

Metal Powder Aerosolizer

Fall 2023 ME Executive Summary

Design Team

Brian Cahill, Matthew Cunningham, Ryan Garrant, Andrew Godfrey, William Lenardson, Ryan Rivard

Design Advisor

Prof. Ozan Ozdemir

Abstract

Cold spray is an additive manufacturing process where fine metal powders are accelerated in a gas stream and launched out of a nozzle at supersonic speeds onto a substrate. The particles deform when they hit the substrate, causing them to bond together. To inject the metal powders into the gas stream they must be aerosolized, which is the process of agitating particles and introducing them into a fluid medium, allowing them to disperse and flow within that medium. The goal of this project is to create a new metal powder aerosolizer to integrate with the current cold spray system at the Northeastern Burlington Laboratory. The prototype should be capable of aerosolizing 0.5-10 μm diameter powders of varied materials at a constant feed rate while preventing agglomeration and controlling particulate concentration and volumetric flow rates. Our design uses a vacuum effect to pick up the powder. This is assisted by small motors vibrating the powder container to loosen the powder, which allows it to be picked up easier, as well as break up any agglomerations of particles. This also creates a self leveling bed which is necessary for a uniform flow profile. The powder container is raised towards the vacuum inlet by two power screws, and the rate at which the container rises controls the rate of powder consumption. This system is designed to fit inside the pressure vessel used by the current powder feeder, making it easy for the researchers at the lab to switch between the old system and the new system as needed. At the conclusion of this project, the researchers will have a metal powder aerosolizer capable of consistently aerosolizing extra fine particles (0.5-10 μm) that the current powder feeder struggles with.

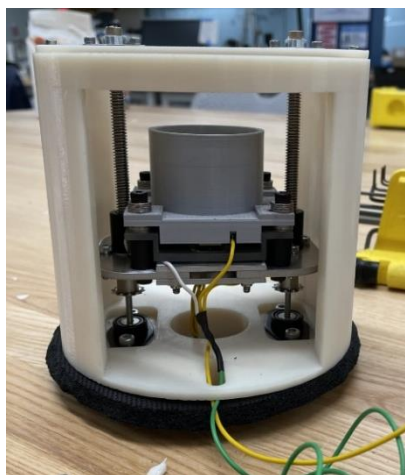


Figure 1: Metal Aerosolizer Prototype

For more information, please contact o.ozdemir@northeastern.edu.

Need

We designed and created this metal powder aerosolizer to replace the VRC rotating drum powder feeder used by Professor Ozdemir and the cold spray lab in Burlington, MA. The current powder feeder has three major problems: it performs sub optimally and tends to clog when using fine particle sizes, it uses a discrete feeding method, which can lead to inconsistent powder feeding, and it has multiple moving parts that interact with the powder, which causes wear and requires constant cleaning. We were tasked with creating a metal powder aerosolizer that consistently aerosolizes fine (0.5-10 micron) particles with controlled volume flow rates and particle concentrations. Some initial targets for the design were to utilize a gas volume flow rate of less than 50 SLM, have a powder capacity of 500 ml, feed at a minimum rate of 0.3185 ml/min. The new powder feeder also must fit into the same pressure vessel that the current powder uses, which makes it easily interchangeable with the current system.

Background and Significant Prior Work

Cold spray is a relatively new technology, so there isn't one method of powder aerosolization that is considered the industry standard. Each method has its own advantages and disadvantages, so this section will focus on the most relevant methods of aerosolization to this project.

Current Solutions

The three most common and applicable current practices of aerosolization include the fluidized bed method, rotary brush dispenser, and the VRC rotating drum feeder.

The VRC rotating drum feeder is the system that the lab currently uses and will be replaced by this project upon completion. The drum is about six inches in diameter and six inches tall, with a ring of small holes (about 1/32 in diameter) around the outside of the bottom of the drum. There is a piece of plastic loaded by a spring with a gas line running through it fixed in place that is pressing on the bottom of the drum. The gas exit line is also directly underneath this piece, so every time a hole lines up with the two gas lines, powder is pressed into it and carried out of the drum. One of the main problems with this system is that this is a discrete feeding method, as there is no powder flowing when the drum is rotating between holes. This can lead to inconsistent particle deposition when the powder is sprayed. Another problem is that some of the powders are so fine that up to 85% can be lost through gaps in the rotating part of the drum, causing extra wear and making it unable to be sprayed. The new system aims to eliminate these problems.

The fluidized bed method is one of the most popular methods of aerosolization. It is accomplished by placing the powder on a vibrating plate that excites the particles, allowing them to be picked up by a gas stream flowing through the container. Because the vibrating plate is the only moving part, this system is easy to clean, which makes using it for different powders very convenient. The major problem with this method is that it is very difficult to control the rate of powder consumption, as there is a lot of randomness with the vibration causing particles to be aerosolized. Another problem with the fluidized bed method is that larger particles tend to settle at the bottom of the container and not get picked up, causing the film thickness and quality of the deposition to decrease [1]. These problems make the fluidized bed method of aerosolization unsuitable for this project's application.

The rotary brush method is a mechanical option for aerosolization with two main components, a piston, and a rotating brush. The piston pushes a reservoir of powder into the brush which sweeps it into a jet stream of carrier gas. This gives the mechanism a lot of control over the deposition of particles because piston and brush rotation speeds can be adjusted, but the fine powder can make its way into small crevices and cause serious wear and tear [1].

