Boundary Layer Measurements in the Trisonic Gas-dynamics Facility using Particle Image Velocimetry with CO₂ Seeding

Daniel B. Wolfe

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BOUNDARY LAYER MEASUREMENTS IN THE TRISONIC GAS-DYNAMICS FACILITY USING PARTICLE IMAGE VELOCIMETERY WITH CO₂ SEEDING

THESIS

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AFIT/GAE/ENY/12-M43

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THESIS

Presented to the Faculty
Department of Aeronautics and Astronautics
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Air Force Institute of Technology
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Air Education and Training Command
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March 2012

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BOUNDARY LAYER MEASUREMENTS IN THE TRISONIC GAS-DYNAMICS FACILITY USING PARTICLE IMAGE VELOCIMETERY WITH CO$_2$ SEEDING

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Abstract

Particle image velocimetry (PIV) is utilized with solid carbon dioxide (CO$_2$) seeding material to conduct boundary layer measurements in the test section of the Air Force Research Laboratory’s Trisonic Gas-dynamics Facility (TGF), which has a 24 inch by 24 inch cross-section. Freestream velocity was set at Mach 0.3, Mach 0.5, or Mach 0.8 while stagnation pressure ranged from 500 to 2400 pounds per square foot (psf). High pressure liquid CO$_2$ was directed through expansion nozzles into shroud tubes which led to solidified particles in the wind tunnel stagnation chamber. Two different sets of shroud tubes were used to modify the size of dry ice particles produced and the particle number density. Shroud tubes with an inside diameter (ID) of 0.824 inches provided good particle count and coverage for stagnation pressures between 500 and 1500 psf, while 0.364 inch ID shroud tubes demonstrated good particle count and coverage for stagnation pressures over 1000 psf. Overall, the PIV results produced freestream velocity measurements and boundary layer profiles which compared well with expected values. After initial processing, turbulence data closely followed trends expected within boundary layer, but levels were somewhat higher than anticipated. When the PIV data was processed using elliptical interrogation regions, elongated in the streamwise direction, resulting turbulence levels were much closer to expectations.
Acknowledgments

First, I would like to express my sincere appreciation to my faculty advisor, Dr. Mark Reeder, for his guidance and support throughout the course of my thesis work. His insight and direction were very much appreciated. I’d also like to thank Mr. John Hixenbaugh for his superb logistics support and expert plumbing skills. The test equipment you helped build was truly vital to the success of this research.

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Finally, I would like to thank Mr. Ben Hagen, for his outstanding support throughout this entire process. Your expert knowledge on PIV techniques and willingness to share that information has helped immensely. Thank you for the countless hours you have spent working with me on this project.

Daniel B. Wolfe
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I. Introduction

The history of aviation has extended over more than two thousand years starting with the earliest attempts to fly kites in China around 200 BC, to the first powered heavier-than-air flight by the Wright brothers in 1903, and leading to the modern supersonic and hypersonic aircraft of today [1]. Developments in aeronautical science and engineering have made world travel easy and efficient, has revolutionized the way warfare is conducted, and was a vital stepping stone into space exploration. In modern history, the field of Aeronautical Engineering has been highly dependent on theory, observation, and experimentation to improve our understanding of fluid mechanics and aircraft design.

The fundamental theories, concepts and equations developed by men like Newton, Bernoulli, Euler, Navier, Stokes, Reynolds, and Prandtl, are the foundation from which human flight in heavier-than-air machines was made possible. In the early 1900s, after several setbacks, the Wright brothers designed and built a wind tunnel to develop their own calculations for airfoil lift and drag. These calculations ultimately provided the data needed to design and build the first successful powered aircraft [1]. Wind tunnels continue to play an important role in the study of fluid mechanics and Aeronautical Engineering. Computer modeling has proven to be a powerful tool in recent years. However, there are numerous instances where actual experimental data of fluid motion is required.
1.1 Motivation

Numerous methods exist to collect experimental data in wind tunnels in order to understand the complex science of fluid mechanics. Each method has distinct advantages and disadvantages which must be taken into consideration prior to the execution of each experiment. For instance, single-point methods like hot-wire anemometry and laser-Doppler anemometry provide a quantitative and accurate sample of the flow at a given point. These methods however, are not able to capture instantaneous flow field data over an entire test region. With the recent development of digital camera technology and the software to efficiently process digital images it is now possible to develop new measurement techniques that are able to simultaneously provide instantaneous spatial flow field visualization and quantitative results. One of the most successful measurement methods to materialize in the past three decades is particle image velocimetry (PIV) [2].

PIV is based on the simple principle that velocity equals the distance traveled per unit of time. If tracer particles can be introduced in a fluid under the right conditions, the particles will move at the same speed as the fluid. Two digital images of the particles are captured over a known time increment and the distance traveled by the particles can be determined by comparing the first and second image. The velocity of the particles can then be determined by dividing this distance by the known time increment between the two images. In order for PIV to provide valuable data the particles must accurately follow the fluid motion and must not alter the fluid properties or flow characteristics [2].

This concept, while easy to understand, is much more complex in the application of experimental aerodynamic data collection as discussed in Chapter 2. Once these complexities are understood, a great deal of information can be collected about the fluid
flow in question. Using the resulting instantaneous flow field data from PIV, boundary layer effects, turbulence characteristics, vortex formation, and momentum thickness, for example, can be determined. As the applications of PIV in aerodynamics and water flows continue to grow, so does the interest in refining this technique to improve its accuracy as well as its practicality [3].

Unfortunately, in some cases the use of PIV is prohibitively inconvenient and costly. Typical seed materials for PIV, such as titanium dioxide, atomized oils, or theater smoke work well for blowdown facilities. However, these materials can lead to significant, and expensive, downtime for large closed-circuit wind tunnel facilities because of residue on the internal surfaces. The Air Force Research Laboratory’s (AFRL) Trisonic Gas-dynamics Facility (TGF), is a closed-circuit wind tunnel capable of creating low subsonic, transonic, and supersonic conditions. In a previous test, an oil-based smoke was used in the TGF to seed the air flow. This caused a residue to build up on the tunnel walls and test section glass, requiring a substantial cleanup effort after the test. These seed materials can also adversely affect measurements executed using pressure- and temperature-sensitive paint. Also, many large-scale tunnel operators are deterred from PIV due to the potential fire hazard of seed materials like polystyrene, ethylene glycol, propylene glycol, ethyl alcohol and acetone. These materials have flash points and auto-ignition temperatures that are near or below the compressor operating temperatures in many closed-circuit tunnels [4]. Water particles have been used in the past also, but increase the probability of tunnel component corrosion and damage to electronic systems. Numerous examples of oil- and water-based seeding are available, including experiments at the Arnold Engineering Development Center’s 16T wind tunnel.
Results show if these seed materials can be replaced with clean seeding methods, many facilities could benefit [5]. The search for a clean seeding material has resulted in the recent study of solid carbon dioxide (CO\textsubscript{2}), or dry ice. CO\textsubscript{2} can exist as a solid and then sublimate, leaving no trace or residue other than the naturally occurring inert gas which mixes into the surrounding air. If dry ice particles can be created, introduced into the air flow, and if they persist long enough to pass through the test section prior to sublimating, they would negate any need for additional maintenance on the wind tunnel due to PIV testing.

1.2 Research Focus

It is important to select a proper seeding material that will allow collection of accurate PIV data and not negatively impact the operation of wind tunnel facilities. The research presented here focuses on developing a method to properly size CO\textsubscript{2} particles and produce the amount of particles needed to collect accurate PIV data in a production scale tunnel. The particles must be small enough to accurately track the fluid flow and also be large enough to scatter a sufficient amount light to be captured by the sensor of a digital camera. Also, the particle density must be close enough to the fluid density to minimize the effects of gravity and velocity discrepancies between the particle and the surrounding fluid. Finally, the density of particles in the test section must be adequate in order to maximize the resolution of the velocity vector field.

The overarching goal of this research is to take the next step toward developing a fully operational PIV capability at the TGF for AFRL and its customers. Previous work by Brian Love, under the direction of Dr. Mark Reeder, demonstrated the feasibility of
collecting PIV data in the TGF [6, 7]. This research refines their methods with the following goals:

- Produce seed particles of consistent size which are suitable for PIV
- Produce a consistent distribution of seed particles throughout the TGF test section
- Analyze the TGF test section boundary layer normal to the window at various Mach numbers and various pressures

Previously, three different injectors of various sizes were used to seed the TGF. Several injection methods and injection locations were tested to find a suitable solution to the seeding problem. During these experiments, only one injector at a time was used which resulted in insufficient particle coverage and limited PIV data collection to basic freestream velocity measurements [6, 7]. The research presented in the following chapters discusses the work done to improve upon this work with the goals listed above.
II. Background

In this chapter, background information is provided on PIV techniques used for this research. First, the basic principles of PIV are discussed, including the component pieces required to collect PIV data. Flow seeding is covered in more detail because of its importance in this research. Recent research pertaining to clean-seeding is discussed. Finally, the theory of boundary layer development and the relevant mathematical relations thereof are discussed.

