Optimization of Flow Quality In the Test Section of The 30-Inch x 40-Inch Subsonic Tunnel

Ahmed F. Elnenaey

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OPTIMIZATION OF FLOW QUALITY
IN THE TEST SECTION
OF THE 30-INCH X 40-INCH
SUBSONIC TUNNEL

By

Ahmed F. Elnenaey

A Thesis Submitted to the
Aerospace Engineering Department
In Partial Fulfillment of the Requirement for the Degree of
Master of Science in Aerospace Engineering

Embry-Riddle Aeronautical University
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OPTIMIZATION OF FLOW QUALITY IN THE TEST SECTION OF THE 30-INCH X 40-INCH SUBSONIC TUNNEL

by

Ahmed F. Elnenaey

This thesis was prepared under the direction of the candidate's thesis committee chair, Prof. Charles N. Eastlake, Department of Aerospace Engineering, and has been approved by the members of his thesis committee. It was submitted to the Department of Aerospace Engineering and was accepted in partial fulfillment of the requirements for the degree of Master of Science in Aerospace Engineering.

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ACKNOWLEDGMENTS

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This statement of acknowledgment would not be complete without a formal expression of sincere appreciation and gratitude to both the author’s family and friends for providing the assistance and encouragement needed to complete the task.
The purpose of this study is to optimize the flow quality inside the 30-inch x 40-inch subsonic wind tunnel. The tunnel is an open circuit with its inlet positioned adjacent to the side door of the lab; forcing the air to make a ninety degrees turn entering the tunnel. The flow suffered from two main deficiencies, high level of turbulence and slightly unsteady flow with a non-uniform velocity distribution across the test section. By utilizing a hot-film anemometer system and a total pressure rake, turbulence and velocity distribution data were obtained. Rounded corners and a turning vane were installed in front of the inlet to minimize boundary layer separation. Furthermore, a screen was attached to the inlet to help reduce the turbulence level. By combining all the configurations the flow reached a uniform distribution for more than ninety percent of the cross sectional area, with a maximum deviation of one percent from the mean center velocity. Turbulence was reduced from one percent to a half percent. This research could be followed by a more comprehensive effort to further improve the flow quality inside the test section, though it does not seem warranted at this time.
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1. Introduction

1.1 Wind Tunnels General Background

A Wind Tunnel is a research apparatus that simulates the conditions encountered by any object moving through the air. An object studied in a wind tunnel remains stationary as air or gas is forced over it. Wind tunnels are used to study the effects of moving air on such objects as aircraft, spacecraft, missiles, automobiles, buildings, and bridges. Wind tunnels vary in size from a few inches to the 24-m by 36-m (80-ft by 120-ft) tunnel located at the Ames Research Center of the National Aeronautics and Space Administration (NASA) at Moffet Field, California. This massive wind tunnel can accommodate a full-size aircraft with a wingspan of 22-m (72-ft).

Wind tunnels play a major and significant role in the design and development of aircraft. The design of the wind tunnel and the characteristics of the flow inside the test section, flow quality, will determine the nature and accuracy of the acquired data. An open-circuit wind tunnel is composed of an inlet (contraction cone), a test section and a diffuser. The contraction cone’s purpose is to take a large volume of low-velocity air and reduce it to a small volume of high-velocity air. As the cross-sectional area decreases, the speed of the air increases. The test section accommodates models of wings or airplanes. As airflow is brought to the desired velocity, sensors measure forces, such as lift and drag, on the test article. Based on the measurements of these forces and the known relationships between the test environment and actual flying conditions, accurate predictions of real-world performance can be made. The diffuser slows the air coming out of the test section prior to exhausting it to the atmosphere. The air slows down due to the
gradually increasing area of the diffuser. This is an important process in the wind tunnel because it saves money by reducing the required power, thus the operating costs.

### 1.2 Statement of the Problem

The work described in this thesis is concerned with improving the flow quality in the subsonic wind tunnel at ERAU. The tunnel is an open-circuit tunnel with a 30 x 40 x 60 inches test section. The tunnel is powered by an electric 50 horsepower DC motor that drives an eight blade 66 inches in diameter fan, providing a maximum speed of 200 (ft/s) in the test section\(^1\). The focus of this thesis will be to optimize the flow quality in the test section. The main deficiencies are turbulence and unsteady flow in the test-section, created by the position of the tunnel's inlet with respect to the main door of the lab where almost all, if not all, of the air is drawn in from the outside of the building. Several modifications will be made to the inlet geometry and detailed velocity measurements will be made for each modification to assess the significance and effect of inlet geometry on the flow quality.

---

\(^1\) Refer to Fig 1, page 3
50 HP D.C. MOTOR
8-BLADE, 66-IN. DIA. FAN
50 UPD OAOTCR
-8-PUbE, &M^. &IA, FNVi
EXnERtoRMLu
SCREEN
TEST SECTION

WEATHER
DOOR

EXTERIOR WALL

SCREEN

TEST SECTION

FLOW

FLOOR

ACCESS HATCH

60 HP A.C. MOTOR/DC. GENERATOR

30x40 INSTRUCTIONAL WIND TUNNEL

All dimensions are in inches
1.2.1 Unsteady Flow

It is required for a good test section to have a uniform velocity profile outside the boundary layer. It is also desirable to have steady flow. It is almost impossible to have a perfect steady flow inside the test section, so the question is how much unsteadiness is acceptable? Any time-dependent velocity fluctuations should be of small magnitude and at low enough frequency so that they are not noticeable in balance or pressure measurements. Typical industrial values for velocity variation across the test section are often quoted in the range of 0.2-0.3% variations from average\textsuperscript{2}. This might be difficult for us to achieve due to several considerations such as space available, position of the tunnel with respect to the door and the configuration of the tunnel as an open circuit, which makes it vulnerable to outside wind interference. Generally speaking, unsteadiness in the flow is a result of separated flow. The right angle that the flow has to turn through from the door to the inlet is our primary initiator of separation. A relatively big rounded corner has to be installed at that side of the inlet to assist in turning the flow smoothly. Study of velocity distribution will be conducted using a 10-tubes total pressure rake and a static port at the same cross section (center of the test section). Local velocities will then be calculated using incompressible Bernoulli's Equation. The local velocity at sixth tube from the left looking downstream will be taken as a reference since it is nearest the center of the test section and the velocity ratio at each location will be calculated to observe the local deviations from the center mean velocity.

