Spray Transport Past Cylindrical Elements found in a Generic Aircraft Engine Nacelle: A PIV and PDA Comparison

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ABSTRACT

To better address the fire protection challenges which exist in aircraft engine nacelles, it is important to understand the transport of high boiling point liquids as they are sprayed past generic clutter elements that are found in aircraft engine nacelles. Specifically, there is a lack of reliable velocity and drop size measurements located downstream of an arrangement of clutter elements found in aircraft engine nacelles. To this end the need to non-intrusively record the drop size and velocity of fire suppressants in generic cluttered nacelle environments are critical. Two common nonintrusive optical methods, particle image velocimetry (PIV) and Phase Doppler Anemometry (PDA) were applied to a suppressant spray nozzle characterization. This characterization was performed upstream and downstream of a cylindrical tube array, which is of special interest in aircraft engine nacelle fire suppressant transport and distribution. A comparison between these two measurement techniques were conducted to analyze and highlight the strengths and limitations of each technique when applied to practical applications with large dynamic ranges. The experimental results demonstrate significant differences in velocity measurements between PIV and PDA due to the methodology each system employs; however, the characteristic trends of the velocity profiles were found to be consistent. In addition the high shear and vortex shedding which follow the clutter elements also contribute to this discrepancy between the two measurement approaches. The following data suggests that careful consideration must be taken when choosing an optical approach for the measurement of applications with large dynamic range applications, as those found in fire suppressant transport.

Keywords: Particle Image Velocimetry, Phase Doppler Anemometry, fire suppressant distribution, high boiling point suppressants, two-phase flow, droplet laden flows

1. INTRODUCTION

Fire protection in aircraft engine nacelles represent a unique fluid thermal state enclosed within a confined environment. The nacelle environment is typically characterized by highly non-uniform flow with large levels of flow unsteadiness, large scale vortical structures, and high turbulence [1]. Further complicating this environment are obstructions due to the presence of wire bundles, fuel lines, mechanical components, and avionics assembles, which are attached to either the engine or mounted directly to the nacelle structure. In addition, some nacelles have relatively large structural members and ribs that further impede the transport of a fire suppressant and typically act as flame holders. The combination of flammable fluids, numerous potential ignition sources, and the presence of a highly turbulent airflow make fire protection within aircraft engine nacelles difficult at best and ineffective in many cases.

Making nacelle fire protection even more difficult is the ban of halon, a very effective, but ozone depleting fire suppressant. In fact, halon is so effective that the inefficient delivery and distribution of the suppressant into the fire zone was never consider and assumed not to be an issue. Although replacement fire suppressants continue to be developed, the effectiveness when compared to halon by weight is very poor. Therefore the need to effectively deliver a fire suppressant to the fire zone is more critical now than ever before. To make matters worse some of the new halon replacements have a high boiling point when compared to Halon 1301, and have been proven to be difficult to transport within the nacelle environment. To this end the reliable measurement of drop velocity and size distribution of a high boiling point agent being produced by a generic fire suppression spray nozzles is needed. This will enable a proper evaluation of potential agent transported through a highly turbulent environment found in a cluttered aircraft engine nacelle. To best evaluate the velocity and size of droplets transported through generic clutter, non-intrusive laser based optical methods are utilized.

Two common laser based techniques for nozzle flow characterization are particle image velocimetry (PIV) and phase Doppler anemometry (PDA). They offer a non-intrusive approach to flow characterization and are advertised as being accurate and simple to operate. Both techniques have the advantage over intrusive velocity measurement techniques such as Constant Temperature Anemometry (CTA), although CTA is very accurate they can't be used for droplet size measurements nor applied in hostile environments. However, the need for repeatable measurements, with high accuracy, has brought into question some laser based methodologies when measuring fire suppressant droplets in highly turbulent air flows. This paper seeks to provide insight into the proper application of a laser based technique within an aircraft engine nacelle.

2. MEASUREMENT METHOD OVERVIEW

In principle, the PIV technique is relatively simple and allows two-dimensional full field measurements to be quickly obtained while being non-intrusive. This technique typically involves seeding the flow field with micron sized particles, and then illuminating these particles with a high energy pulsed laser light sheet. An imaging device is synchronized with the light sheet and captures a single image from each light pulse. This is repeated numerous times, producing a series of images at a pre-specified image acquisition rate. The velocity is then determined from the preset time between two successive images and the corresponding particle displacement. The latter is determined through pixel displacement utilizing particle tracking software algorithms. Once the pixel to length scale is determined through calibration, PIV is capable of simultaneously producing velocities and particle sizes for an entire flow field. Various types of algorithms are applied between images for optimal particle tracking. Further information on PIV algorithm techniques can be found in Riethmuller [1] and Stanislas et al. [2].

The PDA technique is also non-intrusive. This technique is capable of measuring drop size (diameter) and up to three components of velocity, simultaneously. Unlike the PIV technique the PDA system only records drop data at a single point in the flow field. The PDA methodology is the same as that used in laser Doppler anemometry (LDA) or laser velocimetry (LV) when measuring droplet velocity, and differs only in its added ability to also determine drop diameter. The velocity of a drop is calculated at a single point which is illuminated by the crossing of two phase-shifted laser beams of the same base frequency. This crossing region is known as the measurement volume and is approximately ellipsoidal in shape. The measurement volume has a discrete size which depends on the optical arrangement of the system and typically ranges from 100 to 800 μm in diameter and between 1 and several millimeters in length.

