Analytical Constraints of Phase Doppler Particle Anemometry in Non-Traditional Environments

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Phase Doppler Particle Anemometry (PDPA) is an optical diagnostic technique primarily used for evaluating particle size, distribution, and velocity through various mediums. It utilizes phase interference of two laser beams and light scattering to collect data. This non-contact optical method is advantageous in settings where intrusive measurement techniques are undesirable. In the field of aerospace, PDPA is commonly used in combustion, spray dynamics, and fluid mechanics, where understanding particle distribution and motion are essential. PDPA requires careful alignment of its optical components and a controlled environment to ensure accurate results. These ideal conditions include known particle refractive indices, a clearly defined measurement volume, minimal light interference, and an unobstructed laser path. These conditions are attainable in controlled laboratory settings but may not always be ensured when transitioning to industrial and experimental research. PDPA can be a powerful tool to analyze fuel injector properties, where it can be used to optimize the combustion processes. However, there are significant limitations when evaluating these conditions inside a gas turbine combustor. Combustor geometry does not always allow for the appropriate PDPA setup conditions with its complex internal geometry and windows. As fuel particles undergo combustion, the change in particle size can complicate the PDPA measurements more. This experiment aims to investigate the limitations of PDPA in a variety of non-ideal optical configurations for its ultimate implementation in a gas turbine combustor. Assessing the adaptability of PDPA is necessary to determine its efficacy to combustion testing. The findings of this research are applicable not only to aerospace, but to other fields that utilize PDPA as well, such as atmospheric science, pharmaceutical manufacturing, and humidification. By pushing the boundaries of PDPA's application beyond controlled laboratory settings and factoring in real-world conditions, this research aims to explore the practical challenges of implementing PDPA in industrial settings and contribute to the broader understanding of particle dynamics.

I. Nomenclature

β	=	velocity/speed of light
c	=	speed of light in a vacuum
d	=	diameter of particle
D	=	distance between double-slit and receiver
$D32$	=	Sauter Mean Diameter
f	=	focal length
λ_R	=	wavelength observed by receiver
λ_S	=	wavelength of source
LDA	=	Laser Doppler Anemometry
n	=	refractive index

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PDF	=	probability density function
PDPA	=	Phase Doppler Particle Anemometry
Φ	=	phase shift
φ	=	beam intersection angle
Ψ	=	scattering angle
R	=	radius of lens surface
s	=	spacing of fringe pattern
θ	=	angle of oncoming beam relative to the surface's normal
v	=	velocity
w	=	width of double-slit
ζ	=	elevation angle

II. Introduction

Optical diagnostics are a valuable tool in combustion analysis. Gas turbines are a key component in power generation and aviation applications. Gas turbine combustors operate at high temperatures and pressures, making it dangerous to analyze internal components during ignition. Other invasive forms of maintenance can also pose a risk of damaging the expensive equipment involved. Optical diagnostic techniques provide non-invasive means to measure particles within a flow without needing to alter existing configurations. Additionally, optical diagnostic techniques operate at a vast range of frequencies, allowing multiple tests to occur simultaneously. In combustors, optical diagnostics are typically used to analyze the behavior of fuel injectors, particle velocities, and quantities of soot produced. Optical diagnostics are especially applicable in the field of sustainable aviation fuels, where minimizing the amount of emissions is crucial to the mission. Knowing the size and distribution of a fuel spray allows for researchers to accurately assess if the spray is uniform, reaching the combustion zone, and the correct size to optimize the combustion process. Fuel particles that are too large are more difficult to burn, which leads to energy and fuel waste.

The specific optical diagnostic tool being analyzed is Phase Doppler Particle Anemometry (PDPA). This technique uses the Doppler shift of at least two interfering lasers to accurately assess the size of particles in a spray on the order of magnitude of 10^{-6} m. Additionally, the use of two sets of interfering lasers can provide both the *x* and *y* velocities, as well as the particle distribution when analyzed throughout the spray. PDPA can be used during ignition, flame stabilization, and quenching during the combustion process. Receiving real-time feedback on fuel injector sprays reduces risk and optimizes efficiency during the testing and maintenance processes.

While PDPA can be a powerful tool for combustion analysis, it requires specific conditions for the results to be valid. The angle between the receiver and the emitter, known as the scattering angle, must be within a specific range (30° to 70° for first order refraction). The angle variation portion of this study aims to change the scattering angle within this acceptable range to see if there is variation within the acceptability conditions. Additionally, within an operating gas turbine combustor, the high internal pressures and temperatures can change the refractive index of the medium, both air and fuel, to an unknown value. For PDPA to accurately work, the refractive indices must be known. Implementing PDPA in a combustor requires optical access to the region of interest. Combustor windows can be used to provide this access, but passing through these mediums introduces additional variables into the data collection. This means the system is not only dependent on the refractive index of the fuel and air, but the windows too. Even with the addition of windows, complex internal geometries can still block the line of sight. Bypass flows, cooling air, and sensor ports can block portions of the flow that limit the area where PDPA can be used. In turbulent, dense particle sprays, interference of multiple particles like fuel and soot recirculation can interfere and alter the data.

