Boundary Layer Velocity Measurements in a Mach 7 Wind Tunnel using Molecular Tagging Velocimetry

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Laser diagnostic techniques have grown in popularity and have been extensively employed over the last few years for characterizing hypersonic flows. Alternate intrusive techniques such as a traditional pitot probe are often less favorable for measuring velocity in high-speed flows because they can adversely influence the flow being measured. As such, non-intrusive optical techniques are becoming more widely used for measuring velocity profiles in hypersonic ground test facilities as they do not suffer from such limitations. In the present paper, a non-intrusive technique known as Molecular Tagging Velocimetry was utilized to take mean turbulent boundary layer velocity measurements in the Mach 7 Ludwieg Tube located at the University of Texas at San Antonio. A single Nd: YAG 4th harmonic laserline at 266 nm was used to excite the tracer gas molecules in the flow to determine the boundary layer velocity profile. Acetone was used as the molecular tracer gas and was placed in the driver tube section of the wind tunnel. The excitation of acetone molecules led to a laser- induced fluorescence line that was captured by a high-speed camera. The excited molecules were imaged at two separate times, t = 0 ns and t = 400 ns and the data collected from both times were used to obtain the displacement distance of the excited acetone molecules. With this non-intrusive technique, mean velocity profiles were acquired in the turbulent boundary layer of the wind tunnel test section floor. To further characterize the wind tunnel facility, the mean velocity measurements collected from Molecular Tagging Velocimetry were used to validate previous computational fluid dynamics simulations and Pitot probe scans collected from the wind tunnel. A boundary layer profile that matched a third-order polynomial was obtained from this method with mean velocities ranging from 300 m/s measured near the wall to 715 m/s in the freestream and the velocity profile agreed well with both the Pitot probe scans and computational simulations.

I. Nomenclature

Δx = displacement of molecules
Δt = time delay
V = velocity (m/s)
SNR = Signal-to-noise ratio

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II. Introduction

In recent years, the advancement in laser diagnostics has led to utilizing non-intrusive measurements techniques to characterize high-speed flows. Obtaining flow field measurements can generally be characterized by two categories: intrusive and non- intrusive techniques. Pitot probes are intrusive instrumentations used to get a general idea or initial scan of velocity profiles by placing the probe in the air flow. There are some drawbacks with a direct insertion of a Pitot probe into the flow field. This intrusive technique distorts the flow field and generates undesirable shockwaves that propagate in the fluid. On the other hand, non-intrusive techniques are commonly used to induce minimal impact of the flow field because these measurement techniques do not protrude into the flow, and they have no contact with the fluid. Thus, making non-intrusive techniques more desirable for characterizing hypersonic flows.

There are many non-intrusive laser techniques for characterizing high-speed flows [6]. Molecular Tagging Velocimetry (MTV) utilizes molecular flow tracers to obtain velocity profiles. [5] The tracer molecules are “tagged” by a single laser beam at two instances in time to calculate the displacement of the molecules. Tagging occurs by exciting a tracer molecule from its ground state to a higher unstable energy state and as electrons return to a lower energy state a range of energy transfer processes occur one of which is a laser-induced fluorescence that rapidly decays and can be captured by a camera. By capturing the shifted images, velocity profiles can be achieved from looking at the displacement of the fluorescence line at an initial base run compared to the delayed run. In Planar Laser-Induced Fluorescence (PLIF) qualitative and quantitative information can be analyzed by placing a laser sheet in the fluid flow field to capture excited molecules emitting light known as fluorescence [6]. This fluorescence signal is then captured by a camera to measure species concentration, translational, rotational, and vibrational temperatures [6]. Figure 1 shows the excitation process of molecules for both PLIF and MTV. Similar to MTV, Particle Image Velocimetry (PIV) is also a non-intrusive laser optical measurement, but it obtains velocity measurements of the flow by directly visualizing the fluid using tracer particles [7]. This PIV technique measures instantaneous and average flow field velocities. To illuminate and directly visualize the flow, tracer particles like solid TiO_2 are seeded into the fluid and are captured using a camera. An optical light sheet is used to illuminate the particles and the images obtained from PIV show the light scattering of the moving particles. Average velocity measurements are then taken from looking at the displacement of the particles in the flow.

