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Two Powder Stream Diagnostics for Laser Deposition Processes

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Abstract

The velocity, density, and mass flow of particles suspended in a subsonic gas stream are important aspects of plasma spray and laser deposition processes. This paper will focus on two optical diagnostic techniques applied to the metal powder streams out of a powder feeder and into a new nozzle developed specifically for such applications. An important characteristic of the new powder nozzle is that it produces a very small column (approximately 1mm diameter) of powder which can be used for small focus laser deposition and cladding processes. Laser Doppler Velocimetry (LDV) was applied to the nozzle's output to better understand the kinetic parameters (velocity and spatial density) of exiting particles. Optical scattering of the powder stream was used to measure the total mass flow into the nozzle. Different light scattering detector scenarios applied to the input powder stream were used to identify signals useful for mass flow feedback control. Both of these techniques have the advantages of being fast, non-invasive diagnostics of the powder flow characteristics, and with a well established theoretical framework. Together, or individually, these diagnostics can provide real-time control or post-process analysis of the powder stream.

Introduction

As part of the Laser Engineered Net Shape (LENS) program at Sandia Laboratories, we have been interested in the metal powder stream characteristics of the feeder and nozzle. About the same time it was found the mass flow properties from the powder feeder could also have great effects on those processes.

An effort was made to determine diagnostic procedures for both the feeder and nozzle representing their most important characteristics. First, it was necessary to identify those output parameters of both the nozzle and the powder feeder that might have the greatest effect on different processes. The velocity profile of the particles within the nozzle exiting stream was found to be most critical. Laser Doppler Velocimetery (LDV) was selected as the diagnostic technique. It has been widely used[1-4] and instruments which can compute individual particle velocities and accumulated velocity distributions have been marketed.

Temporal stability of the powder feeder output seemed to have the greatest impact on deposition processes. This was deduced from some early qualitative visual inspection of the powder stream and some correlation to resulting ripple type variations on prototype specimens. Finding a diagnostic tool that would quickly and accurately measure powder stream mass flow from the feeder was difficult, since fast response and high sensitivity are hard to find in most sensors. A technique would be required which had a minimum 1msec response time, could detect changes of less than 1g/min in flow, and had a sensitivity of approximately 17μg/msec. A 1-20g/min measurement range was an additional requirement. Non-intrusive techniques were more likely to achieve this sensitivity, than a direct measurement like scaled mass loss.

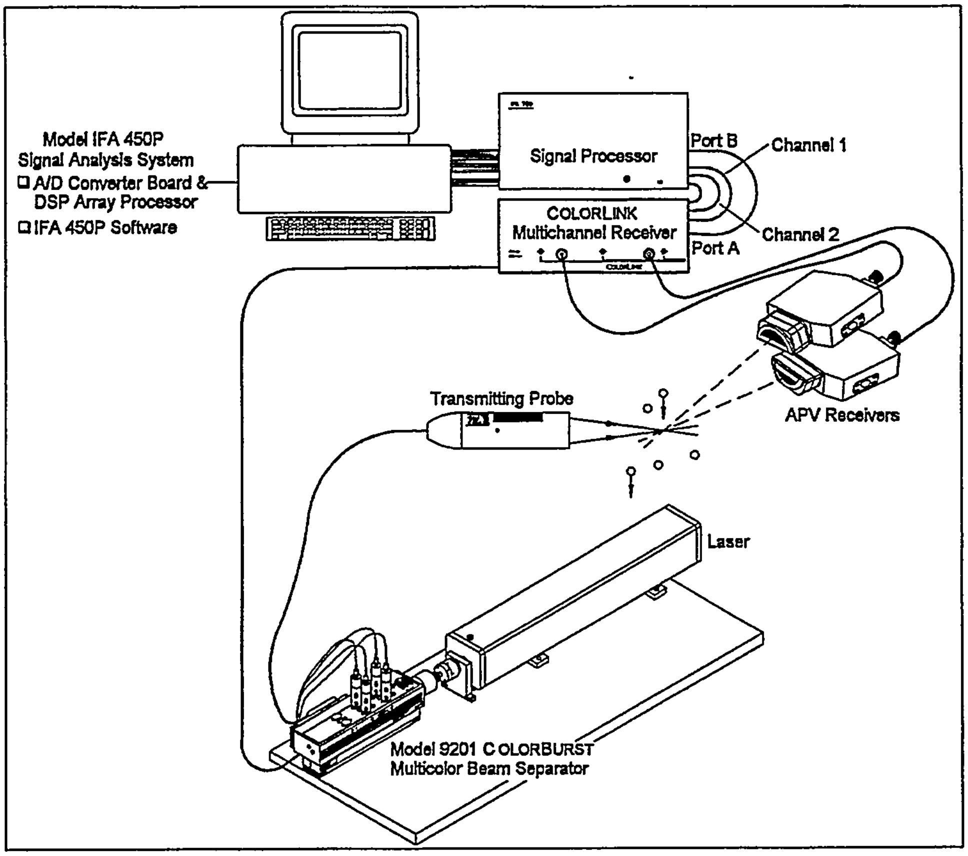
After looking at the feasibility of techniques involving ultrasonics, magnetic fields, capacitance changes, and light scattering techniques, the latter appeared to be most promising. Such a technique was developed for this application at Sandia National Laboratories; however patenting of the light scattering sensor technology prohibits disclosure of further details. This paper will describe some general aspects of particle mass flow as related to metal powder gas flows.

