An investigation on particle emission from a new laser printer using an environmental chamber

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Abstract

In this study, emissions of ultrafine particles (UFPs) from a new laser printer were evaluated as a function of toner coverage, number of pages printed, fuser temperature and cartridge rotation during different printing orders. Eight combinations of printing jobs were specifically designed to represent eight printing orders. The toner coverage was found to be an important factor affecting particle emissions from the printer. The printing job without toner coverage (0%) acted as a cleaning process, which tentatively reduced particle emissions in the next job. While particles generated in printing job with toner coverage (5%) could superimpose onto those emitted from the next job, leading to higher particle number emission in the next job than previous one. Apart from toner coverage, cartridge rotation was an important factor enhancing particle emissions. Cartridge in rotation mode with/without toner coverage all caused particle emissions and high fuser temperature. The relationship between the particle emission and the temperature of the fuser unit was very strong (r^2=0.96). The regression relationship satisfied a positive power law-rise equation. We also found that ventilation for a long period, printing with no cartridge rotation, and/or printing blank pages before toner page printing could reduce particle emissions.

Keyword: Laser printer; Particle emissions; Toner coverage; Cartridge rotation; Fuser temperature.

1 Introduction

In recent years, intensive research on indoor air pollution caused by ultrafine particles (particles with diameter less than 0.1 μm; UFPs) has been carried out [1-2], due to the fact that UFPs are able to enter deep into the human respiratory system and contribute to negative health effects [3-5]. A number of studies have demonstrated that printers are significant indoor sources of UFPs, as well as volatile organic compounds (VOCs) and ozone (O_3) [6-10]. Recently, Sisler et al. [11] investigated the toxicological effects of printer-emitted particles (PEPs) and found that PEPs at low, non-cytotoxic exposure levels are bioactive and affect cellular responses in an alveolar-capillary co-culture model, which raises concerns for potential adverse health effects. Furthermore, Kowalska et al. [12] reported that printers also generated chlorinated organic compounds, inter alia: trichloroethylene-carcinogenic- and tetrachloroethylene-possibly carcinogenic to human. As laser printers are widely used in offices, schools and homes, it is important to deepen our understanding of particles emitted from these sources.

In general, laser printers utilize a photosensitive drum to attract the toner powder and fuse it on the page with a set of rollers that apply high levels of pressure and heat [13]. Earlier studies speculated that toner powder might be the source of particles from a printer [14]. Then, increasing evidence has shown that laser printers do not emit measurable toner particles (around 5-10 μm) but UFPs [7, 9]. Morawska et al. [15] investigated the formation mechanisms of particles in relation to laser printers, and suggested that the emitted particles were seldom directly from any printer components, but formed in the air from VOCs or semi-VOCs (SVOCs) which originated from the paper, toner, fuser roller and other printer components. In addition, many studies revealed that various operational parameters, such as fuser roller temperature, page coverage, printer age, printer speed and newness of toner cartridge, may affect the particle emission rates of a printer [6, 9, 16-18]. In addition to these operational parameters, Wang et al. [19-20] found that during continuous printing jobs the particle concentration decreased with an increase in printer interior temperature, indicating that temperature gradients between the fuser and surroundings rather than the sole fuser temperature drove the particle emission rate. They also observed that particle concentration decreased after short printing durations; but the mechanism for this phenomenon remained unclear. He et al. [21] further found that particle emissions in the printer were dependent processes, influenced by previous printing history, showing a large variation in emissions between different printing runs, even when repeated under exactly the same conditions. These studies highlighted that emission characteristics of particles could vary greatly with different printing order settings. More detailed knowledge about the influence of printing orders and habits on the characteristics of particle emissions from laser printers is still required to determine the associated health effects and viable control strategies.

In this study, we focused on the impacts of various printing procedures on the particle emission patterns. Different printing jobs with consideration of a number of factors such as initial start, toner coverage, number of pages printed and rotation of carousel with cartridge were combined to represent various printing orders. Based on the findings, recommendation on the printing operations and printing order settings was provided to minimize the particle emissions. Because longer use of the printing equipment caused more particle emissions [6-7], to more clearly understand the impact of printing procedures on particle emissions, we used a brand new type of printer which could eliminate the interference of printer model and age, as well as cartridge type and age to the particle emission characteristics.

2 Materials and methods

2.1 Printer and paper

A new HP LaserJet M175a printer was selected in this study. Due to its compact design and multi-function, and recognizable performance and output quality, it was popular in the consumer market. Currently, most colour laser printers use a large rotating belt called a "transfer belt". The toner is first transferred from toner cartridges to the photosensitive drum and applied to the belt, and then from the belt to the paper. Because of the similar operation principle of laser printers, the emission levels of VOCs and/or ultrafine particles from various types of laser printers during printing are mainly determined by the design of interior structure and different materials, rather than by the printing procedures and printing order settings. In other words, the impacts of various printing procedures and printing order settings on the particle emission patterns found in this study will also be applied to a high emission printer. In this study, original toner cartridge specified by the manufacturer was used. Continuous printing speed of the printer was 16 A4-size pages per minute (ppm) monochrome. A fan of the printer was designed to blow air out of the printer. The printer was designed to print papers with 0% and 5% black toner coverage in this study, respectively. For the 5% black toner coverage paper, a standard printing file was used according to the European Computer Manufacturers Association (ECMA International). The paper used in this study was Fuji Xerox Explorer with a density of 75g/m^2. The paper was stored under laboratory conditions of approximately 22-25°C and 50-60% relative humidity (RH). The water content of the paper was tested and found to be 2.7%.

