In-Situ Optoelectronic Powder Flow Measurement Analysis For Directed Energy Deposition Applications

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Directed energy deposition (DED) is a metal additive manufacturing method of creating parts by using a high-power laser to fuse powdered metals into fully dense three-dimensional structures. To ensure the geometric and mechanical integrity of the completed part, the powder flow rate of the DED system must be accurate and repeatable for manufacturability. Due to its opacity and reflectivity, one method of measuring powder flow is by utilizing an optoelectronic sensor. The sensor consists of a diode laser with a line generator that emits a thin defocused light sheet, a photodiode, and a set of lenses. The corresponding lens collimates the laser beam before passing through a transparent chamber where powdered metal is carried by argon gas flow. Due to diffusion, absorption, and reflection of the powder stream passing through the glass chamber, the amount of light detected by the receiving photodiode would change as the density of the powder changes.

Research carried out in the Advanced Research of Manufacturing and Materials Lab is in the process of developing a standard for the use of an optoelectronic sensor for measuring powder flow in DED applications. In-situ experiments used with an OPTOMEC 850M LENS powder feeder measured the mass flow rate of 316L stainless steel powder. The consistency of mass flow rates were monitored in order to develop a standard for the use of this sensor.
IN-SITU OPTOELECTRONIC POWDER FLOW MEASUREMENT ANALYSIS FOR DIRECTED ENERGY DEPOSITION APPLICATIONS

BY

MARK SLIKWA
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A THESIS SUBMITTED TO THE GRADUATE SCHOOL IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE MASTER OF SCIENCE

DEPARTMENT OF MECHANICAL ENGINEERING

Thesis Director:
Nicholas Pohlman
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DEDICATION

To my Shih Tzu Poodle, Oreo
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CHAPTER 1: INTRODUCTION

1.1 Metal Additive Manufacturing

Metal additive manufacturing is a new state-of-the-art and emerging field of manufacturing that has the ability to produce rapid prototypes through the means of 3D printing. More distinctively, directed energy deposition (DED) is a metal additive manufacturing method of creating parts by using a high-power laser to fuse powdered metals into fully dense three-dimensional structures. This type of additive manufacturing is primarily used for low-volume manufacturing of complex metal structures. Industries, especially in areas of automotive, biomedical, or aerospace, are in need of the development of the DED system. A general illustration for a DED machine (OPTOMEC LENS 850-R) is shown in Figure 1.

Figure 1. Schematic of the OPTOMEC LENS 850-R [1].
This type of machine is known as a powder feed system [1]. This system works by conveying powder through a nozzle that is typically determined by a set motor RPM. The motor of the powder supply determines the rate at which powder is deposited, controlling the mass flow rate of the system. Argon carrier gas carries the powder through the nozzle through a coaxial deposition head, depositing powder directly onto the substrate, or the build surface. A laser focused by a lens is concentrated and used to sinter the substrate while metal powder is constantly added into the melted region, resulting in a generated clad. The DED process of conveying powder to the substrate and sintering the deposit to create a structure layer by layer is then repeated until a three-dimensional solid component is built.

1.2 Powder Delivery Rate

In order to optimize the process of creating three-dimensional metal components from computer-aided design (CAD) files layer by layer, processing parameters such as powder flow delivery rate need to be investigated. To create parts devoid of defects such as porosity in the metal requires the process of monitoring the powder delivery rate to be reliable and repeatable. An experiment conducted by Sciammarella et al. in 2018 [2] with 316L stainless steel powder showed that the average mass flow rate of the same RPM value varies by more than 13% (5.24 g/min compared to 6.05 g/min for the second 4 RPM setting), as shown in Figure 2 [3].
Monitoring of this system consisted of an acoustic emissions sensor that found plenty of variances in powder delivery rate over time. Since these variances exist and affect the build quality of materials in the end, a more reliable source to monitor powder flow rate must be established.

1.3 The Optoelectronic Sensor

Due to its opacity and reflectivity, one method of measuring powder flow is by utilizing an optoelectronic sensor. The sensor consists of a diode laser with a line generator that emits a thin defocused light sheet, a photodiode, and a set of lenses. The corresponding lens collimates the laser beam before passing through a transparent chamber, where powdered metal is carried by argon gas flow, as shown in Figure 3 [4].
Due to diffusion, absorption, and reflection of the powder stream passing through the glass chamber, the amount of light detected by the receiving photodiode would change as the density of the powder changes. With this information, the photodiode sensor output over time can be plotted as well as the photodiode sensor output vs. powder delivery rate.

### 1.4 Objective of Thesis

The objective of this thesis is to investigate the optoelectronic sensor for DED applications in close detail by first delving into previous literature associated with the optoelectronic sensor and how it can be used to monitor the mass flow rate in different DED machines. The motivation of conducting this type of research is noted and an experimental setup of the entire system is established in detail. Details are given on the powder-conveying system, the flow system, all dimensions of components associated with the system, and characteristics of the optoelectronic sensor.
Several experiments are explained and conducted based on validating mass flow rate and the correlation of the laser response, and results of all tests are shown. Results are shown for two different setups of the optoelectronic sensor and compared to show which setup of the sensor works more effectively. The experimental setup of both cases is shown in detail. Results are followed by a discussion and close examination of the data and compared to results that were found in literature.

A conclusion of the applicability of using an optoelectronic sensor in DED application is given, followed by suggestions for future work that could be conducted or investigated further by using the same system or a similar experimental setup. More fine details can be found in appendices at the end of the thesis, including a MATLAB code (Appendix A) used for post-processing and SolidWorks drawings of in-house manufactured parts (Appendix B).

This thesis plans to lay a groundwork for using an optoelectronic sensor as a standard method of monitoring the powder flow rate through DED machines by providing as much detail as possible on the research conducted on the sensor itself.
CHAPTER 2: LITERATURE REVIEW

Given the new uses of DED technology, a number of mechanisms have been implemented to prove part uniformity and structure [2,4,5,7,8]. One of the critical drivers of repeatability is the DED system to deliver supply powder at a repeatable, uniform rate. The following articles indicate mechanisms where both the powder flow rate and the build performance are evaluated.

2.1 Implementation of the Optoelectronic Sensor in DED Applications

In order to have established 3D-printed components that do not contain any type of defects such as porosity in the metal, the process of creating these components must be both reliable as well as repeatable. The process known as solid freeform fabrication (SFF) [5] consists of building metal components that are built with consistency and with optimal physical properties, typically used for creating prototypes of models. To be able to remain consistent between builds, the powder flow rate must be monitored and measured as accurately as possible. An optoelectronic sensor was selected to be able to monitor the powder flow through the system in real time. The optoelectronic sensor consisted of laser diode that produced an elliptical red light with a wavelength of 600 – 710 nm and with a power less than 500 mW. A voltage signal was produced through a photodiode that converted the current through a signal pickup circuit. The photodiode is known to produce great linearity between the energy of illumination received and the output current.

Before starting to take measurements in any experiment, the metal powder hopper was allowed to run at a preset rotational speed for exactly two minutes to make sure that there was a
static rate of powder delivery. An in-situ system was developed for metal powder to flow directly from the metal powder feeder through a glass section of tubing that was monitored by the optoelectronic sensor, and an electronic scale was at the end of the system to measure the weight of powder being deposited. With all systems working together, the average delivery rate of powder was calibrated by taking the amount of weight deposited on the scale over that time period. It was found that the average photodiode sensor output displayed a relatively linear trend when compared to the average powder delivery rate. The linear trend exists in the regions between 3-22 g/min of powder delivery rate [5], as shown in Figure 4.

![Figure 4. Output of optoelectronic sensor [5].](image)

Furthermore, Hu et al. [6] developed a system to control the powder delivery rate by having the powder feeder controller obtain weight from an electronic scale at the end of the system and by having the optoelectronic sensor monitor the powder delivery rate through an A/D converter. This was developed to create a feedback loop. That way, the motor speed can be detected and precisely controlled based on feedback from the electronic scale and the
optoelectronic sensor. Therefore, the motor speed would be able to self-adjust to remain at a stable powder flow rate.

Another part of the experiment involved using a coaxial infrared image sensing device to take images of the 3D metal printing process and be able to capture it frame-by-frame. The metal powder used was H13 tool steel powder. A straight wall was built with fifty layers of a single bead thickness. The parameters of the build included a “5-mm/s scanning speed, a 4 g/min powder delivery rate, a 0.25-mm Z-height increment, and a 420-W constant laser power” [5]. This component was built under three different conditions:

1. No preheating with no powder control
2. With preheating and no powder control
3. No preheating with powder control

Preheating refers to heating the metal powder in an oven to a set temperature (up to 400°C) prior to the build. Preheating metal powder results in a more homogeneous microstructure that consists of better mechanical properties [5]. Powder control refers to whether the experimenter uses the motor speed feedback control loop or not.

The sizing, dimensions, and build quality were examined for each circumstance and the wall was built under different power levels between 300W and 600W, making a total of 15 samples to compare, five components for each condition. A geometrical variation between them was calculated and it was discovered that for each laser power level, the geometrical variation of the component was much less when control was applied rather than to those samples where powder control was not used, as indicated by the results in Figure 5 [5].
Even by using the same build parameters from build to build, there was a distinct variation in the quality of the build. Three conditions were cited as having produced poor repeatability, including laser power, beam velocity and powder delivery rate [8]. Xing [8] developed the Intelligent Metal Powder Laser Forming System (MPLF), which includes a CNC-operated control system with metal powder delivery and real-time feedback control. This machine is able to 3D print a fully dense component accurately beginning from a CAD model. The design behind the control of the MPLF system is to keep the temperature of the melt pool stable, to guarantee the repeatability of the shape of the part, and to also keep the powder delivery rate stable.

An optoelectronic sensor was utilized to be able to measure the powder delivery rate in real time. The parts of the sensor were set up so that a laser line generator would emit a laser beam directly through the metal powder stream flowing inside glass tubing where the light is eventually received by a photodiode. The optoelectronic sensor was calibrated by an electronic scale at the end of their system. An average powder delivery rate was calculated by measuring the weight of the powder delivered over a distinct time period. It was found that a linear...
relationship exists between the metal powder delivery rate and the average photodiode sensor output [8].

Figure 6. (a) Schematic of feedback control system, (b) performance of the sensor [8].

From this, a PID (proportional, integral, derivative) controller was developed to control and monitor the feedback based on the powder delivery rate and be able to change the motor speed to have a consistent, stable powder flow. A camera capable of capturing high frame rates was introduced to the system on the side of the deposition head to take pictures of the melt pool with a 640x480 resolution. A computer program had to be established to be able to calculate the layer height of a build. It did this by calibrating the camera to the line laser plane and finding the three-dimensional coordinates, finding a relational matrix from the device’s frame compared to a reference plane, and lastly calculating values for different layer heights.

Collecting feedback data from the sensor, all three of the conditions that produced poor repeatability were able to be controlled accurately. The laser power, scanning speed, and metal powder delivery rate were adjusted simultaneously, and multiple components were built. The processing parameters used to create nickel-based metal parts included a laser power of 1000 W, scanning speed of 5-mm/s, powder delivery rate of 10 g/min, and a scanning space of 1.3 mm.
The parts created had a refined appearance and great surface quality. All components built were free of porosity; they were fully dense and nearly net shaped [8].

Some factors must be considered when looking at the surface quality and manufacturability of parts, which include the power of the laser, the powder delivery rate, and the temperature of the melt pool. A system that monitors these factors and has the capability to control the metal powder delivery rate and melt pool temperature was developed [6]. A thermometer that could read between 500°C to 2500°C was used in the system to detect the temperature of the build area. All data collected by the thermometer was sent to a data acquisition device and processed. The computer running the data acquisition was able to adjust the power of the laser as well as the metal powder delivery rate based on feedback from the information collected. A photoelectronic sensor (OPT301) was used to detect the metal powder delivery rate. This sensor is characterized by reading between 700 nm to 800 nm wavelength. A photoelectronic converter was also used as well as a 700 nm laser line generator. An amplifier was also used to process the electronic signal between the output ranges of 0V to 5V.

The RPM of the metal powder feeder motor was adjusted by a PID system. It worked by identifying changes in powder concentration and making adjustments based on the feedback it was receiving until the powder delivery rate was stable. To test this system, the speed of the motor was set to a fixed 10 RPM which carried 2Cr13 metal powder with a 200-mesh size. The air flow of the carrier gas was 7.5 L/min. Also, the PID controller was tested by using the same parameters and a set powder delivery rate of 5.5 g/min. It was found that by using PID control, the metal powder delivery rate was much more stable than by leaving the metal powder feeder motor at a fixed RPM value. It was found that the standard deviation dropped by 67.9% and the
average absolute deviation was reduced by 68.9%. It can be concluded that a PID control system with a photoelectronic sensor system allows for a stable powder flow, as shown by the results in Figure 7 [6].

