Design of Experiment for the Measurement of Aerosol Droplet Size Distribution of Temperature-Controlled Thermally Atomized Printed Electronic Inks

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In-Space Manufacturing (ISM) centers around NASA's growing need and ability to produce space technologies on demand in space. As the future of long term presence in space and deep space exploration approach, fundamental questions of our dependence on earth resupply to Low Earth Orbit (LEO) remain unanswered. ISM is leading various effort to evaluate the feasibility of producing essential spares and redundant parts on demand to enable a sustainable space-based supply chain model for part resupply. Among the parts and systems being considered, Avionics form the neural network of modern day aircraft and space vehicles providing a wealth of information ranging from Guidance, Navigation, and Control (GN&C) systems to on board Environmental Control and Life Support (ECLS) systems. Recent advances in the use of Aerosol Jet Technology to print Avionics components ranging from electrical traces on a circuit board to complex transistors and sensors raise the possibility of using such technology to reproduce or recreate electronic parts on demand with the help of custom electronics 3D printers. The challenge herein lies within the ability of such printers to generate and deposit an aerosol of electronic material utilizing processes independent of or enhanced by gravity to ensure controllably identical or improved behavior of the aerosol in an International Space Station (ISS) laboratory and on the ground. The behavior as well as the hazards and properties associated with such aerosols in a microgravity environment must be understood well in order to merit a feasible approach to utilizing them for manufacturing in space. In this report, we outline the experimental setup of a modified conventional vaping device to be used as the ideal gravity independent thermal atomization mechanism to generate aerosol. Our objective is to identify the ideal mass, density, and volume of our aerosolized droplets of ink to conclude that there exist a threshold of aerosolized ink droplet sizes that are indeed independent of the effects of gravity and remain stable after atomization. We use a Malvern Spraytec® Spray Particle Size Analyzer to perform real-time laser diffraction measurement of our ink droplets during atomization. The droplet size between conductive ink, dielectric ink and vegetable glycerin have been measured and contrasted. Furthermore, the mechanism of thermal atomization versus traditional pneumatic and ultrasonic atomization for operation in microgravity have been explored.

I. Introduction

In Additive Manufactured Avionics (AMA) development, aerosol jet printing technology demonstrated a very bright future of producing fine featured, and geometrically complexed avionics parts. Aerosol jet printing technology currently uses pneumatic and ultrasonic atomization processes to aerosolize conductive ink droplets to be deposited onto various substrates terrestrially. However, these two conventional atomization process rely on gravity to function properly. With much research and development ahead, the newly developed thermal atomization [15] shows great promise to atomize the droplet independent of gravity.

The process of how the ink is absorbed by the wick is through capillary wicking phenomenon. Wicking is the spontaneous absorption of a liquid into a porous medium by the action of capillary pressure. Capillary pressure during wicking occurs as a result of capillary suction, which is created on the walls of the porous media at the interface of wet and dry matrix. These forces originate from the mutual attraction of the molecules in the liquid medium and the adhesion of liquid molecules to those in the solid medium. The wicking phenomenon occurs when the adhesion is

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greater than the mutual attraction. Wicking is the main cause of absorption in the porous materials, although there may be other factors causing absorbency. [18]

The main principle behind the thermal atomization is the capillary action or wicking concept. It is the ability of the conductive nanoparticle ink fluid to flow in the narrow spaces without the assistance of gravity. The ink is then thermally boiled to be atomized into aerosol droplet. Once thermally atomized, our objective for the project in the next step involved is to characterize the aerosolized droplets.

In the process of characterizing the aerosol, one of the first tasks is to determine the droplet size distribution. In this report, the droplet size was determined experimentally through Malvern Spraytec® equipment. With known size of droplet and based on the existing literature, we can then predict our thermally generated droplet will be independent of gravity and therefore can suspend in the air indefinitely [17]. This scientific fact will provide avionic engineers a new perspective and advantage in designing tools to print electronics in space utilizing aerosol jet printing technology. In addition, we demonstrate the thermally generated droplet sizes measured are in the same size range of conventional pneumatic and ultrasonic atomization. Furthermore, similar liquid droplet sizes has been compared and contrasted.

