Design Construction and Performance Test of a Short Length Subsonic Wind Tunnel

by

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering in the Department of Mechanical Engineering

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Declaration

This is to certify that the thesis work entitled "*Design construction and performance test of a short length subsonic wind tunnel*" has been carried out by *Md. Arifuzzaman* in the Department of Mechanical Engineering, Khulna University of Engineering & Technology, Khulna, Bangladesh. The above thesis work or any part of this work has not been submitted anywhere for the award of any degree or diploma

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Approval

This is to certify that the thesis work submitted by *Md. Ariufzzaman* entitled "*Design construction and performance test of a short length subsonic wind tunnel*" has been approved by the board of examiners for the partial fulfillment of the requirements for the degree of *Master of Science in Engineering* in the Department of Mechanical Engineering, Khulna University of Engineering & Technology, Khulna, Bangladesh in September 2012.

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ABSTRACT

Wind engineering is a field that has been evolving over centuries. Wind engineering is based on using measurements of actual wind flows to predict the forces transferred to engineering structures and machines. A large portion of wind engineering today depends directly or indirectly on wind tunnels. Wind tunnel is a device, by artificially producing airflow relative to a stationary body that measures aerodynamic force and pressure distribution to simulate with actual conditions. Wind Tunnels offer a rapid, economical, and accurate means for aerodynamic research. The most important aspect of wind tunnels is their ability to accurate recreate the full complexity of full fluid flow. Aerodynamicists use wind tunnels to test models of proposed aircraft since the flow conditions can be carefully controlled in the tunnel which affect the forces on the aircraft. In the current project a short length subsonic wind tunnel is designed, constructed and its performance is tested. A 20 kW motor with 10 blades of diameter 1.20 m is used a fan to facilitate the air flow. The cross section of the wind tunnel is of square type with dimension 0.90 m × 0.90 m and the length of the section is 1.35 m. The overall length of the tunnel is about 7.35 m which can be erected in a laboratory room. After testing the performance of the tunnel it is found that the maximum wind velocity inside the wind tunnel is 26.62 m/s and the velocity profile along the height and width of the test section is almost linear in nature excluding the 11.11% allowance in four sides. The constructed wind tunnel has conformed to the design and can be used for different test in the field of aerodynamics.

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Nomenclature

Re	Reynolds number
CR	Contraction ration
D_h	Hydraulic diameter
ϑ_e	Half of the included angle of the diffuser cone
A_R	Area ratio
β_h	Honeycomb porosity
β_s	Screen porosity
Re_Δ	Reynolds number based on material roughness
c_{ts}	Test section air speed
Δp	Pressure loss
ρ_m	Mesh density of screen

CHAPTER I

Introduction

1.1 General

Wind engineering is a field that has been evolving over centuries. A large portion of wind engineering today relies directly or indirectly on wind tunnels. Wind tunnels are used for a variety of different reasons such as their ability to test prototypes early in design cycles, or because of their ability to record a large amount of data. Probably the most important aspect of wind tunnels is their ability to accurate recreate the full complexity of full fluid flow. Wind tunnels are especially used when testing new designs and materials, such as the World Trade Center Twin Towers; this is because of their ability to simultaneously account for wind interactions, as well as material and geometric properties. When testing new materials and designs many times these interactions and properties are not fully known, limiting the use of finite element analysis software. [1]

Aerodynamicists use wind tunnels to test models of proposed aircraft since the flow conditions can be carefully controlled in the tunnel which affect the forces on the aircraft. Experimental information useful for solving aerodynamic problems may be obtained in a number of ways: from flight tests; drop tests; rocket sleds; water tunnels; whirling arms; shock tubes; water tables; rocket flights; flying scale models; ballistic ranges; and subsonic, near-sonic, transonic, super-sonic, and hypersonic wind tunnels. Each device has its own sphere of superiority, and no one device can be called "best". By using special diagnostic techniques, the performance of the aircraft can be understood and hence improved easily. The characteristics of wind, variation of its pressure and speed are the interest of many people all around the world. They are studying the effect of air moving over or around solid objects and at different speed. The nations of the world support aerodynamic research, of which wind tunnel testing is a major item, according to their abilities and desires. Usually each nation sets up a separate organization that augments the activities of the armed services, and further work is farmed out to universities and industry.

In the United States this central agency is the National Aeronautics and Space Administration, with offices in Washington, D.C. and whose laboratories are at the Goddard Space Flight Center in Maryland, the Langley Research Center in Virginia, the John F. Kennedy Space Center in Florida, the Marshall Space Flight Center in Alaama, the Mississipi Test Facility in Mississipi, the Manned Spacecraft Center in Texas, the Lewis Research Center in Ohio, the Flight Research Center in California, the Ames Research Center in California, and the Jet Propulsion Laboratory in California. In addition the armed services have tunnels of their own. The Air Force has several at Wright-Patterson AFB, Ohio, and at Arnold Engineering Development Center, Tennesse. The Navy has tunnels at the David Taylor Naval Ship R&D Center in Carderock, Maryland and the Naval Ordnance Laboratory at White Oaks, Maryland. Army has tunnels at the Aberdeen Proving Grounds, Maryland and Ames Research Center, California. [2]