Also, in the process of trying to find a temporally stable powder source, different powder feeders were examined with this new powder flow sensor, including one commercially available rotary type, one custom rotary type, and one custom screw feed type.

Laser Doppler Velocimetry

Theory

Laser Doppler Velocimetry (LDV) has proven itself to be a useful tool for finding specific flow characteristics of a particle stream. It has the potential for measuring particle density and velocity profile aspects[1-4], as well as particle sizes if forward scattering phase data is further analyzed. The present system computed single axis particle velocity and density data for a variety of powder stream parameters. Figure 1 depicts an LDV system that includes forward scattering receivers. In the absence of forward scattering detectors, a back scattering probe/receiver can derive good velocity density functions and relative particle density data from the measured Doppler signal burst rate.



Model IFA 450P in an APV System

Figure 1. LDV setup including phase probes.

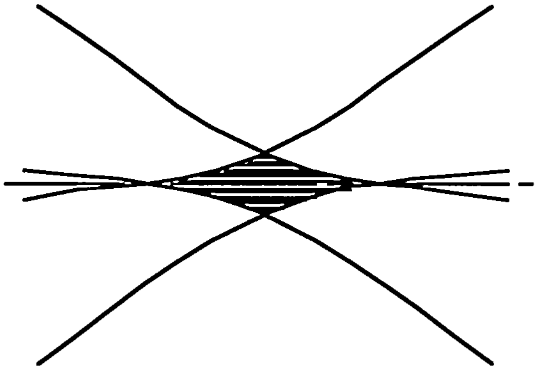


Figure 2. LDV measurement volume.

Forward scattering or back scattering implementation of the LDV system can be used to determine the particle velocity information. Figure 2 shows an enlarged view of the measurement volume created by two intersecting focused beams from the transmitting head. For an argon-ion laser this overlapping beam region is typically formed from a pair of beams at the 514 or 488nm wavelengths. The pair of 514nm beams are formed from a single beam being split evenly in intensity by an acousto-optic modulator. When combined in the small overlap volume, the two beams form an interference pattern with fringes perpendicular to the axis of particle flow. This overlap or measurement volume contains fringes within a tube space of approximate dimensions 165.5μ diameter by 3.4mm long, with a fringe spacing of approximately 5.3μ. This grid of bright and dark regions is typically oriented perpendicular to the direction of particle flow. When individual particles pass through this pattern the laser light is scattered in both forward and backward directions with intensity fluctuations, whose main frequency component should be equal to the fringe spacing divided by the velocity of the particles.

