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## Design, construction and characterization of a wind tunnel

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## **ABSTRACT**

### **DESIGN, CONSTRUCTION AND CHARACTERIZATION OF A WIND TUNNEL**

**by  
Chang Ge**

The wind tunnel is the most fundamental test equipment for aircraft testing and studying aerodynamics. Because of the complexity of the test-subject's geometry, it is difficult to study the aerodynamic pattern simply based on theoretical calculations. Most of the aerodynamics experiments still use wind tunnels. The progress of the wind tunnel is highly related to the advancements in air crafts. Aircraft manufacturing has pushed the wind tunnel technology forward. Wind tunnels can be categorized by the wind speed limit differences, which are controlled by the mechanism of the driving methods, structure applications, etc. In this case, we built a small scale wood based wind tunnel for future testing of "Magnetic Augmented Rotational System (MARS)". This thesis discusses the low speed wind tunnel, subsonic wind tunnel, transonic wind tunnel, supersonic wind tunnel, hypersonic wind tunnel, high enthalpy hypersonic wind tunnel, and puts the focus on low speed wind tunnel. The characteristics of the low speed wind tunnel and the related data will be presented along with its advantages and shortcomings.

**DESIGN, CONSTRUCTION AND CHARACTERIZATION  
OF A WIND TUNNEL**

**by  
Chang Ge**

**A Thesis  
Submitted to the Faculty of  
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in Partial Fulfillment of the Requirements for the Degree of  
Master of Science in Materials Science and Engineering  
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**APPROVAL PAGE**

**DESIGN, CONSTRUCTION AND CHARACTERIZATION  
OF A WIND TUNNEL**

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# CHAPTER 1

## INTRODUCTION

### 1.1 History of Wind Tunnel

Francis Herbert Wenham (1824–1908), a Council Member of the Aeronautical Society of Great Britain, invented, designed and operated the first enclosed wind tunnel in 1871. Table 1.1 lists the year and progress of all classic wind tunnels; it generally reflects the situation of wind tunnel technology.

Firstly, in 1907, the first low-speed wind tunnel with the equal cross-section body made a big impact. However, due to its design, it lost a lot of wind energy. Then people changed to equal cross-section to vary section which is similar to the modern circuit wind tunnel. In 1914, French engineer Eiffel built the open-return wind tunnel. Eiffel significantly improved the efficiency of the open-return wind tunnel by enclosing the test section in a chamber; in fact the open-return low speed wind tunnel is often called the Eiffel-type wind tunnel.

The US Navy in 1916 built one of the largest wind tunnels in the world at that time at the Washington Navy Yard. The inlet was almost 11 feet (3.4 m) in diameter and the discharge part was 7 feet (2.1 m) in diameter. A 500HP electric motor drove the paddle type fan blades.

**Table 1.1** Progress of Classical Wind Tunnel

No.	Year	Test section dimension (meter)	Tunnel or designer name	Wind speed (m/s or M)	Others
1	1871	0.46*0.46	(UK)Wenham	18	
2	1901	0.56*0.56	(US)Wright brothers	12.2	
3	1902	0.75*0.75	(Ru)	9	
4	1907	Φ 1.83	(Ge) Prandtl	9	Single return
5	1914	Φ 2.13	(Fra)Eiffel	39.5	Open return s
6	1917	Φ2.28	(Ge) Prandtl	55	Vary cross section single return
7	1925	0.31	High speed	Close 1	Jet style
8	1926	6.1	Propeller research	49.2	1470 kw
9	1928	1.525	(US)Vary density tunnel	30	Reach 21 atm
10	1932	0.4*0.4	(Swi) Zurich supersonic tunnel	M~2	700kw
11	1935	18.3*9.1	(US) full scale tunnel	52.7	5880kw
12	1942	3.04*2.44	Low speed tunnel for airplane co.	140	1680kw
13	1949	0.28*0.28	Hypersonic wind tunnel	M=6.8~18	Using O <sub>2</sub> N <sub>2</sub>
14	1950	Octagon 2.44Subtense	Transonic wind tunnel	M=0~1.2	12000kw
15	1956	4.88*4.88	AEDC high enthalpy high sonic tunnel	M=1.5~4.0	Continued 161000kw
16	1958	1.22*1.22	Triple sonic wind tunnel of airplane co	M=0.4~5	41 atm within 40~100S 5970kw
17	1964	Φ2.54	AEDC high enthalpy supersonic tunnel	M=12.5~22	N <sub>2</sub> 300~1700 atm 2500~4000K 10~45ms
18	1967	9.2*7.9	VTOL wind tunnel	7~54	6700kw
19	1975	5*4.2	RAE low speed pressure tunnel(UK)	95~110	3 atm 14000kw Re=8*10 <sup>6</sup>
20	1982	2.5*2.5	Low temperature high Re NO. (US)	M=0.2~1.2	9 atm, 389~78K Re=120*10 <sup>8</sup> , 89400kw

Source: D.M. Sykes, A new wind tunnel for industrial aerodynamics, J. Ind. Aerodyn. 2 (1977) 65-78

In 1941, the US constructed one of the largest wind tunnels at that time at Wright Field in Dayton, Ohio. This wind tunnel starts at 45 feet (14 m) and narrows to 20 feet (6.1 m) in



diameter. Two 40-foot (12 m) fans were driven by a 40,000 HP electric motor. Large scale aircraft models could be tested at air speeds of 400 mph (640 km/h).

## **1.2 Basic Principle of Wind Tunnel**

The wind tunnel uses the basic similarity theory; all wind fields should be the same as the environment of planes, cars, etc. However, it is very difficult to replicate nature. For a certain object exposed to a certain speed, we only need to achieve a few conditions; we can ignore the others; then we can have reliable data. Next, we discuss three essential principles of wind tunnel study.

### **Reynolds number**

The Reynolds number is the ratio of inertial forces to viscous forces and consequently quantifies the relative importance of these two types of forces for given flow conditions. Reynolds numbers frequently arise when performing scaling of fluid dynamics problems, and, as such, can be used to determine dynamic similitude between two different cases of fluid flow. They are also used to characterize different flow regimes within a similar fluid, such as laminar or turbulent flow.

Firstly, laminar flow occurs at low Reynolds numbers, where viscous forces are dominant, and is characterized by smooth, constant fluid motion; furthermore, turbulent flow occurs at high Reynolds numbers and is dominated by inertial forces, which tend to produce chaotic eddies, vortices and other flow instabilities.

In practice, matching the Reynolds number is not on its own sufficient to guarantee similitude. Fluid flow is generally chaotic and very small changes to shape and surface roughness can result in very different flows. Nevertheless, Reynolds numbers are a very important guide and are widely used.

## **Turbulence**

Turbulence in aerodynamic study can be defined as a flow regime characterized by chaotic property changes. This includes low momentum diffusion, high momentum convection, and rapid variation of pressure and flow velocity in space and time.

Flow in which the kinetic energy dies out due to the action of molecular viscosity is called laminar flow. While there is no theorem relating the non-dimensional Reynolds number (Re) to turbulence, flows at Reynolds numbers larger than 5000 are typically (but not necessarily) turbulent, while those at low Reynolds numbers usually remain laminar.

## **Bernoulli's principle**

In aerodynamics, when the wind speed is increased, the air pressure decreases simultaneously. Bernoulli's principle can be derived from the principle of conservation of energy. This states that, in a steady flow, the sum of all forms of energy in a fluid along a streamline is the same at all points on that streamline. This requires that the sum of kinetic energy, potential energy and internal energy remains constant. Thus an increase in the speed of the fluid – implying an increase in both its dynamic pressure and kinetic energy – occurs with a simultaneous decrease in (the sum of) its static pressure, potential energy and internal energy.

### **1.3 Different Types of Wind Tunnel**

Nowadays, there are roughly 1000 wind tunnels all over the world, but their types, working function, dimension of test section, power, and speed, are different. We have to categorize the wind tunnels before we design and select one of them to do research. There are many methods to categorize these wind tunnels, but the most basic one is by the wind speed. The reason is firstly, wind speed determines the working function, dimension, structure of that

tunnel. Secondly, for aircraft research, the wind speed is unique for each type of model; that means if the speed is changed, the working condition cannot be perfectly simulated. It is very difficult to present all the speed limits with one wind tunnel.

Wind tunnel can be categorized into six types, by speed limits in the test section.

**Table 1.2** Mach Numbers of Different Wind Tunnels

Wind Tunnel Type	Velocity Limits at Test Section
Low speed wind tunnel	$0 < v < 135 \text{ m/s}$ (or $M < 0.4$ )
Subsonic speed wind tunnel	$0.4 < M < 0.8$
Transonic speed wind tunnel	$0.8 < M < 1.4$ (or 1.2)
Supersonic speed wind tunnel	$1.4 < M < 5.0$
Hypersonic speed wind tunnel	$5.0 < M < 10$ (or 12)
High enthalpy hypersonic speed wind tunnel	$M > 10$ (or 12)

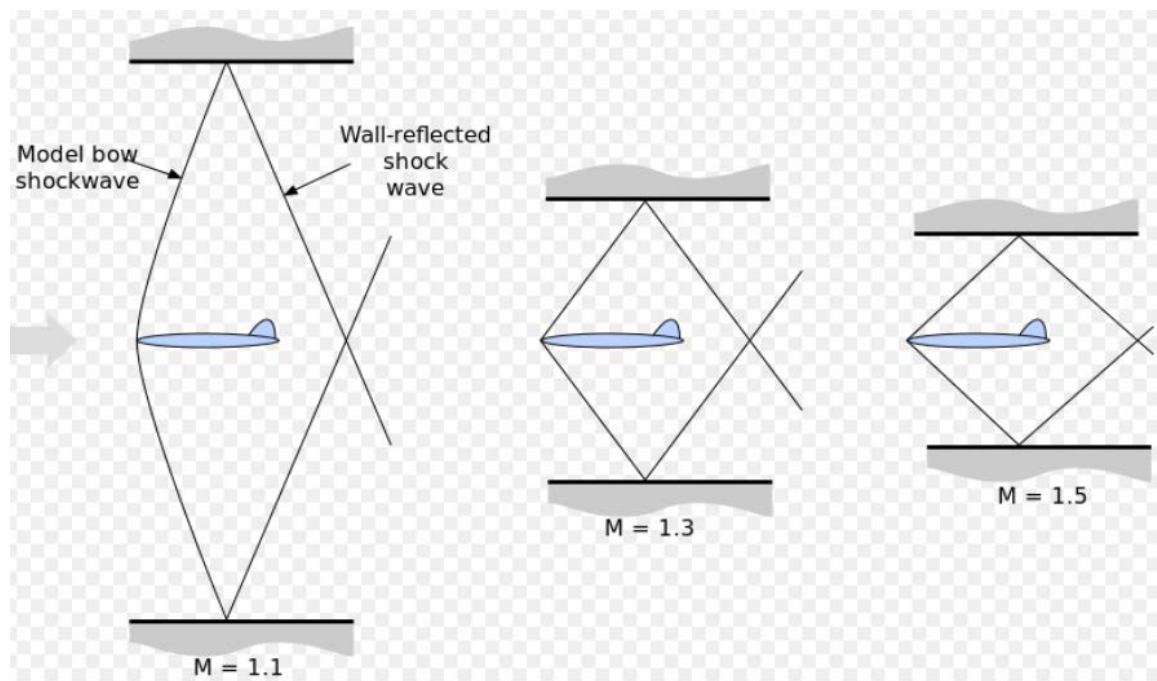
Source: N.J. Cook, Determination of the model scale factor in wind tunnel simulations of the adiabatic atmospheric boundary-layer, J. Ind. Aerodyn. 2 (1978) 311-321

The characteristics of these wind tunnels will be discussed here.

Firstly, the air in the low speed wind tunnel usually cannot be compressed. It will not cost too much power to maintain the speed of the wind, because of the low speed. The test section of the low speed wind tunnel should be big enough to satisfy the Reynolds number for experiment purposes. Usually, the cross sections reach 3~4 meters in the test sections. The relative power should be beyond 2000kw, which makes the low speed wind tunnel run continuously.

In the subsonic case, the wind velocity is much higher than the low speed, which makes the power range from several thousands to 10,000 ~20,000kw. Enormous power loss generates heat during the wind flow; so cooling equipment is necessary to deal with the over heat. For decreasing the energy loss, the efficiency of diffuser part should be high, which makes the diffusion angle very small and diffuser section longer than low speed wind tunnel.

The Mach number of the transonic wind tunnel is approximately 1 with subsonic and supersonic flow regions combined. Testing at transonic speeds presents additional problems, mainly due to the reflection of the shock waves from the walls of the test section (see Figure 1.1). Therefore, perforated or slotted walls are required to reduce shock reflection from the walls. Since important viscous or inviscid interactions occur (such as shock waves or boundary layer interaction), both the Mach and Reynolds numbers are important and must be properly simulated. Large-scale facilities and/or pressurized or cryogenic wind tunnels are used.