2.1 PIV Overview

In recent years PIV instrumentation and data processing techniques have undergone rapid development. While early applications used photographic recording, current techniques rely almost exclusively on digital charge coupled device (CCD) cameras and advanced software algorithms to correlate particle motion between different digital images. A basic PIV configuration is shown in Figure 2.1. Essential components of this technique are flow seeding particles, a light source, imaging optics and imaging sensor. These components are briefly described in the following sections. For an in depth review of PIV please refer to the text by Adrian and Westerweel [3].

2.1.1 Light Source

Light is required to illuminate the seed particles adequately to be detected by the digital camera sensor. Typically lasers are used because they emit collimated, monochromatic light with a high energy density and can be easily directed through optics
to produce a light sheet. The most common type of laser used for PIV experiments is the neodymium-doped yttrium-aluminum-garnet (Nd:YAG) laser. Nd:YAG lasers produce light with a wavelength of 1064 nm that is then frequency doubled to achieve a wavelength of 532 nm in the visible green spectrum [2]. They produce pulse energies between 10mJ and 1J and very short pulse durations ranging from 5-15ns making them ideal for PIV.

Determining the proper light source is also dependent on the seed particles’ light scattering properties. Table 2.1 lists typical air flow seed materials and their diameters. These particles have a diameter larger than the wavelength of the light source and scatter light according to the Mie theory [2]. According to this theory a majority of the light is scattered in the forward direction, the same direction as the incident light energy, and less is scattered backwards and to the sides. For single-camera PIV the optical axis is usually arranged normal to the light-sheet plane, to minimize image distortion. Nd:YAG pulsed
lasers are often used in PIV because they provide a large amount of light energy over a short time duration, usually less than 10 nanoseconds, which can be collected by the sensor in a CCD camera.

Table 2.1: Common seeding materials for gas flows [8].

<table>
<thead>
<tr>
<th>Type</th>
<th>Material</th>
<th>Mean diameter in µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid</td>
<td>Polystyrene</td>
<td>0.5 – 10</td>
</tr>
<tr>
<td></td>
<td>Alumina Al₂O₃</td>
<td>0.2 – 5</td>
</tr>
<tr>
<td></td>
<td>Titania TiO₂</td>
<td>0.1 – 5</td>
</tr>
<tr>
<td></td>
<td>Glass micro-spheres</td>
<td>0.2 – 3</td>
</tr>
<tr>
<td></td>
<td>Granules for synthetic coatings</td>
<td>10 – 50</td>
</tr>
<tr>
<td></td>
<td>Dioctylphthalate</td>
<td>1 – 10</td>
</tr>
<tr>
<td></td>
<td>Smoke</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Liquid</td>
<td>Various oils</td>
<td>0.5 – 10</td>
</tr>
<tr>
<td></td>
<td>Di-ethyl-hexyl-sebacate (DEHS)</td>
<td>0.5 – 1.5</td>
</tr>
<tr>
<td></td>
<td>Helium-filled soap bubbles</td>
<td>1000 – 3000</td>
</tr>
</tbody>
</table>

2.1.2 Flow Seeding

PIV methods rely on the presence of particles in the flow that not only follow changes in the flow velocity but are also sufficient in number to provide the desired resolution of the measured flow velocity. Selecting a seeding material requires balancing two parameters. First, the seed particles must be large enough to scatter sufficient light as discussed in the previous section. Second, the seed particles must be small enough to also respond quickly to the dynamic changes that occur in the flow being studied. The size criterion for flow-following is characterized by the Stokes’ number. The seeding materials shown in Table 2.1 are commonly used for PIV because they often satisfy both criteria.
The background of the development of Stokes’ number criteria is as follows. The equation of motion of a small spherical particle immersed in a viscous fluid flow, originally developed by Basset and independently derived by Boussinesq and Oseen (BBO Equation) [2], is given as:

\[
\frac{4}{3} \pi a^3 \rho_p \frac{dv}{dt} = \frac{4}{3} \pi a^3 \rho_f \frac{dV}{dt} + \frac{4}{3} \pi a^3 (\rho_p - \rho_f) g - 6\pi \mu a \left[ (v_p - U) - \frac{1}{6} a^2 \nabla^2 U \right] 
- 6\pi \mu a^2 \int_0^t \frac{d\tau}{\sqrt{\nu(t - \tau)}} \left[ \frac{d}{dt} \left[ (v_p - U) - \frac{1}{6} a^2 \nabla^2 U \right] - \frac{2}{3} \pi a^3 \frac{d}{dt} \left[ (v_p - U) - \frac{1}{10} a^2 \nabla^2 U \right] \right] + L
\]

(2.1)

where

\[
a = \frac{d_p}{2} = \text{tracer particle radius}
\]
\[
\rho_p = \text{particle density}
\]
\[
\rho_f = \text{fluid density}
\]
\[
g = \text{gravity}
\]
\[
\mu = \text{fluid viscosity}
\]
\[
v_p = \text{particle velocity}
\]
\[
U = \text{fluid flow velocity}
\]
\[
L = \text{lift force}
\]

Particle mass multiplied by acceleration is the left-hand side of Equation (2.1). The terms on the right-hand side of the equation are, in order, the non-inertial force, net body force, quasi-steady viscous force, time history force, added mass force, and the lift force. Various forms of the BBO Equation appear in texts by Melling [9] and Tropea, et al. [2].
For very small particles as used in PIV the quasi-steady viscous term (Stokes drag) dominates the right-hand side of Equation (2.1). The approximation that \( \frac{dU}{dt} \) equals \( \frac{dv_p}{dt} \) allows the difference between the particle velocity, \( v_p \), and that of the surrounding fluid, \( U \), to be estimated as:

\[
v_p - U = \frac{2}{9} \frac{a^2 (\rho_p - \rho_f)}{\mu} \frac{dv_p}{dt}
\]

(2.2)

The difference in velocity, \( v_p - U \), is called the slip velocity. It is apparent from Equation (2.2) the selection of neutrally buoyant particles, \( \rho_p - \rho_f = 0 \), results in tracers that accurately follow the fluid flow. This condition is easily satisfied for liquid flows, but is much more difficult to achieve in gas flows where particle density is on the order of \( 10^3 \) greater than the fluid [2]. In the case where \( \rho_p / \rho_f \gg 1 \), a single exponential decay law is used to model the particle response to a stepwise variation in the flow velocity. The characteristic response time of the particle is defined as

\[
\tau = \frac{2}{9} a^2 \frac{\rho_p - \rho_f}{\mu}
\]

(2.3)

The particle response time should be kept smaller than the smallest time scale of the flow \( (\tau_f) \). The accuracy of the flow tracers in turbulent flows is quantified by the particle Stokes’ number, \( S_k \), defined as the ratio between \( \tau \) and \( \tau_f \). According to the literature when \( S_k < 0.1 \), particle tracing of the flow will achieve acceptable accuracy with errors
below 1% [2]. Instead of using a characteristic response time, Melling calculated a characteristic frequency, \( C \), from the BBO Equation resulting in Equation (2.4).

\[
C = \frac{18\mu}{\rho_p d_p^2}
\]  

(2.4)

Frequency is equal to \( 1/\tau \), and it can easily be shown with simple algebra that Equation (2.3) is equivalent to Equation (2.4).

\[
\frac{1}{\tau} = \frac{9\mu}{2a^2\rho_p} = \frac{9\mu}{2\left(\frac{1}{2}d_p\right)^2 \rho_p} = \frac{18\mu}{d_p^2\rho_p} = C
\]  

(2.5)

2.1.3 Image Acquisition and Correlation

In the past, PIV images were captured on film with 35mm cameras. Today, digital cameras are used to capture a large quantity of images quickly. CCD and complementary metal-oxide semiconductor (CMOS) sensors convert light energy into electrical energy which is used to produce a digital image. Both sensor types are extremely sensitive to light so low ambient light conditions are needed to properly capture images of the seed particles and minimize background noise and reflections.

Using a light sheet, formed by passing a double pulsed laser beam through an optical arrangement, the particles in the flow are illuminated twice with a small time separation between. A digital camera is typically positioned perpendicular to the plane of
the light sheet and its shutter timed to capture the light scattered by the particles. The displacement of particles in the time between the laser pulses is recorded as a pair of two single exposure images. The recorded particle displacement field is measured locally across the whole field of view of the images, scaled by the image magnification and then divided by the known pulse separation time increment to obtain flow velocity at each point. Depending on the flow velocity and the camera lens magnification factor the delay of the two pulses must be determined so adequate displacements of the particle images on the CCD or CMOS are obtained [10].

