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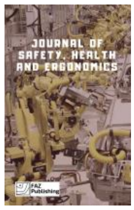

Emission of selected Environmental Exposure from Selective Laser Sintering (SLS) Polyamide Nylon (PA12) 3D printing Process

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Abstract: Indoor Air Quality (IAQ) is very important to the health and comfort of occupants inside building. The quality of indoor air depends on the air pollutant inside the building. A bad IAQ in workplace will lead to negative impacts to the operators such as dizziness, irritation, headache and others. Additive manufacturing is one of the emerging technologies that has been discussed recently. However, the study on emission from 3D printing process are still focused on FDM type 3D printer. Less attention given to the other type of 3D printing especially powder bed fusion particularly selective laser sintering (SLS). Therefore, this study aims to investigates the emission from selective laser sintering of 3D printing process. The design calibration block from SLS printer's manufacturer is selected to be printed to measure the emission from SLS printing. The powder material use in this research was polyamide nylon (PA12) powder material. The data collected for 8 hours during whole printing process. Temperature, relative humidity, carbon dioxide (CO2), total volatile organic compound (TVOC), and formaldehyde were measured and compared to the acceptable limit for Industrial Code of Practice (ICOP) DOSH 2010. The highest concentration of carbon dioxide CO2 is at preparation for during printing phase 999 ppm and almost exceed the limit of 1000 ppm. Meanwhile, TVOC, formaldehyde, RH and temperature were measured at 1.7 ppm, 0.05 ppm, 70.6%, and 27.6 °C accordingly. The concentration of TVOC and formaldehyde are in the range of acceptable limit. RH and temperature meanwhile slightly over acceptable limit during SLS machine operation due to laser temperature. The data collected from the emissions of selective laser sintering (SLS) 3D printing by polyamide nylon powder suggest that ventilation system of the location should be improved to remove excess pollutant air and fresh air is suggest to supply constantly to the occupant.

Keywords : Emission, Environmental Exposure, Selective Laser Sintering, Polyamide Nylon, 3D printing Process

1. Introduction

Indoor air quality (IAQ) is a subset of indoor environment quality (IEQ) which includes other factors including lighting, ergonomics, acoustics, and temperature addition to the building [1]. IAQ is related to health, performance and comfortability of the occupant [2]. Sources that release pollutant gases such as carbon dioxide and respirable dust into the air are the cause of indoor air quality problems. A bad IAQ will lead to many health problems [3]. In modern day, technologies are revolving around us. From

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many kinds of technologies that are emerging, additive manufacturing or three-dimensional (3D) printing technology stand out as one of the technologies that has huge potential towards the society [4]. 3D printers are one of the new technology machines that can turn a digital design into three-dimensional objects, also can make almost every things of human daily life. They are very useful because it can produce different kinds of objects, with different materials from the same machine. 3D printer is widely used by various field such as automotive, aerospace, military, education, health and care, architects, designers, and consumer products. However, additive manufacturing (AM) lead to environmental emission from printing process. [4]–[6]. Occupant of the room inhaled polluted air and will have side effects to their health [7]. The effects of the pollutants produced by these 3D printers may underestimated by people [8]. Hence, this study is to provide data of selected environmental emission produced by 3D printing machine to increase public and users' awareness towards this issue. Additive manufacturing machine can release volatile organic compounds chemical and particles into air when printing [9]. The 3D printer usually not design with air cleaning system [6]. Thus, the situation could be worst if use in an enclosed space without proper air flow or ventilation. Studies show that the emission such as volatile organic compound (VOC), carbon dioxide (CO2) and formaldehyde have negative impacts on human and environmental health [10], [11]. The health effect due to exposure to high VOCs is breathing problems, irritation of eyes, nose, throat, nausea, asthma, headache, and cancer [12], [13]. All this happen is because lack of concern and emission control in this issue [14]. The studies on health impact from fused deposition modelling have been discussed by researchers. However, the studies on impact from powder bed fusion likewise selective laser sintering process are still limited [5], [15]–[17]. Therefore, this study reported the emission of selected environmental exposure from selective laser sintering process.

