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Characterization of particulate matters and total VOC emissions from a binder jetting 3D printer

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ABSTRACT

Binder jetting 3D printing is a popular type of additive manufacturing and a powerful tool for creating parts and prototypes. Due to continuous movement of dry powders inside printer chambers and injection of resin-like binder fluid during printing, binder jetting 3D printers are a potential emission source of fine particulate matters (PM) and volatile organic compounds (VOCs). In this study, real-time measurements of total VOC (TVOCs) and aerosol (10 nm–10 μm) during a 2-h continuous operation of a binder jetting printer were incorporated into a time-varying mass balance model to obtain the emission rates. The particle sizes between 205 and 407 nm had the highest emission rates by count. Time weighted average $PM_{2.5}$ and PM_{10} and TVOC over a 24-h period all exceeded the USEPA ambient air quality standards. Continuous operation of the 3D printer led to a $PM_{2.5}$ level 10 times greater than the standard (344 vs 35 μg/m^3) and a PM_{10} level 3 times higher than the standard (474 vs 150 μg/m^3). TVOC concentrations with a maximum value of 1725 μg/m^3 exceeded upper limit concentrations recommended by the Environment Institute of European Commission, and USGBC-LEED. Ultrafine particles emitted from the binder jetting 3D printer were 10^4–10^5 times lower than those from typical fused deposition modeling (FDM) type of 3D printers using polylactic acid (PLA), but production of particles larger than 200 nm was significantly higher. The results suggest installing binder jetting 3D printers in an enclosure with proper ventilation for reducing the health risks.

1. Introduction

Three-dimensional (3D) printing has introduced revolutionary advantages in prototype manufacturing compared to conventional methods (i.e., injection molding, machining/subtractive technologies) [1]. This process is a form of additive manufacturing (AM) technology wherein a 3D object is created by laying down successive layers of material to directly realize a computer-assisted design (CAD) with no need for part-specific tooling. Popularity of 3D printers through recent improvements in portability, accuracy and affordability of rapid prototyping is fast growing with applications everywhere from households to the International Space Station [2]. The field of application widely extends from the making of cell phone protection cases to the production of medical protheses and aircrafts [3].

Current 3D printing technologies can be classified into seven process categories: 1) vat photopolymerization, represented by stereolithography (SLA), 2) material extrusion, represented by fused deposition modeling (FDM), 3) powder bed fusion, represented by selective laser sintering (SLS), 4) directed energy deposition, represented by laser metal deposition (LMD) and laser engineered net shaping (LENS), 5) sheet lamination, represented by laminated object manufacturing (LOM), 6) material jetting, represented by multi-jet modeling (MJM), and 7) binder jetting, represented by 3D printing (3DP) [4–6].

Of all mentioned AM processes, binder jetting has some distinct features. First, it can reduce the printing time since only a small fraction of the total part volume is dispensed through the print head; second, the combination of powder and binder enables a wider range of material compositions; third, slurries with higher

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solids loadings are possible with binder jetting printers compared to other AM processes. As such, binder jetting is commonly used in medical and architectural prototyping. With an average current cost of $20,000 (at the time of preparing this study, 2015), binder jetting 3D printers are very powerful but affordable for research labs [7–10].

Due to continuous movement of dry powder inside the chambers and injection of the resin-like binder fluid, binder jetting 3D printers are a potential source of fine particulate matters (PM) (from the powder) and volatile organic compounds (VOC) (from the binder solution). Since the average vertical build speed of this type of printers is about 25 mm/h, hours of operation may be required. Such long term PM and VOC emissions may deteriorate indoor air quality (IAQ) of the lab and the exposure consequently threatens the health of the working individuals. According to the material safety data sheets published by ZCorp Inc. and Technology Supplies Ltd., prolonged or repeated exposure to the powder may cause symptoms which include eye irritation, coughing, sneezing, chest pain and lung diseases. Exposure to binders causes nausea, headache and may irritate mucous membranes and upper respiratory tract. Moreover, parts fabricated using binder jetting printers tend to have poorer surface finishes than parts made by direct printing which may be associated with greater emissions of particulate pollutants during the process [4]. Although emission rates of PM, VOCs and ozone emitting from 2D inkjet and laser printers [11–14] and PM emission rates from FDM 3D printers have been investigated [15], there is no equivalent characterization data regarding the binder jetting 3D printers.

This study aims to determine PM and VOC emission rates resulting from the operation of a widely used, commercially available binder jetting 3D printer inside a research laboratory setup. Real-time monitoring of the airborne PM and total volatile organic compounds (TVOC) at three different periods of "before printing", "during printing" and "after printing" was performed. Particle size distribution (PSD) and concentrations were obtained, and comparisons to similar indoor emission sources and standards were provided. Findings from the current study will help assess the exposure risk of emitting particles and gases from binder jetting 3D printers and can be used to develop a comprehensive computational fluid dynamics (CFD) model to identify spatial and temporal concentrations of different particle sizes when a binder jetting 3D printer is in operation.

