

A Comparison of Two Laser-Based Diagnostics for Analysis of Particles in Thermal Spray Streams

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Abstract

This paper discusses two commercially-available laser diagnostics that have been used in thermal spray research at Sandia National Laboratories: 1) a Phase Doppler Particle Analyzer (PDPA) and 2) a Laser Two-Focus (L2F) velocimeter. The PDPA provides simultaneous, correlated measurements of particle velocity and particle size distributions; but, particle sizing doesn't work well with non-spherical particles or particles with rough surfaces. The L2F is used to collect particle velocity and number density distributions, and it can readily distinguish and separately measure particles with off-axis velocity vectors. PDPA and L2F principles of operation are presented along with potential advantages and limitations for thermal spray research. Four experiments were conducted to validate and compare measurement results with the PDPA and L2F instruments: 1) spinning wire, 2) powder in a High-Velocity Oxy-Fuel (HVOF) jet, 3) powder in a cold jet, and 4) droplets in a wire-fed HVOF jet.

TWO DIFFERENT TYPES of commercially-available laser velocimeter systems, a Phase Doppler Particle Analyzer and a Laser-Two-Focus velocimeter have been used in the Thermal Spray Research Laboratory at Sandia National Laboratories. We have one year of experience with the PDPA and ten years of experience with the L2F. Each of these techniques has inherent advantages and limitations for thermal spray, and each involves assumptions that may not be valid for some experimental conditions. This paper describes operating principles and possible sources of measurement error for these two diagnostic systems. Some potential advantages and limitations are also presented. Four types of experiments were also conducted to validate and compare PDPA and L2F measurement results: 1) spinning wire, 2) powder in a High-Velocity Oxy-Fuel (HVOF) jet, 3) powder in a cold jet, and 4) droplets in a wire-fed HVOF jet. We also offer a few observations related to practical issues such as ease-of-use, reliability, and effects of dust and vibration in a thermal spray lab.

Phase Doppler Particle Analyzer

The Phase Doppler Particle Analyzer (PDPA) is a Laser Doppler Velocimeter (LDV) based instrument for simultaneous, correlated measurement of particle velocity and size in two-phase flows. Two coherent laser beams intersecting at a shallow angle

produce an interference fringe pattern in the probe volume (Fig. 1). Light reflected from a particle passing through the probe volume generates a Doppler burst with a temporal frequency that is proportional to the particle velocity. The PDPA sizes particles by using three spatially-separated photomultiplier tubes (PMT's) to sample slightly different regions of the light scattered by a particle passing through the probe volume. A comparison of the phase shift between the signals received at any pair of these three PMT's provides a measure of the scattered-light spatial frequency, which is linearly related to the particle diameter. The maximum Doppler frequency of the PDPA used in this work (Aerometrics, Inc., Sunnyvale, CA, USA) is 150 MHz, allowing a maximum particle velocity up to several thousand meters per second, depending upon the configured beam-crossing angle.

PDPA Probe Volume & Particle Size Limits. The PDPA probe volume is physically bounded by the region of beam intersection, so it varies with the beam-crossing angle (i.e., beam spacing and lens focal length). The probe volume is ellipsoidal,

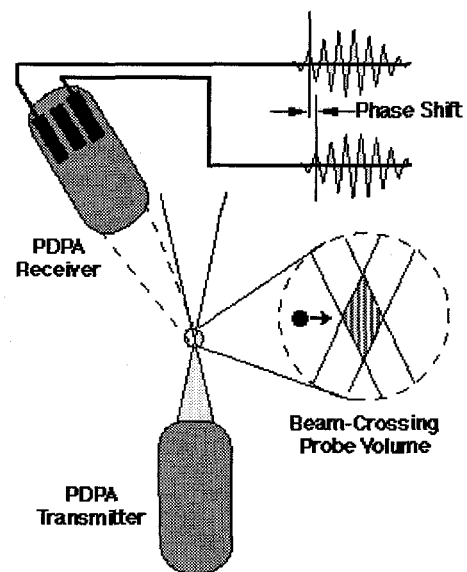


Fig. 1 - PDPA schematic. Light scattered by a particle passing through the interference fringe pattern in the probe volume generates a Doppler burst with a temporal frequency that is related to particle velocity and a phase shift that is proportional to particle size.

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with a typical major axis on the order of 0.5 mm or less and a minor axis of ~ 0.1 mm. The PDPA collects the scattered light off-axis through a spatial filter (slit), effectively imaging only a portion of the probe volume that passes through the spatial filter.

