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The Use of Small Probe Volumes With Phase Doppler Interferometry

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Abstract

Phase Doppler interferometry utilizing a probe volume much smaller than the droplets being measured has been shown to work well when coupled with a phase and intensity validation scheme which is capable of eliminating trajectory dependent scattering errors. Measurements in monodispersed droplet streams have been performed to characterize the probe volume, and an intensity validation scheme and corresponding probe volume correction factor have been developed. Volume flux measurements in dilute sprays have shown a significant improvement over standard phase Doppler interferometry techniques at small beam waist to droplet size ratios.

Introduction

Measurements of particle size, velocity and volume flux in optically dense sprays is an emerging and challenging field. One of the most promising techniques for making these measurements is phase Doppler interferometry. The phase Doppler technique, which works well in low number density sprays (N less than 10^3 cm^{-3}) in the size range of 5-300 μm , is fraught with problems in dense sprays where the number densities can reach 10^5 cm^{-3} in the same size range. The Phase Doppler Particle Analyzer (PDPA) is a single particle counter which relies on the fact that there is no more than one particle in the probe volume at any given time. It is unclear how the instrument responds when several particles are simultaneously present in the probe volume. Sankar *et al.* have shown that the Doppler Signal Analyzer (DSA) can, in some instances, measure one of two particles simultaneously present in the probe volume [1]. The DSA cannot, however, account for the other particle(s) present in the probe volume. The result can be a severe underestimation in the particle number density and volume flux, and a potential biasing in the particle size distribution.

High pressure rocket injector sprays produce a wide range of droplet sizes depending on the injector flowrates, chamber pressure and injector geometry

(shear coaxial, swirl, impinging, etc.). A shear coaxial injector currently being studied at AFRL using water and nitrogen as simulant for LOX and GH_2 , has produced droplet sizes in the range of 2 - 200 μm with peak number densities of about 10^5 cm^{-3} . The conventional phase Doppler technique requires that the diameter of the probe volume be at least twice as large as the largest droplet size to be measured. The probe volume can be estimated by;

$$V = \frac{\pi D_w^2 \cdot D_s}{4 \cdot \sin(\theta)} \quad (1)$$

where D_w is the $1/e^2$ beam waist diameter, D_s is the apparent slit width and θ is the angle of the receiver with respect to the laser beams. For a scattering angle of 30° , a beam waist of 400 μm and an apparent slit width of 200 μm , the probe volume is $5.0 \times 10^{-5} \text{ cm}^3$. The probability of finding n particles within the probe volume can be determined by;

$$P(n) = \frac{(VN)^n}{n!} e^{-(VN)} \quad (2)$$

where V is the probe volume, and N is the particle number density [1]. For the above listed configuration, the ratio, $P(2)/P(1)=2.5$, which means that probability of finding two particles in the probe volume is two and a half times the probability of finding one particle in the probe volume.

Without having the ability to measure multiple particles in the probe volume, it is necessary that the size of the probe volume be reduced until the probability of finding multiple particles within the probe volume is negligibly small. In effect, the probe volume can theoretically be made much smaller than the size of the droplet being measured. The refracted light reaching the receiving optics originates from a very small area on the face of the drop, as shown in Figure 1.

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All other rays incident on the droplet are refracted elsewhere, thus it is not necessary to illuminate the entire droplet. In essence, this small area on the droplet surface acts as a lens which magnifies and projects an image of the fringe pattern onto the receiver lens. The resultant magnified fringe spacing is measured as a phase shift between the detectors and is linearly proportional to the droplet size. The probe size could theoretically be made as small as the size of the projected area on the droplet surface. The minimum usable probe diameter is limited by the droplet transit time and the maximum sampling rate which must be able to measure at least 32 samples while the droplet passes through the probe volume. Currently the DSA has a maximum sampling rate of 160 MHz

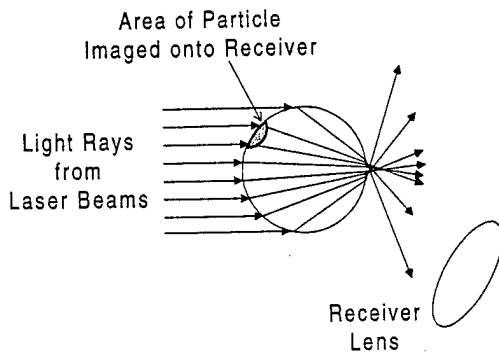


Figure 1: Ray trace of refracted light.