The large number of digital images combined with the number of particles per image, requires the use of sophisticated software to process the vector fields. A variety of PIV analysis techniques exist, but all methods are based on a statistical cross-correlation algorithm [3]. This method breaks the image pairs down into a grid of interrogation regions (IR) as seen in Figure 2.2. Typically, each IR is a non-overlapping square made up of 128 x 128, 64 x 64, or 32 x 32 pixels, and the physical size of each IR can range from micrometers to centimeters, depending on the field of view of the camera. According to the LaVision, PIV software manual, best results from this method are obtained when a minimum of ten particles are present in each IR [10]. The first step in acquiring a flow field vector map is the analysis of the IRs in the frequency domain using fast Fourier transforms (FFT). An IR from the first image is compared pixel by pixel to the same IR in the second image. A peak occurs when the particle reflections in image one match the particle reflections in image two. This correlation peak will be much higher when all particles in the IR have approximately the same displacement as seen in Figure 2.3. If the particles do not all move with the same velocity, the displacement
found by correlation is approximately an average over the particles and will result in several peaks of lower amplitude as seen in Figure 2.4. The correlation, performed in the frequency domain, is converted back into the time domain through an inverse Fourier transform. The result is a vector map of each particle’s pixel displacement between the two images. Initial calibration images are taken in order to determine the number of pixels per unit length known as the scale factor. With the known pixel displacement and known time step between images the velocity vector map of each IR can easily be calculated. This process is executed for all IRs and results in an instantaneous velocity vector map over the entire flow field. Post-processing of the vectors may be accomplished using filters and analysis methods including peak filters, IR shifting, overlapping, and local averaging. Proper post-processing will result in increased accuracy and spatial resolution of the vector field. Figure 2.2 below shows the entire PIV correlation process with a near-ideal result of the peak detection.
Figure 2.2: The cross correlation process.

[10]
Figure 2.3: Correlation peak resulting when all particles have the same displacement.

Figure 2.4: Correlation peaks resulting when particles have different displacements.
2.2 \textit{CO}_2 \textit{Particle Formation and Characterization}

Creating discrete particles for PIV using \textit{CO}_2 has been the focus of several researchers within the last decade and is well documented \cite{4, 6, 7, 11, 12}. Particle production requires a high-pressure dewar of \textit{CO}_2 which is equipped with a siphon tube to access the liquid in the bottom of the container. The liquid \textit{CO}_2 is drawn up the siphon tube and directed through a small diameter expansion nozzle. Attached to the nozzle is a larger diameter shroud tube as seen in Figure 2.5. When the \textit{CO}_2 expands through the nozzle some of the liquid evaporates and lowers the temperature of the remaining liquid spray to form solid particles. The small particles then combine with each other, or agglomerate, to form larger particles of various sizes inside the shroud tube.

![Schematic of CO\textsubscript{2} particle generation system.]

\cite{4}
The use of CO$_2$ to form clean seeding particles for PIV measurements has been studied at AFIT and AFRL in cooperation with Innovative Scientific Solutions, Inc. for several years. Initial work was described by DeLapp, et al. in 2006 [12], where a commercially available system called the Sno-Gun II was used to generate dry ice particles. Several nozzles of varying diameter were used to create particles of different size which were then measured using a Malvern particle size analyzer. The results of this research showed that CO$_2$ particles measuring between 5 to 15 µm could be created using this technique.

Further work by McNiel et al. built on the work of DeLapp to determine if discrete particles could be created and injected into the air flow of a wind tunnel for PIV [13]. This research focused on two methods for particle injection including a capped, multi-port shroud tube and a simple, uncapped shroud tube. The multi-port system, absent shroud tubes, proved unable to produce CO$_2$ particles and only created gaseous clouds through the test section. Successful results were obtained using the simple shroud tube. Discrete particles were created, injected in the flow, and did not sublimate prior to reaching the test section of the wind tunnel [13].

McNiel et al. also explored using various combinations of small and large tubes to control the expansion of CO$_2$ in order to produce seed particles [13]. Greene then researched the effects of varying the size of the feed tube and shroud tube diameters on particle size. He also studied how insulating the shroud tubes would affect the size of the particles [11]. Greene documented that increasing the length of the shroud tube, increasing the inner diameter of the shroud tube, decreasing the inner diameter of the feed tube, and insulating the shroud tube each increased the size of particles generated.
Reversing any of these parameters would result in particles of smaller size [11]. Greene was able to successfully inject particles and collect PIV data in the AFIT 2.5 x 2.5 inch supersonic wind tunnel. Attempts to scale this technique up to the larger 6 x 6.5 inch supersonic blow-down tunnel resulted in decreased particle number density. An increase in the air mass flow rate for the larger tunnel and the greater distance between the injection site and the test section caused more of the CO$_2$ particles to sublime prior to reaching the test section [11].

Research by Love in 2008 focused on improving the method of particle generation and quantifying particle response time for flow across a shock in the 6 x 6.5 inch tunnel at AFIT [7]. Again, feed tubes and shroud tubes of different sizes were tested in addition to the use of a static mixing shroud tube. The particles generated using the static mixing shroud tube were approximately three times smaller than particles made by open flow shroud tubes of the same diameter. Love also led the first attempt at CO$_2$ clean seeding for PIV measurement in the TGF at AFRL Air Vehicles Directorate. Tests were successfully performed at three subsonic speeds and four stagnation pressures. PIV data were successfully collected in the tunnel freestream in each case and streamwise velocities matched expected values [7]. However, due to the limited optical access of the TGF, the light-sheet plane used to collect data was rotated at an angle. This angle was not orthogonal to the tunnel surfaces making it impractical to accurately study boundary layer conditions in the test section. A main goal of the research in this thesis is to accurately capture the boundary layer conditions in the TGF at several Mach numbers and stagnation pressures.
2.3 Boundary Layer Properties

The boundary layer is a thin region of flow adjacent to the surface, where the flow is slowed by the friction forces acting between the flow and the solid surface. Directly at the surface, the flow velocity is zero. This is known as the no-slip condition. Above the surface the velocity increases until it equals the freestream velocity. The thickness of this boundary layer, \( \delta(x) \), is the height above the surface where the flow velocity equals 99% of the freestream velocity. Due to differences in laminar and turbulent flow, two mathematical models are used to calculate boundary layer thickness over a flat plate [14].

For the laminar case

\[
\delta(x) = \frac{5.0x}{\sqrt{Re_x}}
\]  

(2.6)

where

\( x = \text{horizontal distance over plate} \)

\( Re_x = \text{Reynolds number at } x \)

The data collected in this research concentrates on turbulent flow fields. The equation for turbulent boundary layer thickness is as follows.

\[
\delta(x) = \frac{0.37x}{Re_x^{(\frac{1}{5})}^{(\frac{1}{5})}}
\]  

(2.7)
Additionally, the text by Schlichting [15] developed two empirical models for a compressible turbulent boundary layer which relate the normalized velocity distribution, \( \frac{u}{u_\infty} \), to the height above the plate, \( y \), divided by the momentum thickness, \( \delta_2 \), and displacement thickness, \( \delta_1 \), as seen in Equations (2.8) and (2.9).

\[
\frac{U}{U_\infty} = 0.683 \left( \frac{y}{\delta_2} \right)^{\frac{1}{7}} \quad (2.8)
\]

\[
\frac{U}{U_\infty} = 0.737 \left( \frac{y}{\delta_1} \right)^{0.1315} \quad (2.9)
\]

In a turbulent compressible boundary layer, the ratio of boundary layer thickness to momentum thickness is \( 72/7 \) and the ratio of boundary layer thickness to displacement thickness is 8.

\[
\delta = \frac{72}{7} \delta_2 \quad (2.10)
\]

\[
\delta = 8\delta_1 \quad (2.11)
\]

In addition to determining mean velocity profiles, it is an understatement to say that many studies have focused on turbulence measurements in boundary layers. Klebanoff conducted similar wind tunnel studies in a large closed circuit tunnel of turbulent boundary layers over a 12 foot long plate using hot-wire anemometry [16], and the representation of his data offers a straightforward comparison to data collected as part
of this research. The mean velocity data from Klebanoff is given in Figure 2.6, where $U_1$ here represents the freestream velocity. Schlichting characterized the same results in terms of boundary layer thickness and showed that the 90 percent velocity location was located at approximately $0.50\delta$ for this data set.

![Figure 2.6: Distribution of mean velocity from study by Klebanoff.](image)

Klebanoff used hot wire anemometry to determine the profiles. As shown in Figure 2.7, he found that the maximum streamwise turbulence was approximately 11% very close to the wall, while maximum turbulence normal to the flow was much lower, around 4%. In Figure 2.8, Reynolds shear stress normalized by one-half times the square of the freestream velocity obtained by Klebanoff is given, and it remains below 0.003. While many other, more modern, measurements of boundary layers have been performed,
this straightforward presentation by Klebanoff provides a highly useful benchmark for comparison of the PIV results obtained in this study.

Figure 2.7: Distribution of turbulence intensities from study by Klebanoff.

[16]

Figure 2.8: Distribution of turbulent shearing stress from study by Klebanoff.

[16]
III. Methodology

This chapter describes the test equipment and procedures used throughout this research project. First, the pertinent operational details of the TGF are covered. Next, the process for generating CO$_2$ particles is discussed. Finally, the PIV system and its setup are described.

3.1 Trisonic Gas-dynamics Facility

The TGF is an asset of AFRL Air Vehicles Directorate and is located at Wright-Patterson Air Force Base, OH. The TGF is a closed circuit, variable density, continuous flow wind tunnel capable of operating at subsonic, transonic, and supersonic speeds through a range of Mach numbers from 0.23 to 3.0 (Figure 3.1). Separate interchangeable nozzle blocks are used to operate in the supersonic flow regime. Tests for this research were performed at subsonic velocities only and utilized the subsonic nozzle blocks. The 2 x 2 foot subsonic test section can provide Mach numbers from approximately 0.23 to 0.85. At subsonic conditions the maximum achievable Reynolds number per foot is 2.5 million and the maximum attainable dynamic pressure is 350 pounds per square-foot (PSF). The TGF’s subsonic operation envelope is shown in Figure 3.2.