Despite the limitations of PDPA, it remains a valuable tool in combustor analysis. This research aims to characterize the behavior of PDPA outside of a combustor and determine the limitation ranges to eventually implement in a gas turbine combustor. A characterization study of the flow is first conducted and based on these results, specific reference points are chosen. These reference points serve a comparison between trials when scattering angle, focal length, masks, and dimensionality are varied.

III. Background

PDPA is a non-contact optical diagnostic technique performed on single particles in a spray. Focusing two pairs of lasers on a single position within the overall spray allows for a comprehensive analysis of particle size, spray density, and particle velocity. Adjusting the position of the measurement point within the flow allows for mapping of the entire field.

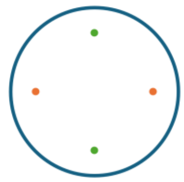

Figure 1. Front view of PDPA emitter laser pairs

PDPA utilizes the Doppler shift (Eq. 1), the change in observed frequency due to relative motion of the source or receiver. The receiver records the frequency shift of light scattered by a particle flowing through an interference volume [3]. PDPA is an extension of Laser Doppler Anemometry but uses two pairs of lasers intersecting at a point instead of only one pair. The two perpendicular pairs allow for the same particle measurement capabilities but can also capture velocity in both the vertical and horizontal directions. PDPA is advantageous over LDA because it does not require calibration since it relies on the absolute physical effects of individual particles. For the assumption to hold, PDPA principles also assume the particles are homogeneous and spherical in its analysis. Using two sets of lasers tuned to different frequencies allows for the phase difference between the scattered light waves and is directly correlated to the diameter of the particle. For reflection measurements, the two detectors measure the phase shift between the two beams to determine the particle's diameter (Eq. 3). One important diameter is the Sauter Mean Diameter (*D32*). This value is used to characterize the spray size at a specified point. The *D32* is defined as the diameter of a sphere that has the same volume to surface area ratio as the average of all the droplets measured at a location. The subscript "32" refers to the ratio of volume to surface area of the particle distribution [4]. The *D32* is an important value in combustion studies because it can be used to estimate the evaporation rate of droplets. A larger surface area to volume ratio leads to a faster evaporation rate, making it an important diagnostic tool for combustion analysis.

$$\lambda_R = \lambda_S \times \left[\frac{1-\beta}{1+\beta}\right]^{\frac{1}{2}} \tag{Eq. 1}$$

$$\beta = \frac{v}{c} \tag{Eq. 2}$$

$$\Phi = \frac{-2\pi d}{\lambda} \times \frac{sin\varphi \times sin\zeta}{\sqrt{2(1 - cos\varphi \times cos\Psi}} \tag{Eq. 3}$$

In addition to the Doppler shift, PDPA also utilizes Snell's law, or the law of refraction. Snell's law (Eq. 4 and 5) describes how waves refract and change speed when passing through mediums of different refractive indices. When a beam of light meets a medium with a differing refractive index, both reflection and refraction can occur. The incident beams when interacting with the droplet at first can reflect backwards or refract through the droplet and out for first order refraction. Since the beam also changes mediums when exiting the droplet, and this change can lead to internal reflection and then second order refraction when this beam exits the droplet. This can continue for higher orders of refraction, but these effects are negligible in comparison to the reflection and first order refraction effects. PDPA can be conducted by analyzing reflection at scattering angles between 80° – 110°, first order refraction between 30° – 70°, and second order diffraction between 135° – 150°.

$$\frac{sin\theta_1}{sin\theta_2} = \frac{\lambda_1}{\lambda_2} = \frac{v_1}{v_2} = \frac{n_2}{n_1} \tag{Eq. 4}$$