\textsuperscript{2} Reference 2, page 73
1.2.2 Turbulence

Turbulence, which arises from wakes of objects, such as vanes, is the second main problem and it can be distinguished from unsteadiness by its high frequency occurrence. Turbulence is reduced by the installation of honeycombs and screens upstream of the contraction. Screens reduce the axial turbulence more than the lateral turbulence. They produce a relatively large pressure drop in the flow direction. This, in turn, reduces the higher velocities more than the lower, and thus promotes a more uniform axial velocity. Honeycombs have small pressure drop and thus have less effect on the axial velocities, but due to their length, they reduce the lateral velocities. In general, both screens and honeycombs reduce turbulence by exchanging energy between the axes as the turbulence tends toward isotropic turbulence downstream. However, despite them being located at the lowest speed portion of the tunnel, they significantly increase the power required to operate the tunnel. A 25% power loss at high speeds with 58% screen porosity was quoted in the General Motors full-scale automotive tunnel.

A main problem usually associated with screens is their ability to accumulate dust. The dust is often in a nonuniform distribution, thus changing the porosity and pressure drop from one location on the screen to the other. This will also result in an angularity in the flow. When screens are used, they must be installed so that they can be easily cleaned, and the quality of the flow inside the test section should be monitored frequently. Screens used for turbulence reduction should have the projected open area to the total area ratio, \( \beta \), greater than 0.57. Screens with smaller ratios suffer from flow
instabilities in the test section\(^3\). Turbulence reduction in theory is based on the pressure loss coefficient \(K\), defined as the pressure loss across the screen \(\Delta P\) divided by the mean flow dynamic pressure \(q\).

\[
K = \frac{\Delta P}{q} = K_o + \frac{55.2}{R_d}
\]

where,

\[
K_o = \left(\frac{1 - 0.95\beta}{0.95\beta}\right)^2
\]

\[
\beta = \frac{\text{Projected open area}}{\text{Total area}} = \left(1 - \frac{d}{M}\right)^2
\]

\(d = \text{wire diameter}\)

\(M = \text{mesh length}\)

\(R_d = \text{Reynolds number based on wire diameter}, d\)

For the screen that we will use in this project

\(d = 0.011 \text{ inches}\)

\(M = 0.0625 \text{ inches}\)

\(R_d = 145.5\)

These values result in the following

\(\beta = 0.679\)

\(K_o = 0.303\)

\(K = 0.682\)

This pressure loss coefficient value indicates less than tenth of an inch of water drop in the static pressure.

\(^3\) Reference 2
The power lost can be calculated as follows

\[ \Delta E = \frac{1}{2} \rho KAV^3 \]
\[ \Delta E = 0.62 \text{HP} \]

Where,

\[ A = \text{Inlet cross sectional area (ft}^2) \]
\[ V = \text{Flow velocity at the inlet (ft/s)} \]

The DC motor is capable of delivering 50 HP to the fan. However, the fan blades do not deliver all motor power to the air with 100% efficiency. At the current pitch angle, the fan efficiency is estimated to be 80%, which means that the power delivered to the air is about 40 HP and thus the power loss due to the screen is approximately 2%.

The turbulence reduction factor \( f \) is defined as the turbulence with manipulators installed divided by the turbulence without manipulators.

\[
\begin{align*}
    f &= \frac{1}{1 + K} \quad \text{for axial reduction} \\
    f &= \frac{1}{\sqrt{1 + K}} \quad \text{for lateral reduction}
\end{align*}
\]

For our screen these values turn to be

\[
\begin{align*}
    f &= 0.594 \quad \text{for axial reduction} \\
    f &= 0.771 \quad \text{for lateral reduction}
\end{align*}
\]

The axial turbulence reduction factor approximately matches the experiment results\(^4\), which indicated that the axial turbulence intensity dropped from 1% to 0.5%. This corresponds to \( f = 0.50 \).

\(^4\) Refer to section 2.4.2, page 50
When multiple screens are used, the turbulence reduction factor is obtained as the product of their individual values. Whereas the pressure drop $K$ is the sum of the individual values. Screens act as turbulence reducers by breaking relatively large eddies to smaller ones that damp out in a shorter distance. Therefore, multiple screens must have a finite distance between them so that the turbulence induced in the wake of the first screen damps out before reaching the second screen. An acceptable turbulence factor for our tunnel is suggested to be about 1.4 in the axial direction. Flow turbulence analysis will be conducted using a hot-film anemometer. The precision and capabilities of this system are specifically designed for acquiring this type of data from the tunnel.

Two main data sets will be collected from the system, the local velocity (profile and mean) and the turbulence level in the flow. At first, an evaluation of the flow quality in the tunnel under the present formation of the inlet will be conducted to assess the significance of improvements needed. Accordingly, different configurations will be designed for the inlet in order to improve the flow quality in the tunnel. Possible configurations include, but are not limited to, rounding the inlet edges, adding screens and installing turning vanes inside/outside the inlet. After collecting data for the different configurations, a complete and comprehensive analysis will be conducted to determine the most effective and practical configuration. Analysis will be based mainly on turbulence level and velocity distribution in the test section.

Considering that the tunnel’s fan is driven by an electric motor, it is important to optimize the pitch angle of the blades after the final configuration is concluded in order to maximize the usage of power delivered by the motor.

\footnote{Page 80, Reference 2}
Fig 2 Inlet Position With Respect to the Lab Door
1.3 Hot Film Anemometer

The anemometer system used in this research is IFA 300 Constant Temperature System, manufactured by TSI incorporated. The System is a fully integrated, thermal anemometer-based system that measures mean and fluctuating velocity components in any fluid. It also measures turbulence and makes localized temperature measurements. It provides up to 300 kHz-frequency response. All operations, including setup, calibration, and data acquisition are software-controlled via an RS-232 interface.