In a society that is growing dependent on computers and always moving towards new technologies, the use of wind tunnels to solve aerodynamic problems may seem obsolete. But the use of wind tunnels to solve both basic and complex aerodynamic problems is still needed today. Unlike computers which produce mostly quantitative data, wind tunnels provide unique flow visualization that can find critical problems and solutions not seen in the pure numbers. With their ability to combine both types of data, wind tunnels are a critical instrument in the quick and thorough design process of anything that involves fluid dynamics. One of the most important parts of a wind tunnel is the flow visualization it provides. Sure lift, drag and efficiency can all be calculated with complex equations. However, it is the visual aspect of a wind tunnel and the controllable environment it provides that allows you to physically see what will happen in multiple real life situations. You can create an environment where you can see how a plane will react when it is taking off, cruising and landing all in the confines of a test lab. Then, with the same machine, you can see how air flows over the body of a racecar when it is zooming around a track to maximize its efficiency. The versatility and tangibility of a wind tunnel is what makes it such an important part of aerodynamic research. Being such an important part of aerodynamic research, it is important to continue to promote wind tunnel testing. In this project, the ultimate goal is to research, design, build and evaluate a real wind tunnel in order to more fully understand basic concepts of aerodynamics and recognize the capabilities and importance of wind tunnels in solving practical engineering problems. [3]

Table1.1 shows some of the many subsonic wind tunnels available here in the United States.

Table 1.1 Wind Tunnels of United States [4]

Organization	**Wind Tunnel**	**Test Section (ft)**	**Speed Range (Mach No.)**	**Reynolds No. (per ft x 106)**
NASA Ames Research Center	80 X 120 ft	80 x 120	0 to 100 kts	0 -1.2
	40 X 80 ft	40 x 80 x 80	0 to 300 kts	0 -3
	12 ft Pressure Tunnel	11.3 x 11.3 x 28	0.05 -0.55	0.1 -12
NASA Langley Research Center	14 X 22 Foot Subsonic Tunnel	14.5 x 21.75 x 50	0 to 0.3	0 to 2.1
	12 foot Low Speed Tunnel	12 ft x 15 ft	0 to 77 ft/sec	0 to 0.5
	Low-Turbulence Pressure Tunnel (LTPT)	7.5 x 3 x 7.5	0.05 -0.5	0.4 -15.
	20-foot Vertical Spin Tunnel	20 dia, 25 H	0 to 85 ft/sec	0.0 to 0.15
NASA Glenn Research Center	9 X 15 ft	9 x 15	0 -0.2	0 -1.4
	Icing Research Tunnel	6 x 9	0 -0.5	3.3
US Air Force Research Laboratories	SARL	10 x 7	0.20 -0.50	
	Vertical Wind Tunnel	12 x 15	0 -150 ft/sec	0 -0.91
Naval Surface Warfare Center, Carderock Division	Subsonic	8 x 10	20 -275 ft/sec	1.75
US Army Aeromechanics Laboratory	Army Aeromechanics	7 x 10	0 -0.33	0 -2.1
Lockheed Martin	LSWT # 1 & 2	30 x 26 (#1)	14 -146 ft/sec (#1)	0 -1
		16 x 23 (#2)	29 -293 ft/sec (#2)	0 -2
	8 X 12	8 x 12	0 -293 ft/sec	0 -1.7
	IWT	4 x 2.5	88 -308 ft/sec	0 -2
Allied Aerospace Industries -Micro Craft	LSWT	8 x 12	0 -0.37	0 -2.5
Northrop Grumman	Research	2.5 x 3.5	Max Q = 60 psf	1.7
	7 X 10	7 x 10	Mach = 0 to 0.36	1.8
United Technologies	Large Subsonic WT	8' Octogonal x 16' long	Mach = 0 to 0.90	4.5
		10 x 15 x 31	Mach = 0 to 0.45	2.6
	Acoustic Research Tunnel	18' Octogonal x 40' long	Mach = 0 to 0.26	1.6
		5' Diameter	Up to Mach = 0.65	4.6
	Pilot Wind Tunnel	50" Diameter x 8' long	Up to Mach = 0.35	4.6
		4 x 6 x 8	Mach = 0.12	0.9
Georgia Institute of Technology	7 X 9 ft	7 x 9	0 -0.22	0 -1.6
	Low Turbulence	3.5 x 3.5	73 ft/sec	0.5
Massachusetts Institute of Technology	Wright Brothers	7.5 x 10 Elliptical	Up to 0.36 @ 0.25 bar	Up to 2.25 @ 1.5 bar
University of Maryland	Glenn L. Martin	7.75 x 11.04	0.0 -0.3	N/A
Old Dominion University	Langley Full Scale Tunnel	30 x 60	38 -132 ft/sec	1
Texas A&M University	7 X 10 ft	7 x 10	0 -0.25	0 -1.9
Virginia Polytechnic Institute	Stability Wind Tunnel	6 x 6	0 -275 ft/sec	1.5
University of Florida	anechoic wind tunnel	2.43 x 3.67 x 6.00 ft	0 -76 m/s	3 -4
University of Washington	Kirsten Wind Tunnel	8 x 12	0 -302 ft/sec	0 -1.8
Wichita State University	Beech Wind Tunnel	7 x 10	0 -264 ft/sec	0 -1.5

Although wind tunnels have been built in many different configurations, they all have four basic parts, which are:

- A contoured duct to control the passage of the working fluid through the test section where the model is mounted.
- A drive system to move the working fluid through the duct.
- A model of the test objects that is either full size or, more often, a reduced-scale model.
- Instrumentation that may either be quite simple, such as a spring scale to measure force, or extremely complex, such as a modern balance feeding its output to relatively large digital computers.