2. Methodology

2.1. Binder jetting 3D printing

Operation of a binder jetting printer is similar to a 2D ink-jet printer. An individual 2D layer (0.0762–0.2286 mm thick) is created by adding a layer of compact powder to the top of a vessel containing powder and the part being built. The successive powder layer is selectively added where the part is to be formed by ink-jet printing of a binder (e.g., resin or epoxy). This is performed by a gantry which carries a print head and a roller allowed to move horizontally over the working area. The print head transfers the binder supply by gravity. Before construction of each layer, the feed chamber is raised by the thickness of the next layer whereas the build chamber is lowered by the same amount. As the gantry moves, the roller pushes and compresses the powder on top of the build chamber while the print head is inactive. Then, the roller stops working and the print head sweeps the surface and fuses the powder by depositing the fluid binder. Through repeating the same procedure for the next layer, the created cross sections are printed one after another from the bottom to top of a design [16]. Proper deposition of the particles requires that the powder flow readies when a small amount of shear force is applied. This requirement is easily fulfilled for dry powder with sizes larger than 50 μm. However, the flow of particles smaller than 50 μm is dominated by interparticle forces that prevent free motion by aggregating the particles, and ultrafine particles (UFPs, <100 nm) requiring the presence of a liquid as a carrier to flow [17].

2.2. Monitoring set-up and conditions

Measurements were conducted in a 157 m^3 radiosurgery laboratory at average room temperature of 19 °C and relative humidity of 35%. The laboratory was equipped with one ZPrinter® 310 System (3DSystems, Rock Hill, SC) located in a corner (See Fig. 1a). This system consisted of two separated chambers: a feed bin filled with powder at the start, and a build chamber which was initially empty. The printer possessed 304 jets and the build chamber could accommodate any object smaller than 25 cm × 25 cm × 20 cm. The feed materials were zp®150 composite powder (the most recent powder developed by 3DSystems composed of 80% plaster, 10% vinyl polymer and 10% carbohydrate by weight), zb®60 binder solution (comprised of 20% humectant, 5% polymer and 75% water by weight) and zbond®90 color bond (composed of cyanoacrylate and hydroquinone) as infiltrator. Powder and binder consumption rates depend on object dimensions, object orientation inside the build

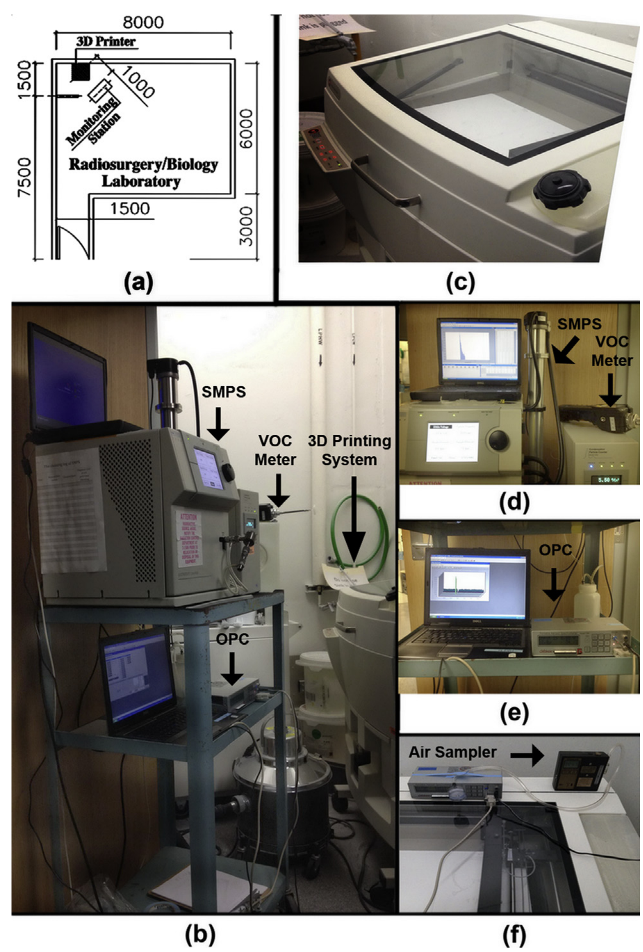

Fig. 1. Real-time monitoring system: a) plan view of the laboratory (units in mm), b) positioning of the instruments, c) standby ZPrinter 310 System, d) SMPS and VOC meter in operation for measuring submicron particles and TVOC, e) OPC in operation for measuring supermicron particles and f) sampling the emitting dust using a low-volume air sampler.