2.2 Instrumentation

2.2.1 Particle size distribution and number concentration

Two different devices were used to measure the particle number concentration and size distribution over the entire duration of the experiment. The total particle number concentration was measured by a condensation particle counter (CPC) (Model 5.400, GRIMM, Germany) and a TSI P-Trak ultrafine particle counter (Model 8525, TSI Incorporated, USA), with a sampling resolution of 1 s and a size range of 5.5 -350 nm for the CPC and 20-1000nm for the P-Trak. The size distribution of UFPs was monitored by a scanning mobility particle sizer (SMPS) system (Model 5.400, GRIMM, Germany) consisting of a differential mobility analyzer (DMA) and a CPC. The SMPS system was operated with a sampling flow rate of 0.3 L min^{-1}, and the concentration of particles with a mobility equivalent diameter 5.5-350 nm was measured. Due to the rapid change of particle size and concentration after the printing job started, the fast scan mode with a sampling resolution of 2 min was set instead of normal scan mode (4 min) during the SMPS measurements.

2.2.2 Fuser surface temperature (FT)

The average fuser heater surface temperature during printing was monitored using a J-type thermocouple placed on the outside surface of the fuser roller. The sensor of thermocouple was put into the interior of the printer through the rear door of the printer. The sensor was placed very close to the surface of the roller and at the outer boundary of the regions of the paper feeding pathway to prevent paper from getting stuck. In addition, the rear door of the printer should be tightly closed. Otherwise, the printer would show error message and could not conduct printing jobs. The data were recorded by a digital multi-logger at 1 min interval. It is noteworthy that the sensor was very close to the surface of the roller but not posted on the roller, and the measured temperature was actually the outside temperature of the fuser and roller unit, not the real fuser temperature. Although the temperature measured was not the inner fuser temperature, which should be much higher, the variation trend of the outside temperature was the same as that of the inner fuser temperature.

2.2.3 Other pollutants and parameters

Ozone (O_3) concentration was monitored by an Ozone Analyzer (Model 400E, Teledyne API, USA) with a lower detectable limit of 0.6 ppb and sampling flow rate of 0.8 L min^{-1}.

The average temperature and RH in the chamber were monitored using a TSI Model 8552 Q-Trak Plus with a sampling resolution of 10 s and an accuracy of ± 0.6 °C for temperature and ± 3% for RH. The instrument was calibrated annually according to the user's manual.

2.3 Study design

2.3.1 Chamber settings

A plexiglass chamber with size 1100(H) × 1000(W) × 730(L) mm was used in this study. Schematic diagram of the experimental system is outlined in Fig. 1. Relative humidity in the chamber was maintained within 55 ± 5% and temperature at 24 ± 2°C, to simulate typical office environment. Filtered air using an activated carbon bed and a high efficiency particulate air (HEPA) filter was delivered to the top of the chamber, and the air was exhausted from the bottom of the right-side of the chamber. The air in the chamber was well mixed by a fixed fan. A recovery efficiency test for carbon monoxide (CO) was conducted in the empty chamber to determine the potential leakage and wall effects at the beginning. The air exchange rate of the chamber was 0.8 h^{-1}. Prior to experiment, inner surface of the chamber was cleaned by scrubbing with distilled water.

The printer was placed in the centre of the chamber. A ~0.5 m conductive tube was used and fixed at the printed page outlet, immediate vicinity of the top of the printer for particle sampling from the chamber to the SMPS+CPC system and P-Trak monitor. The O_3 analyzer used a Teflon tube for air sampling. The temperature sensor of J-type thermocouple was placed at the outside surface of the fuser roller and the probe of Q-Trak was placed in the middle of the chamber, directly above the printer (see Fig.1).

2.3.2 Printing procedures

In order to investigate the effect of different printing procedures on the particle emissions, eight combinations of printing jobs were designed in this study. Description of the combinations is given in Table 1. To assess the influence of the amount of toner and the number of pages on particle emissions, various black toner coverage (0% and 5%) and different number of pages (20 and 80 pages) printed were used. The printing jobs were conducted with/without cartridge rotation using 0% and 5% black toner coverage, respectively, to investigate whether the cartridge rotation could impact the particle emissions. The colour laserjet printer composed four cartridges in different colours (*i.e.*, black, cyan, magenta and yellow) (see Fig.1). It is noteworthy that the colour printer tested in this study is the same as most colour printer models which use a transfer system in which the toner is first transferred from the photosensitive drum to an intermediate transfer belt (ITB), and then from the belt to the paper (see Fig.1). Unless manual instruction was given to the printer, the printer rotated the cartridge carousel, and the cartridges rotated in a cycle even if the printing job only needed the black toner. Hence, to prevent the rotation of toner cartridges, a manual instruction was given to the printer to only use the black toner cartridge before printing. Once the printer was set to prevent cartridge rotation, only the black and white papers were printed. Four printing jobs were defined as one combination. Experiments for each combination were repeated at least 3 times.