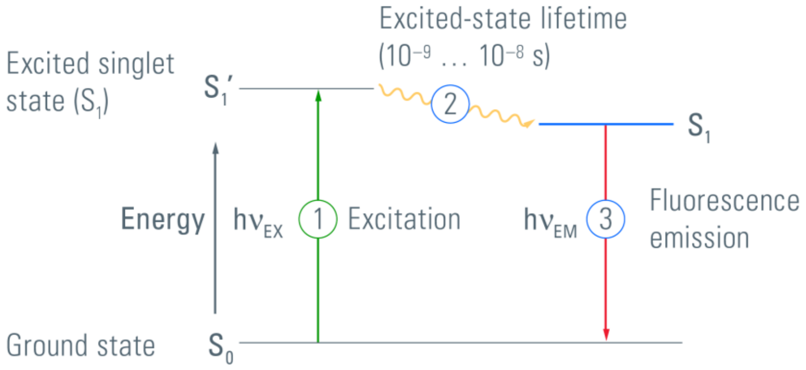

Figure 1: Energy transfer processes as molecules are excited [10]

At the University of Texas at San Antonio (UTSA), many techniques were utilized to characterize the flow in the Mach 7 Ludwieg Wind Tunnel [1]. Some include, Pitot probe scans, computational fluid dynamics (CFD) simulations, and MTV. Both the Pitot probe scans and the CFD simulations characterized the flow in the freestream and boundary layer of the wind tunnel’s test section. The velocity profiles collected from MTV only characterized the mean freestream velocity. Therefore, to further characterize the boundary layer in the Mach 7 facility, this paper presents MTV as a non-intrusive technique to measure the average boundary layer velocities and compare the velocity profile to both CFD simulations and Pitot probe scans. MTV was chosen as opposed to PIV due to the complexity of seeding the flow in PIV.

III. Experimental Program

A. Impulse Facility

This experiment was performed in the Mach 7 Ludwieg Tube Wind Tunnel facility at the University of Texas at San Antonio. The wind tunnel consists of a driver section, converging-diverging nozzle, test section and vacuum tank. The system starts by pressurizing the fluid in the driver tube and bursts the diaphragm at a high pressure. After the diaphragm ruptures, a normal shock wave propagates through the nozzle into the test section and an unsteady expansion wave propagates into the driver tube hitting the endwall. As the expansion wave hits the endwall, reflected expansion waves quickly propagate back to the nozzle entrance creating steady conditions for hypersonic flow through the nozzle and into the test section. Figure 2 presents a rendering of the wind tunnel. The Mach 7 facility is equipped with a 8 in x 8 in cross-sectional test section [1]. A complete description of the facility is described in reference [2].