2. Literature Review

IEQ of a building is determine by four aspects that are thermal comfort , indoor air quality, noise level and lighting level, The IEQ of buildings determines the occupants or employee comfortability, healthy, and productivity [18]. The United States Environmental Protection Agency (USEPA) has performed a comparative risk studies and listed IAQ as one out of five of environmental risks to public health [19]. The Heating, Ventilation, and Air Conditioning (HVAC) systems of a building will impact two parameters of IEQ [20] , that are thermal comfort and indoor air quality [21], [22]. Department of Occupational Safety and Health Malaysia (DOSH) is an agency that protects labours so they can work in a safe and healthy working environment by controlling the standard of working condition [23]. In this research, it is about IAQ. The factors affect IAQ are poor ventilation, poor temperature controlling, humidity, and other activities inside or near the building that contributes to outdoor supply air. OSHA does not provide IAQ standard, but it concerns about air ventilation, it said that a good ventilation can prevent and resolve IAQ problems [3]. The acceptable limit for indoor air exposure recommends by DOSH Malaysia based on Industry Code of Practice of Indoor Air Quality (ICOP DOSH 2010) depicted in Table 1.

Table 1 : Indoor air quality acceptable limits [23]

Indoor Air Contaminants	Acceptable limits		
	ppm	mg/m^3	cfu/m^3
Chemical contaminants			
(a) Carbon monoxide	10	-	-
(b) Formaldehyde	0.1	-	-
(c) Ozone	0.05	-	-
(d) Respirable particulates	-	0.15	-
(e) Total volatile organic compounds (TVOC)	3	-	-
Ventilation performance indicator			
(a) Carbon dioxide	C1000	-	-

Carbon dioxide (CO2) is a natural substance that exist in earth. Carbon dioxide is form when anything or metal carbonate is burn in air. However, a high quantity of CO2 in indoor indicates that the indoor air quality and air ventilation is poor. Increase of air change rate per hour will decrease the average outlet of CO2 concentration [24]. The concentration of CO2 at outdoor is from 300 to 400ppm. Increase in CO2 will increase the acidification of blood, lead to difficulty in breathing.

VOC are the chemical gaseous that emitted from the solid or liquid. VOC is a chemical compound that can change from liquid phase to vapor state, it is a carbon compound bonded to other element such as hydrogen, chlorine, fluorine, bromine, sulphur, and nitrogen. Most of these elements are from periodic table group 17 that is poisonous to human in gas or liquid even solid form. If the gas is inhale by human it may lead to short or long term of health effect [25], [26]. There are few example of long term exposure can cause that is damaged over nerve system and liver, carcinogenic effect which may increase the risk of getting cancer [27]. Short term of exposure can cause headache, eyes, skin allergic and vomit [28]. It is important to measure total volatile organic compounds (TVOC) because it represent the contaminant load in the environment and it is simpler and faster way to analysis compare to compare to high amount of VOCs [29].

Formaldehyde exists in both indoor and indoor at low level, normally it is less than 0.03 ppm. Industrial worker, laboratory technicians, and certain job that are related to formaldehyde may have higher exposure level than general public. Exposure is happening by breath in formaldehyde gas and body contact with liquid formaldehyde. When formaldehyde reach 0.1 ppm or more, some people will start to feel unwell, it can cause coughing, irritation in skin, nose, throat, eyes and hard to breath [29],[30].

Currently, there are many kinds of 3D printing process and technology. 3D printing is a process where material is melting by energy source and let cool to solidify under a computer program system. Normally, 3D printing process start to print from the bottom of the object and makes it from slice by slice, the layer is then stick and hold together to form a real 3D solid object, the design of the object can be very complex, it is easier and faster where usage of tooling, lubricant and coolant can be reduced or even removed [31]. Additive Manufacturing (AM) is one of the family of manufacturing technology, it is a technology that build 3D objects by ejecting layer by layer of material, such as plastic, metal, and concrete.

The American Society for testing and materials (ASTM) has created a set of standards that differentiate the 3D printing processes into seven categories, that is photo polymerization, material extrusion, powder bed fusion, direct energy deposition, sheet lamination, material jetting, and binder jetting [6], [12], [32]. Examples of 3D printing technologies are like stereolithography (SLA), fused deposition modelling (FDM), laminated object manufacturing (LOM), selective laser sintering (SLS), selective laser melting (SLM), direct metal deposition (DMD), laser metal deposition (LMD), and inkjet printing [33].