1.3.1 Principle of Operation

Thermal anemometers measure fluid velocity by sensing the changes in heat transfer from a small, electrically heated element exposed to the fluid. The cooling effect produced by the flow passing over the element is balanced by an electrical current supply to the element, so that the element is held at constant temperature. This process is accomplished through a bridge and an amplifier circuit that controls the sensor. The change in the sensor's voltage (off-balance) is sensed by the bridge and adjusted to the top of the bridge, keeping the bridge in balance. The voltage on top of the bridge is then related to the velocity of the flow and shown up as a voltage at the anemometer output. The output feeds to a personal computer, where data is recorded, analyzed and presented to the researcher in appropriate terms.

A key feature of the thermal anemometer is its capability to detect very small and rapid changes in velocity. This is accomplished by coupling a very fine platinum thin-
film deposited on a quartz substrate, with a fast feedback circuit which compensates for the drop in the natural response of the sensor. The system has a time response of three microseconds. This accuracy will enable us to examine the nature of turbulence in the wind tunnel, which is of crucial importance in determining the flow quality in the test section.

The system includes signal conditioners to provide settings for filtering and increasing the bridge voltage gain to use the entire ±5V-signal range. High-pass filters are used to measure velocity fluctuations since mean voltage information and thus actual velocity is removed from the signal. Low-pass filters allow the removal of high frequency signals, particularly electrical noise, that are out of the range of interest.

The unit contains a microprocessor system board, which controls all functions and settings of the anemometer and signal conditioner via an address and data bus. An RS-232-C interface is used to send commands from the computer to the microprocessor. The interface converts the analog voltage output of the anemometer to a digital form for use by the computer. A thermocouple is connected to an analog signal output to directly input the temperature data to the analog-to-digital converter board.

Once data is acquired by the computer a comprehensive data analysis software (FlowPoint) written using LabWindows CVI and runs under Windows 3.1 offers complete experiment documentation, automated calibration, and data acquisition and analysis. The calibration program is used to calibrate the probe, either by acquiring data or by entering data on the screen. A calibration generates a relationship between the bridge voltage and a reference velocity. The calibration data is then curve fitted with a fourth-order polynomial. The data is stored in a file and used by the Acquisition program
to convert raw data into velocity data. At last, a post-analysis program calculates and
displays velocity statistics and time history. Of the most important data of our interest is
the mean velocity, time history and turbulence intensity.

1.3.2 System Components

As shown in figure 3, the System consists of

1. Anemometer
2. Thermocouple for temperature measurements
3. Probe with sensor
4. Probe support
5. Data acquisition and analysis software and an A/D converter board installed in
the computer
Fig 3 System Components of the IFA300 Constant Temperature Anemometer System
1.3.3 Calibration

The calibration program is used to calibrate the single element sensor, either by acquiring data or by entering data on the screen. We will conduct the calibration via the first method, acquiring data. At the conclusion of this process, the system will generate a fourth-order polynomial that best represents the relationship between the bridge voltage and a reference velocity. All calibration data, including the look-up table, is stored in a file that is typically named by the serial number of the probe, and has the extension .CL. This calibration file is used by the Acquisition program to convert raw data into velocity data.

The following steps are taken after the probe is attached to the IFA 300 unit and we have the probe in the wind tunnel.

1. Open the calibration file.
2. Enter the following data A/D and IF A channels connected to the probe, probe serial number, specified operating resistance of the probe, Film or Wire, offset and the gain, the temperature channel.
3. Attach the shorting probe to measure the cable resistance.
4. Attach the sensor to the probe.
5. From the calibration menu, select probe file. This file will conduct the calibration process by acquiring a specific number of predetermined velocity (14) points using the manometer readings from the 1/8 standard Pitot-Static probe.

---

6 Refer to Fig 4
7 Refer to Fig 5
6. Run the tunnel at the first speed (0 ft/s), enter the velocity at the screen and run the program.

7. Increase the velocity and repeat step 6 for 13 more points for a velocity range from zero ft/s to 130 ft/s. This velocity range is wider than the velocity range of interest. Therefore, no extrapolation is required.

8. After all points are acquired, a new screen will automatically show. Click on curves to calculate the polynomial curve fit, and to generate the calibration curve\(^8\).

9. Observe the curve. If the points on the graph are plotted correctly and the graph looks correct (that is, the graph smoothly increases monotonically), the calibration process is complete and you can proceed to acquire data with the calibrated probe. If a point on the curve does not look correct, you may need to edit one or more data points or repeat the calibration procedure.

10. Finally, acquire several data points throughout the range of the calibrated velocities and check the values of the velocities given by the system by comparing them to the readings from the Pitot-Static probe.

---

\(^8\) Refer to Fig 6
Fig 4 Probe Components

- Probe Cable
- Probe Support
- Alignment Marks
- Probe
### Fig 5 Velocity Calibration Screen

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atm Press</td>
<td>742.70 mm Hg</td>
</tr>
<tr>
<td>Cal Temp</td>
<td>20.0</td>
</tr>
<tr>
<td>Opr Temp</td>
<td>250.00 °C</td>
</tr>
<tr>
<td>Min Velocity</td>
<td>0.00 m/s</td>
</tr>
<tr>
<td>Max Velocity</td>
<td>50.00 m/s</td>
</tr>
</tbody>
</table>

### dP Units
- 10.0 mm Hg = 5.0 Volts
- 0.0 mm Hg = -5.0 Volts

### Manual Acquire
- Acquire E & Acquire dP
- dP Units: mm Hg
- Manual
Fig 6 Calibration-Curve Fit Screen
Fig 7 Velocity Time History Screen
1.4 Total Pressure Rake

A 10 tube total pressure rake will be used in association with a static pressure port at the same cross sectional area as the tips of the total-pressure tubes to acquire velocity distribution data across the test section. The rake is connected to a manometer bank, and by recording the change in the water column height changes with respect to the reference, atmospheric pressure, and utilizing Bernoulli’s equation the velocity profile will be determined for the overall center cross section of the test section.

\[ P_T = P_S + q \]

where,

- \( P_T \) is the Total Pressure
- \( P_S \) is the Static Pressure
- \( q = \frac{1}{2} \rho V^2 \) is the Dynamic Pressure
- \( \rho \) is the air density
- \( V \) is the flow velocity