Agglomeration

Agglomeration, the process in which particles come together to form larger clusters, can occur during aerosolization. These clusters can lead to uneven coatings, reduced adhesion, and altered material properties, which are all undesirable outcomes for cold spray. There are two main cohesive forces between these aerosolized particles, electrostatic forces (Van der Waals forces), and liquid bridging. Liquid bridging occurs as a result of liquid that becomes absorbed onto the surface of the particles. This interaction dominates the other reaction and is highly contingent on liquid being present [2]. For aerosolization, it is important that the environment the powder is contained in is free of moisture to minimize these forces. Van der Waals forces are electrostatic attractive forces between uncharged molecules. These forces are assumed to play the most important role in agglomeration during the aerosolization phase, since the particles are dispersed with the gas, they will come close enough to each other that Van der Waals forces become significant. The strength of these forces is contingent on several factors including material properties of the particle, size, shape, and distance between the particles [2]. In the scope of this project, nanoparticles are expected to be used, causing these forces to become extra potent due to the proximity between particles and the large surface area of the agglomerations. The surface area of these agglomerations is especially large because the surface area of each particle must be accounted for in the total. If the Van der Waal forces are to be calculated, two general assumptions must be made: the particles are spherical and of the same diameter. In reality, the particles will be of rugged contour and will not be the same size, but it is practical to use the average size and assume perfect spheres. From these assumptions comes equation 1:

$$F_{vdw} = \frac{Cd}{x^2} \quad (1)$$

where C is a constant, x is the distance between particles, and d is the diameter of the particles. The quadratic relationship in the denominator explains why particles in close proximity are more difficult to break up. Now that the Van der Waal forces can be quantified depending on the powder being used, the amount of force necessary to exceed and overcome these intermolecular forces is known [2].

Contradictory to equation 1 where it would make sense that larger particles experience higher Van der Waal forces, materials with smaller particles typically experience stronger Van der Waal forces due to larger surface area. This will be important to note when comparing agglomeration results between different powders when testing prototypes of the final product [2]. In addition, density impacts the dispersion of powder and thus the agglomeration. Low-density materials take less kinetic energy to lift and transport than denser powders and denser powders may lead to more agglomeration [3].

There are two main methods to improve the aerosolization of nanoparticles- external additions and surface modifications. Surface modifications are done by adding coarser particles or dispersing agents to limit agglomeration. External additions used to break up the agglomerations include adding an electric field, acoustic field, centrifugal field, vibration, stirring, pulsed gas flow, microjet, etc. For the scope of this project, this research will focus on vibration due to cost and time restraints. In addition, vibration has a wider range of applications than the other methods listed above.

An experiment done to test the effectiveness of the stirring and vibration on the nanoparticles was conducted by the Key Laboratory of Energy Thermal Conversion at Southeast University in Jiangsu, China [4]. The vibration was introduced to the particles by adding a frequency of 30 Hz and amplitude of 2 mm by way of a mechanical vibrator. The stirring motion was made by a 40 mm impeller that could provide up to 400 rpm. This study found that both vibration and stirring successfully improved the fluidization quality of the nanoparticles and reduced the size of agglomerates. It is important to note that at a critical point, both the stirring and vibration no longer improved and even slightly reduced the fluidization quality. Additionally, combining both the stirring and vibration methods led to further fluidization as can be seen in figure 2 below [4].

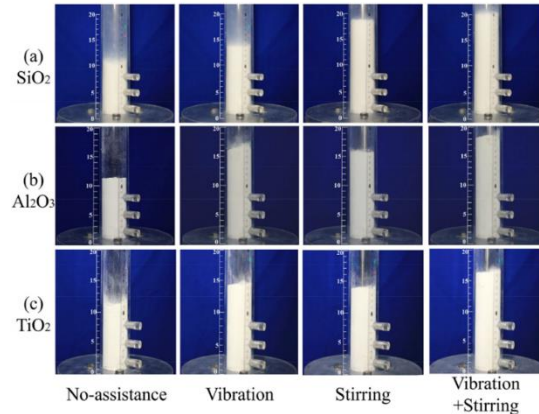


Figure 2: Results of the Vibration and Stirring Experiment [4]

Based on this research, it is important to have some method of de-agglomeration of the powder to assist in its aerosolization. For this project, the vibration method was selected to incorporate into the design to ensure a smooth and consistent pick-up of particles.

Design Solution

The design selected for this project aerosolizes metal powder by raising a vibrating reservoir of powder towards a nozzle that sucks up the powder and injects it into a gas stream. It works using a pressure differential between the high-pressure input and low-pressure output that drives the flow of the carrier gas. Because this solution is intended to be an alternative to the existing rotary powder feeder mechanism, it can be retrofitted into the existing pressure vessel so that powder feeder mechanisms can easily be swapped when a more precise cold spray process is desired for finer particles.

The design consists of multiple subassemblies that work together to accomplish this task. The full assembly can be seen in figure 3 below:

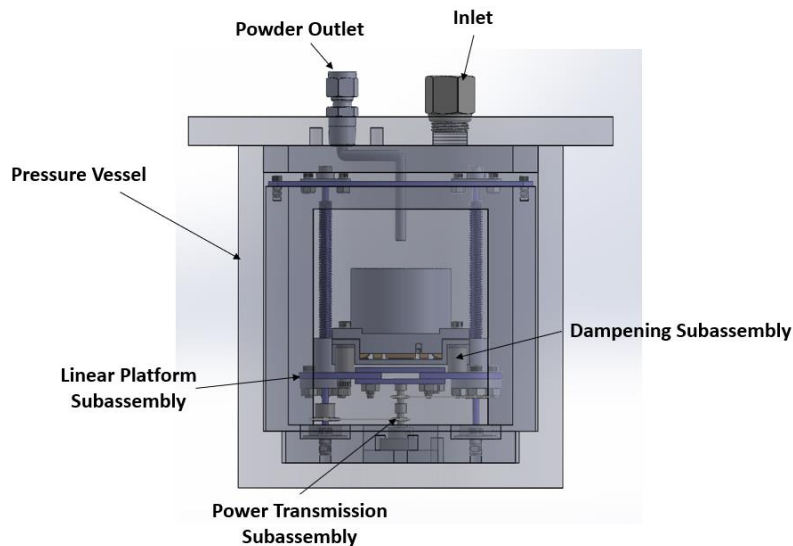


Figure 3: Full CAD assembly including Pressure Vessel

Linear Actuator Platform Subassembly

The first of these subassemblies is the Linear Platform Subassembly. The purpose of the Linear Platform Subassembly is to create a surface to mount the powder reservoir that can slide up and down using two lead screws. The subassembly is described in Figure 4 below:

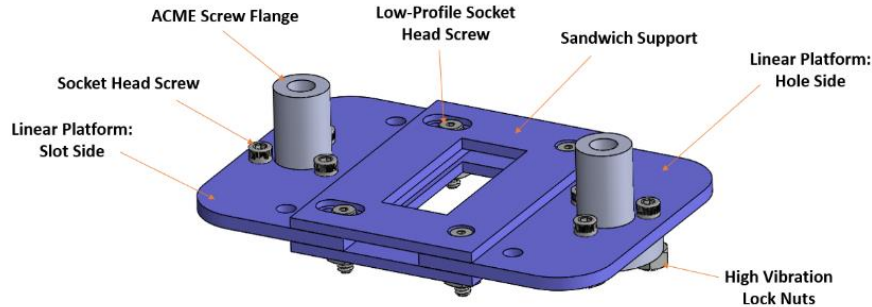


Figure 4: Linear Platform Subassembly

The platform works by utilizing the two ACME screw flanges to engage with the threads on the ACME lead screws. Both the “Linear Platform: Hole Side” and “Linear Platform: Slot Side” are mounted to the ACME screw flanges using socket head screws on one side of the platform, and high vibration locking nuts on the opposing side. The Linear Platform Subassembly is composed of four custom pieces of aluminum, with slots that line up on one side and holes that line up on the other to allow for lateral expansion and contraction during assembly. This is important because the subassembly rides up and down on the two ACME lead screws, so the lateral separation needs to be precise, or else a large stress is placed on the lead screws which can lead to failure down the road. As seen in Figure 5, the “Linear Platform: Slot Side” is designed to have a degree of freedom along the x-axis (shown as the red arrow) so it can slide back and forth to perfectly match the separation distance necessary between lead screws that are determined by a tolerance stack-up of several components.

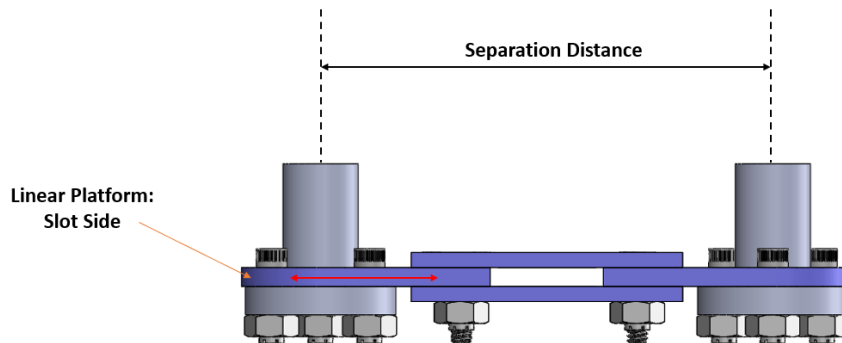


Figure 5: Linear platform front view

Power Transmission Subassembly

The next subassembly is the Power Transmission Subassembly. This Power Transmission Subassembly works by using a shaft coupler to couple the powder feeder’s existing motor to a smaller 3/32” drive shaft. This drive shaft has two 8-tooth sprockets mounted to it by use of set screws. These sprockets connect using

a chain to 12-tooth sprockets on either side of the drive shaft. The 12-tooth sprockets are connected to each respective ACME lead screw using set screws and spin the lead screws in place. The lead screws are press fit into a ball bearing housing, and the bearing housings are mounted to the pressure reservoir sleeve by use of screws and threaded heat inserts. The two parallel lead screws are kept in alignment using the cross beam and the custom flanges. By spinning each of the lead screws connected to the same drive shaft, the lead screws rotate in unison. By rotating the lead screws, the Linear Platform Subassembly can move up and down, thus actuating the power reservoir.

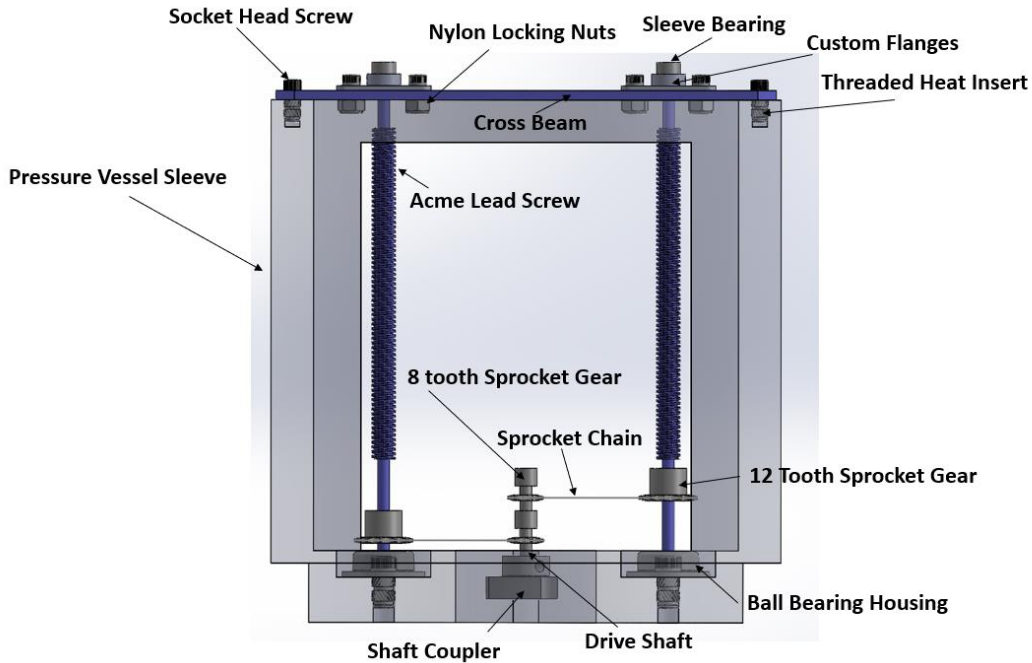


Figure 6: Power Transmission Subassembly

We selected the dual lead screw method of power transmission due to the fine linear control the system allows for, an aspect very important for the project, where to achieve small mass flow rates, a very small rate of platform movement up and down is necessary. In the Engineering Analysis Appendix, the rate of ascension for the linear platform, driven by the power transmission sub assembly is derived. The smallest linear ascension possible for the Power Transmission Subassembly is 0.021 mm/s which gives us margin in feeding powder at the smallest rate the requirements call for.