One of the problems associated with reducing the size of the probe volume is trajectory dependent scattering which is a result of the Gaussian nature of the laser beam waist and occurs when the particle diameter is on the order of the beam waist diameter [2]. Particles of this size which pass through the edge of the probe volume, as shown in Figure 2, have a significant reflection scattering component which can result in the particle being erroneously sized as either a smaller or larger particle depending on the optical configuration. This phenomenon has been previously demonstrated with both theoretical light scattering calculations and experimentation [3]. It has also been shown that these reflection tainted trajectories can be identified by their relatively low light scattering intensity [3].

The purpose of this investigation is to demonstrate with both theoretical calculations and experimentation, that trajectory dependent errors can be eliminated with an appropriate phase and intensity validation scheme and a newly developed probe volume correction (PVC) factor which takes into account the change in probe volume size due to the rejection of droplets passing along the edge of the probe volume. The ability to eliminate trajectory dependent scattering errors allows

for making the beam waist diameter and hence probe volume much smaller than the largest droplet size to be measured, thereby allowing the application of phase Doppler interferometry in significantly more dense sprays.

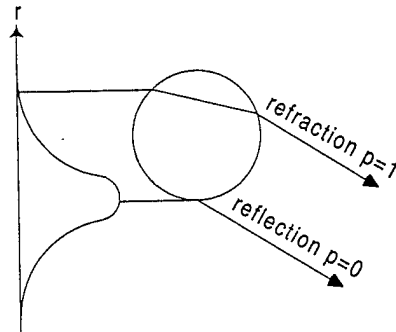


Figure 2: Trajectory dependent scattering.

Theoretical Model

A previously developed phase Doppler response model was used to study the effect of droplet trajectory on phase response and scattering intensity [4]. The model is a geometric optics based scattering model that accounts for the Gaussian nature of the illuminating probe beams by integrating the appropriate scattering functions over the surface of the droplet. The model will not be discussed further here while the reader is referred to the published descriptions of the model [4]. The trajectory coordinate, η , is defined as $2y/D_w$, where y is the trajectory normal to the scattering plane as defined from the center of the probe volume, and D_w is the $1/e^2$ beam waist diameter. The calculations were performed for a beam waist diameter, D_w , of 60 μm , a beam intersection angle, γ , of 2.70° , a forward scattering angle, θ , of 30° and a f5.0 receiver lens.

Figure 3 is a plot of the phase difference that would be measured between detectors 1 and 2 versus droplet diameter for various trajectories including a purely refractive calculation. Figure 3 shows that severe phase errors can occur for trajectories near the edge of the probe volume farthest from the receiver, $\eta < 0$. Purely reflective trajectories ($\eta = -1.0, -0.8$) will be rejected by the phase ratio criteria of the instrument, which compare the phase measured between detectors 1 and 2 to the phase measured between detectors 1 and 3. Figure 4 is a plot of the phase normalized by the purely refractive phase versus the intensity normalized by the maximum intensity for various trajectories and for various droplet sizes. The calculations indicate that trajectory dependent phase errors only occur at scattering intensities well below a scattering intensity that is one tenth of the maximum intensity for each

droplet size. Similar results have been published previously and demonstrate that probe diameters much smaller than the droplets being measured can provide accurate droplet size measurements when phase ratio and scattering intensity are used as criteria to reject trajectory dependent scattering errors.

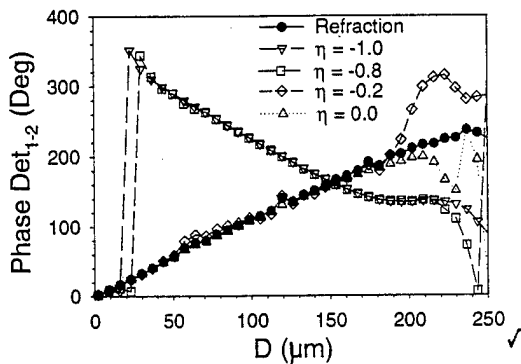


Figure 3: Calculated phase shift versus drop size for various trajectories through the probe volume.

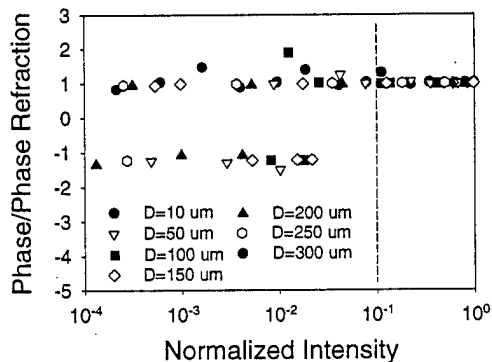


Figure 4: Normalized phase shift versus normalized intensity for various trajectories and droplet sizes.