**Figure 1.1** Illustration of reflection of the shock waves from the walls.

Source:<http://upload.wikimedia.org/wikipedia/commons/thumb/1/1c/Tunnelreflection-en.svg/500px-Tunnelreflection-en.svg.png>

When it comes to the supersonic case, the Mach number is  $1.2 < M < 5$ . The Mach number and flow are determined by the nozzle geometry. The Reynolds number varies by changing the density level (pressure in the settling chamber). Therefore, a high pressure ratio is

required (for a supersonic regime at  $M=4$ , this ratio is of the order of 10). In addition, condensation of moisture or even gas liquefaction can occur if the static temperature becomes cold enough, which means that a supersonic wind tunnel usually needs a drying or a pre-heating facility. A supersonic wind tunnel has a large power demand, so that most are designed for intermittent instead of continuous operation.

The high Supersonic wind tunnel has Mach number from 5.0 to 10 (or 12). When the Mach number is beyond 5.0, heating system has to be introduced in the tunnel to prevent gas liquefaction. This is the basic different between supersonic and transonic wind tunnel. Therefore, if the Mach number is beyond 12, the pressure ratio of the wind becomes enormous. For rockets or space ship simulation, the heat level should greatly exceed the level of gas liquefaction prevention. At such high temperature and pressure, the material selected for a wind tunnel becomes a huge problem. Even though this tunnel can only work milliseconds, how to extend the duration becomes another question.

#### **1.4 Application of Wind Tunnel**

The wind tunnel is mainly used in aerospace technology and military applications. The industrial wind tunnels are also used for other areas like cars, windmills, environmental protection, etc. Users such as car companies use wind tunnels to explore the most efficient streamline for their new cars. There is no doubt that wind tunnel will keep helping our scientists to provide us faster, more reliable and more environmental friendly driving experience for the next decades.

## **CHAPTER 2**

### **RESEARCH BACKGROUND**

#### **2.1 Functions of Different Parts of Wind Tunnel**

The low speed wind tunnel has a speed lower than 130 meters per second and a Mach number below 0.4. In this speed limit, the compressibility of air does not exist. The most significant similarity parameter is only the Reynolds number and characterization of viscosity. In the wind tunnel family, so far, the low speed wind tunnel is the oldest and the most widely used. Nowadays, most industrial wind tunnels are low speed wind tunnels. The characteristics of low speed wind tunnel have been discussed here.

##### 1) Large Scale:

The area of cross section at test part usually can reach or above 3~4 meters. The drive power can be thousands or 10s of thousands of kilowatts because of the huge scale.

##### 2) Continuous Operation:

Because of the low speed, the heating problem from operation can be ignored; low speed wind tunnel can work for a long time or work continuously.

##### 3) Turbulence control:

For the similarity principle, the wind at test section should be even and uniform, which means the low speed wind tunnels have higher requirement for turbulence control, specifically in the test section.

#### **2.1.1 Contraction**

In wind tunnel design, contraction is used to control the flow speed and velocity variations for the test section. By changing the contraction ratio (area of input cross section divided by area of output cross section), we can accelerate the wind speed in the test section. For stabilization of the wind flow at the exit of contraction, the curve inside should be smooth

and should be continued in the later section. The contraction of the wind tunnel accelerates and aligns the flow into the test section. The size and shape of the contraction dictates the final turbulence intensity levels in the test section and hence the flow quality. Further, the length of the contraction should be kept as long as possible to minimize the boundary layer growth and reduce the effect of Gortler vortices. The flow leaving the contraction should be uniform and steady. For a finite-length inlet contraction, there exists a maximum and a minimum value for the wall static pressure distribution along the wall close to the entrance and exit, respectively. Thus, one may consider these two regions as regions of adverse pressure gradients with possible flow separation. If separation occurs, then the flow uniformity and steadiness will be degraded which may lead to an increase in turbulence intensity in the test section. In summary, contractions in the wind tunnels may produce several different unsteady secondary flows which are undesirable and can have significant effects on the behavior of the downstream boundary layers and turbulence intensity in the test section.

### **2.1.2 Test Section**

The test section is the central part of every wind tunnel. Objects will be tested and characterized here. Two critical principles are follows: the wind field stability and the efficiency of the wind tunnel become significant. The quality of the air flow, in the test section, represents the overall performance of a wind tunnel.

In order to obtain the high quality wind flow in the test section, several fundamental criteria should be satisfied:

- 1) The first and foremost is the stability of the wind flow; to reach this goal, all the section designs for the wind tunnel should be incorporated well and the designer should decrease the turbulence as much as possible.
- 2) To decrease the power of the wind tunnel, the cross section should be small enough to amplify the wind velocity. The shape of the cross section should be chosen delicately based on the shape of the object; one can save more space on cross section building, which saves more money and saves more power.
- 3) The wind tunnel designer should know the normal speed of the test section to optimize the location of the driving fan.
- 4) The experimental object and the relative equipment should be easy to load on.
- 5) A door and window are necessary for a wind tunnel for visualization or reading the data.

The area of cross section needs to be determined by the following principles:

- 1) A good wind tunnel should provide stable and even speed for about 90% of the test section area. The test model cannot be larger than this 90% area.
- 2) Considering the model blocking effect, the area of the test model usually cannot be over 5% of the wind tunnel cross section.
- 3) The walls of the wind tunnel can interfere with the wind flow if the test model's wings are too long, which exceed 60% of the width of the wind tunnel.

### **2.1.3 Settling Chamber**

Significant devices for turbulence reduction in wind tunnels are screens. Screens are employed to even the velocity variation of flow out of the settling section. They can remove fine vortex structures, and honeycombs, can remove large vortex structures. They also break large vortices into smaller eddies that decay rapidly at short distances.

Honeycomb and screens are two useful tools in the settling chamber to stabilize the wind flow and minimize the turbulence. After air passes contraction, several corners, and the driving fan, turbulence generated and wind speed are not equal in either vector or velocity number. This is the reason why we need a settling chamber to equalize the wind



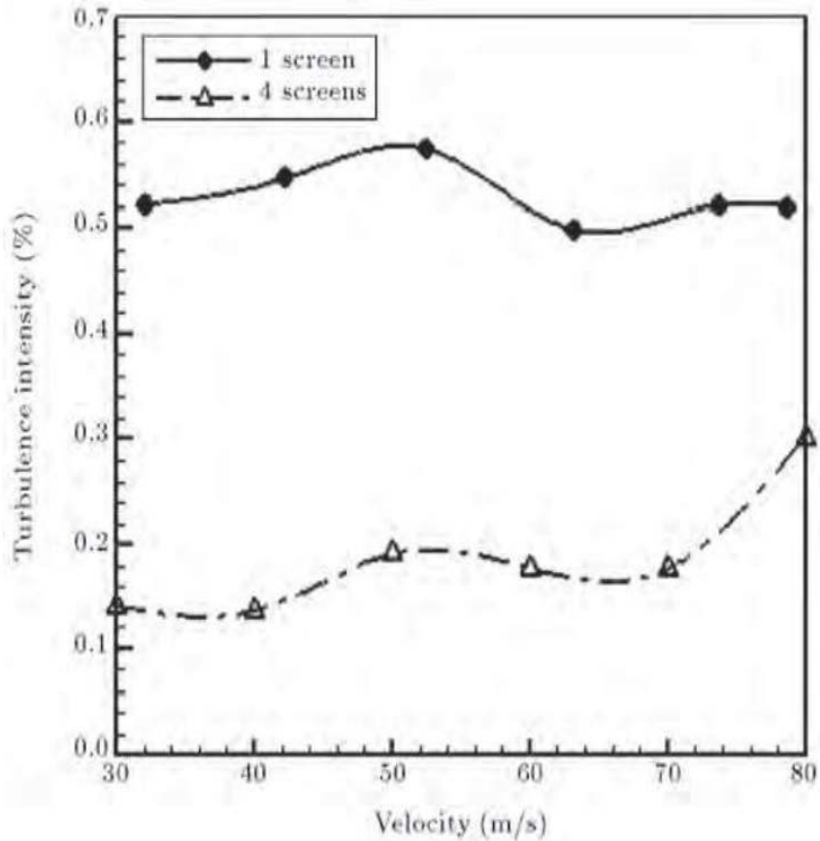
speed and guarantee the wind stability of the test section. The pictures below are wind tunnel honeycombs.



**Figure 2.1** Screens for wind tunnel.

Similar to honeycombs, gauzes are also very efficient tools that can be used in settling chambers to reduce turbulence and inequality. The more the number of layers, the higher is the stabilization efficiency; however, relative resistance is increased as well. In this study, for obtaining precise data, considering the power of the driving fan, we only used the honeycomb structure for stabilization.

Figure 2.2 shows variations of the turbulence intensity for one and four screens. This result exhibits that, by the addition of three anti-turbulence screens located in a suitable place in the settling chamber, the tunnel turbulence was reduced for all operating speeds.



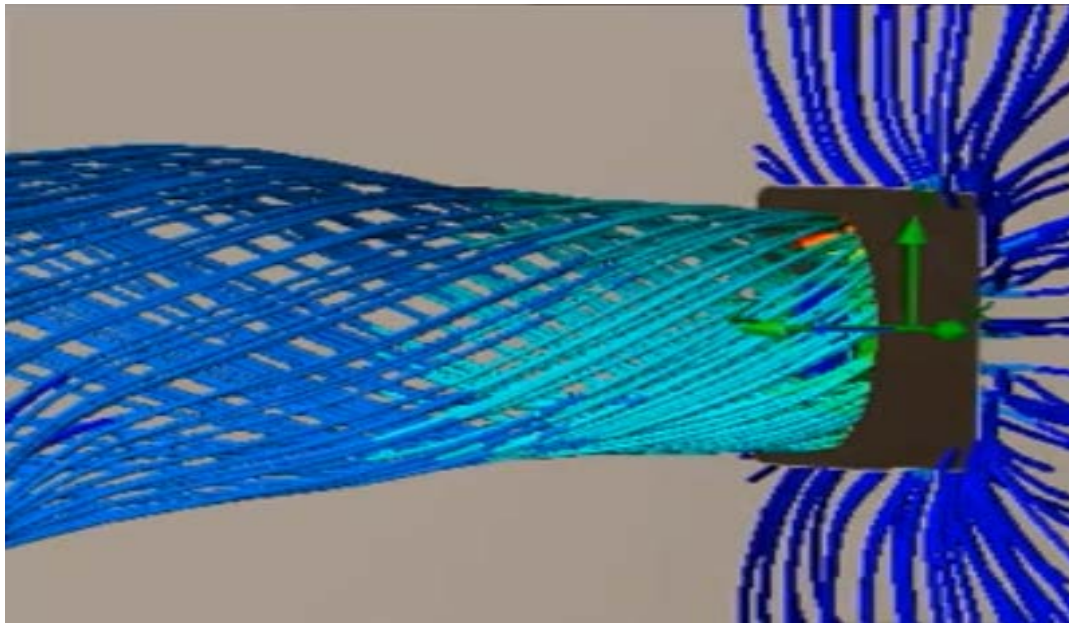
**Figure 2.2** Turbulence intensity for one and four screens.

Source: W.H. Press, B.P. Flannery, S.A. Teukolsky, W.T. Vetterling, Numerical Recipes: The Art of Scientific Computing, Cambridge University Press, New York, 1990

## 2.2 Introduction of the driving Fan

The driving force that was used in this study is an electric motor standing fan. Based on the dimensions of this fan, it was a huge challenge to put it inside the tunnel. Based on the source, we finally decided to put the fan outside the contraction to push the air in. The fan is able to provide enough power to the wind tunnel for later characterization experiments and made it easier to operate this big fan. However, the push-in driving style generated a huge turbulence issue which could not be ignored during the study. For reducing and minimizing

the turbulence, the settling chamber became extremely important because of the short length and uniform area cross section. The figure below presents the pattern of wind flow from the electric fan. From Figure 2.3, we can easily understand why the fan can create so much turbulence as soon as the wind is generated.



**Figure 2.3** Blow pattern of the fan.

The relative data (the AMP, power, working voltage and RPM) of this electric fan presented here and the simulation parameters of this study are based on the fan's parameters as well.



Figure 2.4 Parameter of the motor.

## 2.3 Turbulence

Today, one of most complicated area under discussion in physics, mathematics, fluid mechanics, and also various industries, i.e. aerospace engineering, wind turbines, buildings, combustion, biology, climate behavior and oceanography, is turbulence. Turbulence is highly versatile motion that it is almost impossible to predict it in any way. There are various definitions for turbulence and they are similar concepts. Turbulence has been defined by Bradshaw as: "A three-dimensional, time-dependent motion in which vortex stretching causes velocity fluctuations to spread to all wavelengths between a minimum determined by viscous forces and a maximum determined by the boundary conditions of the flow. It is the usual state of fluid motion except at low Reynolds numbers."

The unwanted effects of turbulence may trigger unfavorable transition and the measurements and velocity profiles may be incorrect. In other words, the flow shifts from laminar to turbulent flow on the model surface significantly upstream of its actual location in an environment where the free stream turbulence level is more than a real value. As a result, the turbulence can lead to more errors in aerodynamic measurements in wind tunnels. A main research tool for the majority of turbulent air/gas flow studies is Hot-Wire Anemometry (HWA) that is used to measure the flow parameters such as turbulent intensity, mean velocity and root mean squares.

