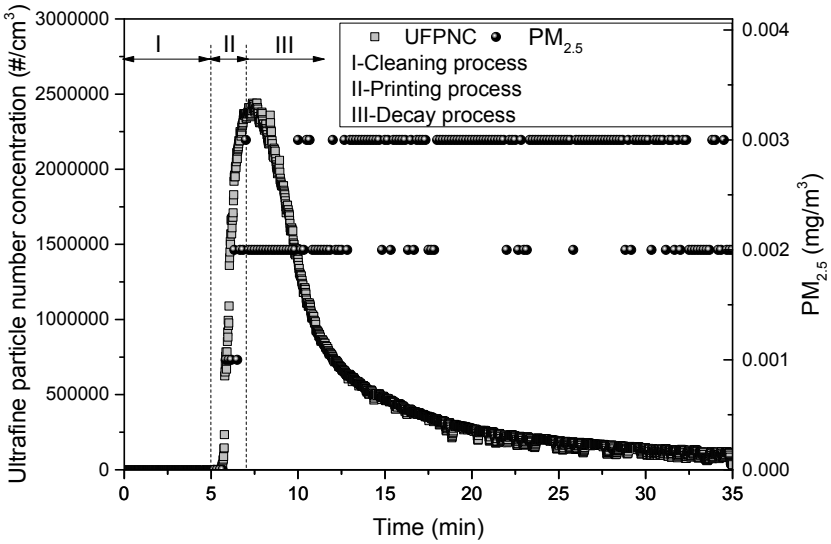
Fig. 2 and Table 3 illustrate the ultrafine particle number emission characteristics and evaluation parameters for three different printers, respectively. It was found that in a short period following the onset of printing, ultrafine particle emissions presented a climbing trend that increased as the printing proceeded. For the three printers, ultrafine particle concentrations peaked near the end of the print job but varied greatly in peak concentration with differences ranging in magnitude between 10^4–10^6. The average particle emission rate also varied and was found to be in the range of 10^3–10^5 for three different printers. Moreover, the peak time was found to be highly associated with the printing speed. Upon completion of the print job, the particle concentrations began to decay. Approximately exponentially decaying curves were observed during the decay process. The printers with higher ultrafine particle concentration

Table 2. Design of experiment (T = 25 ± 1°C, RH = 40 ± 10% and ACH = 1 h^{-1}).

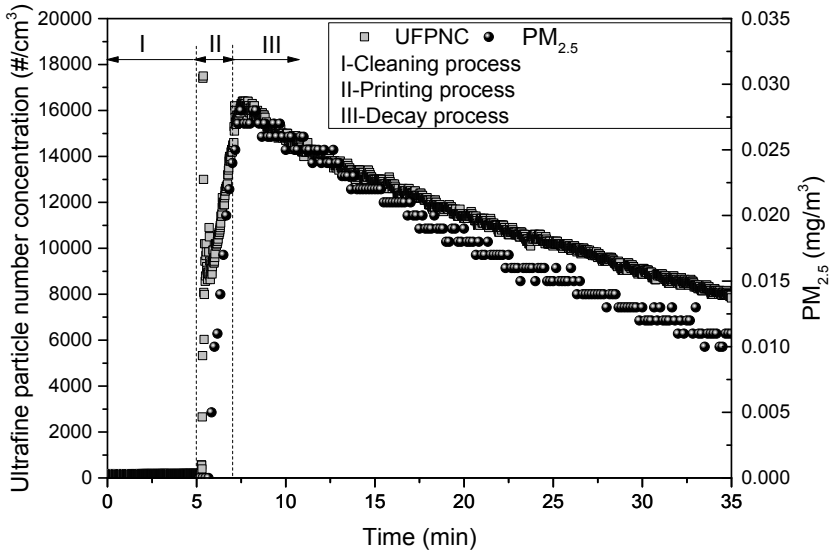
Case No.	Ready process included	Number of pages	Page coverage[a]	Print mode
1	Yes and No	50	5%	Continuous
2	No	25, 50, 100	5%	Continuous
3	No	50	5%, 20%, (40%)	Continuous
4	No	50	5%	Continuous, Intermittent[b]

[a] Refers to the percentage of the page containing toner. The ISO/IEC 19752 monochrome test page is approximately 5% page coverage. This work determined the page coverage based on area ratio by printing a compact block in a piece of A4 paper.