$$n_1 sin\theta_1 = n_2 sin\theta_2 \tag{Eq. 5}$$

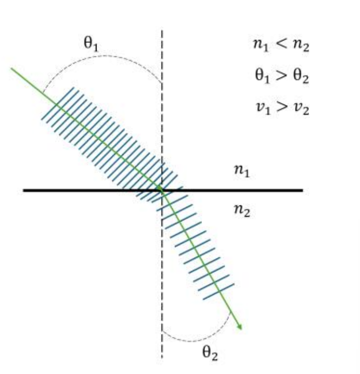

Figure 2. Snell's law of refraction

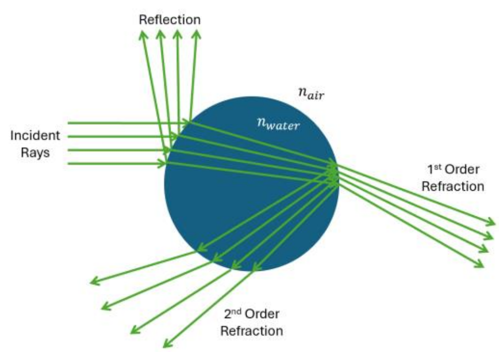

Figure 3. Reflection and refraction orders through a droplet

The focal length of the receiver and emitter can be changed as well. To compensate for the varying focal lengths, different lenses can be used in the laser equipment to ensure the spray particle location remains in focus. The change in focal length depends on the concavity of the lens' two surfaces, as well as the refractive index of the lens material (Eq. 6). For convex lenses, the *R* values are positive, while for concave lenses, the *R* value is negative.

(Eq. 6)

$$\frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

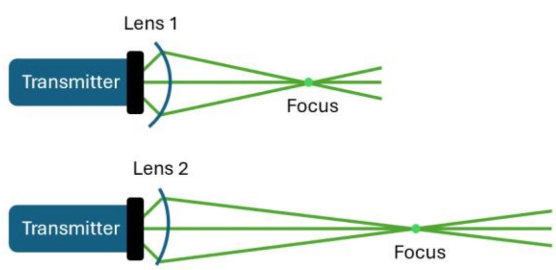

Figure 4. The effect on focal length with varying optical lenses

Additionally, to further adjust with PDPA settings, filters or masks can be applied over the receiver to affect the detection range of the receiver. Placing a mask with two small slits in front of the receiver allows for a wider range of particle sizes to be detected through double-slit diffraction [5].

(Eq. 7)

$$s = \frac{n \times \lambda \times D}{\mathrm{w}}$$

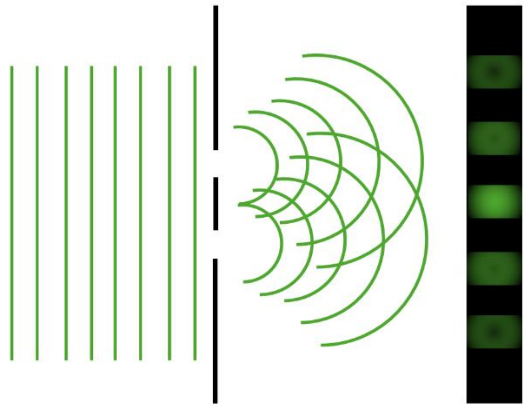

Figure 5. Representation of double-slit diffraction fringe pattern

IV. Approach

The PDPA system comprises of a two-pair DANTEC Dynamics emitter, receiver, and burst spectrum analyzer. The emitter beams have wavelengths of 532 nm and 561 nm. To characterize different points within the spray, the nozzle was attached to an optical traverse with discrete motion controls to precisely move the spray into position. A water spray was used in this study to understand the interactions of fluid sprays in air. The emitter and receiver both have two possible lenses to adjust focal lengths. In addition, there is one double-slit mask that can be applied to the receiver to adjust the detection ranges. The data collected (particle size, distribution, horizontal velocities, and vertical velocities) were all acquired through the DANTEC BSA Flow software and analyzed in MATLAB. The program factored in the different refractive indices of the mediums and the frequency of the emitting lasers. The BSA Flow software was also configured to have 250 bins per trial and run for 10 seconds continuously.

