Characteristics of ultrafine particle emission change depending on the placement of ventilation systems in 3D printer working environment

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Kyung Ho Park
MS in Environmental Engineering
Institution: Korea Conformity Laboratories
Address: Korea Conformity Laboratories #805, I-Valley, 149, Gongdang-ro, Gunpo-si, Gyeonggi-do 15845, South Korea
E-mail: boywan@kcl.re.kr

Sang Cheol Kim
PhD in Chemical Engineering Tecnhology
Institution: Korea Conformity Laboratories
Address: Korea Conformity Laboratories #805, I-Valley, 149, Gongdang-ro, Gunpo-si, Gyeonggi-do 15845, South Korea
E-mail: sangcheol@kcl.re.kr

Woo Chul Sung
MS in Internet Engineering
Institution: Korea Conformity Laboratories
Address: Korea Conformity Laboratories #805, I-Valley, 149, Gongdang-ro, Gunpo-si, Gyeonggi-do 15845, South Korea
E-mail: sungwc@kcl.re.kr

Ah Young Choi
MS in Chemistry
Institution: Korea Conformity Laboratories
Address: Korea Conformity Laboratories #805, I-Valley, 149, Gongdang-ro, Gunpo-si, Gyeonggi-do 15845, South Korea
E-mail: aychoi@kcl.re.kr

ABSTRACT

This study evaluated the emission characteristics of ultrafine particles emitted during material extrusion type 3D printer, called Desktop 3D printer, operation in the test bed and mock-up environmental conditions respectively. For the measurement, a condensation particle counter (CPC) and scanning mobility particle sizer (SMPS) were employed. In the test-bed evaluation, representative materials widely used nowadays such as ABS, PLA, TPU, PC, etc, emitted higher than the UFP criteria (3.5×10^{11}) of 2D printer test method RAL-UZ 171. Particle sizes emitted from materials were found to be less than 200 nm. For the mock-up environment, seven different Desktop 3D printers and mechanical ventilation devices are used to compare the reduction rates of UFP according to the kind and placement of ventilation systems. When the ventilation equipment was installed on the ceiling, the reduction efficiency of UFP emission was not confirmed clearly while the reduction rates were significantly reduced when installed on the window.

Keywords: ultrafine particles, 3d printer (material extrusion machine), emission, ventilation systems, reduction rate.

1 INTRODUCTION

International standard organization, ISO TC 261 and ASTM F42 on Additive Manufacturing (AM) Technologies, classify the range of AM processes into seven different categories according to energy sources and material kinds used for additive manufacturing machines (Wohlers Report,2016). One of them, a material extrusion (ME) type 3D printer which is known as fused deposition modeling fabrication (FFF), is a technology where the thermoplastic filament is forced through a heated extrusion nozzle, melted and deposited layer by layer on the heating bed. Recently, the ME type Desktop 3D printer is widely used either at homes or offices (Stephens et al.,2013; Bumgarner,2013). According to recent studies, the significant number of ultrafine particles (UFPs: particles less than 100nm) emitted by 3D printing may harm humans when inhaled (Yoon et al.,2015; Cao et al.,2016). However, we are not aware of any test method on particle emission from commercially available Desktop 3D printers at a commercial office and residential space. In addition, there have been no specific attempts to prevent or reduce UFPs during 3D printing operation.

This study firstly tries to determine the ultrafine particle emission rates from 3D printer operation in the test bed using an Emission Test Chamber. Secondly, we are going to investigate how ultrafine particle emission rates can be changed depending on the placement of ventilation systems in a real 3D printer operating environment.

2 EXPERIMENTAL METHODS

2.1 EMISSION TESTING PROCEDURE USING EMISSION TEST CHAMBER (ETC)

2.1.1 Emission Test Chamber (ETC)

The large chamber (5 m^3) is designed with surface-treated stainless steel to be low emitting and to be low adsorbing in the test chamber during chamber background test and 3D printer operation. Before loading the 3D printer inside the chamber, the chamber interior walls are cleaned with distilled water and a thermoplastic filament is forced through the extrusion nozzle for setting up the 3D printer with a filament. The 3D printer is placed on the stainless steel table and installed at a (1 ~ 1.5) m height from the floor of the middle of the chamber. Before the start of the 3D printer, the chamber interior is cleaned by circulating fresh air whose volume is equivalent to at least 4 times of the interior capacity to keep the chamber background less than 2 000 cm^{-3}. This chamber during operation is controlled at the constant temperature, humidity, and air exchange as described in Table 1 and the 3D printer inside the chamber prints a three-dimensional test specimen (50 × 50 ×10) mm, for about 4 hours using operating conditions as in Table 2 below.