Vibration and Dampening Subassembly

The next subassembly is the Vibration and Dampening Subassembly. This subassembly is composed of four ERM vibration motors clamped to the bottom side of the powder reservoir. The powder reservoir has cutout profiles for the four ERM motors to mount to. The ERM motors use unbalanced weights to create vibrations in the system. As covered in the background information, it is necessary to vibrate the powder reservoir so that the powder maintains a flat and uniform surface profile for optimal uniform powder feeding. The system is dampened using the four neoprene rubber dampeners in conjunction with a dampening pad adhered to the clamp component as seen in Figure 7.

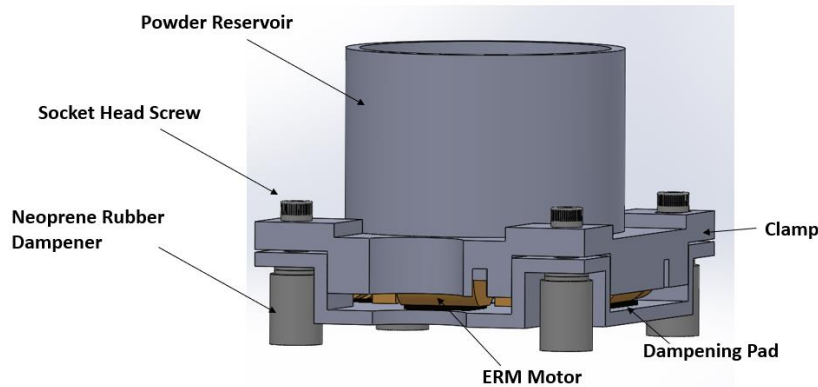


Figure 7: Vibration and Dampening Subassembly

Pressure Vessel Interface Components Subassembly

The last subassembly of this system is the Interface Components Subassembly. In this subassembly, an ORB fitting screws into both the high-pressure inlet and outlet. The ORB connector of the outlet holds the outlet tubing into place, directly above the powder reservoir.

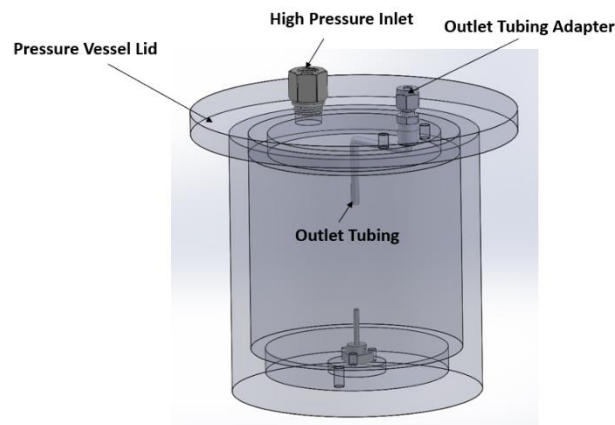


Figure 8: Interface Components Subassembly

Design Process

The first step in the design process was to determine what method of aerosolization method we would use based on our background research and preliminary testing. After iterating through prototypes for a rotary brush and vacuum aerosolizer we selected the vacuum method. We then had to figure out how to create a vacuum strong enough to pick up powder inside the pressure vessel using hand calculations and CFD simulations. At the same time, we needed to design a way to lift the powder container to the vacuum inlet and figure out how to incorporate the vibration of the container inside the pressure vessel. Once all these designs were completed, we were able to order and start manufacturing parts.

Two Methods of Focus

We originally considered two distinct strategies for powder aerosolization and selected the current approach after testing both methods. The first approach was the rotary brush method, based on a commercially available powder aerosolizer from Palas GmbH. Our implementation of this aerosolization method differed from the Palas GmbH application due to the space constraints of the existing pressure vessel, which meant

that the rotary brush setup needed to be much smaller than the existing Palas GmbH solution. The cold spray lab pressure vessel can also be loaded up to 1000 psi, which is much higher than the pressure the existing rotary brush operates at (58-116 psi) [7]. The second approach was the vacuum method, where a vacuum was lowered into the powder container. This method was a completely novel approach not currently being used in academia or industry. The advantage of this method was that there was only one moving part, keeping the system simple and easy to maintain. There was also minimal wear in this system since the powder did not contact anything until it was within the gas stream. This meant the employees at the cold spray lab would have to perform maintenance less often.

Experiment Results

First, we designed and constructed two prototypes to be tested at the Burlington Cold Spray Lab. We determined Taguchi parameters, as seen in Table 1, relevant to testing each method and used baking flour as the powder for safety as well as a conservative representation of powder with very poor flowability. Utilizing a Taguchi experimental design allowed us to efficiently measure the effects of our parameters on the variability of the output. After completing experiments for the rotary brush and vacuum methods, we learned several important lessons about both.

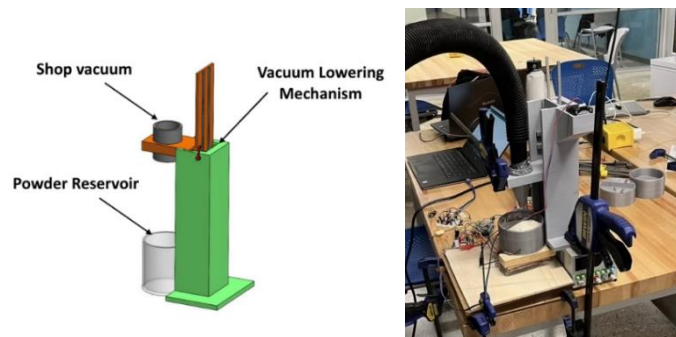


Figure 9: Vacuum Method Prototype

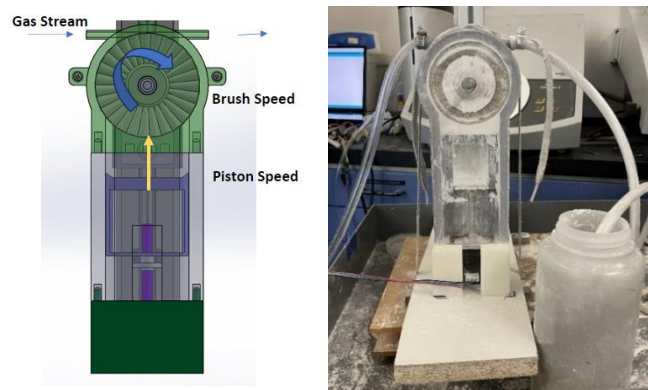


Figure 10: Rotary Brush Method Prototype

<i>Rotary Brush Method (P=3, L=2)</i>	
Parameter	Levels
Vacuum Nozzle Diameter	6 mm
	50 mm
Vacuum Descent Rate	0.1178 mm/s
	1.178 mm/s
Powder Flowability	Poor (flour)
	Good (garnet)

Table 1: Taguchi Parameters of Rotary Brush Method

<i>Rotary Brush Method (P=3, L=2)</i>	
Parameter	Levels
Brush Speed	1000 RPM
	2000 RPM
Linear Actuator Speed	15 RPM
	30 RPM

Table 2: Taguchi Parameters of Rotary Brush Method

Our rotary brush prototype ran into many challenges including sealing and obtaining usable data. We noticed that surpassing the outlet diameter's capacity with carrier gas pressure led to unintended consequences including powder leakage from the reservoir. Then, because the brush spinning on the load cell created too much chaos to get any usable readings, the mass rate data was indecipherable as seen in Figure 11.