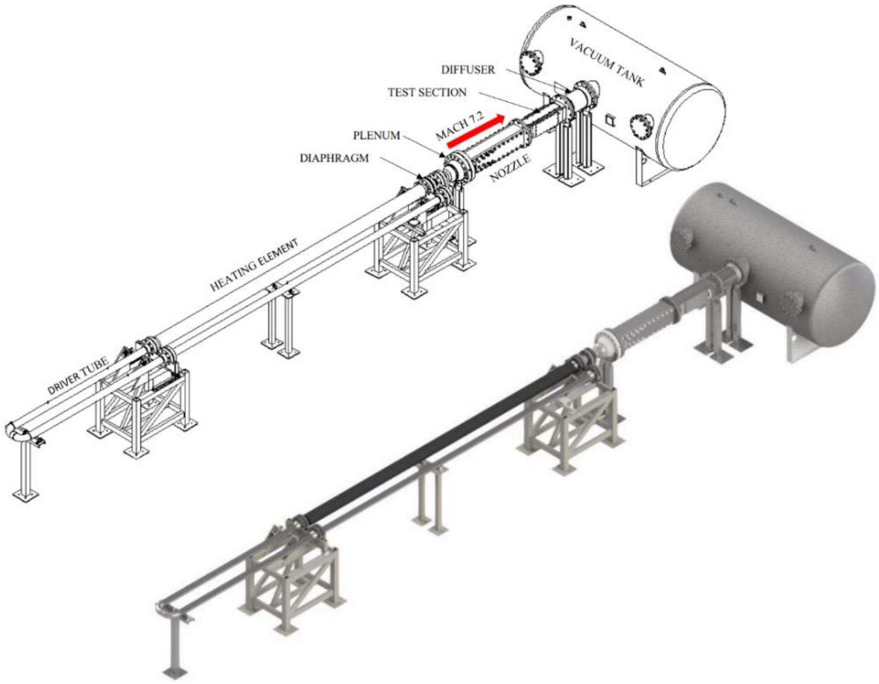

Figure 2: Rendering image of the UTSA Mach 7 Wind Tunnel

B. Background Theory

Molecular Tagging Velocimetry is a non-intrusive technique that has been widely used for analyzing velocity fields from transonic to hypersonic flows [3]. There are four main mechanisms for exciting molecules in the flow: absorbance, vibrational excited-state fluorescence, photoproduct fluorescence and direct phosphorescence. Direct photoluminescence was the mechanism used in this experiment due to the fact that it is the easiest method and a detailed description of the other mechanism cans be found in reference [5]. In direct photoluminescence a single laser is used to produce a long-lived higher excited state luminescence of the tracer molecule. The tracer fluid is excited from its ground state to a higher excited state and the photons released create the emitting luminescence. A disadvantage from direct phosphorescence is that since the tracer molecule has a long-lived excited state and quenching by oxygen molecules can lead to weak signals and lower lifetimes [5]. MTV tags molecules and tracks the fluorescence (a type of luminescence) as the molecules travel in the flow over time. An initial tagged reference is imaged at a given position by an intensifier and high speed camera and after a set time delay a second image is captured as the fluorescence intensity decays. And by calculating the distance the molecules traveled in the region after the set time, velocity profiles can be calculated using the following formula:

$$V = \frac{\Delta x}{\Delta t} \tag{1}$$

Where Δx is the displacement of the molecules and Δt is the time delay used from the initial to the final run. In this experiment, acetone was used as the tracer molecule because the lifetime of acetone molecules after excitation is long enough to capture sufficient displacement. In literature concerning acetone, the radiative lifetime of fluorescence has been found to last several hundred nanoseconds [4]. Figure 3 demonstrates the fluorescence decay of acetone captured at the initial run and the delayed run. Other molecular structures such as Krypton and Nitrogen can also be used to create a laser-induced fluorescence line.

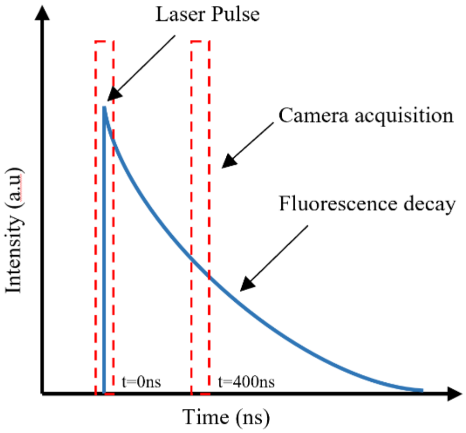

Figure 3: Fluorescence decay after excitation

C. Experimental Setup

A rendering image of the experimental setup is presented in Figure 3. In order to excite the acetone molecules for this non-intrusive technique, a Spectral Energies pulse-burst laser was used. The device was operated using the 4th harmonic of the Nd: YAG pulse-burst laser. The laser settings were set with the following conditions: (1) 266 nm 0-10.5 ms burst mode and (2) 10 kHz frequency. Acetone has a broadband UV wavelength absorbance of light between 220 nm – 320 nm, therefore a 266 nm wavelength to excite the molecules was used [9]. The incident laser beam energy was ~ 10.5 mJ/pulse for the first initial reference run and ~ 4.5 mJ/pulse for the second delayed run. A conjecture for

