



Powder Feeder Redesign for Laser-Assisted Cold Spray

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Date:

March 8, 2016

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Chapter 1: Introduction

With the constant advancement of technology, and the ever present need for specialty materials in a fast paced manufacturing world, new processes are constantly developed to meet this need. The Laser-Assisted Cold Spray (LACS) process is one of many emerging additive manufacturing strategies that combines the high speed, solid state bonding seen in traditional cold spray systems with the addition of a high power laser used to increase heat and thus improve deposition characteristics. This process is being used to deposit metal and create specialty alloys with specific, desirable microstructures and avoids the need for costly post manufacturing heat treatment.

The aim of this study conducted in strong collaboration with an industry partner, IPG Photonics, was to analyze current LACS systems and determine critical subsystems with opportunities for improvement. The project focused on the material handling side of the process with an investigation of powder feeder technology and the design of a new powder feeder for use in the LACS system being developed by IPG. An intrinsic challenge with the handling of metal powders is the difficulty of accurately controlling mass flow rate of the powders. This challenge provided us with an opportunity for the development of a novel feeding concept that used a specially designed, geometrically slotted rotating disk assembly to accurately control feed rate of powders with a wide range of flowability.

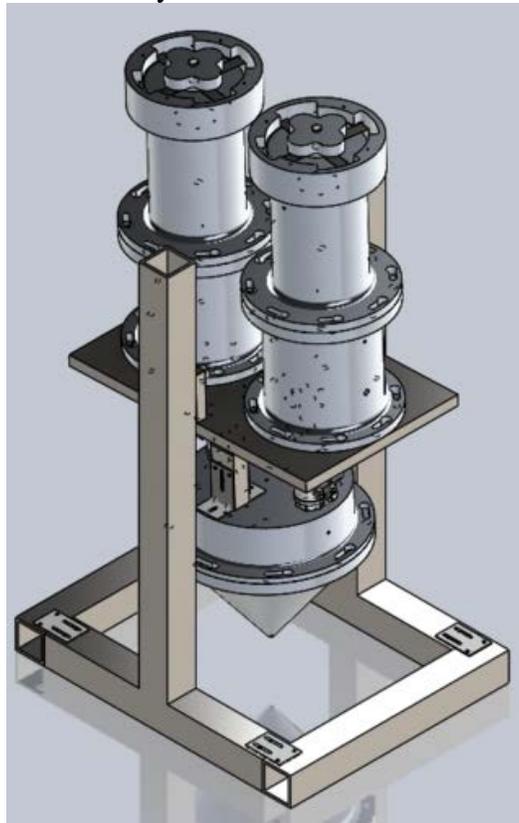


Figure 1 - Final Powder Feeder Model

Chapter 2: Background

Powder feeding for thermal spray processes, specifically laser cold spray, is the overall focus of this paper. This background section is meant to expose the reader to the terminology and science used in the industry as well as to describe the driving forces in the market place that led to the project execution. Section 2.1 discusses the thermal spray field as a group of additive manufacturing processes as well as describes some of its processes and uses. Section 2.2 explains the cold spray thermal process in greater detail. Section 2.3 informs the reader what thermal spray products are currently on the market and what capabilities they have. Section 2.4 discusses the capabilities of the IPG Laser cold spray system in use as of the time of the project. Lastly, Section 2.5 discusses in greater detail Powder Feeder systems, their uses, and areas of improvement, which outlines the overall aim of this project.

Section 2.1 Thermal Spray Technology Field

The thermal spray process is defined as the application of coatings that takes place by means of special devices and systems through which melted or molten spray material is propelled at high speed onto a cleaned and prepared component surface [3]. A diagram of the process can be seen below.

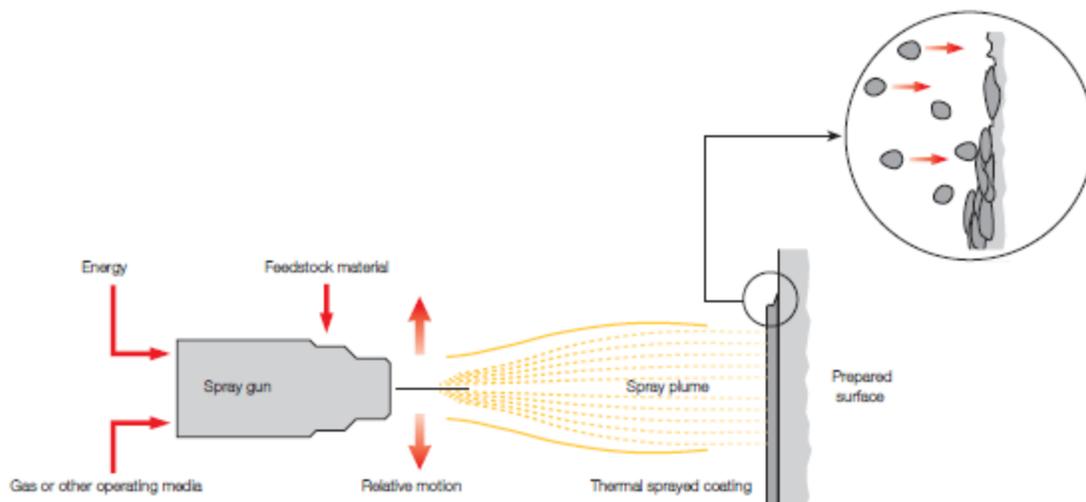


Figure 2 - Overview of Cold Spray Gun and Contact Region from [5]

The thermal spray family encompasses additive manufacturing processes that vary diversely in many areas including the kinetic and thermal energy operating regimes. The purpose of the coating can be for wear protection, corrosion resistance, insulation or can be used as a preparation process for the setup of an additional manufacturing process. The varying temperatures and particle velocities of the different processes allow for differences in coating properties such as bond strength, porosity, coating thickness, hardness, and spray rate which allows for the different uses and purposes of such coatings. The differences among the properties allowed for by certain materials with certain properties and processes govern which process should be used in the appropriate application. The electric arc wire process is capable of delivering 10 to 25 kilograms of coating material per hour of spraying whereas the High-Velocity Oxy-fuel (HVOF) process only delivers 1 to 9 kilograms per hour of spraying. The advantage of HVOF comes in the final product where HVOF is capable of providing a

significantly less porous product with a higher surface hardness [5]. The following subsections provide brief descriptions of several thermal spray processes and provide a sense of their differences and similarities in process and final product.

Table 1 - Comparison of Thermal Spray Processes

	Temperature Range	Particle Velocity	Operating Pressure
Direct Current Plasma Spray	10,000 K	850 m/s	13 atm
High Velocity Oxy-fuel	8,000 K	2,000 m/s	2- 8 atm
Detonation Gun	1,173 K (during explosion)	915 m/s	19.75 atm (during explosion)

Direct Current (D.C.) Plasma Spray

In D.C. plasma spraying, plasma torches are used to create a continuous flow of gas that is heated by an electric arc. The gas used during spraying can be argon, helium, hydrogen, or nitrogen and the possibilities include mixtures of these gases. The temperature can range from 8,000 Kelvin to 14,000 Kelvin and the differences in process gas and temperature can alter gas velocities between 500 and 2,800 meters per second. Powder is introduced to the gas stream and carried at subsonic rates towards the substrate material [4]. The main advantage of this coating process is that very high quality coatings can be produced with high melting point materials which some other processes struggle to spray.

High Velocity Oxy-fuel (HVOF)

HVOF utilizes the combustion of a hydrocarbon in the presence of oxygen or air within a chamber kept anywhere from 2 to 8 atmospheres of pressure. Downstream of the chamber is a converging-diverging nozzle resulting in a drop to atmospheric pressure and allows for gas velocities to reach about 2000 meters per second. Gas is injected upstream of the nozzle and carried towards the substrate by way of the gas stream [4]. Although HVOF spraying has a higher operating cost than plasma spraying, the deposits that are created have optimal material properties. This process has the advantage of creating coatings with low porosity and equally as important, high bond strength.

Detonation Gun

In detonation gun spraying, acetylene is used as the fuel which is detonated in a long tube closed at one end. The detonation causes a shockwave of up to 2 MPa pushing particles that have been heated due to the controlled explosion, towards the workpiece and can achieve gas and particle velocities similar to that of HVOF. One key difference in detonation gun is that powder and gas is introduced cyclically into the detonation chamber as opposed to continuously in the previously mentioned processes [4]. Detonation gun spraying is a slower process as a result of the non-

continuous nature of the spraying but makes up for this flaw in the quality of the coatings produced. Coatings created through the detonation gun process are often looked at as the benchmark for other coating processes.

Section 2.2 Cold Spray Process

This section introduces in greater depth the process of cold spray that forms the main focus of this Major Qualifying Project.

2.2.1 Process Description

In the cold spray process nitrogen or helium is often used as the carrier gas. The carrier gas is compressed or regulated and released out to a pressure of approximately 500 psi depending on the system setup. The gas is then diverted into two streams with one path carrying significantly less volumetric flow rate of gas and leading into a powder hopper where the powder for deposition is contained. The other portion of gas is diverted to a heating system which in turn heats the gas to over 800 Kelvin. The cold spray process is aptly named because the temperature at which the bonding of particles occurs results in the powder never leaving its solid state. The gas stream carrying powder from the hopper is merged with the heated gas stream as it flows into a converging diverging de Laval nozzle which allows for the gas to expand and accelerate to supersonic speeds towards the substrate material or work piece [4]. The powder particles plastically deform upon impact creating a metallurgical and mechanical bond between powder and substrate [4].

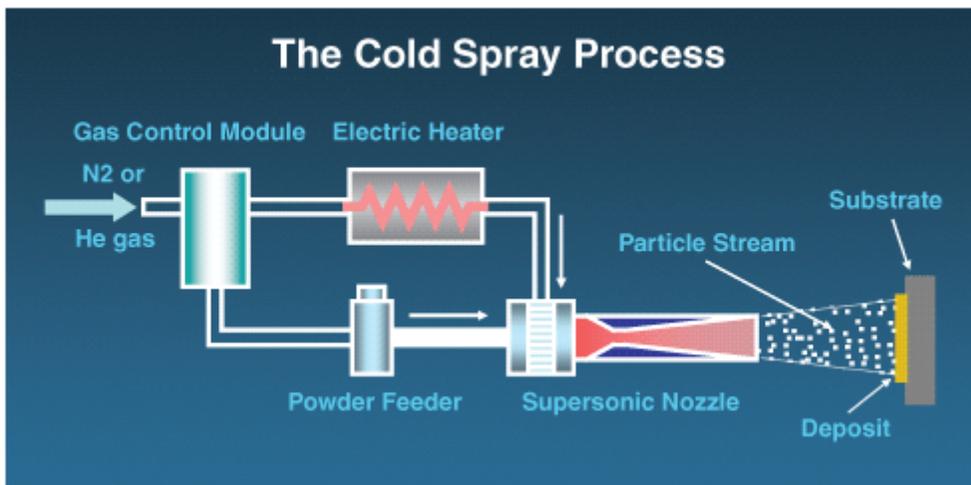


Figure 3 - Outline of Cold Spray Process from [11]

The work piece is sprayed several times after the primary deposition to create what are known as buildup layers. Parameters that can be altered in order to change and optimize deposition characteristics are powder to gas ratio, gas pressure and gas temperature in the main gas stream, as well as the several parameters of motion for the substrate material. Carrier gas is switched to a higher concentration of helium when higher particle impact speeds need to be achieved. One advantage of the process described above is the fact that it is a completely solid state process due to its relatively low temperatures. This allows for advantages such as high bond strength, low porosity, and no oxidation. With the inherent plastic deformation come disadvantages in

properties such as ductility and high residual stress in some depositions. This process is different from most other thermal spray processes in that it has a much higher kinetic energy to thermal energy ratio.

2.2.2 Addition of the Laser

Laser-Assisted Cold Spray (LACS) is a coating fabrication process that combines the supersonic powder stream found in cold spray with laser heating of the deposition zone [1]. The addition of a laser allows nitrogen to be used as the process gas in some applications where helium was necessary to be used in order to achieve the critical particle velocity for bonding. The concentration of heat around the laser spot allows for particle or substrate softening, better deposition efficiency, and lower critical velocity necessary for deposition. LACS allows for coatings to be created with little to no melting and thus allows for reduced thermal stresses, distortion, and microstructural issues [1]. The use of the laser enables potentially higher build rates as well as lower porosity [10].

Section 2.3 Commercially Available Cold Spray Systems

The aim of this section is to discuss commercially available cold spray systems and how they are sold. This section also discusses where such companies are at technology wise in the thermal spray industry and what kind of capabilities the different systems have. Naturally more than these companies function in the thermal spray industry, but only a small sample size of companies is needed to portray a sense of industry wide capabilities.

2.3.1 Oerlikon Metco's Cold Spray System

Oerlikon Metco offers a cold spray system for commercial purchase and breaks their system down by combinations of core components, handling components, and peripheral components [5]. This means that the basic system setup is identical from system to system but depending on customer needs a different spray gun or gas heating system may be chosen. With the cold spray system Oerlikon Metco offers there is only one controller option and one powder feeding option.

For maximum versatility, the spray gun is mounted on a robot manipulation system while the substrate material is manipulated by a specialized turntable so that the spraying of parts with complex geometries can be achieved [5]. One drawback seen in this system is that the powder feeding system is contained within the spray booth itself which would not allow for continuous spraying of material. Some processes may require spraying throughout an entire day of production in a manufacturing environment which means that the system must be completely shut down so that the powder or material feeder can be refilled.

2.3.2 Centerline's Supersonic Spray Technology Division

Centerline, another company adept in the thermal spray field, offers many systems intended to fit a wide range of applications. Centerline offers integrated and robotic systems that allow for fully automated spraying as well as options such as their portable system that could be used in applications where it may be impractical to fit a large part into an enclosed spray booth [2]. A few such examples would be trying to fix the integrity of a car frame that has been compromised

due to exposure to the elements or even spraying large airplane parts that cannot fit in relatively small spray booths and are difficult to maneuver.

Section 2.4 IPG LACS System Setup and Capabilities

IPG Photonics is currently in the research and development stage of designing a LACS system. As seen from the Centerline and Oerlikon Metco products, it is a common practice to manipulate the spray gun with a robot or some other pneumatic multiple degree of freedom handling device and to manipulate the substrate material with a simple mechanism such as a turntable or lathe. This practice allows for the most degrees of freedom in the spraying process and allows for more complex spray path geometries and thus more flexibility in the shape and size of substrate parts. IPG's development stage system currently uses a stationary head unit for the spraying gun and nozzle while the substrate material is controlled by a 6-axis robot which functions primarily as a lathe but has many other capabilities. As a result of the current focus of IPG in the LACS field of developing a database of spray parameters for different spraying applications, the complexity of parts is mostly limited to cylindrical and flat pieces.

Section 2.5 Powder Feeding Systems

The primary focus of this Major Qualifying Project is to design a new powder feeding system that will allow for new spraying capabilities and to improve upon the performance of the current system in use at IPG. This section's aim is to provide more information on different powder feeding systems used in a variety of industries, the types of powder feeding systems currently in existence, and some pros and cons of those system types.

2.5.1 Industries that require use of Powder Feeders

Other than the thermal spray industries, there are a plethora of industries which require the use of powder feeders and serve as potential industries to draw upon for information and inspiration. Almost every manufacturing plant utilizes some sort of feeding technology, but the most important ones to be discussed here are the industries that feed materials similar to the metal that will be fed through the designed powder feeder. Some industries that require the use of powder feeders are the food packaging industry which requires large amounts of powder to be delivered at either a constant or intermittent pace depending on the application, and the pharmaceutical industry which requires powder feeders for both batch and continuous operations such as tablet pressing and continuous coating respectively [4]. It is necessary to take a look at these other industries as there are companies who make powder feeders for multiple industries and concepts from these feeders may be applicable to the industry of interest. The reason this can be done is that no matter what industry that requires a powder feeder is being looked at, similar issues and performance factors are examined. Some of these issues include moisture and temperature sensitivity as well as size and shape of powder particles [4].

2.5.2 Types of Powder Feeders

There are two separate portions involved in powder feeding that help to categorize what type of feeder is being used. The first is based upon how flow rate is measured. The two types of flow measurement predominant in powder feeding are gravimetric flow and volumetric flow.

Gravimetric flow is based on measuring change in weight over time whereas volumetric flow is based on previous calibration of the machine and feeder speed [7]. This is important to be kept in mind when taking into account the accuracy of flow measurements. Each measurement method has intrinsic pros and cons that result from the measurement method. An example of this is that gravimetric feeders can automatically compensate for the density of material as it is delivering a mass or weight of material every specified amount of time. The drawback to this method in the thermal spray field is that very precise amounts of small flow need to be delivered into the carrier gas accurately. This issue means that the use of accurate, fine measurement load cells may be expensive or impractical. Volumetric feeders require user input based on the bulk density of the powder being delivered. When the user input contains accurate data it is more accurate to measure the performance parameters of a delivery mechanism based on volumetric flow as opposed to a mass flow rate when the system is delivering a few grams per second [7]. See the illustration of this concept below.

