Identification of Effective Control Technologies for Additive Manufacturing

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# Supplemental File

Numerous real-time (also called direct reading) instruments and metrics were utilized in published papers that met the criteria of this review to quantify particle levels during printing and associated additive manufacturing (AM) tasks. A brief overview of these instruments and metrics are provided herein; for a more detailed discussion of these topics, the reader is referred to reviews by Kumar et al. (2010), Amaral et al. (2015), Asbach et al. (2017), and Viitanen et al. (2017).

## Instruments

* Mini-aerosol mass spectrometer (m-AMS): An instrument that determines particle mass based on time-of-flight mass spectrometry. Particles are drawn into the instrument, focused into a narrow beam, processed to impart a size- and shape-dependent velocity, impacted on a heated surface, vaporized, and detected by a time-of-flight mass spectrometer. Readings are expressed as mass concentration and size distribution (Katz et al. 2020).
* Aerodynamic particle sizer (APS): A time-of-flight instrument that rapidly measures particle number distribution over a range of sizes that span from a few hundred nanometers to tens of micrometers. Particles are drawn into the instrument, accelerated by an orifice, passed through lasers, and scatter light, which is collected on a photodetector and converted to an electrical pulse that is proportional to particle size (Amaral et al. 2015). Readings are expressed as number distribution and particle aerodynamic size distribution (Kumar et al. 2010).
* Condensation nuclei counter (CNC): An instrument that measures number concentration of particles that are too small for optical methods. Particles are drawn into the instrument and their size grown using a working fluid (usually ethanol, butanol, or water) and optically detected and counted. Readings are expressed as number concentration. The size range over which a CNC can detect particles depends on the instrument model and working fluid (McMurry 2000).
* Diffusion charger (DC): An instrument that places a charge on particles and measures the electrical current induced by the particles to derive surface area. Particles are drawn into the instrument and acquire a charge that is nearly proportional to particle diameter, from which surface area can be determined. Note that surface area from diffusion charging corresponds to the envelope around the particle and does not account for surface area from pores and surface irregularities. Depending on the instrument, readings are expressed as surface area concentration, lung deposited surface area, particle number concentration, and/or particle size. The accuracy of diffusion chargers that determine lung deposited surface area is best in the size range 20 to 400 nm (Asbach et al., 2017).
* Electrical low-pressure impactor (ELPI): A combination aerodynamic particle size classifier and particle charging and electrical detection instrument that gives number and size in the nanoscale to micron scale size range. Particles drawn into the instrument are charged using a corona charger, subject to inertial size classification using a low-pressure cascade impactor, and impact on a size-specific sample stage, which generates an electrical current that is detected using an electrometer (Kumar et al. 2010; Amaral et al. 2015).
* Fast mobility particle sizer (FMPS): An electrical mobility detection instrument that rapidly measures particle number and size distribution in the sub-micron size range. Particles drawn into the instrument are charged, subject to size classification based on electrical mobility using a differential mobility analyzer and detected using multiple electrometers (Kumar et al. 2010). Readings are expressed as number distribution and particle size distribution; assuming geometric relations, estimates of particle surface area concentration can be derived from the data. The specific size range over which a FMPS can detect particles depends on the instrument model and settings.
* Haze detector: An instrument that uses light absorption to measure particle mass concentration. The principle of operation varies by instrument type, with some using light extinction and scattering measurements, some using filter-based measures of light attenuation, and others using photoacoustic spectrometry (Amaral et al. 2015). Readings are expressed as mass concentration distribution. Depending on the instrument, mass concentration distribution can be expressed as particulate matter (PM) with aerodynamic diameter less than 10 µm (PM10) or less than 2.5 µm (PM2.5).
* Optical particle sizer (OPS): An instrument that uses light scattering to determine the size and number of particles. Particles are drawn into the instrument, a light source (visible or laser) shown on the particles, the light is scattered by particles, and detected at a given angle from one or more particles using a photodetector. Upon impact with the photodetector, the scattered light induces an electric pulse; particle size is determined from the height of the pulse (Amaral et al. 2015). Readings are expressed as number distribution and based on calibration with a particle having known density, mass concentration distribution. Depending on the instrument, mass concentration distribution can be expressed as PM10 and/or PM2.5.
* Scanning mobility particle sizer (SMPS): Similar with an FMPS, this instrument uses electrical mobility detection to measure particle number and size distribution in the sub-micron size range. The main difference is that in an SMPS, particles are detected using a CNC (Kumar et al. 2010). Readings are expressed as number concentration distribution and particle size distribution; assuming unit density and geometric relations, estimates of particle mass and surface area concentration, respectively can be derived from the data. The specific size range over which a SMPS can detect particles depends on the instrument model and settings.

## Metrics of particle characteristics

Published papers that met the inclusion criteria for this review reported AM process particle emissions data using multiple metrics (number, surface area, and mass). A brief overview of these metrics is described below. Note that currently, there is no agreement on the best metric for expression of AM process emissions.

* Particle number concentration: A metric that can be measured for multiple size fractions, including coarse particles (CPs), fine particles (FPs), and ultrafine particles (UFPs).
	+ CPs: Particles in this fraction have size less than 10 µm and are sometimes referred to as particulate matter having aerodynamic diameter less than 10 µm or PM10 (Kumar et al. 2010; Amaral et al. 2015). Given their large size, particles in this fraction generally have low number concentration but high mass concentration. CPs are often expressed and regulated on a mass concentration basis (µg/m3) (Virtanen et al. 2017).
	+ FPs: Particles in this fraction have size less than 2.5 µm and are sometimes referred to as particulate matter having aerodynamic diameter less than 2.5 µm or PM2.5 (Kumar et al. 2010; Amaral et al. 2015). Given their size, particles in this fraction generally have low number concentration but high mass concentration. FPs are often expressed and regulated on a mass concentration basis (µg/m3) (Viitanen et al. 2017).
	+ UFPs: Particles in this fraction have size less than 100 nm (or 0.1 µm) (Kumar et al. 2010; Viitanen et al. 2017). Many particles released during industrial operations fall within the UFP size range; particle mass decreases with particle size so UFPs have negligible mass compared with CPs and FPs. The UFP fraction is of concern because their small size permits penetration into the alveolar (gas exchange) region of the lung, entry into systemic circulation, and reaching inner organs (Viitanen et al. 2017). UFPs are often expressed as number per unit volume of air (#/cm3).
* Particle surface area concentration: As particle size decreases, the surface to volume ratio increases. As such, particle surface area may act as a carrier for surface-absorbed chemicals (Viitanen et al. 2017). Diffusion chargers as well as instruments that measure size-classified number distribution can be used to determine surface area concentration. Depending on the type of diffusion charger instrument used to measure particle surface area, the reading can be expressed as particle surface area concentration per unit volume of air (µm2/cm3), or lung deposited surface area (LDSA). The latter metric approximates the surface area of particles that deposit in the alveolar region of the lung and is expressed as particle surface area per unit area of alveolar lung surface (µm2/µm2). Surface area can also be approximated from size-specific number distributions (such as FMPS or SMPS data) assuming geometric relations (usually round smooth spherical shape).
* Particle mass concentration: Historically, an important exposure metric for CPs and FPs (Viitanen et al. 2017). Instruments such as OPS express results in terms of mass concentration. Mass concentration area can also be approximated by calculations from size-specific number distributions (such as FMPS or SMPS data) assuming geometric relations (usually round smooth spherical shape) and particle density.

## Literature searches

Key words from published papers available on additive manufacturing emissions and controls at the time this review article was conceptualized were compiled to develop a list of terms for database searching. These terms were grouped into three strings that were combined using the Boolean operator AND for database searches. The first string was synonyms and variations of “additive manufacturing”, the second string was terms related to emissions and exposures, and the third string was terms related to control technologies. The combined search string was: (additive manufacturing OR advanced manufacturing OR composite manufacturing OR ((Three dimensional OR 3D OR 3-D) ADJ2 printing) OR free form fabrication OR freeform fabrication OR fused filament fabrication OR fused deposition modeling OR metal additive manufacturing OR laser additive manufacturing OR material extrusion OR powder bed fusion OR binder jetting OR material jetting OR vat photopolymerization OR directed energy deposition OR molten extrusion deposition OR powder bed process OR selective laser sintering) AND (((Nanoparticle\* OR particulate matter OR particle size OR ultrafine particle\*) AND (emission\* OR exposure\*)) OR (air pollut\* ADJ2 (indoor\* OR occupational)) OR (health ADJ5 hazard\*) OR occupational health OR occupational safety OR occupational injur\* OR occupational exposure\* OR inhalation OR aerosol\*) AND (Ventilation OR air filter\* OR air filtration OR respirator\* OR ((administrative OR engineering OR contaminant\* OR emission\* OR technical OR temperature\*) ADJ5 control\*) OR protective equipment OR protective device\* OR protection OR prevention OR protective measure\* OR risk management OR risk reduction OR air quality). In this search, ADJ was an adjacency character that specified that the search engine looked for a word(s) within a certain number of words of another word(s), e.g., “((Three dimensional OR 3D OR 3-D) ADJ2 printing)” directed the search engine to find either Three dimensional OR 3D OR 3-D within two words of the word printing.

Results of the literature searches are summarized in Figure S1, and details provided herein. Librarians at the Centers for Disease Control and Prevention (CDC) used the combined string to search for terms in the title, abstract, and key words of literature in the Medline, Embase, Environmental Science Collection, CINAHL, and Scopus databases on May 10, 2021. One author of this manuscript (A.B. Stefaniak) used the same search strings to search for terms in the title, abstract, and key words of literature in the PubMed database on June 7, 2021. These searches of the Medline, Embase, Environmental Science Collection, CINAHL, Scopus, and PubMed database returned 47, 62, 24, 20, 81, and 72 citations, respectfully [N = 306]. After removal of 142 duplicates, there were 164 unique citations. Librarians at North West University queried the Web of Science database using the same search strings on June 4, 2021, which returned 116 citations. These 164 + 116 = 280 citations were merged, and 54 duplicates were removed, which left 226 citations. One author (A.B. Stefaniak) repeated the CDC database searches on June 8, 2021, using the same combined string, but expanded the query to all fields/text, which identified an additional 40 unique citations. From all database searches, there was a grand total of 226 (title, author, key words) + 40 (all fields/text) = 266 unique citations.

The authors were aware of two of our own publications that were available as electronic pre-prints on journal websites, but not yet indexed in any databases at the time of our searches, which increased the total to 268 unique citations. From our existing literature files, another 7 articles were identified that potentially had relevant information on a control technology that were not retrieved by the database searches. For example, as part of a larger study, Azimi et al. (2016) measured particle number concentration inside and outside of a ME-type FFF 3-D printer enclosure and mentioned in their discussion that the enclosure reduced particle emission rates, although it was not the major focus of the article. These 268 + 7 = 275 citations were split amongst the co-authors for detailed review. As part of this detailed review, the references in all 275 citations were cross-checked against the database search results, which identified an additional nine relevant citations. Among the 275 + 9 = 284 citations, 32 met our inclusion criteria (31 peer-reviewed journal articles and one Government report). From June 8, 2021 (date of the last database search) to December 31, 2021 (final cut-off date for inclusion in this review) key word citation alerts were used (i.e., Scopus and PubMed databases) to stay abreast of new literature and identified nine journal articles (electronic pre-prints or final published papers) that met our inclusion criteria. The search of the Web of Science database was repeated on November 8, 2021, which identified one new relevant journal article. The final number of citations included in this review was 32 + 9 + 1 = 42.



Figure S1. Disposition of literature searches. CDC = Centers for Disease Control and Prevention, NWU = North West University, (t, a, kw) = title, author, keyword search.

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