Figure 7. Powder delivery rate comparison between fixed speed control and PID control [6].

To improve build size, production rate, and the ability to produce parts with distinguished material properties, an 8-axis laser-based direct metal addition (LBDMA) system was developed [4]. The motivation of the experiment was to be able to control the metal powder flow rate and be able to control the size of the molten pool during the building process. Metal powder flow rate was determined by using an optoelectronic sensor mounted at the end of the powder feeder. A camera with the ability to take infrared images was set up directly on the laser head and
positioned to be able to view the molten pool from the top. A representation of the optoelectronic sensor is shown in Figure 8 [4].

![Optoelectronic Sensor Diagram](image)

Figure 8. The optoelectronic (a) schematic, (b) photo [4].

The exact characteristics of the optoelectronic sensor consists of “a diode laser with a line generator that emits a thin defocused light sheet with a wavelength of 658 nm and a power less than 500 mW, a photo diode, a small rectangular glass chamber (6.4 mm wide, 2.2 mm thick, 19.5 mm long), and a set of lenses” [4]. It was found that at a given suitable pressure (greater than 10 psi) the powder delivery rate is related to the angular velocity of the motor on the powder feeder linearly. Data was collected by setting the servomotor controlling the motor to run between 0V and 5V with 0.05V increments. The metal powder flow delivery was determined at each set voltage by determining how much weight of the powder was measured at the end of the system. Three trials of 30 seconds were done and then averaged [4].

Data showed that a linear trend exists between the powder delivery and the motor voltage for all powder delivery rates under 1.1 g/s (66 g/min), as shown in Figure 9 [4]. A nonlinear
trend was examined after 1.1 g/s; however, most applications in DED will not reach close to this limit.

![Figure 9. Linear trend of motor voltage and powder delivery rate up to 1.1 g/s](image)

To process the data, an equation in the form of a first-order polynomial was used in order to relate the delivery rate $r$ (g/s) to the voltage signal $h$ (V) [4]:

$$h(r) = -0.377 \times r + 9.475$$  \hspace{1cm} (1)

An error value had to be determined in order to keep a stable powder delivery rate. This would occur when the errors between the powder delivery that was measured and the actual powder delivery were less than a certain value, $\delta$, measured in (g/s) [4]:

$$|(r(p) - r(m))| < \delta$$  \hspace{1cm} (2)

The value of $\delta$ can be found on the basis of the measurement accuracy, and $r$ itself represents the inverse of Equation (1) and is used in the calculation of powder delivery after...
obtaining a voltage signal output from the sensor. This relationship between the output signal and \( r \) was found to be [4]:

\[
r(h) = -2.653h + 25.133
\]

where \( h \) is the output voltage from the sensor (V) and \( r(h) \) is the powder delivery rate (g/s). An error of around 0.005 g/s (0.30 g/min) was found at \( N = 150 \), and from \( N = 200 \) and beyond, the error was less than 0.005 g/s. Here, \( N \) represents the sampling number of a single measurement [4]. Having a large error of powder flow rate can lead to inconsistencies of builds and introduce defects such as porosity and poor surface quality.

### 2.2 Mathematical Modeling of Powder Delivery Rate in DED Applications

It can be shown that metal powder delivery rate can vary even when using the same motor speed setting, even if there is a linear trend between the metal powder delivery rate and the motor speed. Powder delivery rate was measured by using a pressure sensor that was attached to the powder feeder pickup region. The sensor is characterized by a 6.67 mV/psi sensitivity attached to a 10V power supply with a response time of 1 ms. Filtering and amplification of the signal is represented by the following algorithm [7]:

\[
V_m = K_m(\Delta P_t - \Delta P_0)/\Delta P_0
\]

where \( V_m \) represents the voltage signal from the powder delivery rate, \( \Delta P_t \) is the instantaneous pressure when powder flow is flowing, \( \Delta P_0 \) is the pressure in the presence of no powder flow,
and $K_m$ is the sensitivity of the sensor. A carrier gas must also be present to convey powder through the system. A constant carrier gas flow must exist to ensure that [7]:

$$P_q \gg P_d$$

(5)

where $P_q$ is the pressure upstream and, in contrast, $P_d$ is the pressure downstream in relation to the flow meter. As long as this condition is satisfied, it can be certain that the gas flow rate is not changed significantly by the pressure downstream.

Next, the amount of energy required can be derived by taking the difference between two points of the gas pressure since the pressure at the end of the system is atmospheric. This equation can be represented by balancing the energy at the two ends of the system [7]:

$$\rho g \Delta P_t = g \Delta H + 2C_f U_{gm}^2 L_t / D_t + C_d U_{gs}^2 / 2$$

(6)

where $\Delta P_t$ can be represented as the difference in pressure between the entrance and exit of the conveying system, $\rho g$ is the density of the gas, $g$ is the acceleration due to gravity, $\Delta H$ is the change in altitude between the exit and the entrance of the conveying tube, $L_t$ is the length of the conveying tube, $C_f$ is known as the friction factor, $U_{gm}$ is the mean gas velocity inside the tube, $C_d$ is known as the drag coefficient, and $U_{gs}$ is the relative velocity between the solid powder particles and the gas. The terms on the right-hand side of the equation can be split up into three components: the first representing the pressure drop due to elevation, the second representing the friction term, and the third representing acceleration.

If the flow is in the laminar flow region, $C_d = 14/Re$ and $C_f = 16/Re$, where $Re$ is the Reynold’s number. Also, if the condition exists that the flow is nonturbulent and the length of the
conveying tube is much greater than the diameter of the tube, the acceleration of the powder can be ignored, since \( C_f > C_d, U_{gm} > U_{gs} \) and \( L_t \gg D_t \).

The Reynold’s number can be calculated by using [7]:

\[
Re = \frac{\rho_g U_{gm} D_t}{\mu} \tag{7}
\]

where \( \mu \) is known as the coefficient of viscosity (N/m\(^2\)). Also:

\[
C_f = \frac{16\mu}{\rho_g U_{gm} D_t} \tag{8}
\]

\[
U_{gm} = \frac{Q_g}{A_t - \frac{M}{\rho_s U_{pm}}} \tag{9}
\]

where \( M \) is the average mass flow rate inside the conveying tube, \( A_t \) is distinguished as the cross-sectional area with respect to the powder delivery when there is no powder flow, \( \rho_s \) is the powder density or specific weight of the powder, \( U_{pm} \) is known as the mean particle velocity that exists inside the conveying tube, and \( Q_g \) is the gas flow rate. From the conditions shown, \( Q_g \) is considered constant.

Therefore, the friction coefficient on the right-hand side of Equation (6) can be approximated to be [7]:
\[ \Delta P_{gs} \approx \frac{16 \mu L_t}{D_t^2 A_t} \left( \frac{Q_g}{A_t - \frac{M}{\rho_s U_{pm}}} \right) \tag{10} \]

Using a Taylor series expansion and ignoring higher order terms, since \( A_t > M/\left(\rho_s U_{pm}\right) \), a linear relation can be established as follows [7]:

\[ \Delta P_{gs} \approx \frac{16 \mu L_t Q_g}{D_t^2 A_t} \left( 1 + \frac{1}{A_t \rho_s U_{pm}} M \right) \tag{11} \]

Since the cross-sectional area \( A_t = \pi D_t^2 / 4 \), Equation (11) can be written as [7]:

\[ \Delta P_{gs} \approx \frac{64 \mu L_t Q_g}{\pi D_t^4} \left( 1 + \frac{4}{\pi D_t^2 \rho_s U_{pm}} M \right) \tag{12} \]

This expression now represents the friction term as proportional to the gas flow rate, the length of the conveying tube, and the metal powder delivery rate.

To clean up the expression, a term \( K_U \) can be defined as [7]:

\[ K_U = \frac{4}{\pi D_t^2 U_{pm}} \tag{13} \]

The equation for the balanced energy, Equation (6), can now be rewritten as the following [7]:

\[ \Delta P_t = \rho g g \Delta H + \frac{64 \mu L_t Q_g}{\pi D_t^4} + \frac{64 \mu L_t Q_g}{\pi D_t^4} K_U M \tag{14} \]
With no powder flow, $\Delta P_0$ can be represented as [7]:

$$\Delta P_0 = \rho g g \Delta H + \frac{64\mu L_t Q_g}{\pi D_t^4}$$  \hspace{1cm} (15)

The powder delivery rate sensing relationship can be established by combining Equation (4), Equation (14), and Equation (15) [7]:

$$V_m = K_m K_u M \left( \frac{1}{1 + \frac{\rho_s \Delta H D_t^4}{64\mu L_t Q_g}} \right)$$  \hspace{1cm} (16)

It can be shown that the term within the parentheses will converge to a value of one if $\Delta H$ is small and $L_t \gg D_t$. From this expression, a linear relationship is distinguished and verified by an experiment run with aluminum metal powder and 316 stainless steel powder. The results of these experiments are shown in Figure 10, confirming a linear relationship between the sensor output and the powder flow rate [7].

![Figure 10. Experimental relationship between powder flow rate and sensor output for Al and 316 steel powders [7].](image)
2.3 Implementation of the Acoustic Emission Sensor in DED Applications

Although powder delivery rate is measured with an acoustic emission sensor rather than an optoelectronic sensor, the process of this experiment is important because the same exact system is used except for the optoelectronic sensor that is mentioned later in this thesis. The overall goal of demonstrating how a time series is related to a signal output and comparing it to the powder delivery rate has been investigated [2]. Measuring powder delivery rate is considered important because it can alter single-track characteristics of components created with directed energy deposition (DED) techniques. Three primary factors are important in characterizing optimal quality builds: the power of the laser, the travel speed of the deposition head, and the metal powder delivery rate. Using raw data produced by particle impact, an acoustic emission (AE) sensor was able to generate a time series through the use of RMS values. The AE sensor itself is a piezo-electric transducer with a frequency range of 250 kHz to 700 kHz. The powder delivery rate was modeled as a function of the RMS values found as well as the AE signal.

A calibration of powder delivery rate in situ is achieved through data synchronization of the signals using LabVIEW and an electric scale. The powder delivery rate was determined by taking the difference in the weight measurement over a certain time period. Acoustic signal data was collected from “Vallen’s AMSY-6 AE with a 40 MHz sampling rate at 18-bit dynamic range” [2]. In order to develop a relationship between data from the electric scale and the RMS values from the AE signal output, several steps are taken in processing the data. A schematic of the experimental setup is shown in Figure 11 [2].
Figure 11. In-situ powder delivery monitoring with an AE sensor and electric scale [2].

The data collected from this system can give the user feedback in order to change the process to make corrections to the powder deposition. The mass flow rate can be theorized as [2]:

\[ \dot{m}_{AE} = f(RMS, \beta) = \dot{m}_s \]  \hspace{1cm} (17)

where \( \dot{m}_{AE} \) represents the powder delivery rate measured directly by the acoustic emission sensor, \( \beta \) is represented by model parameters and \( \dot{m}_s \) is the powder delivery rate measured directly by the electric scale.

In order to reduce noise, or spikes in the data, a Savitzky-Golay filter was used [2]. This filter works by examining the point before and the point after the point of interest and develops a third-order polynomial function to fit these three points. Next, the output of the AE sensor is
transformed from an RMS signal to a flow rate by the following multiple linear regression method [2]:

\[ E = \sum_{i=0}^{i=N} [y_i - (\beta_i x_i)]^2 \]  

(18)

Using the error that occurs from the regression model and experimental data of the powder delivery rate \((y_i)\), the RMS of the AE signal \((x_i)\), and from setting the gradient equal to zero, the coefficient \((\beta_i)\) can be selected [2].

To compare goodness of fit, Pearson’s correlation coefficient is used. The sample correlation coefficient, \(r\), is defined as [2]:

\[ r = \frac{\sum_i(x_i - \bar{x})(y_i - \bar{y})}{\left(\sqrt{\sum_i(x_i - \bar{x})^2}\right)\left(\sqrt{\sum_i(y_i - \bar{y})^2}\right)} \]  

(19)

where \(x\) and \(y\) are scale data and \(\bar{x}\) and \(\bar{y}\) are the averaged values of the AE signal. As \(r\) converges more closely to 1, the two signals are known to be more positively correlated; \(r\) values ranged from 0.827 based on unfiltered data and up to 0.959 when using the Savitzky-Golay filter for a time frame of 19.1 s [2]. Different methods of filtering including using the Savitzky-Golay filter are shown in Figure 12 [2].
Another experiment with 316L stainless steel powder conducted shows the powder feeding being held for 80 seconds at different RPM values starting with 4 RPM and ramping up to 8 RPM, and then decreasing to certain values between these two RPM values, as shown in Figure 13 [2]. There existed two issues in particular with the consistency of the powder delivery rate. First, fluctuations up to 10% occurred in the powder delivery rate. Second, the measured powder delivery rate was not always the same, even when the same RPM value was chosen. The average of each of the sections of the same RPM value is up to 13% variance. For example, for
two situations of the 4 RPM setting, the first showed a powder delivery rate of 5.24 g/min compared to 6.05 g/min for the second situation [9].