In order to collect the back scattered light, the measurement volume is imaged back into the transmitter housing through the transmitting lens and an aperture to block out stray light. A fiber optic probe placed behind this aperture then collects the scattered light which is transferred to the photo-multiplier tube (PMT) and amplification unit. The temporal signal generated is then sent to an analog-to-digital (A/D) board in a PC, which sends its' output to a digital signal processing (DSP) board in the same PC. A fast fourier transform (FFT) is performed on the signal and a power density function (PDF) in the frequency domain is computed. Conversion of the PDF to a velocity density function (VDF) is a simple calculation by the following relation, since the fringe spacing is known from the optical parameters.

$$VDF = (FringeSpacing) \cdot PDF \tag{1}$$

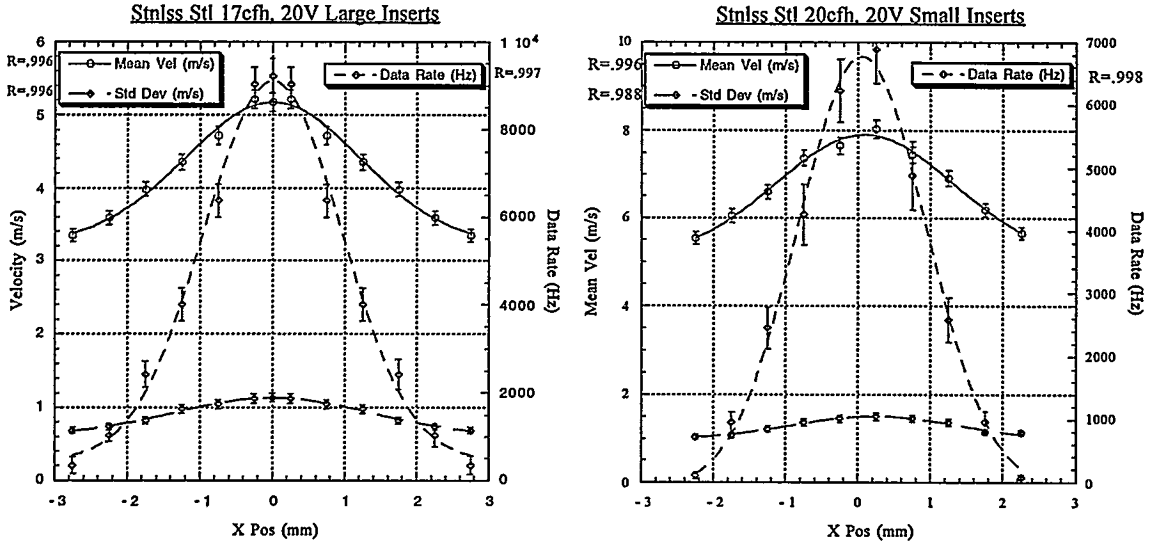
The VDF is a relative (in magnitude) and not absolute density function because the signals used to generate it are essentially random samples from the total scattered light with a large enough Doppler burst signal to trigger the detector system. A single VDF is a collection of Doppler burst signals that make up the typically normal distribution of particle velocities.

One can examine the rate at which the Doppler burst data was recorded by the system to obtain spatial density data. A Doppler burst signal is the result of scatter from small particles passing through the measurement fringe pattern described above. For the small measurement volume referred to above, the data rate corresponds directly to a particle density in that space. The Doppler burst data rate is the rate at which the instrumentation analyzes the Doppler burst signals, within preset parameters. Acceptable parameters for which a single Doppler burst can be analyzed are a minimum signal level threshold and a particular frequency window. Any Doppler burst signals meeting these conditions will be added to the total VDF for that measurement. Assuming that the particles are distributed evenly in the particle stream^5, one can assume the data rate represents a relative particle density distribution function.