The local velocity will be determined at each location across the cross section, and then using the sixth tube, from left looking upstream, as the reference, each individual velocity will be compared to the reference in order to determine the variations in the cross section. This procedure will be repeated for five different elevations (6, 10, 14, 18 and 22 inches from the floor of the test section) in order to obtain the full picture of the velocity profile of the cross section.
The reason behind using the less precise pressure rake in place of the distinctly accurate hot-film anemometer system is the lengthy duration required to acquire all data using a single probe. This lengthy duration might result in inaccuracies in the data acquired due to potential condition change in the nature (temperature, wind, density, pressure) of the flow entering the tunnel. Using the rake will dramatically reduce the time required to collect all the data; however, caution should be exercised to ensure that the flow mean velocity is identical each time the rake is moved vertically. This is another reason for using the rake. Using the rake, the tunnel will be turned on and off five times. On the contrary, utilizing the hot-film anemometer will necessitate replicating this process an astounding fifty times. Since human error is expected through this process, reducing the number of repetitions will in turn reduce the error involved. Moreover, utilizing the rake a slight variation is expected between the different elevations. However, when computing the velocity ratio with respect to the reference location the acquired overall data for the complete cross section is exceptionally accurate. On the other hand, when using the hot film anemometer the predictable velocity change from one local position to other will affect the variation calculations at the same elevation resulting in a greater inaccuracy in the distribution data. A servomechanism could be used to move the probe laterally, but despite the mechanical complexity accompanying the system, the time involved in accumulating all ten data points would still increase the error implicated in the data. Finally, in view of the fact that we are in search of one-percent velocity variations from the reference or more, the pressure rake and the manometer bank arrangement will provide sufficient accuracy in the data collected.
Fig 8 Perspective View of the Rake in the Test Section
2. Method

The gathering of data process involves two main sets of data. First the velocity profile across the center of the test section using a total pressure rake and a static port. Secondly, turbulence intensity will be obtained by the means of the hot-film anemometer system.

2.1 Procedure

2.1.1 Velocity Distribution

1. Mount the rake at the desired elevation (bottom will be six inches above the floor of the test section to avoid the boundary layer, then the rake will be elevated four inches four times so that the top is eight inches below the ceiling to avoid the boundary layer) making sure that the tubes are completely horizontal to avoid misalignments.

2. Connect the rake to the manometer bank.

3. Connect the static port, which is at the same cross section with the tips of the tubes to the manometer bank.

4. Run the tunnel at the desired speed. The chosen speed is 120 ft/s, which is the typical velocity for classroom experiments conducted in the tunnel.

5. Record the following data to ensure the operation of the tunnel at the same velocity after it has been turned off to change the elevation of the rake.
   - Dynamic pressure
• Fan RPM

6. Record all readings from the manometer bank (total pressure readings and static pressure)

7. Record the temperature

8. Turn the tunnel off

9. Change the rake’s height and repeat steps 4, 6 and 7, making sure to run the tunnel at the same dynamic pressure and RPM as before.

2.1.2 Turbulence intensity

The following steps will be conducted for the first configuration (clean configuration with no attachments), and the fourth configurations (screen and the corners are attached to the inlet) only

1. Using FlowPoint, set up the probe (calibration and activation).

2. Set the Probe and the Thermocouple in the flow field.

3. Start the Data Acquisition program.

4. Take readings at zero velocity, and confirm that the system is working adequately.

5. Start the Wind Tunnel.

6. Set the tunnel to a certain speed.

7. Acquire data from the Data Acquisition Program.

8. Repeat the previous step for several frequencies (100 Hz to 100,000 Hz)
9. Run the analysis program to obtain velocity analysis (mean, time history, turbulence intensity)

10. Calculate the turbulence intensity from the time history data by dividing the mean-square-root of the fluctuations by the mean velocity given by the system, and compare to the turbulence intensity given by the system.

11. Determine the adequate frequency that will produce the correct turbulence intensity. This is accomplished when the calculated turbulence intensity matches with the intensity given directly by the system. If the turbulence intensity given by the system is higher, this is an indication that the frequency used is low and thus the mean velocity variation is included in the calculation of the turbulence intensity. A typical frequency used in the study of turbulence is 10,000 Hz.

12. Collect ten consecutive reading for the turbulence intensity at the predetermined frequency.

13. Average the collected ten readings to obtain a more accurate indication of the turbulence intensity and minimize error.
2.2 Velocity Distribution Analysis

2.2.1 Clean Configuration

In this configuration, the inlet has no objects attached to or installed into it.

2.2.1.1 Results

Table 1 Velocity Variation

<table>
<thead>
<tr>
<th>Tube location From left sidewall (inches)</th>
<th>From the floor</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0.978</td>
</tr>
<tr>
<td>9</td>
<td>0.993</td>
</tr>
<tr>
<td>12</td>
<td>0.985</td>
</tr>
<tr>
<td>15</td>
<td>0.993</td>
</tr>
<tr>
<td>18</td>
<td>0.993</td>
</tr>
<tr>
<td>21</td>
<td>1.000</td>
</tr>
<tr>
<td>24</td>
<td>1.000</td>
</tr>
<tr>
<td>27</td>
<td>0.993</td>
</tr>
<tr>
<td>30</td>
<td>0.993</td>
</tr>
<tr>
<td>33</td>
<td>0.993</td>
</tr>
</tbody>
</table>

2.2.1.2 Analysis

As can be seen from the table above, the velocity distribution is not uniform for the greater part of the test section, where it is ranging between 0.97-0.99 % of the mean centerline velocity. However, this was expected due to the large separation region produced at the inlet as a result of the sharp turning angle that the flow has to take. The separation region was visualized by the means of tufts attached to the four walls inside
the inlet and by smoke that was injected at the corners and several other arbitrary points at the inlet. This separated flow in turn produced a lot of unsteadiness in the free stream departing to the test section. Moreover, this separation region pushed the airflow to the right side of the inlet, looking upstream, resulting in some angularity in the flow. Thus, the obvious solution is to eliminate the sharp turns around the beginning of the inlet that the air has to make. This can be achieved by placing rounded corners at the beginning of the inlet. However, the vertical corner that is to be placed at the left side of the inlet, looking upstream, should have a bigger radius relative to the other corners due to the fact that the main flow is coming from that side. Another solution that would produce a similar effect would be adding a screen at the inlet. The primary effect of adding a screen is that it will reduce turbulence in the flow (axial) direction. However, the screen will also to a lesser extent damp out the variations in the lateral fluctuations. This may help to even out the velocity distribution before it enters the test section.