However, in this study, based on the budget limitations, we used another method to characterize the turbulence intensity. Using the anemometer, we can record the wind velocity changes over time; more vigorous rates represent more turbulence intensity. While

the anemometer is not as good as HWA, it did provide us some direct wind turbulence for our study. This method will be explained in more detail in a future chapter.

The source of turbulence of wind tunnel may be briefly divided in two parts; i.e., turbulence due to eddies (vortex shedding, boundary layer, shear stress, secondary flows) and noise (mechanical, vibration and aerodynamic). There is a correlation between them. Manshadi et. al, in their studies, show the effects of turbulence on the sound generation and velocity fluctuations due to pressure waves in a large subsonic wind tunnel. The results of this research determine that, while the share due to the monopole is dominant, the share due to the dipole and quadrupole (generated in the boundary layer) remains less important. Furthermore, it is found that sound waves have a modest impact on the measured longitudinal turbulence and is essentially generated by eddies.

There are two basic methods to reduce the turbulence for wind tunnel. Significant devices for turbulence reduction in wind tunnels are screens. Screens are employed to even the velocity variation of flow out of the settling section. The contraction of the wind tunnel accelerates and aligns the flow into the test section. The size and shape of the contraction dictates the final turbulence intensity levels in the test section and hence the flow quality. More details on these two methods will be discussed in Chapters 4 and 5.

## Chapter 3

### DESIGN AND CONSTRUCTION OF A WIND TUNNEL

#### 3.1 Construction

In this study, for supporting the Magnetic Augmented Rotational System (MARS) that is being developed in this research group, we need to design and construct a low speed small scale wind tunnel. The scale of the test section should be big enough to contain the MARS windmill model and fit the fan that is available in the lab. The material of the wind tunnel should not be too hard to change shape, and should be strong enough to stand the wind flow to at least 15m/s (start speed for regular wind mill) without vibration. In preparation for the construction, we had a long table to support the wind tunnel. So the weight of the wind tunnel should be below the weight limit of the table.

We decided to build a wind tunnel made of wood; the reasons are discussed here.

1. Wood is very easy to manipulate, which minimizes the budget.
2. Unlike metal, the weight of wood is light enough to lay on the table.
3. By appropriately choosing the wood type as well as optimizing the structure, we can obtain a stable section without shaking and movement.

The scale of the wind tunnel is based on multi-situations; the cross section should be big enough to hold the fan blade outside the wind tunnel and we have to make sure that the blade of the object can only take 5% of the cross section area. Secondly, the length of the wind tunnel was limited by the area of the space available in the lab as well as the area of desk support. Figure 3.1 shows the structure of this wind tunnel and the table for supporting the tunnel.



**Figure 3.1** Front view of the wind tunnel.

Above the test section part, a window was installed on the top of the tunnel. The window is covered by a transparent polymer glass. Researchers can easily use this window to watch the object or perform experiments in the presence of wind. Moreover, the window can supply light from the top which facilitates researchers to take readings from anemometer or other electronic devices. Researchers can also use this window to explore the possibility of performing experiments based on optics etc. Figure 3.2 shows the window above the test section.





**Figure 3.2** Window above the test section.

Eight (1.7 × 24 inches) wood posts were used to support the weight of the top board and the window. Four of them were at the inlet and the outlet of the tunnel and the rest of them divided the body of the tunnel into three sections. The boards on the sides have been installed a few inches inside to leave space for the supporting posts. Figure 3.3 shows the position of the supporting posts.



**Figure 3.3** Positions of the supporting posts.

The material of the contraction cone used is composite wood board of dimension (0.2 × 48 × 48, T × L × W). For reduction in the unwanted turbulence, several stable frames have

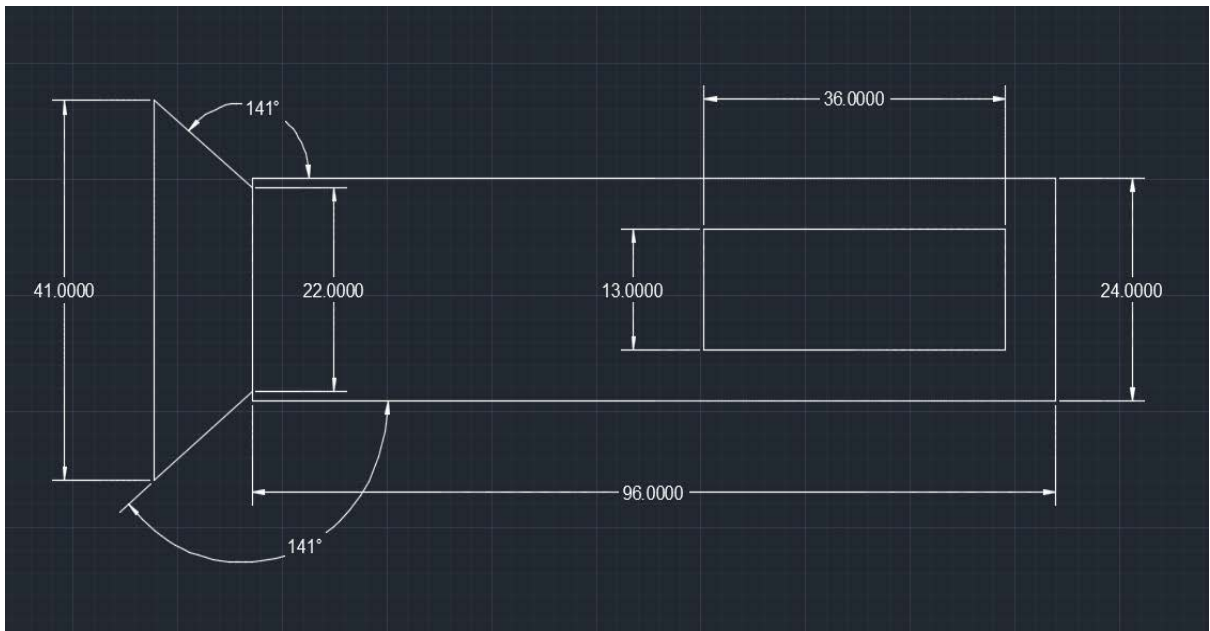
been used to prevent the cone from shaking during the wind flow. For reduction in the wind leakage from the edges, glue has been used on the edges and corners of all the boundaries of the wood board. Figure 3.4 shows the shape of the contraction section before and after completion.



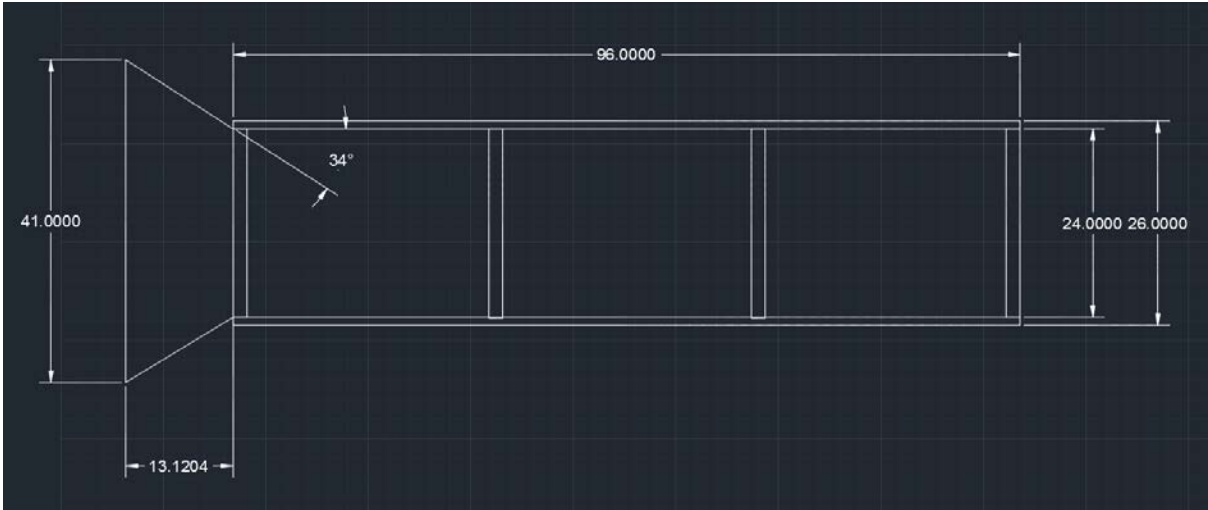
**Figure 3.4** Contraction section.

### 3.2 Design of the Wind Tunnel

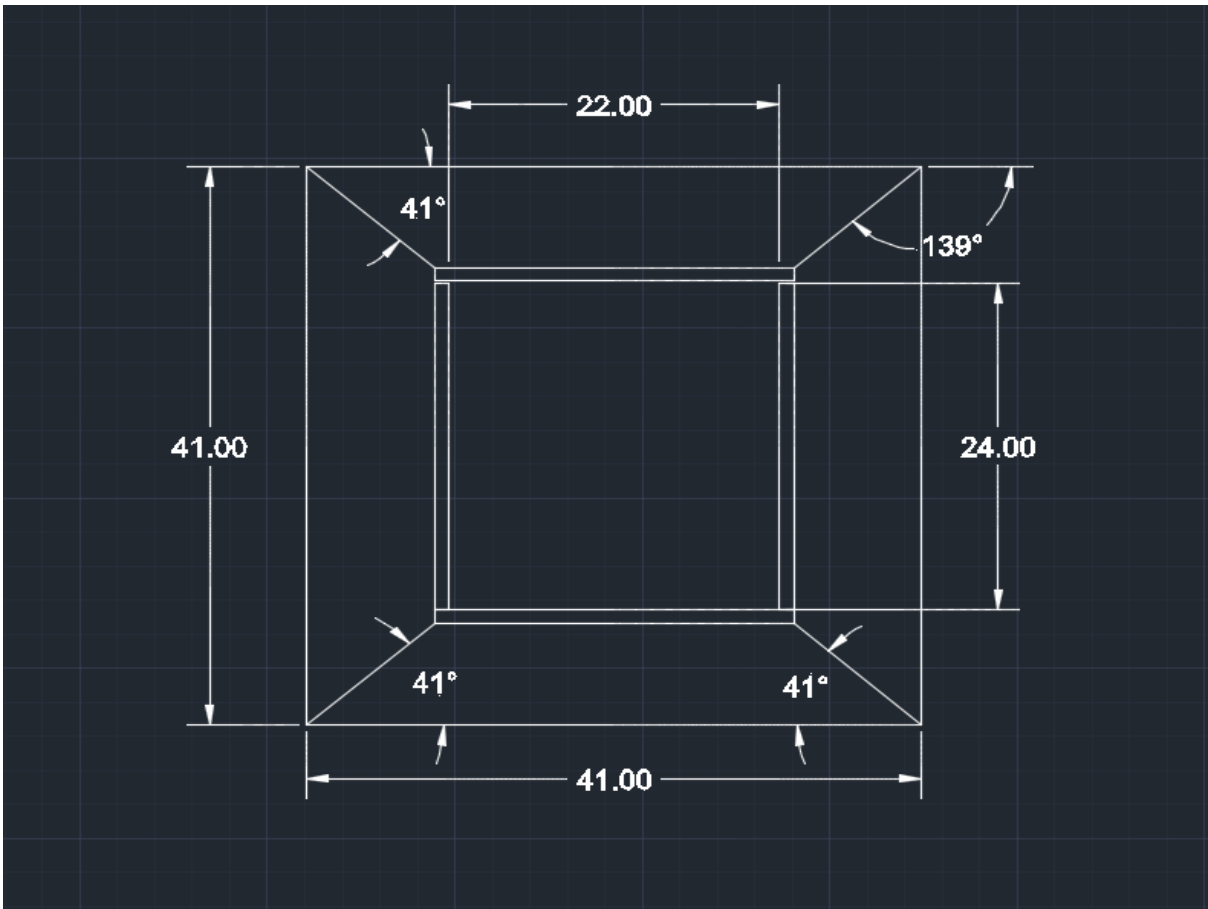
The following three pictures, Figures 3.5, 3.6 and 3.7 show more details of the wind tunnel. These design graphs show the specific dimensions from top, front of the wind tunnel, and the contraction cone as well. The length and degree units of these three design graphs are in inches and degree. The software that was used was AutoCAD 2015 student version. AutoCAD is a commercial software that can be utilized for 2D and 3D computer-aided design (CAD) and drafting—it has been available since 1982 as a desktop application and since 2010 as a mobile web- and cloud-based app marketed as AutoCAD 360.



**Figure 3.5** Wind tunnel top views.



**Figure 3.6** Wind tunnel front views.



**Figure 3.7** Wind tunnel contraction views.

## CHAPTER 4

### THE METHODOLOGY OF WIND TUNNEL CHARACTERIZATION

#### 4.1 Introduction of First Principle Calculation Software COMSOL Multi-physics

In this research, for initiating studies of the turbulence condition and the stabilization of the test section, simulation software COMSOL multi-physics has been used.