No single wind tunnel is adequate for all possible aerodynamics tests. In general, wind tunnels can be divided into four broad categories by their speed ranges: subsonic with a maximum Mach number of up to 0.4; transonic with a maximum Mach number to 1.3; supersonic with a maximum Mach number up to 4.0 to 5.0; and hypersonic with a Mach number 5.0 or higher. [2]

1.2 Historical Background of Wind Tunnel

When the first real scientific investigations into the fledgling field of aeronautics, scientists hoping to achieve heavier than air flight soon realized that they would need to understand airflow dynamics about an airfoil in order to design a practical wing. In order to do this, they would need to reliably measure forces acting on a body passing quickly through the air. Until the early 1700s, natural wind sources such as high ridges and the mouths of caves were used for early testing, but these proved to be inadequate, and so a mechanical means of creating airflow was invented, the so-called whirling arm apparatus. An English mathematician named Benjamin Robins is credited as being the first to use a whirling arm for aeronautical study. The apparatus was driven by falling weights attached via a system of ropes and pulleys to a long arm, which rotated horizontally about a spindle. Test bodies were attached to the tip of the arm and could be positioned so as to obtain varying angles of attack. Robins' first whirling arm was four feet in length, and the tip reached speeds of only a few feet per second, but longer arms could obtain speeds of up to 20 feet per second. [5]

Over the next hundred years whirling arms grew larger and eventually steam engines replaced the falling weights, enabling researchers to obtain tip speeds in excess of 100 mph. Despite this impressive performance, whirling arms were not without their flaws. Some of the larger arm were constructed out of doors and so were still susceptible to the effects of natural winds. But regardless of location, all whirling arms suffered from a common shortcoming – the revolving arm disturbed nearby air, causing it to begin rotating around the apparatus. In addition to this loss of quiescence, results also suffered because the test body experienced appreciable amounts of turbulence caused by repeatedly passing through its own wake. [5]

In 1871, dissatisfaction with the whirling arms led Frank H. Wenham to design and built a twelve foot long blower tunnel with a steam powered fan. The success of Wenham's wind tunnel experiments inspired others interested powered flight to construct their own tunnels. Sir Hiram Maxim used money made from the success of his machine gun to construct a wind tunnel with a three-foot diameter, twice the size of Wehham's, which was powered by a pair of axial fan and capable of airspeeds on the order of 50 mph. Using data from this tunnel Maxim successfully developed and twin engine test plane. The wing design proved so effective that during one test on July 31, 1894 the plane, carrying three passengers, accidentally broke free from its restraining rails and achieved the first powered (albeit uncontrolled) flight, a full decade before the Wright brothers. [5]

The Wright brothers also made extensive use of a wind tunnel during the development of their third flyer after their first two failed to meet their expectations. This was due in large part to the fact that they were trying to apply lift tables compiled by Otto Lilienthal to wing designs very different from those for which they were intended. The Wright brothers interpreted the deviation from their anticipated results as an error in Lilienthal's tables, despite the fact that the German engineer had already design several successful hang gliders with only a whirling arm to collect data, and so built their own six foot wind tunnel. Though their tunnel and measuring devices were rather crude, the Wrights were able to produce data accurate to one tenth of a degree. The brother's tabular compilation of their data, especially lift to drag ratios of over 200 wing designs was a substantial step forward in aeronautical science. [5]

CHAPTER II

Literature Review

2.1 Wind Tunnels

A wind tunnel is a tool used in aerodynamic research to study the effects of air moving past solid objects. A wind tunnel consists of a closed tubular passage with the object under test mounted in the middle. A powerful fan system moves air past the object; the fan must have straightening vanes to smooth the airflow. The test object is instrumented with a sensitive balance to measure the forces generated by airflow; or, the airflow may have smoke or other substances injected to make the flow lines around the object visible. Full-scale aircraft or vehicles are sometimes tested in large wind tunnels, but these facilities are expensive to operate and some of their functions have been taken over by computer modeling. In addition to vehicles, wind tunnels are used to study the airflow around large structures such as bridges or office buildings. The earliest enclosed wind tunnels were invented in 1871; large wind tunnels were built during the Second World War. [6]

2.1.1 Theory of operation

Wind tunnels were first proposed as a means of studying vehicles (primarily airplanes) in free flight. The wind tunnel was envisioned as a means of reversing the usual paradigm: instead of the air's standing still and the aircraft moving at speed through it, the same effect would be obtained if the aircraft stood still and the air moved at speed past it. In that way a stationary observer could study the aircraft in action, and could measure the aerodynamic forces being imposed on the aircraft.

Later on, wind tunnel study came into its own: the effects of wind on manmade structures or objects needed to be studied when buildings became tall enough to present large surfaces to the wind, and the resulting forces had to be resisted by the building's internal structure. Determining such forces was required before building codes could specify the required strength of such buildings and such tests continue to be used for large or unusual buildings.

Still later, wind-tunnel testing was applied to automobiles, not so much to determine aerodynamic forces but more to determine ways to reduce the power required to move the vehicle on roadways at a given speed. In these studies, the interaction between the road and the vehicle plays a significant role, and this interaction must be taken into consideration when interpreting the test results. In an actual situation the roadway is moving relative to the vehicle but the air is stationary relative to the roadway, but in the wind tunnel the air is moving relative to the roadway, while the roadway is stationary relative to the test vehicle. Some automotive-test wind tunnels have incorporated moving belts under the test vehicle in an effort to approximate the actual condition. [6]

2.1.2 Measurement of aerodynamic forces

Air velocity and pressures are measured in several ways in wind tunnels. Air velocity through the test section is determined by Bernoulli's principle. Measurement of the dynamic pressure, the static pressure, and (for compressible flow only) the temperature rise in the airflow can also be made. The direction of airflow around a model can be determined by tufts of yarn attached to the aerodynamic surfaces. The direction of airflow approaching a surface can be visualized by mounting threads in the airflow ahead of and after of the test model. Smoke or bubbles of liquid can be introduced into the airflow upstream of the test model, and their path around the model can be photographed. Aerodynamic forces on the test model are usually measured with beam balances, connected to the test model with beams, strings, or cables. [6]

The pressure distributions across the test model have historically been measured by drilling many small holes along the airflow path, and using multi-tube manometers to measure the pressure at each hole. Pressure distributions can more conveniently be measured by the use of pressure-sensitive paint, in which higher local pressure is indicated by lowered fluorescence of the paint at that point. Pressure distributions can also be conveniently measured by the use of pressure-sensitive pressure belts, a recent development in which multiple ultra-miniaturized pressure sensor modules are integrated into a flexible strip. The strip is attached to the aerodynamic surface with tape, and it sends signals depicting the pressure distribution along its surface.

