Journal of Imaging Science and Technology® 57(1): 010502-1–010502-7, 2013.

New Approaches to Characterize and Reduce the Number of Ultrafine Particles from a Laser Printer

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Abstract. *For better understanding of air quality, ultrafine particles (UFPs) emitted from laser printers were evaluated as a function of toner coverage, printer type, potential submicrometer particle sources, and fuser units. Emission measurements were conducted using 11 printers with different fuser units from a variety of manufacturers. Particle concentrations with different fuser units and temperatures were monitored using a condensation particle counter (CPC) from the chamber. The relationship between the emission rate and the temperature of a fuser unit is very strong. The regression relationship satisfies a positive exponential-rise equation. However, only a weak positive exponential-rise relation was observed with the mixed data from four different fuser units. This is one piece of evidence that suggests that other factors play a role in laser printer fine particle/ultrafine particle emission.*
[DOI: 10.2352/J.ImagingSci.Technol.2013.57.1.010502]

INTRODUCTION

Indoor air pollution including emissions from laser printers is a field that is being focused on recently. Many research studies show multiple risk factors pertaining to health related to indoor air pollution rather than outdoor air pollution.[1] Laser printers in the house and office emit both hazardous organic compounds and fine particles including submicrometer (<1 μm) and ultrafine (<100 nm) particle emissions, as reported in many studies.[1–5]

Kagi et al. and Wensing et al. reported that ultrafine particles emitted from a laser printer have mainly generated from a secondary formation due to volatile organic compounds (VOCs) and moisture. Semi-volatile organic compounds (SVOCs) are also reported as a possible source of ultrafine particles.[2,5]

He et al. and Uhde et al. showed that the particle emission rates from various laser printers are quite different and can be affected by toner coverage.[1,4] Morawska et al. reported that the heated toner powder, paper, fuser roller, and lubricant oil may cause submicrometer particles.[6] However, this still does not explain why various laser printers show different emission rates. To answer this question, Lee et al. and Wensing et al. suggested that the fuser unit in the laser printer may cause the emission of ultrafine particles (UFPs) and that it may be possible to reduce the emission rate by decreasing the temperature of the fuser unit.[5,7] Morawska et al. investigated the emission rate as a function of fuser temperature.[6] The results of the investigation are that the emission rate was decreased by increasing the fusing temperature, which was completely unexpected, given the initial hypothesis.

Recent articles[5,6,8] have revealed the relationship between the temperature of the fuser roller and the gas emissions, and have shown the characterization of nanoparticles and VOCs emitted under various conditions. However, further research is needed for these environmental issues due to the unclear mechanism of overall fine particle (FP) and ultrafine particle (UFP) emissions.

In this study, new methods to analyze the emission rates of fine particles (FPs)/ultrafine particles (UFPs) via controlling the fuser temperature of various fusing systems are discussed. The purposes of the study were to (1) quantify the indoor pollution caused by a laser printer, (2) analyze the relationship between particle emission rate and temperature of a fuser unit, and (3) evaluate a statistical model to predict the emission rate amount according to a temperature of a fuser unit.