COMSOL multi-physics provides a simulation environment designed with real-world applications. It is based on the finite element method, by solving a partial differential equation (single field) or system of partial differential equations (multi-field) to simulate problems in physics. The idea is to mimic as closely as possible effects that are observed in reality. The COMSOL Group provides software solutions for multi-physics modeling. The company was founded in July 1986 in Stockholm, Sweden. They have grown to include offices in Denmark, Finland, France, Germany, the Netherlands, Norway, India, Italy, Switzerland, the United Kingdom, and the U.S.A.

COMSOL multi-physics® software is the most popular software modeling tool for engineers and scientists. With the recent release of v.5.0, it allows the user to create simulated environments for computerized modeling of physical systems and devices.

The second approach is based on the finite element method. This makes it possible to solve each problem with greater precision, but with the requirement of a longer (and often more expensive) implementation time. This parallel approach to the problem-solving process provides the reader with the options and advantages of inclusion of practical exercises and solutions and allows the reader to enhance their understanding by applying these methods to real-life cases.

## 4.2 Introduction of the Experimental Design Method

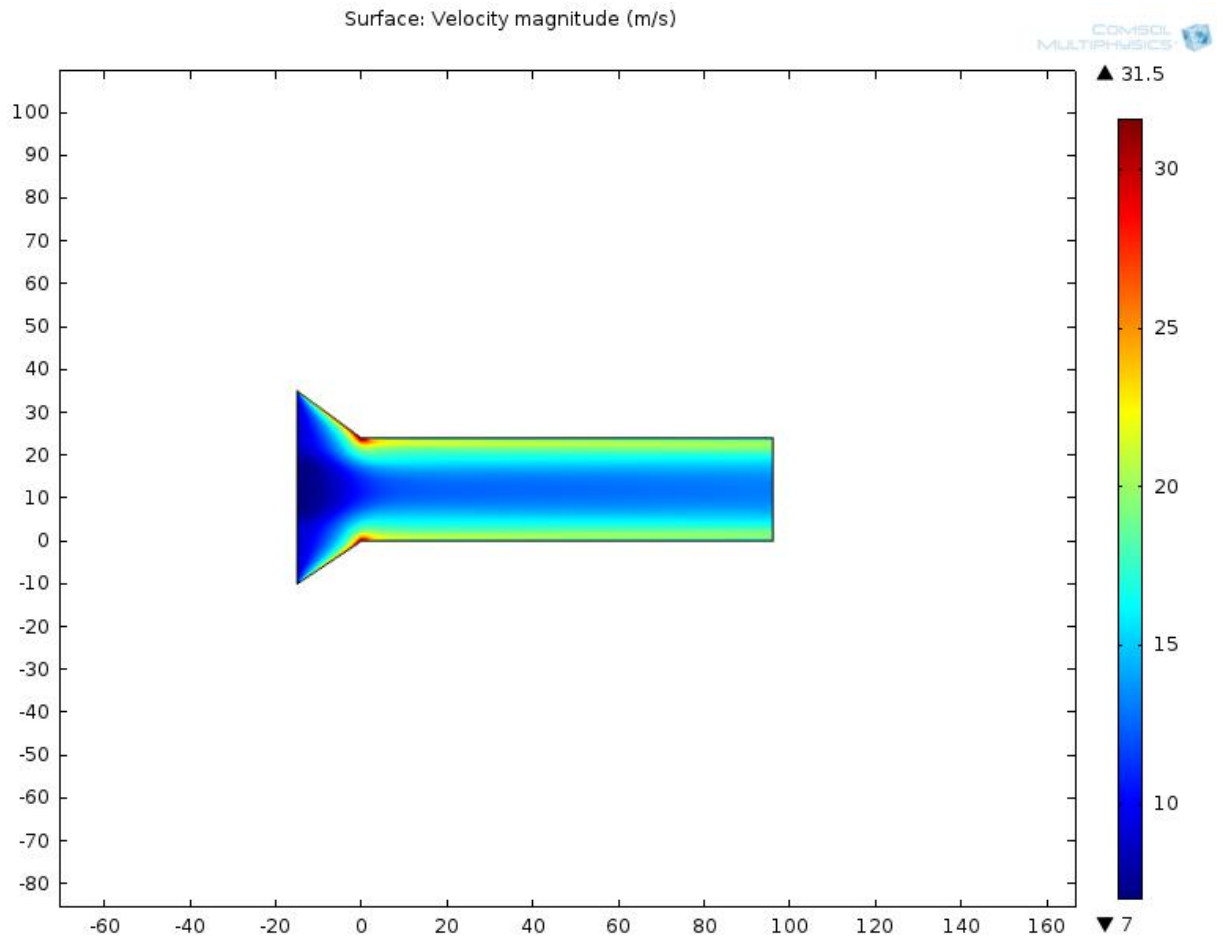
In this study, while we already built a 2×2×8 feet wind tunnel box, the characteristics and the wind flow feature inside the wind tunnel are still unknown. The next step is to test the wind speed in the test section, test the turbulence in the test section and find out a method to minimize the turbulence and optimize the efficiency of this wood base wind tunnel.

Before we try to find a solution for improving the performance of this wind tunnel, we should know the nature of the problem and then identify the solution. We tested the wind flow directly and recorded the wind speed at different locations at different heights, in the center of the test section. The wind speed distribution along the middle vertical phase represents the wind pattern of the fan and as we recorded the wind speed every 10 seconds; the changes in wind speed can show the turbulence intensity at that location.

Then we applied the honeycombs to the contraction and recorded the wind speed data again; this group of data can tell us if the honeycombs can help us to reduce the turbulence. Even if we could reduce the turbulence by the honeycomb, we also need to change the original wind flow pattern of the fan which was generated by the fan. By applying a corner to the contraction entrance, we could change the original wind flow pattern. Then we can test the wind velocity at the same original location to see if this method can truly improve the performance of this wind tunnel. Last but not least, we need to test the wind flow stabilization cross section, to see if the stable zone can be majority of the cross section of the test section. If it could achieve this goal, then this wind tunnel meets the desired requirements. Otherwise, we need to find another solution.

### 4.3 Simulation of Wind Tunnel

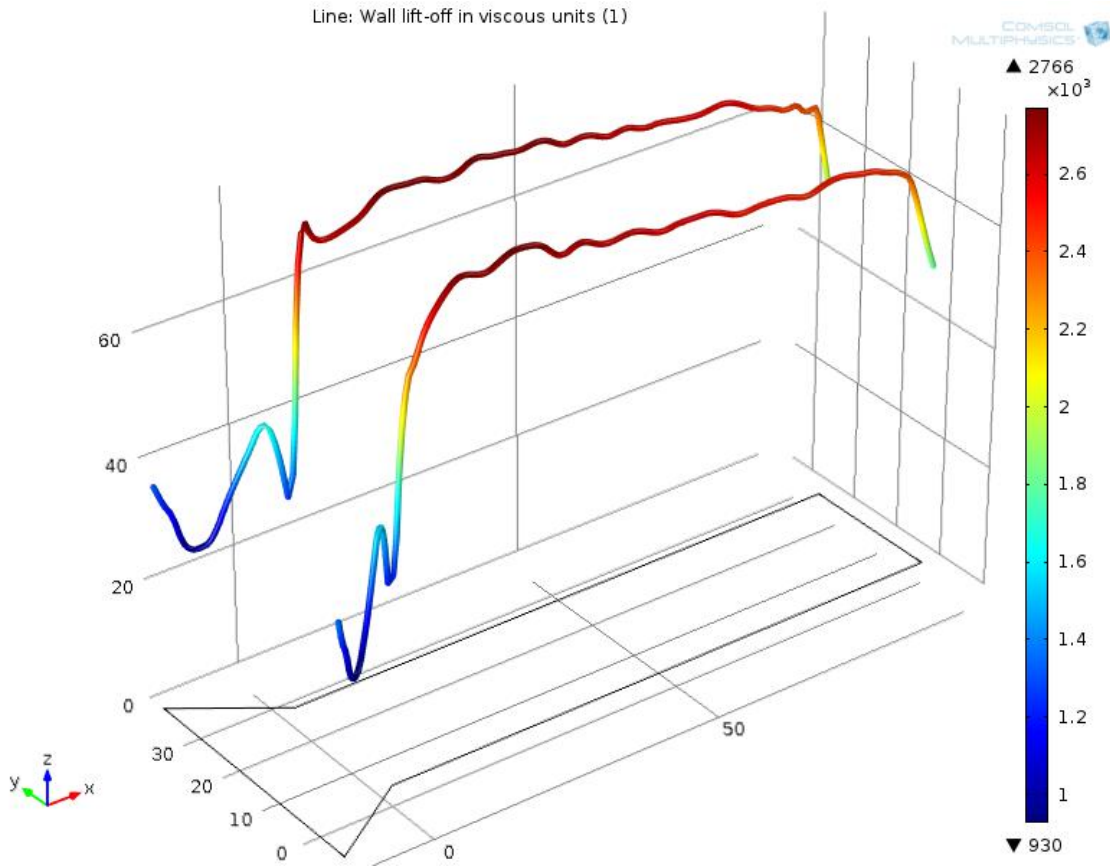
There are two challenging problems that we came across during the wind speed tests which need attention and must be carefully studied. One is the elimination of the vortex from the fan and the other is the enhancement in the stability of the wind flow. Before we did the experiments, several simulations using COMSOL had been done for studying the wind pattern of the wind tunnel. Figure 4.1 presents the velocity gradient caused by the vortex wind flow (Height versus Length, in inches).



**Figure 4.1** Velocity gradient caused by the vortex wind flow.

From Figure 4.1, we can find that the center velocity is usually lower than the velocity close to the wall. The vortex from the fan and the wind tunnel wall squeeze the wind into a

“wind ring” which has hollow lower wind speed. In addition, the dark blue lower wind speed becomes wider at the outlet than at the inlet. This phenomenon confirms the theory that the longer wind tunnel can have more stable wind distribution.



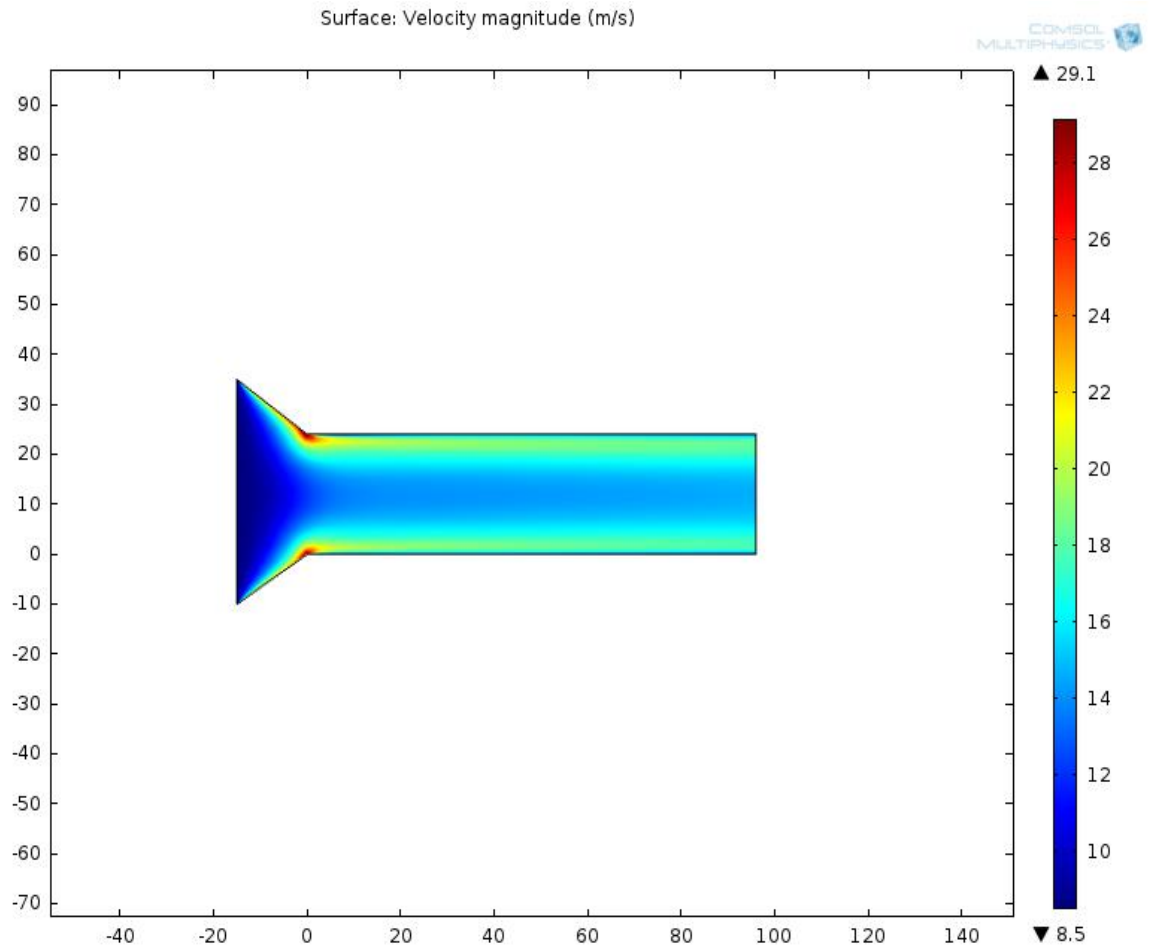
**Figure 4.2** Viscosity rising conditions corresponding to Figure 4.1

Figure 4.2 shows the wind viscosity (viscosity versus length in inches) close to the walls when the wind velocity is lower in the center, which is similar to the fan driving pattern. As can be seen, along the tunnel, the viscosity is extremely high in this formation. This is the reason for the dark blue area in Figure 4.1 to be narrow.

