Study of Biomimetic Micro and Macro Structures for Drag Reduction

Justin S. Schrout
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Justin S. Schrout

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Patrick Browning, Ph.D., Chair
Wade Huebsch, Ph.D.
Edward Sabolsky, Ph.D.

Department of Mechanical and Aerospace Engineering

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The ever increasing demand for global travel coupled with increasing costs of fuels have prompted many researchers to study new methods to save fuel to make travel more efficient. One of the proverbial low-hanging fruits for fuel efficiency is aerodynamic drag reduction. Simple changes in the shape or placement of structures on the surface of different types of vehicles have been shown to increase fuel efficiency by reducing drag (e.g., add-on lower and aft wake fairings on tractor trailers which have seen a tremendous rise in popularity on US highways in recent years). Areas of interest in drag reduction have typically been in flow control of the boundary layer. Flow control techniques include both passive and active methods. Passive methods include biomimetic structures, riblets, and vortex generators. Active control techniques that are zero mass injection include dielectric barrier discharge (DBD) techniques, dynamic roughness (DR) employed by actively moving specific parts of the skin on the aerodynamic surface, or methods as simple as vibrating the entire surface.

Biomimetic micro and macro structures were investigated in these experiments to determine their efficacy as methods of aerodynamic drag reduction. Wind tunnel experiments were conducted to determine the viscous drag on a flat plate covered with several different micro- and macro surface treatments. The biomimetic surface treatment structures use various geometric forms cast in Sylgard-170 and applied to a smooth, flat, glass substrate. The near-wall boundary layer velocity profiles were determined using planar particle image velocimetry (PIV), a method which utilizes a particle-seeded flow and a pulsed laser illumination and a camera system to capture and cross-correlate the flow field within the region of interest to statistically determine its 2D flow field velocity vectors. Four different Reynolds numbers with varying degrees of free stream turbulence were tested, as well as passive and active vibration modes for all of the surface treatment test articles.

Post processing analysis of the flow field within the boundary layer of each model was performed, including determination of the shear stress at the wall of each boundary layer, as well as numeric integration of the velocity profiles for a direct momentum analysis. Boundary layer shape factors were calculated to help determine the likelihood of local flow separation related to viscous drag.

Results indicated that the tested biomimetic micro- and macro surface structures can provide some drag reduction in both passive and active flow control modes in both laminar and turbulent flow at low Reynolds numbers $O(10^4)$. With improved scaling of the casting size, biomimetic micro- and macro structures could potentially be an effective form of drag reduction for many different aerodynamic applications.
Dedication

There have been many people that have guided me and supported me over the years, and I would like to dedicate this thesis to all of those people. Most importantly, I want to thank my family for all of the sacrifices that they have made for me in this pursuit. I would also like to thank my soon-to-be wife, Rachel Mason, for all of her motivation and late nights helping me stay focused while I study. Thank you all.
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Nomenclature

Abbreviations

ANOVA  Analysis of Variance
CAD    Computer Aided Design
DEHS   Di-Ethyl-Hexyl-Sebacic-Acid-Ester
DR     Dynamic Roughness
PIV    Particle Image Velocimetry
SLA    Stereolithography

Greek Letters

δ     Boundary Layer Thickness
δ*    Displacement Thickness
μ     Dynamic Viscosity
ν     Kinematic Viscosity
ρ     Density
τ     Shear Stress
Θ     Momentum Thickness

Symbols

D     Drag
H     Shape Factor
N     Newton
Re    Reynolds Number
U     Velocity
x     Distance
Introduction

History has graced us with many brilliant thinkers throughout the times. Problems that almost predate history and time are those of fluids, specifically hydrostatics and hydrodynamics. Humans have been creating many tools and structures to take advantage of phenomena that occur with fluids, including boats and waterwheels. It wasn't until the time of Archimedes when these ideas were properly formulated, experimented, and written down. This was known as Archimedes' Principle, which is now what we call buoyancy (Archimedes). History continued to evolve, and so did the schools of thought on fluid mechanics. It wasn't until the works of Sir Isaac Newton in 1687 and his series of books called *Principia Mathematica* (Newton) where we started to see terms such as friction and viscosity. It was at this point when Newton revolutionized the field of mathematics and physics that fluid mechanics truly started to flourish. For the purposes of boundary layers and growth, another brilliant scientist was Osborne Reynolds, specifically for his non-dimensional number, and for his work in fluid mechanics determining transition from laminar to turbulent flow, which forms an important component in the current study. This transition from laminar to turbulent flow has impacted the modern world in ways that were unforeseen at the time.

In the modern world, fuel is an ever increasing concern. Due to the limited supply of materials needed to create fuel, it is becoming increasingly important to ensure that the resources that are currently available, or those soon to become available, will be most efficiently used and conserved. Another vantage point aside from the conservation aspect of resources, is the financial aspect. Fuel costs money. As simple as that is, businesses, organizations, and governments are all in a position to attempt to save money, and fuel savings is relatively low
hanging fruit on the proverbial tree. Finding methods to reduce the effects of drag can directly save fuel, and as such, save money. In cargo ships, surface friction drag accounts for over 60% of the total drag. A NASA study has found that a 25% reduction in the drag of train cars can correspond to a 5% fuel savings, totaling 284 million liters of fuel (Bruce Storms). This is equivalent to approximately $141.8 million in 2018.

Common applications of drag reduction methods would include transportation in the automotive industry, which includes both freight moving and passenger moving capabilities, aircraft, UAVs, etc. They may operate in a certain regime of speeds that would allow a reduction in drag.

Reynolds number is a dimensionless number that relates the ratio of inertial to viscous forces, and is commonly used in analytical solutions that deal with velocity profiles, and as such, the drag. Reynolds number is given by:

\[ Re = \frac{\rho vx}{\mu} \]  

Eq. 1

where \( \rho \) is the density, \( v \) is the velocity, \( x \) is the characteristic length, and \( \mu \) is the viscosity. Important to note that \( Re_x \) is Reynolds number where the characteristic length is the distance along the treatment, \( x \), and \( Re_h \) is the Reynolds number where the characteristic length is the average height of the micro or macro structure. Analytically, these terms play into the larger picture of the inherent steadiness of the flow. As the Reynolds number increases, the inertial forces increase faster than the viscous forces. As the inertial forces increase, the phenomena of turbulence is much more likely to appear, and as the flow becomes more turbulent, the steadiness of the flow tends to decrease.
In terms of the biomimetic aspect of the study, many groups have researched into micro- and macro- structures to determine the aerodynamics, structure, and drag of bird feathers in particular (Mohammed Abdulmalek Aldheeb) (Agrim Sareen) (TUCKER) (BHUSHAN).

Most commonly when people think of aerodynamics and biomimetic structures, people often consider birds. Birds are often studied, but many people overlook marine organisms. Frank Fish makes a great point in his paper on *Imaginative solutions by marine organisms for drag reductions* when he wrote, "Both machines and mammals must contend to the same physical laws that regulate their design and behavior" (Fish). Simply stated, machines and mammals both must overcome the same governing laws of drag, viscosity, weight, size, etc. There are just differing ways to achieve this, such as through microscopic structures, oils, chemicals, or a combination of all of the stated.

Lastly, an important topic is the shape of the boundary layer velocity profiles. As shown in Figure 1, laminar boundary layer profiles tend to have a smooth, gradually sloping section as you achieve free stream velocity. In the same figure, it is seen that turbulent boundary layer profiles have a relatively flat bottom with a curve in the shape as the flow achieves the free-stream velocity. The slope of the curves, for Newtonian fluids, is especially important because the equation for shear stress is as follows:

\[ \tau_w = \mu \frac{du}{dy} \bigg|_{y=0} \quad \text{Eq. 2} \]

where \( \tau \) is the shear stress, \( \mu \) is the viscosity, and \( \frac{du}{dy} \) is the slope of the boundary layer evaluated at the wall \((y = 0)\). As is seen in Fig. 1, the larger gradient is seen in the turbulent flow, therefore a higher value of shear stress is found, and shear stress integrated over an area will give
you shear drag, also known as the skin friction drag. Therefore, decreasing the shear stress over
the surface will have a reduction in the skin friction drag.

The last non-dimensional term that may be of use is the skin friction term. The skin friction
arises from the following equation

\[ C_f = \frac{\tau_w}{\frac{1}{2} \rho U^2} \]  

Equation 3

Where \( C_f \) is the skin friction coefficient, \( \tau_w \) is the shear stress at the wall, and the denominator is
the dynamic pressure term.

Figure 1 - Laminar and turbulent boundary layer velocity profiles (Aerodynamics For Students).
Problem Statement

With increasing research into alternative flow control techniques, biomimetic micro- and macro structures have the potential to offer a new method of flow control techniques for aerospace applications. One goal of flow control techniques is to reduce the drag on the surface caused by the shear forces that are imparted onto the surface within the boundary layer. Passive flow control techniques, such as riblets, vortex generators, and vanes have been fundamental for aerodynamic flow control in the previous decades. Active methods that have been studied include dielectric barrier discharge (DBD), dynamic roughness (DR), which is employed by actively moving specific parts of the skin on the aerodynamic surface, or methods as simple as vibrating the entire surface. These active methods of flow control have been shown to reduce drag on aerodynamic surfaces. These differing types of flow control devices are often studied independently. Variations on biomimetic micro and macro structures have been independently shown to have an impact on the flow control, as well as active control techniques, such as dynamic roughness. The fundamental problem under study in this work is whether variations on new biomimetic micro or macro structures operated with both passive and active control, can be an effective form of reduction of the shear drag at varying Reynolds numbers.
Objectives

The goal of this work is to determine the efficacy of varying biomimetic micro- and macro-
structures to alter the boundary layer characteristics, namely the reduction of drag through
reduction of the shear stress at the wall, while employing both active and passive control
methods for testing. This goal will be met by performing work to satisfy the following
objectives:

1. Determine the effects of varying the active flow control techniques when combined with
   biomimetic structures in a range of Reynolds numbers on the order of $O(10^4)$ in both the
turbulent and laminar flow conditions.

2. Analyze the boundary layer velocity profile results when compared to the analytical
   solutions for both laminar and turbulent boundary layers, specifically using the Blasius
   solution and Prandtl's one-seventh power law for their respective boundary layer profiles.

3. Determine the effects of active and passive techniques employed through an analysis of
   variance (ANOVA).
Review of Relevant Literature

Review of Biomimetic Studies for Drag Reduction

Throughout history, flight has largely eluded mankind. It wasn't until 1903 when man achieved powered flight. This was done at the hands of the Wright Brothers in Kitty Hawk, North Carolina on December 14, 1903 (Crouch). During the next half of a century, there were more advancements in manned flight than there were in the proceeding millennia. A few short decades after the Wright Brothers' flight in Kitty Hawk, the first design of a jet engine was produced by Sir Frank Whittle in 1928 (Sir Frank Whittle). At this point, World War II was approaching, and by and large, a lot of countries were using aircraft that were essentially biplanes, similar to the design of the Wright Brothers. Over the next few decades, countries went from producing Bi-planes, to monoplanes made with supercharged engines, and by the end of World War II, aircraft that were powered by jet engines.

Over the next few decades, there were incredible advancements in the technology that would allow aircraft to fly faster, longer, and with a further range. Most of these advancements were in the engines that would make them more efficient, and the materials that would make the aircraft lighter and stronger. To suggest that drag reduction technologies weren't taken into account during this period is misleading. There were many technologies, such as the retractable landing gear, that would significantly reduce drag.

However, as the rate of new technologies that were discovered had slowly decreased, it became more imperative to study newer technologies that would allow aircraft, and other aerodynamic applications, to continue to increase their efficiencies. Such technologies include ideas such as Riblet technologies, such as those patented by Boeing (Thomas K Tsotsis). Other technologies
include Dynamic Roughness testing, as seen by the experiments conducted by Dr. Huebsch's team at West Virginia University, and performed by Vinay Jakkali (Jakkali). These two technologies are most important to the idea behind the research that is being presented.

Riblet technology is the predecessor to biomimetic technology, because riblet technology is essentially raised structures that will influence the boundary layer, as seen in Figure 2. The surfaces studied have a wide range of designs and geometries. As seen in Figure 2, there are long channels in a saw tooth design. The peak to peak spacing in the figure is approximately 62 μm. While the drag reduction varied based on Reynolds number, for the specific set of riblets that were tested in the Figure 2, drag was reduced based on the Reynolds number. These values can be seen in Table 1. Specifically, there was a significant reduction of drag in the regime of Reynolds numbers on the scale of $1.5\times10^6$ for the 62 μm spacing.
Table 1 - Percentage drag reduction for varying Reynolds numbers with 62 μm spacing

<table>
<thead>
<tr>
<th>$Re$</th>
<th>44 μm</th>
<th>62 μm</th>
<th>100 μm</th>
<th>150 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,000,000</td>
<td>0-1%</td>
<td>2-4%</td>
<td>2-4%</td>
<td>+</td>
</tr>
<tr>
<td>1,500,000</td>
<td>1 2%</td>
<td>4 5%</td>
<td>2 4%</td>
<td>++</td>
</tr>
<tr>
<td>1,850,000</td>
<td>0-1%</td>
<td>1-2%</td>
<td>++</td>
<td>++</td>
</tr>
</tbody>
</table>

Other types of designs for riblets include blade designs and scalloped designs, as seen in Figure 3 and Figure 4 respectively. The height to width ratios of these specific riblets tend to be around 0.5-0.7 and the scale from peak to peak is typically anywhere from 25.2-40.6 μm (Brian Dean)
Taking riblet technology a step further, biomimetic micro structures have been shown to have an upward lift effect on the velocity profile caused by the rugged air layer on the surface, indicating drag reduction (H. T. Jingxian Zhang). Importantly, it was discovered that micro clusters and nano particles were influencing the drag of the surface when measured with the PIV system. Other sources have described that the frictional forces could be reduced by as much as 7-10% in laboratory tests, and as much as 1-2% in actual flight testing. The actual flight testing was using riblet technology as opposed to biomimetic structures (PR).

Previously, it has been mentioned that there is a difference between riblet technology and biomimetic technology. Both technologies aim to reduce drag, but the main difference between the technologies is the inspiration. Riblet technology is essentially a raised, long, straight
structure, whereas biomimetic technology is an attempt to mimic the micro and macro structures that are seen on many different flora and fauna. The difference is most notable as seen in Figure 5. Riblet technology are essentially long channels, whereas biomimetic structures can have varying offsets, patterns, shapes, etc. Important to note that both riblet technology and biomimetic structures are both on the same geometric scale.

Another type of structure that is being explored is that of bird feathers. Feathered structures have long since been of interest, due to the nature of flight. Birds and bird wings have long since eluded great thinkers, such as Leonardo Da Vinci. In the modern world, humans have the capabilities to study bird feathers and replicate the structures to a higher degree of accuracy,
specifically recreating structures on the scale of less than a millimeter. This is seen in Figure 6 and Figure 7.

Figure 6 - Scanning electron microscope of bird feather.

Figure 7 - Scanning electron microscope of bird feather.

It is also important to understand how the biomimetic structures and riblet technology work at a fundamental level. It has been demonstrated that micro structures, specifically those in sharks, have been shown to impede the cross-stream translation of the stream wise vortices in the viscous sub layer of the boundary layer, and elevate the high-velocity vortices above the surface, reducing the shear stress and momentum transfer (Becheret D W). Biomimetic structures are
inherently more difficult to produce than riblet structures because biomimetic structures may have less space between them, more complex designs, and designs that follow less of a pattern than riblet structures. An example of this can be seen by a scanning electron microscope image of shark skin, as seen in Figure 8. The green bar in the figure is scaled to 50 μm.

![Scanning electron microscope image of shark skin](image.png)

**Figure 8 -** Scanning electron microscope image of shark skin (Arpith Siddaiah).

While structures such as those found in shark skin may be difficult to replicate, there are simplified models that can be created to test the efficacy of certain biomimetic structures. For example, it is possible to test a grid pattern for the drag reduction capabilities by creating a grid model, such as the one seen in Figure 9. This is a relatively simplified model with micro bumps that are of equal spacing and diameter.
Figure 9 - Grid pattern micro bumps with equal spacing and diameter (Jia Ou).

With a grid pattern that is easier to replicate, variables such as the spacing and diameter of the micro bumps can be altered, as well as the offset between the rows and columns. Models such as these may be able to accurately replicate more advanced structures without the extreme geometric complexity; like the structures found on bird feathers, shark skin, lotus leaves, etc. From this point, the drag of these structures can be determined using non-invasive imaging techniques, such as the one being used in this study.
Review of Particle Image Velocimetry Studies for Flat Plates

Particle Image Velocimetry (PIV) has been a relatively new method of non-invasive testing of fluids and fluid visualization. The basis for how the technology works is further discussed in the Data Acquisition section. According to similar testing using PIV, the accuracy of the flow fields that are generated is acceptable and has been verified by earlier studies (H. T. Jingxian Zhang) (RJ) (Elsinga GE) (Genapathisubramani B) (Westerweel J).

Due to the nature of the PIV system, there are non-physical artifacts that will start to appear at the wall. This is to be expected due to the nature of the laser system. The laser will reflect light, and as such, potentially skew the data points that are immediately touching the wall. This is due to how the cross-correlation algorithm that the software uses is implemented.

To explain cross-correlation, it is first necessary to explain the PIV system that is used. The specific setup that is used in this study is discussed in more detail in the experimental setup section. This description is a general description in order to properly illustrate the method in which a PIV system is setup and used.

Initially, wind tunnel has flow moving through it that has been seeded with particles, which have been created through an atomizing process, of the appropriate size. Commonly used seed particles are that of the scale ~1-10 micron. Two images need to be taken in rapid succession as the flow moves through the cross section of the wind tunnel. To accomplish this, a planar light sheet is created using a laser source, and is shone through the cross section of the wind tunnel, illuminating the seed particles during the process. At this point, a camera trigger is created, taking an instantaneous snapshot of the flow using a CCD camera equipped a band-pass filter that only allows the specific wavelength of light, (i.e. the specific wavelength of the laser
illumination system) to pass through the filter. A differential amount of time, called a $dt$, is passed, and another planar light sheet and instantaneous snapshot is taken and stored on the computer. Once the images have been captured, the images are turned to black and white, and only the objects illuminated by the laser, ideally the seed particles, should be seen. Next, an interrogation window is formed of size $n \times n$. When looking at the same interrogation window at the same spatial location in two different images, it is possible to see a particle shift, as demonstrated in Figure 10. A statistical correlation can be created by looking at the sum of all possible $\Delta x$ and $\Delta y$ changes from within the window, and the highest sum is the most likely possibility for the average motion of the particles in the interrogation window. A 3D plot of what the most likely sum may look like is shown in Figure 11. Incorrect processes from interrogation windows can generate noise in the image, but overall the true displacement will dominate.

![Figure 10 - Shift in particles in two different interrogation windows at the same spatial location (Kiger).](image10)

![Figure 11 - Sum of the most likely change in x and y directions (Kiger).](image11)
Given that boundary layers should have a smooth transition to a speed of 0 m/s, then it is reasonable that the slope of the boundary layer, $du/dy$ should be the same at the wall as it will be a few data points above the wall. Therefore, in cases where there is distortion near the wall, it should be acceptable to take the slope of the curve just a few data points above the wall. To prove the non-physicality of these artifacts, the shape factor is taken into account. The shape factor, as given by

$$H = \frac{\delta^*}{\Theta} \quad \text{Eq. 4}$$

where $\delta^*$ is the Displacement Thickness, and is given by

$$\delta^* = \int_0^\infty (1 - \frac{u}{U}) \, dy \quad \text{Eq. 5}$$

and where $\Theta$ is the Momentum Thickness, and is given by

$$\Theta = \int_0^\infty \frac{u}{U} \left(1 - \frac{u}{U}\right) \, dy \quad \text{Eq. 6}$$

where $u$ is the velocity at a location, and $U$ is the free stream velocity.

The physical meaning of the displacement thickness is the distance the outer inviscid flow is pushed away from the wall by the retarded viscous layer. This essentially modifies that shape of the body that is immersed in the fluid. The physical meaning of the momentum thickness is the distance the outer inviscid flow is pushed away from the wall to account for the reduction in momentum. The shape factor is the ratio of the displacement thickness to the momentum thickness, and is used to describe the nature of the flow. The higher the value of $H$, the stronger
the adverse pressure gradient is, which reduces the Reynolds number at which transition to turbulence, and eventually separated flow, may occur.