The stagnation chamber inlet measures 8 x 8 feet and is 26 feet upstream of the test section windows. Two 28-inch diameter hinged windows are mounted on the test section sidewalls. These windows can be opened quickly to allow easy access to the models for configuration changes. In addition, the two optical quality glass windows allow the collection of Schlieren images, high-speed digital images, and PIV data.

PIV data, for this research, was collected on seven different days throughout the
month of September 2011. All experiments were conducted nominally at Mach 0.3, Mach 0.5, or Mach 0.8. Precise measurements of the tunnel conditions during each test run are presented in Chapter 4.
Figure 3.1: Side view of the TGF
[17]
3.2 \textit{CO}_2 \textit{Particle Generation}

The liquid CO\textsubscript{2} (LCO\textsubscript{2}) used throughout this project was stored in commercially available dewars as shown in Figure 3.3. The dewars have an internal volume of 180 liters and are pressurized to approximately 350 psi. The dewars are equipped with a siphon tube which draws the LCO\textsubscript{2} out from the bottom of the tanks. Two dewars are used simultaneously to feed the distribution manifold pictured in Figure 3.4. Pressurized LCO\textsubscript{2} flows from the dewars through high pressure, flexible, stainless steel Swagelok\textsuperscript{®}
hoses and compression fittings to the top and bottom connection on the manifold. The LCO₂ then flows through nozzles where it expands, rapidly decreasing in pressure and temperature, and forms solid CO₂ particles. While the particles remain in the shroud tubes, they agglomerate and increase in size until exiting the tube.

The distribution manifold is constructed of 0.5 inch outer diameter, stainless steel tube with eight equally spaced connection points for the injector assemblies. Total overall length of the manifold is 22 inches and the injectors are spaced 2.3 inches apart on center. The eight connection points are threaded to accept standard 1/8 inch National Pipe Thread (NPT) fittings. One injector assembly consists of an expansion nozzle, a reducing coupling, and a shroud tube. Washjet®, 1/8-MEG-0002 expansion nozzles, with a 0.034 inch diameter orifice, were used for all experiments. Two different sizes of shroud tubes were used in order to create CO₂ particles of different size. Prior research by Greene [11] and Love [7] demonstrated that using larger diameter shroud tubes will increase the size of the particles while smaller diameter tubes will decrease the particles size. The first set of shroud tubes were 6 inch lengths of 3/4 inch NPT pipe which have an inside diameter of 0.824 inches as seen in Figure 3.5. The second set of shroud tubes consisted of 6 inch lengths of 1/4 inch NPT pipe which have an inside diameter of 0.364 inches as seen in Figure 3.6. A visual comparison of the particles generated by the different size shroud tubes can be seen in Figure 3.7.
Figure 3.3: CO$_2$ storage dewars.

Figure 3.4: CO$_2$ distribution manifold installed in the TGF.
Figure 3.5: 3/4 NPT pipe shroud tube drawing.

[18]

Figure 3.6: 1/4 NPT pipe shroud tube drawing.

[18]
Figure 3.7: Shroud tube and particle size comparison.
3.2.1 Distribution Manifold Installation

Prior to installation in the TGF, a drag force analysis of the CO$_2$ distribution manifold was done to ensure no damage would occur due to the manifold breaking free from its mounts. The drag force was calculated to be less than one pound at the tunnel’s maximum operating limit. The safety review board, held by AFRL/RBAX, rated the CO$_2$ particle distribution system as low risk and approved it for installation in the TGF.

The manifold was mounted in three different configurations within the stagnation chamber of the TGF. This was done to optimize particle distribution in the test section for PIV measurements of the boundary layer perpendicular to the tunnel window. In all configurations the height of the manifold remained constant. The manifold center was aligned with the centerline of the test section when measured from the floor. In the first configuration, the manifold was mounted in the center of the stagnation chamber with the shroud tubes parallel to the flow direction. For the second configuration, the manifold remained mounted in the same location and the shroud tubes were rotated on the vertical axis approximately 40 degrees toward the wall. This forced the CO$_2$ particles closer to the wall of the tunnel where boundary layer measurements were taken. In the third configuration, the manifold was mounted close to the side wall of the stagnation chamber with the shroud tubes parallel to the flow direction. This was also done in an attempt to increase particle coverage near the wall of the test section to optimize PIV measurements of the boundary layer.
3.3 **PIV System**

A commercial, off-the-shelf, PIV system assembled and sold as a package by LaVision was used for this research project. This system consists of a LaVision computer with DaVis 7.2 software package, cameras, and a laser light source. Digital images were captured with two Imager Pro X 2M CCD cameras which have a 1600 x 1200 pixel array. Nikkor 55 mm f3.5 lenses were mounted on both cameras. The laser light sheet was produced by a New Wave Research Solo 200XT, Nd:YAG, frequency doubled laser operating at 532 nm and a maximum power of 200mJ. Precision timing of the laser pulses and camera shutters was controlled by the DaVis software in combination with the integrated Programmable Timing Unit Version 9 (PTU 9). The PTU 9 is a PCI board installed in the LaVision computer and is capable of highly accurate timing synchronization of up to 16 independent channels.

In conventional PIV experiments the camera optical axis is set up perpendicular to the plane of the laser light sheet. This arrangement provides the most direct method to capture two dimensional flow data on the plane of the light sheet. The limited optical access of the TGF prevents simple positioning of cameras perpendicular to the horizontal plane in the test section to study the boundary layer along the side wall or window. To accomplish the boundary layer study a backward-scatter, stereoscopic PIV technique was used. An overview of this approach has been described by Adrian and Westerweel [3] and in the LaVision FlowMaster manual [10]. Two cameras are set at an equal angle on opposite sides of the light sheet plane and the laser light is scattered backward to the cameras as seen in Figure 3.8. This technique not only enabled optical access perpendicular to the tunnel wall, it also enabled the capture of all three components of the
flow velocity, increasing the accuracy of the boundary layer measurements. Single camera PIV can still be accomplished in this configuration but the data may contain bias errors.

After the cameras and laser are mounted, the system must be calibrated to correctly scale the field of view. First, a Type 11, LaVision calibration plate was aligned horizontally with the light sheet plane. This calibration plate, seen in Figure 3.9, is three dimensional and has dots which are equally spaced 10 mm apart. Next, each camera is manually focused to obtain a clear image of each side of the plate. The LaVison software has an automated calibration program which then captures images of the calibration plate from each side, determines the location and angle of both cameras, then removes any warping in the images to correctly display 10 mm between each dot. Figure 3.10 is the pre-calibration image from camera 1, above the calibration plate, and Figure 3.11 is the pre-calibration image from camera 2, below the calibration plate. The corrected, post-calibration images of camera 1 and camera 2 are shown in Figure 3.12 and Figure 3.13 respectively.

The foam blocks seen in the calibration figures were put in place to protect the highly polished tunnel window from being scratched. As a result, there is an unknown separation between the window and the edge of the calibration plate which introduced some ambiguity as to the precise location of the wall measurement in the calibrated images. This ambiguity, of just 3 or 4 mm, resulted in large shifts of the data when plotted and is discussed in Chapter 4.
Figure 3.8: Stereoscopic PIV setup for boundary layer measurements with laser sheet (green) and optical axis of cameras (blue).
Figure 3.9: Type 11 calibration plate.

Figure 3.10: Pre-calibration image from camera 1.
Figure 3.11: Pre-calibration image from camera 2.

Figure 3.12: Post-calibration, corrected image from camera 1.
These corrected images provide a grid of known distance so the scale factor can then be calculated to determine the relative size of each pixel captured on the focal plane. The calibration process resulted in an image of the flow field with a field of view measuring 80 mm x 70 mm and a scale factor of 22.4264 pixels per mm. The software also calculated the focal length of the cameras to be 54.8352 mm. Laser and camera timing were adjusted to properly capture the flow velocity. This calibration was used for the tests which occurred between 8 September and 13 September.

The PIV system was needed for another experiment at a different facility so a new calibration was done on 21 September when the system was again set up at the TGF. This calibration resulted in a 120 mm x 70 mm field of view with a scale factor of 16.5479 pixels per mm. Camera focal length was calculated to be 46.1784 mm. This calibration was used during all tests of the smaller, 0.364 inch ID, shroud tubes on 21 September.
3.3.1 PIV Data Processing

Pre-processing of the image pairs started with a filter to reduce or eliminate reflections which contaminate the data. This process, called Subtracting a Sliding Background acts as a high pass filter where large intensity fluctuations in the background are filtered out while small intensity fluctuations of the particle signal will pass through. A scale length setting of four pixels produced the best results. The next process performed a standard Fast Fourier Transform cross-correlation using an initial interrogation region (IR) of 128 x 128 pixels followed by a smaller 64 x 64 pixel IR. The entire image was processed using a 50% overlap for both IR sizes.