A similar test was conducted, except this time with a different material. Commercially pure titanium (Cp-Ti) powder was used in order to see if the system was capable of measuring other types of metal powders. In conclusion, the acoustic emission sensor was able to accurately monitor the flow rate of this material as well as the 316L stainless steel powder. For the Cp-Ti powder, the sample correlation coefficient $r$ was found to be 0.967 [2].
2.4 Motivation

As seen from the literature, there exists different methods of powder flow sensing throughout the additive manufacturing (AM) industry. By monitoring the powder delivery rate of systems, the quality of 3D-printed metal components was substantially improved in terms of being net shaped, free of defects such as pores, and fully dense. Therefore, the ability to monitor and control the powder delivery rate in situ in a DED process is critical, as it affects the final product that is 3D printed. Most importantly, a robust and repeatable process is needed in order to track the powder flow rate. Standardizing a mass flow processing tool such as the optoelectronic sensor can aid in both AM research and industry as a whole.

Since problems exist with components built without powder flow monitoring (porosity, cracks, bad surface roughness, etc.), the need for the optoelectronic sensor to monitor the amount of powder flowing through the system is vital in creating fully dense three-dimensional structures. If the amount of light detected by the photodiode changes by the amount of powder, the size distribution of the powder, the location within the test area, and by other test parameters, then a mass flow rate can be distinguished and monitored accordingly to ensure a part is made with satisfactory quality.

An extensive look into the functionality of the optoelectronic sensor was taken in the Advanced Research of Manufacturing and Materials (ARMM) Lab at Northern Illinois University in order to develop a standard for the use of the optoelectronic sensor for measuring powder flow in DED applications. In-situ experiments conducted with an OPTOMEC 850M LENS powder feeder with 316L stainless steel powder show the capability of this sensor.
CHAPTER 3: METHODS

3.1 Experimental Setup

3.1.1 Overview

316L stainless steel powder is initially loaded into the OPTOMEC 850M LENS powder hopper which is a reservoir that consists of a rotating disc that spins at a set RPM. As the disc rotates, the powder begins to spin until it reaches a section where it is suctioned into a conveying tube. This system relies on argon carrier gas set to 60 psi to carry the powder through the tubing. A nearby optical table is stationed to have a fixed system for the powder delivery to occur. Posts are erected from the optical table where clamps are attached to hold the tubing to keep it fixed. There exists one 90-degree bend that the tubing undergoes until it attaches to a clear tubing section where the optoelectronic sensor monitors the powder delivery rate. The powder reaches a vortex hopper that allows the argon gas to be released into the atmosphere and allows the powder to drop directly into a container placed on an electric scale. A schematic of the experimental setup is shown in Figure 14.
The optoelectronic sensor itself includes a photodiode, laser and a set of lenses that project the laser through a test section tube placed perpendicular to the laser. The laser is then focused through another lens and directed at the photodiode, producing a voltage signal output reading. This can be shown in the photodiode and laser section in Figure 14. The photodiode collects data as soon as a signal from the laser is received. The photodiode is capable of reading an output between 0V to 10V. As the density of the powder through the test tubing changes, the photodiode sensor output will change as well. A closer look at the powder delivery through the test tube is shown in Figure 15.
The setup can be separated into three sections: the flow system, the collection region, and the optoelectronic sensor itself. A detailed explanation of each section is described below.

### 3.1.2 Flow System

The flow system consists of argon carrier gas, the polyurethane tubing, and the powder feeding system.

- **Argon Gas**
  
  Argon gas obtained from Weldstar (AR95/HY-T) consisting of 95% argon and 5% hydrogen gas. This gas is supplied to the powder feeding system at 60 psi through ¼” polyurethane tubing. The flow of the argon gas is measured through a flow meter at 3.5 L/min.

- **Polyurethane Tubing**
  
  The polyurethane tubing is cut to length with a ¼” outer diameter and a 5/32” inner diameter. It is characterized as firm, opaque, and flexible. It can hold a maximum of 170 psi of pressure. The tubing is attached to various components with ¼” push-to-connect style connectors.
• **Powder Feeder**

The powder feeder of the OPTOMEC 850M shown in Figure 16 conveys powder through a combination of mechanical and pneumatic feeding. The hopper holds the powder at a constant pressure. An auger below the hopper’s outlet directs the powder into a wheel which has small holes that carry the powder as it rotates at a set motor speed. Once the powder reaches a deposit section of the powder feeder, an argon stream carries the powder into the \( \frac{1}{4} \)” polyurethane tubing. The amount of metal powder entering the system changes with respect to the rotation speed of the powder feeder’s motor.

Figure 16. OPTOMEC 850M powder feeder.
3.1.3 Collection Region

After the metal powder passes the optoelectronic sensor, it enters a powder hopper vortex setup. The conical-shaped hopper uses the vortex flow to knock out the powder momentum, causing the powder to drop directly down while the argon carrier gas is released into the atmosphere from the top. A fine mesh is secured at the top of the hopper vortex to ensure no powder up to 150 microns in size escapes into the atmosphere. Connected to the bottom of the vortex hopper is a flexible bellow that allows the metal powder to drop directly into a sample collection container placed on an electric scale, as shown in Figure 17. A support plate was also designed to hold up the powder hopper vortex on four optical posts from the table.

![Diagram](image)

Figure 17. The powder hopper vortex, support plate, flexible bellow, and digital mass scale.

The top view of the vortex hopper shows more detail on the security of the support plate and the fine mesh that does not allow powder to escape from the top of the vortex hopper. A schematic of the top view is shown in Figure 18.
Figure 18. Top view of powder hopper vortex with a mesh top opening.

The collection region includes the vortex hopper, the vortex hopper support plate, and a digital scale.

- **Vortex Hopper**

Before the metal powder can be deposited, the argon carrier gas must be released into the atmosphere and the powder must lose its momentum and drop directly into a container that is placed on the electronic scale. The vortex hopper shown in Figure 19 was manufactured on a CNC lathe from a 3.25” aluminum 6061 bar stock. The features of the vortex hopper include:

- ¼” 18 NPT pipe tap with a connector to attach to the ¼” polyurethane tubing,
- 180x180 mesh size and 0.004” opening size wire mesh to ensure no powder (size up to 150 micron) can escape through the top of the vortex hopper,
- 68° interior angle to ensure powder drops adequately,
- two latch-style toggle clamps to secure the cover holding down the mesh along with two EPDM O-rings to have ample security on the mesh.

The bottom of the vortex hopper was machined with a lip to ensure a hose clamp connection would be in line with the structure and fit securely. A cuffed-end round bellow was attached to the bottom of the vortex hopper and the other end was secured to the top of the container to ensure no powder is lost as it is deposited from the vortex hopper. A SolidWorks drawing of the vortex hopper is presented in Appendix B.

Figure 19. Vortex hopper.
• **Vortex Hopper Support Plate**

In order to ensure that the weight of the vortex hopper is not accounted for by the electric scale, the support plate shown in Figure 20 was machined from a cast aluminum sheet with 0.375” thickness. The outline of the vortex hopper support plate was cut on an OMAX water jet with a 2.00” center hole and four ¼” holes for the locations of the optical posts. The ¼” holes were reamed with a 0.251” high-speed steel reamer to create clearance so that it would fit over the optical posts.

To secure the plate onto the four optical posts, four holes were drilled parallel to the plate with a #7 drill bit and then tapped with a ¼–20 tap. Four knurled plastic head thumb screws were inserted into the tapped holes so that they can be adjusted and secured directly onto the optical posts. By releasing the thumb screws, the height of the vortex hopper support plate could be adjusted accordingly.

![Figure 20. Vortex hopper support plate.](image-url)
- **Digital Scale**

A Mottler Toledo Precision Balance MS802S digital scale shown in Figure 21 is used to weigh the powder at the end of the system. The scale has an 820 g capacity with 0.01 g readability. The advanced connectivity of the scale allows for the connection of a Vernier SensorDAQ via USB. Readings from the scale are recorded from the SensorDAQ and relayed to a PC equipped with LabVIEW for post-processing of scale weight data.

![Digital Scale Image](image)

**Figure 21.** Mottler Toledo Precision Balance MS802S digital scale.

The container that rests on the scale is a standard 250 ml Erlenmeyer flask. The top of the flask has a round bellow secured by a hose clamp. The bellow allows for the powder to drop directly into the container while not contributing to the weight of the system. The collection container is able to move with the flexible bellow.
3.1.4 Optoelectronic Sensor

The optoelectronic sensor consists of a diode laser with a line generator that emits a thin defocused light sheet, a photodiode, and a set of lenses, such as in the schematic in Figure 22.

![Schematic of optoelectronic sensor](image)

Figure 22. Schematic of optoelectronic sensor.

The focus adjustable laser line generator (Thorlabs CPS650F) has a typical center wavelength close to 650 nm and produces an output beam that has an elliptical beam shape with a power of 4.5 mW. The photodiode (Thorlabs PDA10A2) can detect wavelength ranges from 200 to 1100 nm. Two uncoated plano-convex lenses (Thorlabs LA1027) are 1” in diameter with a focal length of 35.0 mm and are held in by retaining rings inside two SM1 lens tubes with 2.00” thread depth (Thorlabs SM1L20). The laser line generator is held in by a threaded adapter (Thorlabs AD11F) and secured inside a cage plate (Thorlabs CP33T) that is held securely by a
½” diameter optical post with an 8-32 setscrew. The laser is powered by a 5 VDC regulated power supply.

- **Lexan Tube Assembly**

  A 12-foot clear extruded square acrylic tube (1/2” OD and 3/8” ID) was purchased and segments of 3.00” were cut on a vertical band saw. The ends of the tubes were secured with square connectors that would attach the ¼” polyurethane tubing to each side of the glass assembly. The square ends were designed to keep a smooth transition from a circular cross-section from the tubing to the square cross-section of the glass through the use of a variable-length fillet. The other end of the connector was designed with a 29/64” hole. Each square connector was 3D printed with UV-treated resin to ensure the maximum tolerance possible when inserting the square connectors to the end of the glass tube. The square connectors were each tapped with a ¼” 18 NPT pipe tap before undergoing another UV light treatment to harden the material. Once the material was hardened, a push-to-connect tube fitting was inserted with Teflon tape to ensure no air or powder was able to escape from the threads. The entire tube assembly requires a square connector on each end of the acrylic tubing, shown in Figure 23.

- **Borosilicate Glass Tubing**

  Borosilicate glass tubing is used for the glass setup of the experiment. A 12” section of glass tubing was chosen with an outer diameter of ¼” and an inner diameter of 5/32”. This was chosen to match the outer and inner diameters of the polyurethane tubing. The glass tubing was connected to the polyurethane tubing with a ¼” x ¼” pressure fitting. More about the circular glass tubing is described in Section 5.1.2.
Alignment Bracket

Due to the precise nature of the optoelectronic setup, an alignment bracket is designed to center the laser, photodiode, and powder flow for optimal light reception with regard to positioning of the powder flow.

The alignment bracket shown in Figure 24 is designed in such a way as to ensure the laser precisely hits the center of the Lexan glass and will focus on the photodiode on the receiving end of the light. A 3A 125V snap switch is placed on the side of the alignment bracket so that when the cover is closed it will engage the switch and turn on the laser line generator. This was made as a safety precaution so that the laser will not fire unless the cover of the alignment bracket is closed.
Figure 24. Alignment bracket for the optoelectronic sensor.

All the components of the alignment bracket were 3D printed with PLA-filament plastic. The alignment bracket is secured on optical posts and the height of the bracket can be adjusted along the length of the optical post, up to 12 inches from the optical table.

3.1.5 LabVIEW VI

A Labview VI was created incorporating several while loops taking input through a SensorDAQ for the photodiode as well as data from the scale and a human input for RPM which is manually changed as the experiment progresses. The data is taken and output through a write-to-measurement file into a four-column .txt file for MATLAB-based post-processing. The optoelectronic sensor is measured at a sampling rate of greater than 200 samples per second. The
photodiode voltage signal ranges from 0V to 10V. Each data point is stored to the 0.000001 decimal place.