The crossing of the two phase-shifted laser beams within the measurement volume creates a moving fringe pattern. As a drop propagates through the measurement volume and across the fringes, the drop scatters the incident light in various modes (reflection, refraction, etc.). This scattered light forms a unique pattern know as a Doppler burst which is collected using receiving optics. The frequency of this Doppler burst is directly related to the drop's velocity.

Recently there has been an increase in the number of two dimensional laser based technique comparison studies applied to various flow conditions. Saga et al [3] applied PIV and laser Doppler velocimetry (LDV) to an induced sloshing flow due to a submersed inlet jet using 20-50 μm diameter polystyrene seeding particles for PIV and 1 μm diameter for LDV. The inlet velocity of the jet was set at 0.33 m/s, yielding turbulence intensities within the tank between 0.7% and 13% measured by the PIV system and 2.6% and 15% measured by the LDV system. Their research showed velocity agreements within 3% between the two techniques despite the difference noted in the lower turbulence intensity values. Hyun et al [4] investigated both techniques on flow over a two-dimensional dune in an open channel with free stream velocity of 0.48 m/s. They seeded the flow with 30 μm mean diameter drops for PIV and 5 μm mean diameter drops for LDV and noted velocity agreement between the two techniques at several spatial locations. All values were non-dimensionalized by the free stream velocity. Non-dimensional horizontal velocities ranged between 0.2 and 1. Non-dimensional horizontal and vertical turbulence intensities ranged between 7% and 20% and 4% and 12%, respectively. The LDV system measured slightly lower turbulence intensities with the greatest discrepancies less than 10% at the shear layer produced by the dune crest. Yildiz et al [5] compared the use of PDA and PIV for measuring drop size and horizontal velocity on a two phase flashing jet at several spatial locations with drop velocities between 10 m/s and 50 m/s. This type of flow provides an optically harsh environment for both measurement systems due to the large dynamic range of droplet sizes and velocities. As a result, the researchers noted low validation rates near the nozzle of the jet for the PDA system. In addition, the PIV system had difficulties in the same area due to the non uniformity of the droplet shapes and the existence of ligaments. Further downstream, similar velocity trends were observed between the two techniques. However, there were discrepancies in the nominal velocity values between the two systems. The research demonstrated discrepancies between the two systems when the flow conditions are not optically conducive.

The current paper applies both PDA and PIV to a two-phase air/water spray nozzle impinging on rows of staggered cylindrical tube array in a low speed wind tunnel. The test facility simulates the transport of a high boiling point fire suppressant through generic clutter elements in a turbulent environment found in aircraft engine nacelles and is conducive for the use of non-intrusive, laser based techniques. Selecting an appropriate technique and configuration is of the utmost importance to ensure the accurate characterization of drop transport which can be used in the validation of fire suppressant transport models currently being developed.

Previous research examining cross flows over cylindrical tubes has been investigated with both LDV [6] and PIV [7, 8], separately. However, previous experiments have only studied single phase flows with wake regions that form behind the cylinders producing a region of vortex shedding characterized by high turbulence intensities [6, 7, 8]. These previously studied flows have utilized seeding particles with a small dynamic size range and well understood free stream flow field.

A comparison study on laser based methods applied to large fire suppressant transport experimental systems with large dynamic range has previously not been conducted. A majority of laser based studies have utilized monodispersed particles resulting in a well-defined and fixed dynamic range, which is ideal for such systems. Currently, there is a void in the research on selecting the appropriate laser based system for practical fire applications with engine nacelles that require non-intrusive techniques.

The spray nozzle represents a practical application not only found in aircraft engine nacelles, but in a variety of fire suppression applications. Laser based techniques offer the optimal method for spray characterization due to their ability to perform non-intrusive measurements. However, many fire suppressant spray nozzles are relatively unsophisticated and produce a large distribution of drop sizes. Furthermore, the intricate nature of the flow environment of the staggered tube array adds to the complexity of the test conditions, yielding an optically harsh setting for the limited dynamic range of laser based systems.

For the purpose of reliably evaluating fire suppressant transport in aircraft engine nacelles the current research explores the limitations and feasibility of both techniques and compares their respective quantitative merits. It provides guidance for improving the accuracy of both techniques and recommends optical methods for two-phase flows with a large dynamic range.

3. SUPPRESSANT SPRAY FLOW FACILITY

Two different non-intrusive laser based systems were utilized in the suppressant spray flow facility located at Wright-Patterson AFB in Ohio. This flow facility is a low-speed wind tunnel configured with a dual fluid suppressant spray nozzle. Test section air velocities between 0.0 and 12.0 m/s with different turbulence levels can be obtained. The suppressant spray facility consists of five major components, namely, an inlet contraction, turbulence generator, test section, clutter section, and return and separation plenum. Each component is described in the following text. The upstream test section consisting of the turbulence generator and the spray nozzle is displayed in Figure 1. The facility is described in detail in reference [9] and the following explanation is a brief summation.