Measured Data

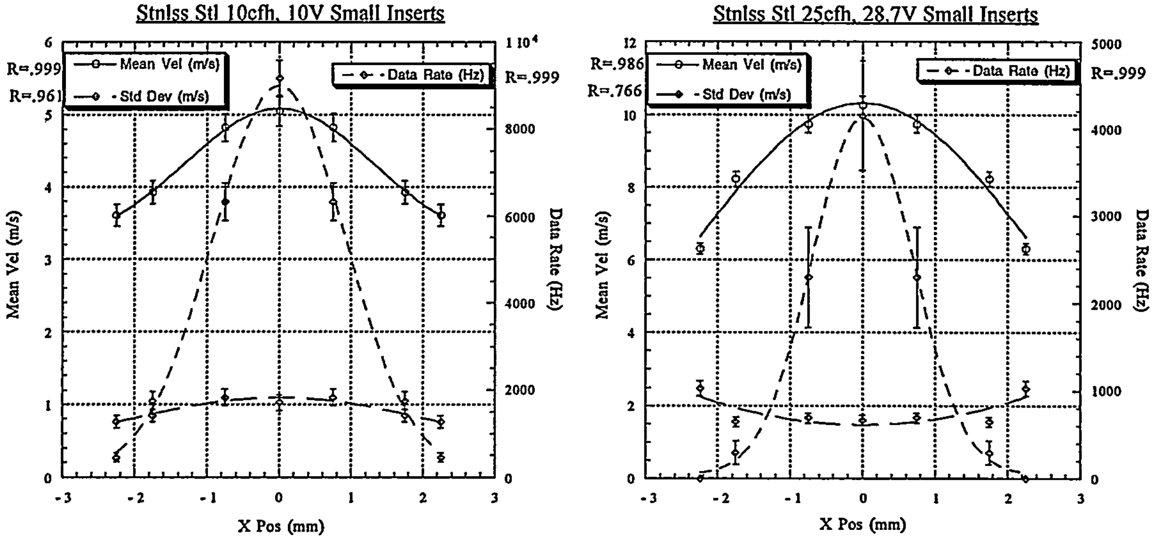
For our particular nozzle the mean velocity, velocity standard deviation, and particle density were measured. These measurements, shown in Figures 3 and 4, were taken at various lateral positions through the nozzles vertical powder stream column, at it's most narrow width. Except for Figure 3b) the data points reverse from the center of the particle flow, outward. The data points are mirrored on the graph in the opposite direction. All data was taken for stainless steel powder, 325/D mesh size (≤45μ). Subsequent SEM scans of the powder revealed a distribution that had a maximum of 200μ, mean of 47.6μ, and standard deviation of 43μ.

The spatially dependent data below was fit by a gaussian equation. The error bars at each data point represents a 95% (or 2 σ) confidence interval for the measurement.



a) Large inserts. b) Small inserts.

Figure 3. Nozzle output velocity & particle density profiles for approximately same conditions.



a) Low flow (7.4g/min.) b) High flow (12.8g/min.)

Figure 4. Nozzle output velocity & particle density profiles.

For the powder column flowing in an open environment there are no spatial boundary conditions. It is possible for the particle column to exhibit a laminar flow. But, the velocity profile may not necessarily be parabolic, such as for fluid flow through a tube[6]. Rather, it was shown that the particle spatial velocity and density profiles were gaussian as the corresponding curve fits all come very close (see correlation coefficients R in Figures 3 & 4) to the actual data, with the exception of one deviation. The data for the high flow conditions in Figure 4b) exhibited a more prominent rounding off of the velocity profile. There is also an anomolous increase in velocity standard deviation towards the edges. This phenomenon which corresponds to a general broadening of the velocity normal distribution at those points is considered an indication of increased turbulence. On the other hand, this situation can be construed as close to parabolic velocity profile due to the slower net velocities generated at the more turbulent edges of the particle density profile.