Because large particles scatter more light, they can be counted whenever they pass anywhere through the probe volume; however, small particles may only scatter enough light to be counted if they pass directly through the center of the probe volume, where the Gaussian-distributed laser energy is greatest. Hence, the "effective" probe volume is slightly greater for larger particles. The PDPA software corrects this size-related sampling bias using an algorithm based on the number of fringe lines crossed by each particle size class.

The manufacturer-stated size range is 0.5 to 10000 μm diameter (spherical) with $\sim 4\%$ accuracy for sizing and $\sim 1\%$ accuracy for velocity. Particles smaller than ~ 0.5 μm scatter as dipoles, and the phase becomes independent of scattering direction, which makes this a theoretical lower limit for PDPA particle sizing. However, other factors may lead to sizing errors for particles smaller than ~ 10 μm [1]. The minimum size for PDPA velocity measurements is primarily limited by signal-to-noise. We have had no difficulty measuring velocities for ~ 8 μm droplets in an HVOF plume, but we have not attempted measurements with smaller particles.

PDPA Advantages/Limitations. The PDPA records correlated particle velocity, size, and arrival time data for individual particles passing through the probe volume. Such data are extremely valuable for analysis of particle size-velocity correlations and time-history of particle behavior. The small probe volume of the PDPA provides good spatial resolution and allows measurements in fairly dense sprays. The maximum data rate for simultaneous velocity and sizing is 91 kHz, while the unit is rated at 800 kHz for velocity only. With the PDPA, we were able to make measurements in a wire-fed HVOF (High-Velocity Oxy-Fuel) thermal spray stream 1 cm downstream from the wire tip, where the droplet number density was too high for our L2F system. Aerometrics claims a maximum measurable number density for the PDPA of 10^6 particles/ cm^3 , but we have been unable to experimentally verify this limit.

In the reflection mode used for sizing of opaque particles or droplets, the light reaching each detector is reflected from a small area on the particle surface, and what is actually measured is the local radius of surface curvature [2]. PDPA sizing assumes a smooth spherical particle, so non-spherical particles or droplets in thermal sprays may be difficult or impossible to size accurately. Such particles can be considered either regular or irregular. For irregular particles with multiple facets and sharp discontinuities (e.g., incompletely-melted angular powder particles) the scattered light pattern will be irregular, and PDPA analysis will fail entirely. For regular, non-spherical particles (e.g., oblate or prolate spheroids), the PDPA will measure the local radius of curvature and, if the droplet orientation is random, the mean measured diameter should be correct. However, if there is a preferred orientation, for example, established by shear forces in the flow, then there will be a systematic error in the measured diameter. For velocity measurements only, without particle sizing, the PDPA technique is not shape dependent and can accurately measure the velocity of even irregular particles.

Other concerns for thermal spray include interference from background light in the thermal spray plume and the effects of vibration. Although the PDPA size measurement is based on phase, not on absolute scattering intensity, an intensity check is included in the signal processing to eliminate particles passing through the edge of the measurement volume, where reflection and refraction can both be important. Since the absolute light level is measured, a laser wavelength notch filter must be used to pass only the scattered light signal of interest. Vibrations due to air

handling equipment, etc., in a typical thermal spray environment can cause the alignment of the PDPA optics to drift. Therefore, it is important to isolate the PDPA from external vibration to insure that it maintains alignment during a thermal spray run. Finally, measurement of particles with off-axis trajectories is very difficult with a single-color PDPA, because the entire transmitter/receiver system must be rotated and aligned along the direction of interest.

Laser Two-Focus (L2F) Velocimeter

The Laser Two-Focus (L2F) velocimeter used in this work (Polytec Optronics, Inc., Costa Mesa, CA, USA) measures transit times of individual spray particles as they traverse a probe volume bounded by two highly-focused laser beam waists or "spots" separated by a known distance (Fig. 2). To form the spots, a $\lambda/4$ wave retarder first converts linearly polarized light from the argon-ion laser to circularly polarized light. A Rochon prism is then used to split the polarization states of the beam. The prism is followed by a lens to focus the split beam into two small spots. Finally, an image of these spots is projected into the probe volume via a large transceiver lens.

As a particle or droplet passes through the "start" beam waist, laser light backscattered by the particle is intercepted by the transceiver lens, focused through a series of lenses, filtered through a dual-pinhole arrangement, and then imaged onto the "start" photomultiplier tube (PMT). This process is repeated a fraction of a second later as the particle traverses the "stop" beam waist and produces a signal at the "stop" PMT. The dual pinholes in the optical train are designed to minimize stray signals from outside the probe volume and to reduce "cross talk" between the reflections from the "start" and "stop" beam waists.