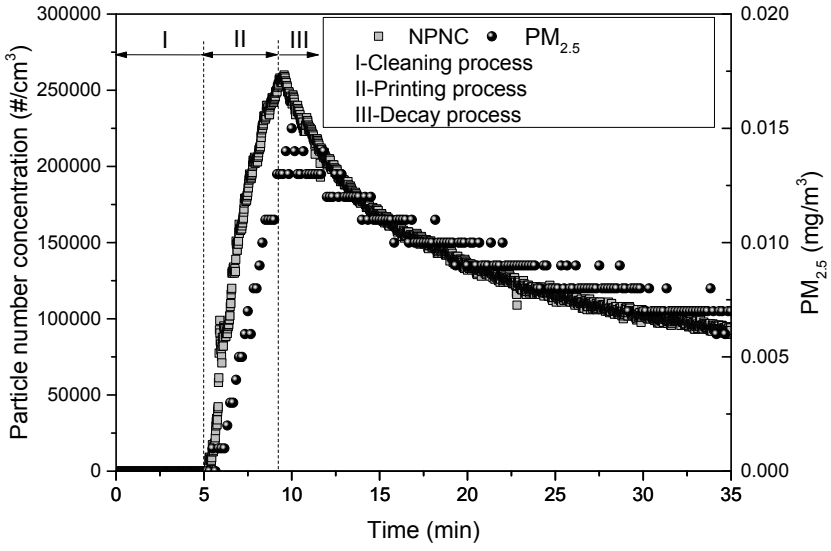
[b] Intermittent 1 = 25 pages + 1 min + 25 pages and Intermittent 2 = 17 pages + 1 min + 17 pages + 1 min + 17 pages.



(a) Printer A



(b) Printer B



(c) Printer C

Fig. 2. Real-time ultrafine particle number and $PM_{2.5}$ mass concentrations for different printers.

Table 3. Emission characteristics for ultrafine particle emission from different printers.

	t_{max} (min)	C_{max} [a]	k (1 min^{-1})	S_{avg} [b]	AUC_{30} [c]
Ultrafine particle number (measured by CPC)					
Printer A	2.38	2.44×10^6	0.139	6.68×10^5	1.63×10^7
Printer B	2.56	1.64×10^4	0.029	4.34×10^3	3.40×10^5
Printer C	4.57	2.60×10^5	0.046	3.82×10^4	4.21×10^6
$PM_{2.5}$ mass (measured by DustTrak)					
Printer A	2.00	0.003	/	/	0.076
Printer B	4.00	0.028	0.038	5.96×10^{-3}	0.528
Printer C	5.00	0.015	0.039	1.51×10^{-3}	0.267

[a] Unit: # cm^{-3} for number and mg m^{-3} for mass.
[b] Unit: # min^{-1} for number and mg min^{-1} for mass.
[c] Unit: # cm^{-3} min^{-1} for number and mg m^{-3} min^{-1} for mass.

emissions presented a higher loss rate than those with lower ultrafine particle concentrations. The ultrafine particle concentrations of printers A, B, and C decreased to about 1/25, 1/2 and 2/5 of their peak concentrations by the end of decay process, respectively. Finally, the exposure parameter AUC_{30} varied between printers with magnitudes ranging between 10^5–10^7.

Usually, when a print job command is received a printer successively starts the main motor, heat-fixing unit, laser scanner motor, transfer roller, and primary charging bias according to the working principle. Once the scanner motor maintains a constant speed of rotation and reaches a preset temperature, the paper is delivered. In this process, the toner powder is heated continuously and fused on the paper, resulting in large amounts of particles emitted. This process explains the sharp increase in particle number concentration after the start of the print job. When the print job finished, particle number concentration presented a decaying trend because of the ultrafine particle loss caused by air exchange, particle deposition (by turbulent diffusion or thermophoresis), and particle coagulation (He *et al*., 2007; Byeon and Kim, 2012). The overall trends of particle number concentration are in agreement with previous reports (He *et al*., 2007; Wensing *et al*., 2008; Byeon and Kim, 2012). However, different performances in particle emissions were observed especially with respect to the C_{max} and AUC_{30} values which indicate a differing property corresponding to the particle source, although the ultrafine particle concentration increased as the print job proceeded in all cases. Printer A seemed to display an initial-burst particle source while Printer B and C more closely resembled a quasi-constant particle source. This can be attributed to the differences in the printer models (heating time and preset temperature), toner models (toner powder size and physicochemical properties), and even printing speeds. Moreover, particle loss coefficients vary between different printers. This indicates that under the same air exchange rate, the deposition rate, influenced by particle physicochemical properties, and the coagulation rate, influenced by ultrafine particle concentration, may be primary factors related to the ultrafine particle loss coefficient. Particularly, a great difference in particle number concentration increases the significance of the coagulation effect on the particle loss coefficient since a high probability of collisions results in the enhancement of particle coagulation.