Particle Mass Flow Sensor

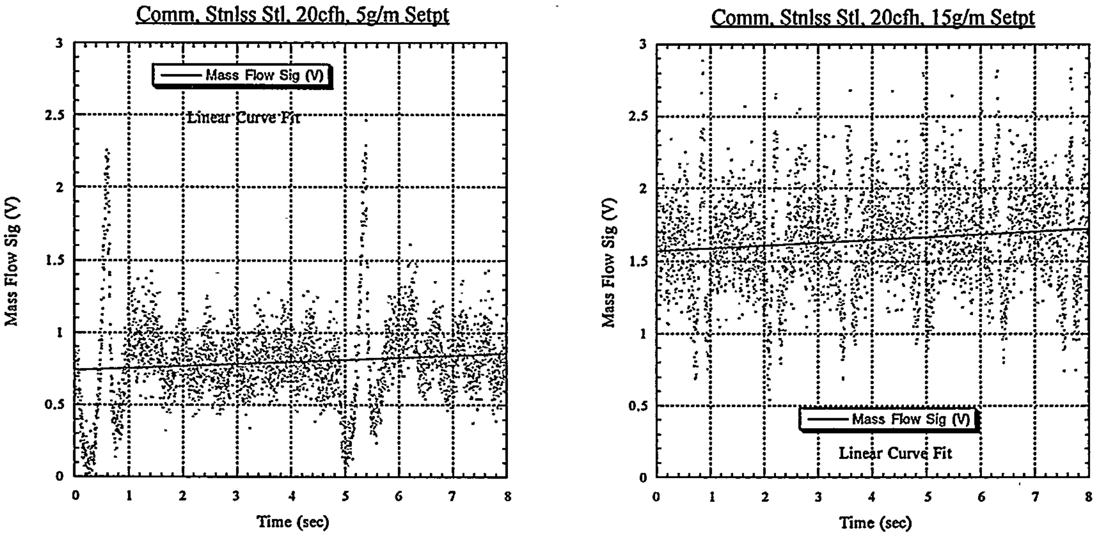
Theory

A light source passing through a particulate medium may undergo complex interactions including absorption, scattering, and diffraction. Particle size, shape, surface condition, and material all have various effects on these phenomenon.

Particles with a diameter that is equal to or less than the illumination wavelength can introduce scattering effects that only Mie theory and similarly complex models can explain[7]. Material dependent diffractive phenomenon may be exhibited for large as well as small particles and adversely affect a measurement[7]. A measurement technique has been developed that represents an inherently linear response. This makes the signal processing simpler. We also used another light scattering technique (labeled 'measurement check' in Figure 8b) built into the sensor to compare to this new technique.

Measured Data

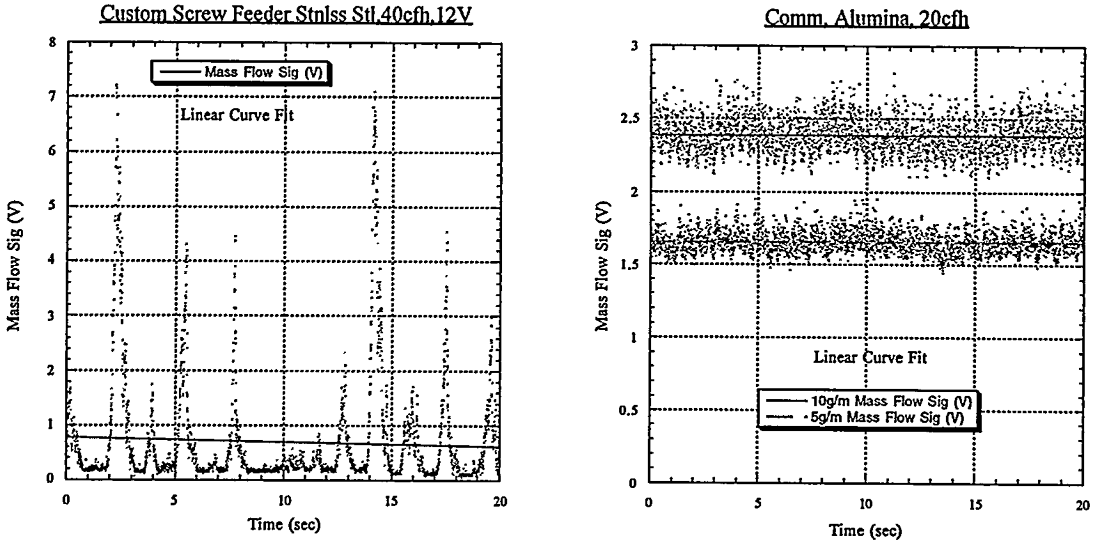
The relative data shown in Figures 5 and 6 were taken before a calibration on the sensor was made. This data is included, not as direct mass flow measurements, but only to illustrate the large temporal fluctuations that can occur. The linearity of this relative data is inferred from the subsequent calibration data showing the sensor is linear over a wide range of signal levels.



a) Set @ 5g/min.

b) Set @ 15g/min.