For each transit-time measurement within a user-specified range, the number of counts in the appropriate channel of a 256 channel Multi-Channel Analyzer (MCA) is incremented, so that a spectrum of counts versus time-of-flight is built up in the MCA. These data are subsequently downloaded to a personal computer for post-processing (e.g., smoothing) and analysis.

The maximum velocity that can be measured is limited by the time resolution, which is a function of the beam separation and the speed of the electronics. Our system can measure velocities up to ~ 3000 m/s, roughly an order of magnitude greater than typical droplet velocities in thermal spray.

"Jitter" and "walk" are two potential sources of error in the transit time measurement. Jitter is caused by noise in the main signal that can shift the absolute point at which a discriminator responds, thus introducing a small timing error. The effect of jitter is reduced by using a pulse shaper to smooth and amplify the input pulse, yielding a near-Gaussian pulse profile.

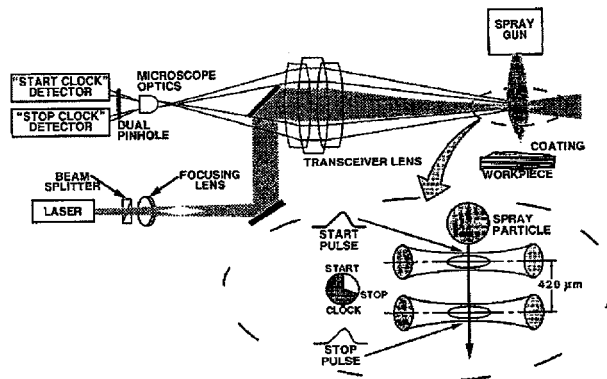


Fig. 2 - L2F schematic. Transit time is measured as a particle passes through a probe volume bounded by two highly-focused laser beams separated by a known distance.

Variations in signal amplitude or rise time lead to another potential error, known as "walk." Walk error is minimized by using a Constant Fraction Discriminator (CFD), which produces an output logic pulse that is independent of the amplitude and rise time of the input pulse. This is accomplished by forming the algebraic sum of an attenuated input pulse and a delayed and inverted full-amplitude pulse, then triggering on the zero-crossing of the resulting composite signal.

Another error source is multiple-particle events, where one particle triggers the "start" pulse, but a second particle triggers the "stop" pulse, causing an erroneous transit time. There is no way to determine whether any given transit-time measurement is a valid single-particle event. For this reason, a few thousand transit times are typically collected at each measurement location. The valid single-particle events tend to be reinforced, and the more randomly distributed multi-particle events are averaged as background noise. Data rates in the central region of a spray plume are typically ~ 1 kHz, so the time required to collect a large number of measurements is relatively short.

L2F Probe Volume and Particle Size Limits. The spot size and separation in the L2F probe volume are determined by the divergence of the beam-splitting prism, the focal length of the lens, and the magnification. According to the manufacturer, the beam-waist diameter for our L2F is 13 μm , and the separation distance between the two beam waists is 420 μm . Since the waist diameter is small in comparison to the separation distance, only particles traveling within a narrow range of flight trajectories that intercept both waists will register valid timing events. From simple geometric arguments, it can be shown that the angular range of measurement is slightly greater for larger particles.

Compared to the PDPA, where the extent of the beam-crossing region physically limits the probe volume, the depth-of-field for the L2F probe volume is less precisely defined, because particles at distances slightly less than or greater than the ideal focal length may produce signals strong enough to trigger a timing event. The effective depth-of-field is greater for conditions that produce stronger reflected signals, e.g., larger particles, higher laser power, or higher PMT gain.

Unlike the PDPA, the L2F does not provide the particle-size information necessary to compute a correction for either of the size-related sampling biases just described. Fortunately, the size range in most thermal spray plumes is relatively narrow and, as shown later in this paper, the PDPA and L2F mean velocity results show good agreement over all conditions that we have investigated. On this basis, we conclude that the L2F produces reasonable mean velocities for typical thermal spray conditions, despite the inherent sampling bias toward larger particles.