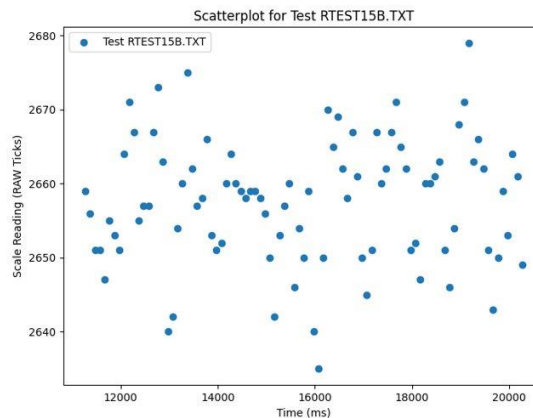


Figure 11: Load Cell Readings for the Rotary Brush

Next, when experimenting with the vacuum method, it demonstrated an exponential powder feed rate tendency with a linear nozzle descent rate as seen in Figure 12. Because of this, ensuring a uniform flow profile during the tube's descent emerged as crucial for maintaining a constant aerosolization rate. Agitation of the powder effectively linearized this feed rate as shown in figure 16. Beyond the exponential feed rate, the vacuum did not have many significant issues. The results of the experiments allowed us to narrow our focus to just the vacuum method because the rotary brush leakage and inability to accurately measure usable data would take more time to resolve when compared to the difficulties with the vacuum method.

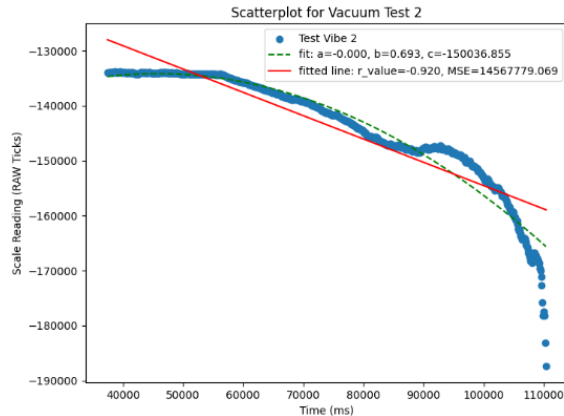


Figure 12: Load Cell Readings for the Vacuum Method

Vacuum Method Technical Analysis

The next step of the design process was to determine the method of suction for the vacuum. We performed hand calculations to create two possible approaches. The first was a venturi system and the second was a direct pressure differential. After creating a simple computer model for both methods and conducting CFD analysis using Ansys (see “Confirming Velocity and Effect of Turbulent Flow” section of the appendix), we determined that the pressure differential would be a better path forward due to the ease of creating the velocity necessary to pick up particles. We also determined from the experimental data that the powder would need to be oscillated to create a level profile of the powder and improve the feed rate's consistency [6]. We used preliminary calculations and experiments with basic prototypes to provide a base of knowledge for the powder oscillation's behavior before designing it for the final design.

Creation of the Final Design

After the technical analysis was completed, our group broke into three main teams. One team continued to work on CFD to determine the parameters and dimensions of the system. This included the location of the nozzle and powder holder to ensure the fluid flow was dispersed evenly. The second team worked on the oscillation subsystem, selecting motors and dampers for the system and how they would interface with the main system. The final team worked on the design of the rest of the system. This included the nozzle and how it would interface with the pressure chamber as well as the powder feeder actuating system and how it would move to keep a constant feed rate.

The first set of CFD simulations was run to make sure our vacuum design produced the velocity required to pick up particles based on the hand calculations (shown in the appendix under *Hand Calculations*) and to make sure the gas inlet velocity into the chamber wasn't high enough to impact the powder in the cup and send it flying everywhere in the pressure vessel. These simulations were run in 3D using Ansys Fluent, and full details can be found in the appendix. The second set of simulations was run to find the ideal distance from the inlet of the vacuum to the top of the powder bed. These simulations were run in 2D using the axial symmetry function in Star-CCM+. Full details for these simulations can also be found in the appendix.

The second team spent time designing and testing oscillation and dampening systems. We tested varying cup sizes and ERM amplitudes to find the right fit to fluidize the powder enough to level the powder surface as it is consumed. Once the correct motors were found, it was necessary to put them in an orientation that would maximize the amount of vibration applied to the cup. This was done through many iterations where the determining factor for success was the rate at which the powder levels. Another constraint that the second team needed to address was the size of the subassembly. We shrunk the subassembly and organized it so that all the components required were able to fit within the pressure vessel's tight confines.

The third team spent time designing the power transmission system as well as ensuring our prototype would interface with the existing pressure vessel. The method of power transmission in the system was determined by choosing a method that would allow us to couple to the existing motor used in the powder feeder, as well as ensure we could feed powder at the minimum rate required. Since no CAD model of the existing pressure vessel could be obtained due to non-disclosure agreements, various aspects of the pressure vessel were measured with a caliper, and necessary fittings were purchased.

Results

Due to delays in acquiring all the parts necessary to finish building our system, as of this moment, we have been unable to test the entire system. We expect to be able to test our powder feeder under 500 psi pressure in the cold spray lab before capstone day.

Success for this powder feeder means that it will be able to consistently aerosolize various powders at a desired concentration. We are defining consistency as how closely the rate of powder aerosolization aligns with a constant setpoint (mass change of the powder in the system is linear). Aerosolization consistency will be evaluated by both a mass measurement over time and laser velocimetry of the cold spray output.