Table 1: Large chamber conditions

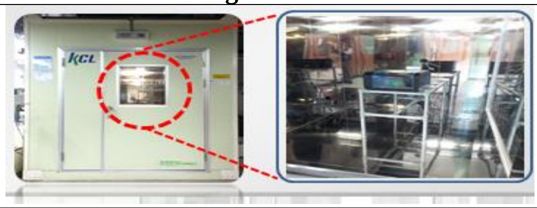
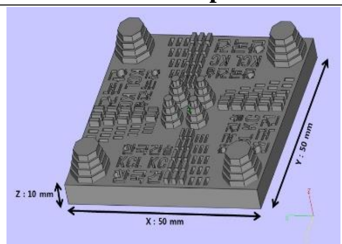
Item	Test condition	Large chamber
Chamber size	5 m^3	
Temperature	(24 ~ 26) ℃	
Humidity	(45 ~ 55) % R.H.	
Air exchange rate	1 air exchange/h	

Table 2 : Test Operating conditions (3D printer)

Item	Setting value	Test Sample
Layer height (mm)	0.2	
Print speed (mm/s)	25	
Infill rate (%)	20	
Nozzle temperature (℃)	250	
Bed temperature (℃)	100	
Material	ABS	

General requirements for the large chamber are compliant with ISO 16000-9. The referenced test methods for measuring UFP emission rates emitted from 3D printer were used considering ISO/IEC 28360 and RAL UZ 171 because there is currently no standard for UFPs emitted from a 3D printer.

2.1.2 Sampling and analysis

A condensation particle counter (CPC, model 3775, TSI Inc.) was used to measure total particle number concentration by the time according to particle size range, particle number concentration range, measurement frequency condition. A scanning mobility particle sizer (SMPS, model 3910, TSI Inc.) with a detectable size range of 10 to 420 nm was used to investigate the particle size distribution. The CPC measures a wide concentration range from 0 to 10^7 particles per cubic centimeter with a sample flow rate of 0.3 L/min. It is located outside the chamber and connected to the chamber exhaust port with conductive material to minimize losses of the particles. UFP measurements are measured during the pre-extruding, extruding and post-extruding phases of the 3D printer and presented as a diagram of particle number concentration [#/cm^{-3}] versus time comprising the period starting from the pre-extruding phase to at least 1 air exchange after the extruding phase end-point. The used CPC was capable of counting particle size range from a minimum of 7 nm to at least 300 nm and the detection efficiency both at the highest size limit and lowest size limit must be equal to or higher than 50 %. The required lower particle number concentration level to the particle size of 7 nm of the CPC is to be 1 cm^{-3} or lower than that and the upper concentration level to the particle size of 300 nm is to be equal or higher than 10^7 cm^{-3}. The calibration for the counting efficiency of the CPC was conducted according to ISO 27891.

2.1.3 UFP emission rate calculation

The following equations are from the RAL-UZ 171 and particle emission rate (PER(t)) emitted from the AM process per unit print time is calculated from total particles (TP) by the total print time in hours.

$$PER(t) = V_c \left(\frac{C_p(t) - C_p(t - \Delta t) exp(-\beta \cdot \Delta t)}{\Delta t \; exp(-\beta \cdot \Delta t)} \right) \quad (1)$$

$C_p(t)$:	smoothed curve of particle number concentration [cm^{-3}]
V_c :	test chamber volume [cm^3]
Δt :	time difference between two successive data points [s]
β :	particle loss coefficient [s^{-1}]

Total particle emission (TP) is calculated from the integral of PER(t) over the emission phase.

$$TP = V_c \left(\frac{\Delta C_p}{t_{stop} - t_{start}} + \beta \cdot C_{av} \right) (t_{stop} - t_{start}) \quad (2)$$

ΔC_p :	difference of ΔC_p(t) between t_{start} and t_{stop}, [cm^{-3}]
C_{av} :	arithmetic average of C_p(t) between t_{start} and t_{stop}, [cm^{-3}]
V_c :	test chamber volume [cm^3]
β :	particle loss coefficient [s^{-1}]
$t_{stop} - t_{start}$:	emission time [s]

Loss rate of particles (β) in the range of specified particle size may be determined by fitting the total particle number concentration decay in totoal particle number concentration digram. It is assumed that the particle loss rates are constant and applied for both the printing phase and post-operating phase.

$$\beta = \frac{ln\left(\frac{c_1}{c_2}\right)}{t_2 - t_1} \quad (3)$$

2.2 EMISSION TESTING PROCEDURE IN THE MOCK-UP ROOM

2.2.1 Mock-up room

In order to check the motional state of ultrafine particles in accordance with the types and locations of mechanical ventilation devices among a variety of environmental conditions in a real 3D printer operating environment, we composed a $31m^3$ mock-up room which is capable of controlling indoor temperature, humidity and installing air exchange an device as below Figure 1.