We have investigated the L2F depth-of-field by sweeping a 32 μm diameter Si/Al wire (suspended from the end of spinning motor shaft) through the measurement volume at various distances ranging ± 2 mm from the ideal transceiver lens focal length of 900 mm. The total depth-of-field increased essentially linearly with laser power, rising from approximately 2 mm at 10 mW (laser power measured at the probe volume) to nearly 3 mm at 40 mW. This should be a "worst case" upper limit, since the "line" reflection from the full illuminated length of a cylindrical wire should be much more intense than the "spot" reflection from spherical droplet of the same diameter.

The minimum particle size for the L2F is fundamentally limited by signal-to-noise and therefore depends upon the measurement conditions. In principle, it may be possible to measure sub-micron particles, but we have not attempted such measurements in a thermal spray environment. We have successfully measured particle velocities for 5 μm alumina particles in an HVOF spray plume [3].

L2F Advantages/Limitations. The transmitting optical train of the L2F includes a stepper-motor-controlled beam rotator

that provides a convenient means to map particle velocities in two-dimensions by changing the relative spatial orientation of the two beam waists or "spots." The "start" spot is always aligned with the central optical axis of the system and remains fixed in space within the probe volume. However, the "stop" spot is slightly off-axis and can be rotated 360° (in 0.36° intervals) around the "start" spot to selectively measure only those particles moving along a specific angular trajectory. By comparing the relative count rates measured over a series of angular orientations, the angular distribution of the velocity vectors at any given location in the spray stream can be determined. By proper orientation of the "start" and "stop" pulses, one can also discriminate between particles moving left-to-right versus right-to-left through the probe volume.

Another potential advantage is that the L2F operates well in a back-scattering mode, whereas the PDPA seems to work better with forward-scattering. The back-scattering mode simplifies the optical setup, especially when working through windows in chambered spray systems (i.e., vacuum or controlled-atmosphere systems) that typically have limited optical access. Also, the two illuminating raypaths in the L2F are greatly expanded and pass through the same cross-section of both the lens and the spray chamber diagnostic window. Hence, the L2F is relatively insensitive to small inhomogeneities in or on the window (bubbles, overspray dust, etc.). Similarly, the L2F is not strongly affected by variations in refractive index along the raypaths due to hot gases in the spray stream.

Finally, it has been our experience that the L2F is somewhat easier to set up, align, and maintain than the PDPA. The optics of the L2F are mounted on a single cast frame and, once aligned by a relatively simple procedure, tend to hold alignment over long periods of time. The entire L2F optical train is also housed in a dust-tight enclosure, which is very useful in a thermal spray environment. A major drawback in comparison to the PDPA, of course, is in the inability to measure particle size.

Spinning Wire Experiments

A "spinning wire" experiment was devised that swept a small wire through the probe volumes of the two instruments at a known velocity. The blue (488 nm) PDPA and green (514.5 nm) L2F beams were coincident upon a 102 μm (.004 in) diameter wire extending radially from a rotating motor shaft. A laser tachometer was used to measure the shaft rotation rate (rpm). The tachometer consisted of a 0.5 mW helium-neon laser and a PIN diode detector,

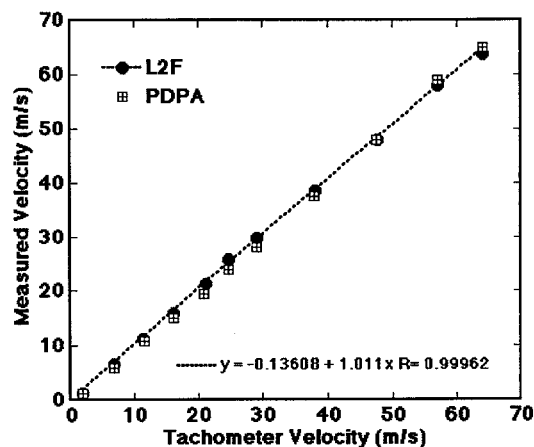


Fig. 3 - Comparison of PDPA and L2F mean velocities vs. the laser tachometer in the "spinning wire" experiments. The dashed line fit to the L2F data falls essentially on a diagonal of ideal agreement.

with the detector sensing light scattered from a reflective strip on the rotating motor shaft. The detector signal was sent to a storage oscilloscope, and the time between light pulses was measured to determine the shaft rpm. The rpm and the distance from the pivot point of the wire to the measurement location were used to compute the linear velocity of the wire. Measurements were taken at eleven different velocities, ranging from 11 to 65 m/s.