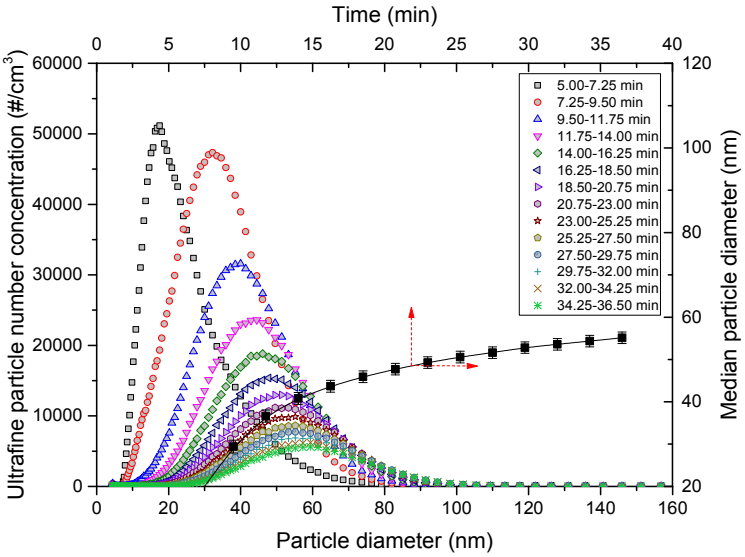
The $PM_{2.5}$ mass emission characteristics for three different printers are also illustrated in Fig. 2 and Table 3. It is interesting that Printer B displayed the highest mass peak concentration C_{max} and mass exposure parameter AUC_{30} while Printer A demonstrated relatively low values. Printer C presented a moderate performance for both factors.

The results suggest that there is not a causal association between number and mass particle emissions from laser printers. $PM_{2.5}$ emissions including the peak time are closely related to the particle size, particle density and particle interaction in addition to particle numbers. In this case, Printer A may have finer particle size and density while Printer B may have the opposite. This phenomenon shows that particle emission from laser printers is a complex process that depends essentially on the fusing process as well as the size and chemical composition of the toner particles. Moreover, Printers B and C did not show significant differences in the particle mass loss coefficient, indicating that the decrease of particle numbers caused by coagulation does not give rise to a significant decrease of particle mass as expected.

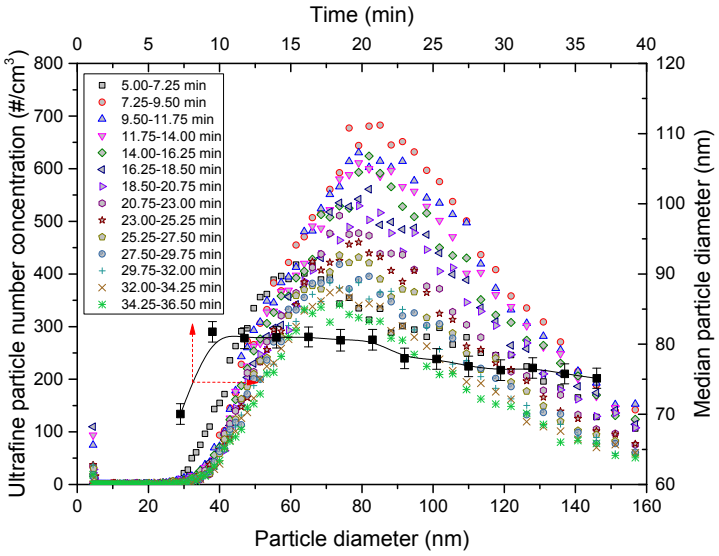
Usually, the printer-emitted ultrafine particle number concentration is more sensitive to the particle size change and particle toxicity than $PM_{2.5}$, and is more refined to characterize the behavior of particles in the nano-scale level. Therefore, the work further focused on the investigation of the ultrafine particle number concentration including particle size distribution and effects of operating parameters.

Ultrafine Particle Size Distribution

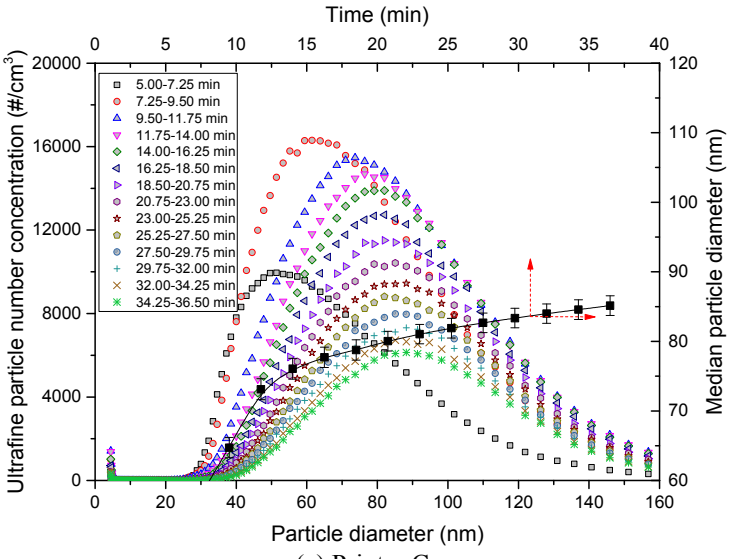
Fig. 3 shows the size distribution of the particles emitted from three different printers. A typical normal size distribution can be observed during the printing and decay processes for each printer tested. The peak value of each particle size range distribution presented an attenuating trend after the printing process finished. For the printers with high concentrations of ultrafine particle emissions (Printers A and C), as the ultrafine particle concentration decreased, the median particle diameter increased and approached a relatively constant value over time (about 55 nm from 18 nm for Printer A and 85 nm from 57 nm for Printer C). The printer with lower ultrafine particle concentrations (Printer B) displayed a median particle diameter in the range of



(a) Printer A



(b) Printer B



(c) Printer C

Fig. 3. Ultrafine particle size distributions for different printers.