Table 1 The eight combinations of printing jobs (the number of pages is 20 unless specified)

No.	Combination	Remark	No.	Combination	Remark
#1	0, 0, 0, 0	NV	**#5**	0, 0, 0, 0	V

#2	5, 5, 5, 5	NV	**#6**	5, 5, 5, 5	V
#3	0, 0, 0R, 0R	NV	**#7**	0, 0, 5, 5	NV
#4	0, 0, 5R, 5R	NV	**#8**	0, 0(80), 5,5	NV

R=Cartridges rotation V=Ventilation on overnight before experiments NV=Ventilation off overnight before experiments

0 = 0% toner coverage 5 = 5% toner coverage

For combination #1, four printing jobs with 0% toner coverage and without cartridge rotation were conducted. For combination #2, four printing jobs with 5% toner coverage and without cartridge rotation were executed. For combination #3, four printing jobs were conducted as well. The 1st and 2nd printing jobs were done with 0% toner coverage and without cartridge rotation, while the 3rd and 4th printing jobs were undertaken with 0% toner coverage and with cartridge rotation. For combination #4, the 1st and 2nd printing jobs were done with 0% toner coverage and without cartridge rotation, while the 3rd and 4th printing jobs were undertaken with 5% toner coverage and with cartridge rotation. During all the printing experiments the ventilation was on. For combination #5 and combination #6, the ventilation of the chamber was on in advance overnight for 12 hours before the printing experiments, whose emissions were compared with those of non-ventilation before the printing experiments in the combination #1 and combination #2, respectively. For combination #7, the 1st and 2nd printing jobs were carried out with 0% toner coverage and without cartridge rotation, whereas the 3rd and 4th printing jobs were undertaken with 5% toner coverage and without cartridge rotation. To compare with the combination #7, combination #8 was tested using 80 pages in the 2nd printing job.

The printer idled for more than 12 hours before each combination experiment was conducted. The chamber ventilation was off for 12 hours before each combination experiment, except for the "ventilation" effect experiment (*i.e.*, combinations #5 and #6). During the chamber testing, the emission measurements were conducted in three phases: (1) background concentration measurements were taken until the particle number concentration (PNC) in the chamber was lower than 200 particles cm^{-3}; (2) concentration measurements were conducted from the beginning of the printing job and continued for the duration of the printing job (unless specified, 20 pages were printed for each printing job), which lasted for <1.5 min; and (3) the concentration decay was measured for about 120 min after each printing job finished. It is noteworthy that 20 pages with 0% toner coverage and cartridge rotation were printed 12 hours before the 1st printing job of every combination to avoid any interference from the preceding printing combination experiment. After each job, the printer was allowed to cool back to the environmental temperature before the next job. The interior surface of the chamber was cleaned after each combination experiment.

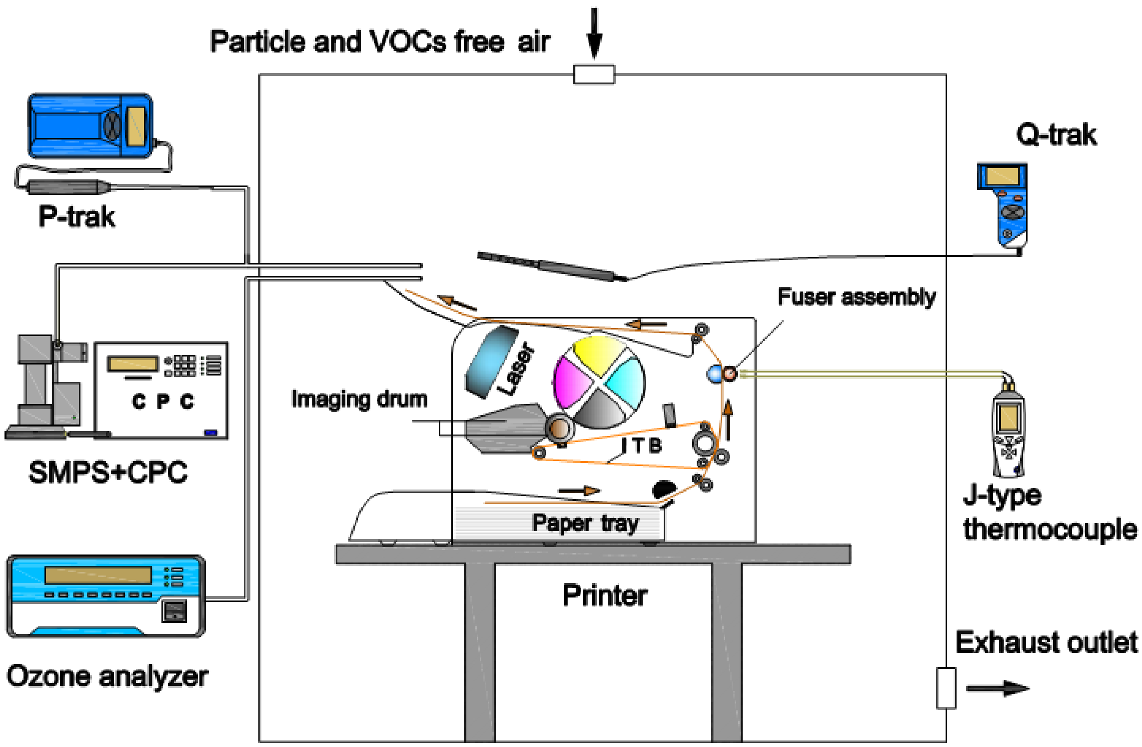

Fig.1 Schematic diagram of the instrumental set-up for the chamber measurements.

3 Results and discussion

3.1 General characteristics of UFP emission during printing

Fig. 2 shows the time series of a typical particle number concentration (PNC) measured by CPC at the paper outlet for a continuous printing of 20 pages with 5% toner coverage from a cold (room temperature) start-up. During the printing process (printing duration= 1.5 min), the PNC rapidly reached a peak concentration of ~1.0×10^3 particles/cm^3, and then decreased sharply when the printing job ended. The PNC almost decreased to the background concentration level after ~4 min. This phenomenon was reported in several studies [*e.g.* 6, 9, 15-16, 19, 21].