According to Thwaite's Method (White), separated flow is anything larger than approximately $H = 3.55$ for laminar flow, and $H = 3.0$ for turbulent flow. Therefore, if a test has flow that isn't smoothly transitioning to the no-slip boundary condition right at the wall, it should be appropriate to use data points that are directly above it, so long as the shape factor is less than 3.55 for laminar flow and 3.0 for turbulent flow.

Therefore, the shape factor is a metric that can be used for analysis. If a specific test result has a shape factor that is greater than Thwaite's criterion for separation, then it is possible that the flow has separated.
Active Control Methods Review

Drag reduction can also be achieved through active methods of flow control, such as dynamic roughness (DR), vibrations, and dielectric barrier discharge (DBD). Often the main goal of active control is to eliminate or prevent flow separation or recirculation bubbles. A diagram of potential flow separation at the leading edge can be seen in Figure 12.

Flow separation occurs after a fluid has been travelling against an adverse pressure gradient for a period of time. An adverse pressure gradient is one in which

\[
\frac{dP}{dx} > 0 \quad \text{Eq 7}
\]
This is explained by the increasing pressure differential as the flow moves in the x direction, leading to a decrease in the fluid velocity in the boundary layer. As the fluid velocity in the boundary layer decreases, it may eventually cease to move or even reverse in direction. If the fluid has become reversed, a recirculation bubble tends to form, which can be seen in Figure 12. A note of importance is that there may be secondary or tertiary recirculation regions within a single recirculation bubble. However if the fluid velocity has slowed down to zero velocity without recirculation, then it is more likely that the flow has separated from the surface and instead can be noted by eddies or vortices in the region.

Dielectric barrier discharge (DBD) is a method of flow control that consists of using plasma for flow reattachment or the prevention of flow separation. It moves away from the traditional mechanical flow control devices, such as flaps, slats, and slots, to plasma actuators. This method uses electrodes to generate plasma over the surface of the wing in a steady mode, or a pulsed mode. A diagram of a typical set of electrodes for DBD is shown in Figure 13.

![Figure 13 - Schematic view of a dielectric barrier discharge plasma actuator (Jonna Tiainen).](image)

A completed aerodynamic body that is equipped with DBD actuators would have a high voltage electrode, a dielectric barrier, and a grounded electrode attached to the surface of an aerodynamic body in a location that would be near the predicted location of where flow separation may occur. For example, a NACA 0012 would have a DBD actuator near the leading edge as shown in
Dynamic roughness is the conceptual idea of being able to manipulate the surface of a body to produce varied amplitudes with varying frequencies in order to control the flow and prevent separation or to encourage reattachment of separated flow. Dynamic roughness is achieved by many different methods, one of which may be to put tiny holes in the structure of an aerodynamic body that allow for a pressurized chamber to be created. A skin would be stretched tightly over the surface of the body and when the pressurized chamber is filled, the surface of the body would experience small fluctuations. An example of an aerodynamic body with small holes in the structure is as seen in Figure 15. The span of the dynamic roughness section is 2 inches, approximately half of the chord length, in the aforementioned figure. The surface was then covered in a thin layer of latex, and the chamber was pressurized. Aerodynamic testing in a wind tunnel showed that dynamic roughness was an effective means to reattach flow to the surface with Reynolds numbers $O(10^4) - O(10^5)$ (Jakkali).
Therefore, periodic forcing as a method of flow control to prevent separation has been shown to be effective in Reynolds numbers $O(10^4)$ using both dynamic roughness methods and DBD actuators.
Experimental Setup

The work that was to be tested was the efficacy of biomimetic structures on surface treatments that were adhered to flat plates made of glass. Reynolds number was varied, along with the laminar screens and the turbulator on the smoke tunnel. The tested skin treatments, Reynolds numbers, flow settings, and frequencies tested are as seen in Table 2.

<table>
<thead>
<tr>
<th>Surface Treatments</th>
<th>Reynolds number</th>
<th>Flow Settings</th>
<th>Frequencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass Smooth Treatment</td>
<td>26,500</td>
<td>Laminar</td>
<td>0 Hz</td>
</tr>
<tr>
<td>Feather Treatment - Parallel to Centerline</td>
<td>52,600</td>
<td>Laminar</td>
<td></td>
</tr>
<tr>
<td>Feather Treatment - Random 90° Offsets</td>
<td>52,600</td>
<td>Laminar</td>
<td></td>
</tr>
<tr>
<td>Feather Treatment - Perpendicular to Centerline</td>
<td>68,600</td>
<td>Turbulent</td>
<td>641 Hz</td>
</tr>
<tr>
<td>Millimeter Bump Pattern Treatment</td>
<td>78,800</td>
<td>Turbulent</td>
<td></td>
</tr>
<tr>
<td>Micro Surface Treatment Pattern #1</td>
<td>78,800</td>
<td>Turbulent</td>
<td></td>
</tr>
<tr>
<td>Micro Surface Treatment Pattern #2</td>
<td>78,800</td>
<td>Turbulent</td>
<td></td>
</tr>
</tbody>
</table>

The mechanism for creating the vibration was a small electric motor with an offset weight attached to the shaft, as seen in Figure 17. When powered, the motor would vibrate at 641 Hz.
and at an amplitude of less than 8 micrometers, as shown in Appendix E. This was determined by using Wenglor OPT2001 photoelectric laser sensor, which has a maximum resolution of 8 micrometers. The total blockage for the setup in the smoke tunnel is 4.1%, and is calculated in the appendix.

A test matrix demonstrating the different combinations of surface treatments, Reynolds numbers, turbulence, and active flow control parameters is shown in Table 3

Table 3 - Experimental Test Matrix

<table>
<thead>
<tr>
<th>Tests</th>
<th>Treatment</th>
<th>Speeds [m/s]</th>
<th>Flow Type</th>
<th>Flow Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-4</td>
<td>Glass</td>
<td>3, 8, 12, 15</td>
<td>Laminar</td>
<td>Passive</td>
</tr>
<tr>
<td>5-8</td>
<td></td>
<td></td>
<td></td>
<td>Active</td>
</tr>
<tr>
<td>9-12</td>
<td></td>
<td></td>
<td></td>
<td>Passive</td>
</tr>
<tr>
<td>13-16</td>
<td></td>
<td></td>
<td></td>
<td>Active</td>
</tr>
<tr>
<td>17-20</td>
<td>Smooth</td>
<td>3, 8, 12, 15</td>
<td>Laminar</td>
<td>Passive</td>
</tr>
<tr>
<td>21-24</td>
<td></td>
<td></td>
<td></td>
<td>Active</td>
</tr>
<tr>
<td>25-28</td>
<td></td>
<td></td>
<td></td>
<td>Passive</td>
</tr>
<tr>
<td>29-32</td>
<td></td>
<td></td>
<td></td>
<td>Active</td>
</tr>
<tr>
<td>33-36</td>
<td>Feather - Parallel</td>
<td>3, 8, 12, 15</td>
<td>Laminar</td>
<td>Passive</td>
</tr>
<tr>
<td>37-40</td>
<td></td>
<td></td>
<td></td>
<td>Active</td>
</tr>
<tr>
<td>41-44</td>
<td>Feather - Random</td>
<td>3, 8, 12, 15</td>
<td>Laminar</td>
<td>Passive</td>
</tr>
<tr>
<td>45-48</td>
<td></td>
<td></td>
<td></td>
<td>Active</td>
</tr>
<tr>
<td>49-52</td>
<td>Feather - 90° Rotation</td>
<td>3, 8, 12, 15</td>
<td>Laminar</td>
<td>Passive</td>
</tr>
<tr>
<td>53-56</td>
<td></td>
<td></td>
<td></td>
<td>Active</td>
</tr>
<tr>
<td>57-60</td>
<td></td>
<td></td>
<td></td>
<td>Passive</td>
</tr>
<tr>
<td>61-64</td>
<td></td>
<td></td>
<td></td>
<td>Active</td>
</tr>
<tr>
<td>65-68</td>
<td>Bump Pattern</td>
<td>3, 8, 12, 15</td>
<td>Laminar</td>
<td>Passive</td>
</tr>
<tr>
<td>69-72</td>
<td></td>
<td></td>
<td></td>
<td>Active</td>
</tr>
<tr>
<td>73-76</td>
<td></td>
<td></td>
<td></td>
<td>Passive</td>
</tr>
<tr>
<td>77-80</td>
<td></td>
<td></td>
<td></td>
<td>Active</td>
</tr>
<tr>
<td>81-84</td>
<td>Micro</td>
<td>3, 8, 12, 15</td>
<td>Laminar</td>
<td>Passive</td>
</tr>
<tr>
<td>85-88</td>
<td></td>
<td></td>
<td></td>
<td>Active</td>
</tr>
<tr>
<td>89-92</td>
<td></td>
<td></td>
<td></td>
<td>Passive</td>
</tr>
<tr>
<td>93-96</td>
<td></td>
<td></td>
<td></td>
<td>Active</td>
</tr>
<tr>
<td>97-100</td>
<td>Micro</td>
<td>3, 8, 12, 15</td>
<td>Laminar</td>
<td>Passive</td>
</tr>
<tr>
<td>101-104</td>
<td>Micro</td>
<td></td>
<td></td>
<td>Active</td>
</tr>
</tbody>
</table>
The experimental setup was performed at WVU's wind tunnel test facility using the WVU low-turbulence flow visualization smoke wind tunnel as seen in Figure 16. An electric motor, as seen in Figure 17, is connected to a power supply. The leading edge was created in CAD, and is as seen in Figure 18, printed on an SLA printer. The assembly of the glass plate and the leading edge can be seen in Figure 19. The PIV setup included a nanoPIV laser as seen in Figure 20, and a CCD camera with a 532 nm band-pass lens on it. Lastly, there were two sets of screens that were used. The first set of screens was attached to the wind tunnel, and produced a laminar flow by having a set of 8 screens that have a mesh size that decreases each stage. Secondly, there is another screen called a turbulator, and it is duct strap that is twisted along its axis and secured to the other side. The purpose of this is to make the flow turbulent before it even reaches the test section. This is seen in Figure 21. Lastly, the schematic of the entire setup of the test section can be seen in Figure 22. The green sheet is the laser sheet, and the red area on that sheet is the test section. The treatment can also be seen on the glass plate.
Figure 16 - West Virginia University's smoke wind tunnel.

Figure 17 - Electric motor with offset weight.
Figure 18 - 17° leading edge for flat plate.

Figure 19 - Assembly of the glass plate and leading edge.
Figure 20 - NanoPIV laser.

Figure 21 - turbulator to create turbulent flow.
Figure 22 - Schematic of setup.
Design of Leading Edge

The leading edge was designed according to the NASA paper on *Extension of Leading-Edge-Suction Analogy To Wings With Separated Flow Around the Side Edges At Subsonic Speeds* (Lamar), and *Observations On Low Aspect Ratio Wings At High Incidence* (Dr. G. V. Parkinson), and there were models tested at 0° angle of attack that were low aspect ratio thin wings that can be viewed as flat plates, and as such, all of the leading edge geometries tested had an angle of the leading edge between 14° and 20°. Using this information, a leading edge was designed to fit within those parameters. As seen previously in Figure 18, a design was created that would fit within the parameters previously tested, and an angle of 17° was chosen. The design was then printed out in West Virginia University's Maker Lab that used an SLA printer. Lastly, for testing, the Leading edge was applied to the thin plate of glass and secured using a piece of Scotch Tape. Scotch tape is acceptable according to Section 5.3 - Surface Flow Visualization in *Low-Speed Wind Tunnel Testing* (Jewel B Barlow).
Design of Patterned Skins

The design of the patterned skins was carried out at West Virginia University by Dr. Edward Sabolsky, and carried out by Allison Arnold. The molds were created using a High Density Poly Ethylene (HDPE) material and laser engraving. There were a total of seven patterned macro and micro structures to be tested, and each set of tests is called a treatment. The treatments were created using the molds, and then applied to the surface of a glass plate. The glass plate with the Smooth treatment is shown in Figure 23. All treatments follow the same shape and orientation of that seen in Figure 23. Due to the nature of the micro structures, it is difficult to see the orientation and the placement on the glass plate at the same time. However, all of the treatments were placed in the same area on the glass plates. In order to see the orientation of the treatments, there was a zoomed in image that was taken of each treatment. The first treatment that was used was the feather - parallel treatment. This treatment is replicated using patterns found in bird feathers, and can be seen in Figure 24. The next treatment used was the feather- random orientation. Each square of the treatment was given an arbitrary orientation that was not in line with the square that was before it, and can be seen in Figure 25. The next treatment used was the feather - rotated treatment, where each square was rotated 90° in the same direction. The orientation of this treatment can be seen in Figure 26. The next treatment that was tested was the bump pattern. The orientation of the squares can be seen in Figure 27. The last two treatments that were tested were micro pattern #1 and micro pattern #2. The orientation of the squares can be seen in Figure 28 and in Figure 29 respectively. The general process for the mold development is as follows: Develop Macro pattern design, develop macro pattern mold using HDPE, cast into molds using
Sylgard-170, perform wind tunnel testing. At this point, the results are taken into consideration, if the results are promising, micro-patterned molds are created using photolithography techniques. This is primarily done with the SU-8 photoresist. SU-8 is commonly used as a negative photoresist, meaning that the part of the solution that becomes exposed to UV becomes cross-linked, while the remainder of the film remains soluble and can be washed away. At this point, with the negative mold created, the micro pattern can be cast using the Sylgard-170. The casts are created in circular wafers, and in order to have square sections that can be pieced together smoothly, a square needs to be cut out of the circle. At this point, a section of three squares can be adhered to the glass plate and cured. Further aerodynamic testing can be performed on the treatments, and improvements and further design iterations can be made.

![Figure 23 - Sylgard smooth treatment applied to one side of the glass plate.](image)
Figure 24 - Sylgard feather treatment, parallel to centerline.

Figure 25 - Sylgard feather treatment, random orientation.

Figure 26 - Sylgard feather treatment, rotated.
Figure 27 - Sylgard bump treatment.

Figure 28 - Sylgard micro pattern #1.

Figure 29 - Sylgard micro pattern #2.
The specific geometry of the structures varied in scale from macro structures to micro structures. For the control treatment, the Sylgard-170 was cast without a pattern at all. An image of the treatment from a digital microscope is seen in Figure 30. The bump pattern geometry is seen in Figure 31. The feather pattern was replicated for all of the feather pattern treatments, and the center stem (barb) had a height of 0.5mm, the side stem (barbule) had an average height of less than 0.1mm, and the barb width was 0.5mm. The geometry can be seen in Figure 32. Lastly, the micro pattern geometry had an average peak height of approximately 0.057mm, and the geometry can be seen in Figure 33.
Figure 30 - Sylgard - 170 with no pattern, image from digital microscope.

Figure 31 - Sylgard - 170 bump pattern geometry, captured with digital microscope.
Figure 32 - Sylgard - 170 feather pattern geometry, captured with digital microscope.

Figure 33 - Micro pattern geometry, captured with digital microscope.
Data Acquisition

The experimental setup used a flow visualization technique and image capturing device that would take 200 individual images, and perform an algorithmic approach based on the cross-correlation technique, that was discussed previously, on the images to extract the flow fields from the individual images, and then average the flow fields together to extract a time averaged, mean flow field from the data.

An important characteristic in determining the flow field from the images is the $dt$. This is the differential time between images. The proper $dt$ values were determined beforehand using the $dt$ optimizer tool found in the software package. There were four specific $dt$'s that were found, one for each Reynolds number that was tested.

The general process is as follows:

1. Turn on the PIV laser pump, laser, computer with the proper software.
2. Choose the proper set of screens for the experiment to be run.
3. The room was filled with DEHS, Di-Ethyl-Hexyl-Sebacic-Acid-Ester. This is called seeding the flow. The wind tunnel should be running at a low velocity in order to have mixing throughout the entire room.
4. Once the room is adequately seeded, turn off the wind tunnel and place the glass plate with the treatment to be tested in the cross section of the wind tunnel.
5. Turn the wind tunnel back on, open the software, and allow the laser to be in continuous capture mode, and adjust the focus on the camera until the particles that are being illuminated by the laser are in focus.
6. At this point, check to make sure that there are enough particles in the flow field, specifically in the boundary layer. Too many particles and the noise will cause issues generating a resolved flow field, and too few particles and the algorithm will not be able to generate an accurate flow field.

7. Make any final adjustments necessary, set the wind tunnel to the desired velocity to generate the proper Reynolds number, and capture 200 images.

8. Run the software tool to process the data
   a. Check for correlation in the flow.
   b. If no correlation found, make adjustments to either the focus of the camera, the particle density in the room, or the $dt$ value and run the test again and repeat until there is correlation in the flow field

9. Choose the next Reynolds number to test at, adjust the wind tunnel velocity, and run steps 5-8 again.

10. After all Reynolds numbers have been adequately tested for, engage the active control flow testing and repeat steps 5-8 for all Reynolds numbers again.

11. After all previous steps have been tested, change the screens to change between laminar and turbulent flow and repeat steps 5-10 again.

12. Once all tests for a specific treatment have been performed, change out the glass plate with the treatment on it and repeat steps 5-11.

13. After all tests have been performed, post processing was performed in Matlab.
Visualization Technique

Visualization of the flow field is broken down into 4 major steps. Seeding, illumination, image capture, flow field algorithm.

**Seeding:** Seeding was performed with Di-Ethyl-Hexyl-Sebacate (DEHS) droplets that are on the scale of ~1-10 micron. The droplets were atomized using a pressure driven atomizer manufactured by LaVision, Inc. The room was allowed to be filled with enough seed so that the laser would illuminate enough of the particles for a cross-correlation technique to work.

**Illumination:** The seed particles were illuminated by a 532nm laser. The output from the laser is a planar light sheet. The laser was pulsed at varying frequencies, corresponding to the respective Reynolds numbers. For this experiment, the $dt$ values were $34\mu s$, $12\mu s$, $10\mu s$, and $8\mu s$, corresponding to an average velocity of $3m/s$, $8m/s$, $12m/s$, $15m/s$.

**Image Capturing Device:** The camera that was used for image capturing was a Nikon CCD camera with a 60mm 2:1 super macro lens attached to a +10 diopter filter and a 532 nm bandpass filter. Using the DaVis software, the $dt$ optimizer tool setup the proper parameters in order to have a maximum pixel shift of 8 pixels per particle while in the boundary layer. From this point, the software will store 200 images that were taken with specific $dt$'s, and then perform a unique algorithm, based on the cross-correlation technique previously discussed, on the images. The algorithm essentially will create what is known as an interrogation window and look at a 48 pixel x 48 pixel square and perform a statistical method between the two images captured. As the algorithm moves along the images, it has a 50% overlap on the windows. This helps to make sure that the results are consistent. After it has processed the entire image with a 48 pixel x 48 pixel interrogation window, it will then perform two passes of decreasing size with an
interrogation window in the shape of a circle with a radius of 12 pixels. Although DaVis offers multiple other algorithms to attempt to create a smoother flow field, they were not used in order to not affect the results when separation occurred or when flow was close to the wall.
Experimental Testing

The experiments were performed in the smoke wind tunnel at WVU. The flow goes through a contraction until the flow is at the test section, as seen previously in Figure 16.

The test section of the wind tunnel has a 6 in x 6 in cross section and a length of 12 in. with transparent walls on three of the sides. As mentioned previously, the laminar screens were installed during half of the testing, and they are a set of screens with decreasing mesh size, followed by the contraction to help provide a uniform flow to the entrance of the test section.

The speeds for the wind tunnel were chosen based on the dial settings 2.5, 5.0, 7.5, 10.0, which correspond to average velocities of approximately 3 m/s, 8 m/s, 12 m/s, 15 m/s. These were chosen for the flow with laminar screens, and the pressure drop across the contraction area was recorded. This would be used later in order to determine the correct settings for the turbulent section, since there isn't as significant of a pressure drop across the contraction area with the turbulator on as when compared to the screens at the same dial settings. As such, the dial settings for the turbulent flow were found to be 1.8, 3.6, 5.5, 7.0, corresponding to average velocities of approximately 3 m/s, 8 m/s, 12 m/s, 15 m/s. These dial settings were chosen to match velocities in the test section, which would in turn match the Reynolds number during testing in order to have comparable results.