The laser velocimetry setup will provide highspeed still images of the cold spray output which we will process to provide a particulate count. We will plot these particulate counts over time and determine the mean squared error of this dataset with the average particulate count as the estimator value. Minimizing this error correlates to an improved consistency. The same process will be applied to the mass rate data, using a linear regression line of best fit for the dataset as the estimator instead.

To test these metrics, we plan to once again use a Taguchi DOE to decrease our test time while still accurately evaluating our prototype. We will test our prototype with parameters of feed rate and powder flowability. The expected data table can be seen in Table 3 below:

Parameters	Associated Levels
Feed Rate (Motor RPM)	1 RPM
	7 RPM
	14 RPM
Flowability (Angle of Repose)	Excellent
	Poor
	Fair

<i>Inputs</i>			<i>Consistent Mass Feed Rate Output</i>	
Trial	Feed Rate	Flowability	Laser Velocimetry Mean Square Error	Mass Rate Mean Square Error
1	1 RPM	Excellent		
2	1 RPM	Poor		
3	1 RPM	Fair		
4	7 RPM	Excellent		
5	7 RPM	Poor		
6	7 RPM	Fair		
7	14 RPM	Excellent		
8	14 RPM	Poor		
9	14 RPM	Fair		

Table 3: Cold Spray Lab Testing Data Tables

Summary and Impact

At the cold spray lab in Burlington, handling micro-sized particles can be challenging, as they tend to infiltrate the crevices of parts and machinery and clump together, resulting in significant wear and tear on cold spray systems that employ moving parts for powder transport from point A to point B. The final issue with the current design is that it has a discrete feed rate and performs sub optimally with micro-sized particles. The metal powder aerosolization team was able to solve these issues by using a vacuum effect to consistently suck up powder and reduce the number of moving parts. While the system has not been tested yet, given the results of the preliminary testing, hand calculations, and CFD simulations, this project should be ready to be integrated into the current cold spray system once the cup ascension rate has been tuned based on test results. This aerosolizer is also designed to operate with under 50 SLM of gas flow, which was another original goal of the project. One goal we were unable to reach was the 500 ml of powder capacity, since fitting our system inside the existing pressure vessel severely limited the size of our powder reservoir. The new system has a capacity of about 120 ml, which is still enough to use for cold spraying and validating the system. With this new system, the researchers at the lab will be able to consistently feed fine powders, which will allow them to expand to more different types of powders such as ceramics, therefore allowing them to do further research in the fine particle range that can provide higher particle impact velocity.

References

- [1] D. Hanft *et al.*, “The Aerosol Deposition Method: A Modified Aerosol Generation Unit to Improve Coating Quality,” *Materials*, vol. 11, no. 9, p. 1572, Sep. 2018, doi: 10.3390/ma11091572.
- [2] Z. Berk, “Fluid flow,” *Food Process Engineering and Technology*, pp. 27–68, 2009. doi:10.1016/b978-0-12-373660-4.00002-8
- [3] J. Yi *et al.*, “Whole-body nanoparticle aerosol inhalation exposures,” *Journal of Visualized Experiments*, no. 75, 2013. doi:10.3791/50263
- [4] Z. Zhao, D. Liu, J. Ma, and X. Chen, “Fluidization of nanoparticle agglomerates assisted by combining vibration and stirring methods,” *Chemical Engineering Journal*, vol. 388, p. 124213, 2020. doi:10.1016/j.cej.2020.124213
- [5] “Sprocket center distance equation and Calculator,” Engineers Edge - Engineering, Design and Manufacturing Solutions, https://www.engineersedge.com/hardware/sprocket_center_distance__13904.htm (accessed Nov. 20, 2023).
- [6] C. E. Brennen, S. Ghosh, and C. R. Wassgren, “Vertical Oscillation of a Bed of Granular Material,” *Journal of Applied Mechanics*, vol. 63, no. 1, pp. 156–161, Mar. 1996, doi: 10.1115/1.2787191.
- [7] D. G. Taylor, R. E. Kupel, and J. M. Bryant, *Documentation of the NIOSH Validation Tests*. U.S. Department of Health, Education, and Welfare, Public Health Service, Center for Disease Control, National Institute for Occupational Safety and Health, Division of Physical Sciences and Engineering, 1977.
- [8] S. Martin and J. R. Williams, *Multiphase Flow Research*. Nova Science Pub Incorporated, 2009.

Appendix: Engineering Analysis

Introduction

Some of the most important analyses for this project were determining the gas velocity necessary to aerosolize particles, and subsequently determining how to create that gas velocity in a way that would direct particles to the inlet of the pipe. To determine these numbers, we first calculated the necessary gas velocity by hand calculating worst-case scenarios, then ran CFD simulations to determine if we would achieve these velocities with our design.

Hand Calculations

To make design selections, pick out parts, run simulations, or even choose dimensions, we first needed to determine the physical constraints, which for this project was the velocity required to pick up a particle. We found this using MATLAB and inputting different particle diameters, particle densities, and vacuum nozzle diameters. To find the velocity required to lift, we equated the drag force to the force of gravity acting on the particle. The drag force equation was calculated using equation 2 below:

$$F_d = \frac{1}{C_u} \cdot C_d \cdot \frac{\rho_g}{2} \cdot V_{req}^2 \cdot A_{proj} \quad (2)$$

where C_u is the Cunningham factor, which is applied to particles less than 10 microns in diameter, C_d is the drag coefficient, ρ_g is the density of the carrier gas, V_{req} is the velocity required to lift the particle, and A_{proj} is the projected area of the particle [8]. We acquired the minimum velocity required to overcome gravity by setting the drag force equation equal to the force of gravity acting on the particle and solving for the velocity. The particle diameter was set at 10 microns, and the density of copper was used at 8.96 kg/m^3 , conservative estimates for the largest particles and densest spray materials.

We found that the minimum velocity carrier gas required to lift a particle of copper was 6.19m/s. For all the calculations going forward in this paper, a factor of safety of 2 will be applied so that the velocity required to lift the particle is 12.38m/s.