EXPERIMENT

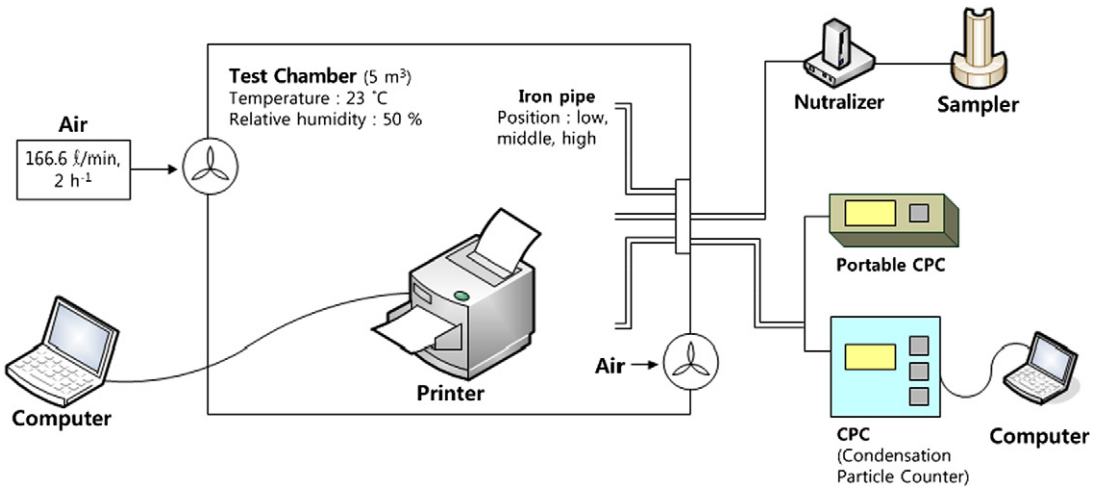
Preparation of emission test

As shown in Figure 1(a), the experiments were conducted in a 5 m^3 environmental test chamber with stainless steel walls. The operating temperature and relative humidity (RH) were 23 ± 2°C and 50 ± 5%, respectively. The air exchange rate for the test chamber was 2 (5 m^3/h). Two fans in the chamber were used to control the uniformity of air mixed inside the chamber. Fig. 1(b) illustrates a monochrome pattern with 5% coverage and a color pattern with 20% coverage.

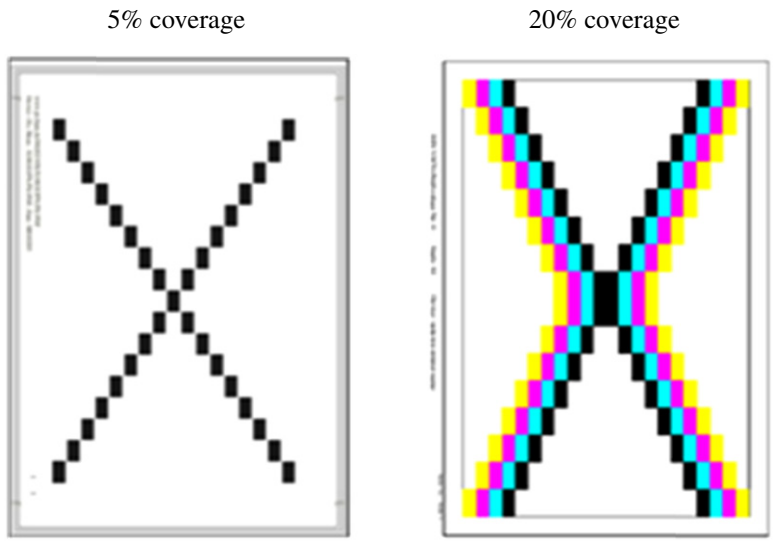
In order to prevent a print from automatically stopping due to paper overload on the exit tray, the test sample was installed with a slight slope. An "automatic finger" operated by pressurized air was used to turn on the power of the test sample with an integrated power button.

Eight monochrome (ML-11 to ML-31) and three color (CL-11 to CL-13) laser printers of different brands were selected as test samples; see Table I. Two-roller-type fusers

Received May 20, 2012; accepted for publication Feb. 20, 2013; published online May 17, 2013.
1062-3701/2013/57(1)/010502/7/$20.00



(a)



(b)

Figure 1. Experiment setup. (a) Schematic of setup measuring ultrafine particle emission. (b) Monochrome and color printing patterns.

were adapted to ML-11 to ML-15, which have printing speed from 18 to 55 ppm (pages per minute). We used fuser units including three rollers for ML-21 and ML-22 and a fusing belt for ML-31 and CL-11 to CL-13. The four printers ML-14, ML-31, CL-11, and CL-12 were chosen for investigations of changing the temperature by controlling the heating coil's current.

The temperatures of the fusers were measured at several places on the inside and outside surfaces of the fuser units. The temperature data was recorded by an NI Compact DAQ system with an NI 9211 thermocouple module (K-type). The temperatures of four printers were measured and recorded before measuring emission in a test chamber.

Test and measuring methods

The test process in Figure 2 illustrates the method to measure the ultrafine particle emission. Gravimetric determinations of FPs/UFPs were not considered for this study. The pre-operating, operating, and post-operating phases shown in Figure 3 were performed for particle measurement based on the ECMA-3281 protocol,[9] which is a standard that specifies methods to determine chemical emission rates of electronic equipment during intended operation in an emission test chamber

1. Pre-operating phase

To start the pre-operating phase, a test printer was powered on and remained in this phase under an air exchange rate of 2 per hour. FPs/UFPs are counted at the pre-operating phase because some printers showed that high particle emission was observed soon after they were turned on.