Once the images were captured using the PIV system, the DaVis software was run, as previously mentioned. The output of the software is a vector field that uses the PIV method that was previously described. A sample of an output vector field may be seen Figure 34. This vector field is highly unreadable and it is difficult to make out what is happening. In order to fix this, it was
reprocessed with only one out of every eight vector points sampled, that way the boundary layers can be seen. This is seen in Figure 34 and is only for illustration purposes.

The general idea behind processing the boundary layers is to write a code that will look at the data that is seen in Figure 35 from right to left, and start at the bottom of the images and collect the data points from the bottom to the top. Once the data points have been collected, a new graph can be created using the boundary layer velocity profiles that will show the velocity and the spatial distance in the y-direction, as can be seen in Figure 36. This graph demonstrates the velocity profiles of the individual boundary layers that were collected, and then the boundary layers were overlaid into one image.

Lastly, in looking at Figure 36, it is possible to see that the data nearest the wall is non-physical, and this is most likely due to the scattering of light nearest the surface itself. In order to account for this, since the slope of the boundary layer slightly above the points nearest the wall is smooth, the slope is taken from that location. The $\Delta y$ that was chosen was 0.03mm, and since this change is so small, it should be acceptable to take the slope at this location, as opposed to at the wall.
Figure 34 - Example of vector field.
Figure 35 - Vector field showing only one out of eight vectors.

Figure 36 - Example of overlaid boundary layers.
Results and Discussion

The results will be broken into sections based on Reynolds number. Tests with similar Reynolds number will be grouped together, including both passive and active, but will be discussed separately. The sections will be Reynolds numbers 26500, 52600, 68600, and 78800. The images displayed consist of overlaid boundary layer profiles versus the appropriate analytical solution. For example, if the flow parameters were for laminar screened flow, a Blasius solution will be displayed. If the flow parameters were for turbulent screened flow, then Prandtl's one-seventh power law solution will be displayed. All analytical solutions provided will show an average boundary layer profile with a thick dashed black line. Important to note that the PIV boundary layer images may not completely follow the analytical solutions, and it is important to remember that the bottom of the boundary layer was setup in the software to have an 8 pixel shift per particle in the software. This was chosen to have the maximum likelihood of having a flow field correlate to a solution within a boundary layer. As the boundary layer moves in the positive \( y \) direction, the solution may start to experience non-correlation, but this is to be expected. Lastly, the shape factor was taken into consideration for certain flow fields, especially at the wall. The shape factor is derived from Thwaite's method, but this has historically been for smooth flat surfaces. With the application of the treatments that have micro and macro structures, the flat plate is no longer smooth. As such, the shape factor cannot be the final and only criteria to consider. Looking at the individual images, the boundary layer growth rates are also taken into consideration visually. Boundary layers that have strong correlation in the boundary layer and very minimal growth rates with a shape factor less than Thwaite's criterion can be considered attached. If the boundary layers have correlated, yet spread apart drastically, and the shape factor is greater than Thwaite's criterion, the flow can be considered separated.
Lastly, the first and last boundary layer velocity profiles will be slightly thicker, and the first boundary layer, the boundary layer at the inlet, will be red and the last boundary layer, the one at the outlet, will be black. The multi colored boundary layer profiles are there to demonstrate the boundary layer growth. If they were a static color, it is possible to miss out on how the boundary layers may be growing.

Viscous drag is a vector, as such, vectors indicate direction as well as magnitude. The boundary layer profiles appear to be backwards from traditional analytical solutions, but this is because the velocity is to the left. Since velocity is a vector that is in the negative x-direction, therefore the individual shear stresses are also negative. The integration of these shear stresses will generate a negative value for drag, indicative of the direction, which is to the left. There is no claim that the magnitude of the viscous drag values are negative, but the direction of the values is to the left. Also, since this method involves a numerical integration, if the flow has separated, the spatial derivative of the velocity may indicate there are non-physical values for the viscous drag, however, there is no claim being made that there is drag with a magnitude less than zero.

Lastly, the results section will be reporting the notable results, namely those in which there was a change in drag, whether an increase or a decrease, from the smooth treatment as a baseline. Only results in which the flow is attached will be mentioned in any detail in this section, separated flows will not be mentioned in this section. There will be a separate section after the results in which the results will be discussed.
Reynolds Number 26500 Laminar Screen, Passive Flow Control

For the tests that were preformed under these conditions, the results are shown in Table 4. The following boundary layer profiles are overlaid and displayed against the Blasius solution because the laminar screens were on the wind tunnel.

The smooth treatment had a local skin friction coefficient of -0.0122, which is considered the baseline for all other skin friction coefficients. This is because the smooth treatment is the treatment with no micro or macro structures on it. As such, all further treatments are compared to this. The overlaid boundary layer graph can be seen below in Figure 37. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The feather - random treatment has a skin friction coefficient of -0.0121, which is very similar to that of the smooth treatment, yet is still a reduction in drag, as also seen when directly comparing the drag values. The reduction in drag is approximately 0.82%. The overlaid boundary layer graph can be seen below in Figure 38. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The last treatment to show a reduction in drag was the micro pattern #1. The skin friction coefficient was -0.0030, and the respective reduction in drag was 75.06%. The overlaid boundary layer graph can be seen below in Figure 39. Given the strong convergence of the boundary layers near the wall, as well as the shape factor being below Thwaite's criterion for separated flow, it is indicative that the flow is locally attached.
<table>
<thead>
<tr>
<th>Test ID</th>
<th>Skin Type</th>
<th>Flow Type</th>
<th>Flow Parameters</th>
<th>Drag [mN/m]</th>
<th>Shape Factor</th>
<th>Separation Predicted</th>
<th>Cf</th>
<th>ΔCf</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>173754</td>
<td>Glass</td>
<td>Laminar Screens</td>
<td>Passive</td>
<td>-0.438</td>
<td>1.63</td>
<td>Attached</td>
<td>-0.0108</td>
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<td></td>
</tr>
<tr>
<td>160749</td>
<td>Smooth</td>
<td>Laminar Screens</td>
<td>Passive</td>
<td>-0.492</td>
<td>1.78</td>
<td>Attached</td>
<td>-0.0122</td>
<td></td>
<td></td>
</tr>
<tr>
<td>232737</td>
<td>Feather</td>
<td>Laminar Screens</td>
<td>Passive</td>
<td>-0.433</td>
<td>4.11</td>
<td>Separated</td>
<td>-0.0107</td>
<td>0.0015</td>
<td></td>
</tr>
<tr>
<td>134431</td>
<td>Feather</td>
<td>Laminar Screens</td>
<td>Passive</td>
<td>-0.488</td>
<td>1.83</td>
<td>Attached</td>
<td>-0.0121</td>
<td>0.0001</td>
<td>0.82</td>
</tr>
<tr>
<td>180059</td>
<td>Feather</td>
<td>Laminar Screens</td>
<td>Passive</td>
<td>-0.109</td>
<td>2.71</td>
<td>Separated</td>
<td>-0.0027</td>
<td>0.0095</td>
<td></td>
</tr>
<tr>
<td>201321</td>
<td>Bump</td>
<td>Laminar Screens</td>
<td>Passive</td>
<td>0.019</td>
<td>5.56</td>
<td>Separated</td>
<td>0.0005</td>
<td>0.0126</td>
<td></td>
</tr>
<tr>
<td>234719</td>
<td>Micro</td>
<td>Laminar Screens</td>
<td>Passive</td>
<td>-0.123</td>
<td>2.97</td>
<td>Attached</td>
<td>-0.0030</td>
<td>0.0091</td>
<td>75.06</td>
</tr>
<tr>
<td>005319</td>
<td>Micro</td>
<td>Laminar Screens</td>
<td>Passive</td>
<td>0.022</td>
<td>7.56</td>
<td>Separated</td>
<td>0.0005</td>
<td>0.0127</td>
<td></td>
</tr>
</tbody>
</table>

Table 4 - Test results for laminar screen testing at Reynolds number 26500, passive flow control
Figure 37 - Overlaid boundary layer profiles for smooth treatment.

Figure 38 - Overlaid boundary layer profiles for feather - random treatment.
Figure 39 - Overlaid boundary layer profiles for micro pattern #1.
Reynolds Number 26500 Laminar Screen, Active Flow Control

For the tests that were performed under these conditions, the results are shown in Table 5. The following boundary layer profiles are overlaid and displayed against the Blasius solution because the laminar screens were on the wind tunnel.

The smooth treatment had a local skin friction coefficient of -0.0122, which is considered the baseline for all other skin friction coefficients. This is because the smooth treatment is the treatment with no micro or macro structures on it. As such, all further treatments are compared to this. The overlaid boundary layer graph can be seen below in Figure 40. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The feather-parallel treatment has a skin friction coefficient of -0.0117, which is very similar to that of the smooth treatment, and yet is still a reduction in drag, as also seen when directly comparing the drag values. The reduction in drag is approximately 4.74%. The overlaid boundary layer graph can be seen below in Figure 41. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.
Table 5 - Test results for laminar screen testing at Reynolds number 26500, active flow control

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Skin Type</th>
<th>Flow Type</th>
<th>Flow Parameters</th>
<th>Drag [mN/m]</th>
<th>Shape Factor</th>
<th>Separation Predicted</th>
<th>Cf</th>
<th>ΔCf</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>191150</td>
<td>Glass</td>
<td>Laminar Screens</td>
<td>Active</td>
<td>-0.220</td>
<td>2.52</td>
<td>Attached</td>
<td>-0.0054</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>173056</td>
<td>Smooth</td>
<td>Laminar Screens</td>
<td>Active</td>
<td>-0.497</td>
<td>2.58</td>
<td>Attached</td>
<td>-0.0123</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>001356</td>
<td>Feather - Parallel</td>
<td>Laminar Screens</td>
<td>Active</td>
<td>-0.474</td>
<td>2.40</td>
<td>Attached</td>
<td>-0.0117</td>
<td>0.0006</td>
<td>4.74</td>
</tr>
<tr>
<td>152114</td>
<td>Feather - Random</td>
<td>Laminar Screens</td>
<td>Active</td>
<td>-0.279</td>
<td>3.75</td>
<td>Separated</td>
<td>-0.0069</td>
<td>0.0054</td>
<td>-</td>
</tr>
<tr>
<td>181830</td>
<td>Feather - Rotated</td>
<td>Laminar Screens</td>
<td>Active</td>
<td>0.049</td>
<td>4.09</td>
<td>Separated</td>
<td>0.0012</td>
<td>0.0135</td>
<td>-</td>
</tr>
<tr>
<td>202809</td>
<td>Bump Pattern</td>
<td>Laminar Screens</td>
<td>Active</td>
<td>0.027</td>
<td>7.67</td>
<td>Separated</td>
<td>0.0007</td>
<td>0.0130</td>
<td>-</td>
</tr>
<tr>
<td>000221</td>
<td>Micro Pattern 1</td>
<td>Laminar Screens</td>
<td>Active</td>
<td>0.047</td>
<td>5.61</td>
<td>Separated</td>
<td>0.0012</td>
<td>0.0134</td>
<td>-</td>
</tr>
<tr>
<td>010707</td>
<td>Micro Pattern 2</td>
<td>Laminar Screens</td>
<td>Active</td>
<td>0.082</td>
<td>7.58</td>
<td>Separated</td>
<td>0.0020</td>
<td>0.0143</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 40 - Overlaid boundary layer profiles for smooth treatment.

Figure 41 - Overlaid boundary layer profiles for feather - parallel treatment.
Reynolds Number 26500 Turbulent Screen, Passive Flow Control

For the tests that were performed under these conditions, the results are shown in Table 6. The following boundary layer profiles are overlaid and displayed against the Prandtl solution because the turbulent screens were on the wind tunnel.

The smooth treatment had a local skin friction coefficient of -0.0140, which is considered the baseline for all other skin friction coefficients. This is because the smooth treatment is the treatment with no micro or macro structures on it. As such, all further treatments are compared to this. The overlaid boundary layer graph can be seen below in Figure 42. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The feather - parallel treatment has a skin friction coefficient of -0.0159, which is very similar to that of the smooth treatment, but is an increase in drag, as also seen when directly comparing the drag values. The reduction in drag is approximately -13.04%, which indicates that the drag has increased. The overlaid boundary layer graph can be seen below in Figure 43. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The micro pattern #2 treatment has a skin friction coefficient of -0.0064, which is less than that of the smooth treatment, and yet is still a reduction in drag, as also seen when directly comparing the drag values. The reduction in drag is approximately 54.29%. The overlaid boundary layer graph can be seen below in Figure 44. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.
Table 6 - Test results for turbulent screen testing at Reynolds number 26500, passive flow control

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Skin Type</th>
<th>Flow Type</th>
<th>Flow Parameters</th>
<th>Drag [mN/m]</th>
<th>Shape Factor</th>
<th>Separation Predicted</th>
<th>Cf</th>
<th>ΔCf%</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>164310</td>
<td>Glass</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>-0.491</td>
<td>1.78</td>
<td>Attached</td>
<td>-0.0121</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>144437</td>
<td>Smooth</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>-0.568</td>
<td>1.97</td>
<td>Attached</td>
<td>-0.0140</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>181750</td>
<td>Feather - Parallel</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>-0.643</td>
<td>1.84</td>
<td>Attached</td>
<td>-0.0159</td>
<td>-0.0018</td>
<td>-13.04</td>
</tr>
<tr>
<td>154706</td>
<td>Feather - Random</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>-0.300</td>
<td>5.42</td>
<td>Separated</td>
<td>-0.0074</td>
<td>0.0066</td>
<td>-</td>
</tr>
<tr>
<td>170238</td>
<td>Feather - Rotated</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>-0.020</td>
<td>3.06</td>
<td>Separated</td>
<td>-0.0005</td>
<td>0.0135</td>
<td>-</td>
</tr>
<tr>
<td>211442</td>
<td>Bump Pattern</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>0.025</td>
<td>7.67</td>
<td>Separated</td>
<td>0.0006</td>
<td>0.0147</td>
<td>-</td>
</tr>
<tr>
<td>223002</td>
<td>Micro Pattern 1</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>-0.063</td>
<td>3.53</td>
<td>Separated</td>
<td>-0.0016</td>
<td>0.0125</td>
<td>-</td>
</tr>
<tr>
<td>013749</td>
<td>Micro Pattern 2</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>-0.260</td>
<td>3.08</td>
<td>Attached</td>
<td>-0.0064</td>
<td>0.0076</td>
<td>54.29</td>
</tr>
</tbody>
</table>

Figure 42 - Overlaid boundary layer profiles for smooth treatment.
Figure 43 - Overlaid boundary layer profiles for feather - parallel treatment.

Figure 44 - Overlaid boundary layer profiles for micro pattern #2 treatment.
Reynolds Number 26500 Turbulent Screen, Active Flow Control

For the tests that were preformed under these conditions, the results are shown in Table 7. The following boundary layer profiles are overlaid and displayed against the Prandtl solution because the turbulent screens were on the wind tunnel.

The smooth treatment had a local skin friction coefficient of -0.0133, which is considered the baseline for all other skin friction coefficients. This is because the smooth treatment is the treatment with no micro or macro structures on it. As such, all further treatments are compared to this. The overlaid boundary layer graph can be seen below in Figure 45. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The feather-parallel treatment has a skin friction coefficient of -0.0161, but is an increase in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately -21.23%, which indicates that the drag has increased. The overlaid boundary layer graph can be seen below in Figure 46. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The feather-random treatment has a skin friction coefficient of -0.0111, which is very similar to that of the smooth treatment, but is an increase in drag, as also seen when directly comparing the drag values. The reduction in drag is approximately 16.63%. The overlaid boundary layer graph can be seen below in Figure 47. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.
The micro pattern #2 treatment has a skin friction coefficient of -0.0059, which is very similar to that of the smooth treatment, but is an increase in drag, as also seen when directly comparing the drag values. The reduction in drag is approximately 55.93%. The overlaid boundary layer graph can be seen below in Figure 48. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

Table 7- Test results for turbulent screen testing at Reynolds number 26500, active flow control

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Skin Type</th>
<th>Flow Type</th>
<th>Flow Parameters</th>
<th>Drag [mN/m]</th>
<th>Shape Factor</th>
<th>Separation Predicted</th>
<th>Cf</th>
<th>ΔCf</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Glass</td>
<td>Turbulent Screen</td>
<td>Active</td>
<td>-0.475</td>
<td>1.85</td>
<td>Attached</td>
<td>-0.0117</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>133036</td>
<td>Smooth</td>
<td>Turbulent Screen</td>
<td>Active</td>
<td>-0.539</td>
<td>2.11</td>
<td>Attached</td>
<td>-0.0133</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>224627</td>
<td>Feather - Parallel</td>
<td>Turbulent Screen</td>
<td>Active</td>
<td>-0.654</td>
<td>2.83</td>
<td>Attached</td>
<td>-0.0161</td>
<td>-0.0028</td>
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<tr>
<td>161656</td>
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<td>Active</td>
<td>-0.450</td>
<td>2.24</td>
<td>Attached</td>
<td>-0.0111</td>
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<td>230823</td>
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<td>Turbulent Screen</td>
<td>Active</td>
<td>-0.032</td>
<td>3.85</td>
<td>Separated</td>
<td>-0.0008</td>
<td>0.0125</td>
<td>-</td>
</tr>
<tr>
<td>022725</td>
<td>Micro Pattern 2</td>
<td>Turbulent Screen</td>
<td>Active</td>
<td>-0.238</td>
<td>2.40</td>
<td>Attached</td>
<td>-0.0059</td>
<td>0.0074</td>
<td>55.93</td>
</tr>
</tbody>
</table>
Figure 45- Overlaid boundary layer profiles for smooth treatment.

Figure 46- Overlaid boundary layer profiles for feather-parallel treatment.
Figure 47- Overlaid boundary layer profiles for feather - random treatment.

Figure 48- Overlaid boundary layer profiles for micro pattern #2 treatment.
Reynolds Number 52600 Laminar Screen, Passive Flow Control

For the tests that were performed under these conditions, the results are shown in Table 8. The following boundary layer profiles are overlaid and displayed against the Blasius solution because the laminar screens were on the wind tunnel.

The smooth treatment had a local skin friction coefficient of -0.0064, which is considered the baseline for all other skin friction coefficients. This is because the smooth treatment is the treatment with no micro or macro structures on it. As such, all further treatments are compared to this. The overlaid boundary layer graph can be seen below in Figure 49. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The feather - parallel treatment has a skin friction coefficient of -0.0113, but is an increase in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately -76.73%, which indicates that the drag has increased. The overlaid boundary layer graph can be seen below in Figure 50. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The feather - random treatment has a skin friction coefficient of -0.0069, but is an increase in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately -7.61%, which indicates that the drag has increased. The overlaid boundary layer graph can be seen below in Figure 51. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.
The feather - rotated treatment has a skin friction coefficient of -0.0010, and is a decrease in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately 84.30%. The overlaid boundary layer graph can be seen below in Figure 52. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The micro pattern #1 treatment has a skin friction coefficient of -0.0017, and is a decrease in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately 74.16%. The overlaid boundary layer graph can be seen below in Figure 53. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Skin Type</th>
<th>Flow Type</th>
<th>Flow Parameters</th>
<th>Drag [mN/m]</th>
<th>Shape Factor</th>
<th>Separation Predicted</th>
<th>Cf</th>
<th>ΔCf</th>
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<tr>
<td>181833</td>
<td>Glass</td>
<td>Laminar Screens</td>
<td>Passive</td>
<td>-0.570</td>
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<td>Attached</td>
<td>-0.0026</td>
<td>-</td>
<td>-</td>
</tr>
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<td>162115</td>
<td>Smooth</td>
<td>Laminar Screens</td>
<td>Passive</td>
<td>-1.412</td>
<td>1.62</td>
<td>Attached</td>
<td>-0.0064</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>233501</td>
<td>Feather - Parallel</td>
<td>Laminar Screens</td>
<td>Passive</td>
<td>-2.495</td>
<td>1.86</td>
<td>Attached</td>
<td>-0.0113</td>
<td>-0.0049</td>
<td>-76.63</td>
</tr>
<tr>
<td>134715</td>
<td>Feather - Random</td>
<td>Laminar Screens</td>
<td>Passive</td>
<td>-1.520</td>
<td>1.69</td>
<td>Attached</td>
<td>-0.0069</td>
<td>-0.0005</td>
<td>-7.61</td>
</tr>
<tr>
<td>180304</td>
<td>Feather - Rotated</td>
<td>Laminar Screens</td>
<td>Passive</td>
<td>-0.222</td>
<td>2.51</td>
<td>Attached</td>
<td>-0.0010</td>
<td>0.0054</td>
<td>84.30</td>
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<tr>
<td>201539</td>
<td>Bump Pattern</td>
<td>Laminar Screens</td>
<td>Passive</td>
<td>0.041</td>
<td>4.75</td>
<td>Separated</td>
<td>0.0002</td>
<td>0.0066</td>
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</tr>
<tr>
<td>234925</td>
<td>Micro Pattern 1</td>
<td>Laminar Screens</td>
<td>Passive</td>
<td>-0.365</td>
<td>2.52</td>
<td>Attached</td>
<td>-0.0017</td>
<td>0.0048</td>
<td>74.16</td>
</tr>
<tr>
<td>005531</td>
<td>Micro Pattern 2</td>
<td>Laminar Screens</td>
<td>Passive</td>
<td>-0.056</td>
<td>3.26</td>
<td>Separated</td>
<td>-0.0003</td>
<td>0.0062</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 49- Overlaid boundary layer profiles for smooth treatment.