Pressure distributions on a test model can also be determined by performing a wake survey, in which either a single pitot-tube is used to obtain multiple readings downstream of the test model, or a multiple-tube manometer is mounted downstream and all its readings are taken. [7]

2.1.3 Some parameters of fluid dynamics

2.1.3.1 Ideal fluid and Real fluid

An ideal fluid is a fluid that experiences no viscous forces. This property of inviscid fluids allows them to flow along walls without velocity decay due to skin friction, and also eliminates drag on adjacent lamina due to velocity gradients. This in turn means that ideal fluids do not form turbulent vortices as these flow past obstructions. Ideal fluids can be thought of as body of tiny frictionless particles, capable of supporting pressures at normal incidence but unaffected by shearing stresses. Ideal fluids are strictly a theoretical conception, but are sometime useful in modeling real-world situations where viscous forces can be neglected to a reasonable approximation. Viscous fluids more commonly found in practical situation are called real fluids, and though their analysis is a great deal more complex due to the addition of viscous forces, they are use in a far broader range of applications. [5]

2.1.3.2 Laminar and Turbulent flow

Laminar flow is the movement of fluid in thin parallel layers who slide one over the other much like sheets of paper. Each layer experiences strong viscous forces from adjacent layers and these forces have a damping effect on disruptions in the flow so that flow downstream of an obstacle quickly returns to its undisturbed state.

Turbulent flow is the highly random and chaotic flow that occurs at high Reynolds numbers characterized by the formation of eddies and vortices of various sizes. Unlike laminar flow, in which fluid behavior is determined primarily by viscous forces, flow behavior in turbulent flow is determined by inertial forces. Calculating fluid behavior in turbulent flow is often very difficult, as the Navier-Stokes equations that must be used are very complex. These equations relate the pressure, density, temperature and velocity of a fluid through the use of rate of stress and strain tensors, and the result is a set of five coupled differential equations in all but the simplest of cases, these equations are extremely difficult to solve analytically, and most solutions must be found through approximations and the use of high speed computers. [5]

2.1.3.3 Fluid viscosity

Viscosity is often defined as a measure of how resistive a fluid is to flow or deformation. Viscosity can be likened somewhat to friction experienced by solid objects, but unlike the frictional forces between solids, viscous forces are independent of pressure. Viscosity is ultimately caused by cohesive intermolecular forces, and can be expressed mathematically as the ratio of shearing stress on a fluid to its velocity gradient. Viscosity can be observed in a number of common liquids. For example, maple syrup has a higher viscosity than water and so flows more slowly. Gases also experience viscous forces and these forces increase as the temperature of the gas increases. This is due to the fact that as temperature increases, so does the kinetic energy of the molecules and so there is an increase in rate of intermolecular collisions. To a good approximation, the viscosity of a gas goes as the square root of its temperature. [5]

2.1.3.4 Skin friction drag

Skin friction drag is the component of the total drag, also called parasitic or profile drag, experienced by a body in a fluid flow due directly to frictional forces between the fluid and the surface of the body. Assuming no boundary layer separation occurs, skin friction is the sole source of friction. [5]

2.1.3.5 Reynolds number

Osborne Reynolds first introduced the dimensionless constant that bears his name in his 1883, in a paper he published in the Philosophical Transactions of the Royal Society. The paper, "An Experimental Investigation Of The Circumstances Which Determine Whether Motion Of Water Shall Be Direct Or Sinuous And Of The Law Of Resistance In Parallel Channels", detailed the findings of his experimental work. Using an apparatus that allowed him to inject a small stream of dye into fluid flowing through a glass tube and using a manometer to determine flow velocities, Reynolds noticed that at lower flow velocities, the stream of dye remained intact but at higher velocities the coherent stream began to diffuse. He also noted that the diffused dye could be reformed into a stream if the velocity was decreased. Reynolds found that there was a critical velocity, which he termed the upper critical velocity, at which the turbulent flow developed and a lower critical velocity at which turbulent flow became laminar. Velocities located between these two points were classified as lying in the transition region. [5], [8]