Excellent agreement was obtained among the three diagnostic measurements (Fig. 3). The average difference between any two measurements was typically one to four percent. The accuracy of the laser tachometer measurement was limited by uncertainty in the distance from the wire pivot point to the measurement location (~ 1.3%), variations in motor rotation speed during the measurement runs (~ 0.4%), and the accuracy of measuring the time between successive light pulses ($\pm 0.5\%$). Therefore, the laser tachometer velocities are good to within a few percent.

Experiments with Spherical Powders

Particle Velocity Measurements. A comparison was made between PDPA and L2F measured particle velocities for a narrow size cut of nearly-spherical molybdenum powder sprayed in a High-Velocity Oxy-Fuel (HVOF) jet. This 64-75 μm , sieve-cut molybdenum was sprayed through a Metco Diamond Jet Rotary Wire (DJRW) HVOF system that had been modified to spray powder. The gas flows were: 47 slpm (100 scfh) propylene, 212 slpm (450 scfh) oxygen, and 519 slpm (1100 scfh) air. Instead of the standard angled-spray aircap, the DJRW was fitted with a special straight aircap, so that the spray stream was aligned along the central axis of the spray device. Details concerning this spray device and aircap have been presented in previous papers [4-5].

As in the spinning-wire experiments, the PDPA and L2F probe volumes were co-located to make simultaneous velocity measurements. Fig. 4 compares typical PDPA and L2F velocity results 4.0 cm downstream from the spray device on the central axis of the spray stream. To facilitate comparison, the data in Fig. 4 have been given a slight smoothing treatment with a three-point moving average (i.e., $\text{Point B}' = [3 * (\text{Point B}) + 1 * (\text{Point A} + \text{Point C})] / 5$), and the results for each diagnostic technique have been normalized. The PDPA and L2F mean particle velocities show good agreement, within approximately 4%. The

velocity distributions for the two techniques are similar, although the PDPA distribution is more narrow with a smaller standard deviation. This is reasonable since the probe volume (primarily depth-of-field) is smaller for the PDPA. The L2F results show some asymmetry, with a comparatively higher percentage of results at the high-velocity end of the distribution, resulting in a slightly higher average velocity for the overall distribution.

Particle Size Measurements. PDPA particle sizing assumes that the scattering particle is a perfectly smooth sphere. Since real particles may be non-spherical or have surface roughness, a comparison of the phase shifts among the three possible pairs of detectors is made and, if they do not agree within user-selectable acceptance criteria, then the signal from that particle is rejected as invalid. The data taken with the molybdenum powder produced a 50% rejection rate, and the PDPA computed a mean particle diameter of $74 \pm 25 \mu\text{m}$. This mean value does fall within the 64-75 μm size range of the feedstock powder; however, the PDPA size distribution was surprisingly broad (Fig. 5a), extending well outside the size range of the feedstock powder.

To determine whether interference from intense background light in the HVOF plume might be affecting the measurement results, the experiment was repeated with the powder carried in a cold gas jet. Virtually the same mean size and size distribution were obtained with the cold jet, indicating that the HVOF plume was not affecting the measurement results and that the refractory molybdenum powder probably was not melting in the HVOF spray plume. (For the purposes of these experiments, melting was considered undesirable, because it could modify the known size range of the feedstock material).

SEM photomicrographs of typical molybdenum powder particles (Fig 5b) suggested a possible explanation for the observed results. There are many particles that are ellipsoidal to varying degrees, and qualitative measurements of particles in the SEM photos indicated that the local radius of curvature varies by as much as 50% from the mean. In addition, the particle surfaces are not perfectly smooth, but have small irregularities.

A second PDPA sizing experiment was performed with a cold gas jet using 64-75 μm steel powder that was more spherical and somewhat smoother (Fig 6b). The variation in the local radii of curvature for the steel powder was estimated to be closer to 20% from the mean. The PDPA mean size for the steel powder was $79 \pm 16 \mu\text{m}$, slightly larger than the 75 μm upper limit of the sieve-cut feedstock. The measured size distribution for the steel powder (Fig 6a) was more narrow than that observed for the molybdenum, but it still extended outside the size range of the feedstock powder.

The broad size distributions observed in the molybdenum and steel experiments were probably caused by local variations in surface curvature. This is consistent with the observation that the molybdenum powder, which contained more ellipsoidal particles and had greater surface roughness, showed a wider PDPA size distribution in comparison to the steel. Despite the rather broad size distributions obtained for these two powders, the mean sizes were close to the actual particle size of the feedstock powders.