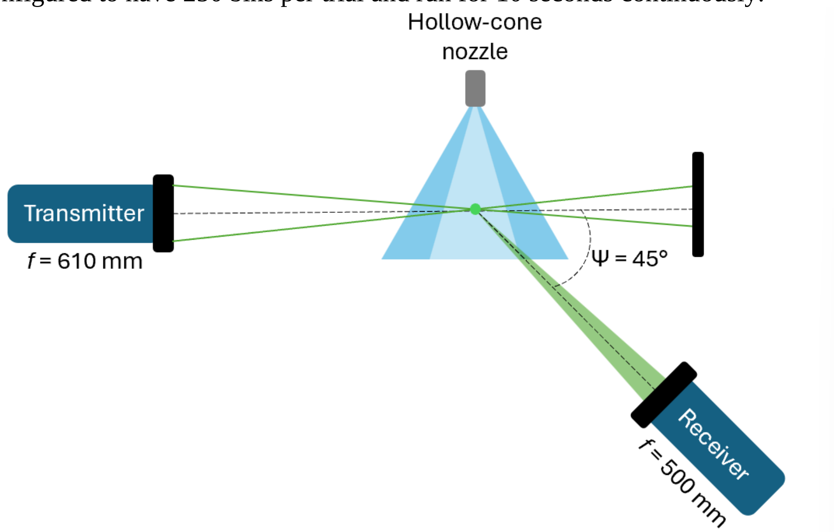

Figure 6. PDPA characterization study configuration

This experiment comprises of a preliminary characterization study of a 75° angled hollow-cone nozzle with water to quantify key points within the spray. The characterization study has a scattering angle of 45° with an emitter focal length of 610 mm and a receiver focal length of 500 mm using Mask A. The goal of the characterization study is to find diverse points within the flow to analyze changes between the variable trials. The characterization survey gathered spray data at intervals of 5 mm in the *x* direction and 10 mm intervals in the *y* direction for a total of 55 data points. The limits of the *x*-direction points were to keep all data points confined within the spray. There was also a collection bin with a vacuum approximately 2 meters below the spray to collect the water during the trials. The vacuum was used to minimize the effects of rising mist and reduce the interference effects. However, to also minimize the suction streams of the vacuum, the limits of the *y*-direction points were stopped at 60 mm downstream.

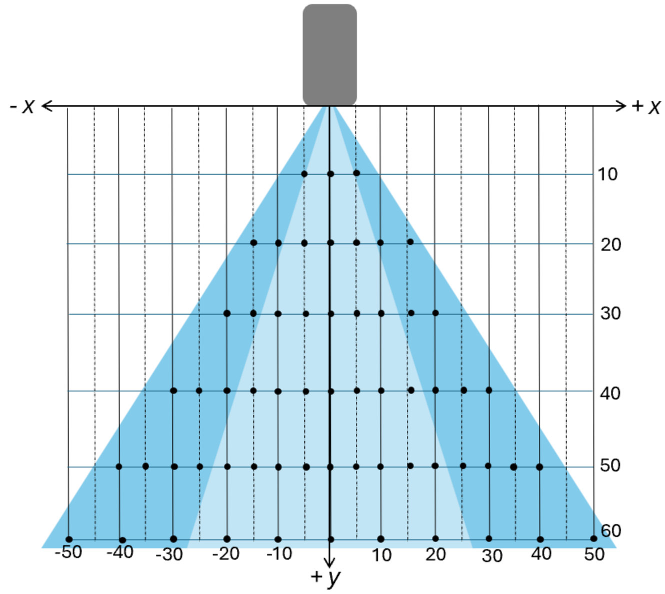

Figure 7. Characterization study test points

After the reference points have been determined, the scattering angle was adjusted between the acceptable range of 35° to 60° and compared to the characterization data. The focal length was also varied by using different lens attachments on the receiver and emitter. The effects of masking were also studied by analyzing the reference points with a double-slit filter over the receiver. Finally, the data collection methods of LDA in one dimension were compared to the two-dimensional data of PDPA.

The original DANTEC mask ('Mask A') that comes installed on the receiver is comprised of three open regions, while the DANTEC Mask B is comprised of a double-slit. Mask B theoretically would allow a wider range of particle sizes to be detected through the principle of double-slit diffraction [10].

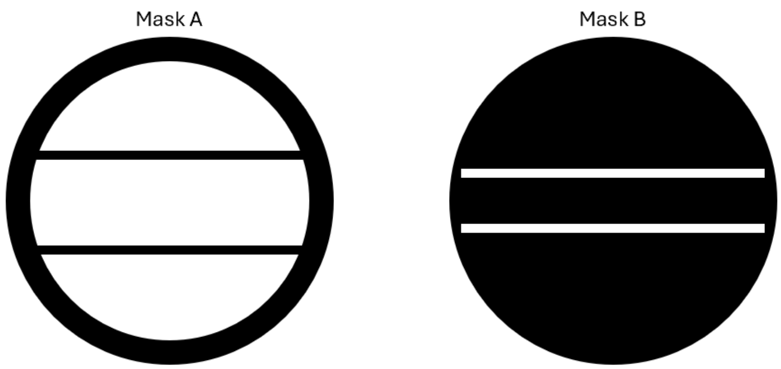

Figure 8. Receiver masks

V. Results

A. Characterization Study

In the characterization study, data points were taken every 5 mm in the *x* direction and every 10 mm in the *y* direction across the spray. The *x*/*y* velocities, particle count, and *D32* particle sizes were measured at each location in the spray. Based on the *D32* values, the reference points of (0, 20), (-10, 20), (0, 40), and (-20, 40) were chosen for analysis in the following sub-studies, represented in probability density functions (PDF). These points were chosen because they provided a range of locations within the stream and had varying *D32* particle sizes. While the point (0, 10) had the largest measured *D32* values, it was not included as a reference point because when the nozzle is installed in a gas turbine combustor, the ignition occurs downstream at a magnitude of 10^{-3} to 10^{0} meters. Choosing a value that is further downstream allows for the data comparisons to accurately reflect the combustor environment.