Selective laser sintering (SLS) is using laser as power source to sinter the material which is in powder form such as nylon 11, nylon 12 also known as polyamide 11 (PA11), and polyamide 12 (PA12). The powder is then sintered on a platform layer by layer and stick together to turn into a solid object. Where in this technology there is no require any support object to print any kind of designed product. In SLS, a container is filled with powder material is selectively sinter by an energy source [34]. In SLS, a high-power laser is use to sinter polymer powders, the scanned polymer powders are then fused together and form a solid. The laser is normally generated by CO2 laser. The chamber for SLS process is presented in figure 1. There are two type of material use for SLS 3D print that are amorphous polymer (polycarbonate, PC) and semi crystalline polymer (polyamide, PA), they are in powder form [35]. So on, the most used material in polymer powder bed process is polyamide (PA) or known as Nylon.

Polyamide also known as Nylon, is a type of plastic polymer. It is the most common material for SLS. Nylon can produce stable product with good strength and resist to most chemicals and produce product that with high mechanical and thermal resistance [5]. They can be made watertight by impregnation. PA material are biopolymer and some are certified as food-safe under certain conditions. The commonly used powder is PA 12 and can be composite with other additive such as carbon, glass, ceramic and others.

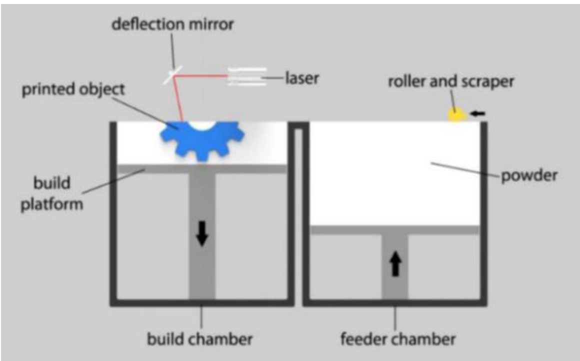

Figure 1: SLS chamber

3. Methodology

The 3D printer used for this project is a machine that is under Selective Laser Sintering (SLS) printing technology operated with scanner of dynamic focusing, high accuracy galvo scanning system. The 3D printing machine has external dimension size of 2660mm x 1540mm x 2150mm with weight of 3000 kg. The maximum printing size is 300 mm x 300 mm x 300 mm. The type of laser is CO2 with 100W power. Next, the laser wave length is 0.3 mm with scanning speed of 12.7 m/s. Thickness of powder layer for every rotating roller pass through is 0.1 mm. The maximum temperature of powder chamber is 190℃, the chamber is heated up in order to make sure enough heat for the laser to melt and sintered the powder [36].

The powder use is polyamide nylon (PA 12). The properties of nylon powder are bulk density of the powder is 0.4 g/cm3, density of part 0.95 g/cm3 with melting point 183°C and the powder is in white colour. The model to print is the calibration block of the 3D printer manufacturer with length 112 mm x width 112 mm x height 17.8 mm in order to fit in the chamber as illustrated in figure 2[17], [37]. Before printing, the design is in gcode form that generated by the SLS 3D printer software. The. stl format of the model is obtained and then redraw by using solid work software.

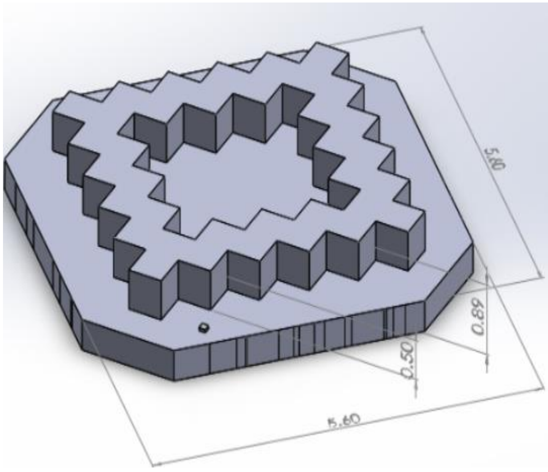

Figure 2: Calibration block drawing by manufacturer

The sampling strategies are number of sampling point, sample position, sampling period and sampling technique according to Industry Code of Practice on Indoor Air Quality 2010. Total time for the measurement are 8 hours, data is collected every five minutes for four phase that is before printing, preparation for printing, during printing and after printing by using apparatus or research tools provided by UTeM. There are two rooms involve in this project with dimension of 6 m length x 4 m width x 3 m height result in surface area of 24 m² as depicted in figure 3 and description of equipment in SLS laboratory illustrated in table 2.