Monodispersed Droplet Experiments

The PDPA used in this study was a standard 2-component, fiber optically coupled, DSA based system manufactured by Aerometrics Inc. The transmitter produces a beam waist of 352 µm with a 500 mm focusing lens. In order to reduce the beam waist diameter, a beam expander was constructed using a pair of positive achromatic lenses ($f_1=10$ mm, $f_2=48$ mm) to expand and recollimate the beams inside of the transmitter from an initial diameter of 2 mm to a final diameter of 9.6 mm. The beam waist, which is

inversely proportional to the original beam diameter was measured to be 60 µm. The standard receiver slit, which was 100 µm was replaced with a 50 µm slit in order to further reduce the probe volume. Due to the factor of two magnification in the receiving optics, the apparent slit width was 100 µm. In an effort to identify the magnitude of trajectory dependent errors, an acoustically driven monodispersed droplet generator was used to produce a stream of droplets of known size which was characterized with a high magnification CCD camera and a strobelight. The droplet stream was traversed through the probe volume both parallel and perpendicular to the slit image using a pair of micrometer driven translating stages.

A schematic of the coordinate system is shown in Figure 5. Various droplet diameters and beam waist diameters were tested which cover a droplet size to beam waist ratio, D_p/D_w , of 0.32 - 3.88. Figures 6a through 6d show plots of the measured D_{10} normalized by the actual droplet size, and the measured peak intensity normalized by the maximum peak intensity as a function of relative position within the probe volume.

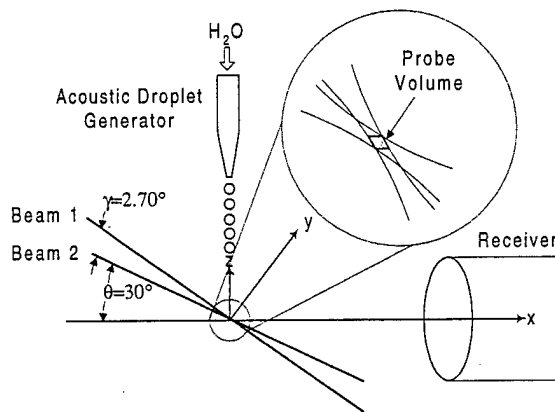


Figure 5: Coordinate system.

As can be seen from the figures, both positive and negative errors in the measured drop size arise near the edges of the Gaussian beam waist, where scattered light intensity and signal to noise ratio is low. Also, the severity of the errors increases as the droplet size approaches the beam waist radius. It is interesting to note that droplets much larger than the beam waist diameter (figures 6c and 6d) show relatively little phase error, for any trajectory through the probe volume.

From these measurements and many others not shown here, it was determined that sizing errors occurred when the signal intensity had decreased to less than 10% of the maximum signal intensity, which occurs near the center of the probe volume. This would indicate that an intensity validation scheme which only

validates particles that lie within a 10 to 1 intensity band, would be able to reject trajectory dependent errors which are not rejected by the phase ratio validation criteria.

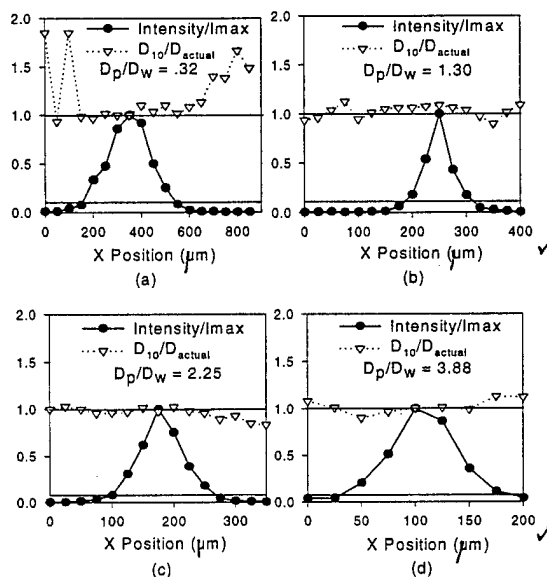


Figure 6: Monodispersed droplet stream traversed along X axis, towards receiver for droplet size to beam waist ratios of; (a) $D_p/D_w=0.32$, (b) $D_p/D_w=1.30$, (c) $D_p/D_w=2.25$, (d) $D_p/D_w=3.88$

It should be pointed out that intensity validation only works when small particles passing through the edge of the probe volume are erroneously sized as larger particles with a resultant low intensity. It can be seen in Figure 3 that certain trajectories and particle sizes will result in a large particle being erroneously sized as a smaller particle with a resultant low intensity, which might be interpreted as a valid measurement. Most of these reflective trajectory errors will, however, be rejected by the phase ratio criteria.