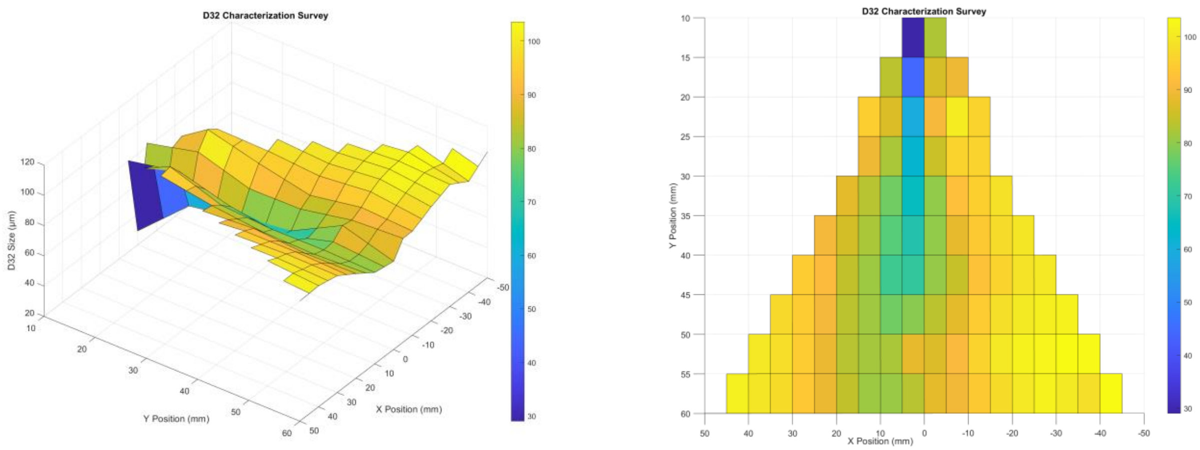

Figure 9. D32 characterization survey contour maps

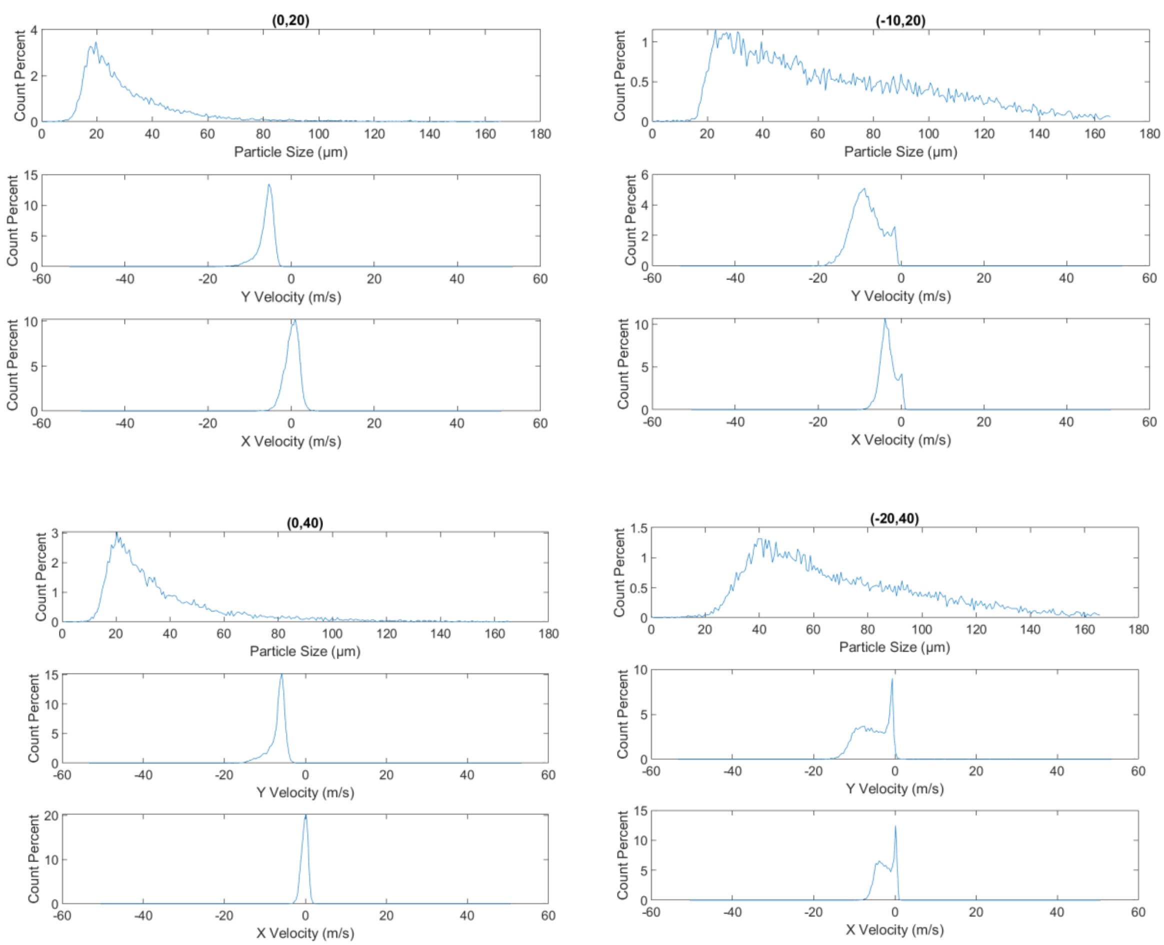

Figure 10. Characterization reference point particle size and velocity distributions