### 3.1.6 MATLAB Post-Processing

A MATLAB script (Appendix A) was developed to post-process data collected after the LabView script has stopped running. The MATLAB script is able to take the four columns of data from the .txt file and divide it into four different arrays:

- `work_array{1}` represents the time (seconds)
- `work_array{2}` represents the scale weight (grams)
- `work_array{3}` represents the sensor output (volts)
- `work_array{4}` represents the motor speed (RPM)

The MATLAB script is able to take these arrays of data and create two plots, one for the plot of voltage vs. time and one for the plot of scale weight vs. time. The script is able to recognize every single time there is an RPM change to plot a vertical line and create a distinct region where the RPM change occurs. It will then calculate both the average voltage and the average powder flow rate and display it as text along with the RPM in each region.
CHAPTER 4: EXPERIMENTATION WITH SQUARE LEXAN TUBE

4.1 Experiments

4.1.1 Incremental Change

In the incremental change test, the motor speed is set to a certain voltage for 20 seconds at a time, starting with 0 RPM and progressing to 20 RPM maximum and back to 0 RPM. The motor speed order is shown in Table 1.

Table 1. Incremental Change Experiment.

<table>
<thead>
<tr>
<th>Motor Speed (RPM)</th>
<th>Duration (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>7.5</td>
<td>20</td>
</tr>
<tr>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>12.5</td>
<td>20</td>
</tr>
<tr>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>17.5</td>
<td>20</td>
</tr>
<tr>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>17.5</td>
<td>20</td>
</tr>
<tr>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>12.5</td>
<td>20</td>
</tr>
<tr>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>7.5</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>0</td>
<td>20</td>
</tr>
</tbody>
</table>
Each RPM is run for 20 seconds, making the test a total of 5 minutes long. Note that 2.5 RPM is skipped since, from previous results, it was found that there is no difference in the photodiode sensor output from 0 RPM to 2.5 RPM.

### 4.1.2 Immediate Change

The immediate change test starts at 0 RPM and immediately ramps up to 20 RPM, then immediately decreases to 0 RPM to observe any photodiode sensor output fluctuations. The motor speed order is shown in Table 2. Each RPM is run for 40 seconds, making the test a total of 2 minutes long.

**Table 2. Immediate Change Experiment.**

<table>
<thead>
<tr>
<th>Motor Speed (RPM)</th>
<th>Duration (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>40</td>
</tr>
<tr>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>0</td>
<td>40</td>
</tr>
</tbody>
</table>

### 4.1.3 Hysteresis Gas Study

A distinction of the photodiode sensor output occurs when the argon gas initially is turned on. The gas study test observes what happens at the start and the end of the immediate change hysteresis test when the argon gas is turned on and off. The test procedure is shown in Table 3. The total time for this test is 3 minutes and 10 seconds.
4.2 Results of Incremental Change Test

As shown in Figure 25, the motor speed as well as the average voltage during that RPM value has been labeled. With no powder flow, the average photodiode sensor output was 2.7071V and remains constant. As the RPMs begin to increase by 2.5 RPM at each step, the photodiode sensor output continually increases until it remains at 3.0903V then it reaches 0 RPM once again. It would be expected for each RPM value to have a consistent value, but an error up to 14% exists between distinct RPM values and the trend of the voltage signals are not following what conventionally should be taking place.

Table 3. Hysteresis Gas Study Experiment.

<table>
<thead>
<tr>
<th>Motor Speed and Condition</th>
<th>Duration (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Only (No Gas)</td>
<td>20</td>
</tr>
<tr>
<td>0 RPM (With Gas)</td>
<td>20</td>
</tr>
<tr>
<td>20 RPM</td>
<td>40</td>
</tr>
<tr>
<td>0 RPM (With Gas)</td>
<td>40</td>
</tr>
<tr>
<td>0 RPM (No Gas)</td>
<td>30</td>
</tr>
<tr>
<td>0 RPM (Gas On)</td>
<td>20</td>
</tr>
<tr>
<td>0 RPM (No Gas)</td>
<td>20</td>
</tr>
</tbody>
</table>
Figure 25. Results of the incremental change test with the Lexan tube.

As seen by the weight vs. time of the incremental change test in Figure 26, the mass flow rate data actually disagrees with what the signal output is representing. The mass flow rate data from the weight vs. time plot shows that the greatest amount of powder flows through the system at 20 RPM and the mass flow rate is close to zero at the 0 RPM regions.
According to the mass flow data, the photodiode signal output is expected to decrease as the powder flow rate increases rather than the consistent increased trend seen in Figure 26. The inconsistency of the signal raised questions about the optical properties of the Lexan tubing since the photodiode signal output did not follow an expected trend.

4.3 Results of Immediate Change Test

The immediate change test exhibited similar behavior between the two 0 RPM values. Figure 27 shows that the photodiode sensor output was initially 2.7210V and remained consistent, but at the end of the test at 0 RPM, the photodiode sensor output was 2.8926V and remained consistently at that value. Also, in the 20 RPM section, there was no real consistency.
Running the motor at such a high motor speed would show the greatest distinctions between data collection, but this trend shows that there is something else interfering with the signal rather than just the powder due to the inconsistencies in the 20 RPM region. It was also found that when the argon carrier gas was initially turned on, the photodiode sensor output also fluctuated. Therefore, the next test, the hysteresis gas study was developed to find out exactly what is happening when the argon carrier gas is turned on and off before and after the immediate change test. The hysteresis gas study test was run three different times under different conditions.

![Hysteresis Test - Immediate Change](image)

Figure 27. Results of the immediate change test with the Lexan tube.

### 4.4 Results of Hysteresis Gas Study Test

In the first hysteresis gas study test, the photodiode sensor output was tested by shutting off the gas during the experiment. First, in Figure 28, the laser voltage was tested by keeping the
gas off for 20 seconds and the photodiode sensor output was at 2.9815V, but as the gas was turned on, the voltage output dropped to 2.7586V while the motor speed remained at 0 RPM. Then as the powder was run through with the motor speed at 20 RPM, the voltage output dropped to an average of 2.7385V. After the 20 RPM, the motor speed was changed back to 0 RPM for 40 seconds with the gas still on. As time continued through the 0 RPM (with gas), the voltage output increased to 2.8960V. Next, the gas was switched off and there was a slight increase in the voltage output at 2.9025V. Then the gas was turned back on while the motor speed was still at 0 RPM, and the voltage output immediately dropped to 2.6447V.

![Hysteresis Gas Study](image)

**Figure 28.** Results of the first hysteresis gas study test.

In the second hysteresis gas study test, the same method was repeated as in the first, with shutting the gas on and off in certain time increments, but as Figure 29 shows the trial was started with the laser only (no gas) the photodiode sensor output voltage began at 2.6052V and kept a steady rate at 0 RPM (with gas). Then the motor speed was switched to 20 RPM, and the
photodiode sensor output voltage decreased to 2.5894V and fluctuations occurred for that 40-second increment. After the motor speed was switched back to 0 RPM (with gas) and the voltage output increased to 2.6700V, the photodiode sensor output voltage continued on a steady pace as the gas was turned on and off for the next 50 seconds, but the last ending result of this trial with the motor speed at 0 RPM (no gas) suddenly dropped to 2.4308V when the argon gas was turned back on.

![Graph](image.png)

Figure 29. Results of the second hysteresis gas study test.

In the third hysteresis gas study test, the old Lexan tube was replaced with a new Lexan tube, and in the new test results, there was a higher initial photodiode sensor output voltage at 4.4750V with the laser only (no gas), shown in Figure 30. Then the gas was turned on, and the photodiode sensor output decreased slightly to 4.4644V. As the motor speed is set to 20 RPM, there was a large decrease in the photodiode sensor output where it decreased to 4.1192V. It had a continual downward trend, which began to fit the expected results. After the motor speed was
turned back to 0 RPM (with gas), the voltage output decreased again to 3.9682V and remained constant along with the 0 RPM (no gas). At the end of the experiment, the gas was turned on once more, and a distinct drop of photodiode sensor output occurred. The value ended at 3.6461V. In an ideal situation, it would be expected for the 0 RPM (with gas) to be roughly the same value. As we see from Figure 30, the first time it was at 0 RPM (with gas), the average was 4.4644V, and when it reaches the same condition at the end, it remains at 3.6461V, a significant drop in photodiode sensor output.

Figure 30. Results of the third hysteresis gas study test.
4.5 Results of Laser On-Off Test

Another quick test was conducted following the procedure of the immediate change test where it was thought that there may be noise from the photodiode sensor output based on prolonged exposure of the laser through the lenses. This test was performed to see if by turning off and on the laser between RPM changes the voltage reading would change. It was discovered that the photodiode sensor output was not affected by turning the laser off and on in between motor speed changes. The results of this test are shown in Figure 31.

![Laser Off / On Test](image)

Figure 31. Results of the laser off-on test.

4.6 Boundary Layer Analysis

To better explain some of the discrepancies in the results presented thus far, a detailed look into the boundary layer formed from the flow passing through a circular ¼” polyurethane
tubing into a square tubing was developed. The transitional region formed from the flow going from a small circular cross-section to a larger square cross-section causes a change of flow, as shown in Figure 32. This introduces a boundary layer where the fluid particles entering the new cross-section come to a complete stop near the tube wall due to the nonslip condition while simultaneously causing the fluid particles in the adjacent layers to slow down (Figure 33) [2]. Factors such as whether the flow is considered laminar or turbulent were calculated along with the Reynolds’s number to better explain what is actually happening with the Argon and metal powder interaction within the Lexan tube (Table 4).

![Figure 32. Boundary layer location of the Lexan tube.](image1)

![Figure 33. Detailed description of the boundary layer formed within the Lexan tube.](image2)
Table 4. Properties of Argon Gas.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Density of fluid:</td>
<td>( \rho = 1.782 , \text{kg/m}^3 )</td>
</tr>
<tr>
<td>Dynamic viscosity:</td>
<td>( \mu = 2.09 \times 10^{-5} , \text{Pa}\cdot\text{s} = 2.09 \times 10^{-5} , \text{kg/m} \cdot \text{s} )</td>
</tr>
<tr>
<td>Flow rate from OPTOMEC:</td>
<td>( \dot{v} = 3.5 , \text{L/min} = 0.05833 , \text{L/s} = 5.833 \times 10^{-5} , \text{m}^3/\text{s} )</td>
</tr>
</tbody>
</table>

First, the area of exit from the polyurethane tube into the Lexan tube must be examined in order to find an exit velocity:

\[
A_e = \left( \frac{5}{32} \right)^2 \times \frac{\pi}{4} = 0.01917 \, \text{in}^2
\]  

(20)

Converting from inches to meters:

\[
0.01917 \, \text{in}^2 = 1.237 \times 10^{-5} \, \text{m}^2
\]

The exit velocity can now be calculated with the area of exit and flow rate measured from the OPTOMEC:

\[
v_e = \frac{\dot{v}}{A_e} = \frac{5.833 \times 10^{-5} \, \text{m}^3/\text{s}}{1.237 \times 10^{-5} \, \text{m}^2} = 4.715 \, \text{m/s}
\]  

(21)

Next, the hydraulic diameter must be found using the inner edges of the Lexan glass tube (3/8 in). Hydraulic diameter is used when dealing with flow in a noncircular tube using A as the cross-sectional area and P as the perimeter of the cross-section [9].

\[
D_H = \frac{4A}{P} = \frac{4 \times \left( \frac{3}{8} \right)^2}{4 \times \left( \frac{3}{8} \right)} = \frac{3}{8} \, \text{in} \text{ or } 0.375 \, \text{in}
\]  

(22)

Converting the hydraulic diameter from inches to meters:

\[
0.375 \, \text{in} = 0.009525 \, \text{m}
\]
The Reynold’s number, \( Re \), can now be calculated with the properties of argon gas, including the density of the fluid, \( \rho \); the dynamic viscosity, \( \mu \); the hydraulic diameter, \( D_H \); and the velocity of the exit, \( v_e \):

\[
Re = \frac{\rho v_e D_H}{\mu} = \frac{\left(1.782 \frac{kg}{m^3}\right) \times \left(4.715 \frac{m}{s}\right) \times \left(0.009525 \ m\right)}{(2.09e^{-5} \ kg/m \cdot s)}
\]  

\[
Re = 3829.20
\]

Depending on the Reynold’s number, the flow can be characterized as in Table 5:

<table>
<thead>
<tr>
<th>Characterization</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laminar</td>
<td>( Re \leq 2300 )</td>
</tr>
<tr>
<td>Transitional</td>
<td>( 2300 &lt; Re \leq 4000 )</td>
</tr>
<tr>
<td>Turbulent</td>
<td>( Re &gt; 4000 )</td>
</tr>
</tbody>
</table>

The flow is characterized as turbulent, so the following condition applies:

\[
\frac{L_{H,turbulent}}{D_H} = 1.359Re^{1/4}
\]  

Reorganizing Equation (24) to solve for the entry length, \( L_{H,turbulent} \):

\[
L_{H,turbulent} = D_H \times 1.359Re^{1/4} = (0.009525 \ m) \times 1.359 \times (3829.20)^{1/4}
\]  

\[
L_{H,turbulent} = 0.1018 \ m
\]

Converting meters back to inches:

\[
0.1018 \ m = 4.009 \ in
\]
The critical Reynold’s number, $Re_x$, will give us an idea whether the boundary layer is considered laminar or turbulent:

$$Re_x = \frac{\rho v x}{\mu} = \left(1.782 \frac{kg}{m^3}\right) \times \left(4.715 \frac{m}{s}\right) \times \left(0.1018 m\right) \left(2.09e^{-5} \frac{kg}{m \cdot s}\right)$$

$$Re_x = 40,925.21 < 10^5 \quad \textbf{Laminar Boundary Layer}$$

It was found that the boundary layer fully forms after 4.009 inches. Since the Lexan tube is only 3 inches long, the laser is passing through a fluid boundary layer, which gives some explanation as to why the photodiode sensor output fluctuates.