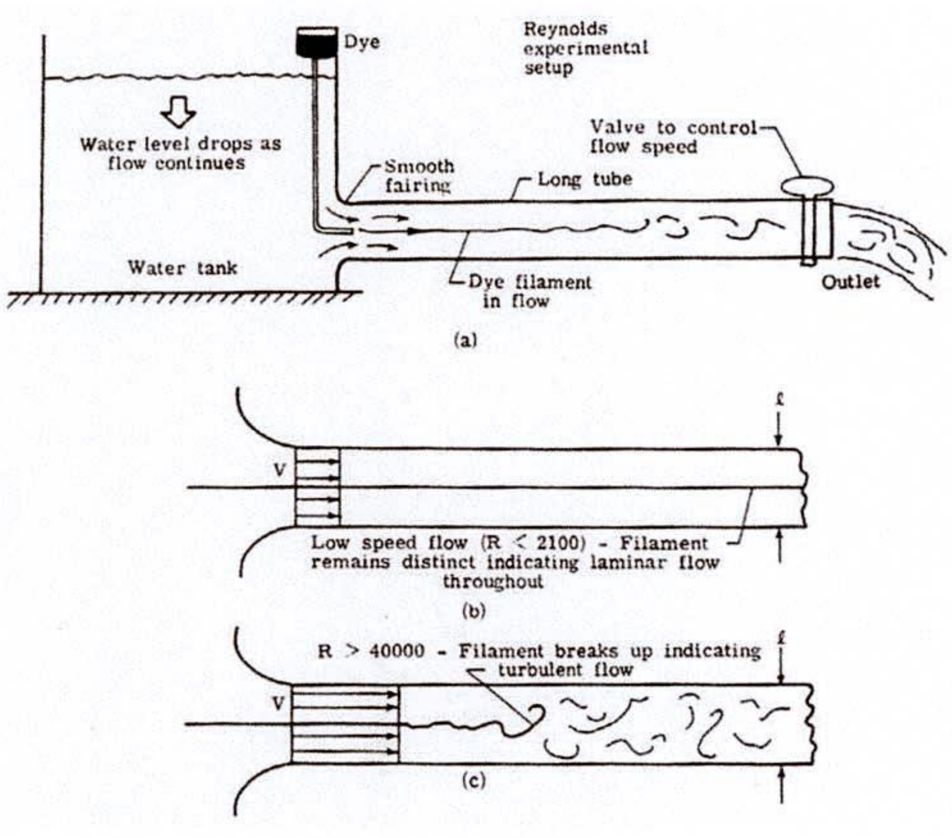

Figure 2.1: Experimental setup similar to that used by Oscar Reynolds

The Reynolds number itself is a dimensionless constant used to distinguish laminar from turbulent flow in a pipe or channel or sometime around an immersed object, with lower values corresponding to laminar flow and higher ones to turbulent flow. The Reynolds number is calculated using mean velocity, pipe diameter, density, and viscosity, and is valid for any fluid. The Reynolds number is also dependent upon the geometry of the pipe, as well as the roughness of the walls. Analysis of the Reynolds number using the dimensionless forms of the Navier Stokes equations reveals that the Reynolds number is really a ratio of inertial forces to vicious forces. As of yet, no successful analytic methods for determining Reynolds numbers have been developed due largely to the difficulty associated with predicting turbulent flow, and so Reynolds numbers for flow through pipes or around immersed objects must be determined experimentally. [5], [8]

2.1.3.6 Boundary layer

Boundary layers are regions of fluid located immediately adjacent to an immersed object or wall in which flow velocities are governed by viscous forces. Drag forces and most of the heat exchange experienced by the object are due to fluid in this region. Boundary layers typically begin as a very thin region of laminar flow that thickens with increasing Reynolds numbers and then gradually transitions to a turbulent layer flowing over a viscous sub-layer. Flow outside of the boundary layer is independent of Reynolds number criteria. [5], [8]

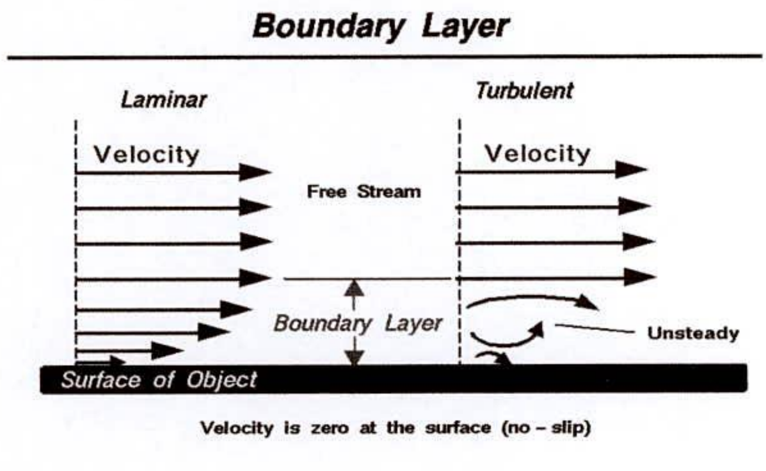

Figure 2.2: Velocity profile for boundary layers along a wall

2.2 Important Testing Parameters:

When a body moves through a medium, forces arise that are due to the viscosity of the medium, its inertia, its elasticity, and gravity. The inertia force is proportional to the mass of air affected and the acceleration given that mass. Thus, while it is true that a very large amount of air is affected by a moving body, we may logically say that the inertia force is the result of giving a constant acceleration to some "effective" volume of air. Let this effective volume of air be kl^3, where l is a characteristic length of the body and k is a constant for the particular body shape. Then we may write

$$\text{Inertia force} = \rho l^3 V / t$$

Where ρ = the air density; V = velocity of the body; t = time.
Substituting I/V for t, we get

$$\text{Inertia force} = \frac{\rho l^3 V}{I/V} = \rho l^2 V^2$$

The viscous force, according to its definition, may be written as

$$\text{Viscous force} = \mu V l$$

Where μ = co-efficient of viscosity.
The gravity force is simply

$$\text{Gravity force} = \rho l^3 g$$

Where g = acceleration of gravity.
By definition, the bulk modulus of elasticity of a gas is the stress needed to develop a unit change in volume. It is given the symbol E and has the units of pounds per square foot. We have then

$$\text{Elastic force} = El^2$$

The speed of sound in air a is related to its elasticity according to

$$E = \rho a^2$$

So that we may write

$$\text{Elastic force} = \rho a^2 l^2$$

The important force ratios then become

$$\text{Reynolds number} = \frac{\text{inertia force}}{\text{Viscous force}} = \frac{\rho}{\mu} Vl$$

$$\text{Mach number} = \frac{\text{inertia force}}{\text{Elastic force}} = \frac{V}{a}$$

$$\text{Froude number} = \frac{\text{inertia force}}{\text{Gravity force}} = \sqrt{\frac{V^2}{lg}}$$

Many wind tunnel tests are seriously sensitive to Reynolds number effects. The last equation, it will be noted, uses square root of the ratio rather than the ratio itself.