Figure 50- Overlaid boundary layer profiles for feather - parallel treatment.
Figure 51- Overlaid boundary layer profiles for feather - random treatment.

Figure 52- Overlaid boundary layer profiles for feather - rotated treatment.
Figure 53- Overlaid boundary layer profiles for micro pattern #1 treatment.
Reynolds Number 52600 Laminar Screen, Active Flow Control

For the tests that were preformed under these conditions, the results are shown in Table 9. The following boundary layer profiles are overlaid and displayed against the Blasius solution because the laminar screens were on the wind tunnel.

The smooth treatment had a local skin friction coefficient of -0.0061, which is considered the baseline for all other skin friction coefficients. This is because the smooth treatment is the treatment with no micro or macro structures on it. As such, all further treatments are compared to this. The overlaid boundary layer graph can be seen below in Figure 54. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The feather - parallel treatment has a skin friction coefficient of -0.0060, and is a decrease in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately 1.93%. The overlaid boundary layer graph can be seen below in Figure 55. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The feather - random treatment has a skin friction coefficient of -0.0048, and is a decrease in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately 21.03%. The overlaid boundary layer graph can be seen below in Figure 56. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.
Table 9- Test results for Laminar screen testing at Reynolds number 52600, active flow control

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Skin Type</th>
<th>Flow Type</th>
<th>Flow Parameters</th>
<th>Drag [mN/m]</th>
<th>Shape Factor</th>
<th>Separation Predicted</th>
<th>Cf</th>
<th>ΔCf</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>190938</td>
<td>Glass</td>
<td>Laminar Screens</td>
<td>Active</td>
<td>-0.288</td>
<td>2.64</td>
<td>Attached</td>
<td>-0.0013</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>201615</td>
<td>Smooth</td>
<td>Laminar Screens</td>
<td>Active</td>
<td>-1.344</td>
<td>1.66</td>
<td>Attached</td>
<td>-0.0061</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>001149</td>
<td>Feather - Parallel</td>
<td>Laminar Screens</td>
<td>Active</td>
<td>-1.318</td>
<td>2.11</td>
<td>Attached</td>
<td>-0.0060</td>
<td>0.0010</td>
<td>1.93</td>
</tr>
<tr>
<td>151912</td>
<td>Feather - Random</td>
<td>Laminar Screens</td>
<td>Active</td>
<td>-1.062</td>
<td>2.57</td>
<td>Attached</td>
<td>-0.0048</td>
<td>0.0013</td>
<td>21.03</td>
</tr>
<tr>
<td>181626</td>
<td>Feather - Rotated</td>
<td>Laminar Screens</td>
<td>Active</td>
<td>0.040</td>
<td>2.81</td>
<td>Separated</td>
<td>0.0002</td>
<td>0.0063</td>
<td>-</td>
</tr>
<tr>
<td>202609</td>
<td>Bump Pattern</td>
<td>Laminar Screens</td>
<td>Active</td>
<td>0.087</td>
<td>5.74</td>
<td>Separated</td>
<td>0.0004</td>
<td>0.0065</td>
<td>-</td>
</tr>
<tr>
<td>000014</td>
<td>Micro Pattern</td>
<td>Laminar Screens</td>
<td>Active</td>
<td>0.013</td>
<td>3.28</td>
<td>Separated</td>
<td>0.0001</td>
<td>0.0062</td>
<td>-</td>
</tr>
<tr>
<td>010509</td>
<td>Micro Pattern 2</td>
<td>Laminar Screens</td>
<td>Active</td>
<td>0.105</td>
<td>5.54</td>
<td>Separated</td>
<td>0.0005</td>
<td>0.0066</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 54 - Overlaid boundary layer profiles for smooth treatment.

Figure 55 - Overlaid boundary layer profiles for feather-parallel treatment.
Figure 56 - Overlaid boundary layer profiles for feather - random treatment.
Reynolds Number 52600 Turbulent Screen, Passive Flow Control

For the tests that were preformed under these conditions, the results are shown in Table 10. The following boundary layer profiles are overlaid and displayed against the Prandtl's solution because the turbulent screens were on the wind tunnel.

The smooth treatment had a local skin friction coefficient of -0.0060, which is considered the baseline for all other skin friction coefficients. This is because the smooth treatment is the treatment with no micro or macro structures on it. As such, all further treatments are compared to this. The overlaid boundary layer graph can be seen below in Figure 57. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The micro pattern #1 treatment has a skin friction coefficient of -0.0008, and is a decrease in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately 86.19%. The overlaid boundary layer graph can be seen below in Figure 58. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The micro pattern #2 treatment has a skin friction coefficient of -0.0024, and is a decrease in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately 60.70%. The overlaid boundary layer graph can be seen below in Figure 59. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.
Table 10 - Test results for turbulent screen testing at Reynolds number 52600, passive flow control

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Skin Type</th>
<th>Flow Type</th>
<th>Flow Parameters</th>
<th>Drag [mN/m]</th>
<th>Shape Factor</th>
<th>Separation Predicted</th>
<th>Cf</th>
<th>ΔCf</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>165629</td>
<td>Glass</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>-1.056</td>
<td>1.69</td>
<td>Attached</td>
<td>-0.0048</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>150024</td>
<td>Smooth</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>-1.320</td>
<td>1.67</td>
<td>Attached</td>
<td>-0.0060</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>181952</td>
<td>Feather</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>-1.427</td>
<td>1.60</td>
<td>Separated</td>
<td>-0.0065</td>
<td>-</td>
<td>0.0005</td>
</tr>
<tr>
<td>154906</td>
<td>Feather</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>-0.993</td>
<td>2.19</td>
<td>Separated</td>
<td>-0.0045</td>
<td>0.0015</td>
<td>-</td>
</tr>
<tr>
<td>170543</td>
<td>Feather</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>0.003</td>
<td>2.60</td>
<td>Separated</td>
<td>0.0000</td>
<td>0.0060</td>
<td>-</td>
</tr>
<tr>
<td>211753</td>
<td>Bump Pattern</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>0.030</td>
<td>7.76</td>
<td>Separated</td>
<td>0.0001</td>
<td>0.0061</td>
<td>-</td>
</tr>
<tr>
<td>223201</td>
<td>Micro Pattern 1</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>-0.182</td>
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<td>Attached</td>
<td>-0.0008</td>
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<td>86.19</td>
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<tr>
<td>013946</td>
<td>Micro Pattern 2</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>-0.519</td>
<td>2.29</td>
<td>Attached</td>
<td>-0.0024</td>
<td>0.0036</td>
<td>60.70</td>
</tr>
</tbody>
</table>
Figure 57 - Overlaid boundary layer profiles for smooth treatment.

Figure 58 - Overlaid boundary layer profiles for micro pattern #1 treatment.
Figure 59 - Overlaid boundary layer profiles for micro pattern #1 treatment.
Reynolds Number 52600 Turbulent Screen, Active Flow Control

For the tests that were preformed under these conditions, the results are shown in Table 11. The following boundary layer profiles are overlaid and displayed against the Prandtl's solution because the turbulent screens were on the wind tunnel.

The smooth treatment had a local skin friction coefficient of -0.0055, which is considered the baseline for all other skin friction coefficients. This is because the smooth treatment is the treatment with no micro or macro structures on it. As such, all further treatments are compared to this. The overlaid boundary layer graph can be seen below in Figure 60. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The feather - parallel treatment has a skin friction coefficient of -0.0065, and is an increase in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately -18.73%, which indicates that the drag has increased. The overlaid boundary layer graph can be seen below in Figure 61. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The feather - random treatment has a skin friction coefficient of -0.0049, and is a decrease in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately 10.50%. The overlaid boundary layer graph can be seen below in Figure 62. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.
The feather - random treatment has a skin friction coefficient of -0.0006, and is a decrease in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately 88.79%. The overlaid boundary layer graph can be seen below in Figure 63. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The feather - random treatment has a skin friction coefficient of -0.0015, and is a decrease in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately 73.44%. The overlaid boundary layer graph can be seen below in Figure 64. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

Table 11 - Test results for turbulent screen testing at Reynolds number 52600, active flow control

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Skin Type</th>
<th>Flow Type</th>
<th>Flow Parameters</th>
<th>Drag [mN/m]</th>
<th>Shape Factor</th>
<th>Separation Predicted</th>
<th>Cf</th>
<th>ΔCf</th>
<th>% Change</th>
</tr>
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<tr>
<td>172510</td>
<td>Glass</td>
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<td>Attached</td>
<td>-0.0055</td>
<td>-</td>
<td>-</td>
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<tr>
<td>141357</td>
<td>Smooth</td>
<td>Turbulent Screen</td>
<td>Active</td>
<td>-1.208</td>
<td>1.61</td>
<td>Attached</td>
<td>-0.0055</td>
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<td>-</td>
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<tr>
<td>224828</td>
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<td>Active</td>
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<td>Attached</td>
<td>-0.0049</td>
<td>0.0006</td>
<td>10.50</td>
</tr>
<tr>
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<td>Turbulent Screen</td>
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<td>Separated</td>
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<td>-</td>
</tr>
<tr>
<td>212834</td>
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<td>Active</td>
<td>0.034</td>
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<td>Separated</td>
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</tr>
<tr>
<td>230556</td>
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<td>Turbulent Screen</td>
<td>Active</td>
<td>-0.135</td>
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<td>Attached</td>
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<td>88.79</td>
</tr>
<tr>
<td>014938</td>
<td>Micro Pattern 2</td>
<td>Turbulent Screen</td>
<td>Active</td>
<td>-0.321</td>
<td>2.91</td>
<td>Attached</td>
<td>-0.0015</td>
<td>0.0040</td>
<td>73.44</td>
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</tbody>
</table>
Figure 60 - Overlaid boundary layer profiles for smooth treatment.

Figure 61 - Overlaid boundary layer profiles for feather-parallel treatment
Figure 62 - Overlaid boundary layer profiles for feather - random treatment.

Figure 63 - Overlaid boundary layer profiles for micro pattern #1 treatment.
Figure 64 - Overlaid boundary layer profiles for micro pattern #2 treatment.
Reynolds Number 68600 Laminar Screen, Passive Flow Control

For the tests that were preformed under these conditions, the results are shown in Table 12. The following boundary layer profiles are overlaid and displayed against the Blasius solution because the laminar screens were on the wind tunnel.

The smooth treatment had a local skin friction coefficient of -0.0033, which is considered the baseline for all other skin friction coefficients. This is because the smooth treatment is the treatment with no micro or macro structures on it. As such, all further treatments are compared to this. The overlaid boundary layer graph can be seen below in Figure 65. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The feather-parallel treatment has a skin friction coefficient of -0.0056, and is an increase in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately -69.02%, which indicates that the drag has increased. The overlaid boundary layer graph can be seen below in Figure 66. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The feather-random treatment has a skin friction coefficient of -0.0042, and is an increase in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately -26.27%, which indicates that the drag has increased. The overlaid boundary layer graph can be seen below in Figure 67. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.
The feather - rotated treatment has a skin friction coefficient of -0.0006, and is a decrease in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately 82.03%. The overlaid boundary layer graph can be seen below in Figure 68. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The micro pattern #1 treatment has a skin friction coefficient of -0.0005, and is a decrease in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately 85.45%. The overlaid boundary layer graph can be seen below in Figure 69. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

Table 12 - Test results for laminar screen testing at Reynolds number 68600, passive flow control

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Skin Type</th>
<th>Flow Type</th>
<th>Flow Parameters</th>
<th>Drag [mN/m]</th>
<th>Shape Factor</th>
<th>Separation Predicted</th>
<th>Cf</th>
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</tr>
</thead>
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<td>Laminar Screens</td>
<td>Passive</td>
<td>-0.789</td>
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<td>-0.0014</td>
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<td>163102</td>
<td>Smooth</td>
<td>Laminar Screens</td>
<td>Passive</td>
<td>-1.810</td>
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<td>Attached</td>
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<td>-</td>
<td>-</td>
</tr>
<tr>
<td>233722</td>
<td>Feather - Parallel</td>
<td>Laminar Screens</td>
<td>Passive</td>
<td>-3.059</td>
<td>1.74</td>
<td>Attached</td>
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<td>-0.0023</td>
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<td>134924</td>
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<td>Laminar Screens</td>
<td>Passive</td>
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<td>Attached</td>
<td>-0.0042</td>
<td>-0.0009</td>
<td>-26.27</td>
</tr>
<tr>
<td>180516</td>
<td>Feather - Rotated</td>
<td>Laminar Screens</td>
<td>Passive</td>
<td>-0.325</td>
<td>2.38</td>
<td>Attached</td>
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<td>0.0027</td>
<td>82.03</td>
</tr>
<tr>
<td>201740</td>
<td>Bump Pattern</td>
<td>Laminar Screens</td>
<td>Passive</td>
<td>0.070</td>
<td>5.63</td>
<td>Separated</td>
<td>0.0001</td>
<td>0.0035</td>
<td>-</td>
</tr>
<tr>
<td>235122</td>
<td>Micro Pattern 1</td>
<td>Laminar Screens</td>
<td>Passive</td>
<td>-0.263</td>
<td>2.70</td>
<td>Attached</td>
<td>-0.0005</td>
<td>0.0028</td>
<td>85.45</td>
</tr>
<tr>
<td>005728</td>
<td>Micro Pattern 2</td>
<td>Laminar Screens</td>
<td>Passive</td>
<td>0.084</td>
<td>5.73</td>
<td>Separated</td>
<td>0.0002</td>
<td>0.0035</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 65 - Overlaid boundary layer profiles for smooth treatment.

Figure 66 - Overlaid boundary layer profiles for feather - parallel treatment.
Figure 67 - Overlaid boundary layer profiles for feather - random treatment.

Figure 68 - Overlaid boundary layer profiles for feather - rotated treatment.
Figure 69 - Overlaid boundary layer profiles for micro pattern #1 treatment.
Reynolds Number 68600 Laminar Screen, Active Flow Control

For the tests that were preformed under these conditions, the results are shown in Table 13. The following boundary layer profiles are overlaid and displayed against the Blasius solution because the laminar screens were on the wind tunnel.

The smooth treatment had a local skin friction coefficient of -0.0029, which is considered the baseline for all other skin friction coefficients. This is because the smooth treatment is the treatment with no micro or macro structures on it. As such, all further treatments are compared to this. The overlaid boundary layer graph can be seen below in Figure 70. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The feather-parallel treatment has a skin friction coefficient of -0.0037, and is an increase in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately -29.83%, which indicates that the drag has increased. The overlaid boundary layer graph can be seen below in Figure 71. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The feather-random treatment has a skin friction coefficient of -0.0033, and is an increase in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately -14.65%, which indicates that the drag has increased. The overlaid boundary layer graph can be seen below in Figure 72. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.
<table>
<thead>
<tr>
<th>Test ID</th>
<th>Skin Type</th>
<th>Flow Type</th>
<th>Flow Parameters</th>
<th>Drag [mN/m]</th>
<th>Shape Factor</th>
<th>Separation Predicted</th>
<th>Cf</th>
<th>deltaCf</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>190701</td>
<td>Glass</td>
<td>Laminar Screens</td>
<td>Active</td>
<td>-0.514</td>
<td>2.20</td>
<td>Attached</td>
<td>-0.0009</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>174148</td>
<td>Smooth</td>
<td>Laminar Screens</td>
<td>Active</td>
<td>-1.570</td>
<td>1.74</td>
<td>Attached</td>
<td>-0.0029</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>000949</td>
<td>Feather - Parallel</td>
<td>Laminar Screens</td>
<td>Active</td>
<td>-2.039</td>
<td>1.91</td>
<td>Attached</td>
<td>-0.0037</td>
<td>-0.0009</td>
<td>-29.83</td>
</tr>
<tr>
<td>151135</td>
<td>Feather - Random</td>
<td>Laminar Screens</td>
<td>Active</td>
<td>-1.800</td>
<td>2.09</td>
<td>Attached</td>
<td>-0.0033</td>
<td>-0.0004</td>
<td>-14.65</td>
</tr>
<tr>
<td>181422</td>
<td>Feather - Rotated</td>
<td>Laminar Screens</td>
<td>Active</td>
<td>-0.053</td>
<td>2.94</td>
<td>Separated</td>
<td>-0.0001</td>
<td>0.0028</td>
<td>-</td>
</tr>
<tr>
<td>202408</td>
<td>Bump Pattern</td>
<td>Laminar Screens</td>
<td>Active</td>
<td>0.106</td>
<td>5.74</td>
<td>Separated</td>
<td>0.0002</td>
<td>0.0031</td>
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</tr>
<tr>
<td>235814</td>
<td>Micro Pattern 1</td>
<td>Laminar Screens</td>
<td>Active</td>
<td>0.110</td>
<td>2.95</td>
<td>Separated</td>
<td>0.0002</td>
<td>0.0031</td>
<td>-</td>
</tr>
<tr>
<td>010314</td>
<td>Micro Pattern 2</td>
<td>Laminar Screens</td>
<td>Active</td>
<td>0.060</td>
<td>4.16</td>
<td>Separated</td>
<td>0.0001</td>
<td>0.0030</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 70 - Overlaid boundary layer profiles for smooth treatment.

Figure 71 - Overlaid boundary layer profiles for feather - parallel treatment.
Figure 72 - Overlaid boundary layer profiles for feather - random treatment.
Reynolds Number 68600 Turbulent Screen, Passive Flow Control

For the tests that were performed under these conditions, the results are shown in Table 14. The following boundary layer profiles are overlaid and displayed against the Prandtl solution because the turbulent screens were on the wind tunnel.

The smooth treatment had a local skin friction coefficient of -0.0043, which is considered the baseline for all other skin friction coefficients. This is because the smooth treatment is the treatment with no micro or macro structures on it. As such, all further treatments are compared to this. The overlaid boundary layer graph can be seen below in Figure 73. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The feather-parallel treatment has a skin friction coefficient of -0.0041, and is a decrease in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately 4.06%, which indicates that the drag has decreased. The overlaid boundary layer graph can be seen below in Figure 74. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The micro pattern #2 treatment has a skin friction coefficient of -0.0016, and is a decrease in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately 61.98%, which indicates that the drag has decreased. The overlaid boundary layer graph can be seen below in Figure 75. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.
Table 14 - Test results for turbulent screen testing at Reynolds number 68600, passive flow control

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Skin Type</th>
<th>Flow Type</th>
<th>Flow Parameters</th>
<th>Drag [mN/m]</th>
<th>Shape Factor</th>
<th>Separation Predicted</th>
<th>Cf</th>
<th>∆Cf</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>170318</td>
<td>Glass</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>-1.630</td>
<td>1.66</td>
<td>Attached</td>
<td>-0.0030</td>
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<td></td>
</tr>
<tr>
<td>151222</td>
<td>Smooth</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>-2.337</td>
<td>1.62</td>
<td>Attached</td>
<td>-0.0043</td>
<td></td>
<td></td>
</tr>
<tr>
<td>182550</td>
<td>Feather - Parallel</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>-2.242</td>
<td>1.58</td>
<td>Attached</td>
<td>-0.0041</td>
<td>0.0002</td>
<td>4.06</td>
</tr>
<tr>
<td>155103</td>
<td>Feather - Random</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>-1.327</td>
<td>3.76</td>
<td>Separated</td>
<td>-0.0024</td>
<td>0.0019</td>
<td></td>
</tr>
<tr>
<td>170853</td>
<td>Feather - Rotated</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>-0.034</td>
<td>2.81</td>
<td>Separated</td>
<td>-0.0001</td>
<td>0.0042</td>
<td></td>
</tr>
<tr>
<td>212003</td>
<td>Bump Pattern</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>0.069</td>
<td>7.94</td>
<td>Separated</td>
<td>0.0001</td>
<td>0.0044</td>
<td></td>
</tr>
<tr>
<td>223402</td>
<td>Micro Pattern 1</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>-0.299</td>
<td>3.07</td>
<td>Separated</td>
<td>-0.0005</td>
<td>0.0037</td>
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</tr>
<tr>
<td>014143</td>
<td>Micro Pattern 2</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>-0.889</td>
<td>2.68</td>
<td>Attached</td>
<td>-0.0016</td>
<td>0.0027</td>
<td>61.98</td>
</tr>
</tbody>
</table>
Figure 73- Overlaid boundary layer profiles for smooth treatment.