2.2.1.3 Conclusion

This configuration does not satisfy the required flow quality characteristics. The left side suffers from great separation at the inlet; a large diameter radius or a screen is required to eliminate this problem. A configuration that will combine both the rounded corners and the screen will be more effective in reducing unsteadiness and turbulence in the flow. However, each individual configuration should be studied separately first to determine the improvement achieved by each configuration. Then the collective configuration can be studied to observe the total effect.
Fig 9 Clean Configuration
2.2.2 Screens

In this configuration, the inlet has only one screen attached to the beginning. The screen has a porosity of 67%, sixteen wires per inch and a 0.011-inch wire diameter.

2.2.2.1 Results

Table 2  Velocity Variation

<table>
<thead>
<tr>
<th>Tube location From left sidewall (inches)</th>
<th>From the floor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>22 inches</td>
</tr>
<tr>
<td>6</td>
<td>0.977</td>
</tr>
<tr>
<td>9</td>
<td>0.977</td>
</tr>
<tr>
<td>12</td>
<td>0.977</td>
</tr>
<tr>
<td>15</td>
<td>0.993</td>
</tr>
<tr>
<td>18</td>
<td>1.000</td>
</tr>
<tr>
<td>21</td>
<td>1.000</td>
</tr>
<tr>
<td>24</td>
<td>1.000</td>
</tr>
<tr>
<td>27</td>
<td>1.000</td>
</tr>
<tr>
<td>30</td>
<td>1.000</td>
</tr>
<tr>
<td>33</td>
<td>0.993</td>
</tr>
</tbody>
</table>

2.2.2.2 Analysis

As can be seen from the table above, the velocity distribution is still not uniform at the left half of the test section, where it is ranging between 0.98-0.99 % of the mean centerline velocity. However, this shows a dramatic improvement from the previous configurations. This is an indication of a more steady flow entering the test section as the fluctuations of the water columns in the manometer almost vanished. Furthermore, the
unsteadiness in the right half section has been almost eliminated. Separation at the left side seems to be reduced but not eliminated because of the presence of the screen. Nonetheless, a significant improvement in the free stream velocity distribution is accomplished.

2.2.2.3 Conclusion

This configuration achieves a significant improvement towards the velocity distribution desired in the test section. The left side still suffers from some separation at the inlet caused by the square corners on the inlet of the entrance cone. A large diameter radius is required to eliminate this problem. The screen eliminated the small unsteadiness produced at the right side of the tunnel, as can be indicated by the virtually perfect velocity distribution on the right side. However, it could not eliminate the unsteadiness on the left side due to relatively larger separation region at the left side, as it is the side where most of the flow enters the tunnel. The next step would be to remove the screen, install the corners, and observe the improvements achieved and compare it to the improvements achieved by the screen. We anticipate the corners will completely eliminate the separation region at the inlet and noticeably help steady the flow. However, this will mainly depend of the size of the radius used. Obviously the larger the radius the greater the improvement. The big radius that has been built to be installed at the left side of the inlet has a radius of nine and one half (9.5) inches, while all the other corners have a radius of six inches.
Fig 10. Screen Configuration
Velocity Distribution
Screens only

Graph 2 Screen Configuration Velocity Distribution
2.2.3 Corners

In this configuration, the inlet has only the four corners installed. The left radius, which has the largest diameter, has to be installed each time testing is conducted because it is in the way of the lab door as it closes. After testing in the tunnel is complete, the radius has to be removed. The radius is attached at the top by a wood rod serving as a locating pin extending from the top corner of the inlet flange, and then a bolt is used to secure the radius to the inlet flange at the center of the flange.

2.2.3.1 Results

Table 3  Velocity Variation

<table>
<thead>
<tr>
<th>Tube location From left sidewall (inches)</th>
<th>From the floor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>22 inches</td>
</tr>
<tr>
<td>6</td>
<td>0.985</td>
</tr>
<tr>
<td>9</td>
<td>0.993</td>
</tr>
<tr>
<td>12</td>
<td>0.993</td>
</tr>
<tr>
<td>15</td>
<td>0.993</td>
</tr>
<tr>
<td>18</td>
<td>1.000</td>
</tr>
<tr>
<td>21</td>
<td>1.000</td>
</tr>
<tr>
<td>24</td>
<td>1.000</td>
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<td>27</td>
<td>1.000</td>
</tr>
<tr>
<td>30</td>
<td>1.000</td>
</tr>
<tr>
<td>33</td>
<td>1.000</td>
</tr>
</tbody>
</table>
2.2.3.2 Analysis

As can be seen from the table above, the velocity distribution is still not uniform at the left half of the test section, where it is approximately 0.99% of the mean centerline velocity. However, this still shows a remarkable improvement from the clean configurations. This is an indication of a more attached flow at the left corner of the inlet. Compared to what we anticipated the improvement fell a little short. The effect of the corner is similar to that of the screen and barely a little better, as the unsteadiness has been entirely abolished on the right side of the test section. Furthermore, the velocity variation is within the one-percent limit now everywhere compared to a two-percent difference with the screen installed. Perhaps, the combination of these two configurations will diminish the separation problem completely; or else, a larger diameter corner will have to be used.

2.2.3.3 Conclusion

This configuration achieves the desired velocity distribution to a great extent. However, the left side still experiences some separation at the inlet, a larger diameter radius is required to abolish this problem totally or perhaps the combination of the screen and the corners will attain the purpose. This would be the next step to combine both the screen and the corners to notice if the superposition will satisfy the desired flow characteristics.
FLOW

Inlet

Corner

Slightly unsteady but Attached Flow

R=9.5 inches

Corner

R=6 inches

Fig 11 Corner Configuration

Test Section
Velocity Distribution

Corners only

Graph 3 Corners Configuration Velocity Distribution
2.2.4 Corners and Screen Configuration

In this configuration, the inlet has both the screen and the rounded corners installed.