4.7 Electrostatic Force

Another possible reason for irregularities in data collection could be explained by an electrostatic force that exists inside the Lexan tube as powder is passing through. This could explain why at the beginning of data collection, the photodiode sensor output was higher than at the end of the data collection, even when the motor speed was set to the same value. An electrostatic charge was first observed when a fluid leak was present from the pressure fitting at the end of the Lexan tube assembly. Due to this effect, the stainless steel powder may be suspended inside the Lexan tube and ultimately affect the photodiode sensor output since powder is still present within the laser stream. Figure 34 and Figure 35 show the electrostatic effect in more detail.
The electrostatic interaction inside the Lexan tube can also be described as the triboelectric effect. This occurs from the vigorous and constant interaction between the fluid molecules, metallic particulates, and the tube surface, which causes a transfer of electrons to the nonconductive tubing. One method of possibly nullifying this effect is by grounding the charge. Experiments were tested to see if grounding the charge to the optical post protruding from the optical table were conducted, but the inconsistencies in data still existed. Thoughts of replacing the plastic pressure fittings with a metal alternative and experimenting with that were introduced, but an inability to obtain such pressure fittings led to finding a new alternative.
4.8 Elongation of the Lexan Tube

In the argon boundary layer analysis in Section 4.6, it was discovered that the laser passes through a fluid boundary layer, which could ultimately affect the final photodiode sensor output since the detection region is not in fully developed flow. From that analysis, the flow becomes fully developed after 4.009 inches. Therefore, if the Lexan tube were elongated, the sensing region could begin after 4.009 inches to ensure that data collection occurred when the flow is fully developed. Three different lengths of the Lexan tube were cut out: 8 inches, 9 inches, and 10 inches long. These lengths were chosen to allow for the fully developed flow to transition back into the ¼” tubing at the other end. An example of this tube is shown in Figure 36.

![Elongated Lexan Tube](image)

Figure 36. Elongated Lexan Tube.

The trend of decreasing in photodiode signal output still persisted even with the elongated Lexan tubing. A few new problems were created with expanding the Lexan tube as well. Even though it was seen through the laser that powder was seen to be much more consistent and the flow direction only followed the carrier flow, powder began to lose momentum and
collect towards the end of the tube. It was also observed that powder would stick on the edges of the tube, which drastically affected the photodiode sensor output. A thorough cleaning of the inside of the Lexan tube was required after about 15 minutes of powder flow testing. Metrics were kept on how long a tube would last before cleaning or replacement was needed. For all three lengths of tubing, the tubing had to be cleaned around the 15-minute mark.

Since most issues persisted after this amount of experimentation, this led to finding a new experimental setup that would eliminate the change in cross-sectional area, the electrostatic force, and the need for cleaning and replacing the tubing every so often. New tubing would have to be found to solve all the criteria mentioned.
CHAPTER 5: EXPERIMENTATION WITH GLASS CIRCULAR TUBING

5.1 Experimental Setup

5.1.1 Overview

It was very apparent that many problems existed with the square Lexan tubing. From the change in cross-sectional area, the electrostatic force created from the vigorous interaction between particles, and the powder clinging to the edges of the tubing, it was clear that a new viewing chamber must take the place of the Lexan tubing. To eliminate the cross-sectional change, it was thought that having circular tubing with the same outer diameter and inner diameter as the polyurethane tubing would serve this purpose best. By keeping the inner diameter of the tube the same as the polyurethane tube, the flow should remain fully developed, and therefore no interaction between particles would cause any type of electrostatic effect. Lastly, the new tubing would have to be particle resistant to prevent the metal powder from sticking to the edges of the tube.

5.1.2 Borosilicate Tubing

Borosilicate glass tubing was chosen to directly replace the Lexan tubing. The outer diameter (¼”) matched that of the polyurethane carrier tubing as well as the inner diameter of 5/32”. A 12” long section of borosilicate glass was used and was connected to the polyurethane tubing with a ¼” x ¼” pressure fitting. Borosilicate tubing was chosen because it is known to be particle resistant as well as having clear optical properties. The setup with the borosilicate glass tube is shown in Figure 37. The laser was set up to take readings at the very beginning of the
glass tube since the most consistent data was taken at this point. Since the change of cross-sectional area from the polyurethane tube to the glass tube is very minimal, flow remains fully developed, so there exists no issue with having the viewing window be at the very beginning of the borosilicate tubing.

Figure 37. Borosilicate glass tubing experimental setup.

5.2 Experimental Procedure for Cycle Testing

5.2.1 Steady-State Baseline Test

The steady-state baseline test presented in Table 6 was designed to see the results of powder buildup and find a baseline signal change due to powder chamber interaction. Each test started at 0 RPM and measures for two minutes, then switched to a set RPM value and measured for ten minutes. The motor speed then returned to 0 RPM for an additional two minutes. Three trials were taken and averaged for the motor speeds shown in Table 6:
Table 6. Steady-State Baseline Experiments.

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Initial Motor Speed (RPM)</th>
<th>Set Motor Speed (RPM)</th>
<th>Final Motor Speed (RPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>2.5</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>7.5</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>12.5</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>17.5</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>20</td>
<td>0</td>
</tr>
</tbody>
</table>

5.2.2 Steady-State Ramp Test

The steady-state ramp test presented in Table 7 is a calibration test for the powder flow rate and motor speed relation. Results from this test can be compared to the baseline test to see whether voltage signal changes are consistent or inconsistent between different motor speeds. The effects of changing RPM values (both up and down) are visible from the results of this test. The motor speeds were tested for one minute per motor speed in the order listed in Table 7:
Table 7. Steady-State Ramp Test.

<table>
<thead>
<tr>
<th>Motor Speed (RPM)</th>
<th>Duration (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>60</td>
</tr>
<tr>
<td>2.5</td>
<td>60</td>
</tr>
<tr>
<td>5</td>
<td>60</td>
</tr>
<tr>
<td>7.5</td>
<td>60</td>
</tr>
<tr>
<td>10</td>
<td>60</td>
</tr>
<tr>
<td>12.5</td>
<td>60</td>
</tr>
<tr>
<td>15</td>
<td>60</td>
</tr>
<tr>
<td>17.5</td>
<td>60</td>
</tr>
<tr>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td>17.5</td>
<td>60</td>
</tr>
<tr>
<td>15</td>
<td>60</td>
</tr>
<tr>
<td>12.5</td>
<td>60</td>
</tr>
<tr>
<td>10</td>
<td>60</td>
</tr>
<tr>
<td>7.5</td>
<td>60</td>
</tr>
<tr>
<td>5</td>
<td>60</td>
</tr>
<tr>
<td>2.5</td>
<td>60</td>
</tr>
<tr>
<td>0</td>
<td>60</td>
</tr>
</tbody>
</table>

5.2.3 Inverse Ramp Test

The inverse ramp test was designed to see the effects of starting at a high RPM and reducing to 0 RPM and returning over time back to a high RPM. Each test started at 12.5 RPM and measured for two minutes and reduced by 2.5 RPM until 0 RPM was reached. Each RPM was measured for the same amount of time. The behaviors of the inverse ramp test were compared to the steady-state ramp test to see if the flow behavior differs between starting at a high powder flow rate versus starting with no powder flow rate. The motor speeds were tested in for two minutes per motor speed in the order listed in Table 8:
Table 8. Inverse Ramp Test.

<table>
<thead>
<tr>
<th>Motor Speed (RPM)</th>
<th>Duration (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.5</td>
<td>120</td>
</tr>
<tr>
<td>10</td>
<td>120</td>
</tr>
<tr>
<td>7.5</td>
<td>120</td>
</tr>
<tr>
<td>5</td>
<td>120</td>
</tr>
<tr>
<td>2.5</td>
<td>120</td>
</tr>
<tr>
<td>0</td>
<td>120</td>
</tr>
<tr>
<td>2.5</td>
<td>120</td>
</tr>
<tr>
<td>5</td>
<td>120</td>
</tr>
<tr>
<td>7.5</td>
<td>120</td>
</tr>
<tr>
<td>10</td>
<td>120</td>
</tr>
<tr>
<td>12.5</td>
<td>120</td>
</tr>
</tbody>
</table>

5.3 Post-Processing

5.3.1 Butterworth Second-Order Section Filter

By increasing the sampling rate of the photodiode to over 200 samples per second, data could be collected more frequently. However, each sample in the data set was plotted all at once. A filter was needed to distinguish where most of the data points were actually on the graph. In order to find this, a Butterworth second-order section filter was developed in MATLAB to plot a more concise data set overlapping the unfiltered data. This graph was a subplot plotted directly on top of the unfiltered data.

The Butterworth second-order section filter was introduced into the post-processing MATLAB script using the ‘filtfilt’ command. The half power frequency was set to 0.0045/2, representing half the power of the laser, to reduce the noise from the unfiltered data and most accurately show where the majority of the data lay on the plot.
5.3.2 Uncertainty

According to the photodiode (Thorlabs PDA10A2) user guide, noise can contribute up to ±1.5 mV of uncertainty in any measurement. The electric scale (Mottler Toledo Precision Balance MS802S) has a readability of 0.010 g and can cause an uncertainty of ±0.01 g. It is also important to mention that the MATLAB file reads a text document containing all the data, and the data is created from LabVIEW, which gives uncertain values. For example, several data points at the beginning of the data collection seem to be sporadic values that affect the plots, especially in the weight vs. time plots. This is accounted for in the MATLAB script by removing the first few data points, but in some cases, they will still be plotted in these graphs. For example, the first data point shows the weight being at a maximum level, but the very next point is exactly 0 grams. This shows a large, negative powder flow rate in the 0 RPM region, when in actuality, the powder flow rate is at 0 g/s or very close to it. When taking a look at the data, it is important to view the powder flow rate of the RPM value of interest, which is unaffected by the data point that appears at the beginning of the data set. Also, data collection starts when the experiment is executed and stops when the DAQ is terminated. The time beyond the experimental process was not considered in the analysis.

Another source of uncertainty occurs because the sampling rate of the photodiode is different than the sampling rate of the electric scale, but they still plot the same amount of points together. This sometimes affects the powder flow rate reading, indicating that the rate is much smaller, even when it is clearly apparent that the number of grams collected by the scale do not match the powder flow rate. When this occurs in the results, these values are indicated with a (*) in Appendix C, where the data points for the scale weight and time were moved to an Excel file.
and the correct rate was calculated on Excel rather than using the MATLAB script. For most cases, the MATLAB script shows an accurate powder flow rate.

### 5.4 Results of Steady-State Baseline Test

#### 5.4.1 Example of Steady-State Baseline Test Data

Plots of photodiode sensor output vs. time and weight vs. time were created for each trial for the motor speeds listed in Table 6. The average signal output in volts and the average powder flow rate in grams/second were recorded for each interval and displayed directly on the graph. An example of two plots are shown below in Figure 38 and Figure 39:

![Graph](image-url)

**Figure 38.** Steady-state baseline test 7.5 RPM Trial 1 photodiode sensor output.
As seen from the plot of the photodiode sensor output in Figure 38, when switching the motor speed from 0 RPM to a set motor speed, there exists a dynamic region before the signal begins to stabilize. This trend is repeated in most trials, as seen in the data shown in Appendix C. Factors such as flow regime through the cross-sectional area of the tube and the effects of the boundary layer can explain the drop in voltage signal when the powder first passes through the laser. Also, the velocity of the gas will change as the powder is first loaded in the system before the velocity of the flow stabilizes. As seen at a later time, the signal also stabilizes. Therefore, it is important to examine the stabilized region after the overshoot of the drop-off region and record the change in voltage.