Experiments with Wire-Fed HVOF

Droplet Velocity Measurements. A series of experiments were performed to measure droplet velocities at various locations in the spray plume of the DJRW device operating under the same conditions described in the previous section, but feeding steel wire instead of powder. The PDPA and L2F probe volumes were co-located and simultaneous measurements were made. The probe volume remained fixed in space, and the measurement location in the spray plume was changed by moving the DJRW spray torch, which was mounted on a high-precision computer-controlled positioning system.

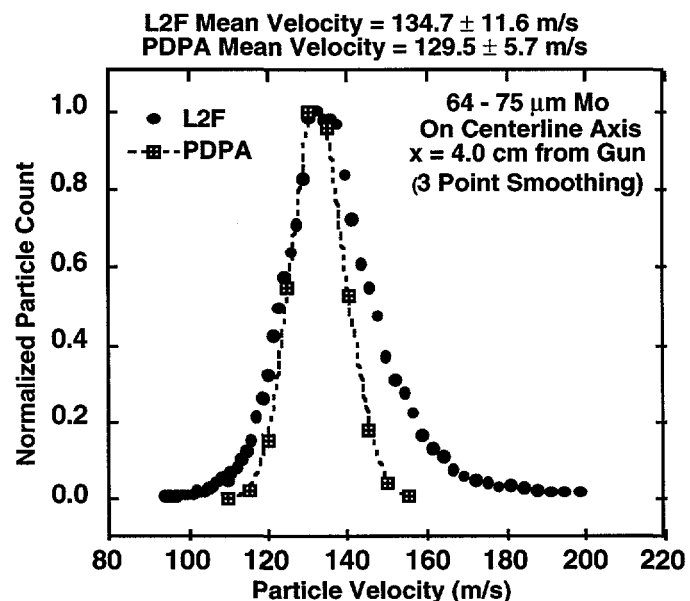


Fig. 4 - Comparison of PDPA and L2F velocity results for 64-76 μm molybdenum powder particles in an HVOF spray plume.

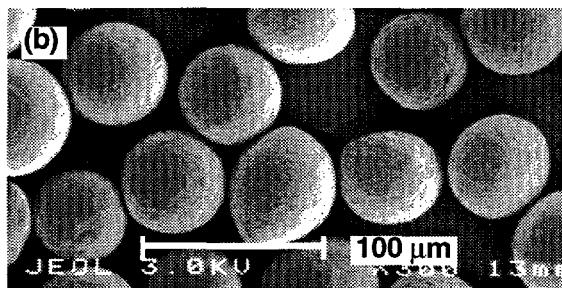
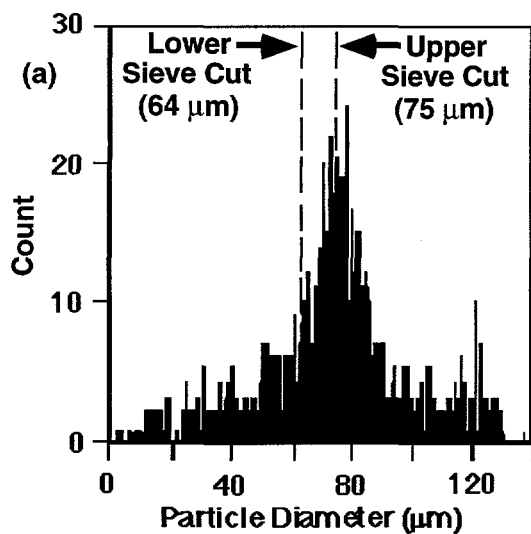


Fig. 5 - (a) PDPA size distribution for molybdenum powder. PDPA mean particle size = $74 \pm 25 \mu\text{m}$. (b) SEM of the molybdenum powder.

Good agreement was consistently observed between the PDPA and L2F velocities at all locations. For example, Fig. 7 shows PDPA and L2F velocity results 6.0 cm downstream from the spray gun along the central plume axis. As with the powder experiments, the L2F has a slightly broader velocity distribution, but the mean velocities are in excellent agreement.