2.2.4.1 Results

Table 4 Velocity Variation

<table>
<thead>
<tr>
<th>Tube location From left sidewall (inches)</th>
<th>From the floor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>22 inches</td>
</tr>
<tr>
<td>6</td>
<td>0.985</td>
</tr>
<tr>
<td>9</td>
<td>0.993</td>
</tr>
<tr>
<td>12</td>
<td>1.000</td>
</tr>
<tr>
<td>15</td>
<td>1.000</td>
</tr>
<tr>
<td>18</td>
<td>1.000</td>
</tr>
<tr>
<td>21</td>
<td>1.000</td>
</tr>
<tr>
<td>24</td>
<td>1.000</td>
</tr>
<tr>
<td>27</td>
<td>1.000</td>
</tr>
<tr>
<td>30</td>
<td>1.000</td>
</tr>
<tr>
<td>33</td>
<td>0.993</td>
</tr>
</tbody>
</table>

2.2.4.2 Analysis

As can be seen from the table above, the velocity distribution is uniform except at some of the first two tubes, where it is ranging approximately between 0.98-0.99 % of the mean centerline velocity. Although there is a noticeable improvement from the individual configurations of the screen and the corners, there are still some locations of slower velocities at the left side. The drop in velocity from the one-percent value obtained in the corners configuration to a two-percent drop in the current configuration is again due to
the tendency of the screen to slow down the flow. In addition, the increased surface area exposed to the flow and subsequently the skin friction contributes to the reduction of the velocity. As mentioned previously, this necessitates the increase of the radius of the corner. Nevertheless, a solution was suggested to overcome the remaining deficiencies in the flow. A single cambered flat metal sheet can be placed close to the big radius. This sheet will act as a converging duct scooping some of the air from the center incoming flow and directing it to the left side to slightly increase the velocity on that side. However, caution should be practiced when positioning the sheet, in terms of its location with respect to the big radius and the convergence angle of the duct created by the sheet and the corner. If too much air is diverted to the side, either by having a high convergence angle or by placing the sheet far from the radius, the velocity will be higher than the mean on the left side and perhaps even reducing the velocity towards the center. On the other hand, if the convergence angle is small or the sheet is too close to the radius the velocity will not be increased enough to meet the mean velocity. Additionally, the camber of the sheet should be smooth to avoid producing separation on the sheet itself, which could be done by placing the sheet at a high angle of attack with respect to the air flow while trying to create a high divergence angle for the duct. This solution has the advantage of saving both time and money, which are needed to design and construct a new bigger radius.
2.2.4.3 Conclusion

This configuration almost achieves the desired velocity distribution except for few deficiencies on the far left side. The screen helped damp out some of the eddies in the separation region at the left side, introducing a further improvement step from the corners alone configuration. A cambered metal sheet will be installed to direct more of the center flow towards the left side to increase the velocity on that side. The position of the sheet with respect to the radius and the angle of the sheet with respect to the airflow will be determined through a trial-and-error process to determine the optimum position and angle of the sheet.
Fig 12 Screen and Corner Configuration
velocity distribution
screen and corners configuration

Graph 4 Screen and Corners Configuration Velocity Distribution
2.2.5 Corner plus Screen plus Turning Vane Configuration

This configuration has combined both the corners and the screen in addition to the cambered metal sheet turning vane plus a symmetric airfoil as a guide vane upstream of the turning vane. This turning vane combination is positioned 20 inches away from the big radius piece.

2.2.2.1 Results

Table 5 Velocity Variation

<table>
<thead>
<tr>
<th>Tube location From the left (inches)</th>
<th>From the floor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>22 inches 18 inches 14 inches 10 inches 6 inches</td>
</tr>
<tr>
<td>6</td>
<td>0.993 0.993 1.000 1.000 0.993</td>
</tr>
<tr>
<td>9</td>
<td>0.993 1.000 1.000 1.000 1.000</td>
</tr>
<tr>
<td>12</td>
<td>1.000 1.000 1.000 1.000 1.000</td>
</tr>
<tr>
<td>15</td>
<td>1.000 1.000 1.000 1.000 1.000</td>
</tr>
<tr>
<td>18</td>
<td>1.000 1.000 1.000 1.000 1.000</td>
</tr>
<tr>
<td>21</td>
<td>1.000 1.000 1.000 1.000 1.000</td>
</tr>
<tr>
<td>24</td>
<td>1.000 1.000 1.000 1.000 1.000</td>
</tr>
<tr>
<td>27</td>
<td>1.000 1.000 1.000 1.000 1.000</td>
</tr>
<tr>
<td>30</td>
<td>1.000 1.000 1.000 1.000 1.000</td>
</tr>
</tbody>
</table>
2.2.2.2 Analysis

As can be seen from the table above, the velocity distribution is uniform everywhere except at the upper left corner and the very bottom left corner of the test section, where it is 0.99% of the mean centerline velocity. This is probably because we were not able to use the small corners that go at the left top and bottom corner due to interference with the turning vane assembly. Redesigning the support construction of the turning vane so it accommodates these corners will probably solve this problem and will be done in the permanent installation. The turning vane helped turn more of the flow to the inside of the inlet. This in turn increased the velocity on the left side and equalized the velocity profile.

2.2.2.3 Conclusion

Overall, the combination of the screen and the rounded corners in addition to the turning vane satisfies the desired flow quality characteristics in the test section. Keeping in mind the configuration of the tunnel as an open circuit, making it exposed to any external wind interference, and the position of the inlet with respect to the door, which forces the air in a sharp turn leading to separation, the achieved results are satisfactory for the current use of the facility. The portion of the cross section which we normally use for testing now has a uniform velocity distribution. Nevertheless, there may still be opportunity for more improvements. These improvements are discussed in the recommendation section.
Fig 13 Screen, Corner and Turning Vane Configuration
Graph 5 Screen, Corners and Turning Vane Configuration Velocity Distribution
2.3 Recommendations

In order to further improve the airflow quality inside the test section, the following recommendations are suggested as a continuation to this research. A set of two or three symmetrical airfoils (which we have on bank) can be placed along a curved line in place of the turning vane to better assist in turning of the flow as it approaches the inlet. This set of airfoils should be placed close to the left side upstream of the screen, and through trial and error, the exact location and angle of attack can be determined to reach the best velocity distribution inside the test section.