Figure 1: Composition of Mock-up room

As mechanical ventilation, a window ventilator ($10m^2$/ h), [250 × 250] mm and air-tightness testing equipment were used. In case of the window type ventilators, the ultrafine particle emission reduction rate was evaluated by installing them on the windows and the ceiling respectively. In case of the air-tightness measuring devices, two air-tight devices of the same performance were installed on the ceiling under controlled indoor air inflow and outflow (1 ~ 3 air exchange/h) and we evaluated the reduction rate of ultrafine particle emission according to the amount of ventilation. After keeping indoor environmental conditions (24 ~ 26) ℃, (48 ~ 52) % R.H using a thermos-hygrostat air system to keep indoor environmental conditions constant before 3D printer operation, we stopped the thermos-hygrostat air system ten minutes before the 3D printer operation and started up seven printers at the same time.

2.2.2 Sampling and Calculation

The sampling method was the same as the method specified in Section 2.12, but the determination of the reduction ratio of UFP emission every 30 minutes was calculated by the ratio of the sum of the particle number concentration during 30 minutes before the test conditions to the decrease of its value over 30 minutes after the test conditions.

3 RESULTS

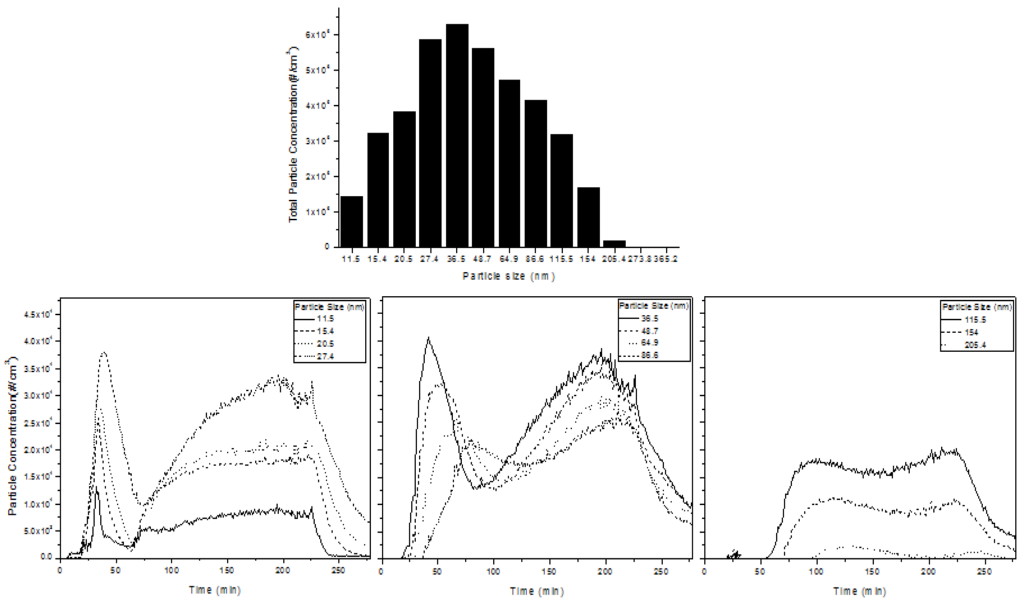
3.1 THE EMISSION RATES OF UFPS EMITTED FROM 3D PRINTER INSIDE EMISSION TEST CHAMBER (5M^3)

UFP emission rates according to all materials(expect for ABS-C and PLA-B) provided by the 3D printer manufacturers A, B and C exceeded the UFP criteria of RAL-UZ 171 which is for the 2D printer as shown in Table 3 below. In addition, most of the results by each material using Manufacturer A's 3D printer exceed the RAL standard when comparing the UFP emission rates, and we also found out that the amount of emission were different depending on the type of material used. 3D printers could take several hours or more to print depending on the kind and shape of the final product and the result values were calculated from the total number of emitted particles divided by the total print time in hours. As shown in Figure 2, most sizes emitted from the operation of a 3D printer with ABS material were observed in the (11 ~ 210) nm size ranges.