The cross-correlation was followed by a peak validation using a value of 1.5 and a smoothing operation. The peak validation measures the relative height of the two tallest correlation peaks in an interrogation region and results in a valid vector if the height ratio of the tallest peak to the second tallest peak is 1.5 or greater. According to the LaVision Flow Master manual, a peak ratio setting between 1.2 and 1.5 is standard for PIV applications [10]. For multi-pass processing, as done in this research, the LaVision software uses a simple 3x3 smoothing filter to reduce noise by default.

Two operations were performed in the post-processing of the flow field vector map. First, a median filter was used which computes a median vector from the 8 neighboring vectors and compares the middle vector plus/minus a selected deviation of the neighbor vectors. The center vector is rejected when it is outside the specified range. Figure 3.14 provides an example of the median filter operation. In this example a median filter RMS setting of 1.4 or less will reject the center vector. The median filter
was set to 1 RMS of neighbors for this research. The second operation sets a minimum threshold for valid vectors at each location on the vector map. If this threshold is not met results will not be displayed for that location. A setting of 200 vectors was used for the experiments where 1000 images were captured. For the case where 10000 image pairs were taken, a minimum of 2000 valid vectors were required.

Figure 3.14: Example of median filter operation.

Two different methods were used to plot the results. The first method creates a two dimensional vector field of the flow field. The second method creates a scalar contour plot of several variables over the entire flow field. These variables include streamwise velocity, $V_x$, perpendicular velocity, $V_y$, RMS of streamwise velocity, $v'_{x}$, RMS of perpendicular velocity, $v'_{y}$, and Reynolds shear stress, $v'_{x}v'_{y}$. Reynolds shear stress is calculated by Equation (3.1).

$$v'_{x}v'_{y} = \frac{\sum_{i=1}^{N}[(V_{xi} - \overline{V_x})(V_{yi} - \overline{V_y})]}{N} \quad (3.1)$$
IV. Results and Discussion

Results for testing conducted at the TGF are presented below. First, a record of all the tests which were performed is discussed. Second, the dependency of CO$_2$ particle size and the particle number density in the test section on Mach number and stagnation pressure is presented. Third, based on the PIV data, boundary layer profiles are calculated for several Mach numbers and stagnation pressure combinations. Finally, results of turbulence data are presented.

4.1 Record of Experiments Performed

Experimental PIV data was collected at the TGF over a period of seven days throughout the month of September 2011. A total of 42 experiments, as seen in Table 4.1, were performed in which Mach number, stagnation pressure, shroud tube diameter, injection manifold location, and injection manifold angle to the flow direction were all varied in several combinations. Tests were run at nominal Mach numbers of 0.3, 0.5 and 0.8. Tunnel instrumentation recorded exact conditions for each experiment which are listed in Appendix A. Experiments 1 through 24 were primarily performed to make adjustments to the settings of the PIV equipment and CO$_2$ injection manifold. PIV data in some of these early experiments is less than optimal and is not analyzed in this document. However, results are presented for Experiments 25 through 42 where data was significantly better. In a majority of the experiments 1000 image pairs were captured for PIV analysis. In several tests only 100 image pairs were captured. These images were quickly analyzed and adjustments to the time between laser pulses ($\Delta t$) were made for each Mach number in order to optimize PIV results. In Experiment 33, ten thousand
image pairs were collected to provide a larger statistical sample for boundary layer turbulence analysis.

Table 4.1: Record of experiments performed.

<table>
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<tr>
<th>Experiment Number</th>
<th>Date</th>
<th>Nominal Mach Number</th>
<th>Stagnation Pressure (lb/ft^2)</th>
<th>Δt (μs)</th>
<th>Number of Image Pairs</th>
<th>Shroud Tube Diameter (inches)</th>
<th>Injection Location</th>
<th>Injection Angle (degrees)</th>
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4.2 Particle Size and Particle Number Density

Analysis of the raw camera images reveals several important trends regarding CO$_2$ particle size and the particle number density in the TGF test section. First, as the stagnation pressure in the tunnel is increased the rate of CO$_2$ sublimation is decreased. Figure 4.1 shows typical particle size and particle number density for Mach 0.3 at the lowest stagnation pressure of 500 pounds per square foot (psf). The particles produced at this condition range in size from two to six pixels. When the Mach number is held constant and stagnation pressure is increased to a mid-range value of 1042 psf, average particle size increases to between four and eight pixels as seen in Figure 4.2. This trend of increasing particle size continues through the 1531 and 2018 psf conditions and is shown in Figure 4.3 and Figure 4.4. At the maximum stagnation pressure of 2395 psf the CO$_2$ particles sublime at the slowest rate and retain a larger portion of their original size. Figure 4.5 shows typical particle sizes for the Mach 0.3, 2395 psf case. Average particle size at this condition ranges from eight to twelve pixels. Occasionally large particles over 12 pixels in diameter are produced at this condition and can be seen in Figure 4.5. This trend is consistent when velocity is held at Mach 0.5 or Mach 0.8 and stagnation pressure is varied.

It is important to point out that camera 1, above the light sheet, is used to display the images from the large, 0.824 inch ID, shroud tubes and particles will appear on the left side of the image, representing the inside of the tunnel. Camera 2, located below the light sheet, is used to display images from the small, 0.364 inch ID, shroud tubes and particles will appear on the right side of the image. The white line in each image is a reflection of the light sheet and represents the approximate location of the window.
Figure 4.1: Seeding from 0.824 inch ID shroud tubes at M = 0.3, P = 500 psf.

Figure 4.2: Seeding from 0.824 inch ID shroud tubes at M = 0.3, P = 1042 psf.
Figure 4.3: Seeding from 0.824 inch ID shroud tubes at $M = 0.3$, $P = 1531$ psf.

Figure 4.4: Seeding from 0.824 inch ID shroud tubes at $M = 0.3$, $P = 2018$ psf.
Figure 4.5: Seeding from 0.824 inch ID shroud tubes at $M = 0.3$, $P = 2395$ psf.

The second trend confirms prior research by Greene [11] and Love [7] showing that decreasing the size of the shroud tubes will decrease the size of the CO$_2$ particles. Figure 4.6 shows typical particle size between five and ten pixels for Mach 0.5 at 1044 psf using shroud tubes with an ID of 0.824 inches. When smaller shroud tubes with an ID of 0.364 are used, particle sizes are noticeably smaller, between two and four pixels, at equivalent tunnel conditions. Particle number density in the test section of the TGF also decreases significantly. An image of particles generated with the smaller shroud tubes at Mach 0.5 and 1042 psf is shown in Figure 4.7. The particle number density at this condition is sufficient to capture PIV data over 1000 image pairs.
Figure 4.6: Seeding from 0.824 inch ID shroud tubes at M = 0.5, P = 1044 psf.

Figure 4.7: Seeding from 0.364 inch ID shroud tubes at M = 0.5, P = 1042 psf.
The final trend revealed as a result of this research is at low stagnation pressures the 0.364 inch ID shroud tubes produce small particles, a majority of which sublimate prior to reaching the test section of the TGF. Figure 4.8 shows the typical particles produced at Mach 0.3 and 750 psf. Particle number density is extremely low and particles are approximately one or two pixels in diameter. Similar results were obtained at stagnation pressures below 1000 psf and flow velocities of Mach 0.5 and Mach 0.8. Above 1000 psf, the small shroud tubes are able to produce sufficient particles to capture PIV data.

![Figure 4.8: Seeding from 0.364 inch ID shroud tubes at M = 0.3, P = 750 psf.](image)

PIV is highly dependent on particle size and particle number density to calculate flow field characteristics. Each image pair must have a sufficient amount of properly sized particles in order to produce a quality vector map of the flow. These individual
vector maps are averaged over the entire set of image pairs to produce an accurate flow field vector map. The resulting vector map of a single image pair with very low particle number density is shown below in Figure 4.9. This single vector map corresponds to an image pair (Figure 4.8) collected at Mach 0.3 and 750 psf in Experiment 34. Particle number density was extremely low in this case and did not produce a valid flow field vector map.

![Figure 4.9: Vector map of image pair with low particle number density.](image)

Image pairs with a high particle number density provide sufficient data to accurately calculate the overall average flow field vector map. Experiment 31 was conducted at Mach 0.8 and 1044 psf. Figure 4.10 shows the high number of particles present in a typical image pair collected at this tunnel condition. The corresponding vector map to this image is shown in Figure 4.11 and shows a significant increase in the
amount of valid vectors calculated. The condensation cloud visible in Figure 4.10 may be a result of moisture condensation where the CO$_2$ has locally cooled the flow field, though this is just a hypothesis.

Figure 4.10: Seeding from 0.824 inch ID shroud tubes at $M = 0.8$, $P = 1044$ psf.

Figure 4.11: Vector map of a single image pair captured at $M = 0.8$, $P = 1044$ psf.
The final step performed by the PIV analysis software is a summing and averaging of the individual vector maps resulting in a single overall average velocity vector map of the flow field. This final vector map provides the means to further analyze the data by producing scalar plots of $V_x$, $V_y$, $v'_x$, $v'_y$ and $v'_x v'_y$ for the entire image. Text files of this data are then exported to another software program for analysis. Boundary layer profiles were calculated by plotting $V_x$ versus distance from the wall for each experiment. Calculations of turbulence in the boundary layer were also performed for several experiments using $v'_x$, $v'_y$ and $v'_x v'_y$.