There are other possibilities as well. Increasing the radius of the large corner to further assist the flow turning inside the tunnel would provide help, but interfere with closing the overhead door. Injecting air on the left side looking upstream will compensate for the velocity loss due to the corner-turning region fan which could accomplish this are on hand, but it does not seem justified at this time. Installing a bigger mesh size screen on the first 4 to 8 inches from the left side, to decrease the velocity reduction by the screen, keeping the current mesh size for the remainder of the inlet would also be a step in the right direction as well.

An important recommendation would be to optimize the fan blades pitch angle to maximize the flow velocity in the test section. We utilized a number of flow quality improvement devices, particularly the screen, which cause a small but significant drop in the dynamic pressure as the flow progresses through the tunnel. Therefore, we observed that the velocity has been reduced in the test section relative to an open inlet. The blade
pitch angle was optimized by trial and error for the clean configuration and thus might need to be readjusted to maximize power usage from the fan motor. This is a trial and error process that constitutes another experimental study.

2.4 Turbulence Intensity Analysis

2.4.1 Introduction

Tests conducted in different wind tunnels and tests made in wind tunnels and in flight will differ in results, even if conducted at the same Reynolds number, if the turbulence intensity is not similar in each test. Turbulence intensity \( I \) is defined as the ratio of the root-mean-square speed fluctuation at a point to the mean speed.

\[
I = \frac{\sqrt{u_{rms}^2}}{U}
\]

However, these variations are those that occur at high frequency. This variation should be distinguished from the velocity variations that will occur at lower frequencies due to external factors, such as wind, objects passing in front of the inlet, etc., which will cause the mean velocity to change slightly as a whole. Turbulence is introduced in wind tunnels as a result of propellers, turning vanes, vibration of the structure and screens. Hence a correction is needed to compensate for this difference in turbulence intensity between different test environments.

Turbulence introduced in the flow will have the effect of making the flow pattern in the tunnel to be similar to the flow pattern in free air at higher Reynolds number. Therefore, the tunnel test Reynolds number could be said to have a higher "effective
Reynolds number. The correction factor is called the turbulence factor. It is found by comparing the tunnel’s critical Reynolds number to the atmospheric turbulence free air Reynolds number. This is achieved by reading surface pressure and/or drag coefficient on a sphere. The critical Reynolds number, which is the Reynolds number at which the boundary layer undergoes transition from laminar to turbulent, has been experimentally verified to depend strongly on the degree of turbulence of the wind tunnel. Experimental measurements on spheres show that in turbulence free atmosphere the critical Reynolds number has the value of 385,000. The critical Reynolds number is determined by finding the Reynolds number at which $C_D = 0.3$ or $\frac{\Delta P}{q} = 1.22$. The critical Reynolds number is then measured using a sphere in the wind tunnel and compared to the 385,000 to obtain the turbulence factor as follows.

$$T.F. = \frac{R_{n_{turb\,free}}}{R_{n_{wind\,tunnel}}} = \frac{385,000}{R_{n_{wind\,tunnel}}}$$

According to reference 1 a small university size wind tunnel will be considered acceptable if has a turbulence factor between approximately 1.4 to 1.7.

During the course of collecting turbulence data the hot film anemometer will be used instead of the sphere to measure turbulence intensity, then referring to reference 2 and using the chart that relates the turbulence intensity to the turbulence factor\(^9\), the turbulence factor will be obtained. This chart was developed through the work of H.L. Dryden, A.M. Kuethe, and et al in the late twenties and mid thirties.

\(^9\) Refer to Fig 14
The decision to use the hot-film anemometer is due to the fact that it is more precise in measuring turbulence than the sphere experiment, which will provide only an average value of the tunnel turbulence. Moreover, the sphere experiment will yield the turbulence factor but the turbulence factor in itself does not give any information on the magnitude of the turbulence in either the axial or lateral direction. Conversely, by using the hot film anemometer the turbulence intensity will be obtained, which is a clear indication of the magnitude of the turbulence in the axial direction. Additionally, the system displays the velocity time history that will show the turbulence pattern in the flow and the frequency at which the turbulence is occurring.

Fig 14 Relationship between Turbulence Intensity and Turbulence Factor
2.4.2 Configurations

2.4.2.1 Clean Configuration

2.4.2.1.1 Results

This configuration contains no attachments to the inlet. Using the hot film anemometer at a frequency of 10,000 Hz, the following data in table 1 is obtained. The probe was positioned at the center of the test section supported by two stands to support the long probe and eliminate vibration.

Table 6 Turbulence intensity

<table>
<thead>
<tr>
<th>Mean Velocity (ft/s)</th>
<th>Variations from Mean (ft/s)</th>
<th>% TURB</th>
</tr>
</thead>
<tbody>
<tr>
<td>125.451</td>
<td>1.297</td>
<td>1.03387</td>
</tr>
<tr>
<td>125.321</td>
<td>1.288</td>
<td>1.027761</td>
</tr>
<tr>
<td>126.147</td>
<td>1.322</td>
<td>1.047984</td>
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<tr>
<td>124.942</td>
<td>1.277</td>
<td>1.022074</td>
</tr>
<tr>
<td>124.442</td>
<td>1.271</td>
<td>1.021359</td>
</tr>
<tr>
<td>125.845</td>
<td>1.291</td>
<td>1.025865</td>
</tr>
<tr>
<td>125.978</td>
<td>1.293</td>
<td>1.02637</td>
</tr>
<tr>
<td>126.338</td>
<td>1.289</td>
<td>1.020279</td>
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<td>126.154</td>
<td>1.313</td>
<td>1.040791</td>
</tr>
<tr>
<td>126.821</td>
<td>1.302</td>
<td>1.026644</td>
</tr>
</tbody>
</table>

Avg Mean Velocity 125.7439 (ft/s)