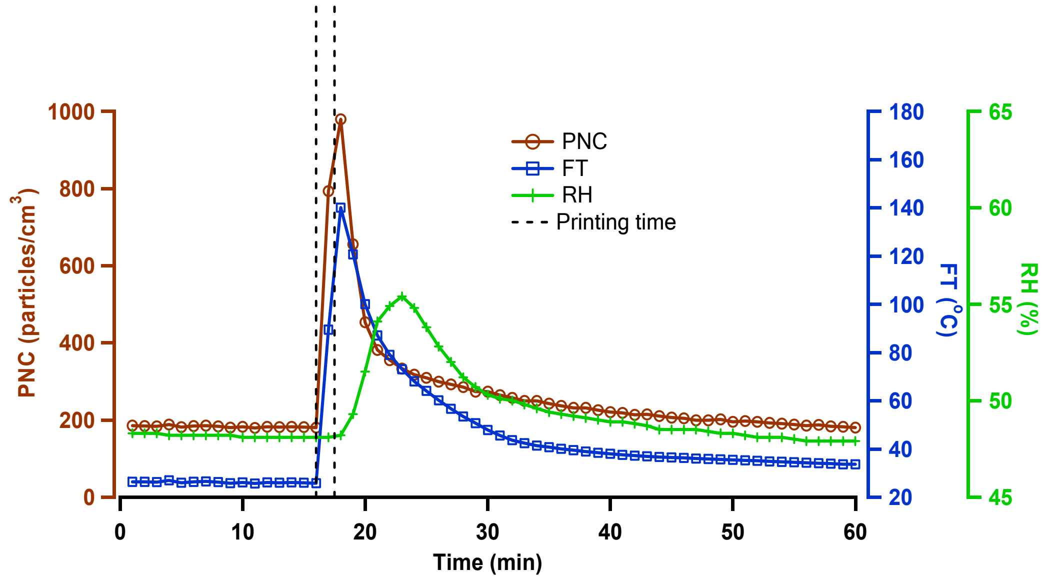

Fig. 2 Time series of particle number concentration (PNC) and relative humidity (RH) at the paper outlet and the fuser surface temperature (FT) inside the printer during a typical printing job

The mean particle emission rate during the printing jobs of 20 pages with 5% toner coverage was calculated using the equations provided by He et al. [6] and found to be 7.8 ± 1.9 $\times 10^7$ particles min^{-1} (Mean ± S.D.). Since the emission rate is dependent on various parameters, *e.g.*, printing job and printer type, there is no literature data available for comparison with the particle number emission rates of the tested printer used in this study. He et al. [6] reported particle emission rates of a new HP LaserJet 5M (classed as low particle emitter) during the printing jobs with 5% toner coverage, which was similar to our experimental settings. Compared to the emission rate (4.0 ± 1.0 $\times 10^7$ particles min^{-1}) obtained by He et al. [6], our result is in the same order of magnitude, approximately two times the emission rate.

It was found that the variation of the fuser roller temperature had similar pattern to that of PNC. Namely, the external temperature of the fuser roller increased sharply when the printing job was initiated and decreased sharply while the printing job completed (Fig. 2), suggesting close association of PNC with the fuser rolling temperature. Before printing, the measured external temperature of the fuser rolling was approximately the same as ambient temperature (25°C). After a continuous 20-page printing job, the fuser temperature increased to 140°C. In addition, an increase of RH inside the chamber was observed with a time lag. The rapid decrease of PNC after the maximum value (from 980 particles min^{-1}

to 330 particles min^{-1}) coincided with the increase of RH (from 48.2% increased to 55.4%), in line with the fact that increased RH could enhance both particle deposition and coagulation leading to increased particle size and decreased particle number concentration (see Fig. 3), apart from the predominant influence of air dilution and dispersion in the chamber.

Ozone was not detected from this new printer, which is opposite to previous finding that O_3 is one of the pollutants emitted by the printers with the concentration range from 1.5 to 6 ppb [7]. Ozone generation actually depends on toner charging type, *i.e.*, tribo- and electrostatic charging. Recently, some brands of laser printers use advanced charging technology that does not generate measurable amounts of ozone. This type of printer seems to be insignificant source of ozone. Another reason for the undetectable O_3 from the printer in this study might be that O_3 emitted from the printer immediately oxidized concurrently-emitted VOCs into other pollutants, such as semi-VOCs (SVOCs) and ultrafine particles. Nevertheless, this speculation needs further investigation.

Fig. 3 presents time-dependent number concentration and size distribution of particles measured by SMPS during a continuous printing of 20 pages with 5% toner coverage, cartridge rotation and cold start-up. There was an observable increase in the particle concentration (3.7×10^3 particles/cm^3) when printing began. Meanwhile, the particle geometric mean diameter increased from 90 nm to 107 nm. The printing job mainly generated small particles with the size range from 80 to 120 nm, consistent with the particle size (*i.e.*, 90-120 nm) released from a printer in the study of Uhde et al. [17]. However, the particle size range observed in this study was different from other studies. Wensing et al. [9] found that particles emitted from printers mainly peaked at ~10 nm, while Schripp et al. [18] and Wang et al. [20] reported a maximum PNC at 20-30 nm. Moreover, a particle size range of 35-94 nm was identified in the work of He et al. [21]. The different particle size ranges observed in different studies imply that particle emissions are printer-type specific, affected by the materials of printer components and the internal structure design. Particles are mainly formed by VOCs or semi-VOCs (SVOCs), originated from the paper, toner, fuser roller and other printer components [15]. Different materials of printer components would cause the evaporation of different VOCs or SOVCs, and subsequently the formation of particles. In addition, the diameters of newly-formed particles during printing could increase via vapour condensation and coagulation, etc. while emitted from the printer. Due to different internal structures of printers, increases of particle diameters during printing in the interior of the printers could be varied, resulting in different particle size ranges.