4.3 Boundary Layer Calculations

4.3.1 Mach 0.3

Boundary layer profiles were calculated by averaging the freestream velocities along ten separate rows of the time averaged flow field vector map. Selection of the rows must be done carefully as to avoid areas in the vector map where light reflections bias the data. The red box in Figure 4.12 shows an area of a final vector map that contains data affected by a reflection. Velocity profile data for the Mach 0.3, 550 psf condition, using 0.824 inch ID shroud tubes, was collected from horizontal rows above and below the boxed area to perform boundary layer calculations. In this image the tunnel wall is located at approximately 62 mm on the X-axis and the flow is moving vertically from the bottom to the top. Tunnel instrumentation indicated a freestream velocity of 105 m/s. PIV measurements resulted in an average freestream velocity of 103.4 m/s yielding an error of less than two percent. Figure 4.13 shows a boundary layer thickness of approximately 59 mm when measured at 99 percent of the freestream velocity. The
initial gap between the wall and boundary layer is due to the ambiguity in the wall location. In order to align with standard convention, the boundary layer profile data has been rotated 90 degrees clockwise from the vector map so the flow direction is from left to right while the distance from the wall is indicated on the Y-axis.

Boundary layer data is also typically plotted according to the “law of the wall” which states the average velocity of a turbulent flow at a certain point is proportional to the logarithm of the distance from that point to the wall. Clauser plots are one method used to graphically represent boundary layer data. Clauser plots of the data from this research are presented in Appendix B.

Figure 4.12: Flow field vector map for 0.824 inch ID shroud tubes at $M = 0.3$, $P = 550$ psf with red box indicating area affected by laser light reflections.
In Experiment 25, tunnel conditions were set to Mach 0.3 and 1042 psf. The large shroud tubes were used in this case and provided excellent particle size and particle number density. The PIV vector map resulted in an average freestream velocity of 103.1 m/s while tunnel data indicated 104.6 m/s. Boundary layer thickness was calculated to be approximately 61 mm as shown in Figure 4.14.

For Experiment 26, stagnation pressure was increased to 1531 psf while velocity was held to Mach 0.3. The PIV calculation of freestream velocity, 100 m/s, was 3.66% lower than the velocity of 103.8 m/s measured by tunnel instrumentation. Figure 4.15 shows an estimate for boundary layer thickness of 67 mm.
Figure 4.14: Velocity profile for 0.824 inch ID shroud tubes at $M = 0.3$, $P = 1042$ psf.

Figure 4.15: Velocity profile for 0.824 inch ID shroud tubes at $M = 0.3$, $P = 1531$ psf.
In Experiments 27 and 28, stagnation pressure was increased to 2018 psf and 2395 psf respectively. In both cases it appears particle size increased to the point where reliable freestream velocities could not be captured by the PIV system. Errors between PIV measurements and actual freestream velocities were over 15% at 2018 psf and 33% at 2395 psf. Boundary layer thickness for Experiment 27 was approximately 66 mm. An estimate for boundary layer thickness cannot be accurately calculated for the Experiment 28. Figure 4.16 and 4.17 are shown to demonstrate how improperly sized particles negatively affect PIV measurements.

Figure 4.16: Velocity profile for 0.824 inch ID shroud tubes at M = 0.3, P = 2018 psf.
The second set of experiments performed at Mach 0.3 used the smaller shroud tubes with an ID of 0.364 inches. Experiments were conducted at 750 psf and 1000 psf but particle number density in the test section was extremely low in both cases making the collection of PIV data impractical. The stagnation pressure was then increased to approximately 1530 psf. This reduced the sublimation rate of the CO$_2$ resulting in a sufficient amount of particles in the test section to resume PIV data collection. Freestream velocity according to the tunnel instruments was 103.7 m/s, while PIV measurements produced an average velocity of 102.4 m/s, a difference of less than 2%. The boundary layer thickness is calculated to be approximately 64 mm as shown in Figure 4.18. A comparison of the results obtained using different sizes of shroud tubes is shown in Figure 4.19. Beyond 35 mm from the wall, the two velocity measurements are reasonably consistent. Below 35 mm, however, the two profiles are inconsistent due to differences in the particles sizes and their ability to follow the flow dynamics.
Figure 4.18: Velocity profile for 0.364 inch ID shroud tubes at M = 0.3, P = 1530 psf.

Figure 4.19: Boundary layer comparison using 0.824 inch ID and 0.364 inch ID shroud tubes at M = 0.3, P = 1530 psf.
The size of the particles produced by the large shroud tubes are significantly larger than the particles generated by the small tubes and may account for this difference.

4.3.2 Mach 0.5

Particle number density was sufficient for PIV data collection in all experiments conducted at Mach 0.5. In Experiment 33, a total of 10000 image pairs were collected at the Mach 0.5, 1044 psf condition using the larger shroud tubes. This data set provides a larger statistical sample for improved boundary layer thickness calculations and turbulence data analysis which is discussed in Section 4.4. Figure 4.20 shows the results for the Mach 0.5 at 1044 psf case using the large shroud tubes. As expected, the velocity profile curve for this test case is much smoother than for the other cases. Freestream velocity calculations using the PIV system were within 1 m/s of the data provided by tunnel instrumentation. The boundary layer thickness is estimated to be approximately 64 mm.

A second experiment was conducted at the same wind tunnel conditions with the small shroud tubes. Results of this test are shown in Figure 4.21 and show a boundary layer thickness of approximately 62 mm. Comparison of the two profiles in Figure 4.22 shows a similar trend in the boundary layer growth. Small changes in the wind tunnel settings or stagnation temperature may account for the different freestream velocity values.
Figure 4.20: Velocity profile for 0.824 inch ID shroud tubes at $M = 0.5$, $P = 1044$ psf.

Figure 4.21: Velocity profile for 0.364 inch ID shroud tubes at $M = 0.5$, $P = 1042$ psf.
Figure 4.22: Boundary layer comparison using 0.824 inch ID and 0.364 inch ID shroud tubes at $M = 0.5$, $P = 1044$ psf.

The final Mach 0.5 experiment was conducted at 1530 psf with the small shroud tubes. Wind tunnel data reveals a freestream velocity of 169.6 m/s compared to a PIV measurement of 168.4 m/s. Based on the mean velocity measured using the wind tunnel instrumentation, the boundary layer thickness for this case worked out to approximately 94 mm as seen in Figure 4.23.
4.3.3 Mach 0.8

Particle number density was very good for all Mach 0.8 experiments. Three sets of data were collected using the large shroud tubes at different stagnation pressures, 798 psf, 1044 psf, and 1239 psf. Trial runs with the small shroud tubes at low pressures revealed a lack of CO$_2$ at pressures stagnation pressures of 500 and 750 psf. As the stagnation pressure was raised to 1000 psf the particle number density increased to acceptable levels for data collection.

Figure 4.24 through Figure 4.26 show velocity profiles for the large shroud tube experiments at Mach 0.8 and 798 psf, 1044 psf, and 1239 psf in order. In all three cases...
boundary layer thickness is estimated to be 59 mm. Errors between freestream velocities recorded by tunnel instrumentation and calculated from PIV data are minimized at low pressures where particle size is small. At 798 psf this error is 1.7%. As stagnation pressure is increased, particle size increases resulting in an increased error between freestream velocity measurements. This error is 2.3% at 1044 psf and 4.3% at 1239 psf.

Figure 4.24: Velocity profile for 0.824 inch ID shroud tubes at M = 0.8, P = 798 psf.
Figure 4.25: Velocity profile for 0.824 inch ID shroud tubes at $M = 0.82$, $P = 1044$ psf.

Figure 4.26: Velocity profile for 0.824 inch ID shroud tubes at $M = 0.82$, $P = 1239$ psf.
Two experiments were conducted at approximately Mach 0.8 with the small shroud tubes. Tunnel conditions for Experiment 41 were Mach 0.84, 272 m/s, and 1045 psf. The average PIV measurement of freestream velocity was 265 m/s and the boundary layer thickness was estimated to be 68 mm. The velocity profile for Experiment 41 is shown in Figure 4.27. Experiment 42 was conducted at Mach 0.79, or 263 m/s, and 1525 psf. The average freestream velocity measured by PIV was 266.9 m/s. In this test the boundary layer thickness was measured to be 71 mm as seen in Figure 4.28.

![Figure 4.27: Velocity profile for 0.364 inch ID shroud tubes at M = 0.84, P = 1045 psf.](image)
4.3.4 Expected Boundary Layers

In this section, boundary layer thickness measurements obtained through PIV are compared to expected values. The expected values for boundary layer thickness are calculated using Equation (2.7), which was developed empirically for flow over flat plates at zero incidence. Solving this equation for $\delta_{99}$ will yield a boundary layer thickness at the point where velocity equals 99% of the freestream velocity, $U_{\infty}$. In the TGF, the straight section wall extends from a convergent nozzle, and so there is some ambiguity in the proper characteristic distance, $x$, to use in Equation (2.7). In order to use this comparison method, a characteristic distance is needed. The boundary layer thickness measured in Experiment 33 is based on an average of 10000 image pairs and therefore provides the most statistically accurate measurement of this value. PIV analysis
of Experiment 33 revealed a boundary layer thickness of 64 mm. This value is set equal to $\delta_{99}$, and Equation (2.7) is solved for the characteristic distance, $x$, resulting in a value of 3.795 m, which seems reasonable given the complex geometry of the TGF. Equation (4.1) is then solved for the other experiments to calculate an expected boundary layer thickness.

$$\delta_{99} = \frac{(0.37)(3.795 \text{ m})}{Re^{\left(\frac{1}{5}\right)}}$$  \hspace{1cm} (4.1)

where

$$Re = \text{Reynolds number based on tunnel condition}$$

Results of these calculations and comparison to the measured boundary layer thickness are shown in Table 4.2. In most cases the difference, $\Delta \delta_{99}$, between the calculated and measured value is less than 10 mm.