Figure 74- Overlaid boundary layer profiles for feather - parallel treatment.
Figure 75- Overlaid boundary layer profiles for micro pattern #2 treatment.
Reynolds Number 68600 Turbulent Screen, Active Flow Control

For the tests that were preformed under these conditions, the results are shown in Table 14. The following boundary layer profiles are overlaid and displayed against the Prandtl solution because the turbulent screens were on the wind tunnel.

The smooth treatment had a local skin friction coefficient of -0.0040, which is considered the baseline for all other skin friction coefficients. This is because the smooth treatment is the treatment with no micro or macro structures on it. As such, all further treatments are compared to this. The overlaid boundary layer graph can be seen below in Figure 76. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The feather - parallel treatment has a skin friction coefficient of -0.0044, and is an increase in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately -10.44%, which indicates that the drag has decreased. The overlaid boundary layer graph can be seen below in Figure 77. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The micro pattern #2 treatment has a skin friction coefficient of -0.0010, and is a decrease in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately 74.15%, which indicates that the drag has decreased. The overlaid boundary layer graph can be seen below in Figure 78. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.
Table 15 - Test results for turbulent screen testing at Reynolds number 68600, active flow control

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Skin Type</th>
<th>Flow Type</th>
<th>Flow Parameters</th>
<th>Drag [mN/m]</th>
<th>Shape Factor</th>
<th>Separation Predicted</th>
<th>Cf</th>
<th>ΔCf</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>172710</td>
<td>Glass</td>
<td>Turbulent Screen</td>
<td>Active</td>
<td>-1.729</td>
<td>1.48</td>
<td>Attached</td>
<td>-0.0032</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>141559</td>
<td>Smooth</td>
<td>Turbulent Screen</td>
<td>Active</td>
<td>-2.152</td>
<td>1.71</td>
<td>Attached</td>
<td>-0.0040</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>225150</td>
<td>Feather - Parallel</td>
<td>Turbulent Screen</td>
<td>Active</td>
<td>-2.377</td>
<td>1.70</td>
<td>Attached</td>
<td>-0.0044</td>
<td>-0.0004</td>
<td>-10.44</td>
</tr>
<tr>
<td>161301</td>
<td>Feather - Random</td>
<td>Turbulent Screen</td>
<td>Active</td>
<td>-1.776</td>
<td>1.88</td>
<td>Separated</td>
<td>-0.0033</td>
<td>0.0007</td>
<td>-</td>
</tr>
<tr>
<td>173154</td>
<td>Feather - Rotated</td>
<td>Turbulent Screen</td>
<td>Active</td>
<td>0.209</td>
<td>3.36</td>
<td>Separated</td>
<td>0.0004</td>
<td>0.0043</td>
<td>-</td>
</tr>
<tr>
<td>212635</td>
<td>Bump Pattern</td>
<td>Turbulent Screen</td>
<td>Active</td>
<td>0.063</td>
<td>8.00</td>
<td>Separated</td>
<td>0.0001</td>
<td>0.0041</td>
<td>-</td>
</tr>
<tr>
<td>230340</td>
<td>Micro Pattern 1</td>
<td>Turbulent Screen</td>
<td>Active</td>
<td>0.031</td>
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<td>Separated</td>
<td>0.0001</td>
<td>0.0040</td>
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</tr>
<tr>
<td>014740</td>
<td>Micro Pattern 2</td>
<td>Turbulent Screen</td>
<td>Active</td>
<td>-0.556</td>
<td>2.82</td>
<td>Attached</td>
<td>-0.0010</td>
<td>0.0029</td>
<td>74.15</td>
</tr>
</tbody>
</table>
Figure 76 - Overlaid boundary layer profiles for smooth treatment.

Figure 77 - Overlaid boundary layer profiles for feather - parallel treatment.
Figure 78 - Overlaid boundary layer profiles for micro pattern #2 treatment.
Reynolds Number 78800 Laminar Screen, Passive Flow Control

For the tests that were performed under these conditions, the results are shown in Table 16. The following boundary layer profiles are overlaid and displayed against the Blasius solution because the laminar screens were on the wind tunnel.

The smooth treatment had a local skin friction coefficient of -0.0024, which is considered the baseline for all other skin friction coefficients. This is because the smooth treatment is the treatment with no micro or macro structures on it. As such, all further treatments are compared to this. The overlaid boundary layer graph can be seen below in Figure 79. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The feather-parallel treatment has a skin friction coefficient of -0.0015, and is a decrease in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately 37.02%, which indicates that the drag has decreased. The overlaid boundary layer graph can be seen below in Figure 80. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The feather-random treatment has a skin friction coefficient of -0.0030, and is an increase in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately -29.27%, which indicates that the drag has increased. The overlaid boundary layer graph can be seen below in Figure 81. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.
The micro pattern #1 treatment has a skin friction coefficient of -0.0003, and is a decrease in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately 87.11%, which indicates that the drag has decreased. The overlaid boundary layer graph can be seen below in Figure 82. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

Table 16 - Test results for laminar screen testing at Reynolds number 78800, passive flow control

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Skin Type</th>
<th>Flow Type</th>
<th>Flow Parameters</th>
<th>Drag [mN/m]</th>
<th>Shape Factor</th>
<th>Separation Predicted</th>
<th>Cf</th>
<th>ΔCf</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>185135</td>
<td>Glass</td>
<td>Laminar Screens</td>
<td>Passive</td>
<td>-1.211</td>
<td>1.76</td>
<td>Attached</td>
<td>-0.0014</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>163939</td>
<td>Smooth</td>
<td>Laminar Screens</td>
<td>Passive</td>
<td>-2.079</td>
<td>1.72</td>
<td>Attached</td>
<td>-0.0024</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>235523</td>
<td>Feather - Parallel</td>
<td>Laminar Screens</td>
<td>Passive</td>
<td>-1.309</td>
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<td>Attached</td>
<td>-0.0015</td>
<td>0.0009</td>
<td>37.02</td>
</tr>
<tr>
<td>135133</td>
<td>Feather - Random</td>
<td>Laminar Screens</td>
<td>Passive</td>
<td>-2.688</td>
<td>1.72</td>
<td>Attached</td>
<td>-0.0030</td>
<td>-0.0007</td>
<td>-29.27</td>
</tr>
<tr>
<td>180717</td>
<td>Feather - Rotated</td>
<td>Laminar Screens</td>
<td>Passive</td>
<td>-0.057</td>
<td>2.72</td>
<td>Separated</td>
<td>-0.0001</td>
<td>0.0023</td>
<td>-</td>
</tr>
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<td>Separated</td>
<td>0.0002</td>
<td>0.0025</td>
<td>-</td>
</tr>
<tr>
<td>235322</td>
<td>Micro Pattern 1</td>
<td>Laminar Screens</td>
<td>Passive</td>
<td>-0.268</td>
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<td>Attached</td>
<td>-0.0003</td>
<td>0.0021</td>
<td>87.11</td>
</tr>
<tr>
<td>005922</td>
<td>Micro Pattern 2</td>
<td>Laminar Screens</td>
<td>Passive</td>
<td>-0.297</td>
<td>3.13</td>
<td>Separated</td>
<td>-0.0003</td>
<td>0.0020</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 79 - Overlaid boundary layer profiles for smooth treatment.

Figure 80 - Overlaid boundary layer profiles for feather - parallel treatment.
Figure 81 - Overlaid boundary layer profiles for feather - random treatment.

Figure 82 - Overlaid boundary layer profiles for micro pattern #1 treatment.
Reynolds Number 78800 Laminar Screen, Active Flow Control

For the tests that were performed under these conditions, the results are shown in Table 17. The following boundary layer profiles are overlaid and displayed against the Blasius solution because the laminar screens were on the wind tunnel.

The smooth treatment had a local skin friction coefficient of -0.0019, which is considered the baseline for all other skin friction coefficients. This is because the smooth treatment is the treatment with no micro or macro structures on it. As such, all further treatments are compared to this. The overlaid boundary layer graph can be seen below in Figure 83. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The feather-parallel treatment has a skin friction coefficient of -0.0023, and is an increase in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately -18.52%, which indicates that the drag has increased. The overlaid boundary layer graph can be seen below in Figure 84. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The feather-random treatment has a skin friction coefficient of -0.0025, and is an increase in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately -28.98%, which indicates that the drag has increased. The overlaid boundary layer graph can be seen below in Figure 84. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.
The micro pattern #1 treatment has a skin friction coefficient of -0.0001, and is an increase in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately -94.45%, which indicates that the drag has increased. The overlaid boundary layer graph can be seen below in Figure 86. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

Table 17- Test results for laminar screen testing at Reynolds number 78800, active flow control

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Skin Type</th>
<th>Flow Type</th>
<th>Flow Parameters</th>
<th>Drag [mN/m]</th>
<th>Shape Factor</th>
<th>Separation Predicted</th>
<th>Cf</th>
<th>ΔCf</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>195659</td>
<td>Glass</td>
<td>Laminar Screens</td>
<td>Active</td>
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<td>1.70</td>
<td>Attached</td>
<td>-0.0015</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>174403</td>
<td>Smooth</td>
<td>Laminar Screens</td>
<td>Active</td>
<td>-1.676</td>
<td>1.86</td>
<td>Attached</td>
<td>-0.0019</td>
<td>-</td>
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</tr>
<tr>
<td>000729</td>
<td>Feather Parallel</td>
<td>Laminar Screens</td>
<td>Active</td>
<td>-1.987</td>
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<td>Attached</td>
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<td>-0.0004</td>
<td>-18.52</td>
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<td>150937</td>
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<td>Laminar Screens</td>
<td>Active</td>
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<td>-0.0006</td>
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</tr>
<tr>
<td>181211</td>
<td>Feather Rotated</td>
<td>Laminar Screens</td>
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<td>2.62</td>
<td>Separated</td>
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<td>0.0018</td>
<td>-</td>
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<tr>
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<td>Laminar Screens</td>
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<td>Separated</td>
<td>0.0001</td>
<td>0.0020</td>
<td>-</td>
</tr>
<tr>
<td>235613</td>
<td>Micro Pattern 1</td>
<td>Laminar Screens</td>
<td>Active</td>
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<td>Separated</td>
<td>-0.0001</td>
<td>0.0018</td>
<td>-</td>
</tr>
<tr>
<td>010116</td>
<td>Micro Pattern 2</td>
<td>Laminar Screens</td>
<td>Active</td>
<td>0.230</td>
<td>3.56</td>
<td>Separated</td>
<td>0.0003</td>
<td>0.0022</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 83- Overlaid boundary layer profiles for smooth treatment.

Figure 84- Overlaid boundary layer profiles for feather-parallel treatment.
Figure 85- Overlaid boundary layer profiles for feather-random treatment.

Figure 86- Overlaid boundary layer profiles for micro pattern #1 treatment.
Reynolds Number 78800 Turbulent Screen, Passive Flow Control

For the tests that were performed under these conditions, the results are shown in Table 18. The following boundary layer profiles are overlaid and displayed against the Prandtl solution because the turbulent screens were on the wind tunnel.

The smooth treatment had a local skin friction coefficient of $-0.0033$, which is considered the baseline for all other skin friction coefficients. This is because the smooth treatment is the treatment with no micro or macro structures on it. As such, all further treatments are compared to this. The overlaid boundary layer graph can be seen below in Figure 87. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The feather-parallel treatment has a skin friction coefficient of $-0.0030$, and is a decrease in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately 8.93%, which indicates that the drag has decreased. The overlaid boundary layer graph can be seen below in Figure 88. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The micro pattern #2 treatment has a skin friction coefficient of $-0.0013$, and is a decrease in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately 60.80%, which indicates that the drag has decreased. The overlaid boundary layer graph can be seen below in Figure 89. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.
Table 18- Test results for turbulent screen testing at Reynolds number 78800, passive flow control

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Skin Type</th>
<th>Flow Type</th>
<th>Flow Parameters</th>
<th>Drag [mN/m]</th>
<th>Shape Factor</th>
<th>Separation Predicted</th>
<th>Cf</th>
<th>deltaCf</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>170921</td>
<td>Glass</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>-1.913</td>
<td>1.88</td>
<td>Attached</td>
<td>-0.0022</td>
<td></td>
<td></td>
</tr>
<tr>
<td>152140</td>
<td>Smooth</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>-2.920</td>
<td>1.66</td>
<td>Attached</td>
<td>-0.0033</td>
<td></td>
<td></td>
</tr>
<tr>
<td>183634</td>
<td>Feather - Parallel</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>-2.659</td>
<td>1.48</td>
<td>Attached</td>
<td>-0.0030</td>
<td>0.0003</td>
<td>8.93</td>
</tr>
<tr>
<td>155305</td>
<td>Feather - Random</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>-1.734</td>
<td>2.81</td>
<td>Separated</td>
<td>-0.0020</td>
<td>0.0013</td>
<td></td>
</tr>
<tr>
<td>171130</td>
<td>Feather - Rotated</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>0.191</td>
<td>2.75</td>
<td>Separated</td>
<td>0.0002</td>
<td>0.0035</td>
<td></td>
</tr>
<tr>
<td>212211</td>
<td>Bump Pattern</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>0.103</td>
<td>7.51</td>
<td>Separated</td>
<td>0.0001</td>
<td>0.0034</td>
<td></td>
</tr>
<tr>
<td>223604</td>
<td>Micro Pattern 1</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>-0.343</td>
<td>3.06</td>
<td>Separated</td>
<td>-0.0004</td>
<td>0.0029</td>
<td></td>
</tr>
<tr>
<td>0014342</td>
<td>Micro Pattern 2</td>
<td>Turbulent Screen</td>
<td>Passive</td>
<td>-1.145</td>
<td>2.69</td>
<td>Attached</td>
<td>-0.0013</td>
<td>0.0020</td>
<td>60.80</td>
</tr>
</tbody>
</table>
Figure 87 - Overlaid boundary layer profiles for smooth treatment.

Figure 88 - Overlaid boundary layer profiles for feather - parallel treatment.
Figure 89 - Overlaid boundary layer profiles for micro pattern #2 treatment.
Reynolds Number 78800 Turbulent Screen, Active Flow Control

For the tests that were performed under these conditions, the results are shown in Table 19. The following boundary layer profiles are overlaid and displayed against the Prandtl solution because the turbulent screens were on the wind tunnel.

The smooth treatment had a local skin friction coefficient of -0.0027, which is considered the baseline for all other skin friction coefficients. This is because the smooth treatment is the treatment with no micro or macro structures on it. As such, all further treatments are compared to this. The overlaid boundary layer graph can be seen below in Figure 90. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The feather - parallel treatment has a skin friction coefficient of -0.0033, and is an increase in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately -21.49%, which indicates that the drag has increased. The overlaid boundary layer graph can be seen below in Figure 91. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.

The micro pattern #2 treatment has a skin friction coefficient of -0.0011, and is a decrease in drag when compared to the smooth treatment, as also seen when directly comparing the drag values. The reduction in drag is approximately 59.49%, which indicates that the drag has decreased. The overlaid boundary layer graph can be seen below in Figure 92. Given the strong convergence of the boundary layers near the wall and the shape factor that is below Thwaite's criterion for separated flow, it is indicative that the flow is attached locally.
Table 19 - Test results for turbulent screen testing at Reynolds number 78800, active flow control

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Skin Type</th>
<th>Flow Type</th>
<th>Flow Parameters</th>
<th>Drag [mN/m]</th>
<th>Shape Factor</th>
<th>Separation Predicted</th>
<th>Cf</th>
<th>deltaCf</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>172909</td>
<td>Glass</td>
<td>Turbulent Screen</td>
<td>Active</td>
<td>-2.096</td>
<td>1.55</td>
<td>Attached</td>
<td>-0.0024</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>141801</td>
<td>Smooth</td>
<td>Turbulent Screen</td>
<td>Active</td>
<td>-2.363</td>
<td>1.70</td>
<td>Attached</td>
<td>-0.0027</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>225401</td>
<td>Feather - Parallel</td>
<td>Turbulent Screen</td>
<td>Active</td>
<td>-2.871</td>
<td>1.82</td>
<td>Attached</td>
<td>-0.0033</td>
<td>-0.0006</td>
<td>-21.49</td>
</tr>
<tr>
<td>161056</td>
<td>Feather - Random</td>
<td>Turbulent Screen</td>
<td>Active</td>
<td>-2.424</td>
<td>1.83</td>
<td>Separated</td>
<td>-0.0027</td>
<td>-0.0001</td>
<td>-</td>
</tr>
<tr>
<td>172956</td>
<td>Feather - Rotated</td>
<td>Turbulent Screen</td>
<td>Active</td>
<td>0.298</td>
<td>3.33</td>
<td>Separated</td>
<td>0.0003</td>
<td>0.0030</td>
<td>-</td>
</tr>
<tr>
<td>212432</td>
<td>Bump Pattern</td>
<td>Turbulent Screen</td>
<td>Active</td>
<td>0.086</td>
<td>7.65</td>
<td>Separated</td>
<td>0.0001</td>
<td>0.0028</td>
<td>-</td>
</tr>
<tr>
<td>230037</td>
<td>Micro Pattern 1</td>
<td>Turbulent Screen</td>
<td>Active</td>
<td>0.220</td>
<td>5.79</td>
<td>Separated</td>
<td>0.0002</td>
<td>0.0029</td>
<td>-</td>
</tr>
<tr>
<td>014543</td>
<td>Micro Pattern 2</td>
<td>Turbulent Screen</td>
<td>Active</td>
<td>-0.957</td>
<td>2.56</td>
<td>Attached</td>
<td>-0.0011</td>
<td>0.0016</td>
<td>59.49</td>
</tr>
</tbody>
</table>
Figure 90 - Overlaid boundary layer profiles for smooth treatment.

Figure 91 - Overlaid boundary layer profiles for feather-parallel treatment.
Figure 92 - Overlaid boundary layer profiles for micro pattern #2 treatment.
Due to the difficult nature of the shear amount of data, involved in processing, trends may be difficult to detect. As such, multiple plots were derived in order to visually determine any trends that may or may not exist. Also to note, the legend for each figure would be extremely large if each color, shape, and fill were taken into account. Therefore, only the shapes are displayed in the legend. The colors used in the plots are blue and red, indicating passive and active flow parameters respectively. Lastly, the fill of the marker indicates whether or not the flow was separated.

In Figure 93 and Figure 97, drag is plotted against Reₙ for laminar screen and the turbulent screen, respectively. At first glance, it appears that there is a positive trend that shows that drag increases with Reynolds number. Upon further inspection, it can be determined that this is mostly due to the change in velocity. As can be recalled from Eq. 1, Reynolds number can change due to \( \rho, v, x, \) and \( \mu \). At the velocities that were tested in the experiments, density and viscosity can be assumed to be constant. the spanwise location that was being tested also remained constant for each test. Therefore, the only variable allowed to change would be the velocity. As can be recalled from Eq. 2, the shear stress can change due to \( \mu \) and \( du/dy \). As mentioned previously, viscosity can be assumed to be constant, but varying the velocity will change the spatial gradient of the velocity profiles, which will affect the shear stress at the wall. Since the shear stress at the wall is being integrated over the surface to determine the viscous drag, it can be reasonably determined that the increase in drag due to the velocity.

A more interesting inspection on the data would be within the Reynolds number regimes themselves. However, it can be difficult to view data in such a narrow range. As such, the next logical step would be to make the data non-dimensional and use the skin friction coefficient. This can be seen in Figure 94 and in Figure 98 for the laminar screen and turbulent screen testing,
respectively. Both figures have a $C_f$ value that is calculated from a change in the skin friction when compared to the smooth treatment for each respective case.