Table 3: UFP emission rates by 3D printer brand and materials

Brand	Air exchange rate	Material	UFP(Particles)	Particles/10 min	RAL-UZ 171 (Particles/10 min)
A	1 cycle/h	ABS-A	1.7×10^{13}	7.1×10^{11}	3.5×10^{11}
B		ABS-B	5.0×10^{13}	2.1×10^{12}	
C		ABS-C	7.8×10^{12}	3.3×10^{11}	
A		PLA-A	9.6×10^{12}	4.0×10^{11}	
		PLA-B	7.0×10^{11}	2.9×10^{10}	
		TPU	2.7×10^{13}	1.1×10^{12}	
		PC	3.8×10^{13}	1.6×10^{12}	

Figure 2: Size-resolved and UFP concentrations(〈 210 nm) measured emitted during 3D printer operation



3.2 THE REDUCTION EFFECT OF ULTRAFINE PARTICLE EMISSION RATES DEPENDING ON THE PLACEMENT OF VENTILATION SYSTEMS IN THE MOCK-UP ROOM OF 3D PRINTER

3.2.1 In the case the ventilation systems are installed on the ceiling and air exchange is set to the range from 1 to 3

In Table 4 below, Test Condition 1 was performed by circulating the inside air and outside air using two air-tightness testing machines and setting the air exchange rate to n = 1 and 3 with ventilation systems set on the ceiling. After 2 hours of 3D printer operation, the air-tightness testing equipment was operated for 90 minutes to keep the air exchange rate of n = 1, and n = 3 was performed for the next 90 minutes. As a result of the Condition 1 in Table 5, it was confirmed that the sum of particle number concentrations decreased by about 5 % during the initial 30 minutes when the ventilation system was adjusted to an air exchange of n = 1 and declined by about 8 % after 90 minutes compared to the initial sum of particle number concentrations with air exchange of n = 3. As shown in Table 4, the room temperature increased by 4℃ while humidity decreased by 11 % during the operation of the 3D printer.

3.2.2 Reduction effect of ultrafine particle emission rates when installing the same ventilation on windows and ceilings

In Condition 2 of Table 4 below, one of the same exhaust fans (10m^3/min) is installed on the ceiling and another on the window to evaluate the change of UFP emissions according to the placement of exhaust fans. In Condition 2 in Table 5, when only the exhaust fan installed on the ceiling was operated 2 hours after the operation of the 3D printer, the sum of particle number concentrations inversely increased by about 16 % over 90 minutes. On the other hand, the reduction rate of UFP emission was reduced to about 46 % when the exhaust fans installed on the ceiling and window were operated at the same time during 90 minutes.

The results of test Conditions 1 and 2 show that the mechanical ventilation systems are able to more effectively reduce UFP emission when installed on the window rather than on ceiling. This indicates that the UFP reduction rate could be changed depending on the placement of the mechanical ventilation device.

Table 4 : Mock-up room – Test environmental conditions

Test conditions	3D printer	Temperature (℃), RH (%)		Operating time by test conditions					
		Before starting the printer	After starting the printer	0.5 hr	1 hr	1.5 hr	0.5 hr	1 hr	1.5 hr
1	7	25, 60	29, 49	Air exchange rate (n =1)			Air exchange rate (n =3)		
2	6		27, 54	Ceiling Exhaust Fan			Ceiling Exhaust Fan & Window Exhaust Fan		

Table 5 : Mock-up room – Test environmental conditions

Test conditions	3D printer	Sum particle number con(#/cm^3)	UFP reduction ratio(%)					
		Test conditions 30 minutes before	Environmental condition time[A]			Environmental condition time[B]		
			0.5 hr	1 hr	1.5 hr	0.5 hr	1 hr	1.5 hr
1	7	1.1 ×10^9	5.2	2.4	-1.7	0.2	1.8	7.5
2	6	2.8 ×10^6	-4.4	-10.7	-15.6	28.9	43.2	45.7

A : Environmental condition time for ceiling exhaust fan
B : Environmental condition time for ceiling exhaust fan & window exhaust fan

4 CONCLUSIONS

In this study, we present some of the results of UFP emitted from a Desktop 3D printer during 3D printer operation. From the test-bed results, we found out that a 3D printer emits a significant amount of UFP depending on the kind of printing material and test conditions of the 3D printer, most of which exceed the UFP criteria of 2D printer of RAL-UZ 171.

From the Mock-up Environment Test, we identified important facts : the room temperature is raised and the relative humidity is relatively low when several 3D printers are operated simultaneously in the same space. In addition, we confirmed that there are differences in the reduction rate of UFP emissions depending on the placement of the mechanical ventilation system. These results suggest that we should be careful considering the placement of the 3D printer and mechanical ventilation when setting up a 3D printer in a certain space. In conclusion, we think it is necessary to do further studies besides this work on the hazardous substance reduction efficiency of different environmental conditions in the place where 3D printers are installed only one space in order to maintain a pleasant indoor environment during 3D printing operation.

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