70–82 nm that slightly declined in the decay process but stabilized between 75–80 nm.

Particle coagulation, when finer particles join to become larger particles, occurs when particles with high number concentrations (Printer A and C) are emitted to space. Reports by Wensing *et al.* (2008) and Byeon and Kim (2012) considered that this phenomenon occurred as a result of the printing speed only. However, physical properties of particles, interactions between particles and particles, and interactions between particles and vapors released from paper during the fusing process may also actually be the most important factors. The coagulation effect may dominate for smaller and lighter particles while for larger and heavier particles, the deposition effect may become more responsible for particle size distribution. This phenomenon might explain the slight decrease in median particle diameter observed for Printer B.

Influence of Ready Process

The effect of ready process (usually refers to the standby step) on particle emission for three printers is illustrated in Fig. 4 and Table 4. Significant ultrafine particle emissions were observed for Printer A while almost no ultrafine particle emissions were found for both Printers B and C during their ready process. Compared with the particle emissions in the printing process as shown in Fig. 2, the peak concentration/time, loss coefficient and AUC_{30} in the ready process had lower values. For instance, Printer A's peak concentration and AUC_{30} values were about 100 times less than those observed in the printing process.

Ultrafine particle emissions during the ready process are associated with the principles and actions of the printer. The principles for a laser printer can usually be described as the charge, exposure, development, transfer, fusing, and cleaning-erase processes. Within the whole process, the standby, initialization, print, and last initialization actions are carried out. For commonly used printers, upon the power being switched on, there are series of specific process in this action including: initializing the CPU, checking the paper tray, starting heat fixing (to a temperature higher than 100°C), starting the main motor and scanner motor, etc. A very important step relating to ultrafine particle emissions is the heat fixing process. This process may cause ultrafine particle emissions even in the absence of a print job to perform. This is consistent with the results reported by Wensing *et al.* (2008). However, not all printers display this characteristic. In this work, only Printer A displayed high particle emissions during the ready process while almost no particle emissions were observed from Printers B and C. Although they have similar self-checking items (Toner, drum, paper or jam error check, 15 s for Print A, 10 s for Print B and 20 s for Print C), this difference may be attributed to the use of transient temperature arising technology. Therefore, for some printers, beginning the cold start process without a print job present may result in additional ultrafine particles released. In that case, it is important to prevent frequent cold starts because it helps to reduce particle emissions during this process.

Influence of Number of Pages

Fig. 5 and Table 4 present the effect of number of pages printed on ultrafine particle emissions for three printers. For print jobs with 20, 50 and 100 sheets of paper, peak ultrafine particle concentrations/peak time and AUC_{30} values for all printers increased as the number of pages increased but no significant linear correlation was observed. Specifically, the increments of the peak concentration and AUC_{30} values decreased with increasing number of pages printed. Nevertheless, for the same printer, particle loss coefficients remained almost constant despite variations in the number of pages to print.

Usually, the particle emissions from a laser printer are considered to be proportional to the number of pages printed. However, this ideal situation does not apply in this study due to the complexity of the ultrafine particle emission process. In the report by Schripp's *et al.* (2008), an almost linear correlation between C_{max} or AUC_{45} (t = 45 min) and

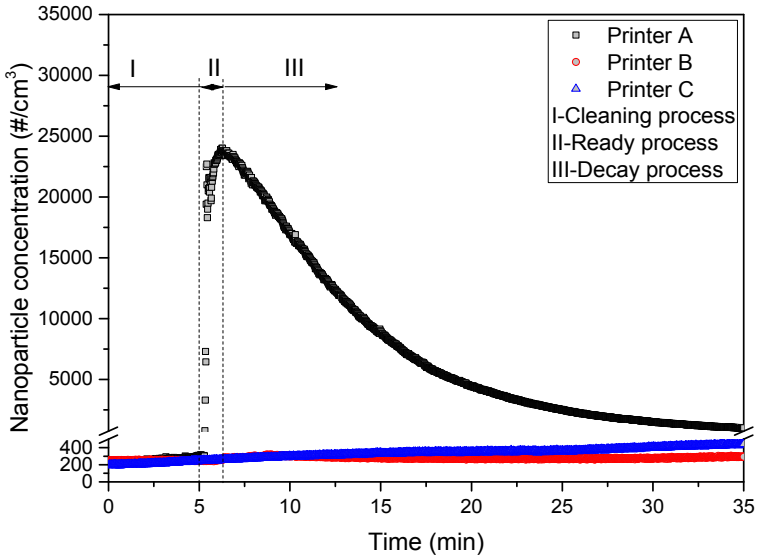


Fig. 4. Effect of ready process on real-time particle emissions.