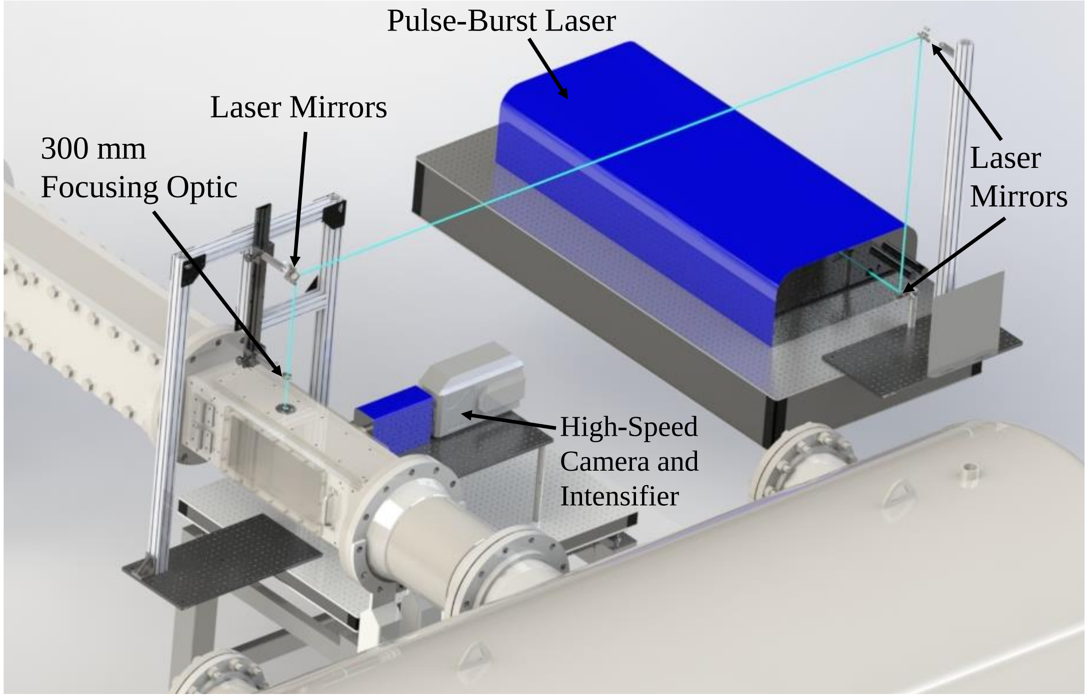

Figure 4: MTV experimental setup

the decrease in laser energy is explained under the MTV challenges section. Three 266 nm wavelength laser mirrors, as seen in figure 3, were used to reflect and guide the laser beam into the wind tunnel test section. A focusing lens with a 300 mm focal point was utilized to focus the laser beam to a diameter of approximately 0.70 mm and a height of roughly 27.17 mm. In reference [1], the approximate boundary layer height of the Mach 7 facility at UTSA is 27 mm, thus the data collected in this experiment captured within boundary layer of the facility. The focused laser beam then passes a 25.4 mm diameter sapphire window into the test section.

The field of view (FOV) for the experimental setup was located about 577 mm from the nozzle exit and roughly 27.17 mm from the bottom of the test section. Optical access for capturing is ensured by acrylic windows. For the purposes of this experiment, the tracer fluid was added through a ~10.41 mm (~0.41 in) diameter inlet hole near the diaphragm in the driver tube. Figure 5 shows a schematic drawing of the laser beam location in the test section.