Implementation of Intensity Validation

The intensity validation technique is implemented by setting the maximum intensity cutoff to be at saturation (500 mv) for a particle one-third the largest particle size to be measured. This will force larger particles to produce maximum intensities larger than the maximum measurable intensity, but this is acceptable because the only requirement for validation is that the measured intensity be above the lower cutoff line. The maximum intensity cutoff then follows an $I \propto D_p^2$ relationship for the other particle size classes. PMT

voltage must be set above 400 volts to insure PMT linearity which was verified in a separate set of experiments. Laser power can then be increased until the maximum intensity reading in each size class falls upon the upper intensity cutoff line. Data can then be collected and post-processed to reject particles in each size class with an intensity less than 10% of the maximum intensity cutoff. It should be pointed out that the measured signal intensities were corrected for signal visibility, or relative amplitude modulation, which is significant for droplets less than about 80 μm with the current optical configuration [5].

Probe Volume Correction

In a typical spray, the range of measured droplet sizes can be quite large. The Aerometrics PDPA is capable of sizing droplets over a dynamic size range of 50:1, with the limit being the dynamic range of the photomultiplier tubes. Due to the nature of the Gaussian intensity distribution at the probe volume and the fact that droplets much larger than the wavelength of light scatter light in proportion to their diameter squared, the cross sectional area of the probe volume varies with the particle diameter being measured [6]. Larger particles will scatter more light and therefore be detected further out from the center of the probe volume than smaller particles. A correction factor, known as the probe volume correction (PVC) is employed in the DSA software and takes this into account. The current PVC is based on either an analytical correction or a transit time correction which measures the maximum path length for each particle size class and assumes that this length is equal to the maximum probe diameter for that size class [7]. The "corrected" number of counts in each size class is calculated as

$$n_c(D_p) = n(D_p) \cdot \left(\frac{L_{\max}}{L(D_p)} \right) \quad (3)$$

where L_{\max} is the maximum path length through the probe volume, which occurs for the largest droplet size class, and $L(D_p)$ is the measured maximum path length for each size class. This PVC does not, however, take into account the decrease in the width of the probe volume when intensity validation is used to "clip" the edges of the probe volume in order to eliminate trajectory dependent scattering errors. A new PVC based on the estimated diameter of the probe volume for each size class at the minimum intensity cutoff is therefore needed.

Assuming a Gaussian intensity distribution in the probe volume, the width of the beam waist at the lower cutoff point can be calculated. For the present optical configuration, $D_{w10\%} = 64 \mu\text{m}$. The probe diameter is

thus fixed at this diameter and is independent of droplet size until the droplet size decreases to a point where the signals at the $D_{w10\%}$ point fall below the minimum signal threshold required for gate triggering. For particles with intensities below this level, a correction factor must be used which calculates the probe diameter at the threshold level for each particle size class. For the current configuration the particle size range was fixed from $6\ \mu\text{m}$ to $300\ \mu\text{m}$ and the threshold level was set at $2.0\ \text{mv}$, which resulted in a reduced probe diameter for particles less than $20\ \mu\text{m}$ in diameter. A plot of the probe diameter calculated from the intensity cutoff scheme and the currently employed analytical PVC from the Aerometrics software is shown in Figure 7.

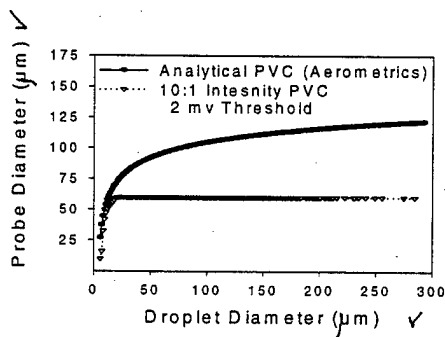


Figure 7: Calculated probe diameter vs. droplet diameter; analytical PVC and 10:1 Intensity PVC.