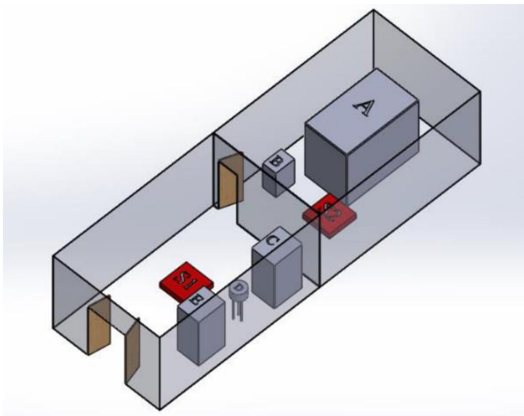

Figure 3: Plan view of SLS laboratory

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There are four type of printing phase that are before printing, preparation for printing, during printing and after print [38]. Before printing phase is where there is no any action related to printing is done. During the preparation for printing phase, the powder material is prepared and mixed in the first room before send to printing machine. During printing phase is where the 3D printer starts printing in second room. Lastly, when the object is finished print the following period is known as after print phase. The total time taken for this project is 8 hours where the time are distributed as 1 hour for before printing, 1 hour for preparation printing, 4 hours for during printing and 2 hours for after printing.

Table 2: Description of equipment in SLS laboratory

Legend	Equipment
A	SLS 3D printer
B	Exhaust fan (Machine coolant)
C	Powder cleaning device
D	Powder mixing machine
E	Manual sand blasting machine
S1	Sampling point 1
S2	Sampling point 2

The quality of IAQ is needed to determine by using data. The data are measured and collected by using some equipment or tools. The equipment used in this experiment are calibrated and presented in table 3.

Table 3: Equipment used for IAQ parameters sampling

Model	Parameter
htV-M	Formaldehyde
EVM	Temperature and relative humidity, carbon dioxie
MiniRAE 3000	Total volatile organic compound

4. Result and Discussion

Temperature and relative humidity data collection are presented in figure 4. During phase of before printing, the air conditioning for the laboratory just start on, and the temperature then reduce to achieved nearly 20 °C. The powder preparation process did not influence the temperature at the SLS laboratory. However, when the printing process start to operate, the temperature gradually increases until 24.7 °C at t= 360 minutes. Meanwhile, the relative humidity obviously influenced by the temperature from the air conditioning system. Nevertheless, the temperature generated at the SLS laboratory are based on the laser temperature generated from SLS machine. The relative humidity meanwhile maintains to gradually decrease to 55%. The RH then start to increase when the air conditioning system turn off.

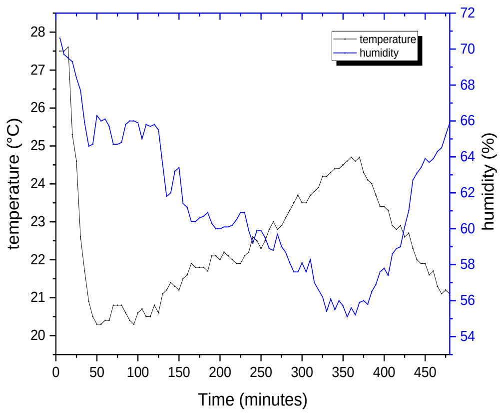

Figure 4: Temperature and humidity effect at SLS laboratory during SLS printing process

Figure 5 present the emission of TVOC, formaldehyde, and carbon dioxide (CO2). Starting from before start printing phase at time 0-60 minutes the carbon dioxide value was still consider stable and then increase constantly from 65-120 minutes in the preparation for printing phase, this is due to the process of weight and mixing powder material. Next, at the start of printing phase 125-360 minutes the carbon dioxide reaches the peak of 999 ppm at 130 minutes which is only less 1 ppm from the acceptable limit. The value rise was because of the SLS 3D printer machine start to heat the powder chamber until desire temperature and laser sintering process begin, after that the value drop slowly over the printing process. Lastly after printing phase, from 365-480 minutes the powder cake was taken out from the SLS chamber and pass to powder cleaning device and sand blasting machine. From the graph CO2 value slightly increase with an unstable trend due to the powder cleaning and sand blasting process [39], [40]. The acceptable limit of formaldehyde is 0.1 ppm. The peak of emission of formaldehyde in this research is 0.050 ppm which is half from the acceptable limit. The graph shows 0.050 ppm between times 80-85 min, 115-130 min, 380-415 min. There are in the preparation of printing, during printing and after printing phase. From the graph, the formaldehyde remains at second peak value 0.04 ppm for a longer period during preparation of powder phase and after printing phase. Other than that, formaldehyde hit 0.04 ppm four time during the printing phase. At the last part, it drops to lowest value 0.02 ppm but then rise back to peak value 0.05 ppm due to process of passing product from powder cleaning device to sand blasting machine [13].