For the laminar screen testing in Figure 94, there is a lot of separation throughout most of the graph, however, most notable is that the micro pattern #1 and micro pattern #2, as well as the feather-parallel and feather-random treatments all exhibit multiple cases of attachment, and varying degrees of influence on the drag on the plate. This will be discussed further.

For the turbulent screen testing in Figure 98, there is a lot of separation throughout a lot of the graph, but most notable is micro pattern #1 and micro pattern #2, as well as the feather-parallel and feather-random treatments. They all exhibit varying degrees of influence on the drag on the plate, and will be discussed further.

In both Figure 95 and Figure 99, there appears to be the same trend, somewhat, as that which was shown earlier in Figure 93 and Figure 97. This is largely due to the same reason, although with this specific instance, the characteristic length, the height of the micro and macro structures, are allowed to vary slightly. However, the height of the micro and macro structures vary in magnitude from $O(10^{-6})$ to $O(10^{-3})$ and the velocity term still dominates the equation. As such, the next logical step would be to make the data non-dimensional and use the skin friction coefficient. This can be seen in Figure 96 and in Figure 100 for the laminar screen and turbulent screen testing, respectively. Both figures have a $C_f$ value that is calculated from a change in the skin friction when compared to the smooth treatment for each respective case.

For the laminar screen testing in Figure 96, there is a lot of separation throughout most of the graph, however, most notable is that the micro pattern #1 and micro pattern #2 have a large
grouping together at respective Reynolds numbers, and the feather-parallel and feather-random treatments all exhibit multiple cases of attachment, and grouping. This will be discussed further.

For the turbulent screen testing in Figure 98, there is a lot of separation throughout a lot of the graph, but most notable is micro pattern #1 and micro pattern #2 have a large grouping together at the respective Reynolds numbers, and the feather-parallel and feather-random treatments demonstrate similar grouping patterns. This will be discussed further.
Figure 93 - Drag Vs Rex with both passive (blue) and active (red) treatments with laminar screens.
Figure 94 - Change in Cf Vs Rex for both passive (blue) and active (red) treatments with laminar screens.
Figure 95 - Drag Vs Reh with both passive (blue) and active (red) treatments with laminar screens.
Figure 96 - Change in Cf Vs Reh for both passive (blue) and active (red) treatments with laminar screens.
Figure 97 - Drag Vs Rex with both passive (blue) and active (red) treatments with turbulent screen.
Figure 98 - Change in Cf Vs Rex for both passive (blue) and active (red) treatments with turbulent screen.
Figure 99- Drag Vs Reh with both passive (blue) and active (red) treatments with turbulent screen.
Figure 100 - Change in Cf vs Reh for both passive (blue) and active (red) treatments with turbulent screen.
Lastly, an analysis of variance (ANOVA) was performed on the data. The results of the ANOVA are shown in Figure 101. The most significant factor in the AVNOVA study is the skin and the next most significant factor is the Reynolds number. The skin and Reynolds number produce a significant interactive effect on the drag. Although there is an interaction between the skin and flow type, it is not as significant as the interaction between the skin and Reynolds number. Vibrating the plate to deliberately trip the boundary layer flow from laminar to turbulent, while somewhat impactful, was nowhere near as important to influencing the drag as Reynolds number and the skin that was used.

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum Sq.</th>
<th>d.f.</th>
<th>Mean Sq.</th>
<th>F</th>
<th>Prob&gt;F</th>
</tr>
</thead>
<tbody>
<tr>
<td>act/pass</td>
<td>5.0585e-07</td>
<td>1</td>
<td>5.0585e-07</td>
<td>15.22</td>
<td>0.0008</td>
</tr>
<tr>
<td>flow type</td>
<td>8.23815e-07</td>
<td>1</td>
<td>8.23815e-07</td>
<td>24.78</td>
<td>0.0001</td>
</tr>
<tr>
<td>skin</td>
<td>6.1039e-05</td>
<td>7</td>
<td>8.6111e-06</td>
<td>265.16</td>
<td>0</td>
</tr>
<tr>
<td>Re</td>
<td>1.3894e-05</td>
<td>3</td>
<td>4.63134e-06</td>
<td>139.33</td>
<td>0</td>
</tr>
<tr>
<td>act/pass*flow type</td>
<td>2.87469e-07</td>
<td>1</td>
<td>2.87469e-07</td>
<td>3.65</td>
<td>0.0078</td>
</tr>
<tr>
<td>act/pass*skin</td>
<td>2.36442e-07</td>
<td>7</td>
<td>3.37775e-08</td>
<td>1.02</td>
<td>0.4485</td>
</tr>
<tr>
<td>act/pass*Re</td>
<td>1.43952e-07</td>
<td>3</td>
<td>4.79506e-08</td>
<td>1.44</td>
<td>0.2588</td>
</tr>
<tr>
<td>flow type*skin</td>
<td>3.49039e-06</td>
<td>7</td>
<td>4.99042e-07</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>flow type*Re</td>
<td>5.28547e-07</td>
<td>3</td>
<td>1.76516e-07</td>
<td>5.31</td>
<td>0.007</td>
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<tr>
<td>skin*Re</td>
<td>1.34474e-05</td>
<td>21</td>
<td>6.40353e-07</td>
<td>19.26</td>
<td>0</td>
</tr>
<tr>
<td>act/pass<em>flow type</em>skin</td>
<td>5.84503e-07</td>
<td>7</td>
<td>8.35005e-08</td>
<td>2.51</td>
<td>0.0482</td>
</tr>
<tr>
<td>act/pass<em>flow type</em>Re</td>
<td>1.06636e-07</td>
<td>3</td>
<td>3.55454e-08</td>
<td>1.07</td>
<td>0.3833</td>
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<tr>
<td>act/pass<em>skin</em>Re</td>
<td>8.508e-07</td>
<td>21</td>
<td>4.06143e-08</td>
<td>1.22</td>
<td>0.2272</td>
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<td>flow type<em>skin</em>Re</td>
<td>2.36075e-06</td>
<td>21</td>
<td>1.12417e-07</td>
<td>3.38</td>
<td>0.0037</td>
</tr>
<tr>
<td>Error</td>
<td>6.9081e-07</td>
<td>21</td>
<td>3.2405e-08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>9.96584e-05</td>
<td>127</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 101 - ANOVA results.
Discussion

The first topic for discussion is the relative lack of agreement between some of the collected boundary layer profiles when plotted against the respective analytical solution, namely the Blasius solution. For example, Figure 37, Figure 38, and Figure 39 all demonstrate this. However, upon further testing of the wind tunnel itself using a constant temperature anemometer (CTA), it was found that the free stream turbulence intensity while using the laminar screens at lower Reynolds numbers was found to be ranging from approximately 2.1% to 2.4%. Furthermore, when tested with the turbulent screen on, the turbulence intensity rose to a range of approximately 3.3% to 4.3%. Low turbulence intensity wind tunnels can range from 0.04% to 1.0% turbulence intensity (C J Pennycuick). Therefore, when analyzing results where the analytical model chosen was that of the Blasius solution, it is important to note that the free stream turbulence intensity, even with laminar screens on, is significant enough to alter the boundary layer profile.

Another topic that needs to be addressed is the bump pattern treatment. It was demonstrated during the testing that drag reduction using this surface yielded results that were not favorable. Upon inspection of the vector fields, it was noted that, even when amplified, the velocity vectors were extremely small near the surface of the treatment. The typical boundary layer shape is non-existent in any of the vector fields that were captured. An example of a vector field for the bump pattern can be seen in Figure 102.
To further explore this topic, flow visualization on the global scale was performed using the PIV laser and the smoke created using the DEHS. There were a total of 50 images that were taken, making sure to fill the room with smoke. The images were then imported to Matlab and then they were composited together. While difficult to see due to the nature of the grayscale, it is possible to observe an area of smoke, and just below that area of smoke, there is darkness, and then below that is the plate with the treatment on it. The darkness is caused by the lack of reflection of smoke particles, due to what is likely global flow separation of the bump pattern, as seen in Figure 103.
In order to account for other local and global effects, flow visualization was performed on two other treatments. These treatments were chosen from Figure 96 and from Figure 100. It was noteworthy that in both the laminar and turbulent regions, there were noticeable reductions in drag while the flow maintained attachment for the micro pattern #2 treatment and there was noticeable attachment with both increases and increases in drag for the feather - parallel treatment. In order to determine the consistency of these results, it was important to make sure that the region of interest during the PIV study didn't fall within some larger global flow phenomena that would affect the results. As such, flow visualization was performed in the same manner as discussed previously, and the feather - parallel treatment and the micro pattern #2 treatments had composite images created and they were then analyzed.
As can be seen in Figure 104 for the feather - parallel treatment, the instantaneous image can contain a lot of information, but can also be hiding information. There could be the potential that a separation bubble with recirculating flow could be lurking in the shadows. In this image, it is possible to see that there may be turbulent eddies swirling around, but overall, there appears to be attached flow at the surface at all locations. There are no glaringly obvious locations in which there is an immediate lack of light due to lack of reflectivity due to particles not being illuminated in an area, which is indicative that there is no flow in that area. When compared to Figure 105, the composite shares a very similar story. It may be noted that there are more noticeable turbulent eddies swirling around in the top of the image, but that is a relic of the post processing that was applied to make the composite image. The images that were the last to be composited in tend to have a pronounced image if it deviates from the average of the previous composite images by too much. In the composite grayscale image, the flow lacks any sort of cyclic or repetitious flow phenomena that would indicate separation of a recirculation bubble in the flow.
For the micro pattern #2 treatment, as seen in Figure 106, the instantaneous image shows what appears to be attached flow that is void of any flow phenomena artifacts. There is some minor swirling happening due to turbulent eddies in the free stream, but nothing appears to be on the surface at all. When comparing this to Figure 107, the composite image, it further supports this idea. There are no distinct separation bubbles, recirculation areas, or separation of the flow that is visible.
Figure 106 - Instantaneous image capture of the micro pattern #2 treatment.

Figure 107 - Composite grayscale image of the micro pattern #2 treatment.
For treatments in which there is a noticeable reduction in drag, it can be noted more often when there is a higher free stream turbulence intensity, in particular, when there is a turbulent screen on the wind tunnel as opposed to laminar screens. In reviewing the images that were previously discussed in the results section, it can be seen that the shape of the boundary layer profile is changing from that of the analytical solution. This is supported by the idea that the turbulent structures are being attenuated near the wall. Since the fluid is moving slower in the boundary layer than near the free stream, and especially since the velocity tapers off to the no-slip condition at the wall, that means that there is very slow moving fluid directly closest to the wall. The low velocity fluid flow in the valleys of the micro and macro structures produces very low shear stresses across the majority of the surface of the treatment. Since there are inherently vortices in any flow, over a flat plate, the vortices can only interact with the tips of the micro and macro structures. By keeping the vortices at or above the tips of the micro and macro structures, the cross-stream velocity fluctuations inside the micro and macro valleys are much lower than the cross-stream velocity fluctuations above a flat plate. This difference in cross-stream velocity fluctuations is evidence of a reduction in shear stress near the surface, which minimizes the effect of the increased surface area by having micro and macro structures (Y.F. Fu).

For an example, an Olympic swimmer covered with a swimsuit patterned in the micro pattern #2 treatment could expect an average of a 40% drag reduction across a range of Reynolds numbers when compared to a swimmer that would potentially be wearing a similar suit with no treatment. This reduction in drag would account for a potential 22% gain in velocity, which would also equate to a 22% decrease in swimming times for a set distance.
Conclusions

Under passive flow control conditions in the Reynolds number 26,500 regime, Micro Pattern #2 was shown to have attached flow when the free stream flow became more turbulent. Feather-Parallel treatment was also shown to have attached flow when the free stream flow transitioned from laminar to turbulent, but at the cost of higher viscous drag than that of the smooth treatment with no pattern. After the flow had transitioned to turbulent and become attached to Micro Pattern #2, there was also a significant reduction in the viscous drag when compared to both the glass plate and the smooth treatment with no pattern.

In the Reynolds number 52,600 regime with passive flow control conditions, Micro Pattern #1 and Micro Pattern #2 had really interesting results. Micro Pattern #1 was able to experience significant viscous drag reduction while maintaining attached flow when the free stream flow transitioned from laminar flow to turbulent flow. The viscous drag was much lower than that of the smooth treatment with no pattern and the glass plate. Micro Pattern #2 was also shown to have flow attached when the free stream flow transitioned from laminar to turbulent. After the flow had transitioned to turbulent and attached to Micro Pattern #2, there was also a significant reduction in the viscous drag when compared to both the glass plate and the smooth treatment with no pattern.

In the Reynolds number 68,600 regime with passive flow control conditions, the Feather-Parallel treatment was able to maintain attached flow during the transition from laminar free stream to a turbulent free stream while experiencing a decrease in the viscous drag. Although the initial viscous drag in the laminar flow was higher than the viscous drag on the smooth treatment, after transition to turbulence the Feather-Parallel treatment had a lower viscous drag
than that of the smooth treatment. Also, interestingly, Micro pattern #2 was able to demonstrate flow attachment from laminar to turbulent flow while experiencing a viscous drag value approximately half that of the glass plate under the same conditions.

Lastly, in the Reynolds number 78,800 regime with passive flow control conditions, the Feather - Parallel treatment was able to maintain attached flow in the transition from laminar free stream conditions to turbulent free stream conditions, albeit at the cost of higher viscous drag. Again, the Micro Treatment #2 was able to demonstrate flow attachment from the transition of laminar free stream flow to turbulent free stream flow while experiencing a lower viscous drag than that of the smooth treatment of the glass plate.

Unfortunately the Bump Pattern treatment experienced flow separation at every single test at every single Reynolds number.

The primary conclusions of the research will indicate that

- Biomimetic micro and macro structures had a quantitative effect on the reduction of viscous drag of the surface ranging from approximately 4% to 62% in cases with attached flow.
- Certain structures had narrow ranges of operating conditions in which they were effective, such as Micro Pattern #2 showing lack of attachment during the laminar screen testing across all Reynolds numbers.
- In the present work, it is clear that there are certain biomimetic micro and macro structures that were able to have an effect on the flow control capabilities on Reynolds number $O(10^4)$.
- Micro Pattern #2 was able to maintain attached flow with both laminar and turbulent screens attached, and in many cases with the added benefit of drag reduction when switching to turbulent screens.

- Micro Pattern #1 was able to maintain attached flow under certain conditions, while demonstrating a noticeable reduction in drag.

- Feather - Parallel pattern was able to maintain flow attachment in certain Reynolds number ranges while occasionally also demonstrating a reduction in drag.
Recommendations

Biomimetic micro and macro structures have many potential uses in many aerodynamic applications, such as lower stall speeds, flow attachment, and the maintenance and upkeep of aircraft. Biomimetic micro and macro structures also have the potential ease of application, such as an adhesive similar to what was used in this study, or laser engraving structures into the paint or structures of many types of vehicles.

These micro and macro structures have been shown to passively alter the boundary layer characteristics, however, the addition of an active component through simple vibrations to induce dynamic roughness was shown to have little quantitative effect. However, there was an effect that was measurable.

For future materials work, it is recommended that larger treatments be designed in sheets or grids that can be interlocked or seamlessly meshed together to be tested on a larger scale. Micro pattern #2 showed many promising results, specific geometries that may have arisen due to the casting process should attempt to be studied or replicated for further testing. Examples of aforementioned geometries may include cracking or starred patterns in the base of the material due to the casting process itself. This cracking was made apparent in the micro structures themselves in the patterns that were tested, and as such, differences between micro pattern #1 and micro pattern #2 should be studied because both patterns performed well in drag reduction capabilities under certain conditions. Further testing on cracked or starred patterns while varying geometric structures at the micro level is recommended. The feather treatment was also effective in altering the boundary layer characteristics, namely in the parallel orientation. Further research
into the shape and dimensions of existing bird feathers should be studied and varying types of bird feathers should be produced for testing.

Dynamic roughness testing should be further improved upon from this particular study. Particularly with varying frequencies with the potential to vary the surface roughness via mechanisms beneath the surface.

For future aerodynamic work should take place with both micro and macro structures. Separation location should be tested, potentially by the use of a wing in a smoke tunnel with varying angles of attack to also test the ability for these micro and macro structures to attach flow. There should also be testing at higher Reynolds numbers that match orders of magnitude that are used more commonly in consumer operations, such as transportation. Testing should also be done with varying degrees of turbulence intensity to simulate varying environmental conditions and the impact on the flow control capabilities themselves.
Works Cited


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Appendix A: Wind Tunnel Test Section Qualifications

Using the following code and choosing a laminar test condition with highly correlated flow, the maximum turbulence intensity captured by the PIV system was 4.34% with the turbulator screen on, and the minimum turbulence intensity was 2.12% with the laminar screens on.

```matlab
%import the files
UMean = mean(U);
u = U-UMean;
u = u.^2;
rmSU = sqrt((1/length(u))*sum(u));
TurbIntensity = rmSU*100/UMean;
```
Appendix B: Matlab Code Used In Post Processing

The Code for processing the viscous drag forces is as shown below.

```matlab
clear
clc

% Need to process images? Switch the next variable from 0 to 1
processImages = 0;

% Need to manually look at Boundary Layers? Switch 0 to 1
manualBL = 0;

% Offset for PIV
offset = -65.88;  % mm

nu = 14.88*10^-6;
rho = 1.184;
mu = 1.846e-5;

% Import the files and set the directory
preamble = 'C:\Users\Justin\Documents\MATLAB\Research\';
location = 'Research\Average';
images = 'Research/Camera Images';

cd(preamble);
load ('profiles.mat');
timeAverageLocation = strcat(preamble,location);
imageLocation = strcat(preamble,images);

fileString = strcat(preamble,'Test_Data.xlsx');
Test_Data = importdata(fileString);
fileNames = num2str(Test_Data.data.Sheet1(:,2));
testNumber = num2str(Test_Data.data.Sheet1(:,1));
skinType = Test_Data.textdata.Sheet1(2:end,3);
speedSetting = num2str(Test_Data.data.Sheet1(:,4));
flowType = Test_Data.textdata.Sheet1(2:end,5);
flowParameters = Test_Data.textdata.Sheet1(2:end,6);
temperature = num2str(Test_Data.data.Sheet1(:,7));
pressure = num2str(Test_Data.data.Sheet1(:,8));
humidity = num2str(Test_Data.data.Sheet1(:,9));
separation = Test_Data.textdata.Sheet1(2:end,10);

cd(timeAverageLocation)
files = dir();
numberOfFiles = numel(dir());

% First, go through the fileNames and make sure all character arrays have
% leading zeros, if not, add them.
for i = 1:size(fileNames,1)
    TF = isspace(fileNames(i,:));
    for j = 1:length(TF)
```
if TF(j) == 1
    fileNames(i,j) = '0';
end
end
end

for counter = 3:numberOfFiles
    cd(timeAverageLocation)
    files = dir();
    cd(files(counter).name);
    currentFolder = pwd;
    file = dir();
    data_1 = importdata(file(3).name);
    cd ..
    for counter_2 = 1:length(fileNames)
        if any(strfind(currentFolder,fileNames(counter_2,1:end)))
            break
        elseif ~any(strfind(currentFolder,fileNames(counter_2,1:end)))
            counter_2 == length(fileNames)
            error('Did not find matching file');
        end
    end
    profileData{counter-2,1} = cellstr(fileNames(counter_2,1:end));
    profileData{counter-2,2} = cellstr(skinType(counter_2,1:end));
    profileData{counter-2,3} = cellstr(speedSetting(counter_2,1:end));
    profileData{counter-2,4} = cellstr(flowType(counter_2,1:end));
    profileData{counter-2,5} = cellstr(flowParameters(counter_2,1:end));
    profileData{counter-2,6} = cellstr(temperature(counter_2,1:end));
    profileData{counter-2,7} = cellstr(pressure(counter_2,1:end));
    profileData{counter-2,8} = cellstr(humidity(counter_2,1:end));

    x = data_1.data(:,1);
    y = data_1.data(:,2);
    u = data_1.data(:,3);
    v = data_1.data(:,4);

    xDim = unique(x,'rows','stable');
    yDim = unique(y,'rows','stable');

    %Create the vector fields
    X = zeros(length(yDim),length(xDim));
    Y = zeros(length(yDim),length(xDim));

    X(:,1) = xDim;
    Y(1,:) = yDim;