The increase of the particle diameter during printing and the decay of particle number concentration after printing might be caused by coagulation and deposition. The deposition rates of particles with different diameters are varied, and smaller particles are deposited faster than larger particles for particles with diameter < 100 nm due to diffusion. Moreover, particles with diameters between 20 and 50 nm have the highest coagulation coefficients [22]. On the other hand, collisional growth, which is a function of the particle number concentration, can cause a significant change in size distribution within minutes or seconds. In addition, water vapour released from the paper near the fuser unit is able to form a condensate. This vapour may increase the particle diameter in the relatively small space inside the chamber.

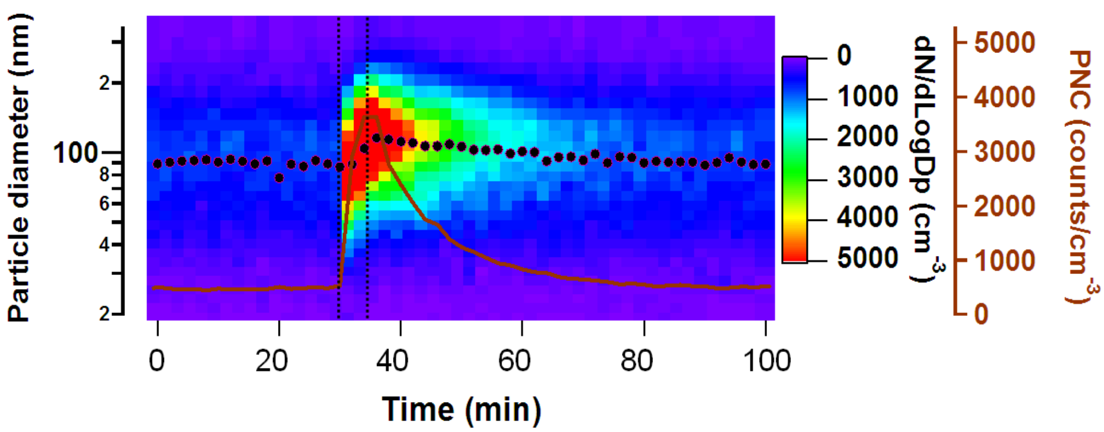

Fig. 3 Time series of size-resolved particle number concentration and particle geometric mean diameter (dots) before, during and after a printing job (dash lines).

3.2 Influence of ventilation on the initial start of printing

During all the printing jobs, the ventilation system was on at an air exchange rate of 0.8 h^{-1}.The only difference was that for combinations #5 and #6, the ventilation was on in advance for >12 hours prior to the 1st printing job. For combination #1 (NV 0, 0, 0, 0), four printing jobs with 0% toner coverage and without overnight ventilation until the commencement of the 1st printing job were conducted. A small peak with a mean value of

120 particles/cm^3 was found for the 1st printing job. No peak, however, was observed for the 1st printing job in combination #5 (V 0, 0, 0, 0) (Fig. 4). This provided evidence that long time pre-ventilation could reduce particle emissions during the 1st printing job.

Furthermore, among the combinations #3, #4, #7 and #8, when the 1st printing job was conducted without toner coverage and overnight ventilation, all showed an increase in PNC. However, when exactly the same type of paper (0% toner coverage) was used in the 2nd printing job for these combinations, no particle emissions were identified. The results suggested that the particle emission from the printer had an "initial start" effect, which was relevant to the overnight ventilation. The observed effect could be explained by SVOCs, which get depleted in the hot area around the fuser, but they will diffuse from other parts (*i.e.*, plastics, lubricants, and toner) to the then cool and clean parts of the printer overnight. Once the 1st job was initiated, fuser was heating up, SVOCs residue will be re-evaporated and form particles in the cooler ambient air inducing initial start effect.

When the 1st printing job was carried out with 5% toner coverage and without overnight ventilation, *i.e.,* the combination #2 (NV 5, 5, 5, 5), particle emissions were found in all the 4 printing jobs. The average peak values reached 380, 310, 330 and 360 particles/cm^3 for the 1st to 4th printing jobs, respectively. For combination #6 (V 5, 5, 5, 5) (see Fig.5), four peaks were also found with average values of 370, 320, 320 and 420 particles/cm^3, respectively. Particle emissions for the 1st printing jobs in combination #2 were similar to those in combination #6 (V 5, 5, 5, 5) (t-test, p-value >0.1). This feature indicated that the above "initial start" effect was concealed when the 1st printing job was carried out with the toner coverage.