If a model test has the same Reynolds and Mach numbers as the full scale vehicle then the flow about the model and the full scale vehicle will be identical. Under these conditions, the forces and moments developed by the model can be directly scaled to full scale. Furthermore, for a free flight model the Froude number must be matched.

The largest portion of wind tunnel tests are made with rigid models held in a fixed attitude within the tunnel thus it is not necessary to match the Froude number. The matching of Mach number usually applies only to flight vehicles in the high speed flight region as Mach number effects predominate and the matching of Reynolds number effects is not as critical. In the low speed flight region Reynolds number effects predominate and matching of Mach number is not as critical. However, for any test a careful evaluation of the effect of Reynolds and Mach numbers should be made to insure that the results are valid.

Despite the fact that it is difficult, if not impossible, to match both Reynolds number and Mach numbers in the most wind tunnel tests, the wind tunnel still is one of the most useful tools an aerodynamics engineer has available to him or her. The wind tunnel is, of course, an analog computer, and in it the aerodynamics engineer can quickly and effectively optimize his or her design. In the last few years the use of dedicated mini digital computers has greatly decreased the time required to present the final corrected data in tabulated form, and in most cases large facilities can provide the results in plotted format in real time as the data are acquired. This enables the aerodynamics engineer both to check his or her predicted results and, based on the results of one wind tunnel tests, with results extrapolated for full scale, can drastically reduce the amount of flight testing required and thus pay for both the model and wind tunnel testing.

2.3 Uses of wind tunnels

There are many uses of wind tunnels. They vary from ordinary to special: these include uses for Subsonic, supersonic and hypersonic studies of flight; for propulsion and icing research; for the testing of models and full-scale structures, etc. Some common uses are presented below. Wind tunnels are used for the following:

To determine aerodynamic loads

Wind tunnels are used to determine aerodynamic loads on the immersed structure. The loads could be static forces and moments or dynamic forces and moments. Examples are forces and moments on airplane wings, airfoils, and tall buildings. A close-up view of a model of an F-5 fighter plane mounted in the test section of a wind tunnel is shown in Figure 2.3. [9]

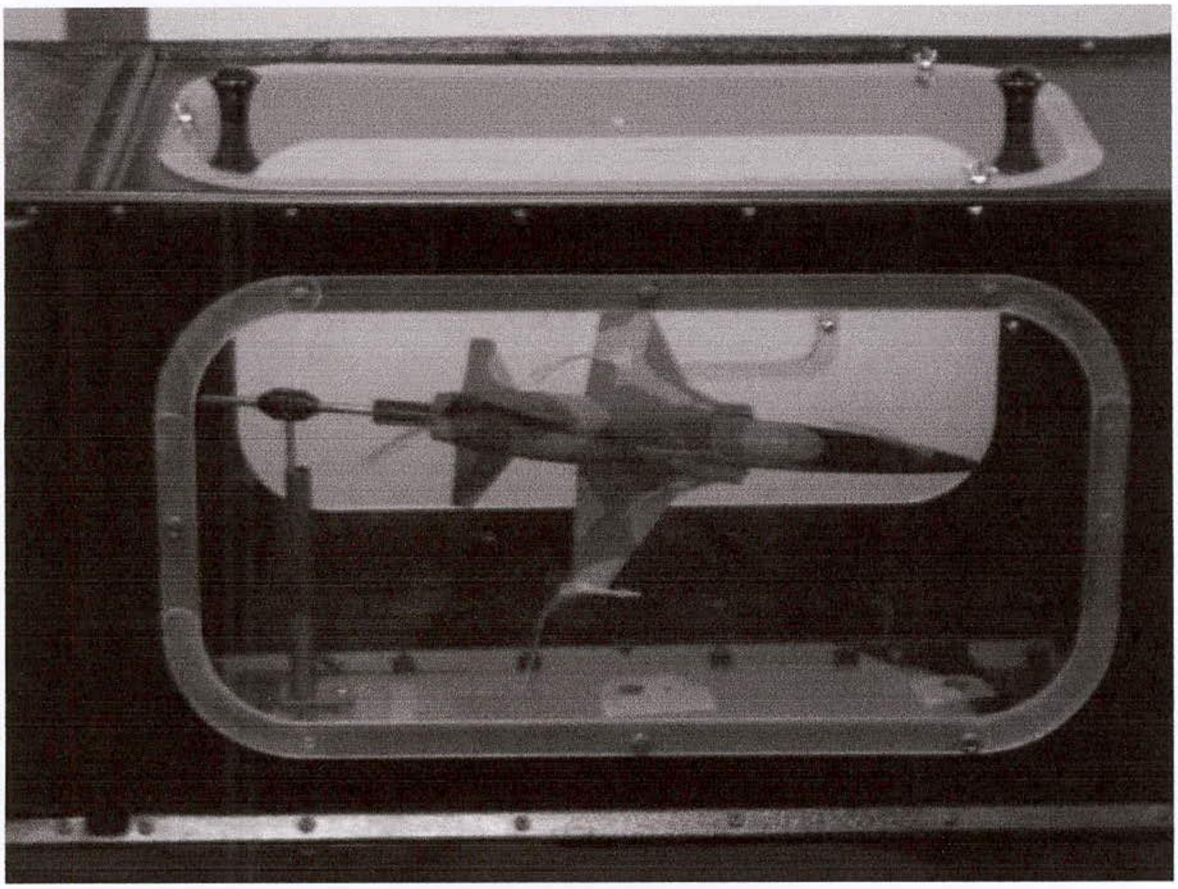

Figure 2.3: Close-up of a tufted model of an F-5 fighter plane in the test section of a wind tunnel (NASA)