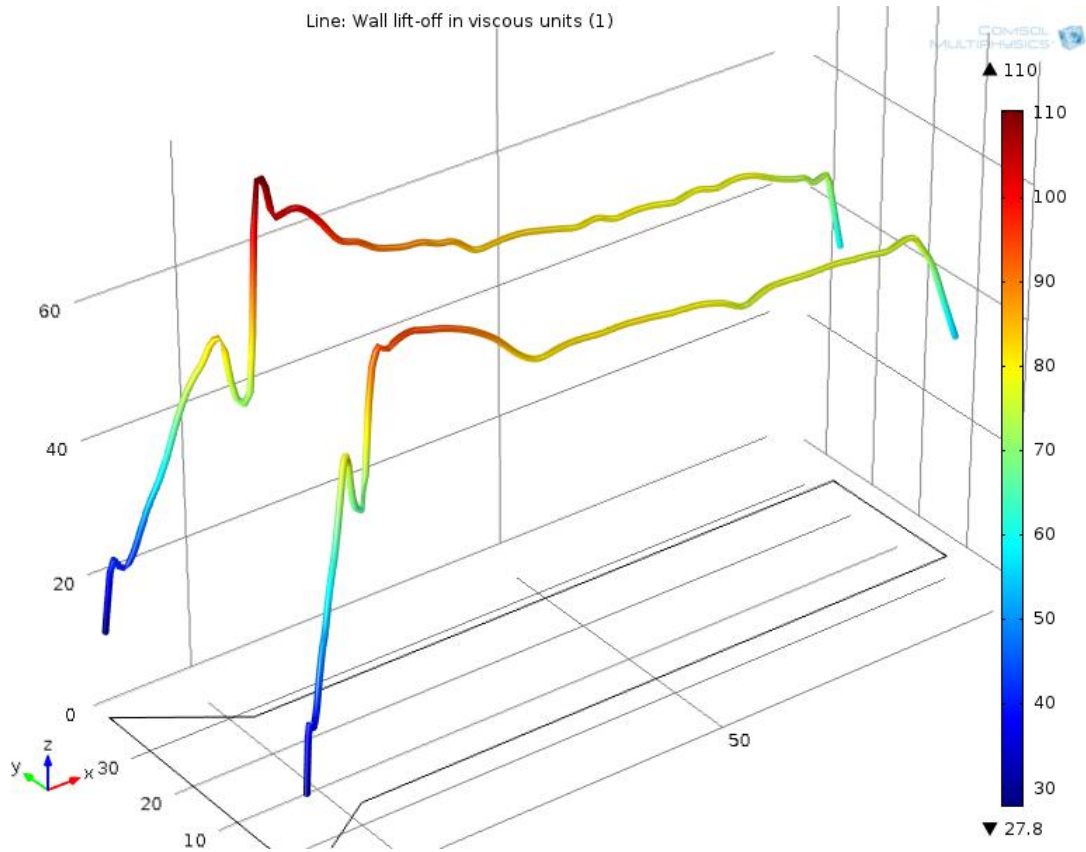
For comparison, Figure 4.3 shows the magnitude in velocity from a uniform wind source. The inlet is still from left, but, at this time, the wind source is of uniform velocity to



the right. Compared to Figure 4.1, this formation has less velocity variance between center and side walls. Figure 4.4 shows similar results – i.e. near the walls, the viscosity is correspondingly decreased compared to that in Figure 4.2.

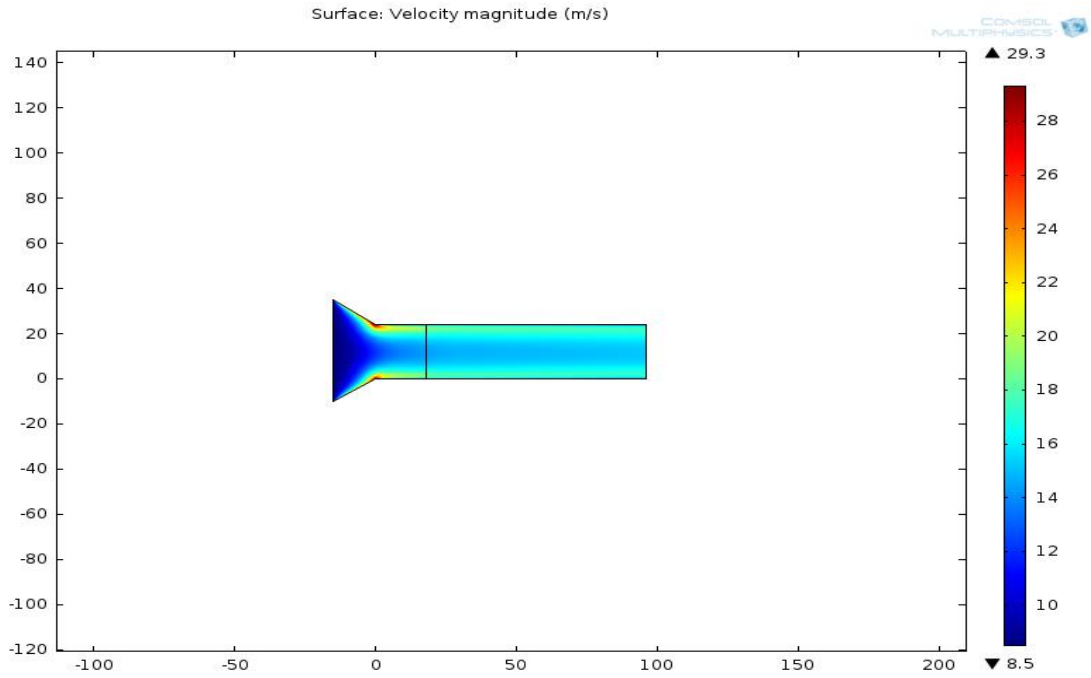


**Figure 4.3** Stable wind simulations.

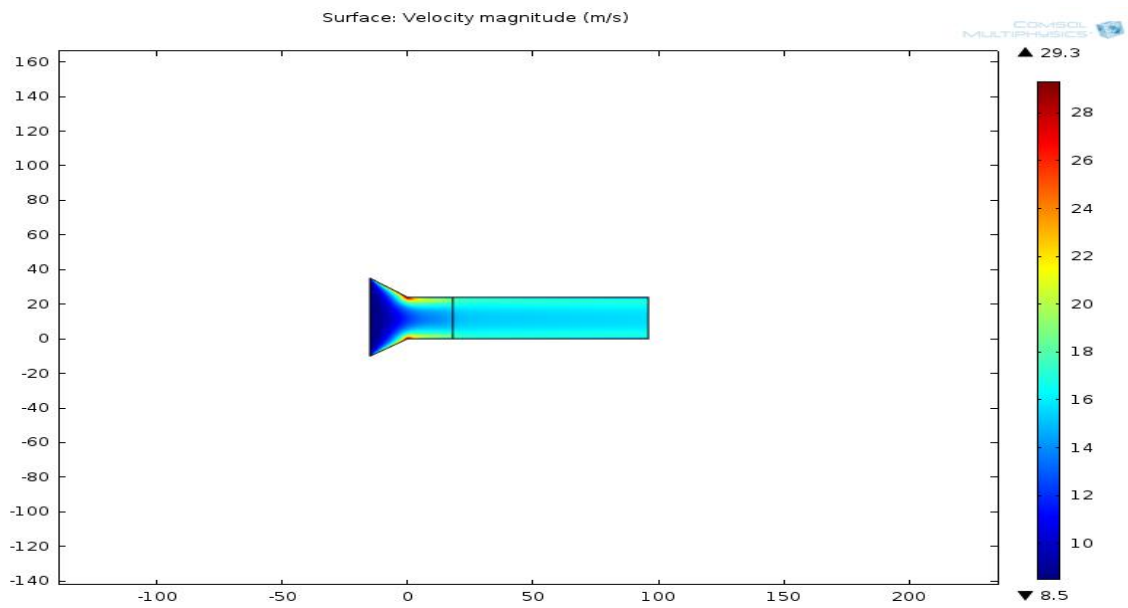


**Figure 4.4** Stable winds viscosity.

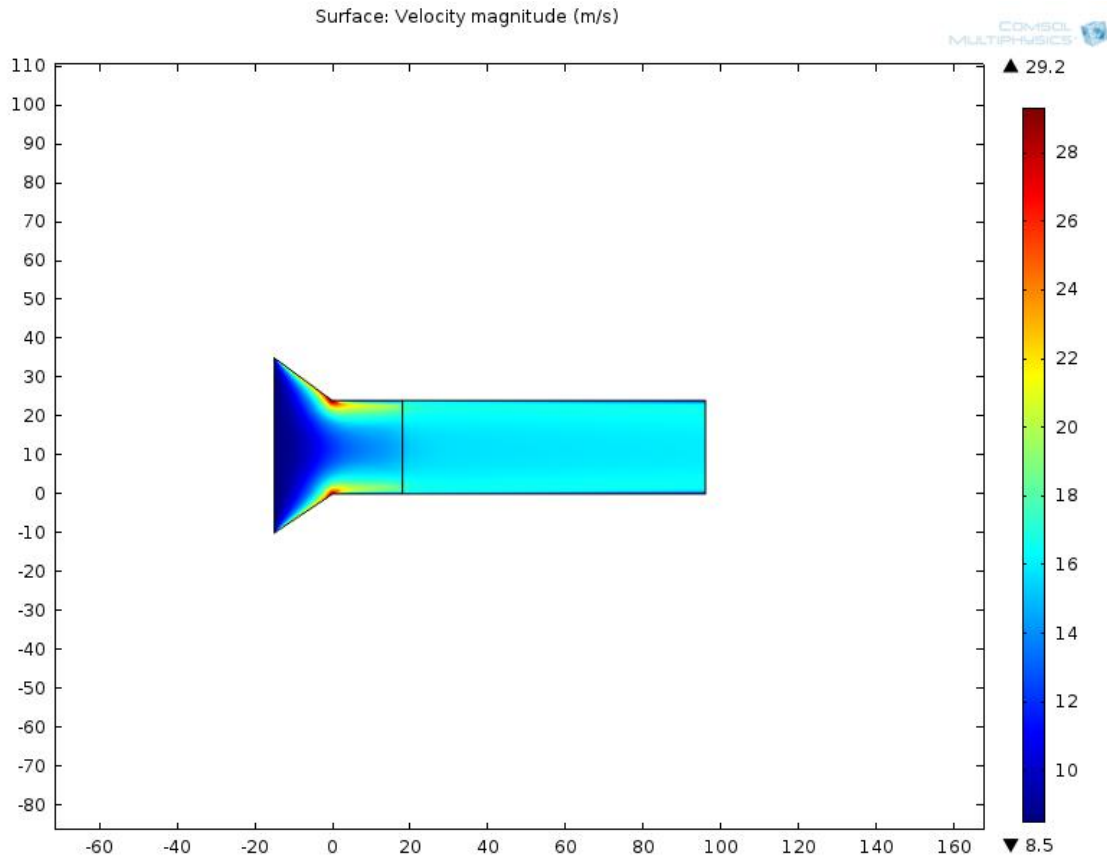
For the turbulence reduction and the vortex elimination, screens had been introduced in the wind tunnel, 16.5 inches inside from contraction section. Before we used the screens, we wanted to know the efficiency of different solidity screens. Solidity is the percentage of the solid area in the whole area of the cross section, and the solidity is related to the diameter of holes of the screens, and more holes means more separation materials, less vacant space and more solidity. Figures 4.5, 4.6 and 4.7 show the wind velocity magnitude with 0.25, 0.4 and 0.5 screens solidities.