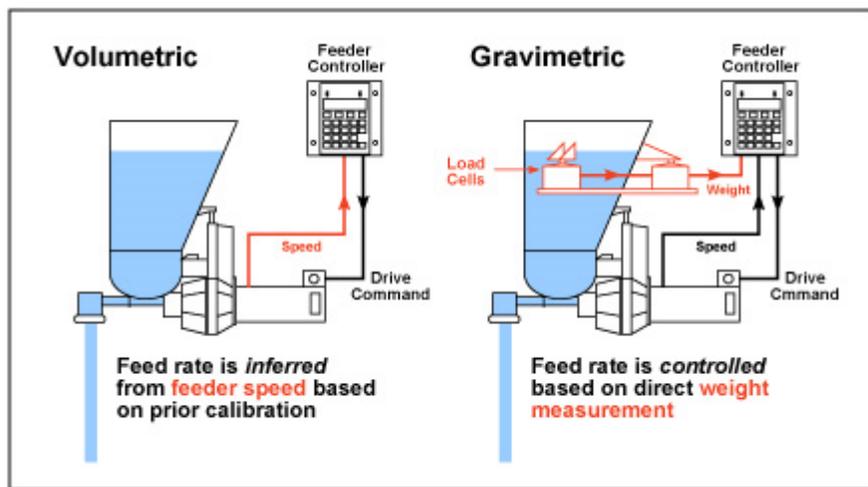


Figure 4 - Volumetric and Gravimetric Feeding Systems from [7]

Section 2.6 Powder Feeding Systems

The other portion of powder feeding is the mechanism by which you deliver powder to its final location or in the case of the thermal spray industry, how powder is delivered into the carrier gas stream. The three most common types of delivery mechanisms are rotating disk, screw fed systems and fluidized bed powder feeders. The benefits of each of these systems are outlined below in Figure 5.

Rotating Disk

Rotating disk powder feeders work by having a hopper of powder sit stationary above a rotating disk. The flow of powder is controlled by a combination of the geometric pattern of the disk, which can be changed, and the disk's angular velocity.

Screw Fed

Screw fed designs deliver powder from a hopper and onto a horizontal screw which delivers powder into the carrier gas stream. The flowrate of the powder is controlled by the geometry of the screw and the screw's angular velocity.

Fluidized Bed

Fluidized bed powder feeders deliver a powder by a different means. Powder is introduced to a volume of gas at high pressure so that the powder becomes “fluidized” into the bed of gas. A converging diverging nozzle then delivers this fluidized powder and gas mixture into the carrier gas stream.

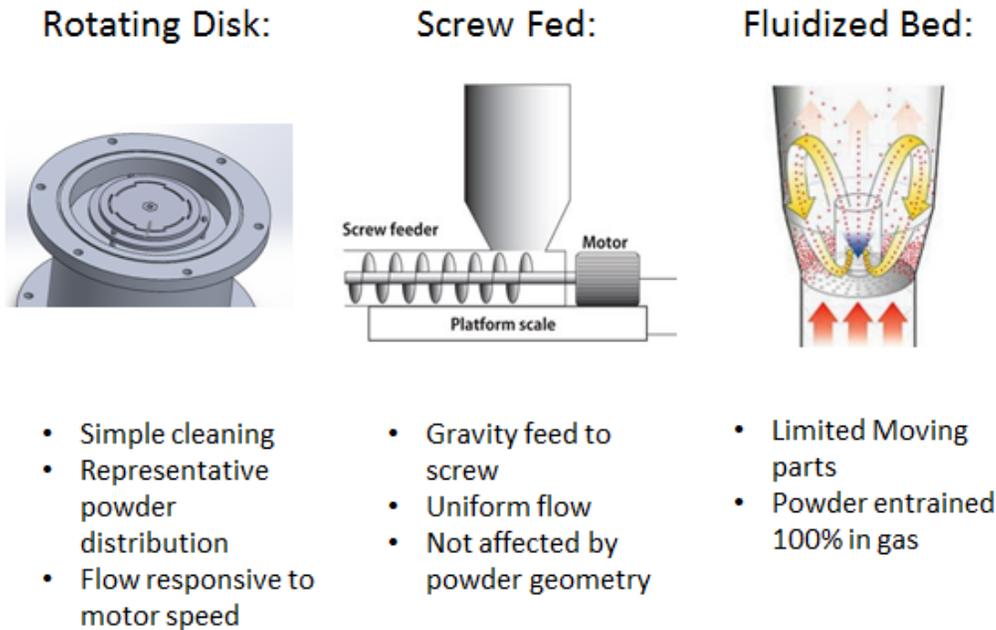


Figure 5 - Benefits of each Powder Feeding System

2.6.1 Commercially Available Powder Feeding Systems

Several powder feeder systems are currently on the market and available for purchase. However, there seems to be a specific group of desirable features or capabilities that IPG photonics wishes to fill a void in the market with a future LACS system. These features include important capabilities that commercially available products do not have such as continuous spraying ability, the ability to spray multiple types of powders on the same substrate, and systems that can operate at pressures that could potentially reach 600 psi. This section will discuss commercially available products to provide a sense of what is currently available in the market, and how a lack of features and capabilities led to the decision for a new powder feeder design.

PowderFeeders.com

PowderFeeders.com’s Industrial Powder handling systems supplies the powder feeder currently in use in the IPG LACS system. The model is the V4-10L-WL-HP which is the 10L capacity model able to withstand pressures of up to 500 psi and is gravimetric type feeder [8]. The fact that this model can operate at such high pressures is an advantage for the cold spray process as this process requires more kinetic energy than other thermal spray processes and this additional kinetic energy is supplied by additional pressure. Most powder feeders designed for a variety of

thermal spray processes can only withstand much lower pressure thresholds. From previous experience and use of this specific feeder, this model is not optimal for IPG's LACS application.

Praxair

Praxair also makes powder feeders for various thermal spraying processes. The strongest consideration was given to the 1264i model powder feeder that was originally designed for specific use in the HVOF process which requires lower pressures than that of LACS [9]. This model is also a gravimetric feeder and is advertised as easy to clean. However, this model can only handle one hopper at a time which does not allow for controlled flow of multiple powders in a single application. Praxair's model can only withstand pressures of up to 125 psi which is much too low for IPG's desired application [9].

Oerlikon Metco

Oerlikon Metco offers several models of powder feeders for specific thermal spray processes. One in particular, the Metco Twin 150, has the capability of spraying multiple powders for a single application and can be equipped to handle large volumes of powder [6]. However, it is only designed to withstand a pressure of 145psi which again brings it far out of the range of operating conditions for our desired application [6].

Section 2.7 Feature Analysis

The market research stage involved researching of specific cold spray systems as a whole as well as powder feeder systems specifically in order to get a sense of what products are currently available commercially. Some of the information found was presented in sections 2.3 and 2.6. From the powder feeding products that are available it is observed that a majority of powder feeding products for thermal spray processes only handle pressure ranges with an upward limit of 150 psi. Many companies provide a canister based system for unloading and reloading powders which limit continuous spraying capabilities. A majority of the powder feeders used for thermal spray rely on the rotating disk method while the screw fed design seemed to be in industries outside of thermal spray.

Features that seemed to be absent from such feeding process were continuous spraying capabilities and multiple powder spraying opportunities. Only the Oerlikon Metco twin model was capable of using two powders concurrently in the thermal spray industry. The multiple powder aspect was present in one product developed by Plastics Technologies [4]. The product had a hopper channel which allowed for the addition of multiple hoppers in a linear fashion but did not have separate feeder lines for each powder.

The overall opening in the market identified was the capability to spray gradient materials. This is the ability to accurately blend from one material to a different material in a controlled ratio gradient. This is needed for applications of cold spray where the desired powder material does not adhere well to the substrate material directly. An example of this is spraying softer aluminum powder onto a hard substrate such as tool steel. In such cases, it is necessary to gradually blend

the aluminum onto the tool steel by having a powder that is a mix of both tool steel and aluminum.

Chapter 3: Methodology

This section discusses the specific objectives and tasks of the project and how they were accomplished. Section 3.1 discusses the development of design requirements and functional specifications. Section 3.2 discusses the innovation stage in which design of the powder feeder and its unique features were created. The simulations run on the design are described in section 3.3.

Section 3.1 Design Requirements

Based on the market research conducted by the team a set of design requirements were formulated and then organized into a list comprised of 3 categories. The categories each requirement could be sorted into were Tier 1, 2 and 3 subcategories.

Tier 1

In the Tier 1 category, each requirement was further sorted into one of 5 subcategories. Those subcategories are physical/functional, powder path and flow, maintenance, future commercialization, and safety. See the chart below of necessity requirements, the driving factor behind those requirements, and the subcategory it was divided into.

Table 2 - Descriptions of Design Requirements

Requirement	Requirement Driver	Subcategory
600 psi pressure capability	IPG desires to spray at this pressure in the future	physical/functional
Multiple powder spraying capability from separate feeds	Multiple powder applications and continuous long term spraying	Physical/functional
Ability to measure 5-20 g/min flow rate	Load cell difficulty in measuring small weight changes	Powder flow control
Continuous powder flow	Pulsation in powder feed compromises product	Powder flow control
Limit excessive preventative maintenance	Maintenance causes downtime in the production facility	Maintenance
		Maintenance
Robust repeatable design	Future sale potential	Commercialization
Rugged locking mechanism	Containment of high pressure	Safety
Limited or mitigated gas backflow	Backflow causes harm to equipment and potentially observers	Safety

Tier 2

Only 4 requirements were placed in the Tier 2 category and thus were not placed into subcategories. The first was powder calibration ability as powders of different densities needed to be fed with different volume flowrates. To go along with this calibration, internal volume

flowrate sensing was placed in desires. Both of these requirements would be beneficial to ensuring the accurate mass flowrate requirement placed in the Tier 1 category. The next requirement placed in the desires category was a powder preheating option. Preheating powders could potentially give rise to more uniform properties in final product. The final requirement in this category is downstream mixing of powders. If two different powders entered the system, they would have to be thoroughly mixed to obtain a uniform final product.

Tier 3

The last subcategory of requirements determined was for additional design benefits. Even without these requirements being filled, the system required by the previous two requirement categories will produce a safe working system when proper safety protocols are used. The first requirement in this category is to have a way of letting the operator know that there is a pressure overload in the system. This increased notification beyond physical observation of the unit could prevent further damage to the powder feeder and system as a whole. The final design requirement is to have a similar warning system for powder overflow. The desire for this is driven by the flammability of the powder and the fact that the risk of fire could be potentially mitigated if the operator knew when the system was dispensing powder improperly or when system is not in use.

Section 3.2 Design Pathway

Based upon the created design requirements, the team began to construct ideas on how to put together a system. These ideas were then created in the SolidWorks computer-aided design package. Specific dimensioning based upon calculated loads will be further discussed in later sections. See below for an image of the product and description of functionality by section.

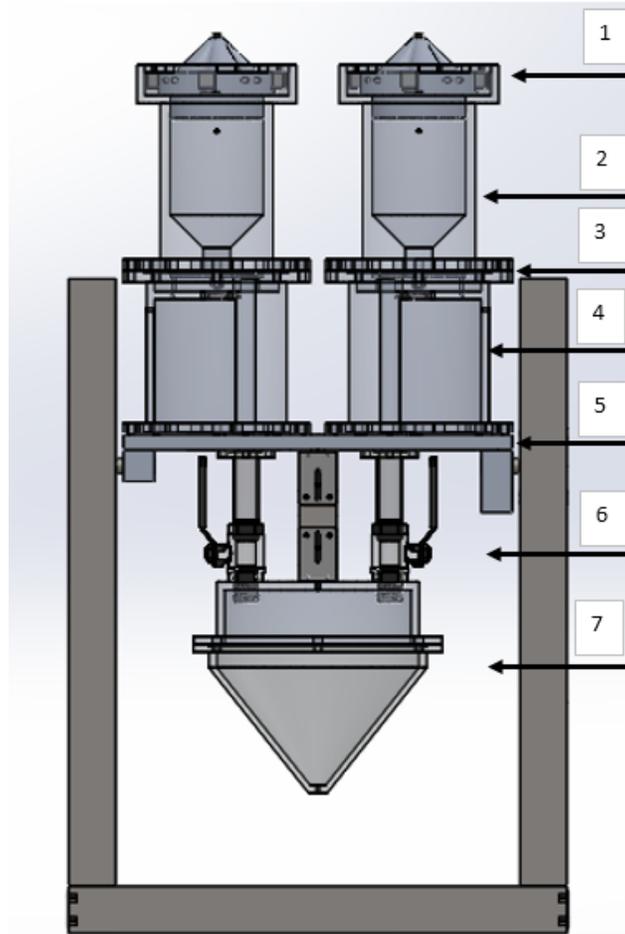


Figure 6 - Powder Feeder, Transparent Front View

Table 3 - Description of Subassemblies in above Figure

Subassembly Number	Subassembly Name
1	Lid Assembly
2	Hopper
3	Feed Control
4	Motor Housing
5	Flat Plate
6	Ball Valve
7	Mixing Chamber

The systems functionality starts from the top with the lid assembly on top which is designed to withstand the intense pressures needed for the cold spray process but also must open to allow insertion of new powder. Subassembly 2, the hopper, contains the powder for operation. At its base is a channel directing powder flow onto the feeding control mechanism. Subassembly 3, feed control, contains the rotating disk mechanism that is used to control the flowrate of powder into the gas stream. Under the feed control section is the motor housing which contains the motor for spinning the drive shaft of the rotating disk. The motor housing also has a tube section that directs powder into the mixing chamber. Subassembly 5, the flat plate, supports both the upper and lower sections of the feeder and is also capable of rotating about its axis to allow for

easier disassembly, powder emptying, and cleaning. Subassembly 6, the valve, is an additive control for shutting off powder feed into the mixing chamber. Turning off the rotating disk ceases powder flow into the chamber, should the need arise, and the valve prevents gas backflow up through the motor housing and hopper and allows for proper depressurization. Subassembly 7, the mixing chamber fluidizes the powder or powders into a uniformly distributed mixture and leads to the downstream nozzle for particle deposition on the substrate material. Unique solutions to the design requirements will be discussed further in following subsections.

Section 3.3 Simulation and Computer Analysis

After the initial design was completed, changes needed to be made for several different reasons. The changes came from a combination of design reviews, simulations results and testing. The following subsections detail the simulations run on the design that resulted in changes to be described in future sections.

3.3.1 Simulation and Analysis

This project used both finite element analysis and particle flow simulation capabilities in SolidWorks to analyze the model, in addition to stress calculations done by the team.

Finite Element Tests

Our personal calculations and the finite element capabilities of SolidWorks were applied to several aspects of the powder feeder including the hopper, lid, baseplate, and mixing chamber. The loads the system would see during operation as well as during other scenarios such as cleaning and maintenance were determined and applied to the specified subsystems using this software package. The results of the finite element package on the hopper can be seen below.

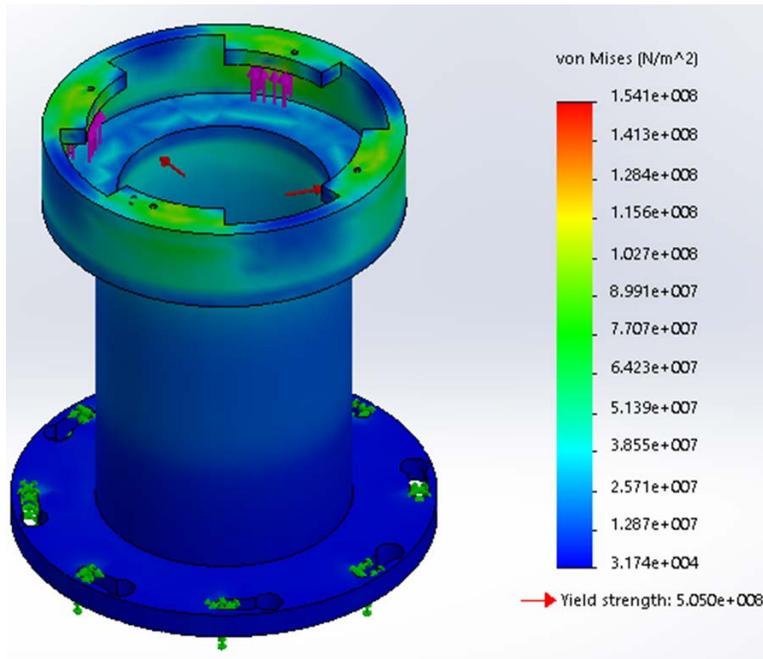


Figure 7 - Powder Hopper FEA showing stresses are well below yield strength of Al 6061

Finite element analysis showed us what the expected stresses can be on our part under the loading conditions. Based on the results for the hopper, the geometry had to be changed in order to accommodate the immense pressures.