II. The measurement of droplet size of thermally atomization

The Description of the device

(1) Power Supply

The power supply we use is a commercial product (SMOK OSUB 40W 1350mAh) of a conventional vaping device for the atomization process. This is a medium size power supply marketed for average consumers. In our experiments of aerosol size measurements, we set the power usage to the maximum value of 40 watts. The power supply has dimensions of 75 mm in depth, 25 mm in height and 54.5 mm in width. The temperature range is between 200 degrees and 600 degrees Fahrenheit and the voltage range is between 0.8V to 9.0V. [15]

(2) Rebuildable Dripping Atomizer (RDA)

The Vandy Vape Mesh 24 mm RDA with mesh wire was chosen for this experiment. The RDA chosen provide a 24 mm diameter dual invincible clamp style postless build deck with an open platform where custom mesh wire could be designed and built. The Mesh RDA was manufactured from 304 stainless steel. The unique build deck has two 11mm terminals with side mounted flathead screws to secure the mesh. Airflow enters the Mesh 24mm RDA via dual adjustable side air slots. The Mesh RDA equipped with two 9 mm drip tips, one ULTEM as well as one Doc drip tip, a 510 drip tip adapter and a bottom feed pin. We build our mesh coils using Vandy Vape mesh wires (SS316L).

(3) Malvern Spraytec® System Description

Aerosol droplet and particle size measurements are critical across a range of applications such drugs delivery to the human respiratory system through automotive fuel injection system. However, aerosol present unique challenges in terms of the measurement environment and the speed of the event which must be characterized. In our experiment, we chose Malvern Spraytec® for the conductive ink and dielectric ink atomized aerosol measurements. It delivers accurate aerosol size measurement and analysis. It provides real-time, high-speed measurements to ensure the complete characterization. In addition, the system offers unparalleled sensitivity to changes in the spray size distribution. Extensive size distribution data is generated rapidly and allows for an instant understanding of the evolution of aerosol over time. The Malvern Spraytec® system measures droplet size distributions through the principle of laser diffraction. This requires the angular intensity of light scattered from aerosol to be measured as it passes through a laser beam as shown in the following Figure 1 between Collimated Optics and Fourier Lens. The recorded scattering pattern is then analyzed using an optical model to yield a size distribution. The angular range over which scattering measurements are made has been optimized within the Malvern Spraytec® to ensure polydisperse size distributions are fully resolved. Particle size calculations are then carried out using a multiple scattering algorithm. Specifically, it provides the in-situ aerosol analysis from a robust platform as illustrated in following Figure 1. As illustrated, it composed of HeNe Laser, Collimating Optics, Fourier Lens, Detector/Data Acquisition system and Adjustable Sliding Rail.

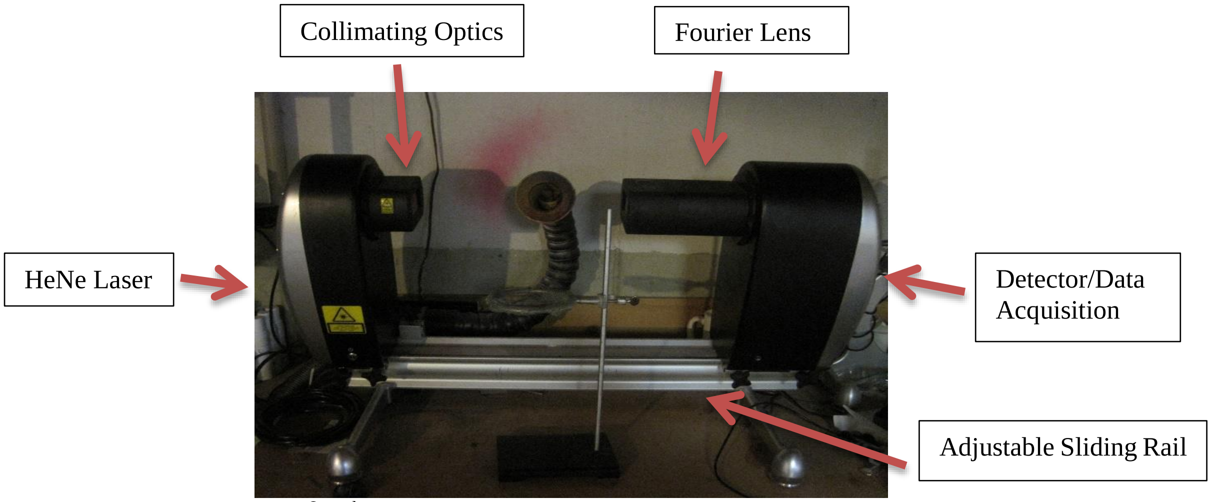


Figure 1. Malvern Spraytec® used in our experiment for the measurement of the conductive and dielectric aerosol