Table 4. Emission characteristics of ultrafine particle emission at different operating parameters.

Operating condition	Parameter	Printer A			Printer B			Printer C		
		t_{max} (min)	C_{max} (10^6 # cm^{-3})	AUC_{30} (10^7 # cm^{-3} min^{-1})	t_{max} (min)	C_{max} (10^4 # cm^{-3})	AUC_{30} (10^5 # cm^{-3}min^{-1})	t_{max} (min)	C_{max} (10^5 # cm^{-3})	AUC_{30} (10^6 # cm^{-3} min^{-1})
Ready process	Standby	1.25	0.024	0.023	0	0	0	0	0	0
Number of page	25 pages	1.73	1.76	1.13	1.33	0.98	1.64	2.17	1.63	2.77
	50 pages[a]	2.38	2.44	1.63	2.56	1.64	3.40	4.57	2.60	4.21
	100 pages	2.63	2.77	2.12	4.70	2.51	5.04	7.52	3.08	5.47
Page coverage	5%[a]	2.38	2.44	1.63	2.56	1.64	3.40	4.57	2.60	4.21
	20%	2.87	3.28	2.15	4.01	2.05	3.93	5.50	2.86	5.11
	40%	3.15	4.56	2.78	NA	NA	NA	NA	NA	NA
Print Mode	Continuous[a]	2.38	2.44	1.63	2.56	1.64	3.40	4.57	2.60	4.21
	Intermittent 1[b]	2.16^{I}	1.57	1.50	1.18	1.03^{I}	3.17	2.38	1.45^{I}	3.30
		4.65^{II}	1.75		3.50	1.69^{II}		5.35	1.82^{II}	
	Intermittent 2[c]	2.21^{I}	1.24	1.58	1.23	0.65^{I}	3.13	1.81	1.39^{I}	3.74
		3.81^{II}	1.71		2.93	1.20^{II}		4.90	1.78^{II}	
		6.20^{III}	1.56		5.25	1.57^{III}		7.62	1.95^{III}	

[a] Using the same operating conditions for discussion purpose.
[b] Intermittent print mode1: 25 pages printing + 1 min interval + 25 pages printing: I = peak 1; II = peak 2.
[c] Intermittent print mode 2: 17 pages printing + 1 min interval + 17 pages printing + 1 min interval + 17 pages printing: I = peak 1; II = peak 2; III = peak 3.

the number of pages printed was found for some but not all printers when printing less than 75 pages. In this work, no such significant linear correlation was observed for all of the printers tested. A nonlinear relationship between the evaluation parameters of ultrafine particle emissions and the number of pages printed was more significant especially for Printer A. This result suggests that the mechanism of ultrafine particle emissions from laser printers may be different than other printers. In the laser printers tested in this study, the ultrafine particle emissions are greatest early on in the printing process and decrease at later times. This effect is more remarkable particularly for the printers with an initial-burst source feature. Moreover, since the printing time is approximately proportional to the number of pages printed, both the peak value of particle concentration and the time required for peak concentration increased with the number of pages printed. As a result, the AUC_{30} values also increased.

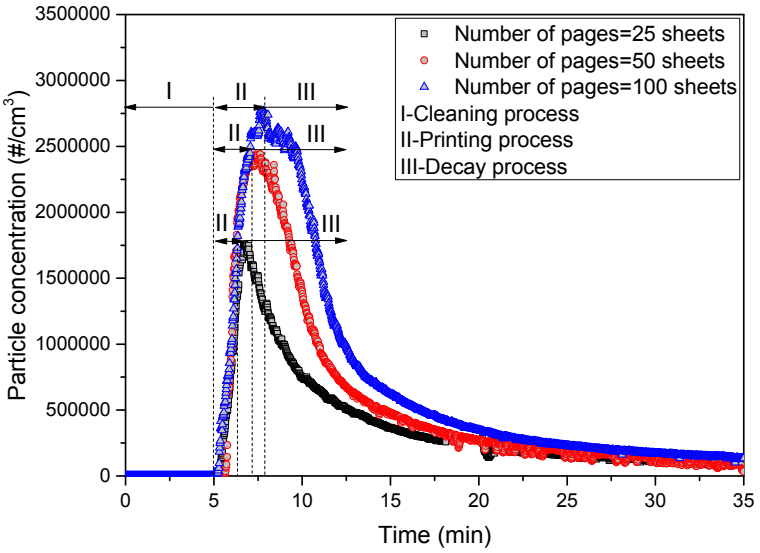
Influence of Page Coverage

Fig. 6 and Table 4 present the effect of page coverage (5% and 20%) on ultrafine particle emissions for three printers. Note due to the huge consumption of toner cartridges, 40% coverage was performed for Printer A only. The peak ultrafine particle concentration and AUC_{30} values for each printer increased as page coverage increased. In addition, despite a constant number of pages printed between printers, the peak time for high page coverage were found to be delayed compared to those for low page coverage. The ultrafine particle loss coefficients displayed slight variations but remained roughly stable at a constant level except for Printer B.