2. Operating phase

The operating phase is entered by starting copying or printing. The output of the first printed page marked the start

Table I. Summary of the test conditions including the test speed.

Printer ID	Type	Fuser temperature	Fuser type	ppm	Volume (cm^3)	Emission rate (#/cm^3)
ML-11	Monochrome	180°C	2Roll	18	27587880	54100
ML-12	Monochrome	190°C	2Roll	24	27587880	562500
ML-13	Monochrome	190°C	2Roll	38	63323964	167000
ML-14	Monochrome	190°C	2Roll	52	105235200	192700
ML-15	Monochrome	190°C	2Roll	55	203599386	74700
ML-21	Monochrome	195°C	3Roll	32	49362000	2850000
ML-22	Monochrome	185°C	3Roll	37	30222000	317900
ML-31	Monochrome	180°C	Belt	52	63210000	374800
CL-11	Color	170°C	Belt	18	80780175	14440
CL-12	Color	175°C	Belt	25	99540064	297100
CL-13	Color	175°C	Belt	33	283986750	43960

of the operating phase. It ended with the output of the last printed page. The duration was at least 10 min.

3. Post-operating phase

The post-operating phase started when the operating phase ended, and lasted for one hour.

Preparation of instrumental analysis

Total particle number concentrations in the size range 4.5–1000 nm were measured using a TSI Model P-Track 8525 (TSI Inc., St. Paul, MN, USA) and Grimm Model 5430 Condensation Particle Counter (CPC 5430 Grimm Aerosol Technik GmbH & Co. KG, Pouch, Germany), with a sample time of 1 s. The particle samples were collected using a nanometer aerosol sampler (TSI Model 3089), which allows one to sample charged particles, like those from the output of a chamber onto sample substrates, for further chemical analysis. The electrostatic precipitator (ESP) sampling flow rate was 5 l/min and the charging current was 18 μA. The samples were analyzed using transmission electron microscopy (TEM) equipped with an energy-dispersive X-ray spectrometer (EDS) to characterize the morphology and elemental composition of the emitted nanoparticles.

Matrix-assisted laser desorption/ionization with time-of-flight (MALDI-TOF) mass spectrometry and gas chromatography–mass spectrometry (GC–MS) were used to characterize the emitted particles gathered from various filters such as Teflon, glass, and polymer filters.

Particle emission rates

The method to calculate the particle emission rates in ECMA-328[9] is summarized in this section. The formula used to determine UFP emission includes the particle loss coefficient (β), particle emission rate (PER), and the total number of emitted particles (TP). The particle loss coefficient is defined as:

$$\beta = \frac{\ln\left(\frac{c_1}{c_2}\right)}{t_2 - t_1} : \text{particle loss coefficient,}$$

where the values c_1, t_1 and c_2, t_2 are indicated in Fig. 3 with high accuracy from the averaged concentration time series. The values c_1, t_1 are read at least 5 min after the maximum of the particle number concentration and the values c_2, t_2 are read at least 25 min after t_1. In general, the factors in the operating phase and post-operating phase dominate the particle emission rates. Thus, the equation above can be rewritten as follows:

$$PER = \frac{1}{L}\left(\frac{\Delta c_p}{t_{stop} - t_{start}} + \beta \cdot c_{av}\right) : \text{particle emission rate,}$$

where L is the loading factor of the chamber, Δc_p (see below) is the difference of total particle number concentrations, and C_{av} (see below) is the arithmetic mean of measured concentration values, i.e.

$$C_{av} - \frac{\sum_{i=1}^{n} c_{p,i}}{n}, \quad \Delta c_p = c_p(t_{stop}) - c_p(t_{start}),$$

where n is the number of measured concentration values during the operating phase, and t_{start} and t_{stop} are the beginning and ending times of the operation phase. The total number of emitted particles is calculated by multiplying the operation period and PER,

$$TP = PER \cdot (t_{stop} - t_{start}) : \text{total number of emitted particle.}$$

The maximum number of particles emitted in the operating phase can be determined as particle emission from a laser printer.