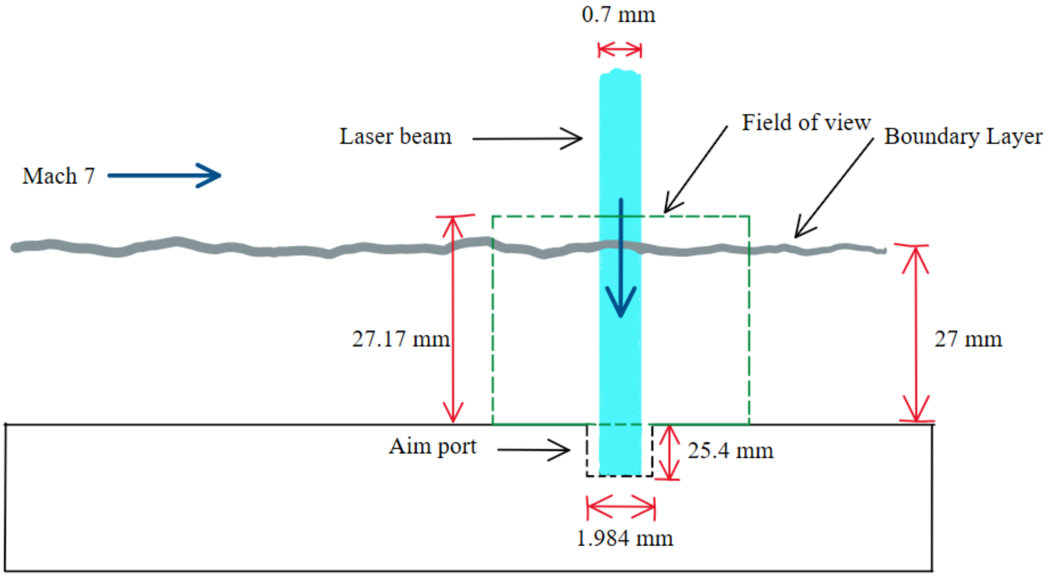

Figure 5: Schematic drawing of the FOV

A LaVision high-speed intensifier was used to operate the intensified relay optics (IRO) controller which allowed for setting the delay, gate, and gain for each run. Each experimental run captured 100 12-bit 1024 x 1024 pixel images using a Photron FASTCAM SA-Z high-speed camera. The camera lens used in this setup was a AF Micro Nikkor 60 mm f/2.8D lens, and the aperture was set to f/2.8. The camera, intensifier and laser were synchronized to align the timing for the MTV technique. A 20 mm extension tube was attached to the intensifier and camera in order to increase the spatial resolution to ~ 23.937 px/mm. In both runs, a Schott N-WG 295 glass filter was placed in front of the lens to filter out the 266 nm laserline. For the initial base run a gate of 80 ns and a 65% gain was applied using the IRO controller. A 400 ns delay was used for the second run at a gate of 80 ns and a gain of 87%. Half of a gallon of acetone was placed in the driver tube of the wind tunnel before pressurizing the driver tube. Based on the driver tube specifications in reference [8], the driver tube has an approximate length of 60 ft (720 in) and an inner diameter of 3 in. Thus, adding acetone into the driver tube is less than ~ 1% of the driver tube volume.

IV. Results

A. MTV Challenges

In the beginning of experimentation, since the laserline was focused down to capture the boundary layer, plasma effects and reflections occurred as the laser beam hit the bottom of the steel test section. The plasma effects and reflections resulted in saturating the camera. Saturation in a camera is undesirable because it damages the camera's light sensitive sensor and prevents the acquisition of useful data due to over saturation of pixels. Therefore in order to counteract the saturation, a ~ 1.984 mm (5/64 inch) diameter aim port was drilled ~ 25.4 mm into the bottom steel plate for the laser beam to travel into. The aim port was located in the cross-sectional centerline, roughly 4 inches from the acrylic windows. Based on the pressure readings and schlieren imaging data collected in reference 3, an aim port with a 1.984 mm diameter would not significantly alter the boundary layer.

Another challenge that was encountered was a decrease in energy from the baseline run to the shifted run. In the initial baseline run the energy was measured to be approximately 10.5 mJ/pulse which resulted in a strong SNR. In the shifted delayed run the energy was about 4.5 mJ/pulse and the SNR was considerably weak as seen in Fig 5. After noticing a weak SNR from the data collected in the delayed run, the Spectral Energies device was opened, and it was discovered that the laser beam burned the 266 nm mirrors inside and decreased the energy after each pulse. The weak SNR in the delayed run was assumed to be from the decrease in energy.

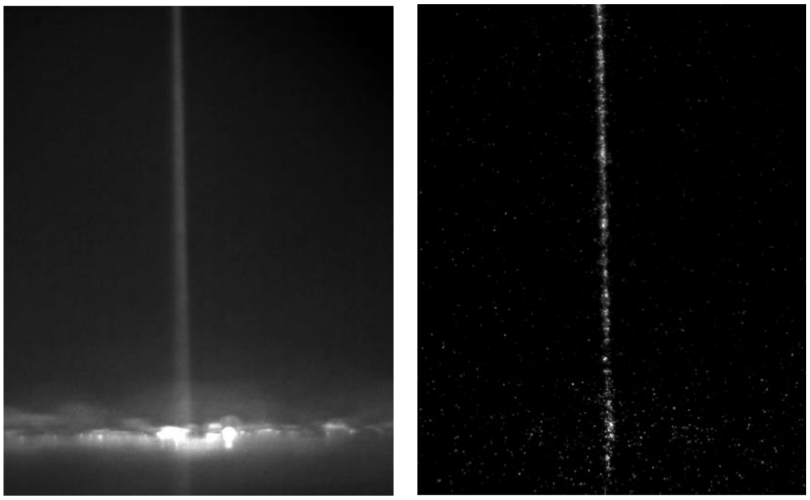

Figure 6: Averaged image of the initial baseline run and shifted delayed run

B. Data Processing

For the results presented in this experiment, the following steps were taken to process the raw data from each run. Both the initial baseline run, and the shifted delayed run consisted of 100 frames each captured by the high-speed