Most importantly, the change of photodiode sensor output from the initial signal to the sensor output of the motor speed region was recorded for each trial and averaged, as seen in
The change in photodiode sensor output was chosen instead of the raw voltage that the sensor detects because the photodiode sensor output does not always start at the same value. Also, the powder flow rates were recorded in each trial and averaged so that they can be correlated with the photodiode signal output, as seen in Table 10.

Table 9. Average Change in Sensor Output from Steady-State Baseline Test.

<table>
<thead>
<tr>
<th>RPM</th>
<th>Average Change in Sensor Output (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>0.0076 ± 0.0117</td>
</tr>
<tr>
<td>5</td>
<td>0.0223 ± 0.0181</td>
</tr>
<tr>
<td>7.5</td>
<td>0.0485 ± 0.0200</td>
</tr>
<tr>
<td>10</td>
<td>0.0594 ± 0.0308</td>
</tr>
<tr>
<td>12.5</td>
<td>0.0812 ± 0.0226</td>
</tr>
<tr>
<td>15</td>
<td>0.0861 ± 0.0196</td>
</tr>
<tr>
<td>17.5</td>
<td>0.0886 ± 0.0135</td>
</tr>
<tr>
<td>20</td>
<td>0.1181 ± 0.0161</td>
</tr>
</tbody>
</table>

Table 10. Average Powder Flow Rate from Steady-State Baseline Test.

<table>
<thead>
<tr>
<th>RPM</th>
<th>Trial 1 PFR</th>
<th>Trial 2 PFR</th>
<th>Trial 3 PFR</th>
<th>Average PFR (g/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>0.0587 ± 0.0073</td>
<td>0.0552 ± 0.0081</td>
<td>0.0560 ± 0.0091</td>
<td>0.0566 ± 0.0082</td>
</tr>
<tr>
<td>5</td>
<td>0.1169 ± 0.0116</td>
<td>0.1163 ± 0.0104</td>
<td>0.1188 ± 0.0111</td>
<td>0.1173 ± 0.0110</td>
</tr>
<tr>
<td>7.5</td>
<td>0.1819 ± 0.0161</td>
<td>0.1806 ± 0.0166</td>
<td>0.1784 ± 0.0168</td>
<td>0.1803 ± 0.0165</td>
</tr>
<tr>
<td>10</td>
<td>0.2376 ± 0.0191</td>
<td>0.2388 ± 0.0223</td>
<td>0.2369 ± 0.0187</td>
<td>0.2378 ± 0.0200</td>
</tr>
<tr>
<td>12.5</td>
<td>0.2979 ± 0.0280</td>
<td>0.2992 ± 0.0255</td>
<td>0.3014 ± 0.0292</td>
<td>0.2995 ± 0.0276</td>
</tr>
<tr>
<td>15</td>
<td>0.3536 ± 0.0246</td>
<td>0.3603 ± 0.0254</td>
<td>0.3641 ± 0.0275</td>
<td>0.3593 ± 0.0258</td>
</tr>
<tr>
<td>17.5</td>
<td>0.4012 ± 0.0607</td>
<td>0.4203 ± 0.0643</td>
<td>0.4174 ± 0.0573</td>
<td>0.4130 ± 0.0608</td>
</tr>
<tr>
<td>20</td>
<td>0.4784 ± 0.0445</td>
<td>0.4747 ± 0.0512</td>
<td>0.4709 ± 0.0484</td>
<td>0.4747 ± 0.0480</td>
</tr>
</tbody>
</table>

5.4.2 Photodiode Sensor Output and Powder Flow Rate Correlation

As shown in the literature [4-7], there exists some functional relationship between the photodiode sensor output and the powder flow rate. The results of the steady-state baseline test were more closely examined to verify the potential linear trend between the sensor output and
flow rate. The values from Table 9 and Table 10 were correlated based on their respective motor speeds. A plot of photodiode sensor output vs. powder flow rate is shown in Figure 40.

![Figure 40](image_url)

**Figure 40.** Photodiode sensor output vs. powder flow rate

The line of best fit represents an algebraic expression for the change in photodiode sensor output ($\Delta V$) with respect to powder flow rate ($\dot{m}$). The equation is represented by Equation (27):

$$\Delta V = 0.26\dot{m} - 0.0037$$  \hspace{1cm} (27)

A linear trend indeed exists between the change in photodiode sensor output and the powder flow rate, a trend that is confirmed from literature. A line of best fit was created and displayed as well as vertical and horizontal error bars relating to the standard deviations of the
sensor output and powder flow rate found at each motor speed interval. According to Ding et al. [4], the linear trend is expected to continue until the photodiode sensor output cannot follow the trend after 1.1 g/s, in which case the signal begins to not increase linearly with the powder flow rate.

5.5 Results of Intermediate Tests

5.5.1 Results of Steady-State Ramp Test

An average powder flow rate and standard deviation were calculated from three trials of the ramp test, as reported in Table 11. A percent difference was calculated between the powder flow rate of the steady-state baseline test and the ramp test to see if the powder flow rate remained consistent when performing the ramp testing. The percent difference was calculated for both the increasing and decreasing portions of the ramp test for each respective motor speed. Note that 20 RPM was the peak of the ramp test; therefore, only one data point could be taken at this motor speed.

Table 11. Powder Flow Rate Comparison Between Baseline Test and Ramp Test.

<table>
<thead>
<tr>
<th>RPM</th>
<th>SS Baseline PFR (g/s)</th>
<th>Increasing PFR (g/s)</th>
<th>Increasing % Difference</th>
<th>Decreasing PFR (g/s)</th>
<th>Decreasing % Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>0.0566</td>
<td>0.0462 ± 0.009</td>
<td>18.37%</td>
<td>0.0610 ± 0.010</td>
<td>7.77%</td>
</tr>
<tr>
<td>5</td>
<td>0.1173</td>
<td>0.1165 ± 0.011</td>
<td>0.68%</td>
<td>0.1208 ± 0.013</td>
<td>2.98%</td>
</tr>
<tr>
<td>7.5</td>
<td>0.1803</td>
<td>0.1767 ± 0.017</td>
<td>2.00%</td>
<td>0.1800 ± 0.018</td>
<td>0.16%</td>
</tr>
<tr>
<td>10</td>
<td>0.2378</td>
<td>0.2369 ± 0.21</td>
<td>0.38%</td>
<td>0.2424 ± 0.22</td>
<td>1.93%</td>
</tr>
<tr>
<td>12.5</td>
<td>0.2995</td>
<td>0.2969 ± 0.025</td>
<td>0.87%</td>
<td>0.3033 ± 0.029</td>
<td>1.27%</td>
</tr>
<tr>
<td>15</td>
<td>0.3593</td>
<td>0.3601 ± 0.31</td>
<td>0.22%</td>
<td>0.3666 ± 0.033</td>
<td>5.65%</td>
</tr>
<tr>
<td>17.5</td>
<td>0.4130</td>
<td>0.4130 ± 0.067</td>
<td>0.00%</td>
<td>0.4236 ± 0.070</td>
<td>2.57%</td>
</tr>
<tr>
<td>20</td>
<td>0.4747</td>
<td>0.4752 ± 0.051</td>
<td>0.11%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
As shown from the data, the greatest difference in powder flow rate is at 2.5 RPM, indicating an inconsistent powder flow rate at such a low RPM. It appears that on the decreasing side of the ramp test, a higher percent difference exists, indicating hysteresis in the system that affects the powder flow rate. If hysteresis is present in the system, it can be expected that the photodiode sensor output would be ultimately affected. Figures 41-43 show the results of the powder flow rates for the three trials to see if the scale data represents any hysteresis.

Figure 41. Steady-state ramp test weight vs. time response Trial 1.

As shown by the powder flow rate in Figure 41, there is no major dropoff in the low-RPM region. In fact, the powder flow rate remains steady. The weight vs. time graph shows the
maximum powder flow rate at 20 RPM and decreasing amounts at each subsequent RPM level until it is a flat line at 0 RPM. The differences in powder flow rates at each respective RPM can be examined. There exists a 91.08% difference between the increasing and decreasing 2.5 RPM powder flow rates (0.0325 g/s vs. 0.0621 g/s). Also, the powder flow rate increased by 6.99% in the 5 RPM region between the increasing and decreasing sections of the ramp test. All other powder flow rates showed a consistent increase in powder flow rate between 2% and 3%.

Figure 42 represents weight vs. time plot of the second trial of ramp test.

Figure 42. Steady-state ramp test weight vs. time response Trial 2.
The second trial shows a steady trend in powder flow rate with the highest flow rate at the 20 RPM region and decreasing as the motor speed decreases. Again, the increasing and decreasing sections were compared with respect to each motor speed. In this case, the opposite of Trial 1 was observed. The percent difference between the 2.5 RPM section was only 0.32%, and the percent difference of the 5 RPM section was 0.08%. The highest percent difference is at 2.15% between the two sections. Hysteresis still exists in this trial since the decreasing section did have a higher powder flow rate than the increasing section. Another trial was conducted to get a better idea of the hysteresis present in the ramp test.

Figure 43 represents the weight vs. time plot for the third trial of the ramp test.

![Figure 43. Steady-state ramp test weight vs. time response Trial 3.](image)
A similar trend is exhibited from the two previous trials. Again, an inconsistent powder flow rate is present in the 2.5 RPM region. A 31.69% difference exists between the increasing and decreasing sections for the 2.5 RPM region. For the 5 RPM region, a 4.27% difference exists. The other motor speeds showed differences of less than 2%. Hysteresis is present at low motor speeds, indicating that there must be a lower limit for detecting changes of powder flow rate in the system.

The results from the photodiode can show some understanding as to whether or not the hysteresis plays a factor in the photodiode sensor output. Figures 44-46 show the results of the photodiode sensor output for the three trials.

Figure 44. Steady-state ramp test photodiode sensor output response Trial 1.
Similar to experiments performed by Sciammarella et al [2], changes between small RPM increments were recorded in order to see if the optoelectronic sensor could record changes consistently. Starting at 0 RPM, the original photodiode sensor output is at 2.2223V and, as expected, the voltage decreases over time and reaches the lowest point at 20 RPM, indicating the highest amount of powder through the laser. After 20 RPM, the trend also continues by increasing, indicating a lower amount of powder through the laser at subsequent motor speeds. However, strange behavior occurs at low motor speeds, such as 2.5 RPM and 5 RPM. A major dropoff occurs at the beginning, starting at 2.5 RPM and through 5 RPM, before correcting itself around 7.5 RPM. On the other end, a major dropoff in photodiode signal output occurs again at 2.5 RPM, and at 0 RPM, it consistently remains at a lower reading of 2.1662V.

Figure 45. Steady-state ramp test photodiode sensor output response Trial 2.
Similar behavior was observed as the first trial. This time, the initial photodiode sensor output was 2.4007V and a decreasing trend occurs until 20 RPM. From there, the photodiode sensor output increases until a small dropoff occurs at 10 RPM and a major dropoff occurs at 5 RPM. Again, it drops at 2.5 RPM and remains at a consistently lower voltage reading of 2.2566V at 0 RPM. The behavior between the region of the first 7.5 RPM and the second 7.5 RPM follows an expected trend and behaves normally. At low RPM, distinctions occur.

Again, it can be shown that perhaps there is a lower limit of detecting powder flow rates from these extreme behaviors exhibited by the 2.5 RPM and 5 RPM regions. One more trial was performed to confirm this behavior, shown in Figure 46.

Figure 46. Steady-state ramp test photodiode sensor output response Trial 3.
The third trial shows major dropoffs at 2.5 RPM and 5 RPM once again. This time, the original photodiode sensor output begins at 2.3273V and has a major dropoff at the low-RPM range. This trial represented the least consistent trend between photodiode signal outputs and motor speeds. Again, the voltage reading drops at the end and remains consistently low, reading 2.2078V at the final 0 RPM region. The most consistent readings occur in the mid-range of motor speeds.

Hysteresis in the system can be a cause of these major dropoffs in the photodiode sensor output. The results from these tests show that at low motor speeds, the distribution of powder is not uniform and thus the optoelectronic sensor has difficulty with measuring.

### 5.5.2 Results of Inverse Ramp Test

The average powder flow rate of the inverse ramp test was compared to the powder flow rates found in the steady-state baseline test. A percent difference was found between the decreasing and increasing intervals of the inverse ramp test and the values found in the steady-state baseline test. The highest percent difference is found in the 2.5 RPM region once again, with an 8.66% difference on the decreasing section of the test. The other percent differences can be seen in Table 12.