Avg % TURB 1.0293
2.3.2.1.2 Analysis

From the data above, the average mean velocity is 125.7 (ft/s) and the turbulence intensity is 1.03 %. This yields a turbulence factor of 1.8, which is a clear indication of the relatively high turbulence in the tunnel and is a suggestion of the need to improve the flow quality in the test section. This high turbulence is primarily a result of the separation region at the left hand side of the inlet, looking up-stream, due to the sharp turn the flow has to make. This separation region creates eddies, which owing to their relatively large size and the short distance from the beginning of the inlet to the center of the test section (10.5 ft), are not totally dissipated or at least significantly reduced. Therefore, eliminating this region is essential to reducing turbulence. This is attainable through the use of rather large radius corners to assist the flow turning from the side door to the inside of the inlet. Furthermore, the utilization of screens at the inlet will serve to break up any large eddies into smaller eddies, which will damp out in a shorter flow distance, and damp out any sudden or unanticipated velocity from outside wind or other external factors.

2.3.1.1.3 Conclusion

The turbulence intensity is relatively high and at the upper boundary of acceptable limits. This is a result of the separation region at the left side of the inlet that produces a modest amount of turbulence in the flow. Introducing screens and rounding the corners should eliminate the separation region and thus the turbulence it initiates into the free stream.
2.4.2.2 Corners and Screen Configuration

2.4.4.2.1 Results

This configuration contains both the rounded corners and the screen attached to the inlet. Table 6 shows the relation between the frequency and the turbulence intensity. Using the hot film anemometer at a frequency of 10,000 Hz, the data in Table 7 are obtained showing the relation between turbulence intensity and the average velocity.

Table 7  Turbulence Intensity as a Function of Frequency

<table>
<thead>
<tr>
<th>Sample Rate (Hz)</th>
<th>TURB %</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>3.389831</td>
</tr>
<tr>
<td>500</td>
<td>2.542373</td>
</tr>
<tr>
<td>1000</td>
<td>1.575342</td>
</tr>
<tr>
<td>5000</td>
<td>0.957291</td>
</tr>
<tr>
<td>10000</td>
<td>0.509175</td>
</tr>
<tr>
<td>100000</td>
<td>0.509525</td>
</tr>
<tr>
<td>1000</td>
<td>0.508475</td>
</tr>
<tr>
<td>10000</td>
<td>0.508665</td>
</tr>
<tr>
<td>100000</td>
<td>0.506589</td>
</tr>
<tr>
<td>1000000</td>
<td>0.506589</td>
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<tr>
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<td>10000</td>
<td>0.510278</td>
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<tr>
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<td>0.509667</td>
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</tr>
<tr>
<td>100000</td>
<td>0.509675</td>
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<tr>
<td>1000000</td>
<td>0.508895</td>
</tr>
<tr>
<td>10000000</td>
<td>0.510061</td>
</tr>
</tbody>
</table>
Table 8  Turbulence Intensity as a Function of Velocity

<table>
<thead>
<tr>
<th>AVG V (ft/s)</th>
<th>Var (ft/s)</th>
<th>TURB %</th>
</tr>
</thead>
<tbody>
<tr>
<td>32.145</td>
<td>1</td>
<td>3.110904</td>
</tr>
<tr>
<td>61.4773333</td>
<td>0.4</td>
<td>0.650646</td>
</tr>
<tr>
<td>93.6563333</td>
<td>0.5</td>
<td>0.533867</td>
</tr>
<tr>
<td>119.2443333</td>
<td>0.6</td>
<td>0.503169</td>
</tr>
<tr>
<td>139.617</td>
<td>0.7</td>
<td>0.501372</td>
</tr>
</tbody>
</table>

2.4.2.2.2 Analysis

The frequency used is of a significant consequence in acquiring accurate turbulence data. Since turbulence occurs at very high frequencies measuring at low frequencies will sense only the mean velocity fluctuations, these which occurs at lower frequencies. These changes are the mean velocity unsteadiness that most likely result from outside wind incorporating only these in the calculation of the turbulence intensity result in indicating higher turbulence intensity than is actually characteristic of the flow. Therefore, the appropriate frequency should be determined in order to account for such variations.

Looking at the data in Table 6 the turbulence intensity reading is constant at frequencies of 10,000 Hz or higher. Thus, a frequency of 10,000 Hz will be our chosen frequency for acquiring any turbulence data. As seen from the data in table 6 the indicated turbulence intensity at lower frequency is much higher compared to frequencies of 10,000 Hz or higher. Specifically, the intensity decreases as the frequency increases until it become constant after the 10,000 Hz and higher, as shown in Graph 5.

The relationship between the turbulence intensity and the free stream velocity is of a significant importance. As seen in Table 7 and Graph 6, as the velocity increases the turbulence intensity decreases until it settles down at approximately ninety feet per
second value. Note that this data described in Table 7 shows that the magnitude of the velocity variations, or eddies, does not have the same relation with the velocity of the free stream as the turbulence intensity. As can be seen the magnitude of the variation is high at low speeds and it decreases rapidly and then starts to climb up again gradually. Since the turbulence intensity does not look at the magnitude of the velocity variations solely, rather as a ratio between the root-mean-square of the variation and the mean velocity, the decrease in turbulence intensity does not necessarily indicate a decrease in the magnitude of the variations in velocity.

2.4.2.2.3 Conclusion

By means of rounding the corners and installing a single screen at the beginning of the inlet we were able to reduce the separation region effectively and thus the turbulence due to that region. The newly obtained turbulence intensity is 0.5%, which corresponds to a 1.4 Turbulence Factor. This turbulence factor is a good value for small wind tunnels according to reference 2. Therefore, no further development or improvement is required in this regard. Nonetheless, it is worth mentioning here that adding several screens in and in front of the inlet will further reduce the turbulence intensity in the free stream. On the other hand, since we are satisfied with the current turbulence intensity, and as mentioned previously, screens reduce the velocity as a whole and require a significant increase of the power. Furthermore, adding screens will seriously limit access to the tunnel through the inlet for any required maintenance or adjustments.
Graph 6 Turbulence Intensity vs. Sample Rate
Graph 7 Turbulence Intensity vs. Mean Velocity