B. Angle Variance

The angle variance trials were conducted with Mask A, emitter focal length of 610 mm, and receiver focal length of 500 mm. Based on the four determined reference points, we can then compare the particle sizes, *x* velocities, and *y* velocities recorded at each varying scatter angle. The *x* and *y* velocities between the angle variation trials are relatively similar, but the particle size recorded varies. Interestingly, the particle size data for the ideal 45° is most similar to the 60° data. All the negative *x*-coordinate points analyzed from this point on will be treated as positive since the flow at *y*-coordinates of 10 to 40 are assumed to be symmetric. The focal lengths, nozzle, and beam wavelengths are kept the same between the characterization and angle variance trials.

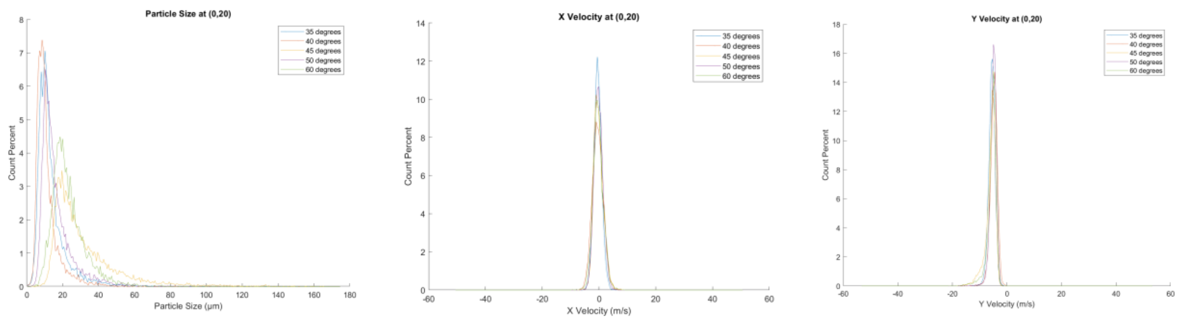

Figure 11. Angle variance data at (0, 20)

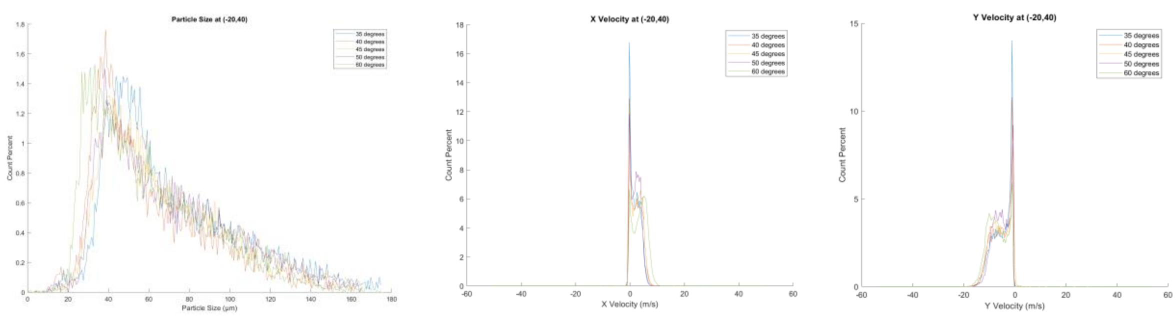

Figure 12. Angle variance data at (-20, 40)

C. Focal Length Variation

The focal length variation trials kept a scattering angle of 45° and Mask A. Theoretically, if the appropriate lens is applied to the receiver or emitter and the focal length is adjusted, the resulting PDPA data should be the same. However, when looking at particle sizes, the default emitter focal length of 610 mm and receiver focal length of 500 mm detect much larger particle sizes than the other configurations.