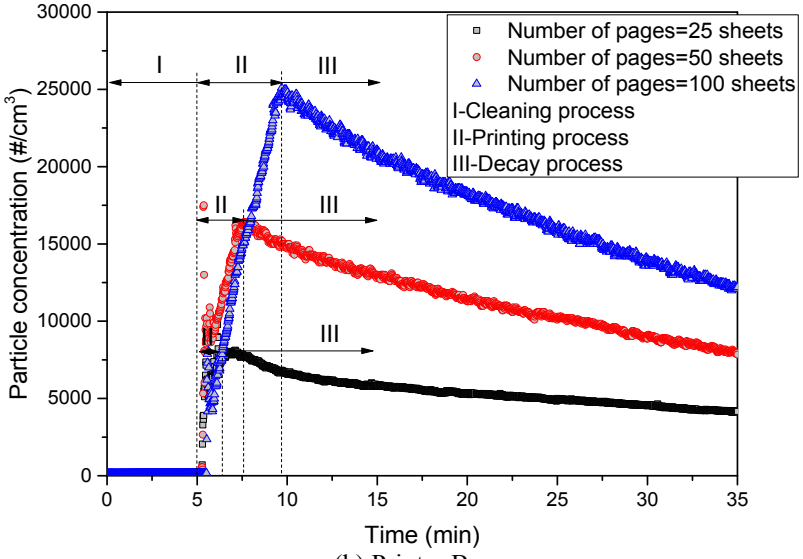
Theoretically, the page coverage is proportional to the amount of toner powder fused. However, this does not necessarily mean that a proportional correlation exists between page coverage and ultrafine particle emissions during the heating and fusing processes. Additionally, the effect of page coverage on ultrafine particle emissions has different degrees of influence for different printers. For instance, page coverage was demonstrated to have a great effect on source emission rate for some printers (He *et al.*, 2007) while almost no change in C_{max} and AUC_{45} was observed for other printers even when page coverage varied from 5% to 20% (Schripp's *et al.*, 2008). In the present case, the ultrafine particle emissions increased with increasing page coverage but did not display a proportional relationship as significant as the effect of number of pages printed. Essentially, ultrafine particle emissions depend on the source property and mechanism of ultrafine particle emission.

Influence of Print Mode

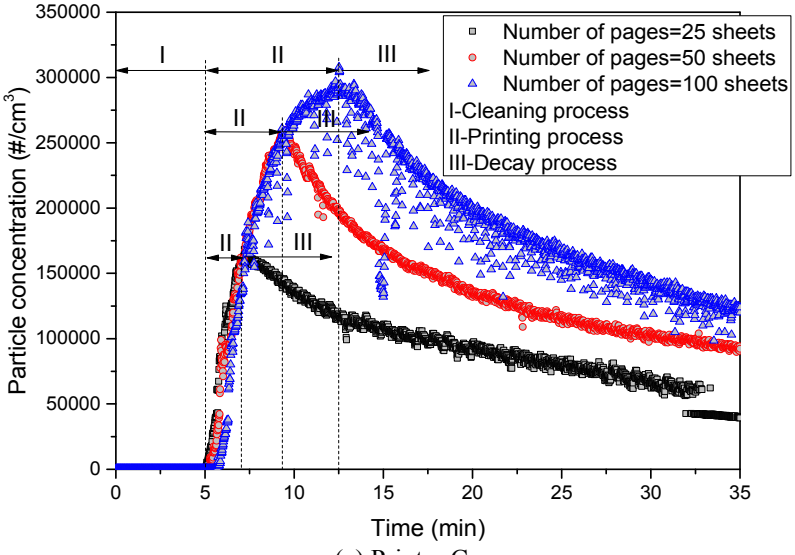
Fig. 7 and Table 4 present the effect of print mode on ultrafine particle emissions for three printers. Compared with continuous printing, intermittent printing was observed to have a so-called "peak shaving" effect for Printers A and C. Despite an insignificant "peak reduction" effect seen for Printer B, a significant "peak shifting" effect was observed for this printer. Consequently, these peak reduction/shifting effects resulted in the reduction of the AUC_{30} for all printers.