RESULTS AND DISCUSSION

To better understand the FP/UFP formation mechanism for laser printers, it is helpful to review the assumptions of the possible sources of FP/UFP generation during laser printer operation. Wang et al.[10] show that the possible sources of FP/UFP include evaporated VOC from toner powder at high temperature. They also suggested that the emitted FP/UFP mainly consists of carbon-based nanoparticles, likely generated by ion-induced homogeneous nucleation and

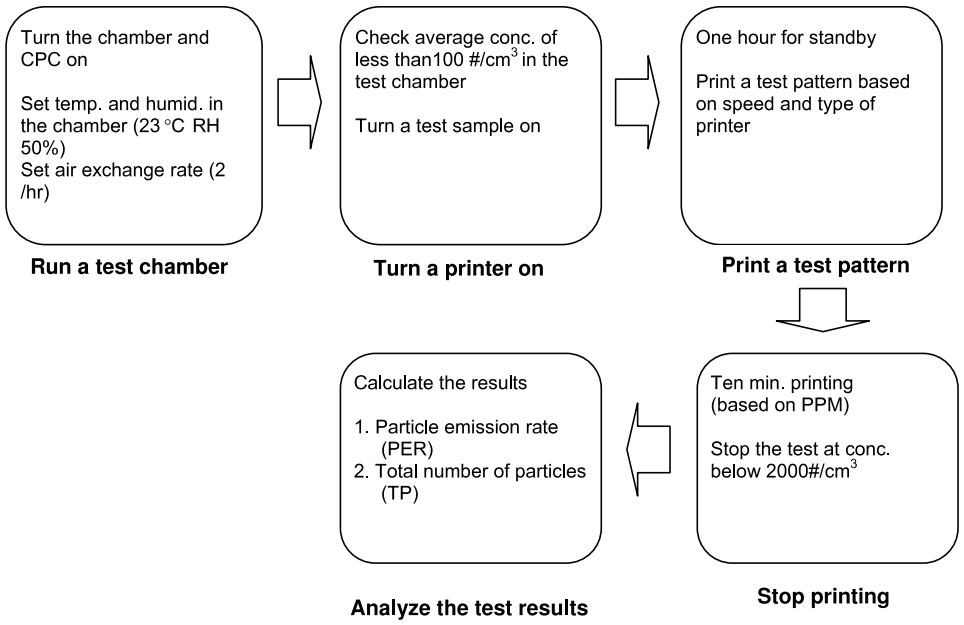


Figure 2. Test process to measure UFP emission based on ECMA-328 5th edition.

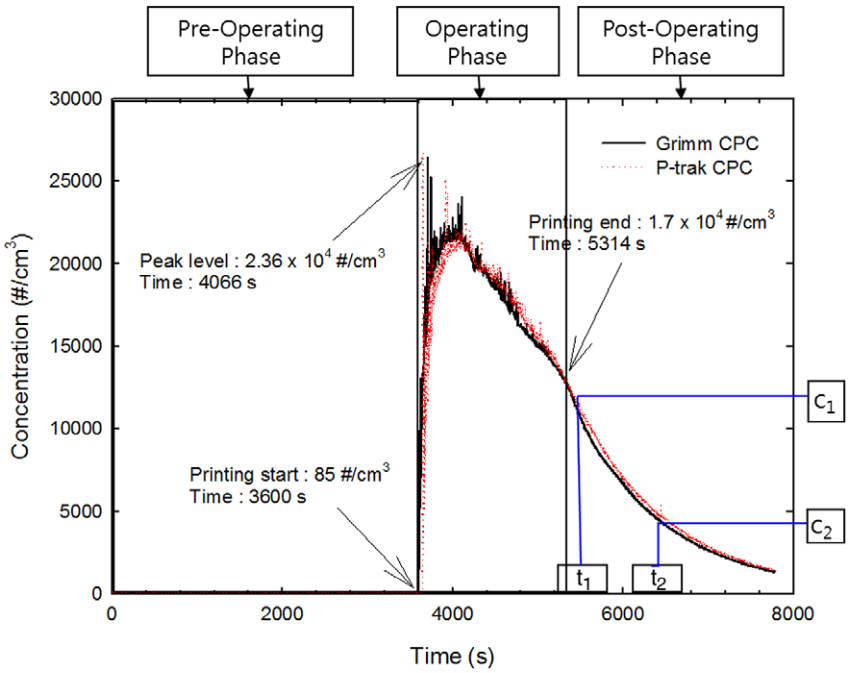


Figure 3. Diagram of a total particle number concentration time series.

condensation from the vapor-phase VOCs evaporated from copolymer toner particles rapidly heated by the fuser.