Computational Fluid Dynamics

There were two main reasons in which CFD was used. The first was to confirm that our design would produce the gas velocity necessary to pick up particles based on our hand calculations and to ensure that there was no turbulent flow around the powder bed that would cause the metal powder to be blown all over the inside of the pressure vessel. The second reason we used CFD was to determine how the relationship between the nozzle and the powder cup would affect the velocity profile of the gas. The results from these simulations were used to determine the dimensions of the nozzle and cup, as well as dictate the rate the cup is moving.

Confirming Velocity and Effect of Turbulent Flow

The software used to run the first set of CFD simulations was Ansys Fluent 2023 R2. The simulations were run as 3D sims, with the fluid body taken from the CAD of the pressure vessel from the top until the level where the powder would be in the cup. The mesh used was the auto-generated mesh by the Fluent software, as we decided the mesh was sufficiently fine around the pipe, which is the area we were most interested in. The larger protrusion on the top of the fluid body was labelled as the inlet, and the smaller protrusion was labelled as the outlet. The viscous model used was SST k-Omega, which was chosen to account for any turbulence that might occur in the flow. The fluid body was Nitrogen gas (N_2), with the fluid properties taken from the Fluent database, the density set to "Ideal Gas". The inlet boundary condition was set to "Mass-Flow-Inlet", with the mass flow set to 0.00097 kg/s, and initial gauge pressure set to 3500000 Pa. This mass flow rate equates to about 50 SLM, the maximum gas flow rate we want to use. The initial gauge

pressure of 3500000 Pa, which is a normal value that the pressure sees in its current usage. The outlet condition was set to “Mass-Flow-Outlet”, and the wall condition was set to “No Slip.” The residual convergence criteria were set to $1e-3$, and the simulation was initialized with Standard Initialization with an initial pressure of 3500000 Pa. It was set to run for 2000 iterations but converged after 1537 iterations.

The simulation results show that the gas velocity is very low inside the pressure vessel everywhere except for the pipe inlet, which means that powder will not be blown outside the cup it is contained in. It also shows that the minimum gas velocity within the pipe is about 20 m/s, which is above the minimum required to carry the largest particles we will need to aerosolize.

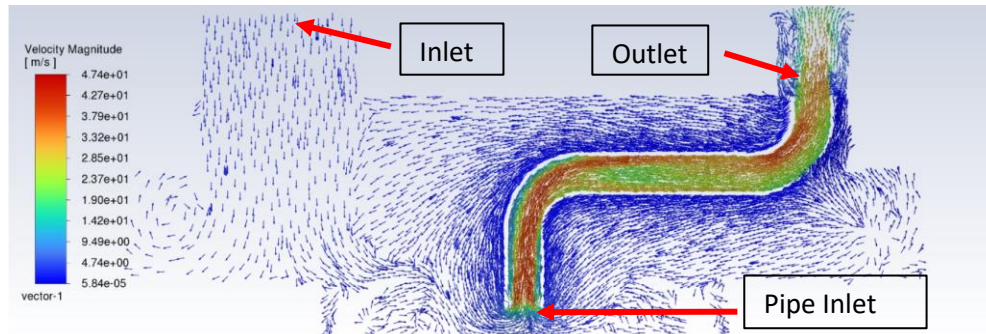


Figure 13: Results of CFD Simulation with vector for gas velocity magnitude and direction

While this simulation gave a good idea of what the gas velocity profile at the inlet of the pipe would be like, we decided to run different simulations to get a more accurate idea of how close the pipe needs to be to the top of the powder to ensure that particles are picked up.

Parameters of the Nozzle and Cup

The software used to run these CFD simulations was Star-CCM+. The simulations were modeled axis-symmetrically, meaning they would show perfect symmetry around an axis thus showing the ideal behavior of a cylindrical-shaped object. The CAD model was drawn in the Star-CCM+ software using the nozzle and powder cup dimensions. The mesh used was the mesh that was auto-generated by Star-CCM+, as we decided the mesh was sufficiently fine around the entrance to the nozzle, which is the area we were most interested in. The inlet was located closest to the axis in the center and the outlet was located around the outside. This model is focused on the interaction at the nozzle so there are no other aspects of the design included in the model. The viscous model used was K-Omega turbulence, which was chosen to account for any turbulence that might occur in the flow. The fluid body was Nitrogen gas (N_2), with the fluid properties taken from the Star-CCM+ database, the density set to “Ideal Gas”. The inlet condition was set to a mass flow inlet with an initial mass flow set at $1.545E-4$ kg/(s*radian) and the outlet condition was set to a mass flow outlet of $1.545E-4$ kg/(s*radian). The reason the mass flow rate is different from the 3D simulation is that the mass flow value needed to be divided by 2π to account for the axisymmetric aspect of this simulation.

By repeatedly running the simulation and adjusting specific parameters each time, we determined that three main variables would have a drastic effect on the velocity profile. The first one was the size of the cup holding the powder. The initial design of the cup was a radius of 0.035 meters. We determined there would only be a drastic change in the velocity profile if the cup radius was significantly decreased. Due to our desire to maximize the amount of powder held in the cup, this variable was ignored because if any changes were made to the cup, it would be to increase the size. The second variable of concern was the size of the outlet tubing. Given the minimum velocity of 12 m/s found in the hand calculations above, we calculated using the simulations that the minimum diameter of the outlet tubing could be 6.35 mm and the maximum diameter could be 12.7 mm. Due to other constraints in the system, we decided that the outlet tubing would

have a diameter of 6.35 mm. Finally, the last variable that had a significant impact on the velocity profile was the distance between the nozzle and the powder. We found that the critical distance between the outlet tubing (6.35 mm) and powder is 1.59 millimeters. At this point, the velocity would exponentially increase and could cause an inconsistent feed rate. The simulations also demonstrated the importance of a constant distance between the nozzle and powder due to the change in velocity.

The two scenes below are taken from the same simulation. Figure 14 shows a vector scene showing the magnitude and direction of the gas. The max and min velocity are auto generated by the software. The figure clearly shows that the velocity is greater than 12 m/s and can pick up particles.