Spray Measurements

Using the 10:1 intensity validation scheme and associated PVC, measurements in a dilute spray were performed to demonstrate the technique. The spray was formed from a Delavan WDB10-45° nozzle operated at $0.34\ \text{MPa}$ psi and at atmospheric back pressure. Measurements of droplet size, velocity and volume flux were made as a function of radial position in the spray at a location of $10\ \text{cm}$ downstream of the injection point. Measurements were made with both the current small probe volume configuration and a more "conventional" probe volume with and without intensity validation. All measurements were made with scattering angle, $\theta=30^\circ$, focal length, $f=500\ \text{mm}$ and beam intersection angle, $\gamma=2.70^\circ$. Measurements of volume flux are presented in Figure 8 along with the volume flux measured with a collection tube. As can be seen in the figure, without intensity validation, the volume flux is greatly over-predicted, even with the larger probe volume. This is a result of small particles passing through the edges of the probe volume and being erroneously measured as much larger particles, thus greatly adding to the measured volume flux. Good agreement between the collection tube measured

volume flux and the volume flux measured with the small probe volume and 10:1 intensity validation scheme can be seen in Figure 8.

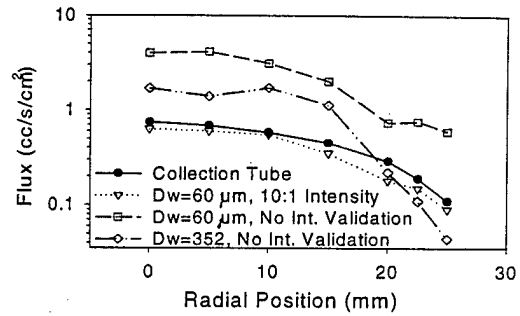


Figure 8: Volume flux vs. radial position, Delavan WDB10-45°, $P=0.34\ \text{MPa}$, $Z=10\ \text{cm}$.

Figure 9 is a scatter plot of intensity versus diameter for the radial position of $0.0\ \text{mm}$. Also shown are the high and low intensity lines. The suspect particles are those larger than about $175\ \mu\text{m}$, which show only low intensity trajectories. Figure 10 is a histogram of the relative volume concentration for the radial location of $0.0\ \text{mm}$ with and without intensity validation, demonstrating the significant change in volume distribution when trajectory dependent errors are eliminated.

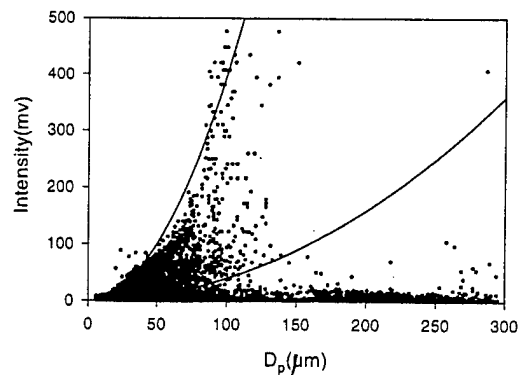


Figure 9: Scatter plot of intensity vs. droplet diameter, Delavan WDB10-45°, $P=0.34\ \text{MPa}$, $Z=10\ \text{cm}$, $r=0.0\ \text{mm}$.

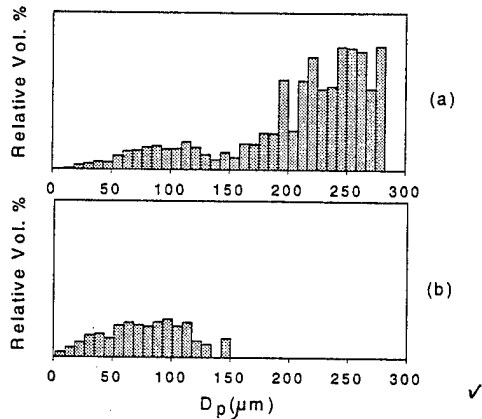


Figure 10: Histograms of relative volume percentage, Delavan WDB10-45°, P=0.34 Mpa, Z=10 cm, r=0.0 mm; (a) without intensity validation and (b) with intensity validation.

Conclusions

The use of small probe to particle diameter ratios in phase Doppler interferometry has been shown to produce accurate droplet size and volume flux measurements when using a combined phase and intensity validation scheme and a probe volume correction based on the diameter of the probe at the lower intensity cutoff level. The use of small probe volumes will greatly improve measurement reliability in dense sprays, where multiple particle occurrences in the probe volume can affect the measurement. The intensity validation scheme allows for rejection of trajectory dependent scattering errors, which become problematic for droplet sizes on the order of the probe diameter.

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