The test results consist of various data obtained from systematic test design based on the mechanism of ultrafine particle emission. A total of 11 printers with four different types of laser printer in terms of fusing system and fusing temperature were investigated in a standard 5 m^3 chamber. The four printers that represent four different fusing systems were selected for demonstrating the effect of fuser temperature on UFP emission.

Effect of temperature around fuser unit on UFP emission

In total, 11 printers were tested for emission rate against fusing temperature of the different printing engines/fuser units. The emission rates of the 11 printers with four different fuser types are shown in Figure 4. The 11 different printers are listed in order of increasing emission rate. Corresponding measured emissions are shown in Table I. Several observations can be made from the figures and tables: (1) emission rates are not strongly related to the fuser temperatures, (2) emission rates are not related to the fuser types, (3) emission rates are not related to print speeds, and

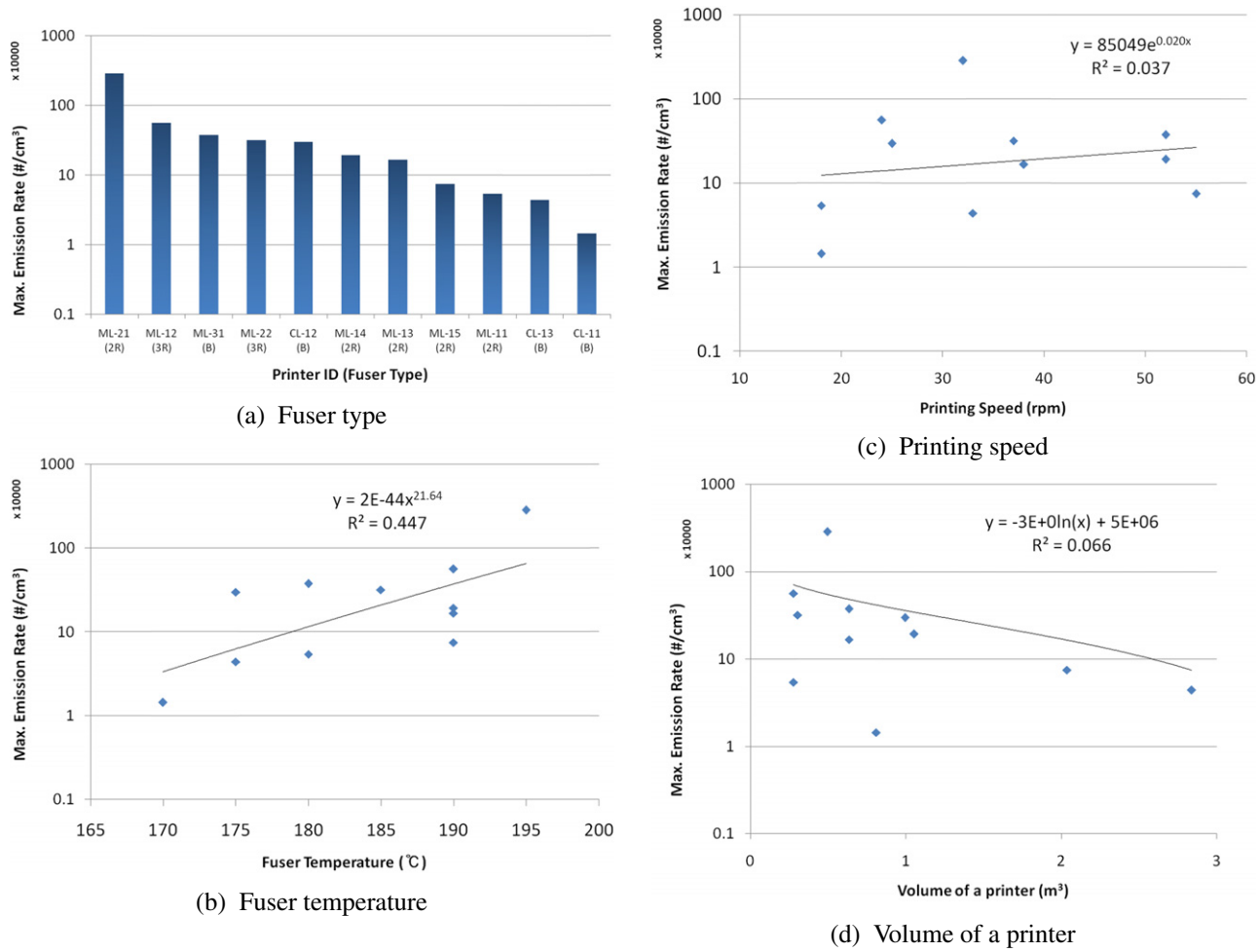


Figure 4. Emission rate of the 11 laser printers against fusing temperature.

(4) emission rates are not related to the sizes of the printer. A relationship between fuser temperature and emission rate was found; however, this evidence is not statistically strong enough to show that the fuser temperature is a factor in creating UFPs in a laser printer. Even in a recent study,[8] the correlations using average emission rate and average fuser temperature obey a power law. Too many unknown factors are involved with this experiment such as fuser structure, different toners and roller material.