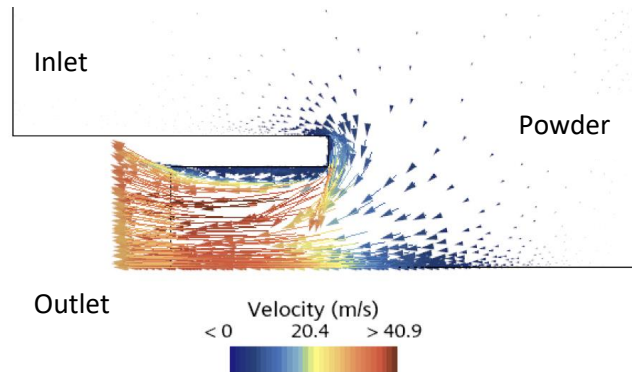


Figure 14: Results of CFD Simulation with vector for gas velocity magnitude and direction

Figure 15 shows a scalar scene that demonstrates the distance from the nozzle from which the velocity is greater than 12 m/s. In this figure, the max and min velocity was changed to 12 m/s so that it is clearly visible. Yellow is greater than or equal to 12 m/s and blue is less than 12 m/s. We used the dimensioning tool built into the Star-CCM+ software to create the distance graphic measuring the distance from the nozzle.

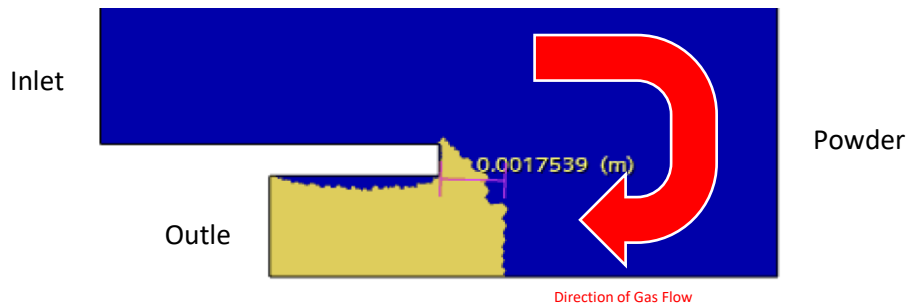


Figure 15: Results of CFD Simulation with edited scalar plot and dimensioning tool

Powder Minimum Feed Rate Analysis

Our aerosolizer is intended to be used for mass volume spraying rates of a minimum of 0.3185 cc/min. This minimum mass volume rate drove our liner actuation design, since we had to ensure we could turn the motor at a slow enough rate to hit this minimum volume flow rate. The volume flow rate of 0.3185 cc/min was translated to linear platform actuation rate, by dividing the volume flow rate by the cross-sectional area of our outlet tube. This means for our 0.25” outlet tube, our linear ascension rate requirement was 0.17 mm/s.

The ascension rate of our design can be back calculated by taking the minimum speed of the existing powder feeder motor that we retrofitted our design from. The minimum speed of this motor is 1 RPM. 1 rotation of the 1/4-20 ACME lead screws is equivalent to 0.063” of linear distance. At one revolution per minute, that gives us a minimum linear ascension rate of 0.021 mm/s. Then due to our 8:12 gear ratio between the middle shaft and two lead screw shafts, resultant minimum linear ascension rate is equivalent to 0.014 mm/s, much lower than the required minimum feed rate of 0.17 m/s.

Measurement of Powder Feed Rate for Prototype Evaluation

For both prototypes, we determined the powder feed rate by measuring the mass of the powder within the machine over time; making use of a 10kg rated load cell combined with a HX711 ADC at a sampling rate of 0.01 Hz. We plotted this data over time to produce a graph which describes the feed rate of each of our prototype trials, as outlined in the Taguchi matrices. An example of one such graph is shown below in figure 16 where the Y axis is the raw scale reading from the ADC.

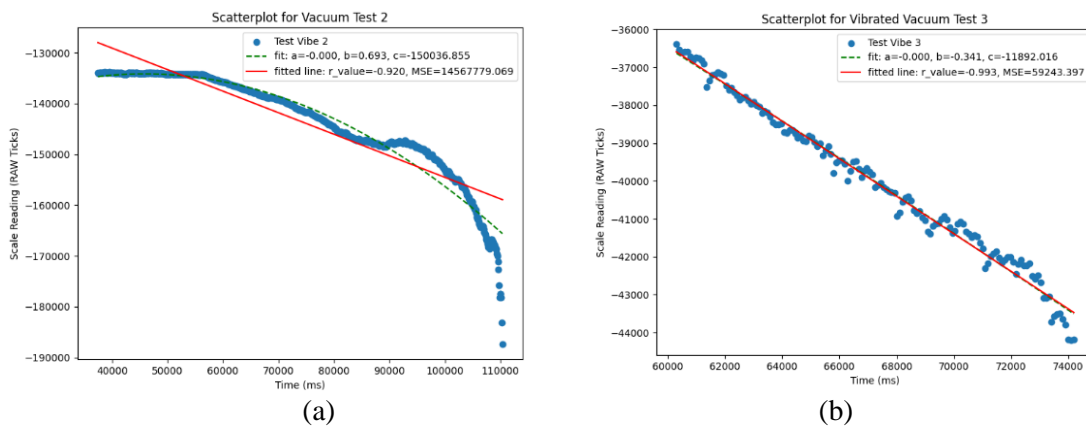


Figure 16: Comparison of no vibration and vibrated vacuum feed system

We were unable to obtain meaningful mass data from the rotary brush system due to the undamped vibrations created by the rotating brush itself as shown in figure 17.

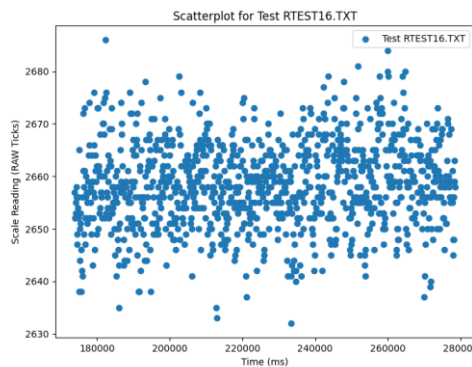


Figure 17: Rotary brush prototype mass data

Figure 16a illustrates a clear exponential trend in the rate of powder consumption by the vacuum prototype. In Figure 16b, the same trial is performed with the addition of vibrational agitation to the powder bed. Figure 16b illustrates the effectiveness of our vibration subsystem in linearizing the rate of powder consumption, thereby improving its consistency of powder feeding.