Powder Flow Simulations

In SolidWorks, the group was able to model how particles would behave in the mixing chamber based on different gas and particle entry configurations. The analysis concentrated on particle residence time in the chamber and the quality of mixing. During the tests, the geometry of the mixing chamber as well as the location and quantity of gas inlets was manipulated in order to obtain the best mixing characteristics.

SolidWorks utilizes a solver that uses computational fluid dynamics (CFD) which falls under fluid mechanics. CFD uses numerical analysis in the form of the Navier Stokes equation to solve problems. The advantage of numerical analysis lies in its ability to solve complex problems much faster than analytical methods. The SolidWorks solver can incorporate a number of different aspects in each simulation to closely resemble the real world application. Some of these aspects include thermal conditions, different types of flow, and the mixing of flows, both of solid particles and of fluid. The downsides to this tool are in its inability to show interactions between particles as well as the limited computation town the software is capable of.

Please see an example of the simulation visual below. The results of these simulations will be further explained in the next section.

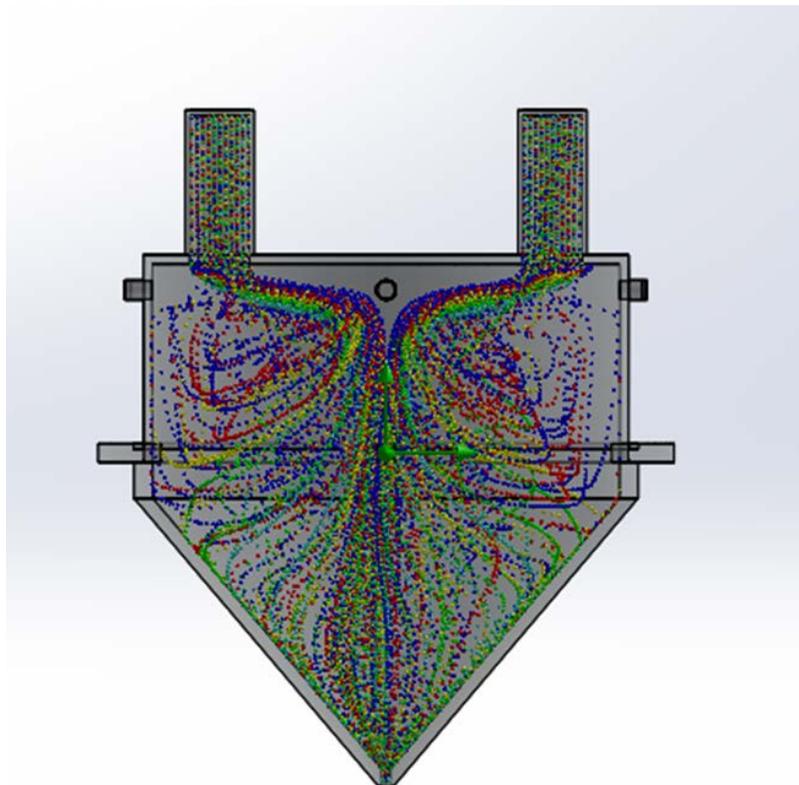


Figure 8 - Particle Flow Simulation of the mixing chamber front view with gas inlets coming from the top left and right

Chapter 4: Design and Innovation

From many design iterations the powder feeder has changed drastically over the course of the project. The purpose of this powder feeder is to accurately deliver a specific mass flow rate of any type of powder to the main gas stream which will eventually be sprayed onto another substrate material. To understand the design completely it is important to go through the gas flow patterns within the feeder and how the system as a whole will be pressurized. The interaction of the gas with each individual component was a strong consideration in the design of the powder feeder. Additionally, understanding the path of the powder from the hopper, through the feeder and eventually into the gas stream is essential to describe the functionality of every component. The following two sections describe the gas pressurization and flow pattern as well as show the path of the powder as it travels through the feeder.

Section 4.1 Gas Flow through the System

In order to prevent any issues surrounding the backflow of pressure inside the powder feeder, the powder feeder was designed to have a specific pressurization sequence. The hoppers are the first to be pressurized. The motor housings are pressurized next and the last component to reach pressure is the mixing chamber. This pressurization sequence can be viewed below in Figure 9.

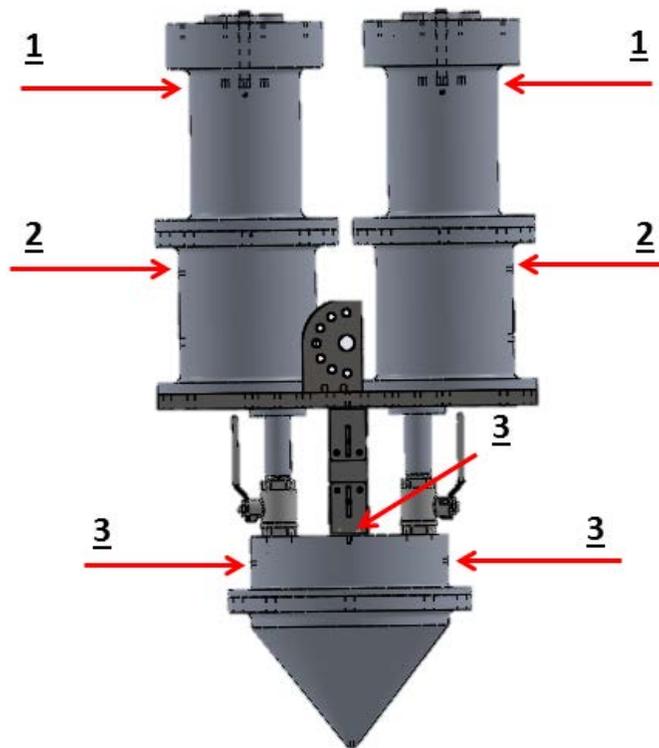


Figure 9 - Pressurization Sequence of the powder feeder for initial pressurization before spraying

Section 4.2 Powder Path through the System

The powder path through this powder feeder design begins with insertion into the hopper by removing the lid. An added feature is the ability to rotate the device, which results in less powder loss during loading. When the lid is closed the powder inside the hopper is static and becomes pressurized. Once the rest of the system is brought to temperature and pressure, powder feeding can begin. Powder fills inlet volumes on the rotating disk. Once each full inlet travels 180°, it falls through an exit hole on the disk assembly and into tubing that brings it rapidly through the motor housing. Once out of the motor housing, the powder flow enters the mixing chamber where it becomes highly fluidized in a turbulent gas stream along with powder from the second, identical hopper. Once mixing is complete, the powder exits the mixing chamber while maintaining the same powder size distribution. From here it is ready to be sprayed.

Section 4.3 Innovative Solutions

Innovative Solution: Dual Hopper

Visible in each full image of the system, it is shown that above the flat plate there are two instances of every major part. This is due to the requirements of multiple powder handling capabilities and long term spraying capabilities. In a multiple powder system, a different powder can be loaded into each hopper and set with its own feed controls. This design also allows for continuous spraying of one powder type. In this instance, both hoppers can be loaded with the same powder. As one gets low, the feed for the secondary hopper takes over and the initial hopper can be depressurized and refilled without interrupting operation. This concept of the flat plate can be expanded in the future to accommodate more than two hoppers to allow for applications requiring more than two powders or for continuous operation of another multiple powder application.

Innovative Solution: Rotating Disk Geometry

One of the requirements was continuous flow of powder due to the fact that inconsistencies in powder feed can compromise the integrity of the final product. This design incorporates a disk feeding mechanism intended to provide a pulsation free powder feed into the gas line. See an image of the disk below.

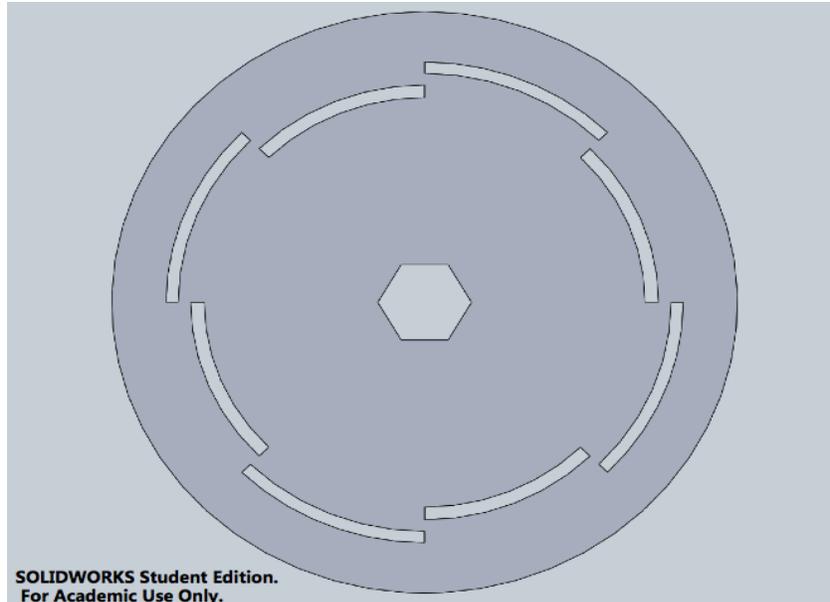


Figure 10 - Rotating Disk Design of "thin normal" disk to be cut from 1/8" thick stainless steel

The disk differs from others in that it is modeled with offset equal volume slots that feed the same amount of powder per rotation. Other disk geometries contain patterns of holes that create gaps in powder feeds while this design allows for uninterrupted powder feed. The calculated geometries also ensure accurate control of volumetric or mass flow rate of the powder being sprayed.

Innovative Solution: Mixing Chamber

Due to the ability of spraying multiple powder types in one operation, the design requires a downstream mixing area so the distribution of particle types and sizes can be uniform in the powder feed. The mixing chamber is designed with a specific geometry and inlet gas configuration to make this possible. See an image of the mixing chamber below.

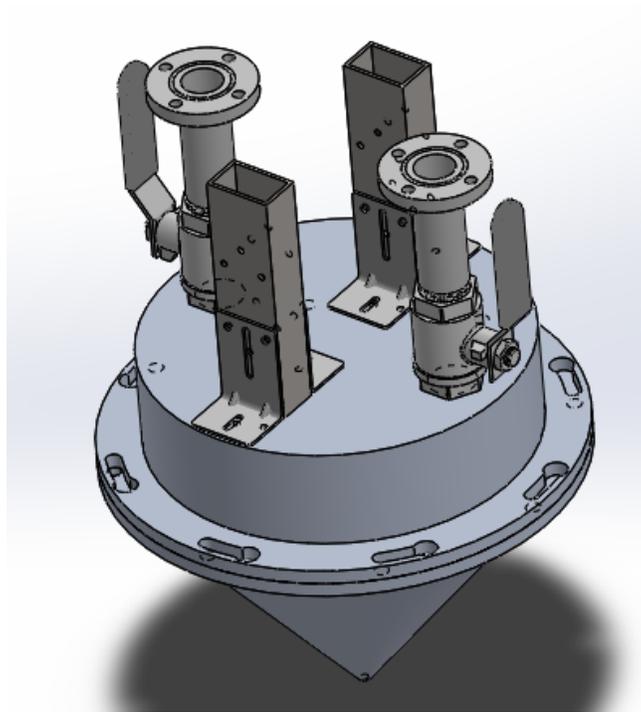


Figure 11 - Mixing Chamber Assembly isometric view including down pipes for powder flow and supportive brackets

Section 4.4 Design Components Overview

When developing the entire device, the design was divided into a series of sub-assemblies for organization and design purposes. From top to bottom the design was created with functionality and innovation in mind. Each system has been analyzed and compared to market standards to construct the optimal solution for an industries' powder feeding needs.

4.4.1 Lid Assembly

The lid to the hopper was one of the more difficult components of the system from a design standpoint. Not only does it have a relatively large surface area which contributes to high forces applied by the pressure of the gas within the system, but it is also one component that is consistently taken off and put back on to allow for addition of new powder into the system. The diameter of the internal section of the lid that is in contact with the assembly is 6 inches which leads to an area of 28.274 in². When the feeder is pressurized to the maximum operating pressure of 600 psi, equation 1 calculates the lid needing to hold a force of 16,965 pounds.

$$Force (lbf) = Pressure (psi) * Area (in^2) \quad (eqn. 1)$$

Due to this extremely high force being applied to the lid by the pressure within the powder hopper, the lid needed to be reinforced better than the initial design. To account for this, additional support bars were added to the assembly, making a total of 4 steel bars used to hold the lid in place. The assembly can be seen below in Figure 12.

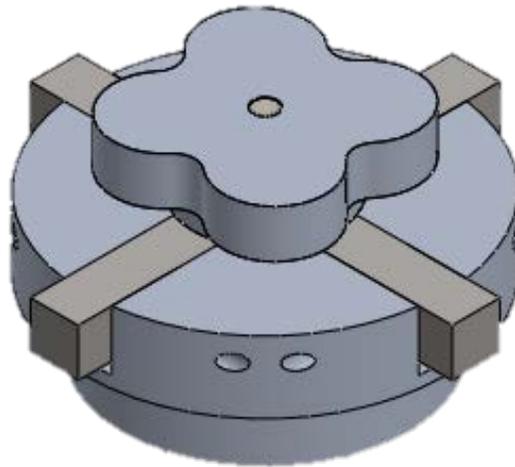


Figure 12 - Isometric View of the Lid Assembly to be made from 6061 aluminum and steel parts

In the figure it is shown that the lid is held down by the four steel bars which pivot around pins inserted into the main body at the holes seen along the top rim of the lid. The exterior ends of the steel bars are held under lips on the main body of the hopper and the interior sides of the bars are held down under the handle which is used for tightening the lid into place. The handle rotates around a threaded steel rod which is held down by a bolt on the bottom side of the lid. The location of this bolt can be seen in Figure 13. In order to make this assembly air tight there are two O-ring slots, highlighted in red, machined into the bottom the lid which can also be seen in Figure 13. The larger diameter O-ring is compressed only when the lid is tightened into place by the handle during spraying. The smaller diameter O-ring is to ensure an air tight seal around the location of the bolt used to hold the threaded rod for the handle in place.

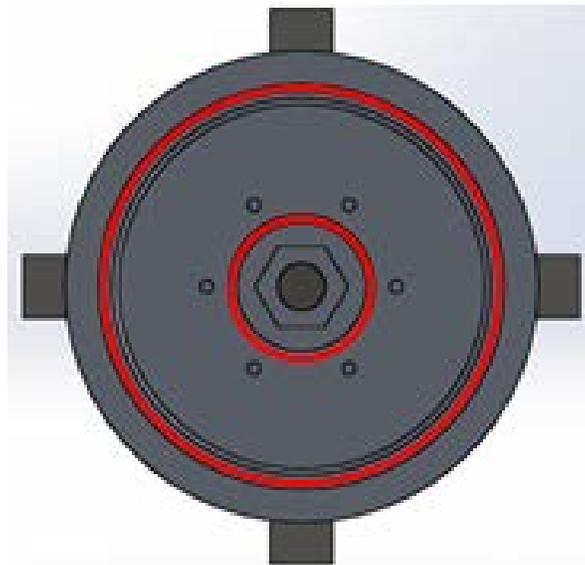


Figure 13 - Bottom View of the Lid Assembly with O-ring slots highlighted in red

For this assembly to hold the 17,000 pound operating force it will undergo, each component needed to be rated for the specific force that it will individually experience. The steel bars will each hold down about $\frac{1}{4}$ of the 17,000 pound force which will be transferred to the steel pins they rotate around. The free body diagram used for calculations is shown in Figure 14a. The SolidWorks simulation of these forces on the bar is below in Figure 14b. This simulation shows the maximum stress the bar will experience is far below the yield strength of the steel it is being made from.

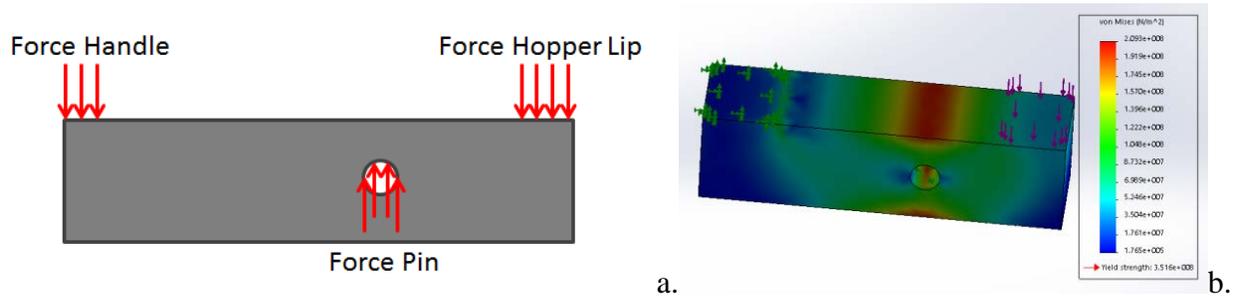


Figure 14 - a. Free Body Diagram of Lid Bars b. Simulation of Forces applied to Lid Bars showing yield strength of the material is not exceeded in the application

The pins being used are rated for forces in excess of double what they will be experiencing in this application. The threaded steel rod, handle, and bolt holding the rod in place have also been examined and it was determined that it would safely hold the pressure and stresses they will be under.