    U = zeros(length(yDim),length(xDim));
    V = zeros(length(yDim),length(xDim));

    %Find and populate the vector fields
    i = 1;
    j = 1;
    for i = 1:size(Y,1)
        for j = 1:size(X,2)
\[
X(i,j) = X(1,j);
Y(i,j) = Y(i,1);
\]

\[
\text{for } k = 1:\text{length}(u)
\]

\[
\text{if } (Y(i,1) == y(k)) \&\& (X(1,j) == x(k))
U(i,j) = u(k);
V(i,j) = v(k);
\]

\[
\text{end}
\]

\[
\text{end}
\]

\[
\text{end}
\]

\[
\text{profiles{counter-2,2} = X;}
\]

\[
\text{profiles{counter-2,3} = Y;}
\]

\[
\text{profiles{counter-2,4} = U;}
\]

\[
\text{profiles{counter-2,5} = V;}
\]

\[
xLower = \text{min(min}(X)));
xUpper = \text{max(max}(X));
yLower = \text{min(min}(Y));
yUpper = \text{max(max}(Y));
\]

\[
\text{if(processImages)}
\]

\[
\text{cd(imageLocation);}
\]

\[
\text{files = dir();}
\]

\[
\text{cd(files(counter).name);}
\]

\[
\text{figure(1)}
\]

\[
\text{hold on}
\]

\[
\text{img = imread('B00001.bmp');}
\]

\[
\text{im = img(1:753,1:938,:);}
\]

\[
\text{image([xLower,xUpper],[yUpper,yLower],im)}
\]

\[
\text{ax = gca;}
\]

\[
\text{ax.YDir = 'normal';}
\]

\[
q = \text{quiver}(X,Y,U,V);
\]

\[
q.Marker = '\text{x}';
\]

\[
\text{hold off}
\]

\[
\text{testNumber = cellstr(fileNames(counter_2,1:end));}
\]

\[
\text{profiles{counter-2,1} = testNumber;}
\]

\[
\text{disp(counter_2)}
\]

\[
\text{for } i=2:\text{size}(U,2)-2
\]

\[
\text{currentX = X(1,i);}
\]

\[
\text{currentY = Y(\text{end},i);}
\]

\[
\text{xlim([currentX-0.1,currentX+0.1])}
\]

\[
\text{ylim([currentY,currentY+2])}
\]

\[
\text{currentBL = i-1;}
\]

\[
\text{lastBL = size(U,2)-2;}
\]

\[
\text{str = strcat('Test#',testNumber,{'}','...}
\]

\[
\text{num2str(currentBL),'/',num2str(lastBL));}
\]

\[
\text{title(str)}
\]

\[
[-,yInput] = \text{ginput(1)};
\]

\[
yStart = \text{closestY}(y,yInput);
\]

\[
iY = \text{find}(Y(:,1) == yStart);
\]

\[
\text{profiles{counter-2,i}(;1) = U(1:iY,i)};
\]

\[
\text{profiles{counter-2,i}(;2) = U(1:iY,i)};
\]

\[
\text{profiles{counter-2,i}(;3) = Y(1:iY,i)};
\]

\[
\text{profiles{counter-2,i}(end,2) = 0;}
\]
UMeanCorner(counter-2,1) = mean(mean(U(2:7,end-7:end-2)));     
VMeanCorner(counter-2,1) = mean(mean(V(2:7,end-7:end-2)));    
end

cd ..

%Now get an average profile, and we can plot the average, individual ones, 
%the individual ones overlaid, etc.

averaged = averageProfiles(profiles);

%Blasius Solution
[eta,f]=ode45(@fprime, [0,10], [0 0 0.332]);

treatment = createCell();

for i = 1:size(profiles,1)
    X = profiles{i,2};
    Y = profiles{i,3};
    figure(1);
    fig = figure(1);
    if strcmpi(profileData{i,4},'Laminar')
        blasiusX = offset + mean(profiles{i,2}(1,:));
        blasiusY = eta/sqrt(UMeanCorner(i)/(2*nu*(blasiusX*10^-3)));
        blasiusY = blasiusY * 1000;
        blasiusU = f(:,2).*UMeanCorner(i);
        plot(blasiusU,blasiusY,'k--','LineWidth',4)
        for j=6:size(profiles,2)
            normalizedY = profiles{i,j}(3:end,3)-profiles{i,j}(end,3);
            velocityProfile = profiles{i,j}(3:end,2);
            if j == 6
                normalizedY1 = profiles{i,end-10}(3:end,3)-profiles{i,end-10}(end,3);
                velocityProfile1 = profiles{i,end-10}(3:end,2);
                plot(velocityProfile1,normalizedY1,'r','LineWidth',2)
                legend('Blasius Solution','First BL Profile','Last BL Profile');
            else
                plot(velocityProfile,normalizedY);
            end
        end
    end
end
fileName = profiles{i,1};
title(strcat('Test#',fileName,...
    ' Overlaid Boundary Layers Vs. Blasius Solution'));
ylabel('y [mm]');
xlabel('u [m/s]');
ylim([0,6]);
hold off
end
path = getPath(i,profileData);
cd(path)
str = strcat('Test#',char(fileName));
print(fig,str,'-dpng')
close all

fig = figure(1);
hold on
plot(blasiusU,blasiusY)
plot(averaged{i,1}(:,1),averaged{i,1}(:,2))
title(strcat('Test#',fileName,' Skin:',profileData{i,2},...
    ' Speed Setting:', profileData{i,3}, ' Flow Type:', ...
    profileData{i,4}, ' Flow Parameters:', profileData{i,5}));
ylabel('y [mm]');
xlabel('u [m/s]');
ylim([0,6]);
legend('Blasius Solution','Average Profile');
hold off
path = getAveragePath(i,profileData);
cd(path)
str = strcat('Test#',char(fileName), ' - Average');
print(fig,str,'-dpng')

close all
end
if strcmpi(profileData{i,4},'Turbulent')
    mid = size(profiles,2)/2;
    aveNormalizedY = profiles{i,mid}(3:end,3)-profiles{i,mid}(end,3);
    aveRex = abs(UMeanCorner(i)*profiles{i,2}(1,mid)/nu);
    aveDel = abs(0.38*profiles{i,2}(1,mid)/(aveRex^(1/5)));
    aveTurbulentU = UMeanCorner(i)*(aveNormalizedY/aveDel).^(1/7);
    plot(aveTurbulentU,aveNormalizedY,'k--','LineWidth',4)
    for j=6:size(profiles,2)
        normalizedY = profiles{i,j}(3:end,3)-profiles{i,j}(end,3);
        velocityProfile = profiles{i,j}(3:end,2);
        Rex = abs(UMeanCorner(i)*profiles{i,2}(1,j-5)/nu);
        del = abs(0.38*profiles{i,2}(1,j-5)/(Rex^(1/5)));
        turbulentU = UMeanCorner(i)*(normalizedY/del).^(1/7);
        hold on
        if j == 6
            velocityProfile1 = profiles{i,end-10}(3:end,2);
            normalizedY1 = profiles{i,end-10}(3:end,3)-...
                profiles{i,end-10}(end,3);
            velocityProfile2 = profiles{i,16}(3:end,2);
            normalizedY2 = profiles{i,16}(3:end,3)-...
                profiles{i,16}(end,3);
            plot(velocityProfile1,normalizedY1,'r','LineWidth',2)
        else
            plot(velocityProfile,turbulentU,'k--','LineWidth',4)
        end
    end
end
plot(velocityProfile2,normalizedY2,'k','LineWidth',2)
legend('Prandtl\'s Solution','First BL Profile','Last BL Profile');
end
if j == size(profiles,2)
    velocityProfile1 = profiles{i,end-10}(3:end,2);
normalizedY1 = profiles{i,end-10}(3:end,3)-...
    profiles{i,end-10}(end,3);
    velocityProfile2 = profiles{i,16}(3:end,2);
normalizedY2 = profiles{i,16}(3:end,3)-...
    profiles{i,16}(end,3);
    plot(velocityProfile1,normalizedY1,'r','LineWidth',2)
plot(velocityProfile2,normalizedY2,'k','LineWidth',2)
else
    plot(velocityProfile,normalizedY);
end
fileName = profiles{i,1};
title(strcat('Test#',fileName,...
    ' Overlaid Boundary Layers Vs Turbulent Solution'));
ylabel('y [mm]');
xlabel('u [m/s]');
ylim([0,6]);
hold off
end
path = getPath(i,profileData);
cd(path)
str = strcat('Test#',char(fileName));
print(fig,str,'-dpng')
close all

fig = figure(1);
hold on
plot(turbulentU,normalizedY)
plot(averaged{i,1}(:,1),averaged{i,1}(:,2))
title(strcat('Test#',fileName,' Skin:',profileData{i,2},...
    ' Speed Setting:', profileData{i,3}, ' Flow Type:', ...
    profileData{i,4}, ' Flow Parameters:', profileData{i,5}));
ylabel('y [mm]');
xlabel('u [m/s]');
ylim([0,6]);
legend('Turbulent Solution','Average Profile');
hold off
path = getAveragePath(i,profileData);
cd(path)
str = strcat('Test#',char(fileName), ' - Average');
print(fig,str,'-dpng')
close all
end
[q,r,s,str] = getValues(i,profileData);
n = treatment{1,q}{1,r}{1,s}{1,3};
treatment{1,q}{1,r}{1,s}{n,1} = char(fileName);
treatment{1,q}{1,r}{1,s}{n,2} = str;
treatment{1,q}{1,r}{1,s}{1,3} = n + 1;
end
%Coordinate Transformation
theta1 = -90;
theta2 = 90;
%Need to get just u and y vectors
P = profiles(:,6:end);
normalizedProfiles = cell(size(P,1),size(P,2));
for i = 1:size(P,1)
    for j = 1:size(P,2)
        normalizedProfiles{i,j}{:,1} = P{i,j}{:,2};
        %Divide by 1000 to get from mm to m
        normalizedProfiles{i,j}{:,2} = (P{i,j}{:,3}-P{i,j}(end,3))/1000;
    end
end

transform = cell(size(P,1),size(P,2));
dudy = cell(size(P,1),size(P,2));
for i = 1:size(P,1)
    for j = 1:size(P,2)
        transform{i,j}{:,1} = -normalizedProfiles{i,j}{:,2}*sind(theta1);
        transform{i,j}{:,2} = normalizedProfiles{i,j}{:,1}*sind(theta1);
        ws = warning('off','all');  % Turn off warning
        p = polyfit(transform{i,j}{:,1},transform{i,j}{:,2},7);
        k = polyder(p);
        warning(ws)  % Turn it back on.
        xprime = linspace(.0005,0,30);
        yprime = polyval(k,xprime);
        dudy{i,j}{:,1} = -yprime*sind(theta2);
        dudy{i,j}{:,2} = xprime*sind(theta2);
    end
end

deltaX = (profiles{1,2}(1,2) - profiles{1,2}(1,1))/1000;%mm to m
tau = cell(size(dudy,1),size(dudy,2));
for i = 1:size(dudy,1)
    for j = 1:size(dudy,2)
        %To allow for a little room for PIV error, grab at 18 instead of
        %at the end
        tau{i,j} = mu * dudy{i,j}(18,1);
    end
end
for i = 1:size(tau,1)
    for j = 1:size(tau,2)-1
        drag(i,j) = (tau{i,j} + tau{i,j+1})*deltaX/2;
    end
end
drag = sum(drag,2);
for i = 1:size(profileData,1)
    profileData{i,9} = drag(i,1);
end
function [ x1 ] = closestX( x, val )
tmp = abs(x-val);
[~, idx] = min(tmp); % index of closest value
closest = x(idx); % closest value
x1 = closest;
end

function [ y1 ] = closestY( y, val )
tmp = abs(y-val);
[~, idx] = min(tmp); % index of closest value
closest = y(idx); % closest value
y1 = closest;
end

function [ path ] = getPath(i, profileData)
str1 = 'C:\Users\Justin\Documents\MATLAB\Research\Overlaid Boundary Layers';
switch(str2double(cell2mat(profileData{i,3})))
    case 1
        str2 = '\Reynolds Number 26500';
    case 2
        str2 = '\Reynolds Number 52600';
    case 3
        str2 = '\Reynolds Number 68600';
    case 4
        str2 = '\Reynolds Number 78800';
end
if strcmpi(profileData{i,4}(:,1),'Laminar')
    str3 = '\Laminar';
else
    str3 = '\Turbulent';
end
if strcmpi(profileData{i,5}(:,1),'Passive')
    str4 = '\Passive';
else
    str4 = '\Active';
end
path = strcat(str1, str2, str3, str4);
end

function [ path ] = getAveragePath(i, profileData)
str1 = 'C:\Users\Justin\Documents\MATLAB\Research\Average Boundary Layers';
switch(str2double(cell2mat(profileData{i,3})))
    case 1
        str2 = '\Reynolds Number 26500';
    case 2
        str2 = '\Reynolds Number 52600';
    case 3
        str2 = '\Reynolds Number 68600';
    case 4
        str2 = '\Reynolds Number 78800';
end

if strcmpi(profileData{i,5}(:,1),'Passive')
    str3 = '\Passive';
else
    str3 = '\Active';
end

path = strcat(str1,str2,str3);
end

% Short script to run after the code. It looks at all of the
% displacement thicknesses, the momentum thicknesses, and then the
% shape factors, which can be used to determine separation

displacementThickness = cell(size(P,1),size(P,2));
momentumThickness = cell(size(P,1),size(P,2));
shapeFactor = cell(size(P,1),size(P,2)+1);
deltaY = P{1,1}(end-1,3)-P{1,1}(end,3);
for i = 1:size(P,1)
    for j = 2:size(P,2)
        f = 1-(P{i,j}(:,2)/UMeanCorner(i));
        g = (P{i,j}(:,2)/UMeanCorner(i)) .* f;
        for k = size(P{i,j},1):-1:4
            f(k,2) = (f(k,1)+f(k-1,1))*deltaY/2;
            g(k,2) = (g(k,1)+g(k-1,1))*deltaY/2;
        end
        displacementThickness{i,j} = sum(f(:,2));
        momentumThickness{i,j} = sum(g(:,2));
        shapeFactor{i,1} = profiles{i,1};
        factor = displacementThickness{i,j}/...
            momentumThickness{i,j};
        if factor > 10 || factor < 0
            continue
        end
        shapeFactor{i,j} = displacementThickness{i,j}/...
            momentumThickness{i,j};
    end
end
j = 1;
for i = 1:size(P,1)
    meanShapeFactor{i,1} = profiles{i,1};
    meanShapeFactor{i,2} = mean(cell2mat(shapeFactor(i,2:end)),2);
    if meanShapeFactor{i,2} > 3.55 || meanShapeFactor{i,2} < 1
        separatedFlow{j,1} = meanShapeFactor{i,1};
        separatedFlow{j,2} = meanShapeFactor{i,2};
j = j + 1;
end
end
%plotting graphs
close all
clf
figure(1);
title('Laminar Flow-Active and Passive Drag Results at Reynolds Numbers')
xlabel('Reynolds Number')
ylabel('Drag [mN/m]')
ax1 = gca;
hold on
figure(2);
ax2 = gca;
title('Turbulent Flow-Active and Passive Drag Results at Reynolds Numbers')
xlabel('Reynolds Number')
ylabel('Drag [mN/m]')
hold on

%creating the legends
scatter(ax1,nan,nan,'square','filled');
scatter(ax1,nan,nan,'diamond','filled');
scatter(ax1,nan,nan,'^','filled');
scatter(ax1,nan,nan,'v','filled');
scatter(ax1,nan,nan,'>','filled');
scatter(ax1,nan,nan,'<','filled');
scatter(ax1,nan,nan,'pentagram','filled');
scatter(ax1,nan,nan,'hexagram','filled');
scatter(ax2,nan,nan,'square','filled');
scatter(ax2,nan,nan,'diamond','filled');
scatter(ax2,nan,nan,'^','filled');
scatter(ax2,nan,nan,'v','filled');
scatter(ax2,nan,nan,'>','filled');
scatter(ax2,nan,nan,'<','filled');
scatter(ax2,nan,nan,'pentagram','filled');
scatter(ax2,nan,nan,'hexagram','filled');

legend(ax1,{'Glass','Smooth',' Feather-Parallel',' Feather-Random',...'
 Feather-Rotated',' Bump Pattern',' Micro Pattern #1',...'
 Micro Pattern #2'},'Location','northeastoutside');
legend(ax2,{'Glass','Smooth',' Feather-Parallel',' Feather-Random',...'
 Feather-Rotated',' Bump Pattern',' Micro Pattern #1',...'
 Micro Pattern #2'},'Location','northeastoutside');

for i = 1:size(profiles,1)
    switch(str2double(cell2mat(profileData{i,3})))
        case 1
            Re = 26500;
        case 2
            Re = 52600;
        case 3
            Re = 68600;
        case 4
            Re = 78800;
    end
dragValue = drag(i)*1000;
if strcmpi('Separated',separation(i,1))
    filled = 'none';
else
    filled = 'filled';
end

if strcmpi('Glass',profileData{i,2})
    mkr = 'square';
elseif strcmpi('Smooth',profileData{i,2})
    mkr = 'diamond';
elseif strcmpi('Feather - Parallel',profileData{i,2})
    mkr = '^';
elseif strcmpi('Feather - Random',profileData{i,2})
    mkr = 'v';
elseif strcmpi('Feather - Rotated',profileData{i,2})
    mkr = '>'; 
elseif strcmpi('Bump Pattern',profileData{i,2})
    mkr = '<';
elseif strcmpi('Micro Pattern 1',profileData{i,2})
    mkr = 'pentagram';
else
    mkr = 'hexagram';
end

if strcmpi('Active',profileData{i,5})
    col = 'red';
else
    col = 'blue';
end

sz = 60;

if strcmpi('Laminar',profileData{i,4})
    if strcmpi('Separated',separation(i,1))
        scatter(ax1,Re,dragValue,sz,mkr,col)
    else
        scatter(ax1,Re,dragValue,sz,mkr,col,'filled')
    end
else
    if strcmpi('Separated',separation(i,1))
        scatter(ax2,Re,dragValue,sz,mkr,col)
    else
        scatter(ax2,Re,dragValue,sz,mkr,col,'filled')
    end
end
set(ax1,'Ydir','reverse')
set(ax2,'Ydir','reverse')
grid(ax1,'on')
grid(ax1,'minor')
grid(ax2,'on')
grid(ax2,'minor')
Appendix C: Blockage Derivation

The blockage was derived using the following equation:

\[ BL\% = \frac{A_{\text{Frontal}}}{A_{\text{TS}}} \]  \hspace{1cm} \text{Eq. 8}

Where the frontal area is given by the summation of the individual areas of the individual components used, and the test section area is given by the cross sectional area of the test section in use.

\[ A_{\text{Frontal}} = A_{\text{Plate}} + A_{\text{Motor}} \]  \hspace{1cm} \text{Eq. 9}

\[ A_{\text{Plate}} = w \cdot h = 6 \text{ in} \cdot 0.125 \text{ in} = 0.750 \text{ in} \]  \hspace{1cm} \text{Eq. 10}

\[ A_{\text{Motor}} = \frac{\pi D^2}{4} = \frac{\pi(0.969^2)}{4} = 0.737 \text{ in}^2 \]  \hspace{1cm} \text{Eq. 11}

\[ A_{\text{Frontal}} = 0.750 + 0.737 = 1.487 \text{ in}^2 \]  \hspace{1cm} \text{Eq. 12}

and where the test section had known measurements of 6in x 6in.

\[ A_{\text{TS}} = w \cdot h = 6 \cdot 6 = 36 \text{ in}^2 \]  \hspace{1cm} \text{Eq. 13}

Therefore, the percent blockage is as follows:

\[ \% BL = \frac{A_{\text{Frontal}}}{A_{\text{TS}}} = \frac{1.478}{36} = 4.1\% \]  \hspace{1cm} \text{Eq. 14}
Appendix D: Uncertainty Analysis

PIV Uncertainty

The uncertainty analysis performed was followed in accordance to the recommended procedure that was developed by the International Towing Tank Conference that views in-depth sources of uncertainty in the PIV measurements (ITTC Recommended procedures and guidelines for Uncertainty analysis in Particle Image Velocimetry). The parameters used in the analysis are shown below, in Table 20. The uncertainties for the measurements of velocity, distance, and time, along with the associated error sources are shown in Table 21, Table 22, and Table 23 respectively.