Figure 5. Relative powder sensor signals for commercial rotary powder feeder.



a) Custom screw feeder with stainless steel. b) Commercial rotary feeder with alumina.

Figure 6. Relative powder flow sensor signals for other feeder/material combinations.

The relative measurements in Figure 5 from a commercially available powder feeder show some large mass flow transients that correspond to the rotation of the feeders delivery wheel. Both of the data sets were taken while the control system was still in the process of ramping up to the set feed rate. In Figure 6 a screw type feeder with large transient characteristics is shown along with the commercial feeder used for the data in Figure 5. Instead of using a small stainless steel powder (≤200μ, mean=47.6μ, standard deviation=43μ), a medium sized alumina powder was used (≤300μ, mean=108.8μ, standard deviation=93μ). Figure 7 shows two SEM scans for the types of powders used for the above data.

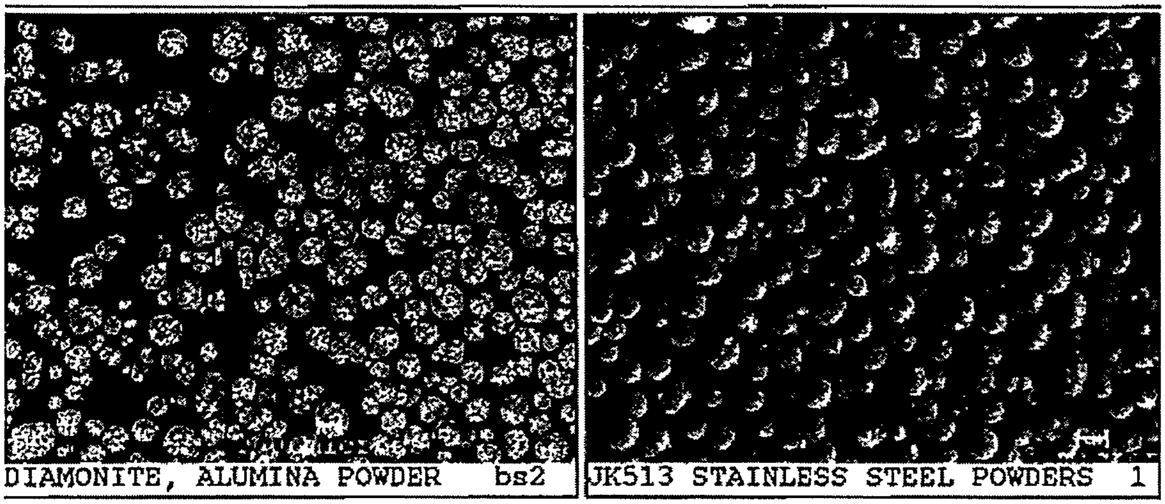
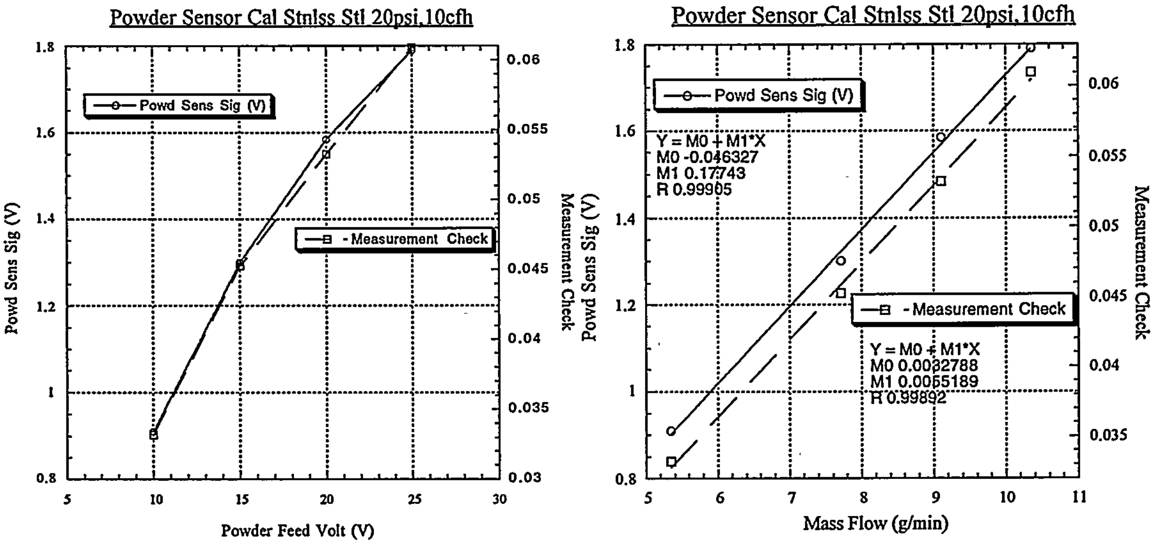