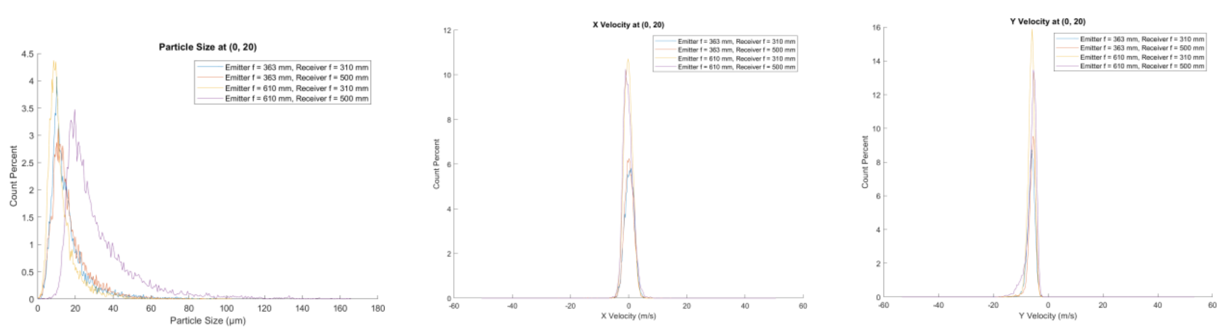

Figure 13. Focal length variance data at (0, 20)

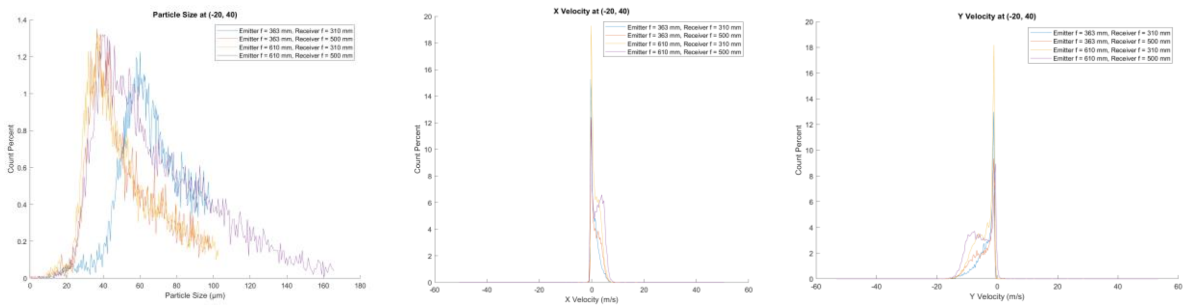

Figure 14. Focal length variance data at (-20, 40)

D. Masking

The mask variation was conducted with the original configuration of a scattering angle of 45°, emitter focal length of 610 mm, and receiver focal length of 500 mm. While in theory, Mask B would detect larger particle sizes due to double-slit diffraction, the data shows this is not the case. Mask A, for both the (0, 20) and (-10, 20) cases, was able to detect the larger particle sizes when compared to Mask B. This could be due to the slits not being small enough relative to the wavelength of the oncoming beams. For double-slit diffraction to work, the slits should be on the same order of magnitude as the wavelength or relatively close. However, the oncoming waves were 532 nm and 561 nm, while the slits were 1 cm wide each. The waves were able to pass through without diffraction occurring, and the large covered areas blocked out some of the refracted signals.

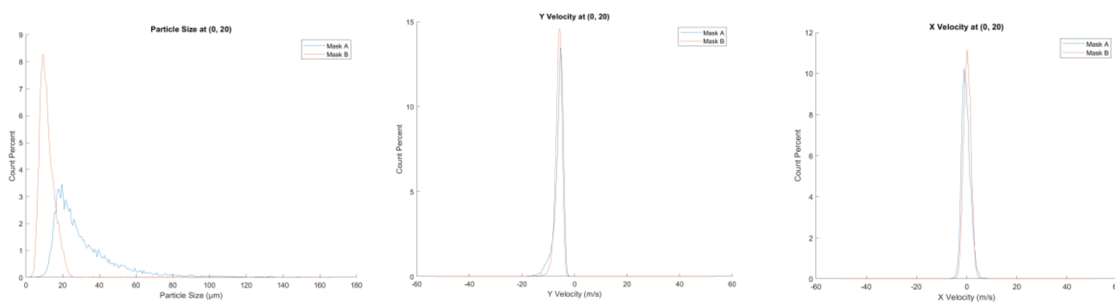

Figure 15. Mask A and B comparison at (0, 20)

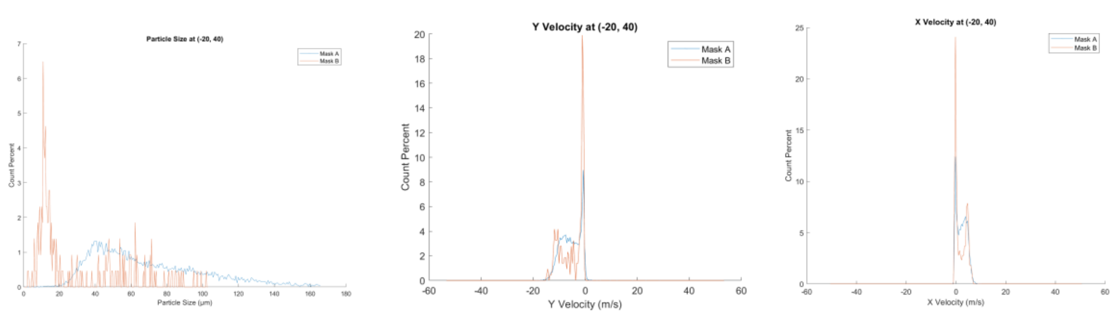

Figure 16. Mask A and B comparison at (-20, 40)