<table>
<thead>
<tr>
<th>RPM</th>
<th>SS Baseline PFR (g/s)</th>
<th>Decreasing PFR (g/s)</th>
<th>Decreasing % Difference</th>
<th>Increasing PFR (g/s)</th>
<th>Increasing % Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.5</td>
<td>0.2995</td>
<td>0.2934 ± 0.028</td>
<td>2.04%</td>
<td>0.3000 ± 0.030</td>
<td>0.17%</td>
</tr>
<tr>
<td>10</td>
<td>0.2378</td>
<td>0.2462 ± 0.025</td>
<td>3.53%</td>
<td>0.2382 ± 0.021</td>
<td>0.17%</td>
</tr>
<tr>
<td>7.5</td>
<td>0.1803</td>
<td>0.1821 ± 0.018</td>
<td>1.00%</td>
<td>0.1754 ± 0.015</td>
<td>2.72%</td>
</tr>
<tr>
<td>5</td>
<td>0.1173</td>
<td>0.1229 ± 0.014</td>
<td>4.77%</td>
<td>0.1165 ± 0.012</td>
<td>0.68%</td>
</tr>
<tr>
<td>2.5</td>
<td>0.0566</td>
<td>0.0615 ± 0.011</td>
<td>8.66%</td>
<td>0.0577 ± 0.009</td>
<td>1.94%</td>
</tr>
</tbody>
</table>

Table 12. Powder Flow Rate Comparison Between Baseline Test and Inverse Ramp Test.
Figure 47 shows the weight vs. time response for the first trial of the inverse ramp test. The percent difference in powder flow rate between the 2.5 RPM region was 5.79% and the powder flow rates are typically higher on the decreasing motor speed portion of the inverse ramp test.

![Graph showing weight vs. time response for the inverse ramp test](image)

**Figure 47. Inverse ramp test weight vs. time response Trial 1.**

Trial 2 showed the same trend as the first trial, as shown in Figure 48. The percent difference in powder flow rate for the 2.5 RPM region was 6.57%, and for 5 RPM, the difference was 5.75%, whereas the other powder flow rates for the other motor speeds differed up to 3.50%. Hysteresis is still present in tests that involve variable motor speeds. The scale data shows a consistent trend, so the photodiode sensor output was examined next.
Figure 48. Inverse ramp test weight vs. time response Trial 2.

Two trials of the inverse ramp test were conducted to see if these fluctuations in the photodiode sensor output still exist even if the test starts at a high motor speed. As shown in Figure 49, the same dropoffs occur at lower RPM values, especially in the 2.5 RPM and 5 RPM regions. As expected, at higher RPM values, the lower the average signal, since there is more powder flowing through the system. This is seen both at the beginning and ending of the test. In the 0 RPM range, the signal sits at a consistent 2.2776V before dropping once again when the motor speed was set to 2.5 RPM. Consistent results occur at 7.5 RPM and above, as seen in the steady-state ramp tests performed previously.
Figure 49. Inverse ramp test photodiode sensor output response Trial 1.

A second trial was conducted with a slight change. The behavior of switching back to 0 RPM for two minutes at the very end of the test was investigated to see if the photodiode sensor output would be consistent with the 0 RPM in the middle of the test (Figure 50):
Figure 50. Inverse ramp test photodiode sensor output response Trial 2.

The highest voltage should be present when no powder is flowing through the system. The 0 RPM at the end of the trial follows the consistency found in the steady-state baseline tests, but the 0 RPM in the middle of the test still does not follow a consistent pattern. Again, the drop-off occurs at the 2.5 RPM region. This shows that the motor speed lower limit results around the 5 RPM to 2.5 RPM region. Consistent results are found at 7.5 RPM and above. The signal ends at 2.3697 V when no powder is flowing through the system.
In summary, the results of the cycle testing show that mass flow rates that are low will not have consistent cross-sectional powder dimensions. That is, the distribution of powder flowing through the system is not uniform when the motor speed is low. According to the weight vs. time plots, it appears that the flow may be consistent when looking at the total mass with respect to time since there are no fluctuations in data given by the scale, but the flow remains variable along the cross-sectional or axial areas. This would best explain the fluctuations seen in the voltage vs. time plots at low motor speeds.
CHAPTER 6: DISCUSSION, CONCLUSION, AND FUTURE WORK

6.1 Discussion

As discovered from the research performed on the optoelectronic sensor, it can be said that the sensor can reliably read the density of powder flowing through a system under certain conditions. For example, the sensor is able to get discernable signals starting with a 7.5 RPM motor speed up to 20 RPM, but clearly there exists a lower limit of measuring the powder flow. Several factors can contribute to this lower limit. When such little powder is flowing through the system, the distribution of the powder does not stay consistent, as seen in the dropoffs of data found in the steady-state ramp tests. The signal requires some time after the overshoot region (typically 30 to 100 seconds) to stabilize and read the powder flow rate accurately.

There are several other factors worth mentioning about the reliability the optoelectronic sensor. Factors such as the boundary layer, cross-sectional area between the test tube section and piping, turn radius of the tubing, pipe friction and roughness, gravity, etc., can all contribute to a change of sensor output. As shown from the experiments performed, the Lexan tubing was clearly not a viable option to be used with the optoelectronic sensor. The change in cross-sectional area was too great, which caused a boundary layer of flow that would make the powder stream behave nonuniformly. When trying to correct this behavior by elongating the tube, powder began to collect at the end of the tube, indicating that the flow was not consistent and not optimal for measurement. Another factor that caused undesired signal outputs was the fact that over time, the metal powder would stick to the edges of the Lexan tubing and would decrease the
signal greatly. An electrical charge was also discovered inside the Lexan tubing, known as the electrostatic force, that was caused constant particle interaction with the Lexan tubing, the piping, and other particles, causing the powder to act nonuniformly in the chamber during testing.

Switching to circular glass tubing, although more reliable, still has some downfalls. Although it corrected the cross-sectional area issue and the powder buildup on the edges issue, the circular nature of the tubing causes the laser to diffract, thus not giving an entirely perfect signal to the photodiode from the dispersion of the light that defocuses the effect of the laser. An idea to correct this issue is to custom order or create a small rectangular glass tube with the same cross-sectional area as the piping and make the length of the rectangular tube as small as possible so as not to create a large viewing window. That way, flow would remain consistent throughout the system and the laser would have a flat edge to measure from.

Another explanation for the dropoff region in the steady-state tests is because of the nature of the powder feeder. The powder feeder is a gravity-driven device, where powder is suctioned off a plate at the bottom of the feeder that rotates at a certain motor speed. As seen with the gas testing done with the Lexan tube, there exists powder in the system even at 0 RPM, sometimes when the gas is turned off at the end of the test; then, when turned back on, a distinguishable sensor output is given. Because of gravity, the powder is able to enter the flow stream without initiation from the powder feeder but is still picked up by the carrier gas when turned on. This also brings the question of whether or not saltation, or settling of the powder in
the system, is occurring due to a low fluid velocity not being able to pick up and carry the powder [10]. Therefore, it might be important to analyze the gas velocity of the system to ensure that what was found in the hysteresis gas study was indeed correct.

From the powder feeder and throughout the system, there is tubing that does not follow a straight-line path to the electronic scale at the end of the system. In fact, the experimental setup was designed with a 90° bend to see the effects of turn radius on the signal output. Regardless of the positioning of the tubing, whether it is horizontal or vertical, the optoelectronic sensor is able to show a consistent powder flow when the flow stabilizes. Perhaps a better sensor output would be found if the sensor were placed closer to the powder feeder, not allowing as many bends in the tubing before it reaches the sensor. Other small factors can affect the signal output such as the temperature and humidity of the room. Also, even if the test tube system is contained in a closed container, any outside light can affect the sensor output. Having the laser pass through the powder stream in complete darkness would give the most realistic sensor output. Also, human error due to the experimental setup can affect the average sensor output since one user changes the motor speed while another user changes the value of the motor speed on the LabVIEW program at the same time. Since it cannot be perfectly timed, some values might be slightly miscalculated due to this human error.

6.2 Conclusion

In the end, the optoelectronic sensor is a device that is capable of tracking the powder flow rate through a DED system. By correlating the photodiode sensor output to the powder flow
rate through the system, a linear trend was found to match the signal output to the flow rate of
the powder through the system. The optoelectronic sensor proves to be able to track powder flow
better when the motor speed of the powder feeder is not variable. During variable tests such as
the steady-state ramp test, the optoelectronic sensor can detect changing powder flow rates from
7.5 RPM and above. It was found that a lower limit exists at low motor speeds, particularly in the
2.5 RPM to 5 RPM range. The inconsistency of the photodiode signal can be attributed to a
nonuniform distribution of powder when a small amount of powder is flowing through the
system. Other factors, such as the boundary layer, cross-sectional area, and material used for a
test chamber, affect the photodiode sensor output greatly and play an important role when
utilizing an optoelectronic sensor in DED applications.

6.3 Future Work

A more precise look at the dynamic response characterization of the data is needed since
there are some common dynamic properties in the steady-state baseline tests that were not taken
into consideration. There exists some overshoot and settling that is occurring in the temporal
data. Because the overshoot was taken into consideration in the data collection, more accurate
data could be taken if only the data points after the settling time were taken into consideration.
Also, the overshoot, settling time, and rise time could be characterized for each trial if the
dynamic trend exists. These dynamic characterizations could ultimately explain the physical
dynamics of the flow within the tube.
Overall, the optoelectronic sensor proves to be a viable way of monitoring powder flow rate in DED applications and can prove to also be useful in other industrial applications. The next steps for utilizing this sensor is to examine the powder flow through the OPTOMEC while a build is being created at different motor speed settings. The measurement section of the tubing can be replaced easily with pressure fittings and the optoelectronic sensor can be securely mounted on the side of the machine. The optoelectronic sensor would be able to tell the user the actual powder flow rate by detecting changes in density of the powder.

The consistency of the builds can further be examined by implementing a PID controller that would be able to adjust the motor speed based on feedback received from the optoelectronic sensor, as shown in Figure 51. That way, if the signal becomes inconsistent, it will adjust the motor speed to keep the desired sensor output consistent. Builds can be compared with and without using a PID control, and the quality of the parts as well as geometric variations can be calculated. The amount of error associated with the control can be monitored and adjusted as well until it can be shown that the quality of builds remains repeatable and reliable.

Figure 51. Possible PID control of powder flow rate.
If a consistent powder flow rate is established, then a further step can be taken to examine the melt pool interaction between the laser and the powder. The size and consistency of the melt pool from laser deposition and powder fusion can be monitored using a melt pool camera mounted directly perpendicular to the melt pool along the deposition head. Again, instead of monitoring the consistency and quality of builds where many different factors can change the uniformity of the component, the size of the melt pool can contribute a greater perspective of consistency. The effects of using a PID control and not using the control can be examined by measuring the size of the melt pool at different motor speeds. If the melt pool remains at a uniform size, then it can be shown that a single bead or track of beads should remain consistent and parts would be able to be built as net shaped to the designed part as possible.
REFERENCES


APPENDIX A

MATLAB SCRIPT
clear all; % Clears all variable data
close all; % Closes all open figures
clc; % Clears all command history

% retrieve and read file
[filename, path] = uigetfile('*.*','Select powder flow .lvm file');
current_file = fopen(strcat(path, filename));
work_array = textscan(current_file, '%n %n %n %n');
work_array_length = length(work_array);
fclose(current_file);
% celldisp(work_array);

t = work_array{1}; % Time (1st column from data) (seconds)
w = work_array{2}; % Scale Weight (2nd column from data) (grams)
V = work_array{3}; % Sensor Voltage Output (3rd column from data) (volts)
RPM = work_array{4}; % Motor Speed (4th column from data) (RPM)

% Correction since first data point of time is always zero.
t(1) = t(2);
t = t - t(2);
dt = t(3) - t(2); % Change in time
n = length(t); % Number of data points

% dts = 1000;
% pfri = (w(1:dts:end-1) - w(2:dts:end))./dt/dts;

iline = 1;
while RPM(iline)==0
    iline = iline + 1;
end
iend = iline;

while RPM(iend)==RPM(iline)
iend = iend + 1;
end

Vmin = min(V); % Minimum voltage
Vmax = max(V); % Maximum voltage
Vrange = Vmax - Vmin; % Range of voltage

wmin = min(w); % Minimum scale weight
wmax = max(w); % Maximum scale weight
wrange = wmax - wmin; % Range of scale weight

pfri = 0*w; % Initialize powder flow rate instantaneous
pfri(2:end) = (w(2:end) - w(1:end-1))./dt; % Calculate instantaneous powder flow rate
% [pfrit,j] = pfri(pfri~=0);

n1=1;
for i=iline:iend
    if w(i) ~= w(i-1)
        wc(n1) = w(i);
        t1(n1) = t(i);
        Vc(n1) = V(i);
        n1 = n1+1;
        irpm(n1) = i;
    end
end

pfc = (wc(2:end)-wc(1:end-1))./(t1(2:end)-t1(1:end-1));