(a) Printer A

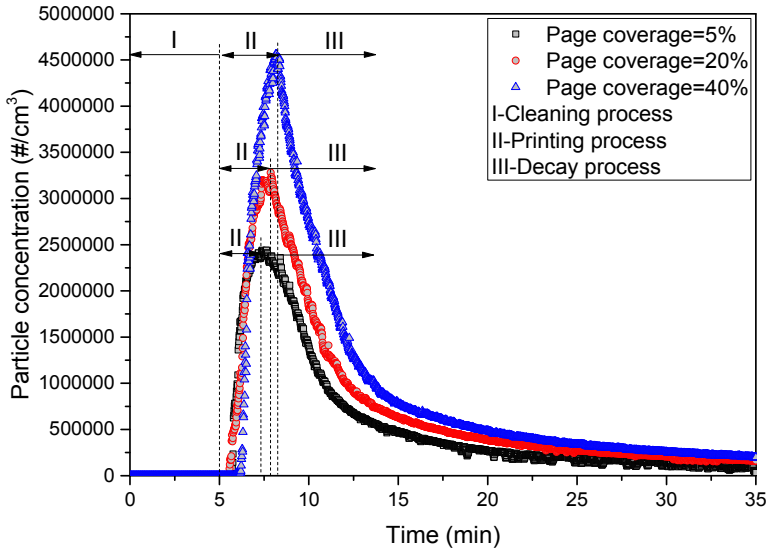


(b) Printer B

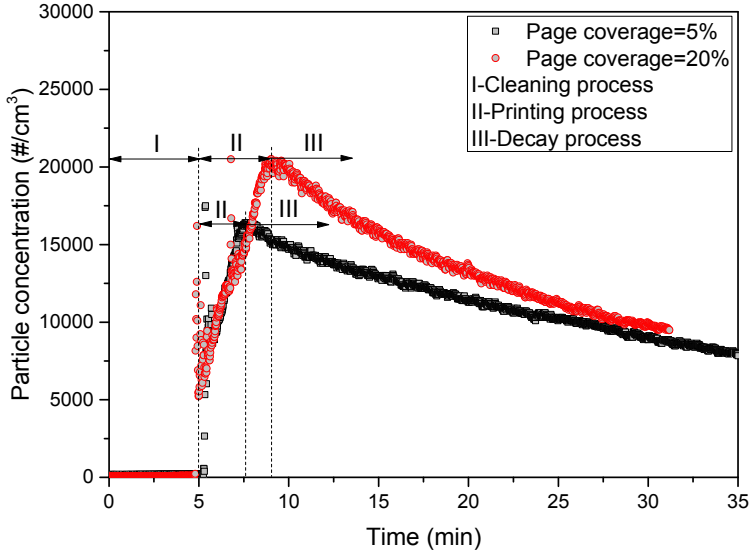


(c) Printer C

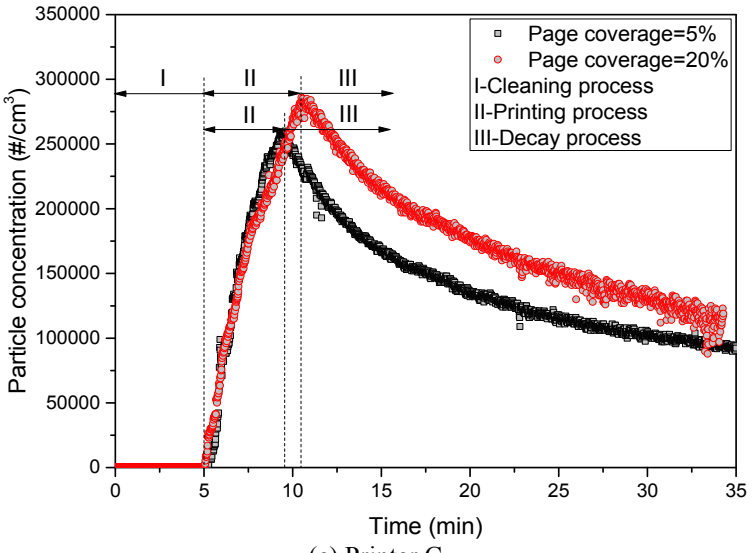
Fig. 5. Effect of number of pages on real-time ultrafine particle emissions.