E. 1-D LDA vs 2-D PDPA

The one-dimensional LDA setup could only record particle sizes and *y* velocity. This was conducted with the original configuration of a scattering angle of 45°, Mask A, emitter focal length of 610 mm, and receiver focal length of 500 mm. While the two-dimensional PDPA setup has the capabilities to record both *x* and *y* velocities, only the *y* velocities are compared with the available LDA data. PDPA is regarded as more accurate than LDA because of its two-dimensionality, but the velocities show up relatively similar. The difference is in particle sizes, where the LDA detected much smaller particles, PDPA was unable to register them. For analyzing smaller particles (0 to 50 μm), LDA may be more beneficial, but the tradeoff comes with the lack of a second-dimensional velocity profile.

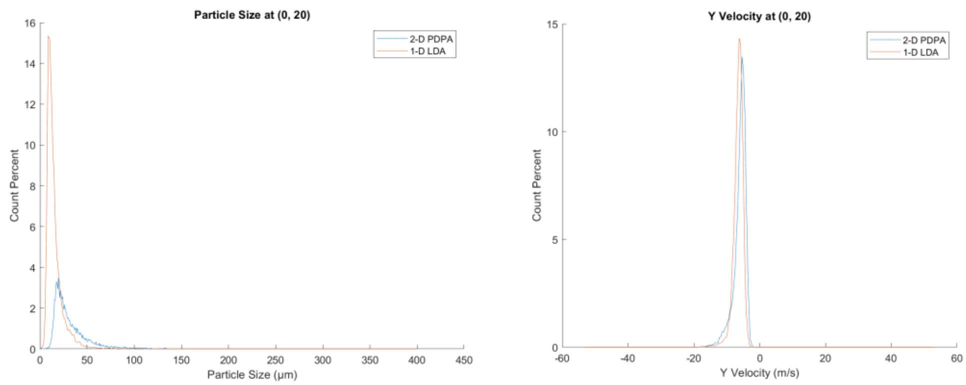

Figure 17. 1-D LDA and 2-D PDPA comparison at (0, 20)

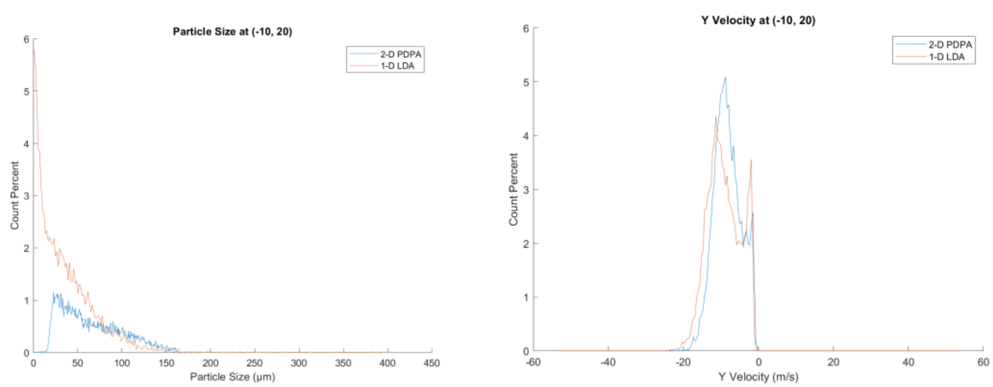

Figure 18. 1-D LDA and 2-D PDPA comparison at (-10, 20)

VI. Conclusion

This study provided valuable information on the advantages of PDPA when altering its typical settings. The angle variance trial showed that the ideal 45° and 60° produced similar results, while 40° was vastly different. The focal length variation indicated that an emitter focal length of 610 mm and receiver focal length of 500 mm were more susceptible to detecting larger particle sizes. The masking experiment showed the importance of characterizing equipment before using it in industrial settings, because the theory associated may not always apply on a larger scale. Finally, the 1-D and 2-D comparison showed that the "better" option may not always be beneficial in certain scenarios, like small particle analysis.

This project helped characterize the equipment that will then be used in future experiments. Having this data allows future researchers to understand the limitations of their equipment and help them make informed decisions on which optical configuration is optimal for their project. This research will be used in the Ben T. Zinn Combustion Laboratory at the Georgia Institute of Technology for implementing PDPA in a gas turbine combustor as part of the Aviation Sustainability Center (ASCENT) Project 070.

Acknowledgments

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