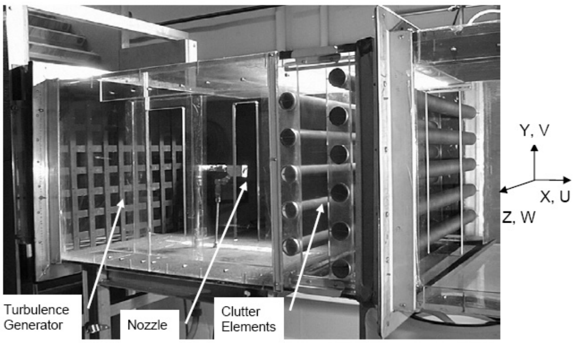

Figure 1 Suppressent Spray Flow Facility

An inlet contraction with a 3.5:1 area ratio accelerates ambient air, drawn from the laboratory. Prior to entering into the test section the air passes through a flow-conditioning unit located at the inlet of the contraction to minimize random flow disturbances. Downstream from the contraction exit, this air flow, referred to as the co-flow passes through a turbulence generator grid, prior to entering the test section.

The turbulence generator consists of thick, sharp-edged steel slats that span the cross-sectional area of the test section and have dimensions of 25.4 mm in width and a thickness of 6.35 mm. These slats were assembled in a checkerboard fashion with a square, open cell dimension of 50.8 mm between slats. Using hot-wire anemometry, velocity data were acquired at x = 711.20 mm downstream of the turbulence generator. As expected the results indicated a wave-like distribution in the mean streamwise velocity component. The measured velocity ranged from 3.7 m/s to 5.0 m/s.

Entering the test section, two key elements of the suppressant spray flow facility are observed; a spray nozzle and a clutter package. This test section has a cross-sectional area of 609.6 mm wide x 914.40 mm height and has a total streamwise length of 3.657 m. The leading edge of a replaceable clutter package is located 952.50 mm downstream of the turbulence grid. Due to the rough nature of the piping the spray nozzle was slightly misaligned and tilted downwards at 4° and was located 355.60 mm, or in terms of clutter diameter (D), 7 D upstream of the current clutter package. The spray nozzle exit was positioned in the center of the coflow, and was located 457.20 mm vertically above the floor and horizontally 304.80 mm away from the test section walls.

The current clutter package was manufactured to simulate generic clutter found in an aircraft engine nacelle. The clutter is comprised of 16, two-dimensional, cylindrical elements composed from PVC plastic pipe spanning the width of the test section. Each cylindrical element had a diameter (D) of 50.8 mm. When assembled, the clutter elements form three distinct and equally spaced arrays consisting of five, six, and five cylindrical elements, respectively, each with a vertical separation of 47.75 mm (0.94 D), as shown in Figure 2. The streamwise spacing between the clutter element arrays was variable, ranging from 12.70 mm (0.25 D) to 101.60 mm (2.0 D).

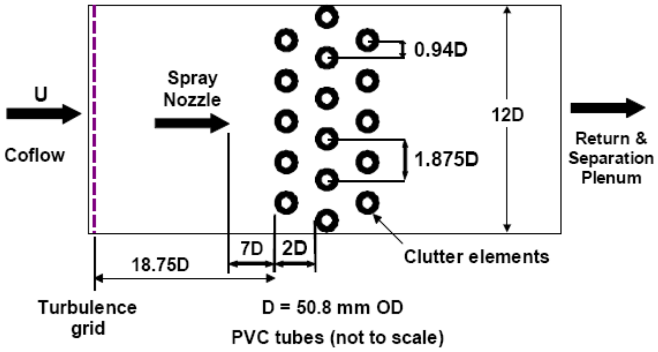

Figure 2 Side View Schematic of Test Section

4. EXPERIMENTAL STRATEGY

Measurements in the current study were acquired utilizing both PIV and PDA methodologies at three streamwise locations, two downstream and one upstream from the clutter package. Distances of 101.6 mm, or 2 diameters downstream (D), and 279.4 mm (5.5 D) were selected for the downstream measurements and a distance of 101.6 mm (2 D) upstream of clutter was chosen to characterize the incoming spray.

The flow facility settings were kept fixed for each set of measurements. The coflow speed was set at 5.0 m/s with the streamwise clutter spacing fixed at 2D. Coflow turbulence intensities at these settings ranged from 10% to 14% upstream of the clutter. The air water spray nozzle was set to a water flow rate of 17.1 L/min at a water pressure of 158.0 kPa. Likewise, the supplied air to the spray nozzle was pressurized at 171.8 kPa.

4.1PDA System Configuration and Operation

A Dantec 3-D fiber-optic PDA system was utilized for the current investigation. A 300 mW air cooled argon-ion laser was used for the incident light source. The laser output was directed into a Bragg cell where the laser light was split into three separate wavelengths: 514.5 nm, 488.0 nm, and 476.5 nm. The Bragg cell further splits each wavelength into two beams; however one is phase shifted by 40 MHz, thereby resulting in a total of three pairs of beams, each at a specified wavelength. Data acquisition was computer controlled through a Dantec 58N80 MultiPDA signal processor using Dantec BSA Flow Software v2.0.