A second way of analyzing the boundary layer thickness is to calculate a value for $\delta$ at the location where velocity in the boundary layer reaches 90% of the freestream. One motivation for using the 90% threshold is that it is difficult to determine the 99% location with a high degree of confidence. By comparison, the 90% location is reasonably clear and allows for a simple comparison of boundary layer thickness for different tunnel operating conditions. As discussed in Chapter 2, Klebanoff’s research revealed that the $\delta_{90}$ value for turbulent boundary layers is approximately half of the $\delta_{99}$ measurement. Calculated and measured values for the 90% boundary layer thickness are also compared in Table 4.2. While measured values generally fall below those calculated, they do follow a noticeable trend as seen in Figure 4.29 below.
A comparison between selected boundary layer profiles and the 1/7th power law, Equation (2.8), is presented in Appendix C. Momentum thicknesses for the power law curves were calculated using Equation (2.10).

Table 4.2: Comparison of calculated and measured boundary layer thickness.

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* This case was used to estimate the characteristic length \( X \).

Figure 4.29: Calculated versus measured 90% boundary layer thickness.
4.4 Planar Velocity Maps and Turbulence Data

Ten thousand image pairs were captured in Experiment 33 to provide a large statistical sample to conduct PIV analysis of the turbulence in the boundary layer. The flow field vector map for this experiment is show in Figure 4.30. Each vector in the final map is calculated by summing and averaging valid vectors calculated from individual image pairs. To determine the statistical accuracy of the final flow field vector map it is important to know how many individual valid vectors were used. Figure 4.31 shows a scalar plot of the number of valid vectors used to calculate the vector map at each location. At most locations, over 5000 vectors were used to calculate the flow field vector map. Closer to the wall, the number of valid vectors decreases to between 2000 and 4000 per location.

Figure 4.30: Flow field vector map for Experiment 33, M = 0.5, P = 1044 psf.
The LaVision software is also capable of producing scalar plots of the streamwise velocity ($V_x$), perpendicular velocity ($V_y$), RMS fluctuations of streamwise ($V_x'$) and perpendicular ($V_y'$) velocity, and the Reynolds stress ($V_x'V_y'$). The data from these plots is needed to study the turbulence characteristics of the boundary layer. The scalar plots of these variables are shown in Figures 4.32, 4.33, 4.34, 4.35, and 4.36. Streamwise velocity shows the expected trend of being lowest at the wall and growing quickly to match the freestream velocity. The perpendicular velocity component remains low throughout the entire test region. Initially, all data was processed using the approach documented in Section 3.3.1 of this document.
Figure 4.32: Streamwise velocity ($V_x$) for Experiment 33, $M = 0.5$, $P = 1044$ psf.

Figure 4.33: Perpendicular velocity ($V_y$) for Experiment 33, $M = 0.5$, $P = 1044$ psf.
Figure 4.34: RMS streamwise velocity (\(V_x'\)), Experiment 33, \(M = 0.5\), \(P = 1044 \text{ psf}\).

Figure 4.35: RMS perpendicular velocity (\(V_y'\)), Experiment 33, \(M = 0.5\), \(P = 1044 \text{ psf}\).
The streamwise and perpendicular turbulence values are calculated by normalizing the RMS fluctuations, $V_x'$ and $V_y'$, by the freestream velocity $U_\infty$. The Reynolds shear stress, $V_x'V_y'$, is normalized by the square of the freestream velocity to produce a non-dimensional quantity. Turbulence values with respect to distance from the wall, for Experiment 33, are plotted in Figure 4.37. The turbulence data follows a couple expected trends. First, turbulence is the greatest near the wall where the no-slip condition creates a velocity gradient that interacts with the flow velocity. Second, the streamwise turbulence is greater than that for the perpendicular direction. However, the magnitude of the turbulence data is much greater than expected and does not represent actual conditions in the TGF.
Turbulence data was also analyzed for Experiment 25, Mach 0.3 at 1042 psf, and Experiment 31, Mach 0.8 at 1044 psf, for comparison. This data is presented in Figure 4.38 and Figure 4.39. In all cases streamwise turbulence peaks between 33 and 35%, while perpendicular turbulence peaks at approximately 18 or 19%. The shear stress turbulence peaks negatively between 0 mm and 10 mm then fluctuates near zero as distance from the wall increases. Analysis of the data reveals that the turbulence in the freestream is greatest for the Mach 0.3 case at about 12%. At Mach 0.5, freestream turbulence is approximately 7.5%. The minimum value for turbulence in the freestream occurs in the Mach 0.8 case between 3 and 4%. While the trends of this turbulence data are correct, the magnitudes of the data are incorrect and required further investigation to determine actual values.
Figure 4.38: Turbulence data for Experiment 25, $M = 0.3$, $P = 1042$ psf.

Figure 4.39: Turbulence data for Experiment 31, $M = 0.8$, $P = 1044$ psf.
4.4.1 Refined PIV Processing for Turbulence Measurements

The large values of the turbulence, especially in the freestream appeared unrealistic and prompted further investigation. Prior research done by Humble, Scarano and Oudheusden [19] suggested that using a PIV processing technique with rectangular IRs elongated in the streamwise direction to capture turbulence data. This may in part be explained by the fact that more particles will remain within the interrogation region while spatial resolution in the direction normal to the flow remains uncompromised. The LaVision software does not use rectangular IRs, but does allow for the use of elliptical areas. For the first pass an elliptical IR with a 1:2 diameter ratio was used with 50% overlap. The second pass utilized an elliptical IR with a 1:4 diameter ratio with 50% overlap. All other settings remained the same. Turbulence data for the Mach 0.5, 1044 psf case was calculated with this technique and is shown in Figure 4.40 below. Results show that turbulence in the freestream is at approximately 2% which is more in line with the expected value. While the maximum streamwise turbulence of 34% in the boundary remains high, it is skewed by the two points nearest the wall. Given the ambiguity in the exact wall location, one might argue that maximum turbulence levels are better represented as just over 15%. The perpendicular turbulence was measured to be less than 5% near the wall while shear stress turbulence remained low throughout the boundary layer. This turbulence data compares quite closely with the results of Klebanoff, given in Chapter 2, which is very encouraging. Further processing of data using elliptical interrogation regions, in particular the 10,000 image pair data set, is planned for the near future.
4.5 Sources of Error

There are several potential sources of error which may explain the disagreements between PIV data and the expected results of freestream velocity, boundary layer thickness, and turbulence. The largest source of error is ambiguity of the exact wall location in the calibrated images due to the foam blocks used on the calibration plate. While these blocks were necessary to protect the highly polished tunnel window from being scratched, their use resulted in an unknown separation between the window and the edge of the calibration plate. This ambiguity, of just 3 or 4 mm, greatly affects the results of boundary layer thickness and turbulence data.
The production of CO$_2$ particles is sensitive to the stagnation pressure in the tunnel and introduces errors in two ways. First, the large particles formed at high stagnation pressures have greater mass and are not able to accurately follow accelerations in the flow field. This will create biases in the PIV measurements of freestream velocity and turbulence. Second, at lower stagnation pressures the particle number density decreases which reduces the statistical sample for analysis.

Laser light reflections off of the glass and metallic surfaces in the TGF limit PIV analysis of some regions of the raw images. In most cases, the LaVision software was not able to completely eliminate these reflections which introduce biases into the measurements.

Finally, the filter settings used to post-process the image pair vectors maps may not have eliminated some spurious vectors. These incorrect vectors are included in the final calculation of the flow field vector map and skew the PIV results. More stringent filter settings can be implemented at the risk of eliminating all data at certain points in the vector map where particle number density is very low.
V. Conclusions and Recommendations

5.1 Overview of Research Effort

PIV is a highly effective flow field analysis technique, but its usefulness is dependent on the proper selection of the particles used to seed the flow. Particle characteristics such as density and size are crucial to ensure the particles accurately respond to the flow dynamics. Additionally, particles must be large enough to reflect a sufficient amount of laser light to the cameras. Proper selection of seeding particles is especially important for use in closed-circuit wind tunnels where they can create safety hazards, cause corrosion, or leave behind residues which require extensive maintenance and down time. Facilities like the TGF, operated by AFRL/RB, have avoided using PIV in the past because of the impact of the seed material on tunnel components. Therefore, a method of cleanly seeding closed-circuit wind tunnels for PIV measurements is needed.