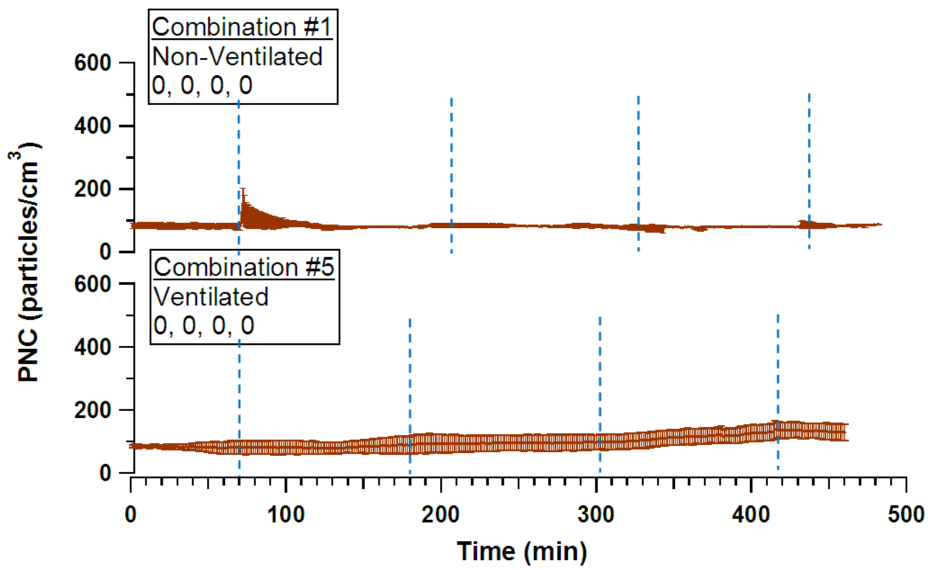

Fig. 4 Time series of particle number concentrations for the four printing jobs in combinations #1 and #5 (The blue line indicates when each printing job was started. The error bars show the standard deviation of the mean)

3.3 Influence of the printing order

The relationship between PNC and printing sequence is shown in Fig. 5. For combination #7 (NV 0, 0(20), 5, 5), particle emissions were found for the 1st, 3rd and 4th printing jobs with average concentrations of 360, 180 and 540 particles/cm^3, respectively. The 2nd printing job did not generate any peak. This phenomenon was also observed in combination #8 (NV 0, 0(80), 5, 5), using 80 pages in the 2nd printing job.

As discussed in section 3.2, the peak in 1st printing job was caused by "initial start" effect in both combinations #7 and #8 due to the particle coagulation and accumulation during the idling time of the printer. No peaks were found in the 2nd printing job of both combinations #7 and #8. It seems that semi-volatile compounds and particles were removed from the printer by the 1st job after heating up the fuser. Particle emissions in the 3rd printing job showed lower values than those in the 4th printing job in both combinations, suggesting that the 2nd printing job with 0% toner coverage acted as a cleaning process, which tentatively reduced particle emissions in the 3rd job, or particles generated in the 3rd job could superimpose onto those emitted from the 4th job, leading to higher PNC in the 4th job. The higher emissions in the 4th printing job suggest that when the fuser was rapidly heated up, the evaporation of VOCs present in the toner particles, which were deposited on the fuser from previous printing jobs, might contribute to nanoparticle emissions.

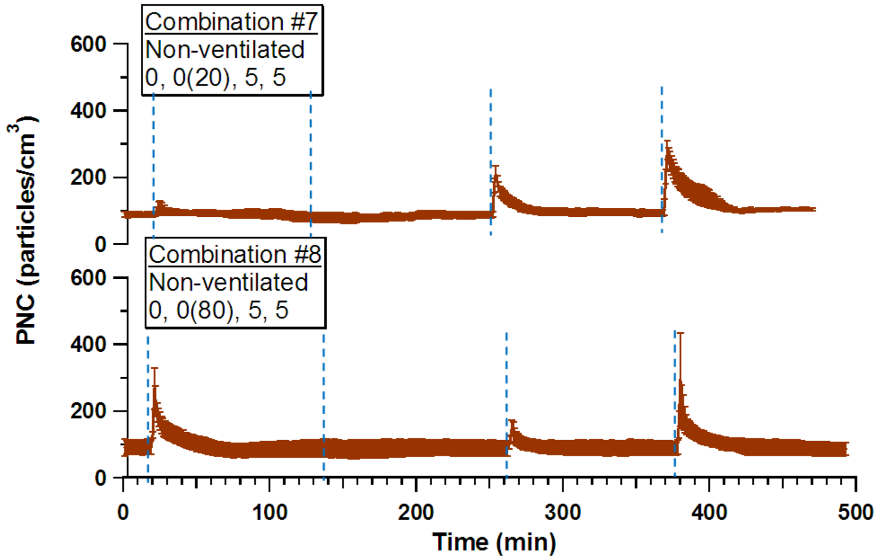

Fig. 5 Time series of particle number concentrations for the four printing jobs in combinations #7 and #8 (The error bars are standard deviations of the mean values)

3.4 Influence of the toner coverage and cartridge rotation

For combination #5 (V 0, 0, 0, 0), the emission tests were repeated in the same manner without toner (*i.e.,* printing blank pages with 0% toner coverage). No observable peaks were found in all the printing jobs. For combination #6 (V 5, 5, 5, 5), four peaks were found corresponding to the four printing jobs. As expected, increasing the toner coverage had a direct impact on the number of particles emitted. This is in agreement with the observations in a previous study [6], which found that toner coverage was a main factor responsible for particle emissions.