4.4.2 Hopper Design

The hopper as a whole was designed with both functional and fiscal intentions. The material had to handle an operating pressure of up to 600 psi, while also having a low enough coefficient of friction for all powders to flow smoothly. The interior geometry needed to be machined such that static powder moving at a low feed rate will maintain full mass flow as opposed to funnel flow. To accomplish this, the original design involving an elaborate bottom cone which directed the powder to a single side. Instead, a symmetrical cone would streamline the flow of powder to the center of the hopper and then a small angled channel directs the flow to the correct side of the rotating disk. This change also decreased machining costs as completing the complicated, off-center, cone geometry would have required extremely complicated tooling and machine paths.

A collection of design changes were made from design reviews and advice acquired from both Mark Labbe and part manufactures in charge of machining the system components. An example of one major change was the switching of material for several components. Purchasing the original aluminum material for one 16 inch diameter part was projected to cost over \$1,200 for the stock alone. This material was switched to a 6061 aluminum alloy because a piece of that same size was only a significantly lower price. The new material also decreased machining costs as a result of better machinability and a large amount was getting machined away from the interior.

When designing the hopper, the portion the lid locks into is a critical component. These lips become an area with major stress concentrations when the system is pressurized. Through further

examination using *SolidWorks* finite element analysis tool it was found that the new material choice would not meet the safety factor requirements set for the system. To account for this material change and give the feeder a sufficient factor of safety, the thickness of these lips was increased to increase the amount of material experiencing the forces. These changes give the hopper lips sufficient area of contact with the lid bars to handle consistent loading and unloading.

4.4.3 Disk Assembly

The rotating disks were a critical subassembly of the powder feeder because they are what allow the feeder to attain final goal of predictable, consistent mass distribution. The assembly was designed to include three disks. One of which has the inlets to collect the powder from its essentially static position in the hopper. This disk will be rotating at very low angular velocities to give the powder sufficient time to fill each inlet volume completely. The specification of total inlet volume of our disk allows the accurate control of powder flow by altering the rotation speed of the motor and thus the disk. The other two disks essentially sandwich the rotating, slotted disk carrying the powder both to create replaceable wear surfaces as well as to determine the exact location the powder is dropped from the slotted disk.

Powder flow phenomenon can never be overlooked even when working with such small volumes for the inlets. The original disk designs involved inlets that kept a constant radius around the disk. Through a design review with engineers at IPG and Jenike & Johanson, a concern arose about the rat holing effect that could cause clogging of powder and blockages in the disk. After a redesign of the rotating disk, tapered geometries were tested in hopes of attaining a reduction in possible rat-hole effects. The testing of the disk assembly described in later sections showed that the original design resulted in better flow characteristics and extremely limited particle hang up.

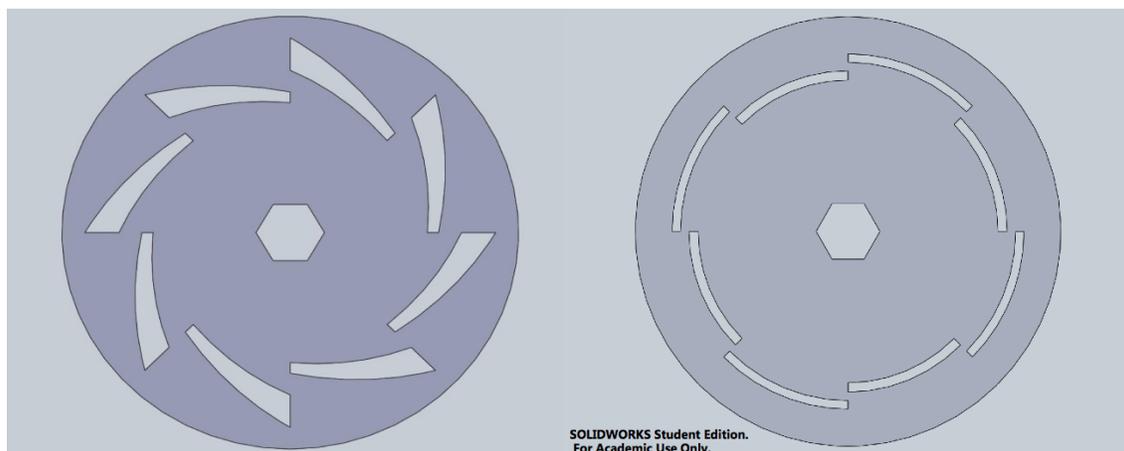


Figure 15 - Comparison of one of two new inlet geometries tested described as the tapered disk (left) to original rotating disk design (right)

4.4.4 Motor Controls and HMI Capabilities

Another important component of the powder feeder design is the ability to accurately control the angular speed of the rotating disk assembly by means of a strong motor and control panel. The

motor being used is an indexing motor which is controlled through an indexing servo drive that contains its own software package. This allows the motor to be controlled through the drive by any computer connected through Ethernet to the drive. The software allows a user to control the motor by specific speed, time, and even position. This allows the control of mass flow rate from the hopper into the system when combined with rotating disks that have slots of known geometry. The design of multiple disks can be seen in Figure 16. The testing of these disks, described further in later sections, led to the conclusion that different disks better suit different powders.



Figure 16 - Multiple Disks for Testing with the "thin normal" disk top left, "thick normal" disk top right and the thinner tapered disk bottom middle

The ultimate goal of the powder feeder is to be able to integrate these motor controls into the program used to run the LACS system as a whole. In order to do this the HMI must have inputs that allow a user to specify disk rotation speeds. As a result of having two separate powder hoppers, the HMI must have controls for each motor individually. For gradient spraying of materials, it would be beneficial for there to be settings that allow for control of the motors' speed based on time or completed rotations. For continuous spraying operations, one motor must be able to be stopped while the other motor simultaneously begins operation. This will allow for continuous spraying without pulsation from switching hoppers and will allow for the hopper not in use to be isolated, depressurized, and refilled with new powder.

4.4.5 Motor Housing Design

Throughout the design process, the motor housing had gone under several modifications. The significant changes that it underwent consist of the addition of fillets in several areas, steel thread inserts, and modifications to the interior of the housing itself. The fillets were added for ease of manufacturing and to minimize stress concentrations in areas that were exposed to repeat tensile loading. The locations of the added fillets can be seen below in Figures 17 and 18.

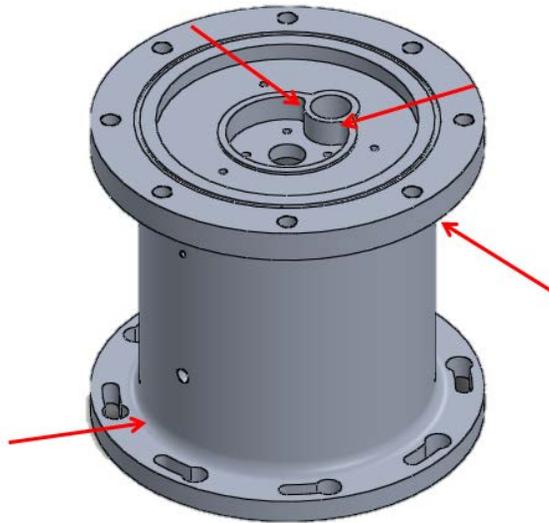


Figure 17 - Motor Housing Fillet Additions – Isometric View, fillets added in locations to reduce stress concentrations and for machining purposes

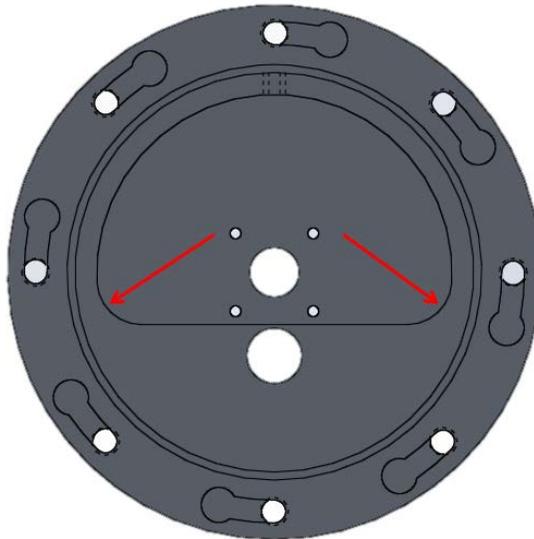


Figure 18 - Motor Housing Fillet Additions - Bottom View, fillets added to interior geometries for machining purposes

In addition to the numerous fillets, steel thread inserts were added to the tapped holes in the mixing chamber. The motor housing was being fabricated out of aluminum which raised concerns surrounding the performance of the threaded holes when being exposed to the continuous screwing and unscrewing of the hardware.

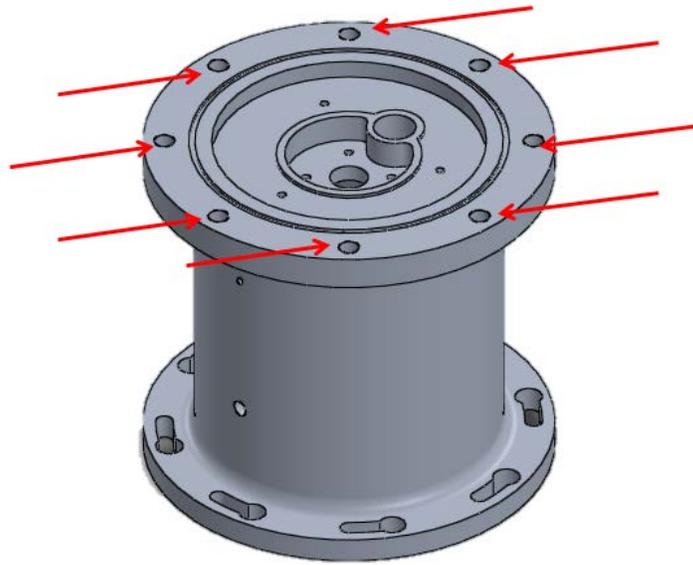


Figure 19 - Motor Housing Steel Thread Insert Locations

The last modification highlighted in this section is the change to the interior of the motor housing. In prior versions of the motor housing, the entire interior was bored out and steel pipe connected the top of the motor housing to the bottom of the motor housing as part of the powder pathway. To save on fabrication cost, the design was altered to feature an interior that is only partially machined out to provide space for the motor to be mounted. Instead of running a steel pipe through the housing, there would be a hole bored out to now act as the new powder pathway through this component. For a visual of this, see Figure 20 below.

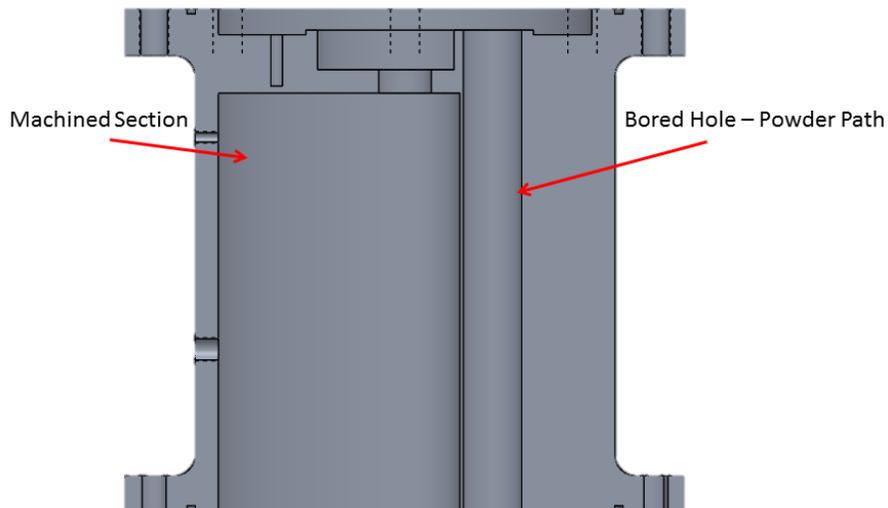


Figure 20 - Motor Housing Interior - Section View

4.4.6 Flat Plate and Other Mounting Options

Similar to the iterative design process of the other components, the flat mounting plate followed the same procedure. Two of the major changes occurred during the communication with the manufacturer. In order to ensure the safe and correct functionality of the design, it was imperative to include a tight flatness specification with an electroless nickel plating surface finish to the top and bottom faces of the mounting plate. These specifications were imperative to maintain the proper seal necessary for the design to be capable of operating at high pressures, as specified.

Including the flat mounting plate in the design has multiple advantages. Two of the major advantages of this configuration are that it is easy to expand upon and it provides multiple options for mounting. One of the major advantages to the powder feeder design as a whole is that it is capable of spraying more than one powder at a time which is desirable when the sprayed deposit is intended to be made up of a gradient of material. By having a this particular flat plate design, the user has the capability of spraying two different powders or to spray continuously by shutting off one side of the assembly and refilling powder while the other side runs. However, if the user desired spraying capabilities of more than two powders, the flat plate could easily be expanded to have the capability of spraying as many powders that the user desired. Aside from the multiple spraying capabilities, the flat base plate creates a centralized area for mounting. This is advantageous because it can be placed wherever is convenient for the user's system. It does not necessarily have to be mounted the way it is shown in our design. For example, if the user wanted to mount the hoppers on the top of the spray booth and have the mixing chamber inside the booth, this would be possible.

Support and Structural Changes

Due to changes made in the hoppers rotating ability extra supports were needed in the powder feeder. The threaded pipe that originally connected the mixing chamber was replaced with steel supports to better support the torque on the parts created by the rotation. In addition to that, support ears were added to the baseplate for increased rotational support. A visual of the support ear can be seen below.

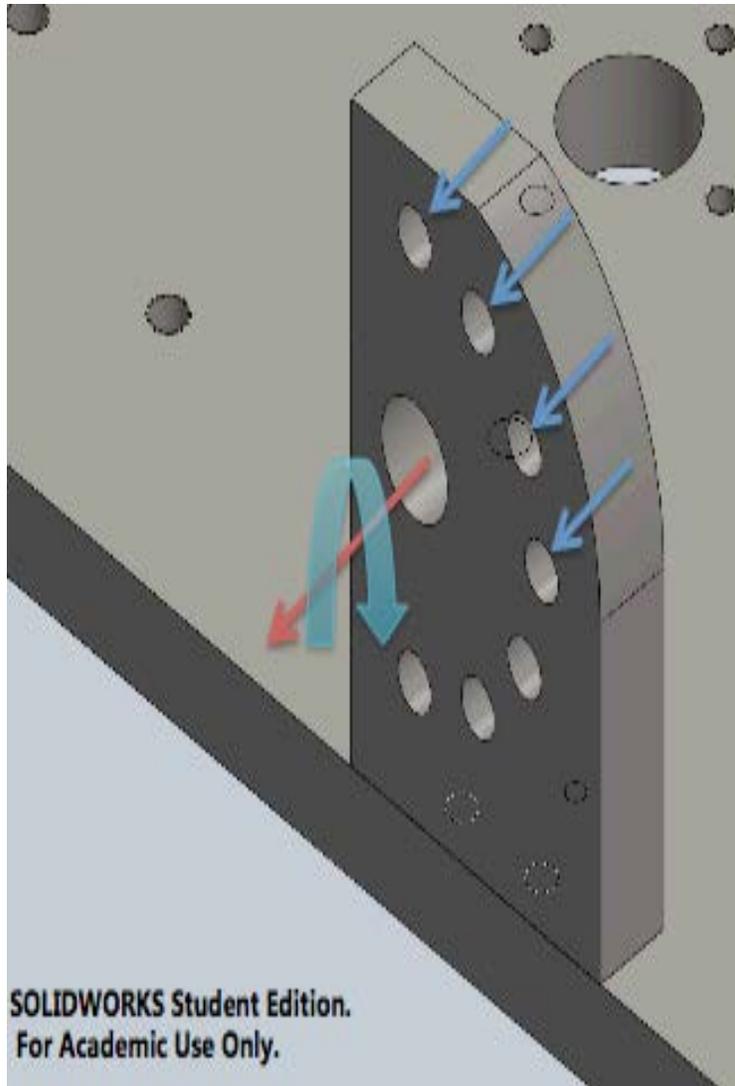


Figure 21 - Baseplate Support Ear showing axis of rotation for the assembly and locking pin holes

Other changes were made to the original threaded holes in the baseplate. These holes were made larger to accommodate steel inserts for increased strength over a lifetime from constant disassembly and reassembly.