**Figure 4.5** Efficiency of screens, solidity 0.25.



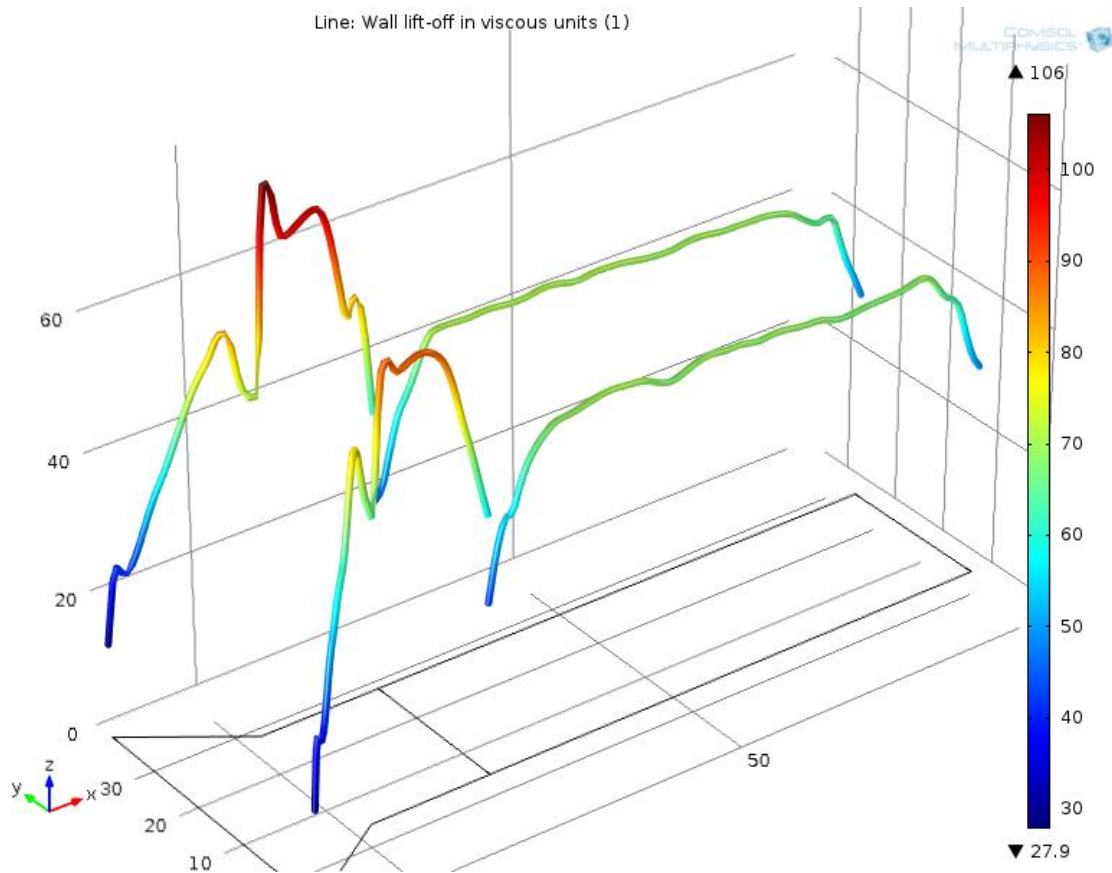
**Figure 4.6** Efficiency of screens, solidity 0.4.



**Figure 4.7** Efficiency of screens, solidity 0.5.

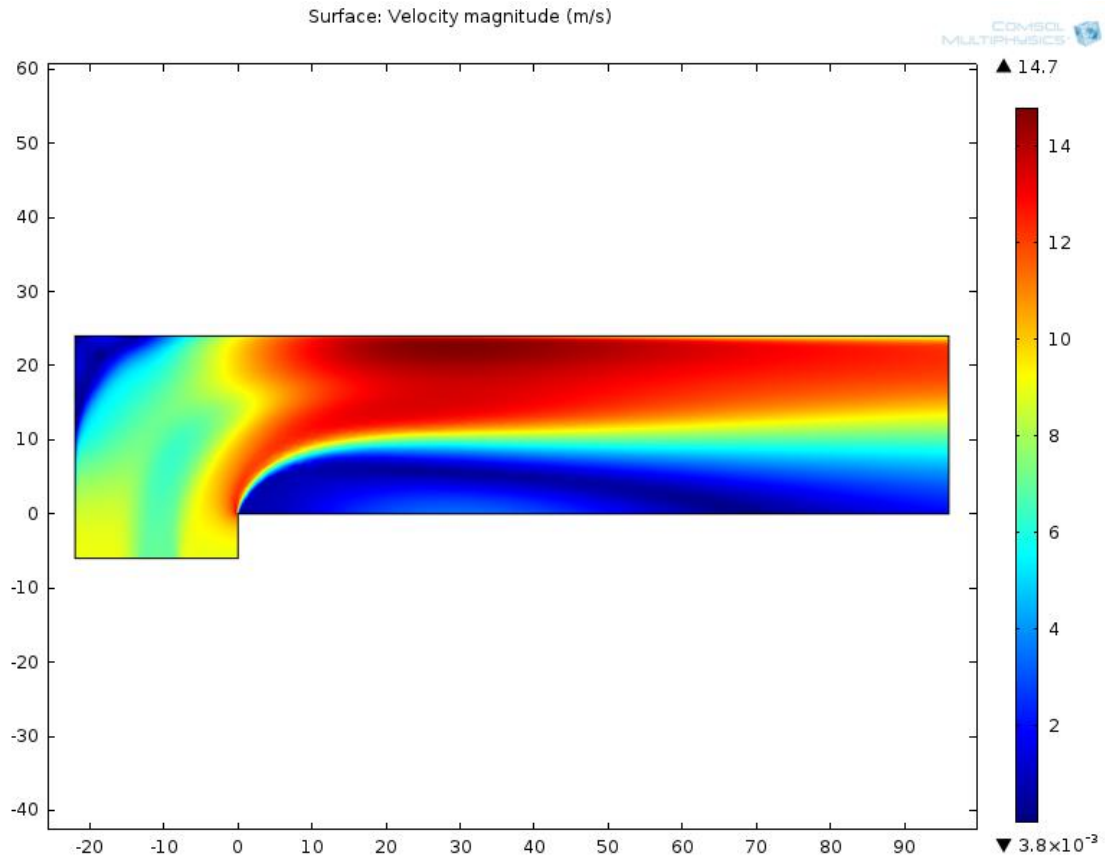
From Figures 5.5, 5.6 and 5.7, we can see the improvement in the uniformity of the wind speed. The holes from the screens cut the air flow into several small sections which reduce the vortex and turbulence significantly. From Figure 5.7, we can see a perfectly equally good wind flow through the test section. This remarkable quality is very hard to achieve because, in the simulation, we assumed the pressure of inlet to be very high and the resistance from inside could be ignored; however, in real experiments, we cannot have this condition and the velocity decreases with increase in screen solidity. But, these figures also show the efficiency of reasonable screens which can be obtained.

Figure 4.8 shows the viscosity along the wind tunnel when we applied a 0.5 solidity wind tunnel. Comparing to Figure 4.2 and Figure 4.4, we can conclude that the screens can have significant reduction in the viscosity and great improvement in the wind quality.



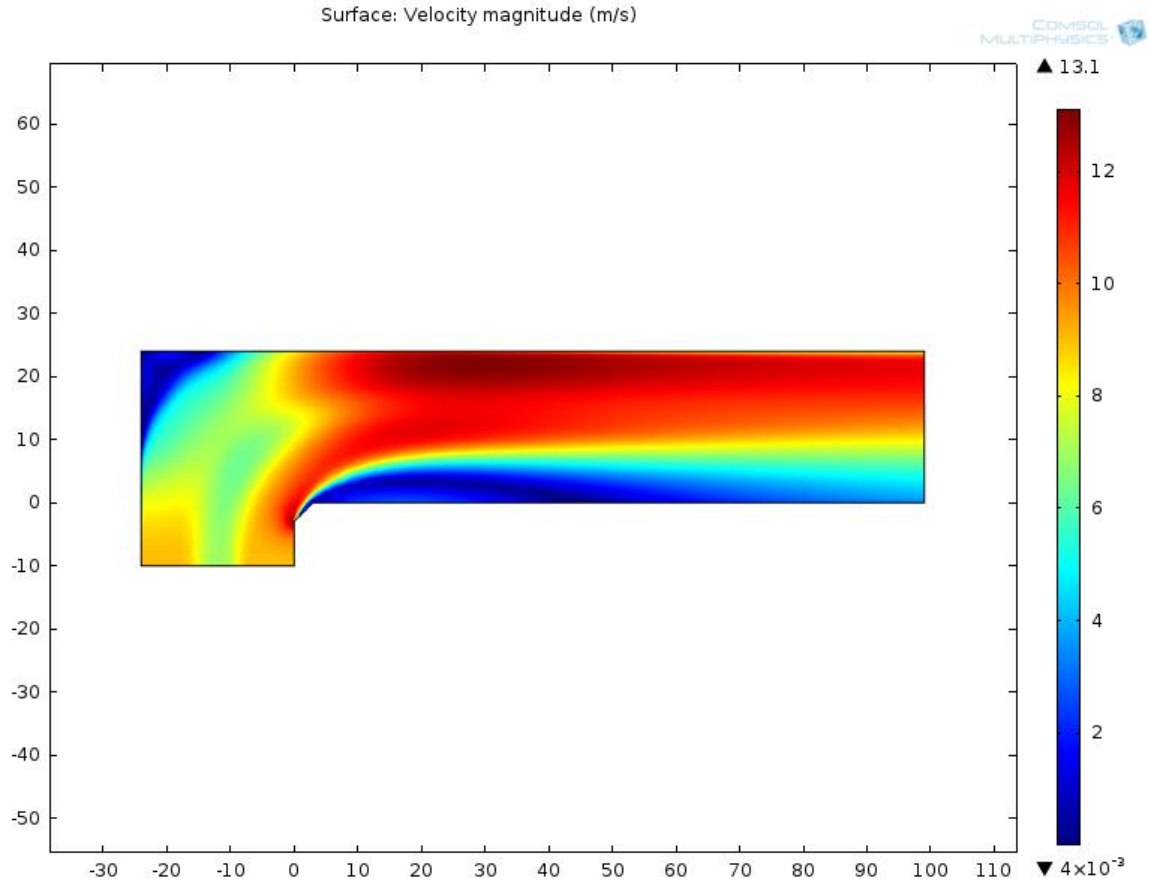
**Figure 4.8** Viscosity of wind after applied screens.

In order to eliminate the vortex from the fan, a corner can be applied to the wind tunnel to change the wind flow direction and wind flow pattern. Some simulations of the corner efficiency was completed to study the wind flow characteristics.



**Figure 4.9** Corner to eliminate vortex.

Figure 4.9 shows the wind flow pattern using corner. We can notice that the highest wind speed appears at the back opposites of the inlet. The back wall pushes the wind flow to opposite direction and reforms the wind shape. We can also notice the long blue zone beneath the red area. The red zone represents the higher level speed; this is the area that can be taken advantage of - for future testing, however, the blue area is wide. So the next step is to minimize the blue zone and gain more red area.

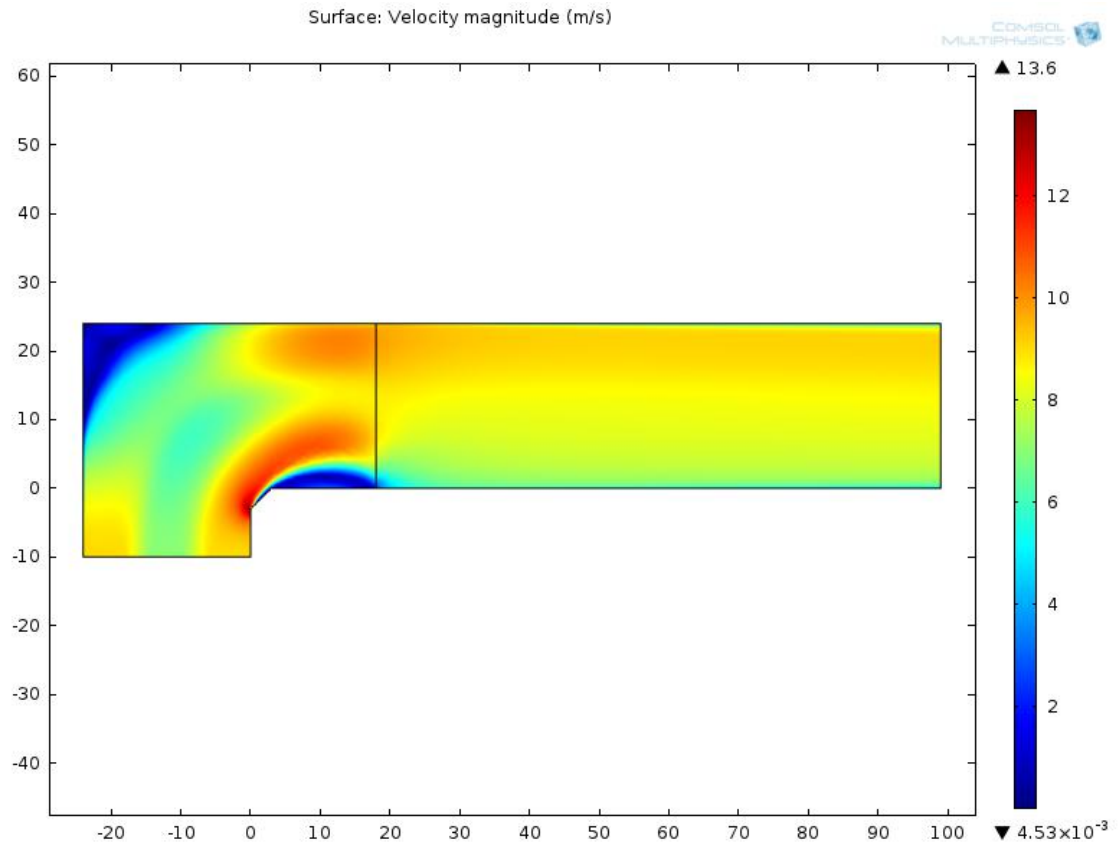


**Figure 4.10** Wind pattern after chamfered the corner.

From Figure 4.9, we can see that the blue zone is generated by the corner it passes by; so chamfering this corner could be a very right way. Figure 4.10 gives the answer to this question. After chamfering this corner, we notice that the blue area is decreasing instantly which saves more area for the red zone. From Figure 4.9, we can see that the width of the red zone in the test section only takes about 40% , but from Figure 4.10, it increases to about 60%.