To study how to improve energy consumption by automobiles

They can also be used on automobiles to measure drag forces with a view to reducing the power required to move the vehicle on roads and highways. [9]

To study flow patterns

To understand and visualize flow patterns near, and around, engineering structures. For example, how the wind affects flow around tall structures such as sky scrapers, factory chimneys, bridges, fences, groups of buildings, etc. How exhaust gases ejected by factories, laboratories, and hospitals get dispersed in their environments. [9]

Other uses include

To teach applied fluid mechanics, demonstrate how mathematical models compare to experimental results, demonstrate flow patterns, and learn and practice the use of instruments in measuring flow characteristics such as velocity, pressures, and torques. [9]

Applications of wind tunnels in teaching fluid mechanics

This section discusses nine different laboratory exercises in which the wind tunnel is used to measure fluid flow parameters. They are: 1) measurement of air speed; 2) verification of the existence of the boundary layer over a flat plate; 3) determination and characterization of the boundary layer over a flat plate; 4) searching for evidence of turbulence in boundary layer flow; 5) measurement of pressure distributions around a circular cylinder in cross flow; 6) determination of the viscous wake behind a circular cylinder in cross flow; 7) determination of lift and drag forces around airfoils; 8) reduction of drag by the introduction of turbulence in the boundary layer; and 9) determination of the Richardson's annular effect in flow through a duct. [9]

2.4 Open Circuit Wind Tunnel

In open circuit wind tunnel the air follows a straight path from the entrance through a contraction to the test section, followed by a diffuser, a fan section, and an exhaust of the air. An open circuit wind tunnel is shown in figure 2.4. [2]

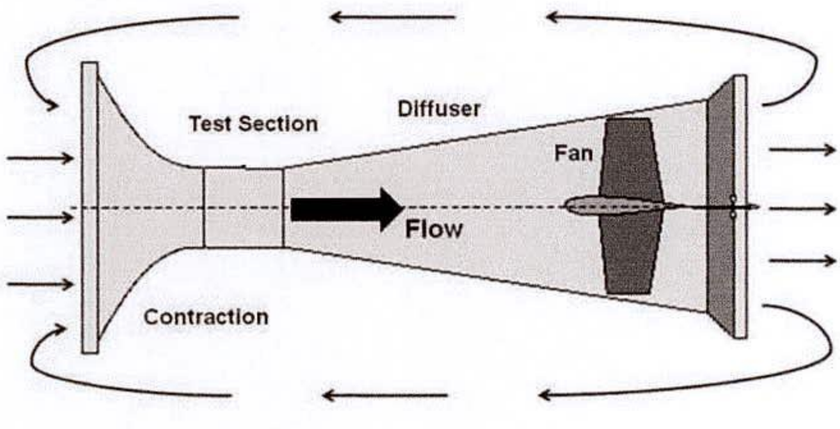

Figure 2.4: An open circuit wind tunnel

Advantages

1. Construction cost is less.
2. If one intends to run internal combustion engines or do much flow visualization via smoke, there is no purging problem if both inlet and exhaust are open to the atmosphere.

Disadvantages

1. If located in a room, depending on the size of the tunnel to the room size, it may require extensive screening at the inlet to get high-quality flow. The same may be true if the inlet and /or exhaust is open to the atmosphere, when wind and cold weather can affect operation.
2. For a given size and speed the tunnel will require more energy to run.
3. In general, a tunnel is noisy. For larger tunnels noise may cause environmental problems and limits on hours of operation.

2.5 Closed Circuit Wind Tunnel

This type of tunnel has a continuous path for the air. The great majority of the closed circuit tunnels have a single return, although tunnels with both double and annular returns have been built. Again, the closed circuit tunnel may have either an open or closed test section, and some have been built that can be run with either an open or closed test section, as desired. A closed circuit wind tunnel has been shown in figure 2.5. [2]