4.4.7 T-Support and Stand Design

The T-Supports on both sides of the final assembly were designed primarily to provide structural support for the powder feeder. However, they additionally provide an axis for the powder feeder to rotate around. This is important in the preservation of leftover powder after a spraying process is completed. The T-Supports also feature a hole for a locking pin location. This locking pin has a number of different angles that it can hold the powder feeder at due to the “ear” attachment on the flat base plate. The locking pin location and the “ear” attachments can be seen below in Figures 22 and 23.

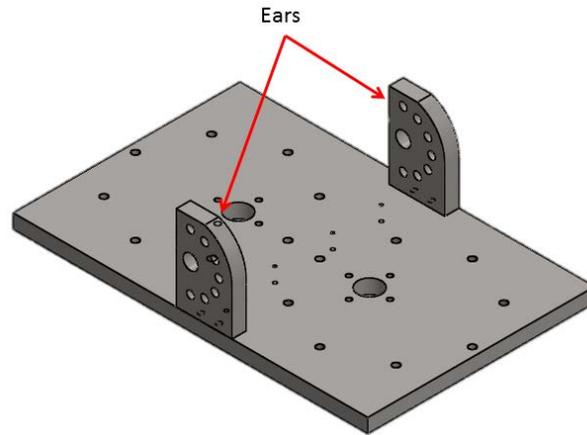


Figure 22 - "Ear" Locations showing axis of rotation for the assembly and representing where they will be attached in the final assembly

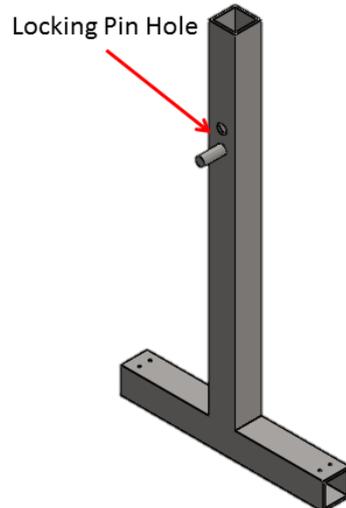


Figure 23 - Locking Pin Hole Location to allow for controlled rotation and locking of the assembly in different angular positions

4.4.8 Powder Delivery to the Mixing Chamber

The steel pipe connection that connects the motor housing were designed to provide a pathway for the powder to reach the mixing chamber, to provide a shut off to the mixing chamber, and to ensure proper pressurization of this portion of the system. The powder flows down out of the motor housing and into the pipe connection which takes it through a ball valve and ultimately into the mixing chamber. This pathway is vertical to decrease the possibility of the powder getting stuck to or conglomerating on the sidewalls of the pipe. Additionally, the pipe connection has a ball valve to make it possible to shut off one side of the system. This allows the user to depressurize half of the system to add powder while allowing the other side to continue feeding powder to the mixing chamber. The pipe connection features a flange with an O-ring groove to ensure proper sealing of the connection when the system is operating at high pressures. To

ensure that the pipes are not load bearing, additional support beams were added to the mixing chamber that bear the load. The pipe connection in its place in the assembly can be seen below in Figure 24.

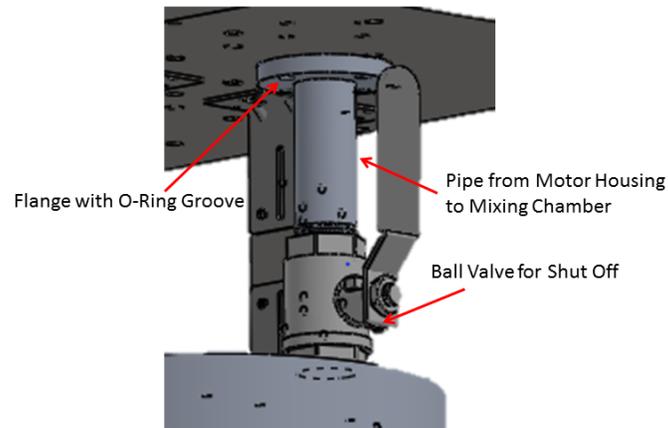


Figure 24 - Pipe Connection and Components

4.4.9 Mixing Chamber Design

The mixing chamber is used to blend the powder from the two hoppers prior to the powder exiting to the nozzle. The chamber went through design changes such as added fillets, steel thread inserts, and dimensional changes. Fillets were added in two locations that experienced repeated tensile loading to reduce the stress concentrations. These locations can be seen in Figure 25 below.

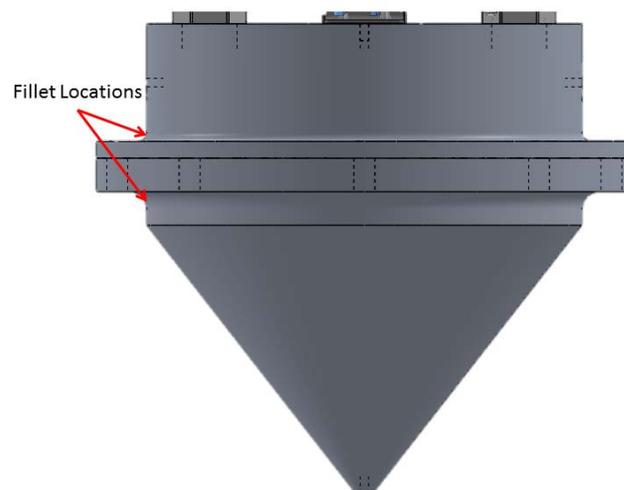


Figure 25 - Mixing Chamber Fillets on parts made of 6061 Al

The steel threaded inserts were introduced to this portion of the design because of the wear concern on the aluminum threads. The frequent use of these threads during the assembly and

disassembly of the mixing chamber for cleaning purposes would lead to significant wear on the soft aluminum threads. The insertion of steel threads resolved this potential issue. The location of the steel inserts can be seen below in Figure 26.

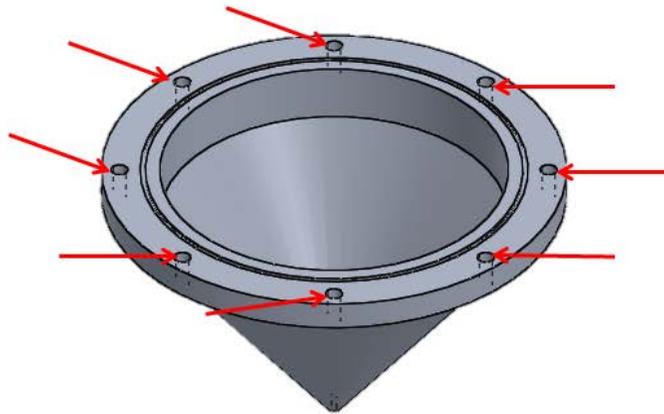


Figure 26 - Steel Thread Insert Locations - Mixing Chamber

The dimensions of the mixing chamber were based on the spacing between the two pipe connections. Bending of the pipes was a possibility but it was not chosen in order to minimize the wall contact of the pipes and the powder. The pipe connection spacing was influenced by how close the motor housings could be on the flat plate in which they were mounted on. Additional testing was done with other sizes of mixing chambers and they yielded no definitive results on the effect of the size of the chamber.

Chapter 5: Validation

Once the design was set, several of the critical components were tested. The following subsections describe the tests that were performed on each component and show the validation behind design decisions made in the iterative design process.

Section 5.1 Pressurization and Load Handling Validation

Each component in the design that was intended to handle a pressure or resulting load was analyzed using FEM software included in the SolidWorks package. Based on stress concentrations that were observed in the software, changes had to be made to the design so that the material each component was being made of could safely handle its loads. Some part geometries were changed and many flanges were added to reduce these stress concentrations. An image of such changes can be seen below.

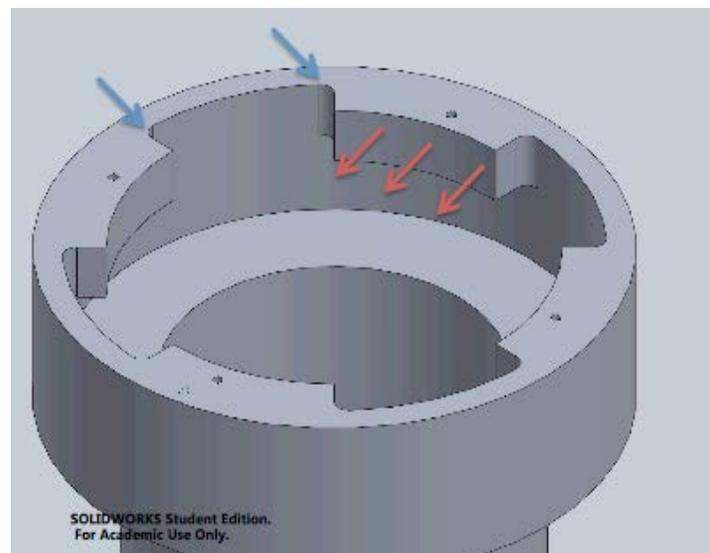


Figure 27 - Altered Hopper Geometry to hold 600 psi pressure with 6061 Al

Similar analysis on the mixing chamber led to geometry changes as well. The image of the FEA results can be seen below.

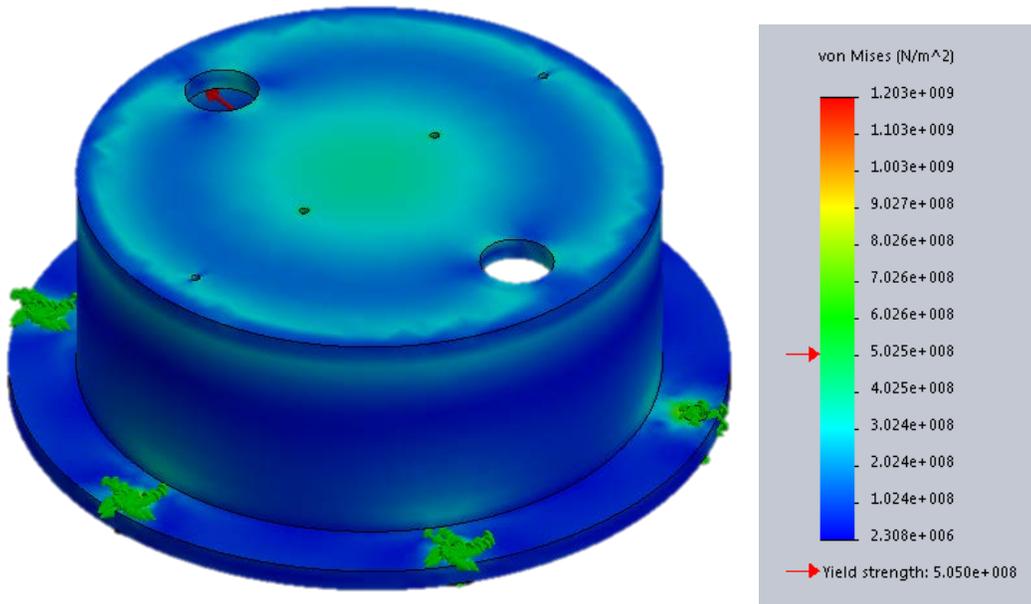


Figure 28 - Mixing Chamber Top FEA showing stress does not exceed yield strength of 6061 Al

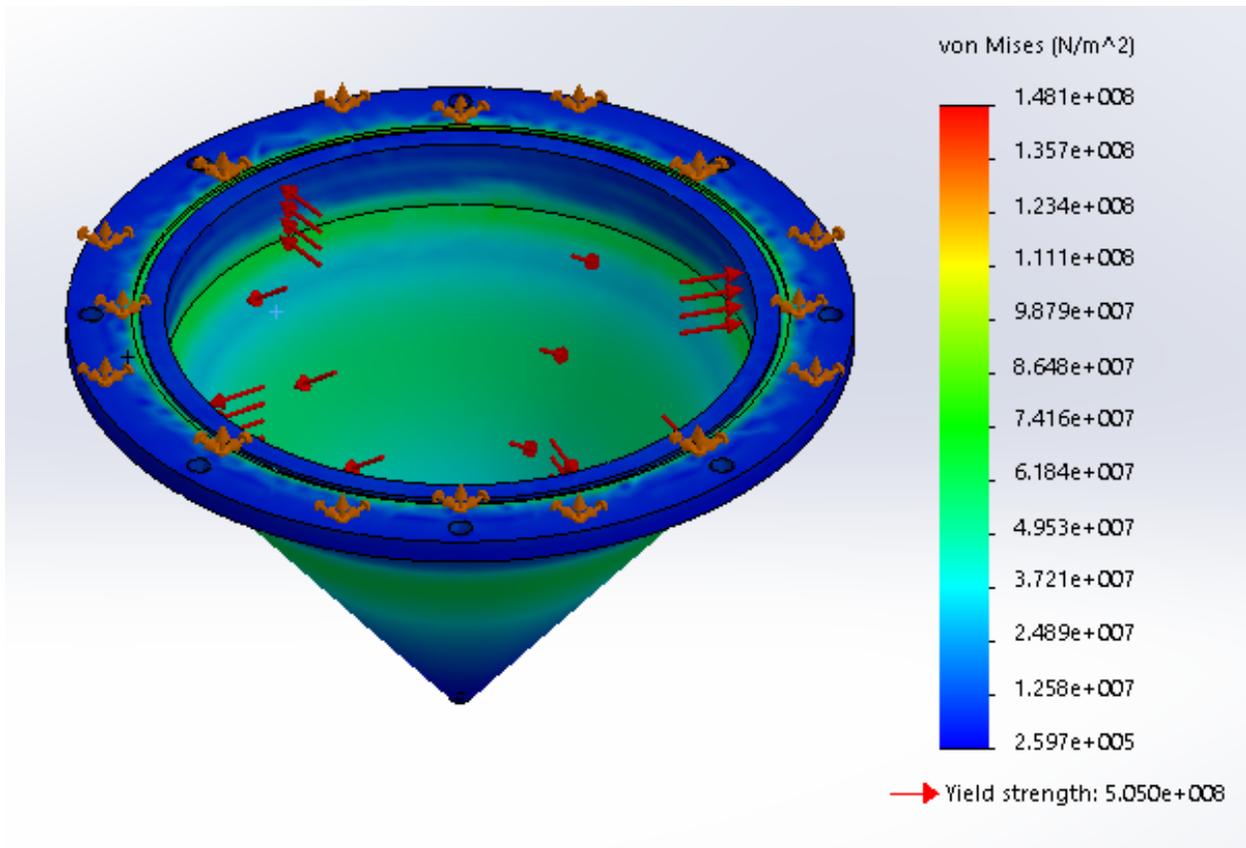


Figure 29 - Mixing Chamber Bottom FEA showing stress does not exceed yield strength of 6061 Al

When originally working with the model shop it was determined that the mixing chamber parts and the hopper could not be made out of the specified material, the geometry was subsequently changed to accommodate.

The finite element method was also applied to the baseplate to make sure it could withstand the load of the considerably heavy assembly. The results for which can be seen below.

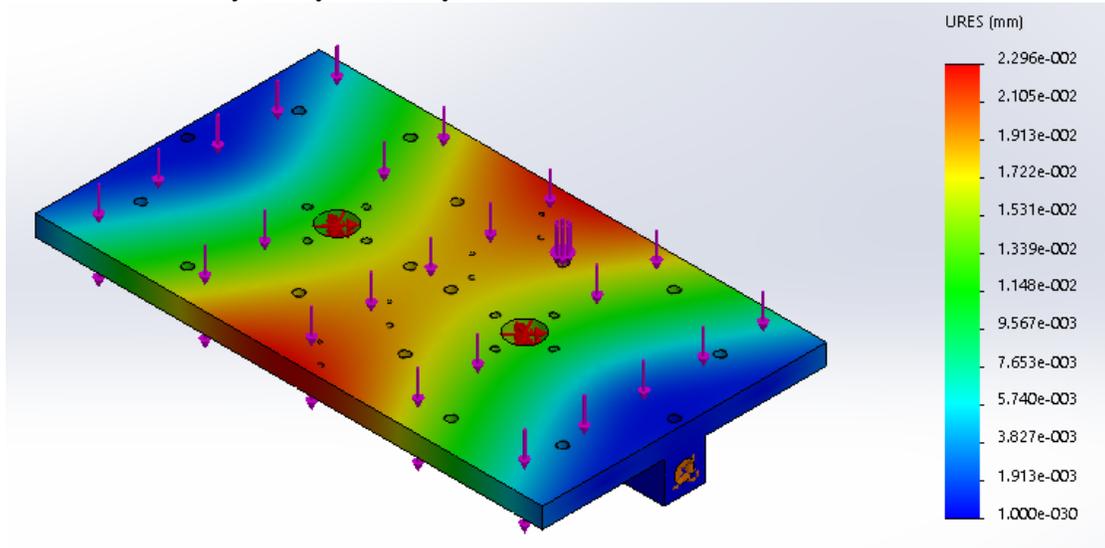


Figure 30 - Baseplate FEA showing stress does not cause significant deformation of the steel

A center of gravity analysis was also applied to the base plate due to the fact that it rotates around to allow for better access during maintenance. After the center of gravity was found it was determined to be close enough to the axis of rotation to allow for safe and practical maintenance. The center of gravity analysis was completed for an empty hopper under the assumption that at the time rotation is needed, the hopper will be almost, if not completely, empty.