Table 20 - Parameters used in the Uncertainty Analysis.

<table>
<thead>
<tr>
<th>Target Flow of Measurement</th>
<th>2-D Air Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement Facility</td>
<td>WVU Wind Smoke Tunnel</td>
</tr>
<tr>
<td>Measurement Area</td>
<td>8x6 mm²</td>
</tr>
<tr>
<td>Uniform Flow Speed</td>
<td>14 m/s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Calibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance of Reference Points</td>
</tr>
<tr>
<td>Distance of Reference Image</td>
</tr>
<tr>
<td>Magnification Factor</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Calibrated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance of Reference Points</td>
</tr>
<tr>
<td>Distance of Reference Image</td>
</tr>
<tr>
<td>Magnification Factor</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flow Visualization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracer Particle</td>
</tr>
<tr>
<td>Average Diameter</td>
</tr>
<tr>
<td>Standard Deviation of Diameter</td>
</tr>
<tr>
<td>Average Specific Gravity</td>
</tr>
<tr>
<td>Light Source</td>
</tr>
<tr>
<td>Thickness of Light Sheet</td>
</tr>
<tr>
<td>Time interval</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Image Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera</td>
</tr>
<tr>
<td>Spatial Resolution</td>
</tr>
<tr>
<td>Sampling Frequency</td>
</tr>
<tr>
<td>Gray Scale Resolution</td>
</tr>
<tr>
<td>Cell Size</td>
</tr>
</tbody>
</table>

Optical System

<table>
<thead>
<tr>
<th>Optical System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance From Target</td>
</tr>
<tr>
<td>Length of Focus</td>
</tr>
</tbody>
</table>
### Table 21 - Uncertainty for Velocity.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Category</th>
<th>Error Sources</th>
<th>$u(x)$</th>
<th>Unit</th>
<th>$c_i$</th>
<th>Unit</th>
<th>$u(x)$</th>
<th>$u_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>Calibration</td>
<td>Affine Image</td>
<td>7.00E-01 px</td>
<td>$9.378E+00$ mm/px$^2$</td>
<td>$5.60E+00$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Physical Distance</td>
<td>2.00E+00 mm</td>
<td>$7.990E+00$ mm/px$^2$</td>
<td>$1.54E-05$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Image Distortion By Lens</td>
<td>2.00E+00 px</td>
<td>$9.378E+00$ mm/px$^2$</td>
<td>$1.87E-04$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Board Position</td>
<td>5.00E-03 mm</td>
<td>$1.58E+00$ mm/px$^2$</td>
<td>$7.88E-07$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pixel Board</td>
<td>5.00E-03 px</td>
<td>$4.06E+00$ mm/px</td>
<td>$1.43E-05$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Acquisition</td>
<td>Laser Power Fluctuation</td>
<td>1.00E+00 mm</td>
<td>$1.00E+00$ mm/px$^2$</td>
<td>$1.00E+00$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Image Distortion By CCD</td>
<td>2.00E+00 mm</td>
<td>$1.13E+00$ mm/px$^2$</td>
<td>$8.33E+00$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Normal View Angle</td>
<td>2.00E-03 deg</td>
<td>$4.06E+00$ mm/px</td>
<td>$1.43E+00$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Matching Error</td>
<td>2.00E+00 pixels</td>
<td>$1.00E+00$ mm/px$^2$</td>
<td>$2.00E+00$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sub-Pixel Analysis</td>
<td>2.00E+00 pixels</td>
<td>$1.00E+00$ mm/px$^2$</td>
<td>$3.00E+00$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Acquisition</td>
<td>1.00E+00 mm/s</td>
<td>$1.00E+00$ mm/px</td>
<td>$1.00E+00$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Particle Trajectory</td>
<td>1.2 mm/s</td>
<td>$1.00E+00$ mm/px</td>
<td>$1.20E+00$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>SD Effects</td>
<td>5.7 mm/s</td>
<td>$1.00E+00$ mm/px</td>
<td>9.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Summary</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$u_i$ 14.0 mm/s</td>
</tr>
</tbody>
</table>

### Table 22 - Uncertainty for Distance.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Category</th>
<th>Error Sources</th>
<th>$u(x)$</th>
<th>Unit</th>
<th>$c_i$</th>
<th>Unit</th>
<th>$u(x)$</th>
<th>$u_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_1$</td>
<td>Acquisition</td>
<td>Digital Error</td>
<td>0.5 px</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gaussian</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Non-Uniformity of Distribution</td>
<td>12 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$x_2$</td>
<td>Calibration</td>
<td>Origin Correlation</td>
<td>2 px</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Magnification Error</td>
<td>1.76E+00 mm/px</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Combined Uncertainty $u_i$ 8.8 mm

### Table 23 - Uncertainty for Time.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Category</th>
<th>Error Sources</th>
<th>$u(x)$</th>
<th>Unit</th>
<th>$c_i$</th>
<th>Unit</th>
<th>$u(x)$</th>
<th>$u_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_1$, $t_2$</td>
<td>Acquisition</td>
<td>Delay Generator/Pulse Time</td>
<td>1.00E-05 s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Combined Uncertainty $u_i$ 1.00E-06 s

### Reynolds Number Uncertainty

Reynolds number uncertainty was calculated using the maximum likely uncertainty, derived from the maximum from the maximum uncertainty at the maximum velocity in the PIV calculations. The list of measured quantities is measured quantities is shown in Table 24. These quantities were used to calculate the Reynolds number using the mean flow that was captured using the PIV analysis.
Table 24 - Measured quantities and uncertainties.

<table>
<thead>
<tr>
<th>measured/calculated value</th>
<th>P (in hg)</th>
<th>T (°F)</th>
<th>x (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>obtained/calculated</td>
<td>30.09</td>
<td>83</td>
<td>31.347</td>
</tr>
<tr>
<td>(\delta) measured/calculated value</td>
<td>0.005</td>
<td>0.5</td>
<td>0.0008</td>
</tr>
</tbody>
</table>

The Reynolds number uncertainty was calculated using quadrature, following the given equation.

\[
\delta Re = Re \sqrt{\left(\frac{\delta Pa}{Pa}\right)^2 + \left(\frac{\delta U}{U}\right)^2 + \left(\frac{\delta x}{x}\right)^2 + \left(\frac{\delta T}{T}\right)^2}
\]

And the values for the velocities and uncertainties in velocity and Reynolds numbers are given in Table 25.

Table 25 - Reynolds number uncertainties.

<table>
<thead>
<tr>
<th>(U_{\text{measured}}) (m/s)</th>
<th>(\delta U_{\text{measured}})</th>
<th>Re</th>
<th>(\delta Re)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.69</td>
<td>0.014</td>
<td>26500</td>
<td>189</td>
</tr>
<tr>
<td>7.02</td>
<td>0.014</td>
<td>52600</td>
<td>334</td>
</tr>
<tr>
<td>11.77</td>
<td>0.014</td>
<td>68600</td>
<td>421</td>
</tr>
<tr>
<td>14.39</td>
<td>0.014</td>
<td>78800</td>
<td>481</td>
</tr>
</tbody>
</table>

**Blockage Uncertainty**

Using the values calculated earlier in the appendix section on blockage, the uncertainties will be derived here.

\[
\delta A_{\text{Plate}} = 0.750 \sqrt{\left(\frac{0.0005}{0.125}\right)^2 + \left(\frac{0.0005}{6}\right)^2}
\]

\[
= 0.003 \text{ in}^2
\]
\[ \delta A_{Motor} \]
\[ = 0.737 \sqrt{\left(\frac{0.0005}{0.962}\right)^2 + \left(\frac{0.0005}{0.962}\right)^2} \]
\[ = 0.0005 \text{ in}^2 \]

\[ \delta A_{Frontal} = \delta A_{Plate} + \delta A_{Motor} \]  
\[ = 0.003 + 0.0005 \]
\[ = 0.0035 \text{ in}^2 \]

\[ \delta \% BL \]
\[ = \% BL \sqrt{\left(\frac{\delta A_{Frontal}}{A_{Frontal}}\right)^2 + \left(\frac{\delta A_{TS}}{A_{TS}}\right)^2} \]

\[ \delta \% BL \]
\[ = 0.041 \sqrt{\left(\frac{0.0035}{1.487}\right)^2 + \left(\frac{0.004}{36}\right)^2} \]
\[ = 0.04\% \]
Appendix E: Frequency Derivation

The code for the frequency derivation is shown after Figure 108. The general idea was to record the motor in operation using a microphone, and then import the .WAV file into Matlab and perform a Fourier Fast Transform on the data. The data is as shown in Figure 108. The maximum amplitude was slightly higher than unity, and the frequency at which it occurred was approximately 641 Hz.

![FFT of .WAV file](image)

Figure 108 - FFT of the recording of the motor in operation.
%wavfft
[y,fs] = audioread('data.wav');

t = linspace(0,length(y)/fs,length(y));
nFFT = 1024;
f = linspace(0,fs,nFFT);
G = abs(fft(y,nFFT));
figure(1)
plot(t,y)
title('.WAV File Plotted In Time');

figure(2)
plot(f(1:nFFT/2),G(1:nFFT/2));
title('FFT of .WAV file');
xlabel('Frequency [Hz]')
ylabel('Magnitude');
Reynolds Number 26500 Laminar Flow, Passive Flow Control

Figure 109 - Glass, Reynolds number = 26500, laminar, passive.

Figure 110 - Smooth, Reynolds number = 26500, laminar, passive.
Figure 111 - Feather - parallel, Reynolds number = 26500, laminar, passive.

Figure 112 - Feather - random, Reynolds number = 26500, laminar, passive.
Figure 113 - Feather - rotated, Reynolds number = 26500, laminar, passive.

Figure 114 - Bump pattern, Reynolds number = 26500, laminar, passive.
Figure 115 - Micro pattern #1, Reynolds number = 26500, laminar, passive.

Figure 116 - Micro pattern #2, Reynolds number = 26500, laminar, passive.
Reynolds Number 26500 Laminar Flow, Active Flow Control

Figure 117 - Glass, Reynolds number = 26500, laminar, active.

Figure 118 - Smooth, Reynolds number = 26500, laminar, active.
Figure 119 - Feather - parallel, Reynolds number = 26500, laminar, active.

Figure 120 - Feather - random, Reynolds number = 26500, laminar, active.
Figure 121 - Feather - rotated, Reynolds number = 26500, laminar, active.

Figure 122 - Bump pattern, Reynolds number = 26500, laminar, active.
Figure 123 - Micro pattern #1, Reynolds number = 26500, laminar, active.

Figure 124 - Micro pattern #2, Reynolds number = 26500, laminar, active.
Reynolds Number 26500 Turbulent Flow, Passive Flow Control

Figure 125 - Glass, Reynolds number = 26500, turbulent, passive.

Figure 126 - Smooth, Reynolds number = 26500, turbulent, passive.
Figure 127 - Feather - parallel, Reynolds number = 26500, turbulent, passive.

Figure 128 - Feather - random, Reynolds number = 26500, turbulent, passive.
Figure 129 - Feather - rotated, Reynolds number = 26500, turbulent, passive.

Figure 130 - Bump pattern, Reynolds number = 26500, turbulent, passive.
Figure 131 - Micro pattern #1, Reynolds number = 26500, turbulent, passive.

Figure 132 - Micro pattern #2, Reynolds number = 26500, turbulent, passive.
Figure 133 - Glass, Reynolds number = 26500, turbulent, active.

Figure 134 - Smooth, Reynolds number = 26500, turbulent, active.
Figure 135 - Feather - parallel, Reynolds number = 26500, turbulent, active.

Figure 136 - Feather - random, Reynolds number = 26500, turbulent, active.
Figure 137 - Feather - rotated, Reynolds number = 26500, turbulent, active.

Figure 138 - Bump pattern, Reynolds number = 26500, turbulent, active.
Figure 139 - Micro pattern #1, Reynolds number = 26500, turbulent, active.

Figure 140 - Micro pattern #2, Reynolds number = 26500, turbulent, active.
Reynolds Number 52600, Laminar Flow, Passive Flow Control

Figure 141 - Glass, Reynolds number = 52600, laminar, passive.

Figure 142 - Smooth, Reynolds number = 52600, laminar, passive.
Figure 143 - Feather - parallel, Reynolds number = 52600, laminar, passive.

Figure 144 - Feather - random, Reynolds number = 52600, laminar, passive.
Figure 145 - Feather - rotated, Reynolds number = 52600, laminar, passive.

Figure 146 - Bump pattern, Reynolds number = 52600, laminar, passive.
Figure 147 - Micro pattern #1, Reynolds number = 52600, laminar, passive.

Figure 148 - Micro pattern #2, Reynolds number = 52600, laminar, passive.
Reynolds Number 52600, Laminar Flow, Active Flow Control

Figure 149 - Glass, Reynolds number = 52600, laminar, active.

Figure 150 - Smooth, Reynolds number = 52600, laminar, active.
Figure 151 - Feather - parallel, Reynolds number = 52600, laminar, active.

Figure 152 - Feather - random, Reynolds number = 52600, laminar, active.
Figure 153 - Feather - rotated, Reynolds number = 52600, laminar, active.

Figure 154 - Bump pattern, Reynolds number = 52600, laminar, active.
Figure 155 - Micro pattern #1, Reynolds number = 52600, laminar, active.

Figure 156 - Micro pattern #2, Reynolds number = 52600, laminar, active.
Reynolds Number 52600, Turbulent Flow, Passive Flow Control

Figure 157 - Glass, Reynolds number = 52600, turbulent, passive.

Figure 158 - Smooth, Reynolds number = 52600, turbulent, passive.
Figure 159 - Feather - parallel, Reynolds number = 52600, turbulent, passive.

Figure 160 - Feather - random, Reynolds number = 52600, turbulent, passive.
Figure 161 - Feather - rotated, Reynolds number = 52600, turbulent, passive.

Figure 162 - Bump pattern, Reynolds number = 52600, turbulent, passive.
Figure 163 - Micro pattern #1, Reynolds number = 52600, turbulent, passive.

Figure 164 - Micro pattern #2, Reynolds number = 52600, turbulent, passive.
Reynolds Number 52600, Turbulent Flow, Active Flow Control

Figure 165 - Glass, Reynolds number = 52600, turbulent, active.

Figure 166 - Smooth, Reynolds number = 52600, turbulent, active.
Figure 167 - Feather - parallel, Reynolds number = 52600, turbulent, active.

Figure 168 - Feather - random, Reynolds number = 52600, turbulent, active.
Figure 169 - Feather - rotated, Reynolds number = 52600, turbulent, active.

Figure 170 - Bump pattern, Reynolds number = 52600, turbulent, active.
Figure 171 - Micro pattern #1, Reynolds number = 52600, turbulent, active.

Figure 172 - Micro pattern #2, Reynolds number = 52600, turbulent, active.
Reynolds Number 68600, Laminar Flow, Passive Flow Control

Figure 173 - Glass, Reynolds number = 68600, laminar, passive.

Figure 174 - Smooth, Reynolds number = 68600, laminar, passive.
Figure 175 - Feather - parallel, Reynolds number = 68600, laminar, passive.

Figure 176 - Feather - random, Reynolds number = 68600, laminar, passive.
Figure 177 - Feather - rotated, Reynolds number = 68600, laminar, passive.

Figure 178 - Bump pattern, Reynolds number = 68600, laminar, passive.
Figure 179 - Micro pattern #1, Reynolds number = 68600, laminar, passive.

Figure 180 - Micro pattern #2, Reynolds number = 68600, laminar, passive.
Reynolds Number 68600, Laminar Flow, Active Flow Control

Figure 181 - Glass, Reynolds number = 68600, laminar, active.

Figure 182 - Smooth, Reynolds number = 68600, laminar, active.
Figure 183 - Feather - parallel, Reynolds number = 68600, laminar, active.

Figure 184 - Feather - random, Reynolds number = 68600, laminar, active.
Figure 185 - Feather - rotated, Reynolds number $= 68600$, laminar, active.

Figure 186 - Bump pattern, Reynolds number $= 68600$, laminar, active.
Figure 187 - Micro pattern #1, Reynolds number = 68600, laminar, active.

Figure 188 - Micro pattern #2, Reynolds number = 68600, laminar, active.
Reynolds Number 68600, Turbulent Flow, Passive Flow Control

Figure 189 - Glass, Reynolds number = 68600, turbulent, passive.

Figure 190 - Smooth, Reynolds number = 68600, turbulent, passive.
Figure 191 - Feather - parallel, Reynolds number = 68600, turbulent, passive.

Figure 192 - Feather - random, Reynolds number = 68600, turbulent, passive.
Figure 193 - Feather - rotated, Reynolds number = 68600, turbulent, passive.

Figure 194 - Bump pattern, Reynolds number = 68600, turbulent, passive.
Figure 195 - Micro pattern #1, Reynolds number = 68600, turbulent, passive.

Figure 196 - Micro pattern #2, Reynolds number = 68600, turbulent, passive.
Reynolds Number 68600, Turbulent Flow, Active Flow Control

Figure 197 - Glass, Reynolds number = 68600, turbulent, active.

Figure 198 - Smooth, Reynolds number = 68600, turbulent, active.
Figure 199 - Feather - parallel, Reynolds number = 68600, turbulent, active.

Figure 200 - Feather - random, Reynolds number = 68600, turbulent, active.
Figure 201 - Feather - rotated, Reynolds number = 68600, turbulent, active.

Figure 202 - Bump pattern, Reynolds number = 68600, turbulent, active.
Figure 203 - Micro pattern #1, Reynolds number = 68600, turbulent, active.

Figure 204 - Micro pattern #2, Reynolds number = 68600, turbulent, active.
Reynolds Number 78800, Laminar Flow, Passive Flow Control

Figure 205 - Glass, Reynolds number = 78800, laminar, passive.

Figure 206 - Smooth, Reynolds number = 78800, laminar, passive.
Figure 207 - Feather - parallel, Reynolds number = 78800, laminar, passive.

Figure 208 - Feather - random, Reynolds number = 78800, laminar, passive.
Figure 209 - Feather - rotated, Reynolds number = 78800, laminar, passive.

Figure 210 - Bump pattern, Reynolds number = 78800, laminar, passive.
Figure 211 - Micro pattern #1, Reynolds number = 78800, laminar, passive.

Figure 212 - Micro pattern #2, Reynolds number = 78800, laminar, passive.
Reynolds Number 78800, Laminar Flow, Active Flow Control

Figure 213 - Glass, Reynolds number = 78800, laminar, active.

Figure 214 - Smooth, Reynolds number = 78800, laminar, active.
Figure 215 - Feather - parallel, Reynolds number = 78800, laminar, active.

Figure 216 - Feather - random, Reynolds number = 78800, laminar, active.
Figure 217 - Feather - rotated, Reynolds number = 78800, laminar, active.

Figure 218 - Bump pattern, Reynolds number = 78800, laminar, active.
Figure 219 - Micro pattern #1, Reynolds number = 78800, laminar, active.

Figure 220 - Micro pattern #2, Reynolds number = 78800, laminar, active.
Reynolds Number 78800, Turbulent Flow, Passive Flow Control

Figure 221 - Glass, Reynolds number = 78800, turbulent, passive.

Figure 222 - Smooth, Reynolds number = 78800, turbulent, passive.
Figure 223 - Feather - parallel, Reynolds number = 78800, turbulent, passive.

Figure 224 - Feather - random, Reynolds number = 78800, turbulent, passive.
Figure 225 - Feather - rotated, Reynolds number = 78800, turbulent, passive.

Figure 226 - Bump pattern, Reynolds number = 78800, turbulent, passive.
Figure 227 - Micro pattern #1, Reynolds number = 78800, turbulent, passive.

Figure 228 - Micro pattern #2, Reynolds number = 78800, turbulent, passive.
Reynolds Number 78800, Turbulent Flow, Active Flow Control

Figure 229- Glass, Reynolds number = 78800, turbulent, active.

Figure 230 - Smooth, Reynolds number = 78800, turbulent, active.
Figure 231 - Feather - parallel, Reynolds number = 78800, turbulent, active.

Figure 232 - Feather - random, Reynolds number = 78800, turbulent, active.
Figure 233 - Feather - rotated, Reynolds number = 78800, turbulent, active.

Figure 234 - Bump pattern, Reynolds number = 78800, turbulent, active.
Figure 235 - Micro pattern #1, Reynolds number = 78800, turbulent, active.

Figure 236 - Micro pattern #2, Reynolds number = 78800, turbulent, active.