To this end, research has been performed on the use of solid CO$_2$ particles for flow seeding and collecting PIV data. Dry ice particles are produced by directing high pressure liquid CO$_2$ through and expansion orifice into a shroud tube which creates solidified particles that are injected into the wind tunnel stagnation chamber. Prior work had shown that the technique provided accurate freestream tunnel measurements in the TGF. However, prior to the current effort, the technique had not been applied to more complex flow fields where spatial resolution is a concern. This research primarily focused on using CO$_2$ particles for clean seeding to collect stereoscopic PIV data of the test section boundary layer in the TGF. Two different sets of shroud tubes were used to modify the size of CO$_2$ particles produced and the particle number density throughout the subsonic operating envelope of the TGF. Freestream velocity was set at Mach 0.3, Mach
0.5, or Mach 0.8 while absolute stagnation pressure ranged from 500 psf to 2400 psf. PIV data was analyzed to produce measurements of boundary layer thickness and compare results to theoretically expected values. Typically, 1000 image pairs were collected for PIV analysis of each tunnel condition. However, in one experiment, 10000 image pairs were collected to study the turbulence characteristics in the TGF test section.

### 5.2 Conclusions

The results of the study showed that boundary layer profiles can be accurately measured in the TGF using CO\(_2\) seeding in combination with the LaVision PIV system, though some care must be exercised in generating properly sized particles and using correctly sized interrogation regions. Particle size and particle number density in the test section of the TGF is influenced by shroud tube diameter, stagnation pressure, and freestream velocity. The larger shroud tubes have an ID of 0.824 inches and consistently lead to larger CO\(_2\) particles, compared to the small shroud tubes with an ID of 0.364 inches, at equivalent wind tunnel conditions. This research shows stagnation pressure has a large effect on particle sublimation rate in the TGF. At stagnation pressures under 1000 psf, small particles generated by the 0.364 inch ID shroud tubes sublimate prior to reaching the TGF test section making PIV measurement difficult if not impractical. The larger shroud tubes produce particles large enough to provide sufficient laser light reflection and flow field coverage at all tested Mach numbers under a stagnation pressure of 1000 psf. However, at higher stagnation pressures, over 2000 psf, the 0.824 inch shroud tubes produce relatively large particles. These large particles have slower response times and do not respond as quickly to the dynamics of the flow field being
studied. Finally, freestream velocity affects particle size and particle number density in the test section. CO$_2$ particles begin to sublimate after leaving the shroud tubes. Particles traveling at higher velocities will reach the test section faster and therefore retain a larger portion of their original size than particles dispersed in a flow field with lower airspeed. For example, the smaller shroud tubes produced better particle coverage at Mach 0.8 conditions than at Mach 0.3 conditions for a given pressure.

Boundary layer profiles were analyzed in detail for thirteen cases. In general, the measured boundary layer thickness closely matched expectations, based on flow over a flat plate, if a length scale of 3.8 meters is utilized. Given the dimensions of the TGF nozzle and test section, this value is reasonable.

Finally, PIV data of 10000 image pairs was collected in order to analyze the turbulence near the wall of the TGF test section at Mach 0.5. RMS fluctuations of the streamwise and perpendicular velocities were normalized by the freestream velocity while Reynolds shear stress was normalized by the square of the freestream velocity and plotted against distance from the wall. Data followed expected trends showing the highest turbulence in the streamwise direction and a decrease in total turbulence as distance from the wall increases. Turbulence data from Mach 0.3 and Mach 0.8 showed similar results and revealed that freestream turbulence decreases as velocity increases. The initial processing method resulted greater than expected magnitudes for the turbulence values. A refined PIV method, using elongated elliptical interrogation regions, significantly improved the turbulence data results.
5.3 **Impact of Research**

For the first time a CO\textsubscript{2} distribution manifold was used to inject clean seeding particles in the TGF stagnation chamber in order to analyze the test section boundary layer through stereoscopic PIV. Closed-circuit wind tunnel facilities like the TGF can benefit from this method because of the low cost and availability of liquid CO\textsubscript{2}, the ability to tune particle size to tunnel conditions, and because the particles do not cause safety hazards or maintenance problems. Properly sized particles can be used in combination with PIV systems to accurately analyze freestream and boundary layer velocity profiles and determine turbulence characteristics in production scale wind tunnels. Finally, the CO\textsubscript{2} injector design may be adjusted to produce correctly sized particles in other closed-circuit tunnels. The distance between the injection point and the test section, the speed of the air flow, and the stagnation pressure are important variables that affect the sublimation rate and residence time of the CO\textsubscript{2} particles.

5.4 **Future Work**

This and previous research have demonstrated the capabilities and limitations of CO\textsubscript{2} particle flow seeding for PIV measurement. The technique has been successfully implemented in small scale tunnels and the TGF. Future work at the TGF may be devoted to improving optical access for the laser light sheet in the test section. Currently the light sheet cannot be projected in a vertical plane over a model in the test section. This improvement would allow future researches to capture clean seeding PIV data of flow fields around aerodynamic models significantly expanding the capabilities of the TGF for AFRL.
CO₂ has been used as seed material for supersonic flow in small scale tunnels at AFIT. However, this technique has not yet been executed in the TGF at supersonic speeds. Future work may be done to design injectors that produce properly sized particles at sufficient particle number densities to perform PIV measurements in this flow regime at the TGF.

Finally, future work could include the full scale introduction and use of dry ice seeding in large scale facilities such as the 16-foot transonic (16T) wind tunnel located at Arnold Engineering Development Center, Arnold Air Force Base.
### Appendix A. Wind Tunnel Instrumentation Data

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Appendix B. Clauser Plots

Figure B.1: Clauser plot for 0.824 inch ID shroud tubes at $M = 0.3$, $P = 550$ psf.

Figure B.2: Clauser plot for 0.824 inch ID shroud tubes at $M = 0.3$, $P = 1042$ psf.
Figure B.3: Clauser plot for 0.824 inch ID shroud tubes at $M = 0.3$, $P = 1531$ psf.

Figure B.4: Clauser plot for 0.824 inch ID shroud tubes at $M = 0.3$, $P = 2018$ psf.
Figure B.5: Clauser plot for 0.824 inch ID shroud tubes at $M = 0.3$, $P = 2395$ psf.

Figure B.6: Clauser plot for 0.824 inch ID shroud tubes at $M = 0.5$, $P = 1044$ psf.
Figure B.7: Clauser plot for 0.824 inch ID shroud tubes at $M = 0.8$, $P = 798$ psf.

Figure B.8: Clauser plot for 0.824 inch ID shroud tubes at $M = 0.82$, $P = 1044$ psf.
Figure B.9: Clauser plot for 0.824 inch ID shroud tubes at M = 0.82, P = 1239 psf.

Figure B.10: Clauser plot for 0.364 inch ID shroud tubes at M = 0.3, P = 1530 psf.
Figure B.11: Clauser plot for 0.364 inch ID shroud tubes at M = 0.5, P = 1042 psf.

Figure B.12: Clauser plot for 0.364 inch ID shroud tubes at M = 0.5, P = 1530 psf.
Figure B.13: Clauser plot for 0.364 inch ID shroud tubes at M = 0.84, P = 1045 psf.

Figure B.14: Clauser plot for 0.364 inch ID shroud tubes at M = 0.79, P = 1525 psf.
Appendix C. Boundary Layer Profiles Compared to 1/7th Power Law

Figure C.1: Velocity profile compared to 1/7th Power Law at M = 0.3, P = 1042 psf.

Figure C.2: Velocity profile compared to 1/7th Power Law at M = 0.5, P = 1044 psf.
Figure C.3: Velocity profile compared to $1/7$th Power Law at $M = 0.8$, $P = 1044$ psf.
Bibliography


Boundary Layer Measurements in the Trisonic Gas-dynamics Facility
Using Particle Image Velocimetry with CO\textsubscript{2} Seeding

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14. ABSTRACT
Particle image velocimetry (PIV) is utilized with solid carbon dioxide (CO\textsubscript{2}) seeding material to conduct boundary layer measurements in the test section of the Air Force Research Laboratory’s Trisonic Gas-dynamics Facility (TGF), which has a 24 inch by 24 inch cross-section. Freestream velocity was set at Mach 0.3, Mach 0.5, or Mach 0.8 while stagnation pressure ranged from 500 to 2400 pounds per square foot (psf). High pressure liquid CO\textsubscript{2} was directed through expansion nozzles into shroud tubes which led to solidified particles in the wind tunnel stagnation chamber. Two different sets of shroud tubes were used to modify the size of dry ice particles produced and the particle number density. Shroud tubes with an inside diameter (ID) of 0.824 inches provided good particle count and coverage for stagnation pressures between 500 and 1500 psf, while 0.364 inch ID shroud tubes demonstrated good particle count and coverage for stagnation pressures over 1000 psf. Overall, the PIV results produced freestream velocity measurements and boundary layer profiles which compared well with expected values. When the PIV data was processed using elliptical interrogation regions, elongated in the streamwise direction, resulting turbulence levels were much closer to expectations.

15. SUBJECT TERMS
Particle Image Velocimetry, Carbon Dioxide, Clean Seeding, Boundary Layer, Trisonic Gas-dynamics Facility, Wind Tunnel

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