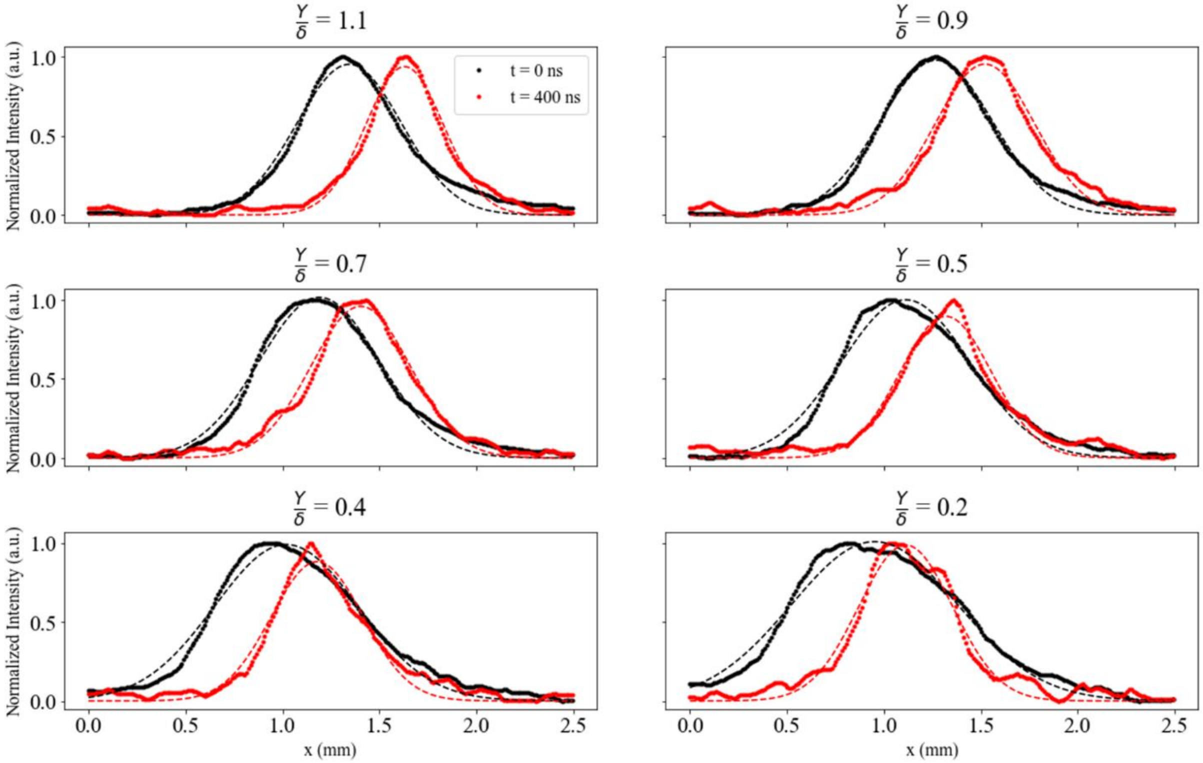

Figure 7: Gaussian curve fitting at multiple locations in the boundary layer

camera. From the baseline run, 100 frames were time averaged using ImageJ in order to obtain one time-averaged image. Because the delayed run had a weak SNR, the first 26 frames were time-averaged to obtain one image. To further process the data, both time-averaged images were upscaled to produce a better scaling image and then were space-averaged to output the velocity profiles. A cross correlation analysis was performed in order to measure the strength of the relationship between the initial and the shifted run as well to show the pixel shift between the runs. A 0.5 pixel shift error was taken into account to calculate the uncertainties in this experiment. The boundary layer profile resulted in an uncertainty velocity of approximately ± 52.22 m/s. Figure 7 shows the normalized gaussian curve fitted to the initial run and the delayed run at multiple positions in the boundary layer.

Figure 8 demonstrates the plotted mean velocity data with uncertainty values along with a 3rd order polynomial fit. The last step was to remove any outliers that conflicted with the velocity profile and a polynomial curve fit was fitted to the data to compare it to the Pitot probe scans and the CFD simulation.