For further improvement in the performance and the efficiency, the screen has been used again at the same location as the simulations discussed before.

Figure 4.11 shows the magnitude of the wind velocity using corner and a 0.4 solidity screen. The screen apparently reduces the blue zone significantly and helps us to equalize the wind speed at the test section. The even area is about 90% of the cross section which satisfies our original goal.



**Figure 4.11** Simulation of corner and a 0.4 solidity screen.



**CHAPTER 5**  
**RESULTS AND DISCUSSION**

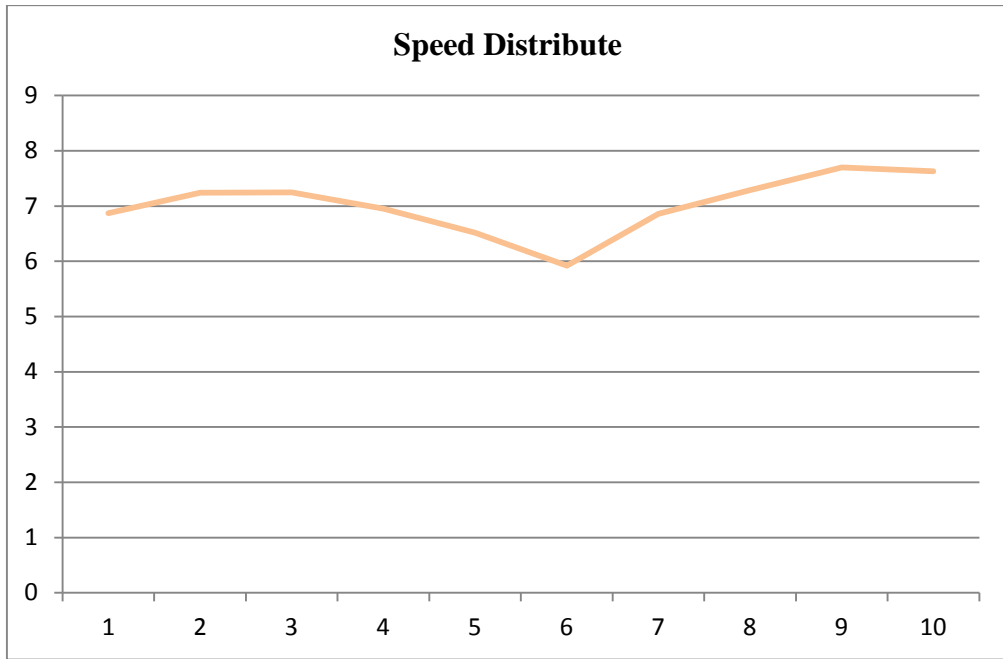
**5.1 Wind Characteristics at Test Section of Original Wind Tunnel**

In this study, before we apply the setting chamber to the wind tunnel, we need to study the initial wind flow condition in the test section for comparison. Both the average wind speed and wind speed changes every 10 seconds which represent the turbulent condition at each point have been discussed. All the data, we selected, are in the middle of the cross section with varying height. The data shows the fundamental condition of the wind speed changes versus height and the rough turbulence distribution without setting chamber.

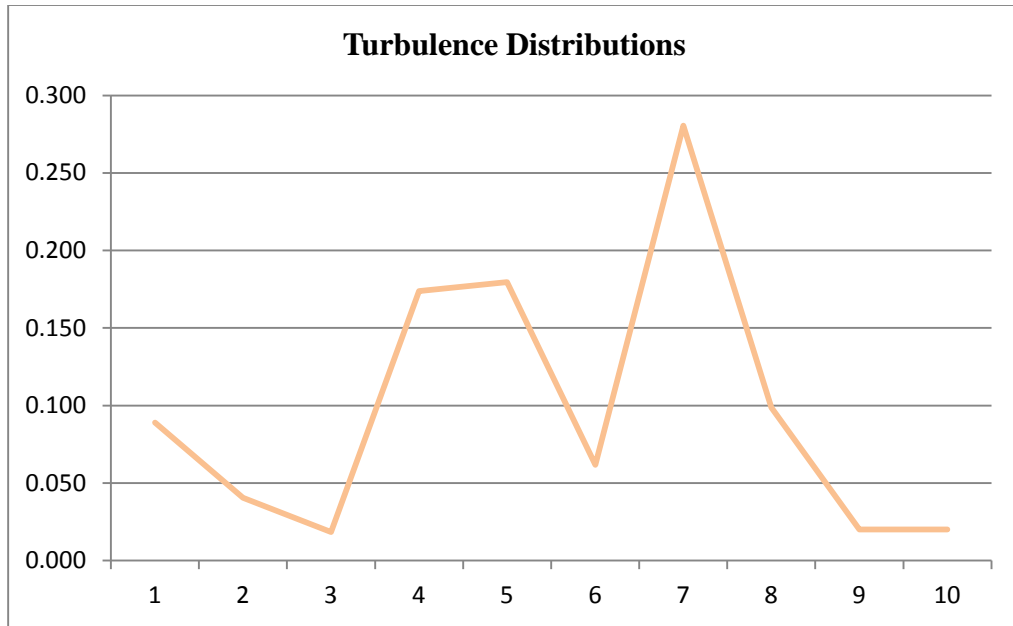
**Table 5.1** Wind Speed Changes Vertically from Test Section (2' from Exit)

<b>NO.</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>	<b>8</b>	<b>9</b>	<b>10</b>
Height	2"	4"	6"	8"	10"	12"	14"	16"	18"	20"
wind speed m/s	7.3	7.2	7.3	7	6.5	6.3	6.6	7.2	7.6	7.7
	6.4	6.9	7.2	7.2	6.9	6.1	7.2	7.4	7.6	7.7
	6.6	7.3	7.1	7.3	6.5	6	7.7	7.5	7.6	7.7
	6.9	7.3	7.3	7.2	6.6	6.1	7.2	8	7.6	7.5
	6.9	6.9	7	6.6	7.5	6	6.6	7.1	7.6	7.6
	7	7.2	7.3	6.2	6.2	6	6	6.8	7.6	7.7
	6.5	7.4	7.5	7.5	6.3	5.9	6.1	7.3	7.9	7.7
	7.2	7.3	7.3	6.4	6.5	5.6	7.1	7.2	7.9	7.8
	6.8	7.5	7.3	7.1	6.1	5.5	7	7.1	7.9	7.3
	7.1	7.4	7.2	7	6.1	5.7	7.1	7.3	7.7	7.6
variance	0.089	0.040	0.018	0.174	0.180	0.062	0.280	0.099	0.020	0.020
average	6.87	7.24	7.25	6.95	6.52	5.92	6.86	7.29	7.7	7.63

Figure 5.1 and Figure 5.2 are from Table 5.1 and show the wind velocity and turbulence distribution.



**Figure 5.1** Wind speed distributions at test section vertically.



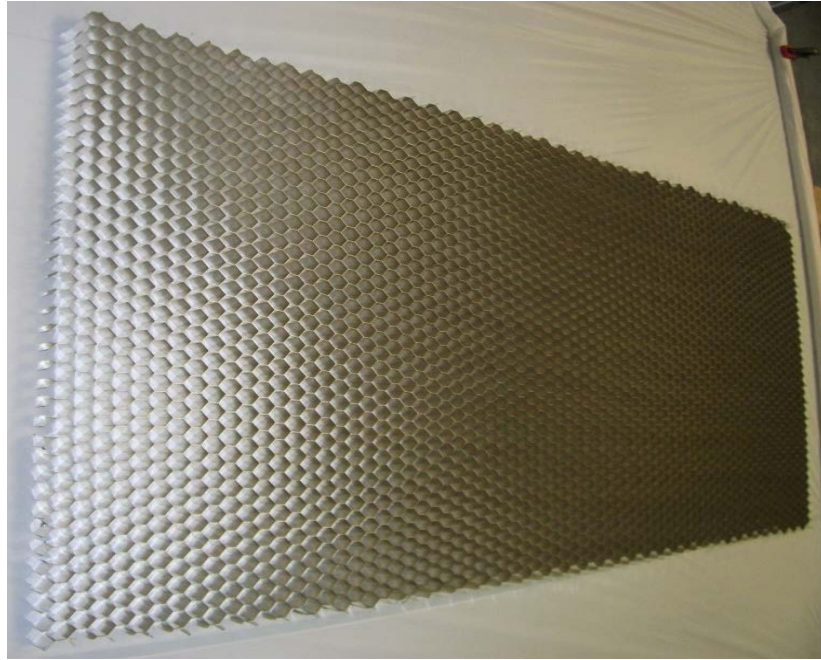
**Figure 5.2** Speed variance.

Figure 5.1 and Figure 5.2 are from one group of data. Figure 5.1 describes the wind velocity variance at different heights at test section. Because of the driving fan pushing the air from the contraction into the wind tunnel, there is an obvious hollow wind zone in the center of the wind tunnel. This nature of the fan pushing characteristic is similar to the wind speed data above.

The second picture represents the wind turbulence condition at different positions. If the number is higher, the wind turbulence is more. The point 6 is the center of the wind tunnel and the wind speed is lowest as well; so it has the lower turbulence. At point 3 and point 9, these two points have the fastest wind velocity and most stable wind speed as well, which represents that the strong wind can lower the wind turbulence and can keep the wind stream stable. From other similar height data, we see the same effect. So, for stable and even wind velocity, we need to equalize the wind stream, and make wind flow at the same speed along the cross section.

## 5.2 Screens for stabilization

In order to stabilize the wind flow and reduce the turbulence first, an aluminum honeycomb structure has been applied to the wind tunnel. The details of this aluminum Honeycomb has been given below.



**Figure 5.3** Honeycombs.

Source: <http://www.topnetting.com/products/aluminum-honeycomb.html>

This structure is of one slice of unexpanded 3000 series commercial grade aluminum honeycomb grid. This slice will have an expanded dimension of 24"x48" when properly expanded by the buyer. The thickness of the expanded sheet is 1.000". Cell size is 1". Foil is perforated. Material Tolerances: Thickness (T) =  $\pm 008$ ".

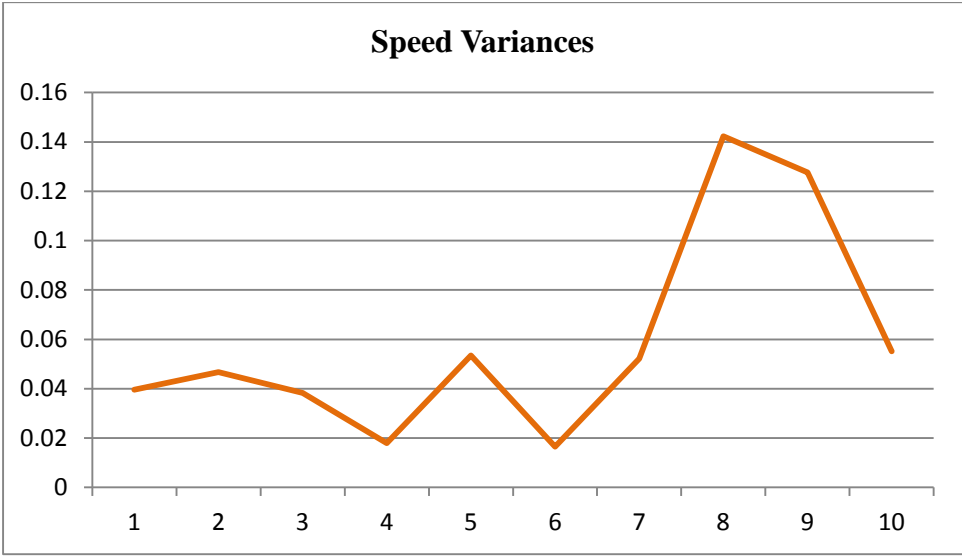
We applied this honeycomb at 16.5 inches inside the contraction (entrance). We made it completely vertical.