Figure 5 shows maximum emission rates during a particle number concentration measurement with fuser temperatures of the four printers with different types of fuser unit, which were controlled by changing the current used in the fuser unit. Original graphs of the particle number concentration measurement are shown in each figure. The data of original graph was collected during the pre-operating phase, operating phase, and post-operating phase for the various fuser temperatures. Fig. 5(a) shows the emission rates for three different fusing temperatures using the CL-11 fuser unit. The fuser system consists of two rubber rollers and one aluminum tube or belt. The two lamps increase the temperature of either the tube or belt. The emission rate of CL-11 is increased from 120,200 to 902,800 on increasing the temperature from 160 to 180°C. Fig. 5(b) shows emission rates for five different fusing temperatures using the CL-13 fuser unit. The unit consists of one rubber roller and a belt. The moving belt is heated to transfer energy to the paper being used for printing. The emission rate of CL-13 is increased from 51 to 374,800 on increasing the temperature from 150 to 190°C.

Fig. 5(c) shows the emission rates of ML-11 with a two rubber-roller system. The maximum emission rates are increased from 2113 to 192,700 on increasing the temperature from 140 to 170°C.

Fig. 5(d) shows the emission rates of ML-15 with a two rubber-roller system. The fusing system consists of one rubber roller and a belt heated by a single lamp. The emission rates are increased from 77 to 14,440 on increasing the temperature from 160 to 180°C.

The relationship between the emission rate and the temperature of a fuser unit were analyzed statistically. Individual graphs clearly show strong relationships with the fuser temperature. However, the data combined from the four cases showed only a weak positive exponential-rise relationship. This is still very important because it is one piece of evidence that suggests there are other confounding factors.