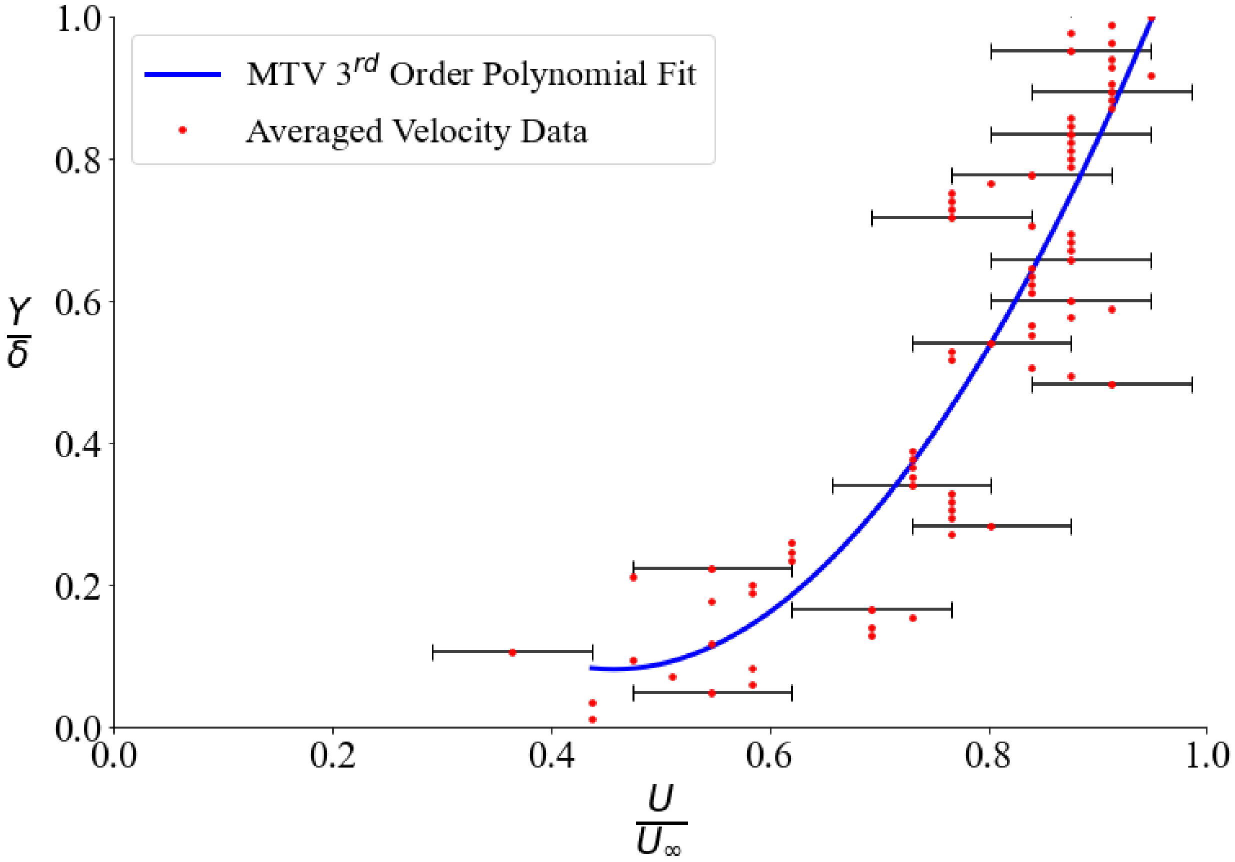

Figure 8: Normalized mean velocity profile with uncertainty analysis

In theory, velocity measurements in a boundary layer should decrease as they get closer to the wall due to friction, and the mean velocity measurements calculated from the data agree with this concept. Table 1 below presents some approximate mean velocity measurements along the boundary layer regime.

Location in Boundary Layer	Mean Velocity Calculated
5 mm	468 ± 52 m/s
10 mm	550 ± 52 m/s
15 mm	608 ± 52 m/s
20 mm	658 ± 52 m/s
25 mm	707 ± 52 m/s

Table 1: Mean velocity measurements based on the location in the boundary layer

C. Velocity Profile Comparisons

In order to confirm the boundary layer velocity profile collected from the non-intrusive technique, MTV was compared to Pitot probe scans and CFD simulations conducted in reference [1]. Figure 9 demonstrates a comparison of all three measurement techniques. The mean velocity boundary layer profile with a negative uncertainty had a closer agreement with the CFD data gathered, while the 3rd order polynomial fit velocities had a closer agreement to the Pitot probe results. However, MTV was able to show mean velocity measurements closer to the wall compared to Pitot probe scans. And computational simulations are based upon known nozzle parameters but often predict fluid flow properties and do not reflect flow field data collected from experimental methods.