(a) Printer A

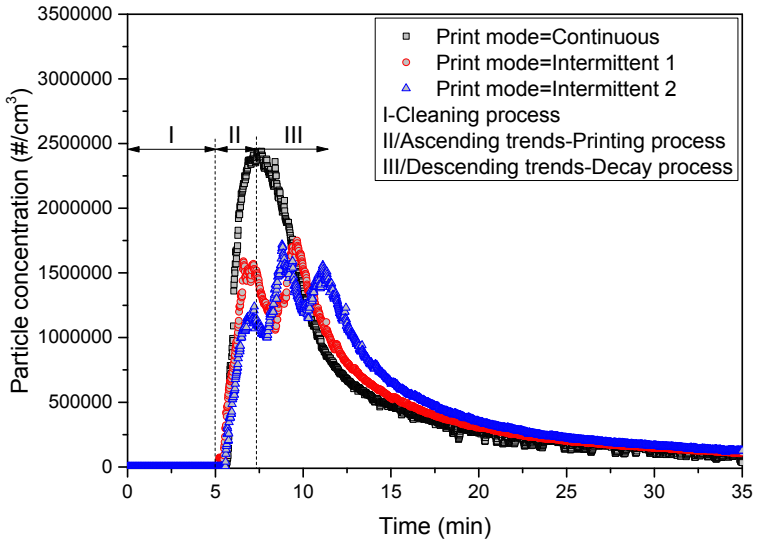


(b) Printer B

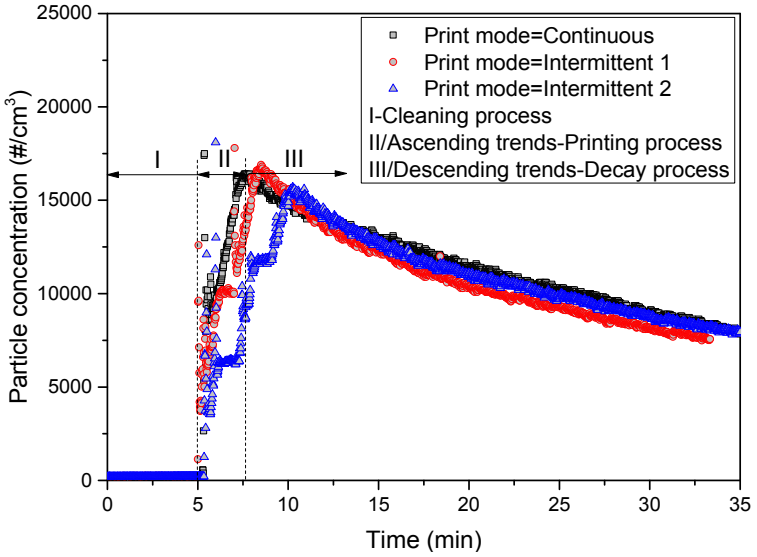


(c) Printer C

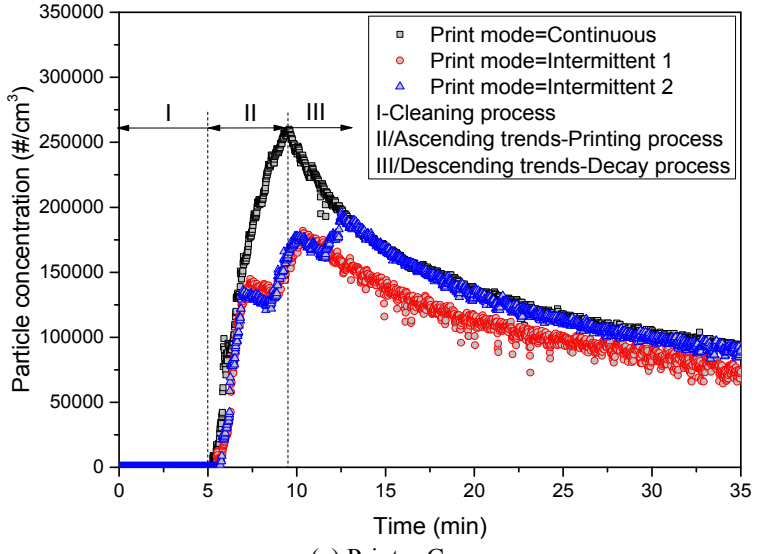
Fig. 6. Effect of page coverage on real-time ultrafine particle emissions.



(a) Printer A



(b) Printer B



(c) Printer C

Fig. 7. Effect of print mode on real-time ultrafine particle emissions.

Print mode is closely associated with the printing job and printing habit. Given a specific printing job, the use of an intermittent print mode can effectively reduce the ultrafine particle concentration distribution in space. For printers with high particle number emissions such as Printers A and C, printing in intervals cause particle concentrations to decay and therefore no "accumulative effect" due to high decay rate. For printers with low particle number emissions such as Printer B, a superimposed effect caused by decay and cumulative effects finally gave rise to a backward concentration peak. As a result, total emissions were reduced.

CONCLUSIONS

There were strong response relationship between operating parameters and the ultrafine particle emissions from laser printers. For different laser printers, ultrafine particle number concentration did not present a positive correlation with the $PM_{2.5}$ mass concentration.

Not all printers had ultrafine particle emissions in the ready process. Ultrafine particle emissions increased with increasing number of pages and page coverage as expected, but presented a nonlinear relationship. Compared with continuous printing, intermittent printing displayed so-called "peak-shaving" or "peak-shift" effects.

The results are helpful in providing an understanding of the ultrafine particle emission trends for laser printers with varied operating parameters, and present simple and effective approaches of control and reduction of ultrafine particle emission from laser printers. From the environmental and health point of view, at least those printers with the functions of energy-saving standby, adjustable print mode and schedulable job are expected to be selected for use.

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Received for review, April 10, 2017
Revised, May 30, 2017
Accepted, May 30, 2017