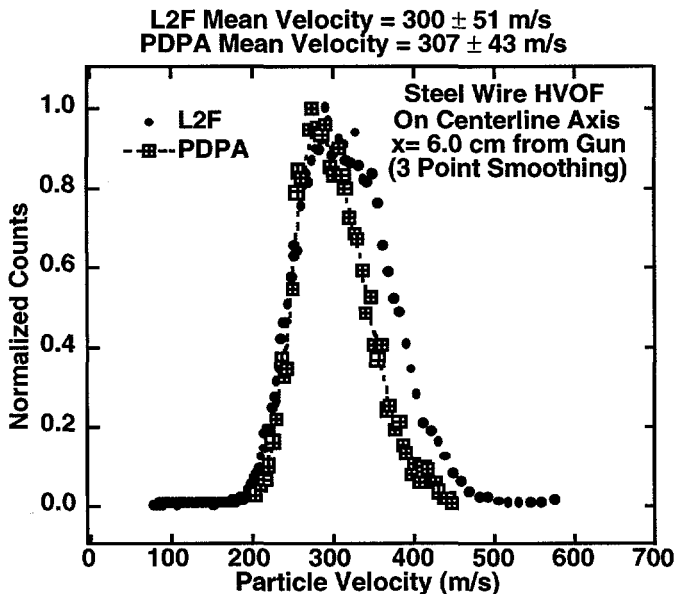


Fig. 7 - Comparison of PDPA and L2F droplet velocity results for steel droplets in a wire-fed HVOF spray plume.

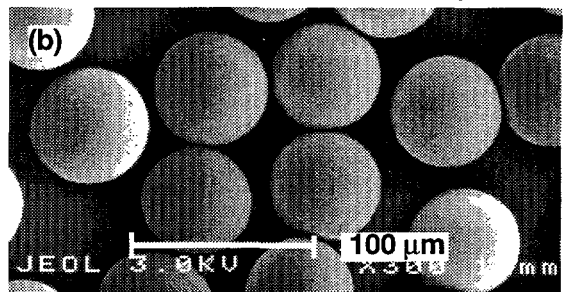
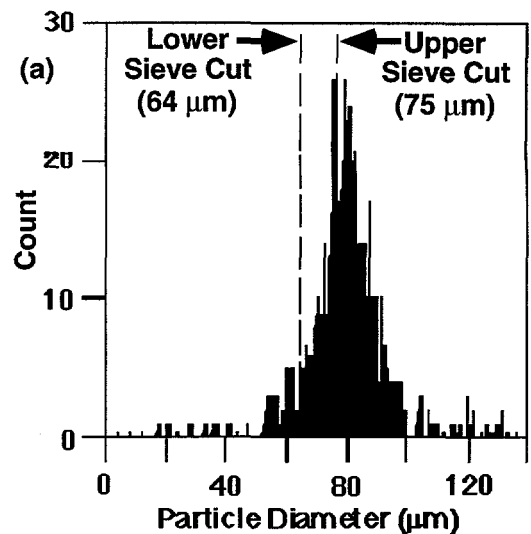


Fig. 6 - (a) PDPA size distribution for steel powder. PDPA mean particle size = $79 \pm 16 \mu\text{m}$. (b) SEM of the steel powder.

Droplet Size Measurements. The PDPA was used to measure droplet size at 1 cm intervals along the central axis of the spray plume out to a distance of 10 cm from the DJRW spray gun. A multi-position scan normal to the spray axis was also performed at an axial distance of 4 cm from the spray gun. Fig. 8 shows a typical droplet size distribution for a location 4.0 cm from the gun on the central plume axis. All of the PDPA arithmetic (d_{10}) mean

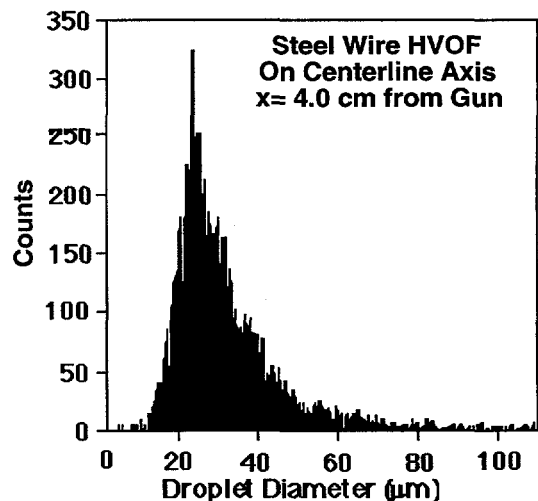


Fig. 8 - PDPA droplet size distribution for steel wire-fed HVOF spray plume. Distribution has been corrected for size-dependent measurement volume. Arithmetic mean diameter, d_{10} , is $32.1 \mu\text{m}$.