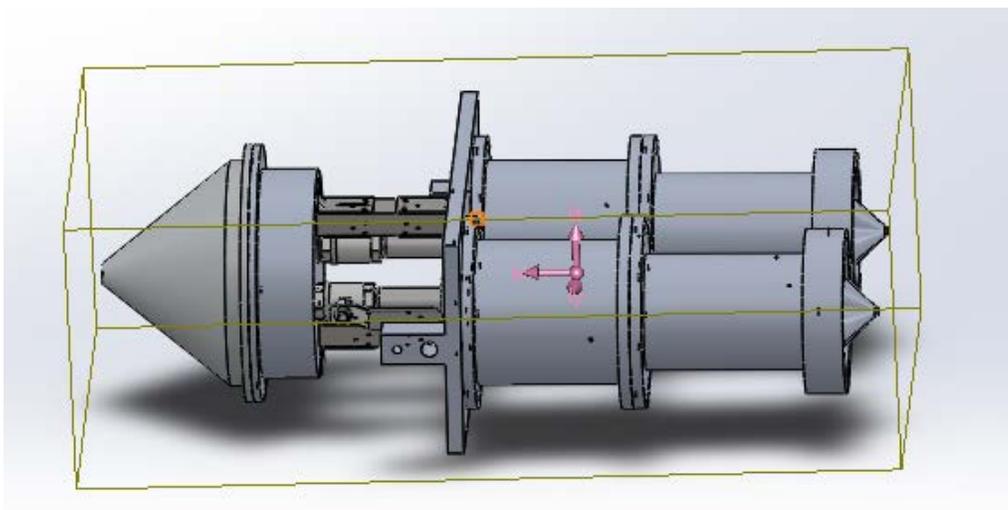


Figure 31 - Center of Gravity during Rotation of Feeder

Section 5.2 Hopper Testing

When it comes to the hopper, two things needed to be tested. The first was the angled surface down to the disk. The powder needed to flow freely over the surface finish and angle in order to allow for continuous operation. The other aspect of the hopper that needed to be inspected is the “rat-hole” effect that Jenike and Johanson informed the team about in which the feed mechanism design creates a selection bias of powder by its position in the hopper.

5.2.1 Analysis of Hopper Geometry and Flow

In order to be confident with the interior hopper geometry design, there was a need to simulate powder flow within the hopper. To do so, anodized aluminum sheets were ordered that had a coefficient of friction similar to the 6061 anodized aluminum that will make up the final machined hopper. The sheets ordered had a thickness of 100 μm and could be easily molded into three simulation hoppers of different angles. The reason for testing and not instantly designing a hopper with an extremely steep pitch is because a steeper pitch removes a large portion of the possible interior hopper volume capacity.

The aluminum sheets were cut into three different hopper pitch selections, 30°, 45°, and 60°. The hopper geometries were then assembled with the most effective rotating disk determined by testing and mass flow calculations. The following preparation and analysis was conducted for each of the three hopper geometries.

A constant, predetermined amount of 25 grams of new Ti-64 was poured into the hopper and disk assembly. From a stationary position each hopper was loaded and the powder was dispersed evenly over the top surface area. The motor was then run at a slow, constant speed of 5 rpm until the inlets were no longer being filled completely. In true operation conditions spraying would cease at this point. During testing, funnel flow was observed clearly in the 30° simulation hopper, as rat holing started almost immediately (Figure 32). Although this may not seem important 360° of the cone around the hopper exit has agglomerated powder surrounding it which accounts for a large amount of powder not being sprayed. If the hopper was filled to a capacity of 5 kg of powder, all the stagnant powder touching the interior walls would not be sprayed. This can lead to several issues including the creation of uncertainty with the powder size distribution leaving the hopper. Additionally, the rat holing present in the 30° could result in over fluidization of the center powder and fines, which can easily lead to a dumping effect within the system.

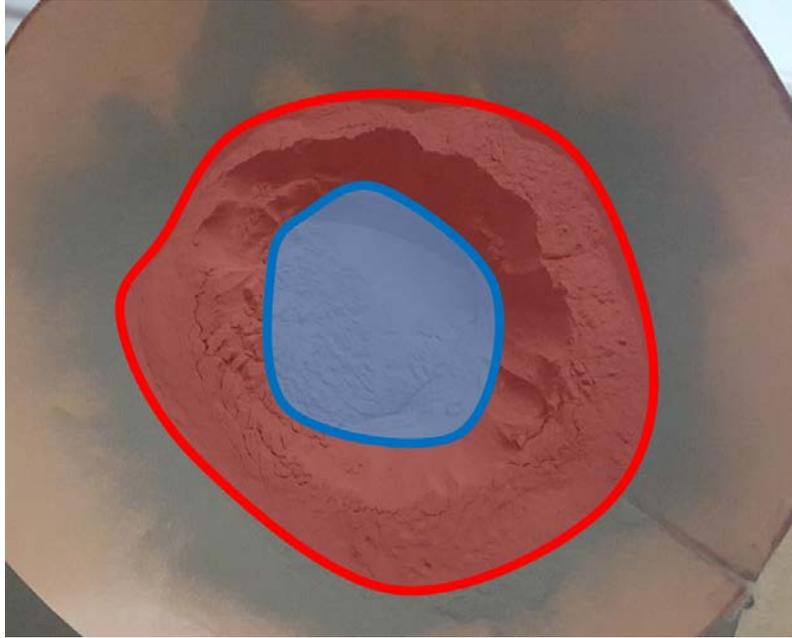


Figure 32 - Rat Holing effect in 30° hopper setup. Red shaded area contains larger, left behind powder particles. The blue shaded area shows where the smaller, fluidized powder particles exiting through a central canal

With each hopper setup, as the powder remaining became low, it conglomerated toward the inside of the hopper exit circle because nothing was pushing it from leaving there. Both the 45° and 60° pitch hopper setups produced very close to mass flow instead of funnel flow. This was evident due to the powder left stuck to the anodized aluminum surface area once the motor was turned off. With all of the pitch arrangements, a very thin layer of powder stuck to any exposed cone surface area. This remaining powder is unavoidable due to atmospheric humidity, and because the powder had been outside of an inert environment. However, with all pitches the powder that gets stuck or left towards the inner edge of the hopper exit circle is shown in blue below in Figure 33.

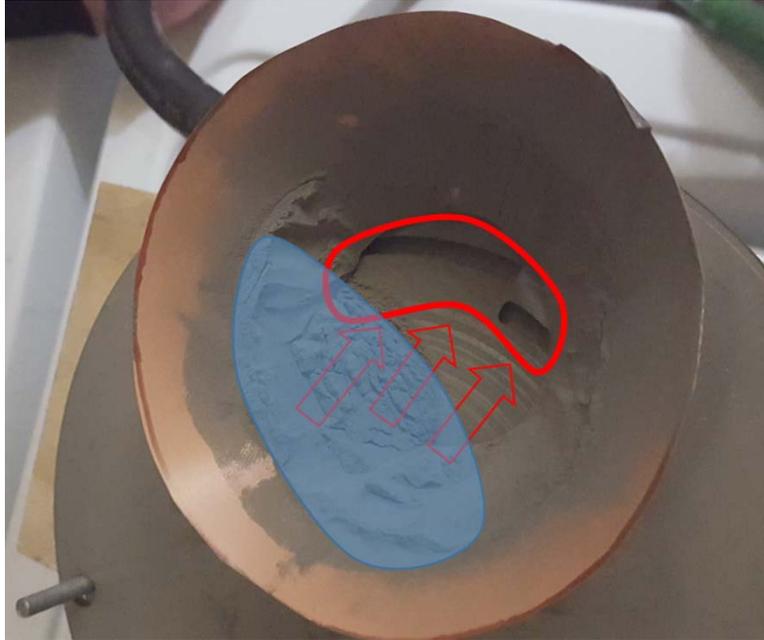


Figure 33 - Powder that cannot be sprayed is shown in blue, proposed new hopper exit shown in red

The entire hopper pitch analysis study confirmed the fact that rat holing can occur if the selected hopper interior does not have the correct pitch and surface finish. From the post testing photos shown in Figure 34, it is easy to tell which powder was flowing during rotation. Both the 45° and 60° allowed the powder to exhibit mass flow and keep the size distribution leaving the hopper similar to our predicted values. The final ordered hopper has a pitch of 45° because it displayed almost the same flow characteristics as the 60° pitch. By preventing rat holing and keeping mass flow within the hopper, powder feeder cleaning is drastically reduced, mass flow predictions are more accurate, and powder waste is minimized.



Figure 34 - Pictures taken once all powder was done flowing and the motor was turned off. Notice a large difference between the 30° and 45° but little change between 45° and 60°. The disks are highlighted in yellow to differentiate between remaining powder and the disk..

The hopper flow analysis examined powder that is moving so little that it can be considered static. However, the crucial aspect of a powder feeder is its ability to effectively dispense mass based on the operator's inputs. Using known rotating disk inlet geometry and an accurate step motor, powder distribution can be accurately predicted and controlled.

Section 5.3 Motor Control and Rotating Disk Testing

The rotating disk designs had two facets to its testing. The first was wear testing because the disk is designed to rotate between two other flat surfaces that it is in contact with as well as has metallic powders flow through it. The second set of tests run on the rotating disk designs tested the flowability of powder through our different disk geometries to test how different powders could flow through the rotating disk assembly. Data observed in these tests included mass flow control with the disk geometry compared to the theoretical mass flow we should get with a certain powder and disk and the amount of pulsation the geometry allowed.

5.3.1 Motor Control Testing

The motor controls needed to be set up and tested before the plates could be assembled and powder was run through the system. The setup, shown in Figure 35, incorporates the connection of a laptop running the motion software which can control the motor by speed, index and/or position. The drive runs on 240V A/C power with the backup power source being run through a power supply that converts 240V A/C to 20V D/C. This 20V D/C power supply runs the computer chips in the drive as well as being used for program start and emergency shutoff switches. These requirements followed warnings shown in the motion software of low voltage when the motor was being run on 120V.



Figure 35 - Motor Control Setup with computer running included driver software

This testing setup allowed for control of the speed of the motor and for confirmation of actual rpm compared with input rpm through marking a disk and counting rotations through a period of time. The motor was not extremely accurate at the low speeds needed for running the powder through the disks, but the speed stayed constant through multiple trials. This meant that for testing with the disks, the counted values of rpm would be used instead of input values. When a gear box is added to the motor, it will allow for more accurate control at lower angular speeds.

5.3.2 Testing of Plates

The testing of multiple rotating plates with different slot geometries was essential to determine optimal flow of powder from the hopper, around the disk assembly, and into the mixing chamber. The disks were tested with the motor and control panel setup in addition to a structure

used to hold the motor in place and held the disks in the correct location to be rotated by a 3-D printed drive shaft used only for testing purposes. On top of the rotating disk assembly the hopper was simulated by a representative hopper used for testing and allowed visual analysis of what was occurring inside the hopper during operation. This testing setup is shown in Figure 36.



Figure 36 - Setup of Motor, Disk Assembly and Hopper for Testing

This setup allowed for the testing of the different plate geometries and analysis of the powder flow through them. From visual analysis during the testing of each disk, the best disk geometry was the thicker, normal geometry shown in Figure 37a. This disk had the smoothest and most continuous stream of powder exiting the rotating assembly. Although the other disks had mostly smooth flows when tested with metal powder, it was clear that they were not optimal during testing that consisted of running corn starch through the assembly. Corn starch has similar flow characteristics to some of the more sticky powders that can be used in spraying operations. Both the thinner, normal slotted geometry, Figure 37b, and the tapered plates, Figure 37c, had extremely pulsed flows and did not even drop most of the powder when the slot passed over the exit hole of the assembly.

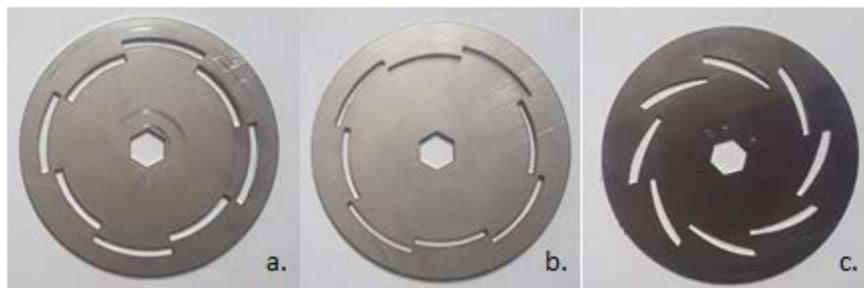


Figure 37 - a. Thick Normal Disk b. Thin Normal Disk c. Tapered Disk

Another observed benefit of the normally slotted disks was observed when there was a limited amount of powder left in the hopper. As a result of the slots passing through the outer side of the hole at the bottom of the hopper and the forces exerted on the powder by the rotating disks, there is an extremely small amount of powder that may be left in the hopper after the slots stop

completely filling up. This phenomenon is explained with a picture of the bottom of the hopper and the disks, shown in Figure 38.

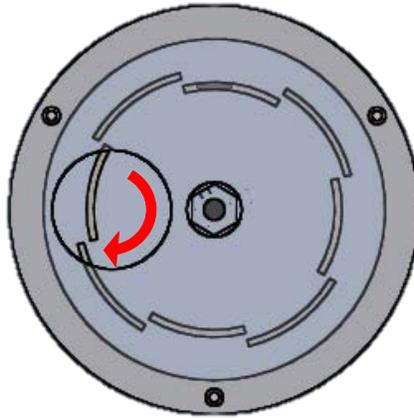


Figure 38 - Flow of Powder into Slotted Disk when limited powder is remaining in the hopper

This effect caused by the forces of rotation limit the “rat-hole” effect sometimes seen when a large area of material is excavated from a hopper by a smaller area exit mechanism. The tapered disks were created in the hopes of eliminating this effect but they had a negative effect and resulted in a larger amount of powder left in the hopper at the critical time when the slots no longer are completely filled with powder before rotating out of the entrance point of powder.

5.3.3 Mass Flow Rate Analysis

The most important function of the geometrically slotted rotating disks is to be able to accurately control mass flow rate. This is accomplished by knowing the volume of each of the slots around the rotating disk and controlling the speed of the motor to alter the mass flow rate. The apparent density of the powder being sprayed also needs to be known to convert volume of the slots to mass of powder contained in each slot. Intuitively it is clear that the faster the motor rotates, the more powder will be introduced into the system through the main gas stream. The accuracy of the disks needed to be tested so that the theoretical mass flow could be confirmed. Table 4 below gives the theoretical values of mass flow rate in grams of powder delivered per rotation of the disk. The theoretical values are compared with multiple test values in Figure 39 which shows the theoretical value in blue next to the average test value in red. The equations used to determine these theoretical mass flowrates are given below. The first is a generic form used for complex disk geometries and the second is geometry specific to standard slots. The green column represents the range of measured mass values from the highest to lowest values.