(4) The aerosol droplet of fluid to be atomized

We experimented with thermal atomization of conductive silver nanoparticle ink, dielectric polyimide ink and vegetable glycerin. The samples were investigated for droplet size distribution and the final testing was performed as follows:

Distance from measurement zone: < 3 inches

Data collected in triplicate over 3s at acquisition rate of 100Hz with 300 mm lens

Results obtained by averaging the full spray

Beam steering was corrected for in all analysis

Samples sprayed by vape device set to 40.0W output

Wicks and wire mesh changed between fluids tested

(5) Experimental Results

Experimental Setup:

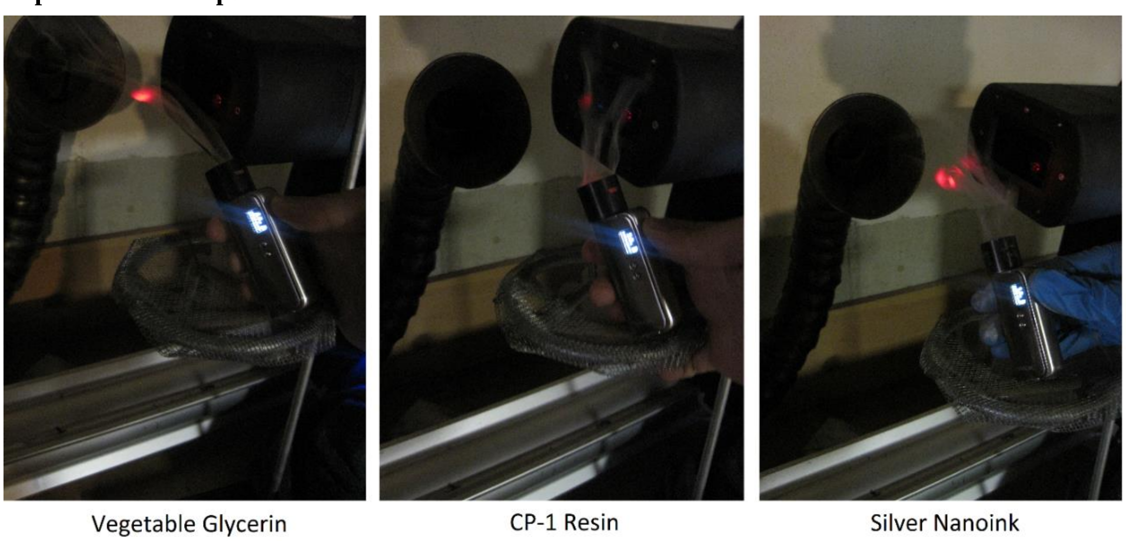


Figure 2. Experiment Setup for the measurement of different fluids

For each sample tested, the vape device was placed next to the instrument detector. The vacuum was turned on to ensure material flows through the measurement beam.

Noteworthy on the above picture is the CP-1 Resin where the wick was charred on removal. It appears this sample experienced some combustion during testing. This may have resulted in fast atomization that utilized the resin on the wick quickly. The other two fluids did not experience the same effect. Notice the CP-1 Resin wicks being charred from the testing at 40.0W.

Wicks after Testing:

Figure 3. Photographs of wicks after testing of three different fluids.

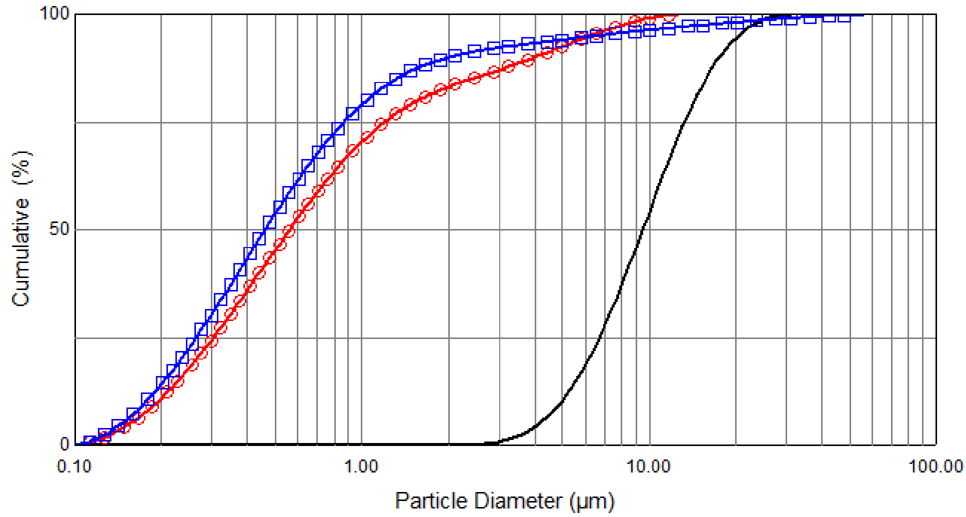
Results:

	Trans	**Dv(10)**	**Dv(50)**	**Dv(90)**	**%V < 10u**	**%V < 5u**	**%V < 3u**
Vegetable Glycerin 1	91.707	5.946	10.498	18.131	45.685	4.405	0.015
Vegetable Glycerin 2	89.196	4.935	9.508	17.610	53.938	10.485	0.709
Vegetable Glycerin 3	94.719	5.460	10.042	17.942	49.652	6.947	0.100
Average	91.874	5.447	10.016	17.894	49.758	7.279	0.275
CP-1 Resin 1	68.526	0.178	0.442	1.304	99.310	95.582	94.241
CP-1 Resin 2	57.258	0.193	0.559	4.002	99.028	92.491	87.106
CP-1 Resin 3	66.480	0.202	0.646	4.953	94.523	90.085	84.990
Average	64.088	0.191	0.549	3.420	97.620	92.720	88.779
Silver Nanoink 1	81.971	0.187	0.531	6.027	92.068	89.458	88.474
Silver Nanoink 2	75.092	0.176	0.460	1.995	96.240	93.949	92.157
Silver Nanoink 3	80.070	0.183	0.500	1.745	99.085	97.300	95.438
Average	79.044	0.182	0.497	3.256	95.798	93.569	92.023

Table 1. Aerosol size distribution of (a) Vegetable Glycerin (b) Nexolve® Polyimide and (c) Novacentrix® Conductive Ink

Analysis and Interpretation:

Comparison of the three fluids tested with the Vape device at 40.0W



	Date-Time	File	Dx(10)e	Dx(50)	Dx(90)
[V]	Aug 15 2018-12:18:43.1100	Vegetable Glycerin 1 2	4.93	9.51	17.61
[V]	Aug 15 2018-11:12:49.7004	CP1 Resin 2	0.19	0.56	4.00
[V]	Aug 15 2018-11:45:30.8248	Silver Nanoink 1 2	0.18	0.46	1.99

Figure 4. Comparison of different fluid tested for the Particle Diameter

Above plotted is the cumulative droplet size curves of the second measurement of each of the three fluids. The S curve farthest to the right of the curve is that of the Vegetable Glycerin. This marks a much larger droplet size in comparison with the other two samples. The CP-1 Resin and Silver Nano ink have a much smaller size than that of the Vegetable Glycerin with the Silver Nano ink appearing to be the smallest droplet size as marked by the graph that is farthest left on this plot. An additional observation from the prior table relates to the Transmission (Trans column). The transmission value relates to the approximate concentration of droplets being measured. The value relates to the transmission of the measurement beam through the sample. This means the lower the Transmission value, the more droplets/particles are in the beam. In the study performed, the CP-1 Resin shows the lowest transmission value which may correspond to a faster and more complete atomization. This could have caused the combustion present during the testing as the resin may have been used quicker than the other fluids.

The vegetable glycerin showed the largest droplet size which corresponds to the highest transmission value which would be expected.

III. The Comparison of Droplet Size for Three Different Atomization Processes

The Additive Manufactured Avionics (AMA) laboratory within NASA Marshall Space Flight Center (MSFC) ES 43 Electrical, Electronic and Electromechanical (EEE) parts packaging group use Optomec Aerosol Jet® Deposition System 300 (AJ 300) as shown in Figure 1. AJ 300 is capable of generating aerosol droplet that possess conductive inks to deposit onto various substrates to create functional electronic parts. Currently, there are two major conventional atomization processes to create aerosol. There are pneumatic atomization process and an ultrasonic atomization process. Here we briefly report these two main atomization principles and provide the droplet size through existing literature [16]. The main reason we attempt the thermal atomization is its unique mechanism that is independent of gravity influence. As described in the introduction section, conventional pneumatic and ultrasonic atomization rely on gravity to hold the ink in the reservoir. These two conventional mechanisms cannot function under microgravity condition. However, the newly developed thermal atomization does not rely gravity to work. The wicking material draws the ink from a juice well through capillary action. Once the wicking material is full of the ink, we then thermally boiled the ink through the heating element. The ink aerosolized to form the liquid droplet. The main contribution for this summer work is to design the experiment to adopt the possible droplet measurement of characterization best suited for our application. We have identified Malvern Spraytec® to measure the droplet size experimentally.