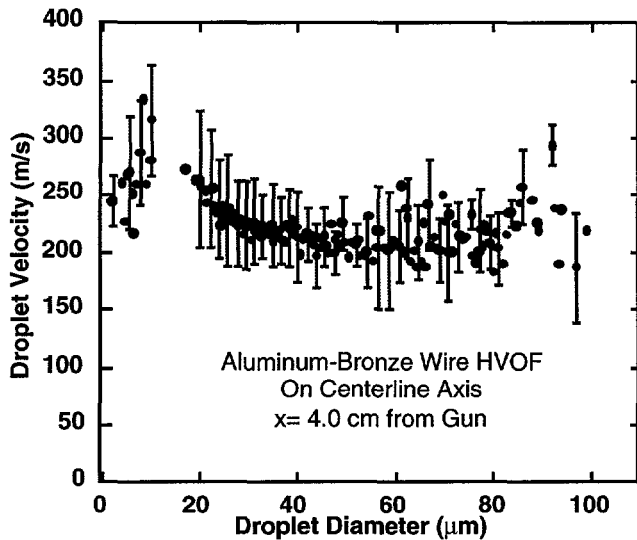


Fig. 9 - Correlated PDPA droplet velocity/size results for aluminum-bronze wire-fed HVOF. The vertical bars are the rms variability in the velocity results (only every fifth point has a bar for the sake of clarity).

droplet sizes fell in the range of 30-40 μm , which is consistent with a rough estimate of the droplet size range based on analysis of solidified spray droplets physically collected further downstream from the spray device. This size range is also qualitatively consistent with expectations based on Weber breakup of molten material from the steel wire [6].

Interesting particle-size trends that were observed include slight increases in the mean particle size with increasing axial distance downstream and with radial distance away from the central axis of the spray plume. We propose that these trends may be related to droplet distortion caused by high shear forces along the central axis of the spray plume. As noted in the earlier discussion of the molybdenum and steel powder results, the PDPA appears to be very sensitive to small variations in surface curvature, so distortion of the molten spray droplets due to local shear forces might account for the curious axial and radial trends observed in the measurement results. However, this issue has not been adequately resolved and further research is needed.

When correlated PDPA droplet velocity/particle-size results were plotted, the smaller particles had higher velocities, as expected due to their lower particle mass. However, the droplet-size dependence of the velocity results was much less than anticipated on the basis of a simple drag-force model [6]. A plot of correlated PDPA droplet velocity and size data for the DJRW steel wire experiments is presented in a companion paper at this conference by Neiser, et al [6]. A similar plot is shown in Fig. 9 for the DJRW with aluminum-bronze wire. As with the steel wire experiments, the aluminum-bronze results show a surprisingly small decrease in particle velocity with increasing particle size. The interested reader is referred to the companion paper [6] for a discussion of the observed size/velocity relationships.

Summary Comparison

We have discussed advantages and limitations for both the PDPA and L2F as applied to thermal spray research. Some key advantages and limitations are summarized in Table I.

Simultaneous PDPA and L2F velocity measurement were made with spinning wire, powder-fed HVOF, and wire-fed HVOF experiments to directly compare these two diagnostics. As summarized in Table II, the PDPA and L2F mean velocity results

Table I. Summary of Advantages and Limitations

PDPA Advantages:	PDPA Limitations:
<ul style="list-style-type: none"> • Correlated Size & Velocity • Smaller probe volume (~ 0.1 x 0.5 mm) • High number-density sprays 	<ul style="list-style-type: none"> • Sizing assumes "spheres" • Off-axis & viewport measurements are tough • Questionable sizing below ~ 10 μm
L2F Advantages:	L2F Limitations:
<ul style="list-style-type: none"> • Easy off-axis measurement • Backscatter mode easier for viewport measurements • Simpler & more robust 	<ul style="list-style-type: none"> • No particle sizing • Larger probe volume (depth-of-field may be > 1 mm) • Lower number-density limit

Table II. Summary of Representative Mean Velocity Results

Experiment	PDPA	L2F
Spinning Wire	65.5 \pm 0.8 m/s	64.4 \pm 1.0 m/s
Mo Powder HVOF	129.5 \pm 5.7 m/s	134.7 \pm 11.6 m/s
Steel Wire HVOF	307 \pm 43 m/s	300 \pm 51 m/s

were consistently in good agreement under all conditions investigated, spanning a broad range of velocities. Velocity distributions were slightly more broad for the L2F, possibly due the larger probe volume.

The droplet size measurement capability of the PDPA, though potentially very important, appears to be very sensitive to small variations in the local radii of the spray droplets. Even though the mean droplet sizes determined in the powder experiments were close to the actual size, further work is needed to better characterize and more fully exploit the size measurement capabilities of the PDPA under thermal spray conditions.

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