Table 4 - Theoretical Mass Flow Values

Geometry	Thick Normal	Thin Normal	Tapered
Theoretical Mass Flow Rate (g/rev)	9.65	6.5108	6.51

$$\text{Mass flowrate} \left(\frac{\text{grams}}{\text{second}} \right) = \rho \left(\frac{\text{grams}}{\text{volume}} \right) * \text{slot volume} \left(\frac{\text{volume}}{\text{rotation}} \right) * \omega \left(\frac{\text{rotations}}{\text{second}} \right)$$

(eqn. 2)

$$\begin{aligned} \text{Mass flowrate} \left(\frac{\text{grams}}{\text{second}} \right) &= \rho \left(\frac{\text{grams}}{\text{volume}} \right) * \text{width}(\text{of slot}) * \text{thickness}(\text{of the disk}) * 2 \\ &* \text{radius}(\text{center of disk to center of slot}) * \pi * \omega \left(\frac{\text{rotations}}{\text{second}} \right) \end{aligned}$$

(eqn. 3)

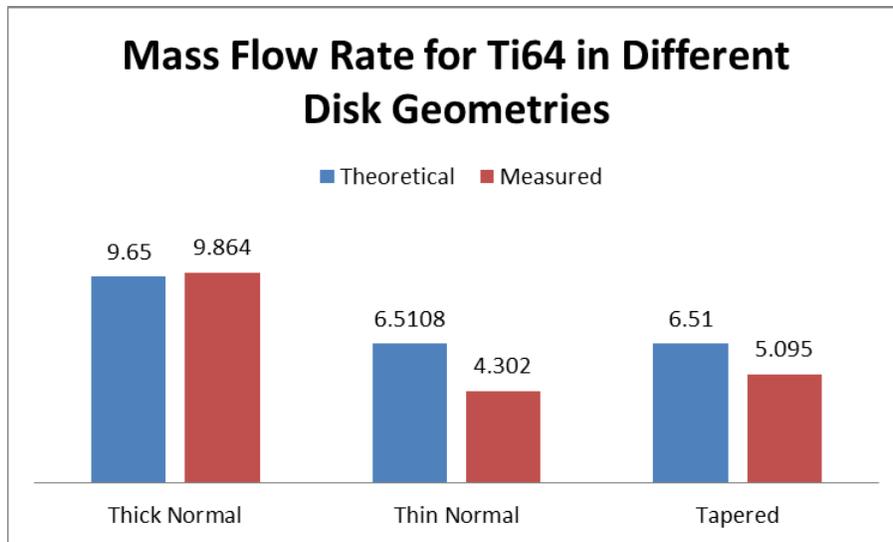


Figure 39 - Theoretical and Measured Mass Flow Rates with Range of Measured Values

It is clear that the thick normal slotted disk has the most accurate and precise mass flow rate for the powder tested. The slight difference between the theoretical value and measured values is most likely a result of a slight delay in stopping the rotating disk at the exact moment the end of the test was intended to be. Considering this slight error, the precision of the measurements is quite impressive with a range of less than ± 0.05 grams per revolution of the disk. The other disk

geometries were not nearly as accurate when compared to theoretical values of mass flow rate. This is most likely a result of not all the powder falling from the slots when they pass over the exit region of the disk assembly.

Section 5.4 Simulation of Gas and Particle Flow in the Mixing Chamber

In order to determine mixing and distribution of powder particles within the mixing chamber portion of our powder feeder, analysis needed to be performed on the flow of gasses and powder particles through the chamber. Using SolidWorks flow analysis and particle simulation tools the expected boundary conditions were defined, then a particle distribution which was found to be common among some titanium powder samples was introduced. After running the simulations, videos were created that illustrated the predicted particle flow under different inlet configurations. However, the simulations only gave this qualitative measure of mixing through looking at the different flow patterns and seeing which ones appeared to mix well. By just watching the videos, it was impossible to tell which had better mixing capabilities beyond pure visual intuition. This left the challenge of figuring out how to quantitatively measure the mixing and distribution of the powder particles.

The first thought to measure the distribution was to utilize image or video analysis tools, such as *ImageJ*, to create distributions for the particles exiting the mixing chamber. These distributions would then be compared to the inlet distribution to ensure incoming particles were not getting caught up in the chamber. Unfortunately, these image tools only work in two dimensions and are unable to account for small portions of particles that are mostly hidden behind other particles. Even when multiple shots from a quick time range are analyzed, the hidden particles remain mostly hidden and sometimes even eclipse completely behind other particles as they approach the exit of the chamber. For this reason, the analysis needed to be completed by human eyes. The first way that this was completed was to draw a line near the exit of the chamber which was determined as a critical level under which all particles were heading directly to the exit of the chamber. Then the videos were played in super-slow-motion multiple times so that each size range of particle crossing into the critical level could be counted accurately and recorded. A time chunk of 15 seconds per video were analyzed at a speed 25% of normal speed. It was determined that this speed allowed for accurate counting of particles and a time frame that did not result in a loss of attention by the end of the slowed simulation. These results are shown below in the graphs with the names of the distribution alone. The second method used to analyze the distribution again used the critical region in the chamber, but this time the video was paused at specified time intervals and each size range of particles within the level was counted and recorded. The best distributions from this analysis are shown below in the graphs with the names of the distribution and (2) below in Figure 40. Additional distributions can be found in Appendix A. The names of the best distributions are described in images included in Figure 41 with additional descriptions in Appendix B, but follow the general form below. In the figure the red arrows symbolize locations of gas inlets into the chamber.

[Number of Gas Inlets] [General Description of Inlet Layout]

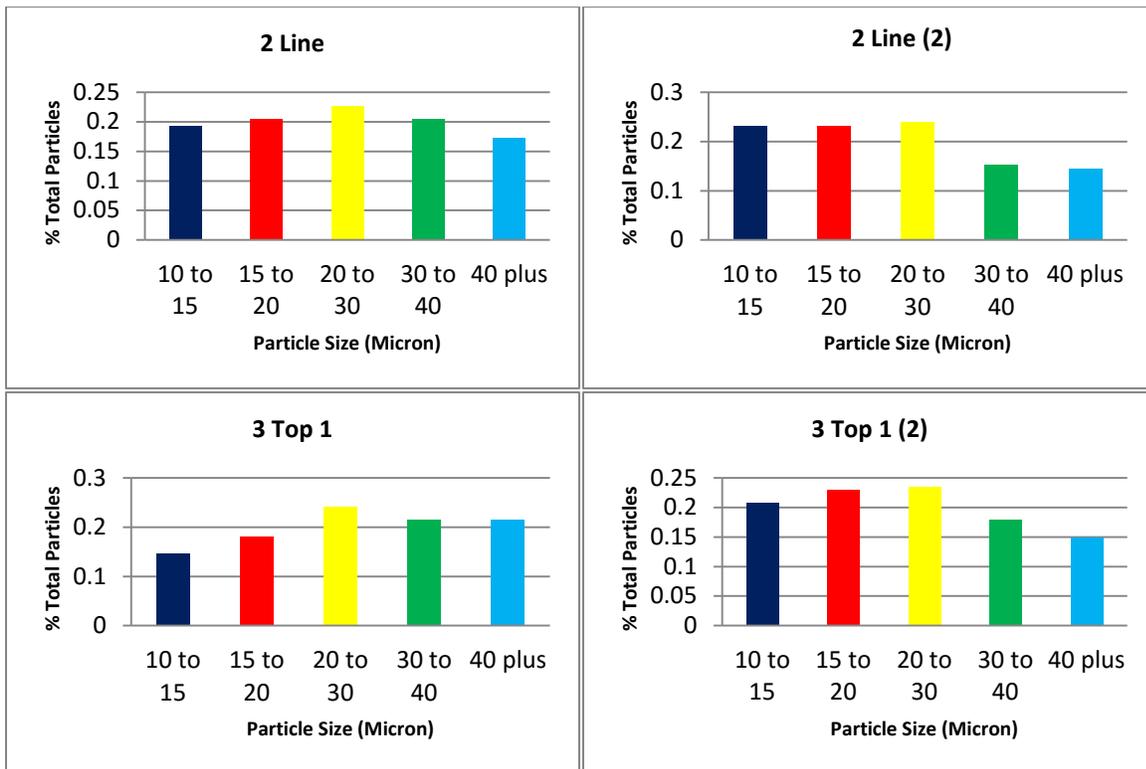
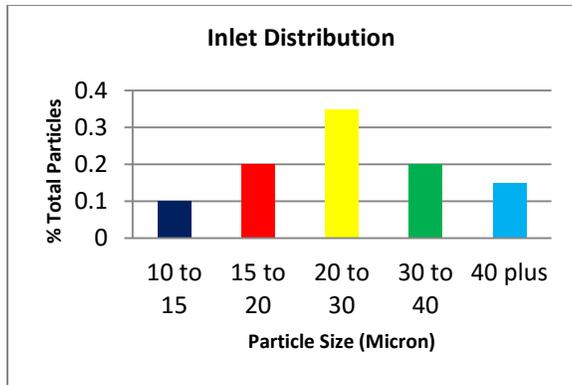


Figure 40 - Particle Flow Distributions

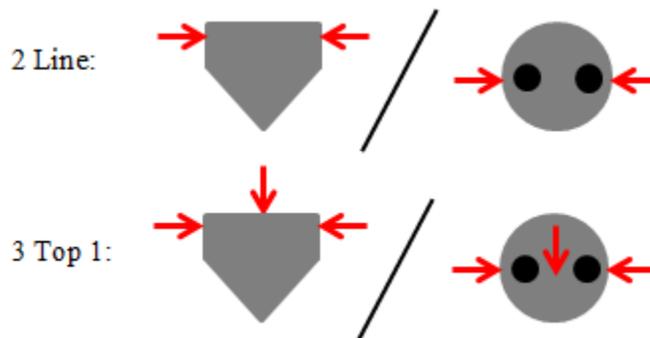


Figure 41 - Configuration Descriptions

When analyzing these created distributions, it was observed that some of the distributions taken from the same mixing chamber configurations did not exactly match up. When examining why this was the case it was determined the differences in the data came from the difference in analyzing a video versus a still image. In the setups with drastically different distributions, one or more of the size ranges was moving much slower but with a higher flow density through the critical region when compared to the other size ranges. The video analysis for this situation could show the same number of particles for a very dense slow stream of particles as for a less dense but faster stream. In the still version of the analysis, the dense, slow stream would account for a higher number of particles than a less dense but fast stream of particles. When taking this all into account, the best mixing chamber setup appears to be “3 Top 1” which has a similar distribution in both cases when compared to the inlet distribution. This means that this setup leads to each size range traveling well through the chamber and no size range traveling substantially faster or slower than the other size ranges.

In the complete set of distributions shown in Appendix B, the results vary drastically between different configurations and no configuration is exactly the same as the inlet distribution. The distributions that are radically different all show certain particle sizes that get hung up in the chamber during the simulation. Extreme cases of this were found in configurations that are not included in this report because of multiple particle ranges and in some cases even all of the particles got caught up in the chamber and did not exit. Descriptions of these cases can still be found in Appendix B and are titled the Cyclone Group. In the configurations that result in close distributions to the inlet but not exactly identical distributions minimal particle hang up is seen in the chamber. The differences could come from particles that are not visible exiting the chamber from the two dimensional view. They could also be a result of the minimal particle hang up seen during the mixing process.

The lack of a distribution that appeared close enough to the inlet distribution led to further research into additional testing methods. After this additional research into the computer software and the tools being used to simulate the fluid and particle flow, it was determined that the software also kept track of some valuable statistics. After each iteration of the simulation the SolidWorks package recorded the trajectories, travel distance, resonance time and fate for each individual particle starting location. The statistics that were determined to be most important were the resonance time of the particles, or how long they were actually in the mixing chamber, and the fate of the particle. The fate of the particle is a qualitative measurement whether or not the particle exited the mixing chamber within the computational domain of the simulations. The box and whisker plot shown below in Figure 42 depicts the spread of resonance times for each mixing chamber setup.

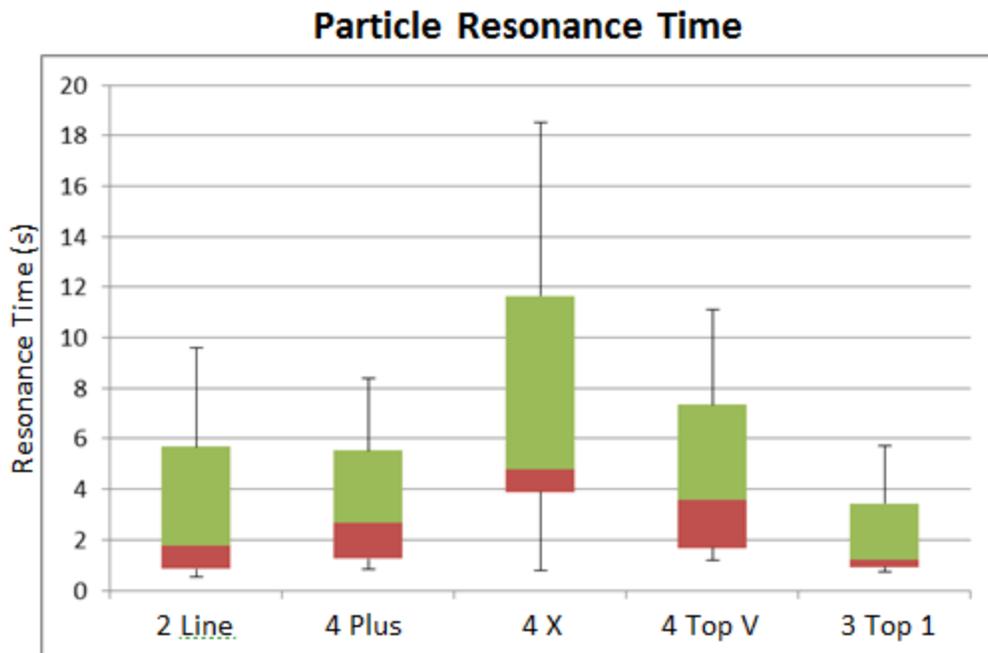


Figure 42 - Resonance time of particles in mixing chamber configurations

The center rectangles in this plot account for the middle 50% of particles for each configuration and the split between red and green depicts the median resonance time. The top whisker shows the maximum particle resonance time and the bottom shows the minimum. With this more reliable form of testing, the configuration titled “3 Top 1” still appears to be the most efficient option. It has the lowest maximum resonance time and most of the particles are skewed towards the shorter times in the mixing chamber. In addition this configuration had the highest percentage of particles with the end condition of exiting the mixing chamber. All configurations had at least some particle hang up that resulted in particles not reaching the exit before the computation done by the software package ended. “3 Top 1” resulted in 94% of all particles entering the mixing chamber reach the exit before this critical simulation maximum time. The resonance times for “3 Top 1” are consistent between different particle size ranges.

Through all analysis it has been determined that “3 Top 1” is the most efficient and effective mixing chamber configuration that has been analyzed. During the first visual analysis to attempt to classify the amount of mixing occurring in the chamber, it was decided that the flow patterns within this configuration showed the best mixing without extreme amounts of particle hang up. In the video and still analysis through counting the particles, the distribution seen exiting the chamber in “3 Top 1” most closely resembles the distribution entering. Lastly, the statistics computed by the program in the simulation show the best configuration again to be “3 Top 1.” Below on the left is the simulation of “3 Top 1” next to the simulation of “4 Top V”. The figures show how the particles mix better in “3 Top 1” and there is significantly less particle hang up.

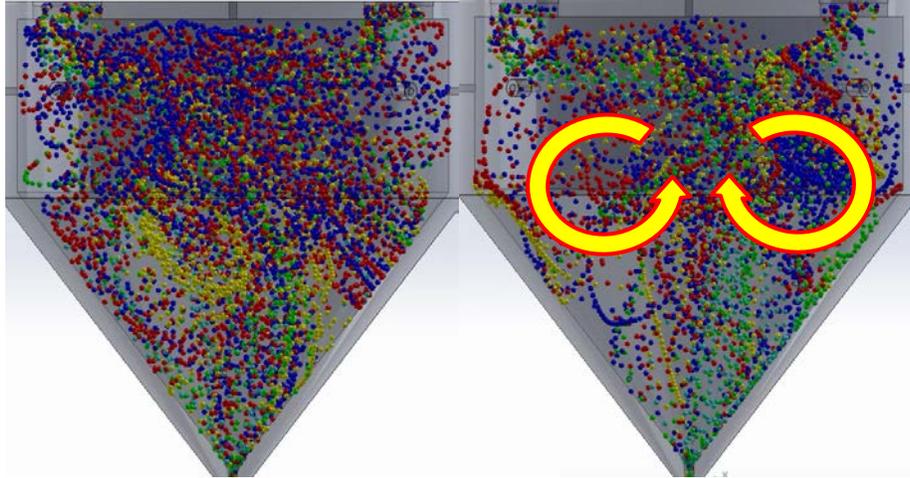


Figure 43 - "3 Top 1" (left) and "4 Top V" (right) Simulation Stills

Chapter 6: Conclusions and Recommendations

The design of a powder feeder system ended up being a much larger task than originally anticipated, but led to the learning of many lessons and ability to make numerous conclusions. Testing on components of the final design allowed educated decisions to be made about the design of the powder feeder as a whole and resulted in a design that when fully assembled will create new opportunity in the field of LACS.

Section 6.1 Conclusions

It has been concluded that an ideal angle for the flow of powder out of the hopper portion of the powder feeder is 45°. Testing revealed that as the angle of the interior hopper geometry was increased, mass flow became the prominent mode of powder exiting the hopper. The difference between stagnant powder left in the 45° hopper design and the 60° hopper design at the end of emptying was essentially the same. However the very slight advantage the 60° design had in amount of powder left over is completely eliminated by the drastic difference in capacity of the hopper to hold powder. The increased angle made for a hopper that did not hold the required volume of powder without severely increasing the height of the design.

Rotating disk geometries with constant radius holes and wide slots allow for the most optimal powder flow patterns. Although the initial hypothesis that tapered disks would solve the issue with rat holing of powder at the bottom of the hopper and thus result in better flow characteristics, the constant radius disks showed less of a rat hole effect. The wide inlets also reduced sticking which caused problems with some powders. The less flowable powders sometimes stuck to the walls of thinner cut inlets and did not drop over the designated exit location for powders from the disk assemblies. This showed that different disks could be used for different powders and the stickier a powder is, the wider the inlet geometry will need to be.