(a) Pneumatic Atomization Process method and its generated droplet size

The Additive Manufactured Avionics (AMA) laboratory within NASA Marshall Space Flight Center (MSFC) ES 43 Electrical, Electronic and Electromechanical (EEE) parts packaging group Aerosol Jet® printer (AJ 300) has traditionally adopted a pneumatic atomization process. According to Aerosol Jet® User Manuel [16], the pneumatic atomization process generated the droplet size of 1-5 um.

(b) Ultrasonic Atomization Process method and its generated droplet size

According to Aerosol Jet® User Manuel, the ultrasonic atomization process takes place for the AJ 300 is to agitate the conductive nanoparticle ink material to create the dimension of (3-5 um) aerosol nucleic droplet [16].

(c) Thermal Atomization Process method and its generated droplet size

As discussed in the above, the thermal atomization aerosol droplet measurement through Malvern Spraytec provide the silver nanoparticle conductive ink of 1-2 um.

The following Table 2 illustrate the droplet size comparison of three different atomization mechanisms:

Pneumatic Atomization	Ultrasonic Atomization	Thermal Atomization
1-5 um	3-5 um	1-2 um

Table 2. The droplet measurement comparison of three different atomization processes

We can conclude our novel thermal atomization aerosol droplet size is at the same ballpark as pneumatic and ultrasonic atomization. This is to state that the process itself offer the same benchmark comparison as far as the droplet size is concerned.

IV. The Mechanics of Aerosol Transmission [11]

According to [13], viruses without the associated water, mucus and pus droplet is in the size range of 0.02 um to 3 um. Bacteria is the size range of 5 um to 100 um. The fungal spores is in the size range of 1 um to 10 um. The most important factor for the virus to travel in the free air is their size and airflow pattern. The droplet size will change with time based on the environmental condition such as the humidity in the air. The humidity in the air will change the rate of the drop evaporation process and subsequently altering the size of the aerosol droplet. Based on this general observation, one can easily see why the dry air droplets evaporate quickly, reduce in size and fall to the ground more slowly. The changing size of the droplet affects how it responds to the airflow pattern. This condition ultimately decides the rate of how quickly it could settle. Stoke's settling law determines aerosol's movement in the air. In general, it stated that a sphere falls under the opposing forces of gravity downwards and air friction upwards. Knight [17] estimated the time taken for the aerosol for various diameter to fall for 3 meter. Particle of diameters 1-3 um will suspended almost infinitely. Aerosol with diameter of 10 um will take 17 minutes to settle. Particle with diameter 20 um will take 4 minutes to settle. Aerosol with diameter 100 um will take 10 second to fall to the floor.

V. Prediction of Aerosol Behavior in Microgravity

Our measured diameter for the conductive ink aerosol is 1-2 um. Our measured diameter for the dielectric ink aerosol is 1-2 um. We conclude that our lightweight nanoparticle aerosol of silver conductive ink will suspend in the air free of gravity effects. Furthermore, if we direct the aerosol onto the substrate, it will be deposited without bouncing off in other directions with controlled humidity conditions.

VI. Conclusion

The purpose of this project was to determine the size distribution of the aerosol nuclei droplet of the conductive and dielectric ink of alternative novel aerosol atomization approaches.. Based on the scientific measurement under the condition where the controlled temperature (68 degree Fahrenheit and ambient air pressure of 3 psi), Malvern Spraytec® equipment provided the aerosol nuclei droplet size readings of 1-2 um. We conclude that aerosol nuclei under this condition will suspend in the air infinitely without the influence of gravity. This scientific fact will enable us to design the next generation space rated aerosol printer for In-Space Manufacturing (ISM) to enable higher quality printed electronics processes to be utilized in space. This capability will enable higher complexity printed avionics products to be developed to support future mission needs. In addition, the aerosol nuclei droplet size of conventionally terrestrial pneumatic and ultrasonic atomization has been compared to the new novel thermal atomization process.

Acknowledgments

I graciously appreciate the opportunity to work with my mentor Furman Thompson and thank him for his excellent guidance, motivation and support. I also want to thank Jordan Rine of Eco Smoke store of Huntsville, AL for his expert opinions on the conventional vaping device selection and consultation. I also want to thank Kyle Butz of Spray Analytics for his assistance of aerosol size droplet size distribution measurements.

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