Figure 7. SEM scans of alumina (50X) and stainless steel (150X) powders used.

Below in Figures 8 and 9 is the calibration data and linearity check for the new sensor. The 'Powder Feed Voltage' x-axis data in Figure 8a) is the powder feeder control voltage. The 'Mass Flow' x-axis data in Figure 8b) was obtained from weighed mass flow samples. The linear correlation coefficient (R) for the new sensor is greater than 0.999. The calibration curve in Figure 8b) can then be used on data such as exemplified in Figures 5 and 6 to determine real-time flow rates in a particle stream.



a) Calibration to powder feeder.
b) Linearity check.

Figure 8. Powder flow sensor calibration.

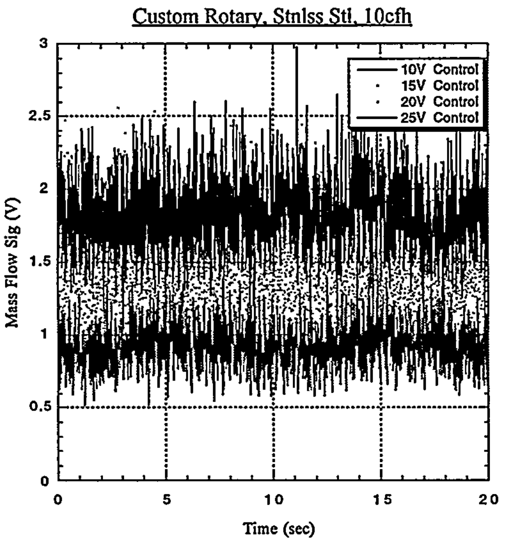


Figure 9. Calibration powder flow sensor signal for custom rotary type feeder.

Conclusions

We have demonstrated the use of two valuable powder gas flow analysis tools. These are an LDV measuring the particle velocity and density distributions at the output of a new nozzle and a new light scattering mass flow sensor showing temporal mass flow characteristics of the powder feeder. Not only can velocity data be measured with the LDV, but relative particle density data can also be derived directly from the measurement system data rate. Also our nozzles' output exhibited gaussian velocity profiles for all but high flow conditions.

The feasibility of using light scattering techniques as a temporal diagnostic tool for powder gas flows has also been demonstrated. The fast response time and linearity of the new powder mass flow sensor can reveal powder feeder mass flow characteristics that are not readily apparent from slower control systems or weighed sample data.

Acknowledgments

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Meet the author

Paul Schanwald is a native New Mexican and received his BS in electrical engineering from UNM in June of 1992. He is a current member of SPIE and has worked in laser related technologies from 1979 with organizations such as the Air Force Weapons Lab, EG&G, Rockwell International, Hughes Aircraft, and presently with Sandia National Laboratories.