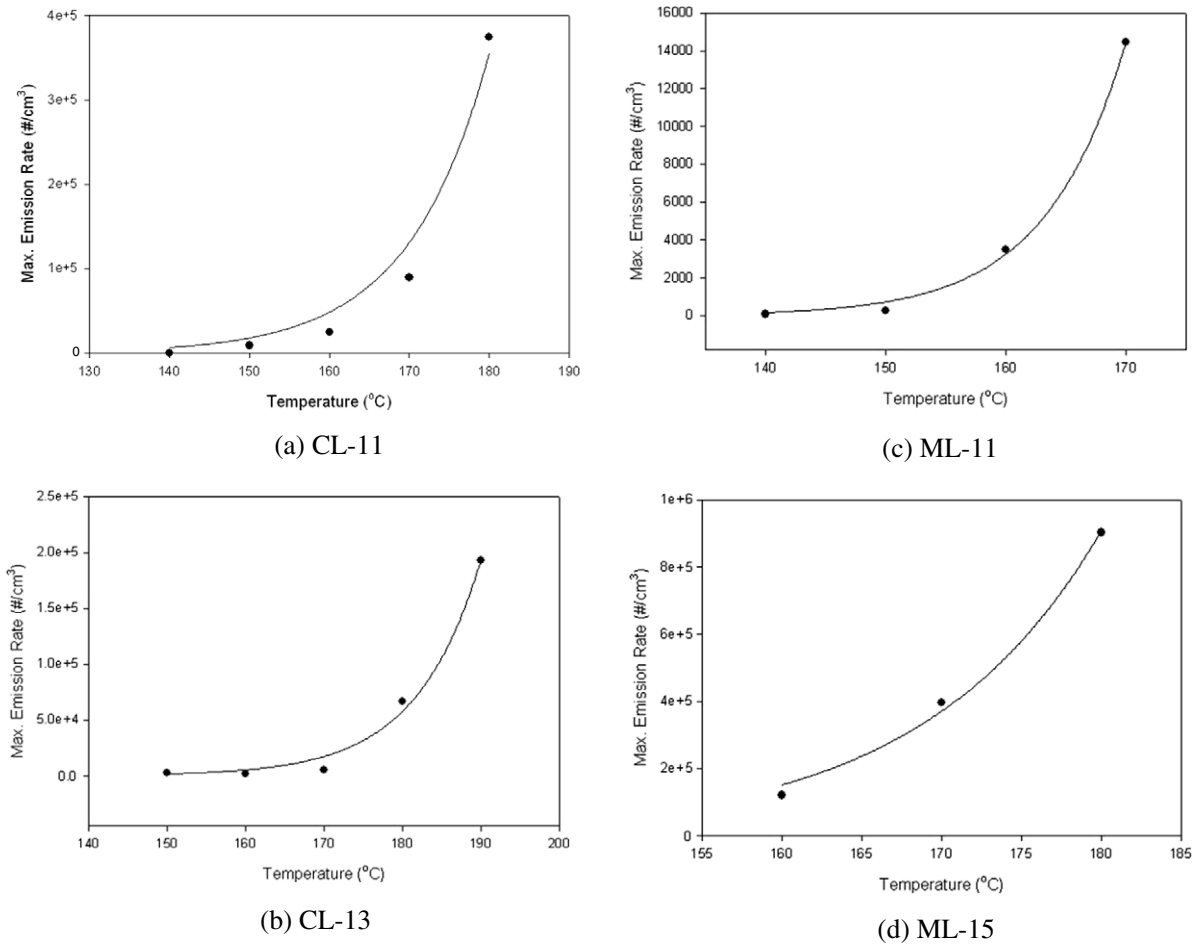


Figure 5. Effect of fusing temperature on ultrafine particle emission with different printing speed of printers.

Using SigmaPlot, the regression equation was derived using maximum particle emission rates and average fuser temperatures. The general equation is written as follows:

$$C_p = a\exp(bT),$$

where C_p is the maximum particle number emission rate (particles/cm^3); T is the temperature (°C); a is a parameter that is a function of a fuser type and b (=0.15) is an empirical constant. The exponential relationship should be applicable to all laser printers. For different printers, b is an empirically determined value while a varies with different fusing units. According to the test results, the emission rate is highly dependent on the temperature of the fuser. The fuser was specially designed for the fusing temperature of the toner at the nip area, which is usually 20–50°C lower than the temperature of the fuser unit from the heating lamp.

CONCLUSION

Systematic tests were performed to better understand the mechanism of ultrafine particle emission. 11 printers with different fuser units were selected. Several observations can be made (1) emission rates are not strongly related to the fuser temperatures, (2) emission rates are not related to the fuser type, (3) emission rates are not related to printer speeds, and (4) emission rates are not related to the sizes of the printer.

The relationship between emission rate and the temperature of a fuser unit is very strong; however, only a weak positive exponential relation was observed with mixed data from four different fuser units. This suggests that some other factors in the laser printer affect FP/UFP emissions. These factors are (1) printer fuser structure, (2) fusing temperature for printing, (3) type of toner, and (4) amount of toner used on a printed page. Possible solutions to reduce emissions are (1) reducing the fusing temperature, (2) developing new toner that possibly can be fused at lower temperatures, (3) reducing the amount of SVOC material in the toner, and (4) reducing the temperature decreasing rate between the surface and boundary.

ACKNOWLEDGMENT

We would like to thank Professor Taesung Kim and Professor Sunpark Gwon for advice regarding the ultrafine particle analysis and Dr. Jinmo Hong and Dr. Sunhyung Lee for advice and help setting up and operating the printers.

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