Figure 5 also present the emission of average total volatile organic compounds. The acceptable limit of TVOC is 3 ppm. The TVOC trend rise slowly from 0.1 ppm to 0.4 ppm for 0-120 minutes before printing and preparation of printing phase. When entering the printing phase at 120-360 minutes the TVOC slightly increase to 0.5 ppm and remain unchanged from 155-210 minutes, then rise to 0.6 ppm and remain steadily again until the end of printing phase. Next, for after printing phase the powder cake product was being taken out from the SLS 3D printer chamber and continue with powder cleaning and sand blasting process, so the value of TVOC drastically change to 1.5 ppm and show unstable trend until 410 minutes. At 410 minutes the TVOC value hit peak value of 1.7 ppm, it is then drop gradually until 0.6 ppm at 445 minutes and stay constant until the end of the whole process

[34], [41]. The powder material affect by laser temperature, hence contribute to the rise of TVOC [5], [11], [12], [42]. Table 4 summarizes the data captured for the selected emission from SLS printing process.

Table 4 : Comparison of value on selected parameter detected to the ICOP DOSH 2010 acceptable limit [23].

Parameters	Peak value	ICOP acceptable limit
Formaldehyde	0.05 ppm	0.1 ppm
Total volatile organic compounds	1.7 ppm	3 ppm
Carbon dioxide	395-999 ppm	1000 ppm
Relative humidity	55.1-70.6 %	40-70 %
Temperature	20.3 -27.6 °C	23-26 °C

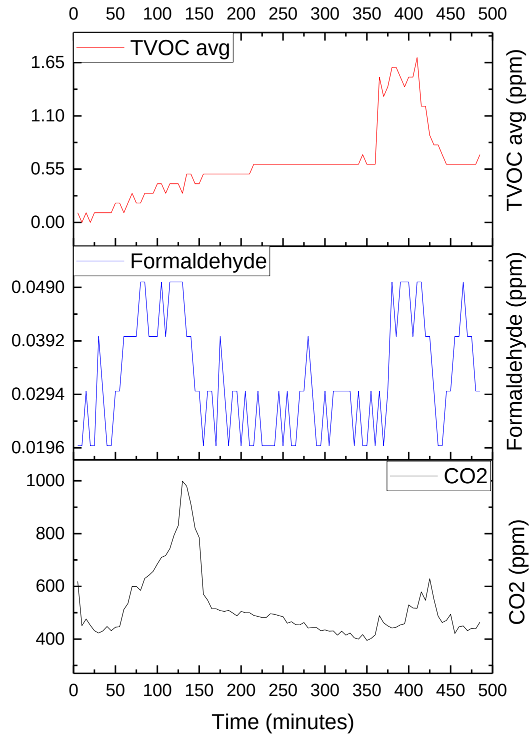

Figure 5: TVOC, Formaldehyde, and carbon dioxide effect at SLS laboratory during SLS printing process.

5. Conclusion

This research is concerning about the indoor air quality effect by the SLS 3D printer. The data collected is used to compare with the standard of Industry Code of Practice (ICOP) on Indoor air Quality 2010 executed by the Department of Occupational Safety and Health ministry of human resources, Malaysia. It expected that some reading of the data may exceed the acceptable limit of the standard. For chemical contaminants, the limits are eight-hour time-weighted average airborne concentrations. From the data collected, the formaldehyde, TVOC, RH and temperature were still in acceptable limit based on ICOP DOSH 2010. However, the peak value of CO_2 is 999 ppm at during printing phase which is only less 1 ppm to reach the ICOP acceptable limit. Based on this study, the study on respirable particulate and particle counter shall be discuss for SLS 3D printing process in future. The data based on this study should be a preliminary study in promoting better strategy in mitigate and reduce the occupational exposure to the SLS machine operator.

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