Fig.6 illustrates the time series of particle number concentrations and fuser temperatures for the four printing jobs in combinations #3, #4 and #7. For combination #7 (0, 0, 5, 5), the peaks with mean values of 160 and 220 particles/cm^3 were found in the 3rd and 4th printing jobs, respectively, which did not use cartridge rotation. For combination #3 (0, 0, 0R, 0R), the 3rd and 4th printing jobs were carried out with 0% toner coverage and cartridge rotation. Peaks were found in the 3rd and 4th printing jobs with average concentrations of 500 and 240 particles/cm^3, respectively. Since 0% toner coverage was used during the 3rd and 4th printing jobs, the particle emission was not caused by the toner coverage effect, but probably due to that the cartridges contained different colours of toners, as rotating the cartridges would cause toner residue on the surfaces of cartridges floating in the printer. During printing, the fuser temperature sharply increased which led to the evaporation of VOCs from the toner residue and subsequently the formation of the particles [15-18]. This explanation was further proved by the fact that the 3rd printing job produced more particles than the 4th printing job in combination #3, because the toner residue was largely cleaned after the first cartridge rotation (*i.e.*, the 3rd printing job), and fewer toner particles in the printer induced lower particle emission during the 4th printing job. In addition, the fuser temperature during the 3rd and 4th printing jobs was much higher than that during printing without cartridge rotation.

For combination #4 (0, 0, 5R, 5R), the 3rd and 4th printing jobs were undertaken with both 5% toner coverage and cartridge rotation. Two sharp peaks with mean values of 2180 and 2120 particles/cm^3 were found, respectively. By comparison, the printing job (5R) had much greater impact on the particle emission than other printing jobs with only toner coverage and/or with only cartridge rotation (*i.e.*, 5 and 0R), indicating that there was a synergy effect on the particle emissions from printing jobs with certain percentages of toner coverage and cartridge rotation. As shown in Fig.6, the external temperature of the fuser during printing jobs with cartridge rotation (5R) (165-175°C) was higher than that (135-145°C) during printing jobs for sole 5% toner coverage. Furthermore, the printing speed of this printer was up to 16 ppm monochrome (without cartridge rotation) and 4 ppm colour (with cartridge rotation). That is, the printing speed with cartridge rotation was slower than that without cartridge rotation. This was confirmed by the longer time for the elevation of PNC and FT during printing with cartridge rotation (see Fig.6). The longer time rotation of fuser belt when cartridges were rotated would further enhance the fuser roller temperature and subsequently accentuate the evaporation of more VOCs/SVOCs of toner particles in the printer. The results suggested that cartridge rotation was an important factor enhancing fuser temperature and particle emissions, apart from toner coverage.

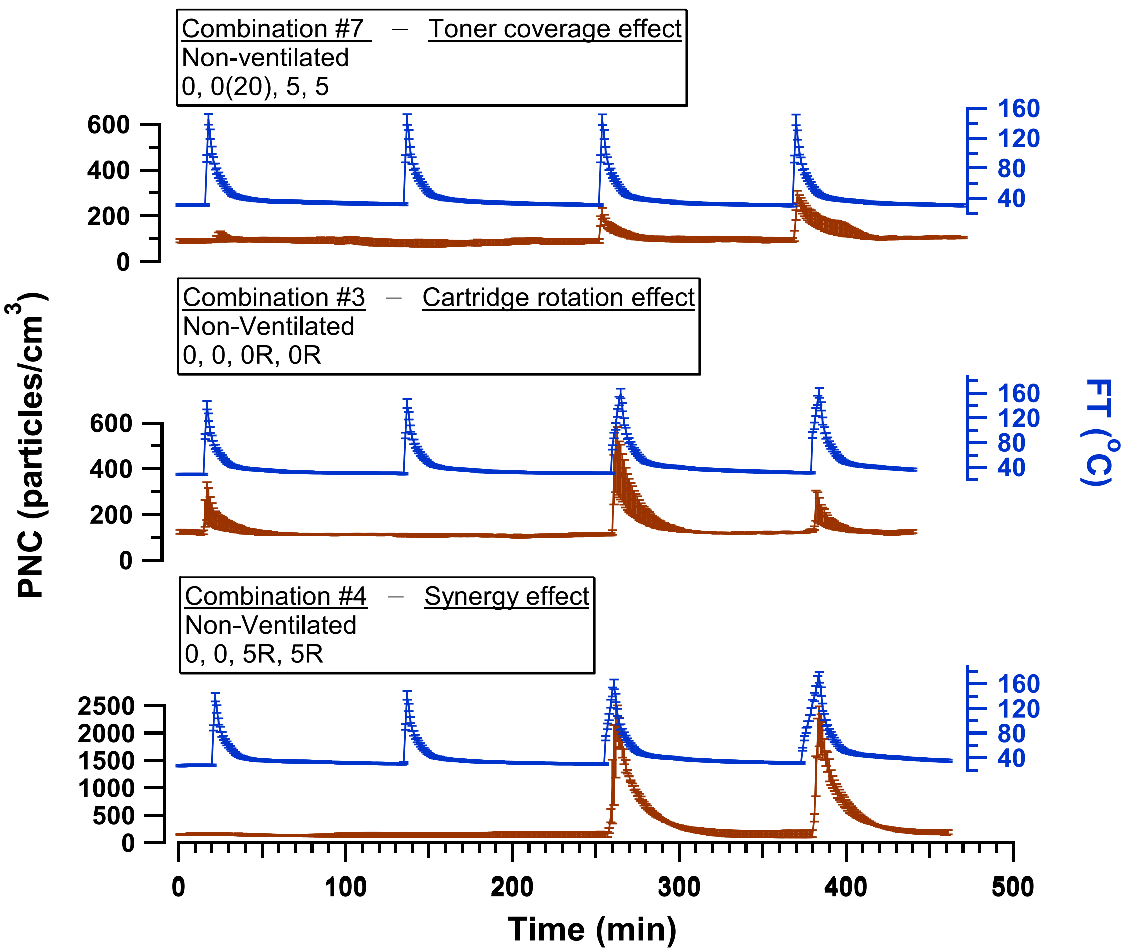

Fig. 6 Time series of particle number concentrations and fuser temperatures for the four printing jobs in combinations #3, #4 and #7 (The error bars are standard deviations of the mean values)