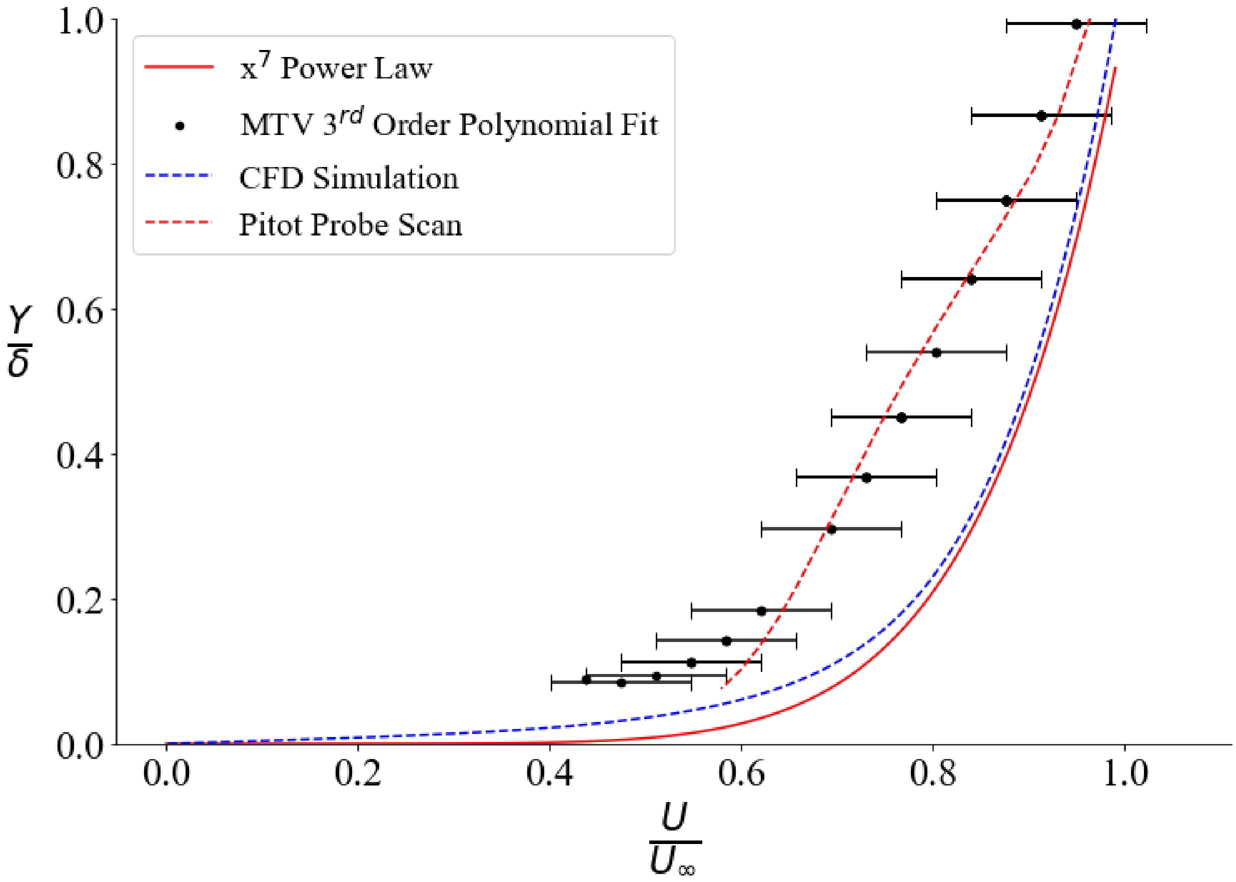

Figure 9: Normalized velocity profiles of MTV, CFD, and Pitot probe measurements

V. Conclusion

Molecular Tagging Velocimetry was used as a non-intrusive technique to obtain mean boundary layer velocity measurements in the Mach 7 facility at UTSA. Data from two runs were obtained to observe the pixel shift between the images in order to compute a mean velocity profile for the boundary layer regime. Challenges faced in this experimentation were reflections from the steel test section, plasma effects, and a weak SNR from the delayed run. From the uncertainty analysis preformed in this experiment, the mean velocity uncertainty resulted in a ± 52.22 m/s. This technique was compared to previous data collected at UTSA from Pitot probe scans and CFD simulations and demonstrated that non-intrusive techniques are suitable for characterizing high-speed flows. Future recommendations for MTV experimentation would be replacing the current burned 266 nm mirrors with one with a higher burn threshold in order to have a stronger SNR and keep a constant laser energy after each pulse.

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