The current PDA optical setup is shown in Figure 3. This PDA system was configured in the 2nd order of refraction (backscatter) measurement mode using 1000 mm focal length optics on both the transmitting and receiving optics. This configuration was chosen due to physical constraints of the facility test section. The receiving optic uses apertures (spatial filters) to effectively change the diameter dynamic range of the PDA system. The largest aperture, Mask A, was chosen for the current study. In this configuration, the PDA system is theoretically capable of measuring a maximum diameter of 810.8 μm. This PDA setup was based on a previous study by Davis and Disimile [10].

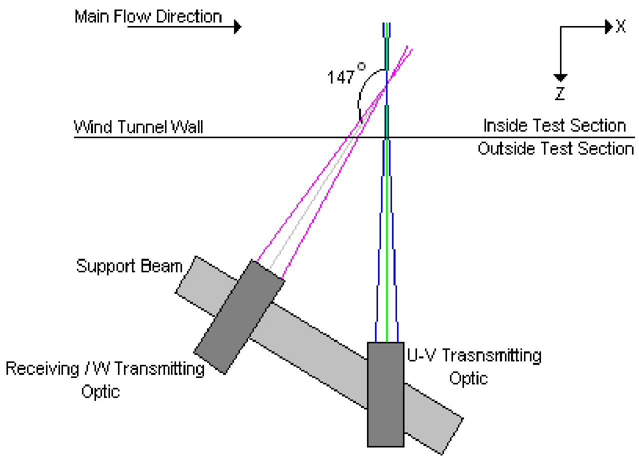

Figure 3 PDA Optic Schematic

The PDA system was set to acquire 20,000 samples at each spatial location within the three vertical traverses. Although only two velocity components are desired for the current study, the PDA measurements were validated on three components of velocity as well as the diameter signals, providing the maximum validation. This validation was chosen such that the data could be used for a separate study involving the drop distributions.

Upstream PDA measurements were acquired through the entire spray jet exiting the nozzle (approximately ± 50 mm from the centerline) in 3.155 ± 0.022 mm (0.124 ± 0.001 inches) increments. After passing through the clutter the spray pattern increased in cross section, thus requiring a wider measurement traverse. Downstream traverses were acquired from y = -140.00 ± 0.79 mm (5.51 ± 0.03 inches) to y = +140.00 ± 0.79 mm. All downstream measurements were taken in 12.70 ± 0.022 mm (0.500 ± 0.001 inches) increments. Figure 4 shows the three dimensional measurement volume positioned downstream of the clutter elements which are illuminated by the three pairs of laser beams. One can clearly see the drops being transported through the clutter package. As these drops pass through the measurement volume, the incident laser light is scattered off the drops and collected by the receiving optics.

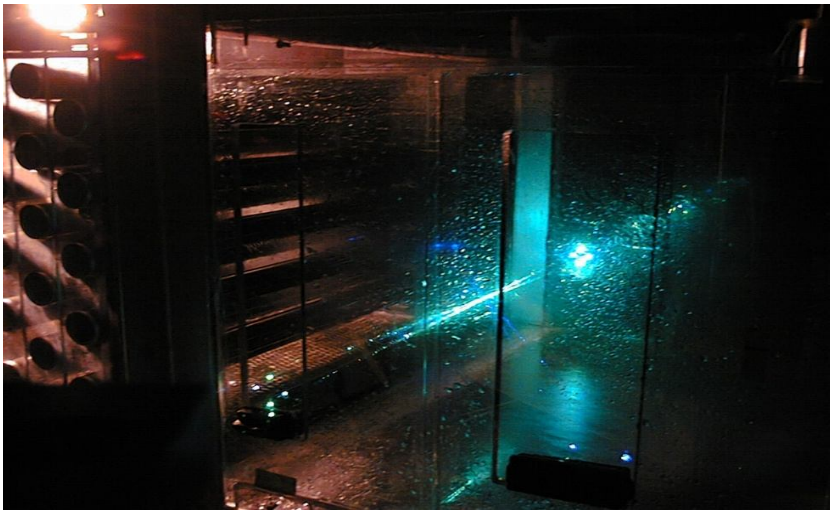

Figure 4 The PDA measurement volume produced by the intersection of 3 pairs of laser beams

4.2PIV System Configuration and Operation

A double pulsed, dual cavity, Nd:YAG laser source provided a two dimensional light sheet for illumination of the spray droplets. Specifically, a 1.5 mm thick laser light sheet is produced by impinging the coherent beam exiting the laser cavity on to a 60 divergent optic. The pulsing nature of the laser provides a laser power (as provided by the manufacturer) of 20 mJ at 1000 Hz repetition rate with an output wavelength of 532 nm. A Nanosense XS-4 CMOS high speed digital camera manufactured by IDT was utilized to capture the flow field images. This camera has a physical pixel size of 16 µm and a maximum resolution of 512 x 512 pixels. Furthermore, it has an onboard memory storage capacity of 4 GB or approximately 16,000 images.

In the current study the laser was positioned on top of the wind tunnel as to illuminate the x-y plane of the flow field (Figure 5) through a 6.35 mm thick standard glass plate. The camera was positioned normal to the light sheet along the z-axis, 330.4 mm from the streamwise centerline of the test section. A 60 mm Nikon lens with the aperture set to f/2.8 was installed on the camera to view the light sheet. The camera and laser system were synchronized using a trigger box connected to a personal computer (PC). Software from Dantec Dynamics (FlowManager v4.5) controlled the laser and the camera, and was also used for all data post processing. The PIV system connections and setup are displayed in Figure 5.

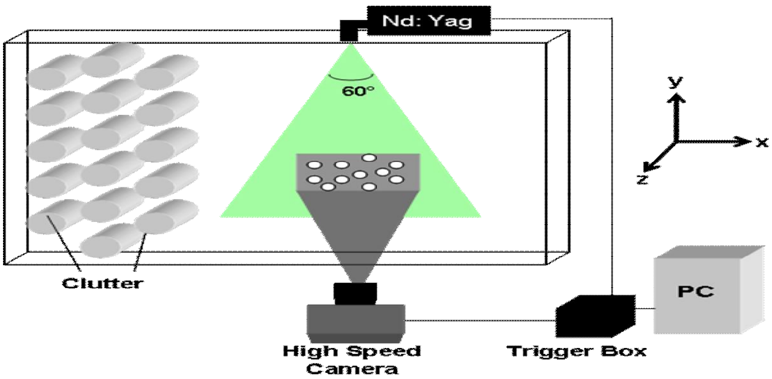

Figure 5 PIV System Setup

Before quantitative measurements could be produced, the spatial resolution of the PIV system had to be established. The spatial resolution is determined using a calibrated scale located at the specified area of interest. A single image of the scale was captured and utilized by the software in determining the scale factor of the image with the corresponding field of view. The resulting calibration verified a spatial resolution of 0.154 +/- 0.004 mm/pixel.

To maintain a high spatial resolution, the camera had to maintain its standoff at different vertical locations to encompass the three center clutter elements of the third row. Four sets of vertical measurements were necessary at each downstream measurement, 2D and 5.5 D. A calibrated scale was placed in the plane of the light sheet and was used to position the height of the field of view of the camera with respect to the bottom of the facility. The bottom of the field of view was set at the following four locations relative to the bottom of the wind tunnel: 165.1 mm, 228.6 mm, 304.8 mm, and 355.6 mm. For the 2 D upstream measurements, the camera was only positioned in two locations relative to the bottom of the wind tunnel so that the camera could encompass the entire spray. The bottom of the field of view was set at 228.6 mm for the first set of measurements and 304.8 mm for the second set.

The PIV system acquired 200 single frame images at 3500 frames/sec in single pulse mode for each measurement, which provided a 286 μs temporal resolution. Since the camera frame rate is below the maximum frame rate of a single laser cavity (10,000 Hz), only one cavity was utilized. Once the series of images were captured on the onboard memory of the camera, they were transferred via USB 2.0 to the PC for post processing.

For quantitative image analysis, an appropriate correlation method needed to be chosen. Cross correlation methods described in [1, 2] have been popular methods in the past for post processing calculations. An improved method on the cross correlation method for image analysis known as the adaptive correlation method has shown promise in increased measurement accuracy. The adaptive correlation method offers advantages over cross correlation methods. Two interrogation areas containing a group of drops are displayed in Figure 6 showing the standard cross correlation method (left) and adaptive correlation method (right). As seen in Figure 6, the adaptive correlation method decouples the interrogation area between the two frames by introducing a predetermined interrogation area offset between the two images. The second frame is represented as dashed lines. Once a drop has been tracked and validated, a new offset of the interrogation area between frames is determined from the validation and employed for tracking other drops. This allows for tracking droplets that travel out of an interrogation region between images. Furthermore, the adaptive correlation increases signal strength and permits the refinement of the interrogation region size. This method is suggested by the manufacturer for a flow with a large dynamic range and non-uniform seeding densities and thus was chosen for the current investigation.

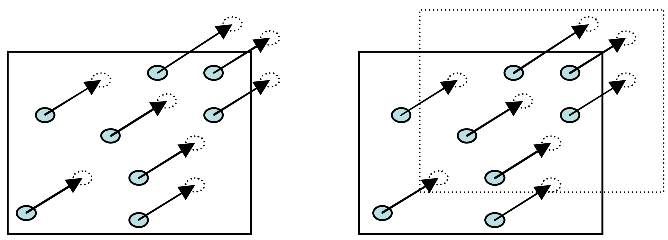

Figure 6 Cross correlation (left) and adaptive correlation (right) methods

After the frames were acquired and stored on the onboard camera memory, they were downloaded to the PC for post processing. Each frame was combined with its next successive frame, producing a double framed image. The adaptive correlation method was employed to generate local velocity vectors for each of the double frame images processed, thereby producing a time sequence of 199 velocity fields. The interrogation area size was set to 32 x 32 pixels with 25% overlap to achieve similar measurement resolution between the two systems. Due to a lack of droplets, some interrogation areas were unable to produce a vector for each image in the measurement set. The resulting set of vector fields was then averaged to produce a representative vector field over the duration of the acquisition. Since vectors were not produced for each interrogation area, each average vector of the representative flow field was determined utilizing a different number of samples. To enable a direct comparison to the PDA data, only the vectors corresponding with the specific spatial locations examined by the PDA system were calculated. The total field examined encompassed the three center clutter elements.

5. RESULTS

The velocity was decomposed into streamwise and vertical components and exported from the measurement software. The outputs of the two laser based systems were than plotted for comparison. In Figure 7, the PIV system records a higher streamwise velocity component at each vertical location compared to the PDA system. However, the two systems measured a consistent jet profile with matching profile widths at half maximum velocity point. Figure 7 also supports the fact that both systems locate the peak spray velocity just below the vertical centerline of the facility, which is consistent with the nozzle placement error described in the experimental design section.

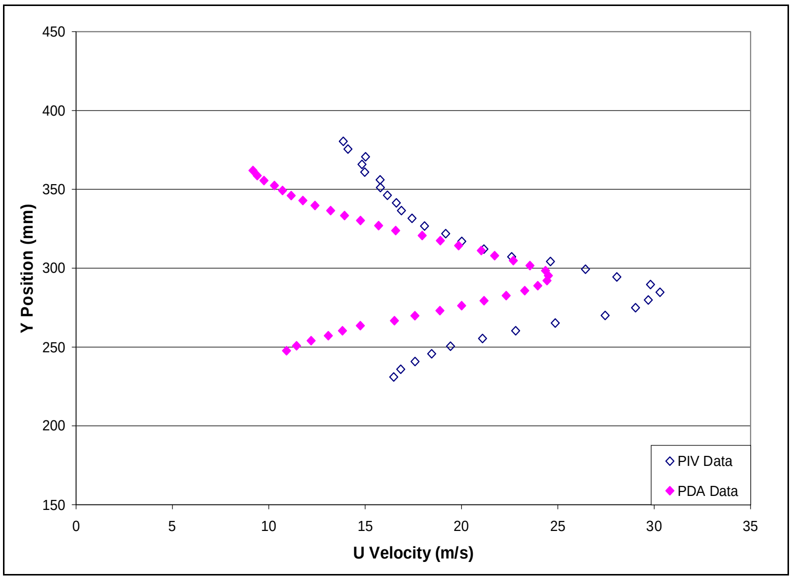

Figure 7 U Velocity at 2 D downstream of the spray nozzle

Figure 8 presents the droplet size profile acquired 2D downstream of the spray nozzle. The drop size is presented as both the arithmetic mean droplet diameter and the Sauter mean drop diameter along the y axis. This definition of diameter is defined in terms of a spherical droplet with its' size determined by the ratio of volume to surface area. However, it must be realized that the spatial data which makes up the Figure 8, is an average of 20,000 samples acquired at each spatial location. Measurements were acquired 10 inches downstream of the spray nozzle exit.

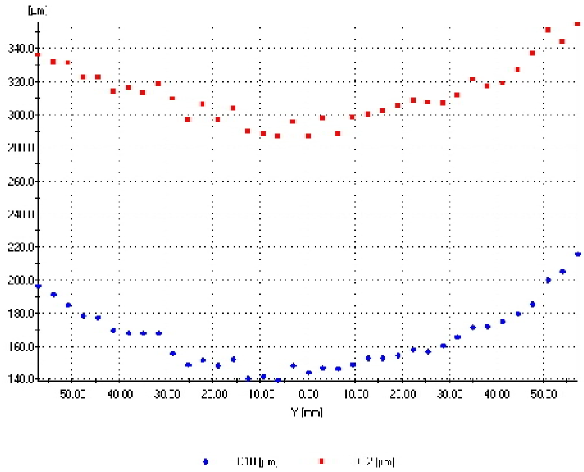

Figure 8 Mean and Sauter diameter distribution downstream of the spray nozzle.

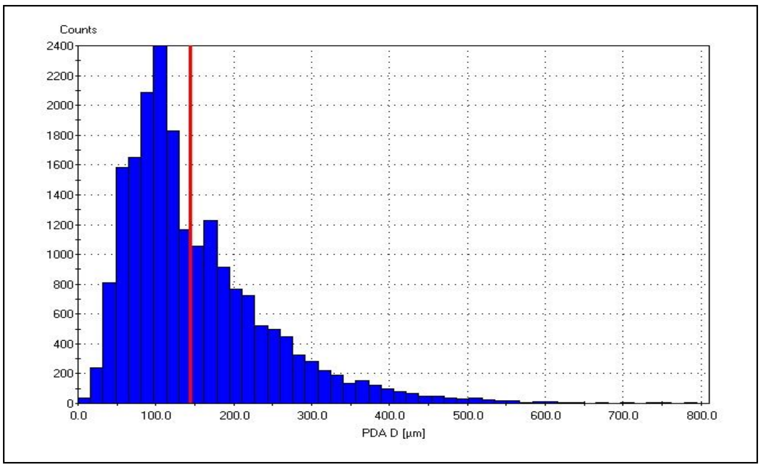

Figure 9 Droplet size histogram acquire downstream of the spray nozzle.

Figure 8, is the actual histogram of drop measurements acquired downstream of the nozzle exit at the nozzle centerline (y=0). Although an average diameter of approximately 143 microns was determined, it can be seen in Figure 9 that drop sizes typically range from 50 to 200 microns.

For the current test conditions the air coflow speed was set to 5 m/s and the clutter spacing 2D. The following figure indicates that less than 4% of all the liquid flow was transported through the clutter such that both small and large drops made it through the clutter. This provided a droplet distribution, downstream of the clutter package, with a very large dynamic range.

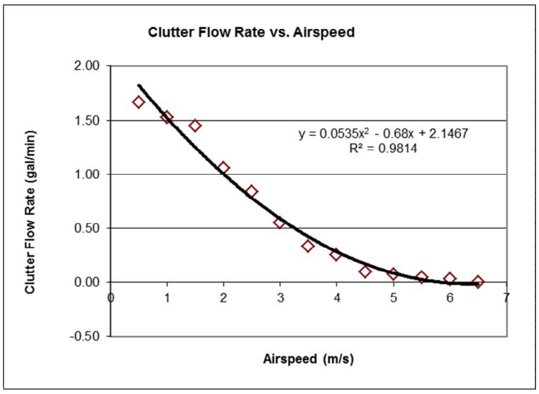

Figure 10 The liquid flow that was transported through the clutter package.

The streamwise velocity component of the flow field at 2D and 5.5 D has been measured by both systems and resented in Figure 11 and Figure 12, respectively. The PIV system consistently measured lower velocities than the PDA along the vertical axis of the spray facility for all u-velocity measurements downstream of the clutter package.

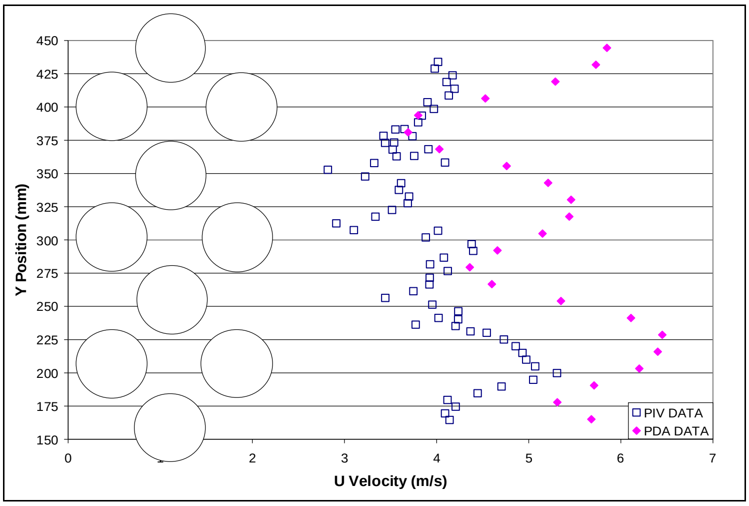

Figure 11 U-Velocity measured at 2 D downstream of the clutter.

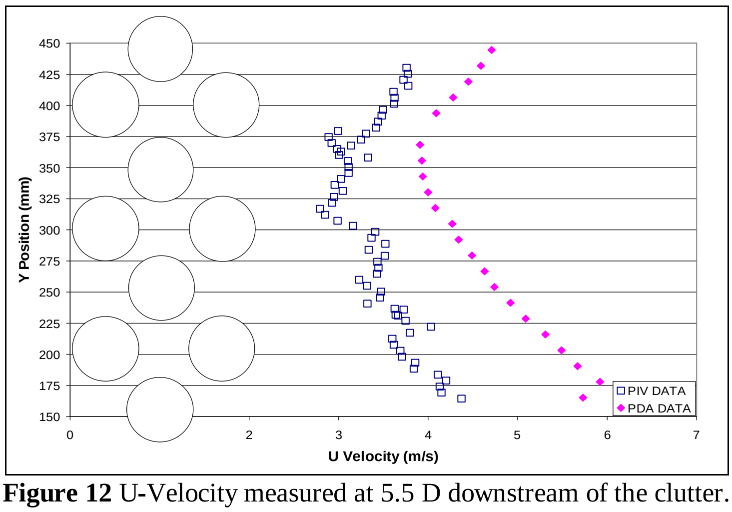

Figure 12 U-Velocity measured at 5.5 D downstream of the clutter.

The vertical velocity (v-velocity) component of the downstream spray drops was also recorded by both systems at 2 D and 5.5 D downstream of the clutter package. The results are presented below in Figures 13 and 14. In Figure 13, a wave like pattern is observed by both systems and there is a fair level of agreement between the two systems with the exception of a perturbation observed by the PIV system between y = 350 mm and y = 425. Figure 14 also displays agreement between the two systems below the streamwise centerline, however, a perturbation is observed by the PIV system above the centerline that was not observed by the PDA system.

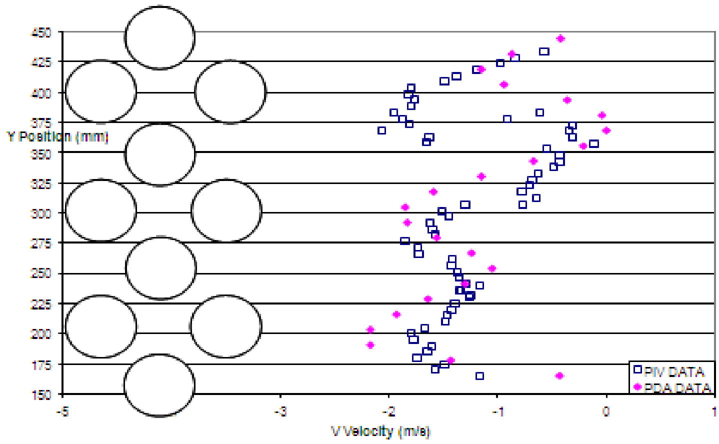

Figure 13 V-Velocity measured at 2 D downstream of the clutter.

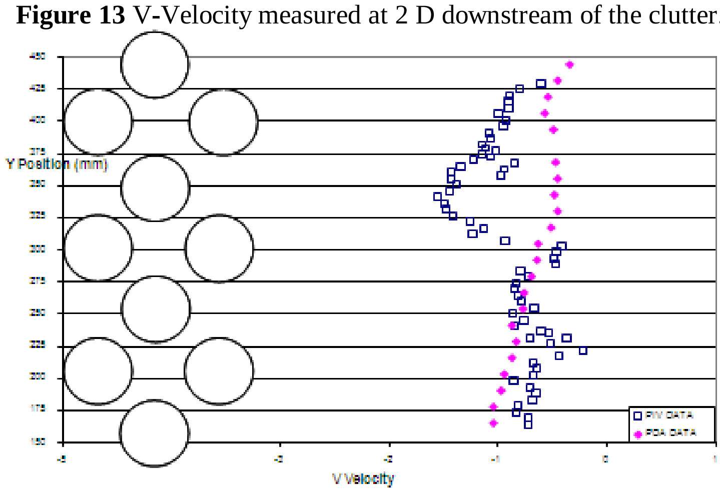

Figure 14 V-Velocity measured at 5.5 D downstream of the clutter.

6. DISCUSSION

Both the streamwise and vertical velocities are presented to provide insight into how flows with a large dynamic range can affect the quantitative results for non-intrusive, laser based systems. Each system was optimized to characterize the spray nozzle both upstream and downstream of the clutter elements. The PDA system typically measured drops with mean diameters between 100 µm and 700 µm; whereas, the PIV system captured a larger range of droplet sizes, some greater than 1 mm in mean diameter. Each system determines the velocity of a droplet only if it is validated by the system. However, if the size of a droplet is outside the range of the PDA system, it is not validated by the system; whereas the PIV system captures all drops that are illuminated by the light sheet. However, the PIV will only track drops that displace roughly 25% of the interrogation area size between images.

For the upstream measurements, Figure 7, there exists similarities between the spray nozzle velocity profiles measured by each of the systems; however, there is a quantitative discrepancy. The PIV system measured a higher centerline velocity by nearly 20% and has the spray nozzle pointed slightly lower than the PDA system. Spatially, the PIV system measured the peak velocity of the spray at y = 285 mm and the PDA system measured the peak velocity at y = 295 mm. If the PDA is utilized as the reference system, the PIV system measured 80% higher at y = 250 mm and 25% higher near the centerline of the jet, yet excellent agreement is noted at y = 312 mm. These discrepancies lead to the belief that there are inherent differences in the two systems that will make agreement difficult when characterizing large dynamic range flows.

In measurements acquired at the 2 D location, Figure 11, it was noted that there is a velocity trend along the clutter elements. There is agreement at the lower velocity locations between the two systems but the PIV did not measure the peak velocities of the trend as high as the PDA system did. Both systems were able to observe the velocity wave pattern that exists behind the clutter elements, which is due to the wake region produced by the airflow over the cylinder. This wake region was also validated by the CTA data obtained in [9].

At 5.5 D, Figure 12, the two systems did not coincide at any of the vertical spatial locations. This may be due to the discrepancy between the sizes of the typical drops measured by each of the systems. Larger drops would tend to fall through the wake regions and not be influenced to follow the coflow. These large drops could bias the PIV system and lower the measured velocity values. However, both systems measured similar velocity trends along the vertical plane of the facility.

The vertical velocities are in better agreement between the two systems as compared to the streamwise velocities. In Figure 13 at 2 D, excellent agreement was noted between the two systems below y = 375 mm; however, above that location, the PIV system measured a higher vertical velocity magnitude. At 5.5 D, Figure 14, the PIV system measures a higher vertical velocity magnitude above the center clutter element than the PDA system. This data discrepancy between the two systems at the 2 D and 5.5 D locations suggest that the PIV system measurements were biased by larger drops that tend to vertically traverse the wake region of the cylinder while smaller drops tend to follow the coflow. The smaller drops were typically measured by the PDA system. A spike in vertical velocity measured by the PIV system above the center clutter element was observed at both the downstream spatial locations.

7. SUMMARY

The streamwise and vertical velocity components downstream of the clutter elements provide insight to the differences between the two systems. Since similar qualitative velocity trends were noted in the streamwise velocity measurements, it is believed the discrepancy in the qualitative measurements is due to the range of droplets each system tracks. Since smaller drops typically have higher velocities, it is believed that this caused the PDA to characterize the flow field with higher velocities than the PIV system. This was supported by analyzing the vertical velocities. The large dynamic range of spray droplets in this system provided an optically harsh environment for each of the non-intrusive laser based techniques to perform measurements. The research suggests that when the laser based techniques of PIV and PDA are applied to large dynamic range systems, care must be taken to ensure a proper optical and post processing configuration is set up to obtain accurate results. Also, increased research in post processing techniques is necessary to make PIV a more reliable tool.

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