RPMn(1) = 1; %RPM indice
RPMC(1) = RPM(1); %temporary RPM

vRPM = t*NaN;
wRPM = t*NaN;
lRPM = t*NaN;

t_lines = t;
i = 2;
j = 1;

% Initialize data
for i=1:n
    if RPM(i) ~= RPMC(j)
        RPMC(j+1) = RPM(i);
        RPMn(j+1) = i;
        j = j+1;  %j counter
        t_lines(i+1) = t(i);
        vRPM(i) = 0;
        vRPM(i+1) = Vmax*1.25;
        wRPM(i) = 0;
        wRPM(i+1) = wmax*1.25;
    end
end
RPMn(j+1) = n;  %Final location of RPM
RPMC(j+1) = RPM(n);

nRPM = length(RPMn);  %Number of RPMs
V_avg = RPMn(1:end-1)*0;  %voltage average
w_avg = RPMn(1:end-1)*0;  %weight average
pfr_avg = RPMn(1:end-1)*0;  %average powder flow rate

% Calculate averages for a given RPM
for i=2:nRPM
    V_avg(i-1) = mean(V(RPMn(i-1):RPMn(i)));  %voltage
    w_avg(i) = sum(w(RPMn(i-1):RPMn(i))-w(RPMn(i-1)))/(t(RPMn(i))-t(RPMn(i-1))));  %weight
    pfr_avg(i-1) = mean(pfri(RPMn(i-1):RPMn(i)));  %powder flow rate
% Filtering

dl = designfilt('lowpassiir', 'FilterOrder', 12, ...
    'HalfPowerFrequency', 0.0045/2, 'DesignMethod', 'butter');

d1 = designfilt('lowpassiir', 'FilterOrder', 12, ...
    'HalfPowerFrequency', 0.075, 'DesignMethod', 'butter');

y = filtfilt(d, V);

% Standard Deviation Calculations

y2 = y(iLine:iEnd);
pfcf = filtfilt(d1, pfc);

sd_pf = std(pfcf);  % powder flow standard deviation
sd_V = std(y2);  % std dev of the rpm range data
st_V = settlingtime(y2, 300);  % settling time of the rpm range data

st1_V = st_V(1);  % first settling time for voltage
steady_V = find(y2 >= st1_V);  % settling voltage time index
tVsteady = t(steady_V:iEnd);  % steady-state voltage time range

y3 = y2(steady_V:end);  % steady-state voltage range
Vsteady_avg = mean(y3);  % steady-state mean voltage
Vsteady_sd = std(y3);  % steady-state voltage standard deviation

rt_V = risetime(y2, 200);  % rise time of the rpm range data
os_V = overshoot(y2);  % overshoot time of voltage for rpm range data

Vsteady = find(t >= st_V);

% Plot of Voltage vs. Time

figure(1)
subplot(1,1,1)
plot(t, V, '.')
hold on
plot(t, y, '.');
VvsT = strcat('Voltage vs. Time: ', '{ ', ')', filename);

% title('Voltage vs. Time')
title(VvsT)
xlabel('Time (s)')
ylabel('Photodiode Sensor Output (V)')

ylim('manual')  % Sets boundaries in the y-direction
hold on;
plot(t_lines, vRPM)  % Vertical line plot
yRPM = Vmin + 0.02*Vrange;  % RPM display in the y-direction
yV = Vmin + 0.98*Vrange;  % Voltage display in the y-direction

for i=1:nRPM-1
    txt = sprintf(' %.2f RPM', RPMC(i));  % 2 decimal place RPM reading
    text(t(RPMn(i)), yRPM, txt, 'FontSize', 7);  % apply text on graph (RPM)
    strjust(txt, 'center');
vtxt = sprintf(' %.4f V n 0.0015', V_avg(i)); % 4 decimal place voltage reading
    text(t(RPMn(i)),yV,vtxt, 'FontSize', 7); % apply text on graph (V)
    strjust(vtxt, 'center');
end
hold off;

% % Overshoot and Settling Time
S1 = stepinfo(y(iline:iend),t(iline:iend),V_avg(2))

% Plot of Scale Weight vs. Time
figure(2)
plot(t,w)
WvsT = strcat('Weight vs. Time: ', {' '), filename);
% title('Weight vs. Time')
    title(WvsT)
    xlabel('Time (s)')
    ylabel('Scale Weight (g)')
    ylim('manual') % Sets boundaries in the y-direction
    hold on;
    plot(t_lines,wRPM) % Vertical line plot
    yRPM2 = wmin + 0.02*wrange; % RPM display in the y-direction
    yw = wmin + 0.98*wrange; % Scale weight display in the y-direction
for i=1:length(RPMn)-1
    txt = sprintf(' %.2f RPM', RPM(i)); % 2 decimal place RPM reading
    text(t(RPMn(i)),yRPM2,txt, 'FontSize', 7); % apply text on graph (RPM)

    wtxt = sprintf(' %.4f g/s n 0.010', pfr_avg(i)); % 4 decimal place powder flow reading
    text(t(RPMn(i)),yw,wtxt, 'FontSize', 7); % apply text on graph (g/s)
end
APPENDIX B

VORTEX HOPPER DESIGN
DIMENSIONS THAT CORRESPOND TO O-RING PLACEMENT:
0.09375 - THICKNESS
0.06 - DEPTH
2.989 - INSIDE DIAMETER
(O-RING DIMENSIONS ARE MIRRORED ON HOPPER BASE)
APPENDIX C

STEADY-STATE BASELINE TEST DATA
2.5 RPM

For the first trial at 2.5 RPM, the average photodiode sensor output was 2.1169V and had an average powder delivery rate of 0.0587 g/s (3.522 g/min). The original photodiode sensor output at 0 RPM was 2.1219V and the final photodiode sensor output was 2.1418V.

For the second trial at 2.5 RPM, the average photodiode sensor output was 2.0954V and had an average powder delivery rate of 0.0552 g/s (3.312 g/min). The original photodiode sensor output at 0 RPM was 2.1210V and the final photodiode sensor output was 2.1048V.
For the third trial at 2.5 RPM, the average photodiode sensor output was 2.0798V and had an average powder delivery rate of 0.0560 g/s (3.360 g/min). The original photodiode sensor output at 0 RPM was 2.0720V and the final photodiode sensor output was 2.1147V.

For the first trial at 5 RPM, the average photodiode sensor output was 2.1059V and had an average powder delivery rate of 0.1169 g/s (7.014 g/min). The original photodiode sensor output at 0 RPM was 2.1104V and the final photodiode sensor output was 2.1344V.
For the second trial at 5 RPM, the average photodiode sensor output was 2.0910V and had an average powder delivery rate of 0.1163 g/s (6.978 g/min). The original photodiode sensor output at 0 RPM was 2.1244V and the final photodiode sensor output was 2.1196V.

For the third trial at 5 RPM, the average photodiode sensor output was 2.0889V and had an average powder delivery rate of 0.1188 g/s (7.128 g/min). The original photodiode sensor output at 0 RPM was 2.1180V and the final photodiode sensor output was 2.1426V.
For the first trial at 7.5 RPM, the average photodiode sensor output was 2.0871V and had an average powder delivery rate of 0.1819 g/s* (10.914 g/min). The original photodiode sensor output at 0 RPM was 2.1431V and the final photodiode sensor output was 2.1236V.

For the second trial at 7.5 RPM, the average photodiode sensor output was 2.0678V and had an average powder delivery rate of 0.1806 g/s (10.836 g/min). The original photodiode sensor output at 0 RPM was 2.1214V and the final photodiode sensor output was 2.1067V.
For the third trial at 7.5 RPM, the average photodiode sensor output was 2.0671V and had an average powder delivery rate of 0.1784 g/s (10.704 g/min). The original photodiode sensor output at 0 RPM was 2.1030V and the final photodiode sensor output was 2.1045V.

For the first trial at 10 RPM, the average photodiode sensor output was 2.2360V and had an average powder delivery rate of 0.2376 g/s (14.256 g/min). The original photodiode sensor output at 0 RPM was 2.2861V and the final photodiode sensor output was 2.2942V.
For the second trial at 10 RPM, the average photodiode sensor output was 2.2328V and had an average powder delivery rate of 0.2388 g/s (14.328 g/min). The original photodiode sensor output at 0 RPM was 2.3035V and the final photodiode sensor output was 2.2874V.

For the third trial at 10 RPM, the average photodiode sensor output was 2.2395V and had an average powder delivery rate of 0.2369 g/s* (14.214 g/min). The original photodiode sensor output at 0 RPM was 2.2395V and the final photodiode sensor output was 2.3193V.
12.5 RPM

For the first trial at 12.5 RPM, the average photodiode sensor output was 2.2263V and had an average powder delivery rate of 0.2979 g/s (17.874 g/min). The original photodiode sensor output at 0 RPM was 2.2436V and the final photodiode sensor output was 2.3139V.

For the second trial at 12.5 RPM, the average photodiode sensor output was 2.2332V and had an average powder delivery rate of 0.2992 g/s* (17.952 g/min). The original photodiode sensor output at 0 RPM was 2.3157V and the final photodiode sensor output was 2.3222V.
For the third trial at 12.5 RPM, the average photodiode sensor output was 2.2352V and had an average powder delivery rate of 0.3014 g/s (18.084 g/min). The original photodiode sensor output at 0 RPM was 2.3151V and the final photodiode sensor output was 2.3078V.

15 RPM

Figure A-16. Steady-state baseline test 15 RPM Trial 1 results.
For the first trial at 15 RPM, the average photodiode sensor output was 2.2131V and had an average powder delivery rate of 0.3536 g/s (21.216 g/min). The original photodiode sensor output at 0 RPM was 2.2757V and the final photodiode sensor output was 2.3093V.

![Graph](image1)

**Figure A-17. Steady-state baseline test 15 RPM Trial 2 results.**

For the second trial at 15 RPM, the average photodiode sensor output was 2.2137V and had an average powder delivery rate of 0.3603 g/s* (21.618 g/min). The original photodiode sensor output at 0 RPM was 2.3131V and the final photodiode sensor output was 2.3100V.

![Graph](image2)

**Figure A-18. Steady-state baseline test 15 RPM Trial 3 results.**
For the third trial at 15 RPM, the average photodiode sensor output was 2.2091V and had an average powder delivery rate of 0.3641 g/s (21.846 g/min). The original photodiode sensor output at 0 RPM was 2.3054V and the final photodiode sensor output was 2.3123V.

**17.5 RPM**

Figure A-19. Steady-state baseline test 17.5 RPM Trial 1 results.

For the first trial at 17.5 RPM, the average photodiode sensor output was 2.1758V and had an average powder delivery rate of 0.4012 g/s (24.072 g/min). The original photodiode sensor output at 0 RPM was 2.2869V and the final photodiode sensor output was 2.2709V.

Figure A-20. Steady-state baseline test 17.5 RPM Trial 2 results.
For the second trial at 17.5 RPM, the average photodiode sensor output was 2.1763V and had an average powder delivery rate of 0.4203 g/s (25.218 g/min). The original photodiode sensor output at 0 RPM was 2.2814V and the final photodiode sensor output was 2.1672V.

Figure A-21. Steady-state baseline test 17.5 RPM Trial 3 results.

For the third trial at 17.5 RPM, the average photodiode sensor output was 2.1730V and had an average powder delivery rate of 0.4174 g/s (25.044 g/min). The original photodiode sensor output at 0 RPM was 2.2423V and the final photodiode sensor output was 2.2702V.

20 RPM

Figure A-22. Steady-state baseline test 20 RPM Trial 1 results.
For the first trial at 20 RPM, the average photodiode sensor output was 2.1645V and had an average powder delivery rate of 0.4784 g/s (28.704 g/min). The original photodiode sensor output at 0 RPM was 2.2864V and the final photodiode sensor output was 2.2779V.

For the second trial at 20 RPM, the average photodiode sensor output was 2.1424V and had an average powder delivery rate of 0.4747 g/s (28.482 g/min). The original photodiode sensor output at 0 RPM was 2.2567V and the final photodiode sensor output was 2.2637V.

Figure A-23. Steady-state baseline test 20 RPM Trial 2 results.

For the second trial at 20 RPM, the average photodiode sensor output was 2.1424V and had an average powder delivery rate of 0.4747 g/s (28.482 g/min). The original photodiode sensor output at 0 RPM was 2.2567V and the final photodiode sensor output was 2.2637V.

Figure A-24. Steady-state baseline test 20 RPM Trial 3 results.
For the third trial at 20 RPM, the average photodiode sensor output was 2.1434V and had an average powder delivery rate of 0.4709 g/s (28.254 g/min). The original photodiode sensor output at 0 RPM was 2.2097V and the final photodiode sensor output was 2.2591V.