Fig. 7 illustrates the relationship between PNC and FT during the printing. In this study, all the experiments commenced when the fuser temperature was close to the ambient room temperature. This minimized the bias of the comparison of the particle number concentrations among the printing experiments under the same initial fuser temperature conditions. It can be seen that the particle number concentration enhanced with the increase of fuser temperature. Cartridge rotation (*i.e.*, 5R and 0R) and more page number (*i.e.*, 80 pages) resulted in higher temperature than no rotation (*i.e.*, 5% and 0%) and fewer pages (*i.e.*, 20 pages).

Based on the data set of fuser temperature at a 5°C interval, a statistically significant ($p < 0.05$) positive power-law relationship was found between average FT and average PNC.

An equation was derived by fitting a power curve with a good correlation coefficient (r^2 = 0.96) (see Fig. 7). It was found that the PNC was low (~200 particles/cm^3) when the FT was 135-140°C and 140-145°C. However, when the FT was upto 145-150°C the PNC significantly increased more than twice (Fig. 7). This could be explained by the fact that the TVOC emission gradually enhanced with the increase in temperature, leading to subsequent formation of new particles, and would have a sudden increase when the temperature increased to a certain threshold value. The rapid increase of FT would significantly increase the emissions of VOCs and/or semi-VOCs which caused accentuation of particle emissions. This feature is in agreement with the findings of Morawska et al. [15], who investigated the emissions from the idle belts of the fuser rollers, paper, toner powder and lubricating oil while they were heated in a controlled-temperature furnace. They found that when the temperature was up to 150°C, all of the volatile species contained in the toner powders and other materials almost evaporated and/or decomposed to gas phase species. This finding provided further understanding of the particle emissions at various fuser temperatures during printing, which could be helpful to reduce or prevent from the risk of exposure to particles emitted from printing by controlling the FT below a threshold temperature.

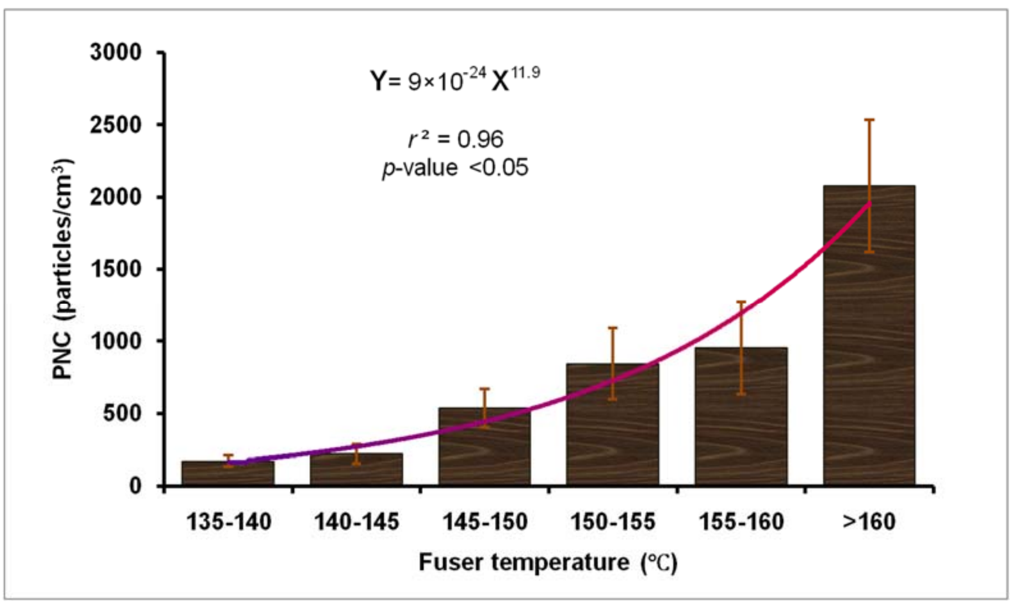

Fig. 7 Relationship between particle number concentration and fuser temperature

4 Conclusions

A new HP LaserJet printer was found to emit ultrafine particles during printing with a concentration of 10^2 - 10^3 particles/cm^3 and a mode of 80-120 nm, depending on ventilation condition, printing order, number of pages printed, the toner coverage and cartridge rotation, which would also be applied to other types of laser printers. In this study, UFPs were exclusively emitted during the 1st printing job when there was no overnight ventilation, likely due to the fact that overnight residues of semi-volatile or volatile compounds were re-evaporated and condensed into particles when the fuser was heating up. We found that toner coverage and cartridge rotation were the main factors influencing particle emissions from the printer. Synergy effect on particle emissions was observed if toner was used together with cartridge rotation. In addition, long time pre-ventilation and the use of printing papers with 0% toner coverage reduced particle emissions.

A positive relationship between the fuser temperature and particle number concentration for this printer was quantified. This quantitative correlation could be used by the printer manufacturer to determine the best-fit temperature during the printing jobs in order to minimize particle emissions. The findings suggest that people who use laser printers should choose the printing modes without cartridge rotation when printing monochrome papers. Furthermore, room ventilation should remain on and be high enough whenever possible. At last, to minimize the initial start effect, it is recommended that 1-2 pages of blank paper be printed before the first routine printing jobs each day.

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