After we finished all the construction work, we tested the wind speed 2 feet from exit again. We have the following data:

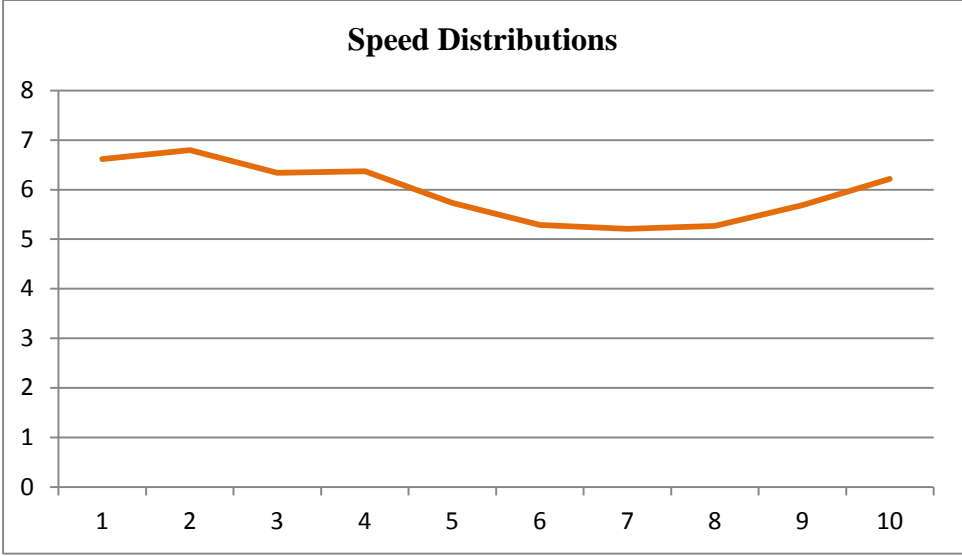
**Table 5.2** Wind Speed Changing Vertically from Test Section (2' from Exit)

NO.	1	2	3	4	5	6	7	8	9	10
Height	2"	4"	6"	8"	10"	12"	14"	16"	18"	20"
wind	6.9	6.5	6.5	6.5	6.1	5.3	5.5	5.3	5.3	5.9
speed m/s	6.9	6.7	6.4	6.3	5.7	5.1	5.3	5.4	5.4	6.5
	6.7	6.7	6.5	6.5	6	5.4	5.4	4.7	6.1	6.5
	6.5	7.2	6.4	6.4	6	5.4	5.5	4.9	5.8	6.5
	6.7	6.8	6.1	6.5	5.7	5.3	4.9	5.2	5.3	6
	6.3	7.1	6.5	6.4	5.7	5.1	5	5.7	5.7	6.4
	6.7	6.6	6.4	6.1	5.4	5.3	4.9	5.6	6.1	6.1
	6.5	6.7	6.1	6.4	5.5	5.2	5.3	4.8	5.3	6
	6.4	6.9	6	6.2	5.6	5.5	5.1	5.8	6.2	6.2
	6.6	6.8	6.5	6.4	5.6	5.3	5.2	5.3	5.7	6.1
variance	0.039	0.047	0.038	0.018	0.053	0.016	0.052	0.142	0.128	0.055
average	6.62	6.8	6.34	6.37	5.73	5.29	5.21	5.27	5.69	6.22

Figures 5.4 and 5.5 show the average speed and variance changing at different heights.



**Figure 5.4** Speed variances after applied a screen.



**Figure 5.5** Speed distributions.

By comparing Figure 5.1 with Figure 5.5, we can see that the wind speed decreases by about 1m/s. Because of the slight resistance of the aluminum honeycomb, the wind speed decreases slightly at same locations. However, the improvement in the performance of the wind tunnel is significant in this experiment. From Figure 5.2 and Figure 5.4, we can see that the turbulence is decreasing significantly which demonstrates the efficiency of the honeycomb.

### **5.3 Corner for Stabilization**

From Table 5.1 and Figure 5.1, we can conclude that the wind speed is lowest at the center and highest between center and edge. Even if we use honeycomb to reduce the wind turbulence, from Table 5.2, Figures 5.4 and 5.5, we can see that the wind speed is not even on the cross section. This effect is called as hollow phenomenon which is necessary to be eliminated. Based on circuit wind tunnel design, in this study, we use a 90 degree square-cross section corner to change this hollow phenomenon. The corner is 1 meter long stretch out of the contraction and 90 degree change in direction connected to the fan.

After we apply the corner on the wind tunnel, we test the wind characteristics 2 feet from the exit at the center which is the same location as the previous experiments. Table 5.3 represents the wind speed distribution.

**Table 5.3** Wind Speed at Test Section after Applied Corner

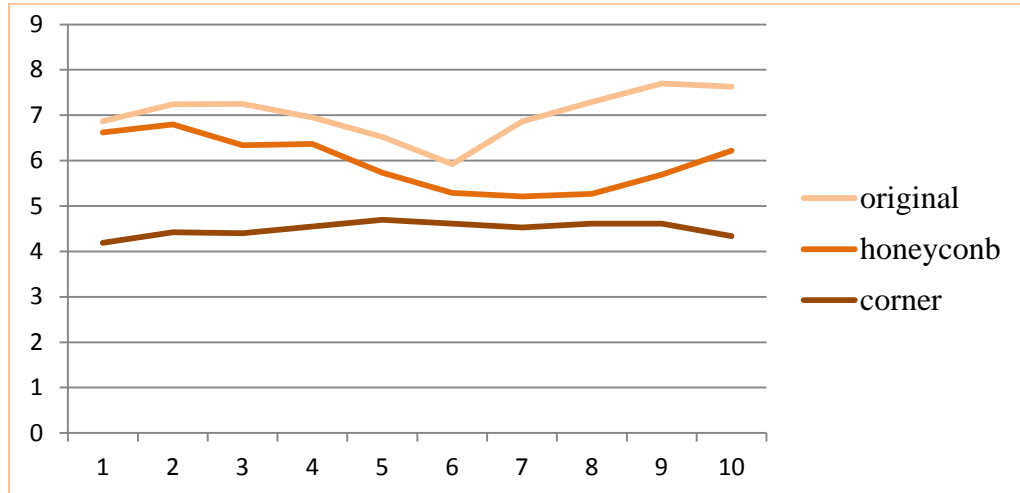
<b>NO.</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>	<b>8</b>	<b>9</b>	<b>10</b>
Height	<b>2"</b>	<b>4"</b>	<b>6"</b>	<b>8"</b>	<b>10"</b>	<b>12"</b>	<b>14"</b>	<b>16"</b>	<b>18"</b>	<b>20"</b>
wind	4.4	4.6	4.3	4.6	4.7	4.6	4.6	4.6	4.6	4.3
speed	4.2	4.5	4.3	4.5	4.8	4.7	4.6	4.6	4.6	4.5
m/s	3.9	4.5	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.4
	4	4.5	4.3	4.6	5	4.7	4.5	4.5	4.5	4.2
	4.2	4.2	4.5	4.5	4.7	4.7	4.4	4.6	4.6	4.4
	4.1	4.5	4.4	4.5	4.6	4.6	4.6	4.6	4.6	4.5
	4.4	4.3	4.3	4.6	4.6	4.4	4.3	4.7	4.7	4.2
	4.2	4.4	4.5	4.4	4.7	4.6	4.6	4.6	4.6	4.2
	4.3	4.5	4.3	4.6	4.6	4.6	4.5	4.7	4.7	4.3
	4.2	4.2	4.5	4.6	4.7	4.6	4.6	4.6	4.6	4.4
varianc	0.025	0.019	0.013	0.005	0.015	0.007	0.011	0.003	0.003	0.013
es	4	6	3	0	6	7	2	2	2	8
average	4.19	4.42	4.4	4.55	4.7	4.61	4.53	4.61	4.61	4.34

From this data, we notice that the wind speed decreases again; the reason is that the corner creates more resistance to the motor of the fan. After using corner, the resistance to the wind speed decreased. During the experiment, we also noticed that the motor generated more heat than before, which showed that it is harder to drive the wind because of the 90 degree shift in the direction. On the other hand, the equalization of the wind speed on the cross section improved significantly as well as the reduction in turbulence. We can see that

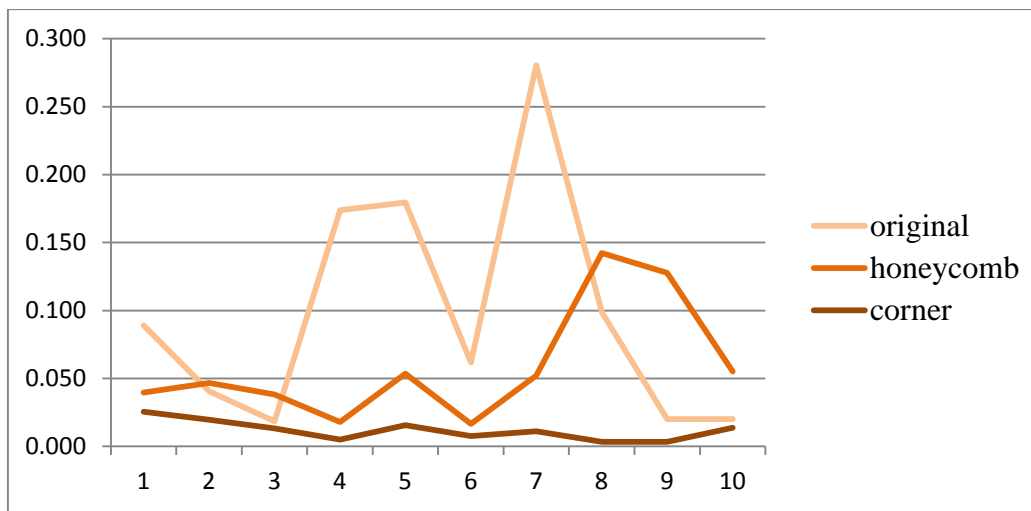


the wind speed is around 4.6 meters per second at all heights, and at the same height, the wind speed changes slightly over time which means the turbulence is extremely low.

Table 5.3, Figure 5.7 and 5.8 support this observation.



**Figure 5.6** Average speeds at different heights.

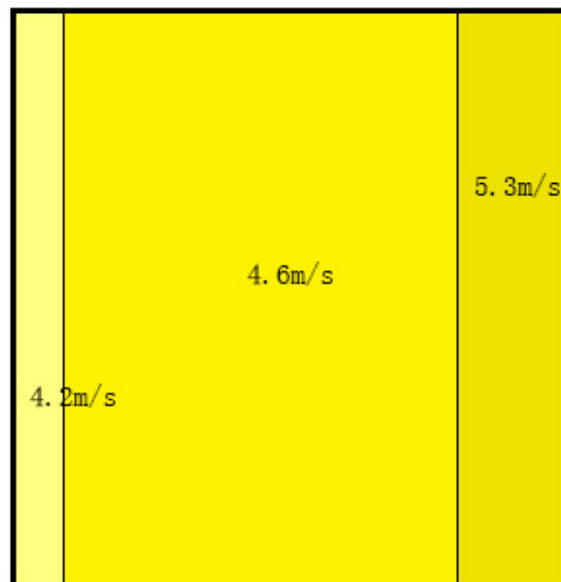


**Figure 5.7** Wind speed variance at different heights (turbulence).

From Figures 5.7 and 5.8, we notice that the average speed is almost even at different heights by using corner and honeycomb. The variance, after applying the corner and honeycomb, decreased. By using honeycomb and corner, we obtain the high stable wind

quality we expect. In addition, from Figure 5.7, we conclude that the vortex generated by the fan is apparently eliminated.

After we test the wind speed variance vertically, we also need to test how much percentage of the average wind speed can take place at the cross-section of the test section. We tested the wind speed of all the test section. Figure 5.8 shows the whole wind speed distribution, at the test section. The tolerance is  $\pm 0.2$ . The majority of the stable wind area is 4.6m/s which takes 72.22 % of the entire cross-section.



**Figure 5.8** Wind speed distributions of cross-section.

## **CHAPTER 5**

### **CONCLUSIONS**

Wind tunnel is the most fundamental test equipment for testing aircrafts and studying aerodynamics. Because of the complexity of the test-subject's geometry, it is difficult to study the aerodynamic pattern simply based on theoretical calculations. Most of the aerodynamics experiments still use wind tunnels. The progress of the wind tunnel design, construction and technology is highly related to the advancements in air crafts. Aircraft manufacturing has pushed the wind tunnel technology forward. Wind tunnels can be categorized by the wind speed limit differences, which are controlled by the mechanism of the driving methods, structure applications, etc. In this case, we built a small scale wood based wind tunnel for future testing of "Magnetic Augmented Rotational System (MARS)". The characteristics of the low speed wind tunnel and the related data have been presented along with its advantages and shortcomings.

A wood based 2×2×8 feet wind tunnel with a corner, a contraction section, a settling chamber, and a test section have been constructed. The vortex and turbulence resulting from the fan can be disadvantageous. Screens can reduce the turbulence but cannot eliminate the vortex. Vortex can be eliminated by corner and settling chamber. 72.22% area of the test section is stable (4.6 meters per second) by using corners and screens. Changing the driving force and adding more corners can provide better wind quality for the wind tunnel. The design of the wind tunnel, in this study, is limited by the driving fan. If more powerful fan can be used, the current designs and simulations have to be reconsidered.

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