Slotted disk geometries allow the accurate control of volumetric flow rate which can be converted into mass flow rate with the apparent density of the powder. Mass flow rate testing with the rotating disks and motor assembly led to extremely accurate and precise results. The normally slotted disk with wider inlets gave a mass flow rate almost exactly the same as the theoretical value. More impressively the precision of mass flow rate between trials was consistent. The measured flow ended up being within less than ± 0.05 grams per revolution of the disk. With more than 9grams of powder exiting the disk on each of these rotations this small variation in mass is negligible when accounting for intrinsic human error in the testing.

Slotted flange through holes reduce assembly and cleaning time by eliminating the need to keep track of loose parts. The slots on the through holes allow for the assemblies to be taken apart without completely removing the bolts. The bolts only have to be loosened enough for a technician to rotate the slotted part and lift away that component. This will decrease assembly and disassembly time and make accessing parts to be cleaned much easier.

Steel threaded inserts increase part life expectancy and eliminate the need for nuts that could increase cleaning time. Similar to the slotted holes, these inserts take away the risk of losing loose parts during cleaning and will allow a technician to clean the inside of the powder feeder with ease. Steel inserts also create a stronger contact area with the steel bolts and have a longer part life expectancy for thread locations that will see repeated tightening and loosening.

The mixing chamber setup termed “3 Top 1” provides the best mixing of powders and keeps the most steady powder size distribution. All testing of the mixing chamber through SolidWorks flow and particle simulation pointed to the fact that this setup gave the most optimal flow characteristics. The visual analysis pointed to the fact that the flow within the chamber appeared to have the best flow patterns and had the least particle hang up. This setup also appeared to provide the best mixing of the 2 distributions of powder. A numerical analysis of the particles exiting the chamber also pointed to the number of each size range of particles exiting the chamber to be most similar to the distributions coming into the chamber. The statistics kept by the simulation software pointed to this configuration having the lowest particle resonance time as well as having the highest percentage of particles exiting the chamber before the computational domain of the simulation ended.

The new powder feeder design will open up opportunity for innovative applications through gradient or continuous spraying operation. The ability to continuously feed powder during a spraying operation allows for spraying large objects or even ingots of specialty materials. These specialty materials can be created through continuous spraying operations and eliminates the need for expensive heat treating operations that are currently being used to create these specialty materials. The ability to spray gradient materials is important for the bonding characteristics of sprayed samples and can even allow the spraying of ceramics onto softer metals. Gradient materials are important in a lot of thermally demanding applications such as layered fuel cells.

Section 6.2 Recommendations

Addition of a hopper attachment would allow for the inert insertion of powder into the powder feeding system. As powder processing becomes more and more important to attain optimal deposit characteristics, keeping powder in an inert environment until immediately before spraying has become an area for improvement in the powder feeder field.

Continue looking into powder pre-treatment operations to eliminate large and fine particles. In the simulation of the mixing chamber the fines as well as the larger particles were always the particles that got caught up in the mixing chamber and created issues with particles not leaving the chamber. These sizes of particles also do not always result in good bonding to the substrate so spraying them is not a necessity. Looking into treatment options to eliminate these particles before adding powder to the mixing chamber would solve several issues.

Development of a coating that reduces friction between the powder and walls of the hopper would reduce the need for cleaning between different powder spraying operations. Although there is currently minimal powder that sticks to the walls of the hopper, if a coating could be developed that eliminates this, cleaning the hopper could be an eliminated cost of production. This would also eliminate any lost powder within the system and save money spent on powder that is inevitably not sprayed.

Use of a less complex motor could reduce production cost of powder hoppers that use only variable speed rotation. The motor currently being used in this design is extremely powerful and able to perform operations not needed in a powder feeder. There is no need for an indexing motor that can keep control of its exact angular position. The only need of the motor for this design is a variable speed motor with relatively high torque capability.

Expansion of the number of hoppers in the assembly will allow for continuous, gradient spraying operations. The current design with two hoppers allows for gradient spraying or continuous spraying but not a combination of the two. Additional hoppers would allow for continuous gradient operations as well as a possibility for spraying gradient materials with more than two different powders.

A change of material for some components in this design could drastically reduce the weight of the final assembly. Although most other materials that could be used in this design are much more expensive than aluminum or steel, the weight of the final assembly is a concern. Lightweight engineering materials are constantly being developed and newer more expensive materials have similar engineering properties to aluminum and steel but a lower density that would result in a lighter assembly.

Section 6.3 Next Steps

Please see below for a Gantt chart of the team’s further steps of the project for March through May of 2016.

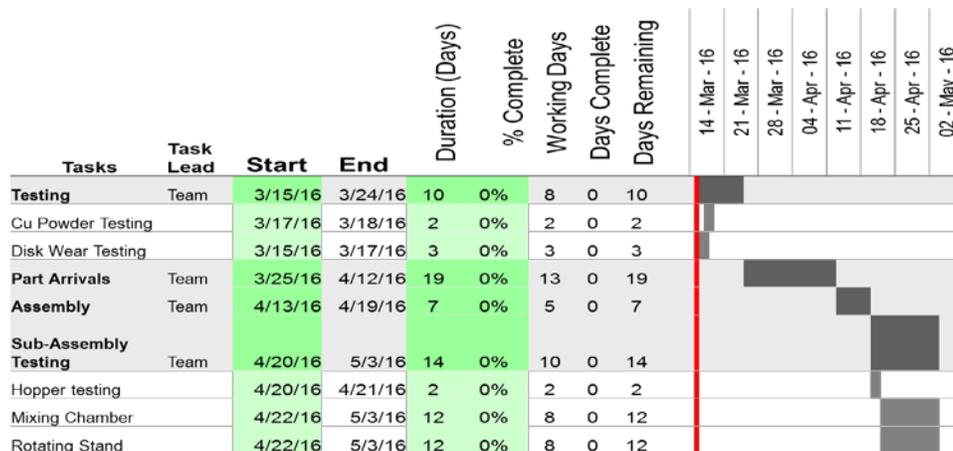


Figure 44 Gantt chart of future steps

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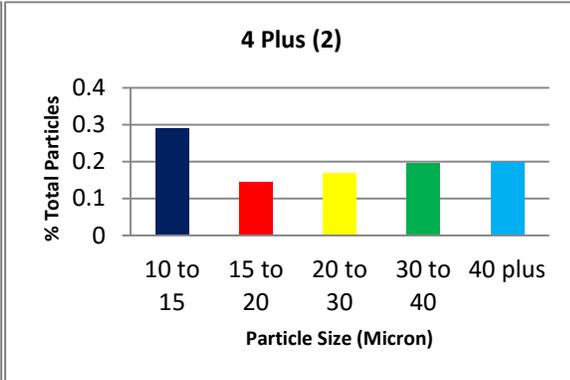
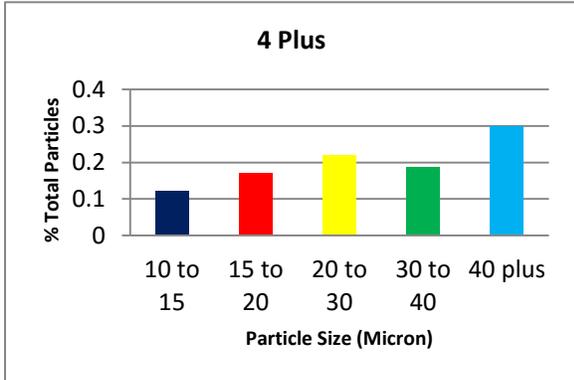
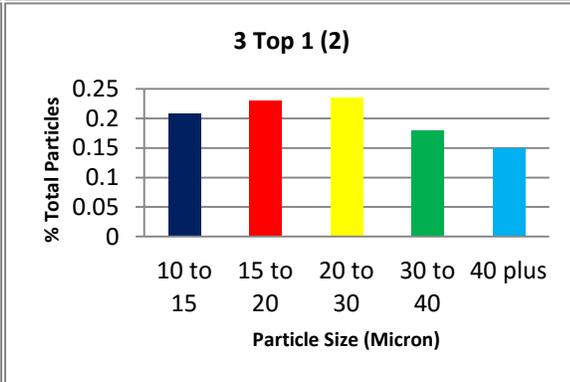
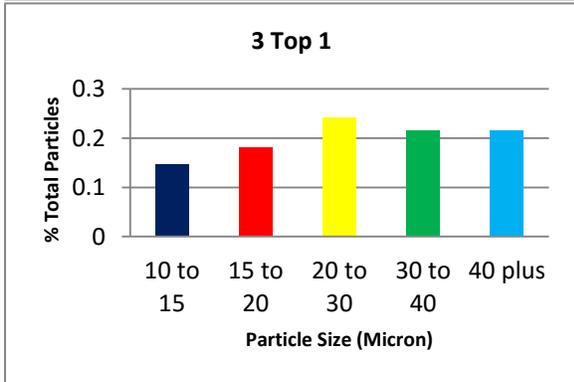
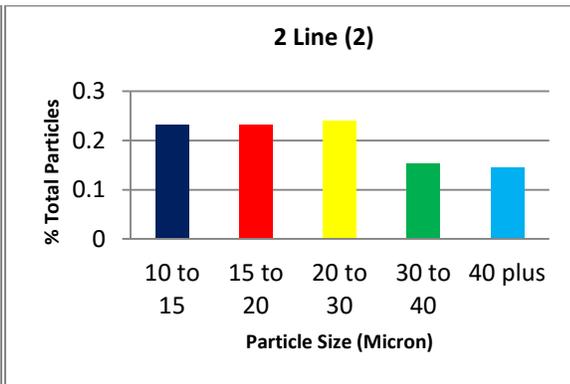
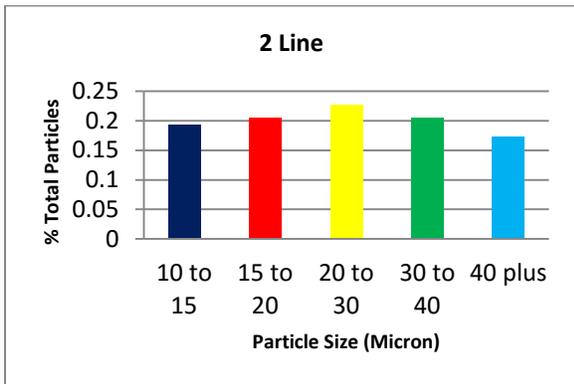
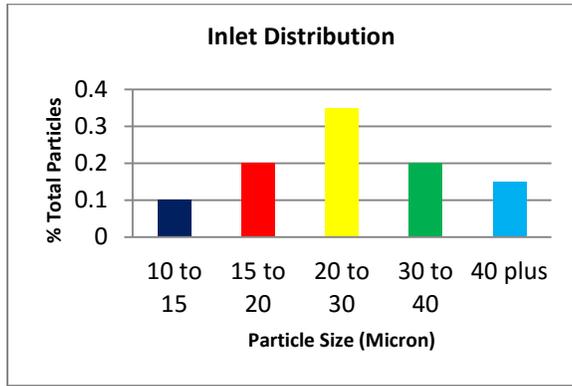
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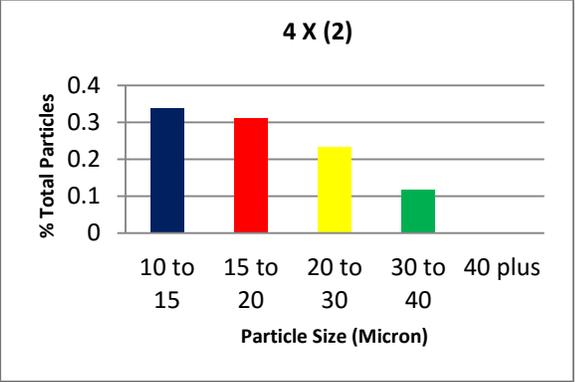
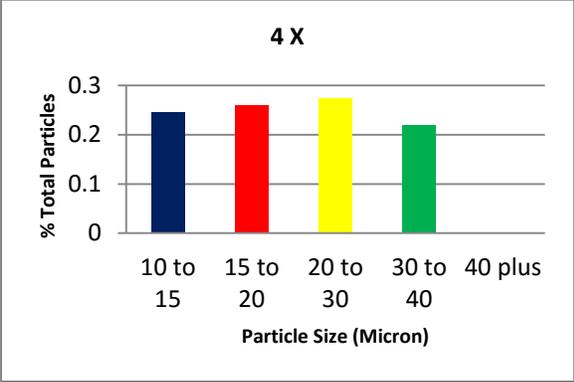
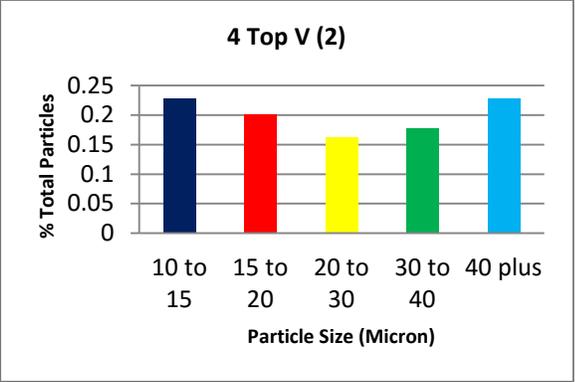
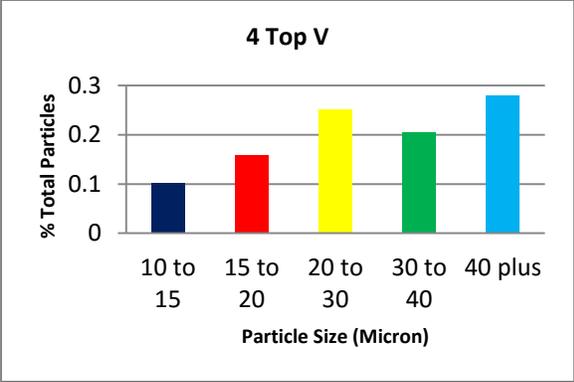
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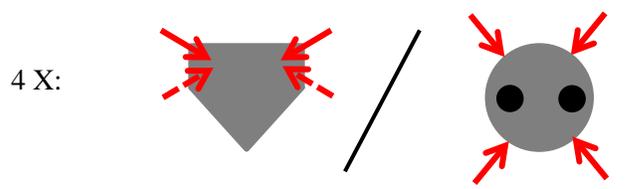
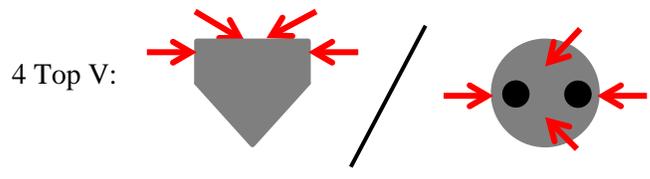
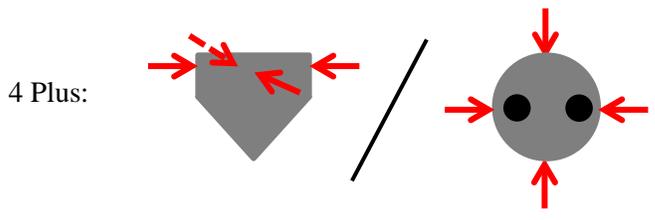
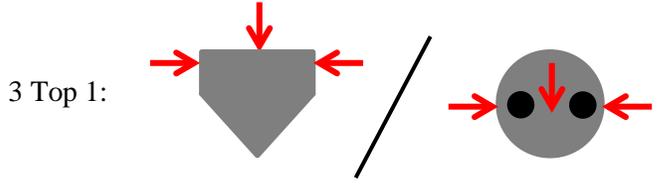
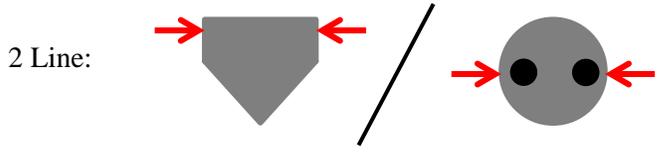
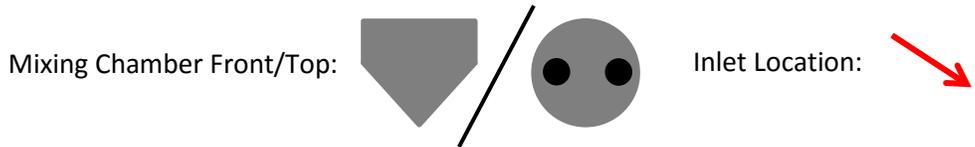
Appendix A - Particle Distributions





Appendix B - Gas Inlet Layouts

Key:



Cyclone Group:

