5-2015

Characterization and Development of TSI Three-Dimensional Laser Doppler Velocimetry System

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Characterization and Development of TSI Three-Dimensional Laser Doppler Velocimetry System

An Undergraduate Honors Thesis

in the

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College of Engineering

University of Arkansas

Fayetteville, Arkansas

by

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ACKNOWLEDGEMENTS

I would like to thank my mentor Dr. Tom Spicer for all his guidance and support throughout the project, Dr. Heather Walker who shared her experience at the wind tunnel and with the old LDV system, and for the graduate and undergraduate students who assisted in my project including Zach Ritchie, Ty Austin, Kristen Roberts, Chase Swaffer, and Jessica Morris. Finally, I would like to thank the University of Arkansas Honors College for their support through an Honors College Research Grant.

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ABSTRACT

The study of dense gas dispersion at atmospheric conditions is critical to understand the safety concerns of industrial operations where large amounts of toxic or flammable materials are stored and generated. A large airborne release of these materials into the atmosphere could have catastrophic effects. The Chemical Hazards Research Center (CHRC) at the University of Arkansas performs important research on dense gas dispersion. The CHRC houses the world's largest ultra-low speed wind tunnel, which is used to simulate dispersion at atmospheric conditions. Substantial amounts of data, including velocities, are recorded for modeling real life gas dispersion events. Before conducting experiments, an accurate characterization of air flow within the wind tunnel, especially at the lower boundary layer, must be established. The goal of this project was to upgrade the existing two-component LDV system to a three-component system and use the system to characterize the vertical velocity profile of the wind tunnel. The major phases of the project included the physical installation of the LDV system, alignment of the laser probes within the tunnel, and characterization velocity measurements. Once the system was properly installed, the vertical velocity profile of the wind tunnel was determined as part of the characterization process. The air velocity decreased for measurements closer to the wind tunnel floor, which agreed with the previous experimental data from the CHRC's wind tunnel and other ultra-low speed wind tunnels.

INTRODUCTION

An understanding of denser than air gas clouds and their atmospheric dispersion patterns is extremely important when working with large quantities of toxic gases. Gravity pulls these gases down to ground level where they form large toxic clouds [1]. The clouds disperse over large areas very close to the ground putting thousands of people at risk in the surrounding community. In 1984, this scenario ocurred at a Union Carbide Ltd. insecticide plant in Bhopal, India, leaving thousands dead and many more injured [2]. Research leading to a better knowledge of how these gases behave will allow for improved regulations and inherently safer design parameters to prevent such disasters and enhanced responses to disasters should they occur.

The Chemical Hazards Research Center (CHRC) located at the University of Arkansas researches gas dispersion at atmospheric conditions. According to the CHRC's founder, Dr. Jerry Havens, "the primary interest of the Chemical Hazards Research Center (CHRC) at the University of Arkansas has been the study, using mathematical modeling and physical (wind tunnel) modeling, of the effects on atmospheric dispersion of gaseous/aerosol materials with density greater than air" [2]. The research team, led by Dr. Tom Spicer, uses the world's largest ultra-low speed wind tunnel to simulate atmospheric conditions to collect data and observe dense gas dispersion. The research done at the CHRC has modeled past accidents such as the Bhopal disaster and developed a greater understanding of how dense gases behave when released into atmospheric conditions and how the turbulence caused by obstacles and terrain affects the flow. The research has and will continue to provide insight into dense gas behavior, which will help determine proper response measures after a disaster and regulations to increase safety and prevent such tragedies from occurring.

LASER DOPPLER VELOCIMETRY

A Laser Doppler Velocimetry (LDV) system measures the velocity of a fluid. Small seeding particles moving at the same velocity as the fluid scatter light to provide a velocity measurement [3]. The particles travel through the intersection of two laser beams. The beam intersection creates a fringe pattern that allows the particle's velocity to be measured as a function of the light scattering [3]. The light scattering pattern from a seed particle has a Gaussian nature similar to the wave function in Figure 1.

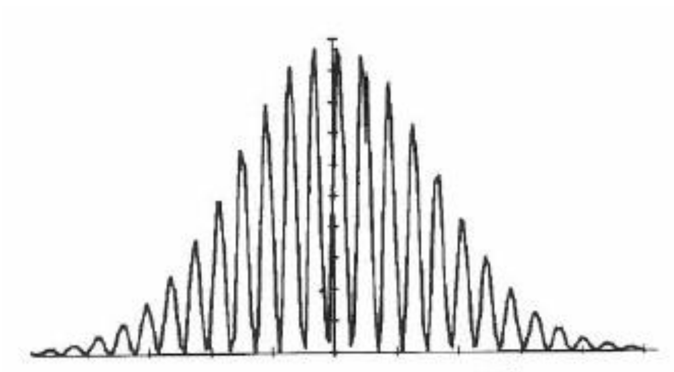

Figure 1: Light scattering pattern from a seed particle [3].

The scattering pattern is translated into an electrical signal and finally into actual velocity values. The resulting velocity measurement is one-dimensional. Multiple sets of laser beams intersecting at the same point in space are configured to measure two and three-dimensional velocities. The system is able to handle one, two, and three-dimensional velocity measurements.

A three-dimensional LDV system requires several pieces of equipment to produce the laser beams, transmit the scattered light, generate electrical signals, and calculate the fluid velocities. Figure 2 displays the equipment configuration for the LDV system. The laser and its auxiliary components produce a laser beam. The Colorburst separates the initial laser beam into the three wavelengths and divides each wavelength into pairs. The wavelengths are green (514.5 nm), blue (488 nm), and violet (476.5 nm) [3]. Couplers attached to the Colorburst focus the beams on fiber-optic cables that transmit the light to the probes inside the wind tunnel. Once the seeding particles scatter the light, the same probes and fiber-.optic cables capture and transmit the scattering to a Photo Detector Module (PSM) and Signal Processor (FSA) where it is translated into an electrical signal, filtered, and mixed with other signals. This electrical signal is fed into the FlowSizer software package where the resulting frequencies and velocities are recorded and displayed.

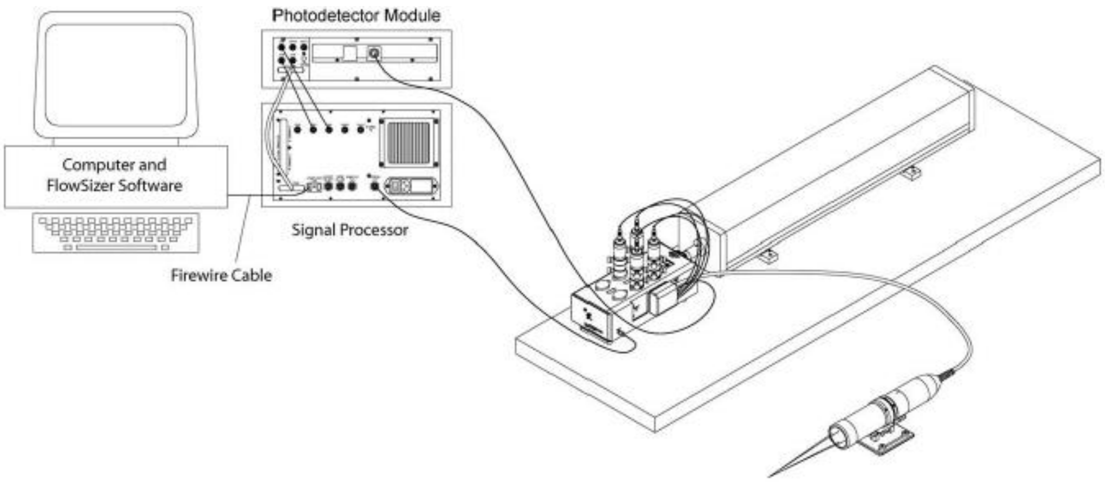

Figure 2: LDV system equipment configuration [4].

LDV SYSTEM ALIGNMENT

LDV system alignment is an important procedure that optimizes the laser beams. Optimized and aligned beams provide an adequate fringe pattern to produce light scattering and velocity measurements. The alignment procedure includes five stages: laser alignment, Colorburst alignment, coupling and beam optimization, three-dimensional alignment, and FlowSizer adjustments.

Laser Alignment

The CHRC's LDV system uses the Coherent Innova 70C ion laser, which consists of a laser head, power supply, remote control module, and water chiller. The laser operator's manual describes the proper power needs and equipment configuration for the laser [8]. Prior to alignment, the laser head must be installed on an optical rail. The laser should be placed on the right side of the rail with the beams traveling to the left. Figure 3 displays the hardware connections necessary to securely attach the laser to the rail. Any loose connections may cause inconsistencies with future alignment procedures. The button head screws should remain loose until the laser has been properly aligned to allow the swivel pad setscrews to raise or lower the laser head. The power of the laser beam is optimized by adjusting the mirror steering knobs on the back of the laser head.

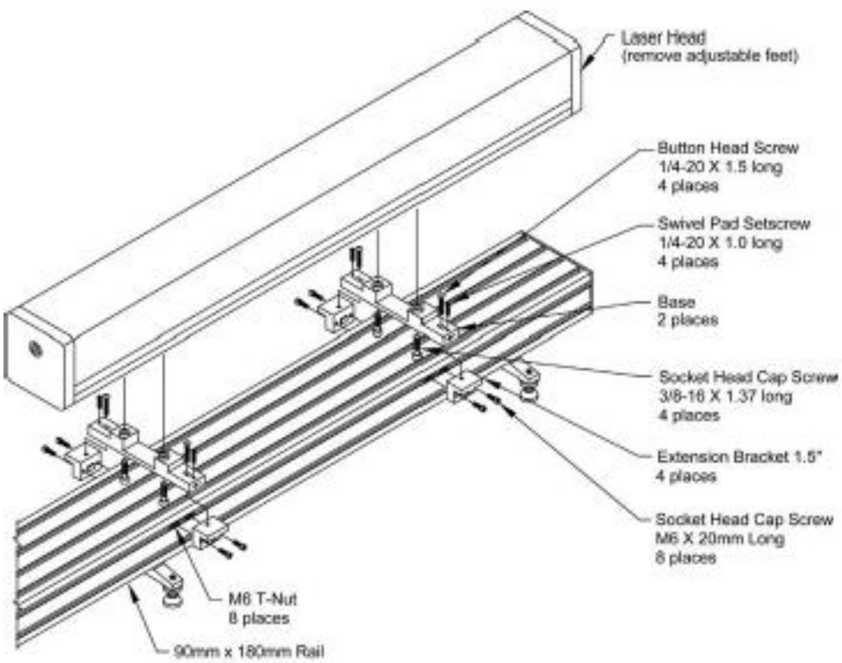

Figure 3: Laser installation on optical rail [4].

Once the laser is attached to the rail and the beam is optimized, the beam must be aligned with alignment blocks. An alignment block should be placed on the far left side of the rail, and the other should be placed about six inches in front of the laser. Figure 4 displays the alignment block configuration. With the alignment blocks in place, the laser should be powered on. The goal of the alignment is project the beam through the center hole of the two alignment blocks.

Adjusting the swivel pad screw on the laser supports will raise and lower the laser head to the proper height. The aligned beam will be 13.5 cm high and perfectly parallel to the rail. Figures 5, 6, and 7 show how a properly aligned beam will appear

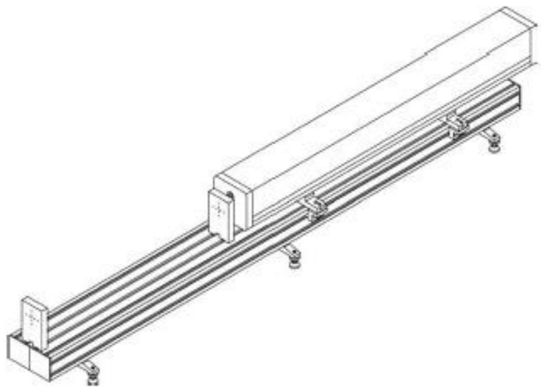

Figure 4: Alignment block configuration.

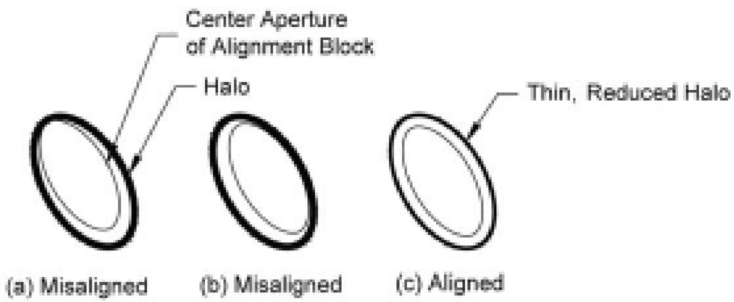

Figure 5: Beam alignment through block center aperture.

Figure 6: Beam aligned through center aperture.

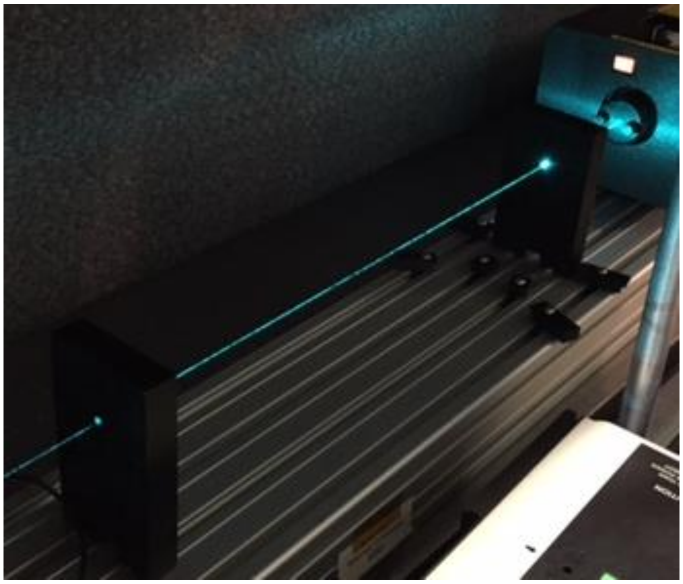

Figure 7: Aligned laser beam.

<u>Colorburst Alignment</u>

Once the laser beam is aligned, the Colorburst with the natural density filter attachment should be placed in front of the laser beam. Apertures in the natural density filter may be used to help align the apparatus with the laser beam. The aligned beam projecting through the apertures will look similar to the beam in Figure 5c. The position of the Colorburst may need to be adjusted until three beams appear through the unshifted output ports, circled in Figure 8. Ordering form left to right, the beams will be violet, blue, and green. The beams must be aligned onto the center of the alignment masks. This is achieved by slightly moving the Colorburst or using the beam steering setscrews on the backside of the Colorburst. Light may be visible through the three shifted output ports. Figure 8 displays the Colorburst with the three unshifted beams centered on the alignment masks. Once the three unshifted beams are aligned, the Colorburst should be attached to the optical rail with dog-ears provided in the equipment box.

Figure 8: Aligned Colorburst.

With the unshifted beams aligned, the shifted beams are aligned. Prior to the alignment, the cable between the Bragg In on the Colorburst and the Bragg Out on the FSA must be connected, and the FSA must be powered on. The first step in the shifted beam alignment is to visually maximize the intensity of the shifted beams with the Bragg Angle Adjustment setscrew on the side of the Colorburst. Once the sifted beams are visually maximized, the power between the shifted and unshifted pairs is equilibrated by adjusting the Bragg Power Adjustment setscrew on the back of the FSA. An optical power meter is used to measure the power from each outlet port. The pairs of beams do not have to be exactly equal, but the two power measurements must be close in value. Table 1 displays the power readings for the LDV alignment at the CHRC. The laser power was set to 240 mW for the measurements.

Table 1: Power measurements from outlet ports of the Colorburst.

Component	Power, mW
G-US	32
G-S	33
B-US	35
B-S	36
V-US	8.6
V-S	8.2

Coupling and Beam Optimization

With all six beams aligned on their respective masks, couplers are attached to each of the outlet ports. The couplers use five adjustments to direct the beam onto fiber-optic probes. Prior to connecting to the Colorburst, each coupler should be adjusted to the default position. The focus on the top should be turned down all the way, and each of the 5 knobs should be tightened until the small wrench provided fits tightly between the knob and coupler. Once tight, the knob should be turned half a turn to release the wrench and zero the adjustment.

Individually, an alignment mask should be attached to the top of the coupler. Using the bottom two knobs, the beam should be steered onto the center of the crosshairs. To assist in alignment, orient the crosshairs so they are parallel with the angle of the knobs protruding from the couplers. These are the axes on which the bottom knob angle adjusts steer the beam. If the beam is too bright to see its exact position, the OD2 filter may be turned on with the ring adjustment on the natural density filter. Once the beam is centered inside the coupler, the probe designated for the beam should be attached to the top of the coupler. The fiber-optic cables with two pairs of double rings for the corresponding beam wavelength attach to the unshifted couplers, and the fiber-optic cables with a double ring of the wavelength and a white double ring attach to the shifted couplers. It is important to note that some of the couplers have two notches where the pin on the fiber optic cable fits into the screw. The pin must be placed into the notch parallel to the initial laser beam. If the fiber optic cables are attached perpendicularly, the polarization of the beams will not be correct. If the beam is seen projecting from the probe, it should be visually optimized by adjusting the top two knobs and the focus ring. This is an iterative process, and the beams will greatly increase is intensity. Using a piece of paper as screen may be helpful for viewing the beams. Once the beams are visually optimized, the power meter is used to maximize the beam power. Adjustments should be made with all four knobs and the focus in an iterative fashion. The process described in this paragraph is then repeated for the other five couplers.

Table 2 displays the beam power measured from the probes inside the tunnel. The power for each pair of beams should be within a 1 mW of each other. The power of the green shifted beam was lowered to 10.0 mW, and the power of the blue unshifted beam was lowered to 9.6 mW. The green and blue beams will have similar powers, but the violet powers will be significantly lower. All six beams are optimized in Figure 9.

Table 2: Power of beams projected from probes.

Component	Power, mW
G-US Probe	9.6
G-S Probe	12.2
B-US Probe	10.8
B-S Probe	9.2
V-US Probe	2.2
V-S Probe	2.8

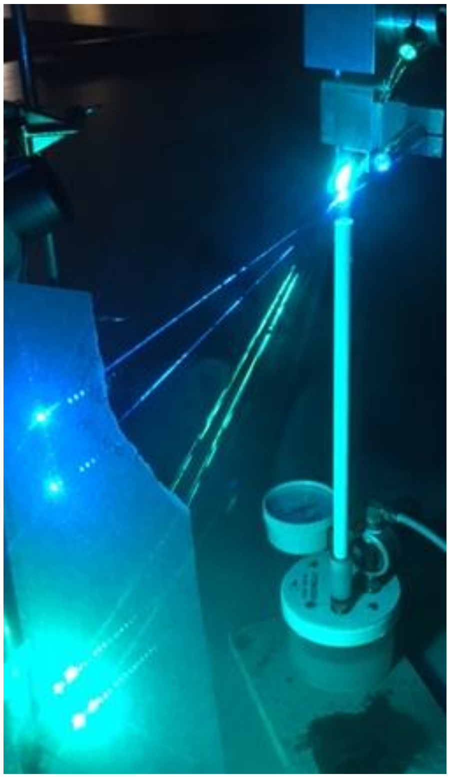

Figure 9: Optimized beams.

Three-Dimensional Alignment

Once the beams are optimized, the beam pairs must be aligned to cross at one point. The two pairs from one probe should cross at the same point without any adjustments; however, this may be confirmed using the microscope provided with the system. To align the beam pair from the second probe with the other pairs, the 100 micrometer aperture or 3-D alignment transverse is needed. The transverse will align the crossing at a very exact point; however, the alignment process is very difficult. If the beam crossings only need to within a few tenths of millimeters, the 100 micrometer aperture may be used. This was the method utilized for the alignment of the LDV at the CHRC. To determine if the probes are properly aligned, the aperture is placed at the beam crossing point. If all six beams are visible on a screen behind the aperture, the beams are aligned properly. If this is not the case, adjustments must be made to one or both the probes by adjusting their positon, angle, or focal length. The probes' focal lengths are adjusted by turning the front end of the probe. Once all six beams are aligned to cross at one point in space, the physical alignment process is complete.

<u>FlowSizer Adjustments</u>

With seeded flow in the tunnel, measurements may be made using the FlowSizer software. The software interface displays the data rate and burst efficiency. The data rate is the number of measurements per second, and the burst efficiency is a function of the accuracy of the data. The software includes several control adjustments to the electrical signal to help optimize these values and obtain the most accurate velocity data. The controls are PMT voltage, burst threshold, band pass filter, SNR, and downmix frequency. Figure 10 highlights the locations of these controls and readings on the computer interface.

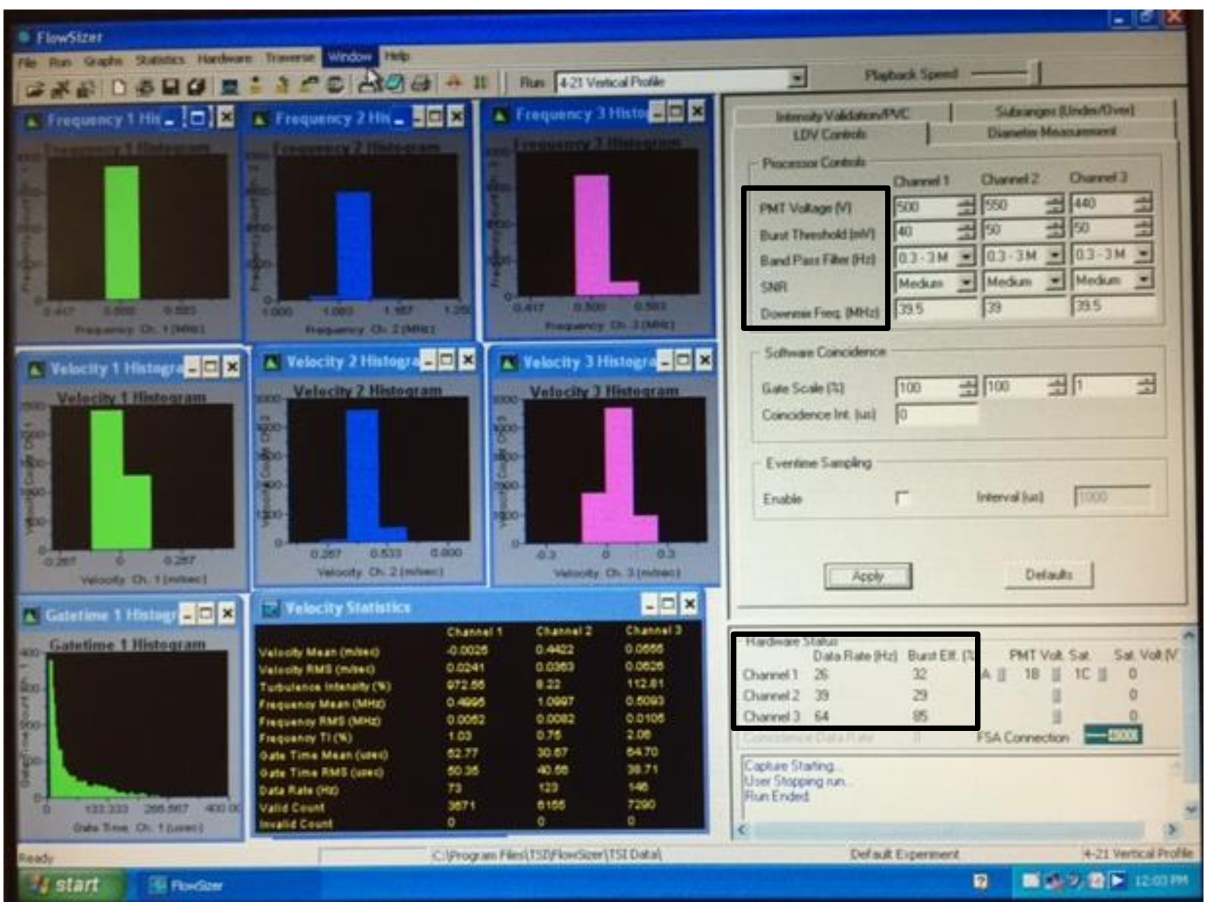

Figure 10: FlowSizer computer interface.

Table 3 displays the suggested initial values for the control parameters. The PMT voltage should be kept between 350 and 600 with a maximum value of 700 if the data rate for previous values is zero. A PMT voltage of 400 is ideal for accurate measurements. Higher burst thresholds reduce the noise in the signal. The band pass filter is used to zero in on the frequency signal. Values will change depending on signal, but if the frequency plot is clearly cut off on one end, the band pass filter is too small. The plots for both frequency and velocity should be Gaussian in nature with both ends reducing to zero. The desired SNR is medium. The downmix frequency should be optimized for each data run. The value will most likely be between 34 and 39.5. Adjusting the controls is an iterative process that should be performed each time the seeding or probe location changes. If the data rates cannot be increased to acceptable values, the seeding should be adjusted, or the laser power may be increased up to one watt. Acceptable data rates are above 100 Hz, but values above 200 Hz are most desirable. For measurements where proper seeding is difficult, the data rates might be below 100 Hz. The burst efficiency should be above 10%, but values above 30% are best.

Table 3: Initial control parameter values.

Control	**Value**
PMT Voltage	600
Burst Threshold	30
Band Pass Filter	1-10 M
SNR	Low
Downmix Freq.	34

To collect velocity data, click the “Run” tab on the toolbar, click “New Run”, and name the run. On the lower tool bar, click the “Start Run” button to begin collecting data. When data collection is finished, click the stop sign on the same tool bar. The data run may then be completed and saved. The computer interface will display frequency and velocity histograms for all three components and a chart with important values such as mean velocity, burst efficiency, and data rates. Other plots may be displayed by adjusting the view settings.

WIND TUNNEL CHARACTERIZATION

With the LDV system aligned and configured, it was used to characterize the wind tunnel. The characterization focused on the vertical velocity profile and turbulence intensity. Both of these parameters are important to the development of a boundary layer inside the tunnel during experiments. The boundary layer, roughly one meter in height, simulates atmospheric air flow conditions, which is crucial for accurate modeling of dense gas dispersion [5].

Determining the vertical velocity profile of the wind tunnel consisted of measuring the air velocity at different heights from the tunnel floor while maintaining a constant downwind and crosswind location. These measurements focused on the air flow down the tunnel. The first measurement was taken from the highest probe location. The probe height was lowered in increments of ten centimeters and five centimeters until the probe measured the air velocity just above the floor of the wind tunnel. Two important elements necessary for collecting accurate results were adequate seeding of the air flow and proper settings for the FlowSizer software.

Seeding particles were generated using a TSI Model 9302 Atomizer, which is pictured in Figure 11. This apparatus utilizes compressed air to produce small droplets of the seeding fluid, a dilute mixture of glycerin in water. The jet of aerosol particles traveled through a piece of plastic tubing where it was released into the air flow one meter upwind of the LDV probe. A ring stand and clamp held the tubing, which was lowered to the same height as the probe. Maximizing the seeded flow through the beam crossing maximized the data readings for each velocity component. Figure 12 displays the experimental configuration inside the tunnel for the vertical velocity profile characterization.

Figure 11: TSI Model 9302 Atomizer.

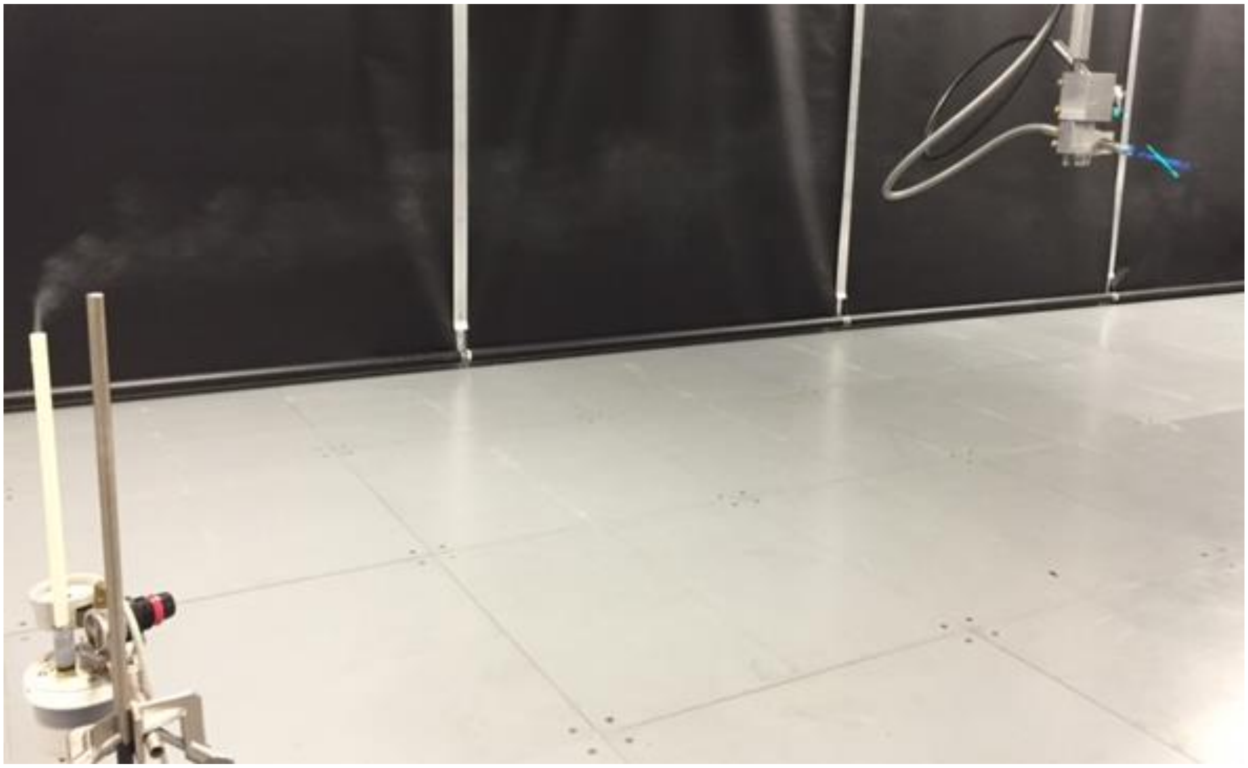

Figure 12: Experimental configuration inside the wind tunnel.

As described in the previous section, adjustments must be made to the light scattering signal to obtain adequate and accurate data. These adjustments include the PMT voltage, burst threshold, band pass filter, SNR, and downmix frequency. Adjustments were made on the software to optimize the number of measurements for each velocity dimension and its burst efficiency.

Turbulence intensity is a percentage quantification of the fluctuation in air flow. The values of turbulence intensity range from 0%, no fluctuation in air speed or direction, to values greater than 100%. Turbulence intensity is calculated in Equation 1 [6]. u' is the root-mean-square of the velocities at a location over a period of time, and U is the average of these velocities.

$$T.I. = \frac{u'}{U} \tag{1}$$

For an empty wind tunnel, this value is expected to be low. When the tunnel contains upwind obstacles and roughness elements, the turbulence intensity will increase to values typical of air flow along Earth's surface.

CHARACTERIZATION RESULTS

Figure 13 presents the experimentally determined vertical velocity profile inside the wind tunnel. For these measurements, the fans were run at ninety rotations per minute. The probe location for the X transverse direction was 32.424 cm, and the probe location for the Y transverse direction was 381.819 cm. The Z transverse direction was varied with each experimental run. The data points in Figure 13 are the average of five experimental measurements for each height. Each measurement consisted collecting velocity data for fifteen to thirty seconds, which allowed for the collection of an adequate number of measurements.

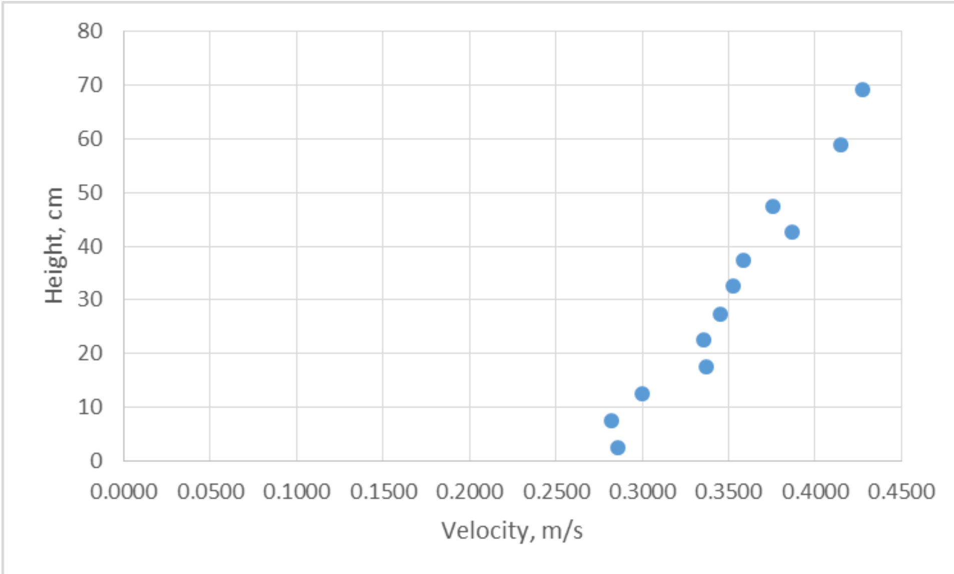

Figure 13: Vertical velocity profile.

The results of the vertical velocity profile characterization were expected. The air velocity decreased as height decreased. The vertical velocity profile agreed with Wilkes's boundary layer for laminar flow past a flat plat [7]. As the air flows down the flat plate, the air near the plate slows because of the drag from the plate. Inside the wind tunnel, the floor acts as a flat plate, which forms the boundary layer. This behavior is similar to the boundary layer formed by air flowing along Earth's surface.

Figure 14 presents the turbulence intensities calculated from the vertical profile velocities. Because the tunnel was empty, the turbulence intensities were expected to be low. The low experimental values were a result of no surface roughness or obstacles being placed upwind of the probes. The turbulence would greatly increase with their presence. According to Synder, the turbulence intensity should increase near the floor; however, the turbulence intensity remains at 1% for all readings over the sixty centimeter elevation change [5]. This is a result of the flow over a flat plate. Although air flow over a flat place decreases velocity near the plate, it does not cause significant mixing of the air vertically or laterally, which results in turbulence.

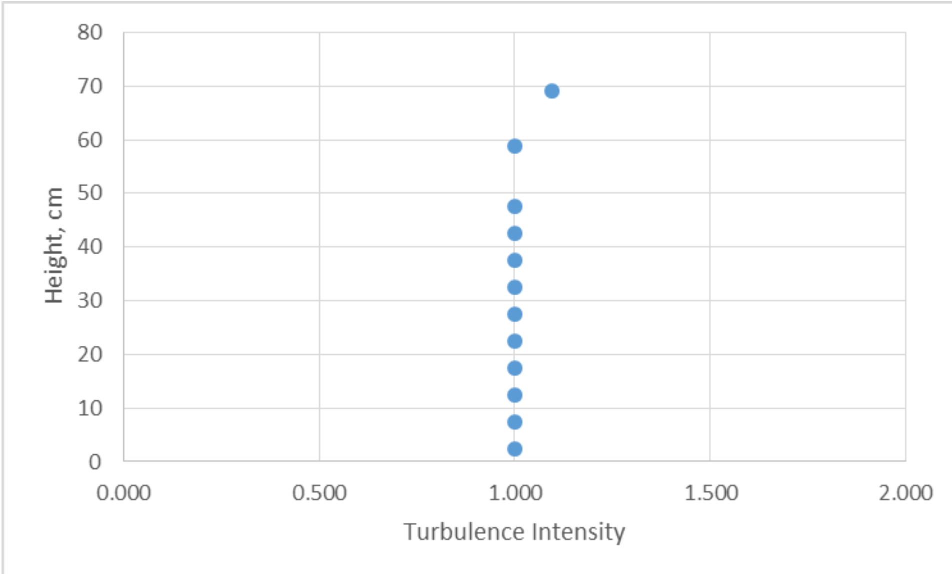

Figure 14: Turbulence intensities from the vertical velocity profile.

CONCLUSION

The LDV system was successfully installed and upgraded to a three-dimensional system. The addition of the third dimension allows for a more comprehensive velocity profile of the air flow inside the wind tunnel. Alignment procedures were developed for the CHRC's retrofitted LDV system. The CHRC's wind tunnel was characterized with the newly aligned LDV system. A vertical velocity profile was determined for the tunnel. The decrease in velocity as the measurements lowered toward the floor was in agreement with literature and previous experimental results. From the velocity measurements, the turbulence intensity was calculated. For all heights, the turbulence intensity was 1%. This was a result of no surface roughness or obstacles being positioned upwind of the probe. With the LDV system aligned and the vertical velocity profile and turbulence intensities calculated, research in the CHRC's wind tunnel may move forward with further tunnel characterization measurements and gas dispersion experiments.

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