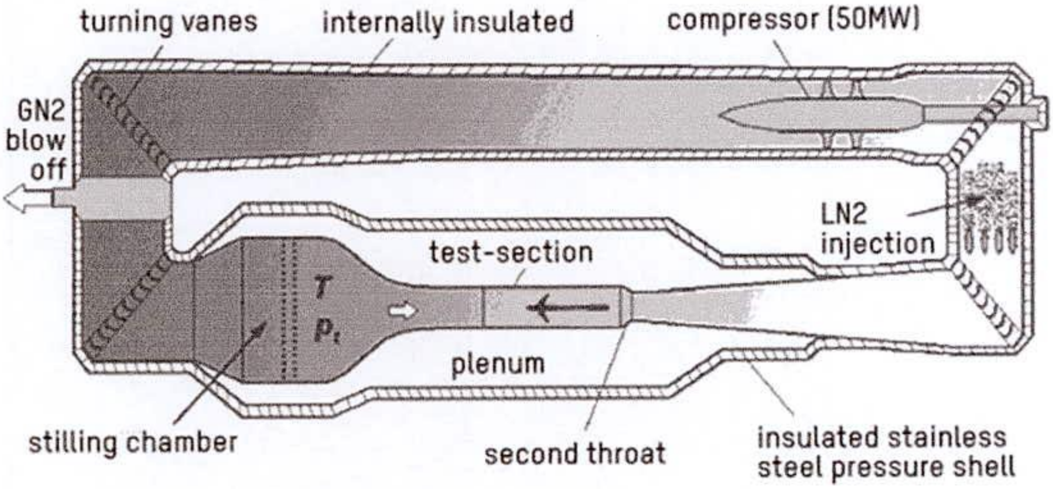

Figure 2.5: A closed circuit wind tunnel

Advantages

1. Through the use of corner turning vanes and possibly screens, the quality of the flow can be easily controlled.
2. Less energy is required for a given test-section size and velocity. This can be important for a tunnel used for developmental testing with high utilization.
3. Less noise when operating.

Disadvantages

1. Higher initial cost due to return ducts ad corner vanes.
2. If used extensively for smoke tests or running of internal combustion engines, there must be a way to purge tunnel.
3. If tunnel has high utilization, it may have to have an air exchanger or some other method of cooling during hot summer months.

2.6 Special Purpose Tunnels

Over the years there have been many tunnels built to meet either specific research or testing requirements. Many of these tunnels have been decommissioned and dismantled for a large variety of reasons or have been adapted to other uses. Some of the testing done in these tunnels can also be accomplished by adaptation of general-purpose tunnels, which are quite versatile. Some of these are listed below: [2]

a. Variable Density Tunnels
b. Free-Flight Tunnels
c. Spin Tunnels
d. Stability Tunnels
e. Propeller Tunnels
f. Propulsion Tunnels
g. Ice Tunnels
h. Smoke Tunnels
i. Automobile Tunnels
j. Environmental Tunnels

2.7 Wind Tunnel Components

Although wind tunnels have been built in many different configurations, they all have five basic parts.

1. Test Section
2. Contraction Cone
3. Settling Chamber
4. Diffuser
5. Fan

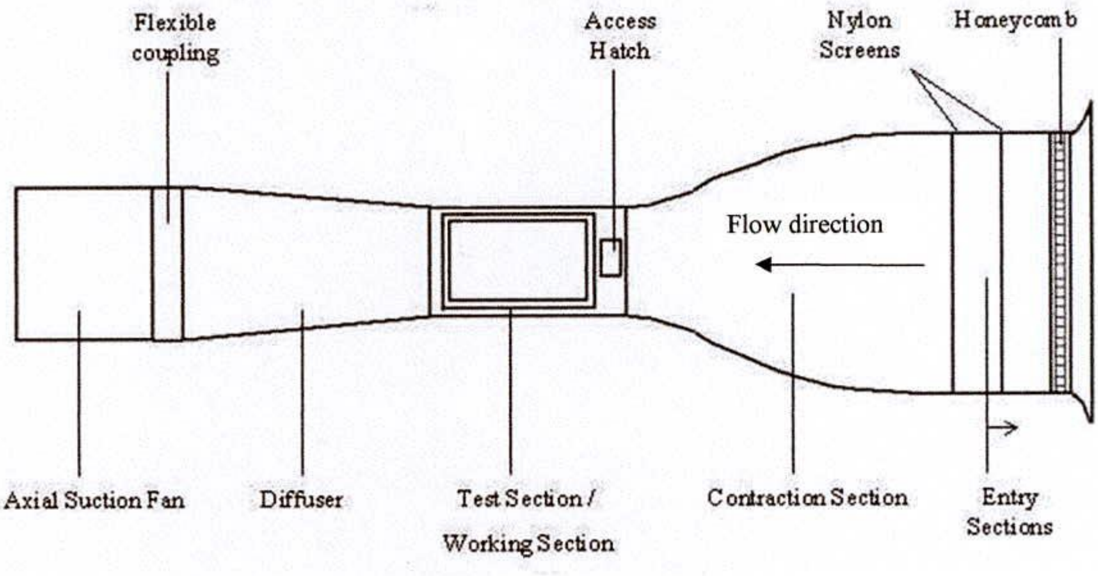

Figure 2.6: An open circuit wind tunnel showing different components

2.7.1 Test Section

The test section is the chamber in which measurements and observations are made and its shape and size are largely determined by the testing requirements. The cross sectional area of the tunnel test section basically determines the overall size of the facility. The test section size, speed, and design will determine the required power. The size of the facility will determine the structural or shell costs, and the power and operating hours will determine the energy portion of the operational cost. Although the major cost of operation is the electrical energy costs to run the tunnel and its auxiliaries is not an insignificant cost, and it is doubtful that this cost will decrease in the long term. Thus, in the design there is a balance between initial costs and operating costs. In the past many tunnels have been built with short-length diffusers, and so on, and hence short circuit length to hold down initial costs, while accepting higher energy costs of operation. This trade off should be carefully examined owing to escalating energy costs. The test section size is the starting point in the design of a wind tunnel. The purpose of a wind tunnel is to provide a uniform and controllable air flow in the test section that passes over the model. In an ideal case, the model should be tested at the same Reynolds and Mach number as the full-scale vehicle. This, of course, leads to a full-scale model, a very large tunnel, and very expensive models, or smaller pressurized or cryogenic tunnels, also with expensive models. Matching

Reynolds and Mach number are mutually contradictory when using scale models. The Reynolds number is proportional to the ratio of inertia forces to viscous forces and the behavior of boundary layers and wakes is influenced by Reynolds number. The Mach number is proportional to the ratio of inertial to elastic forces, taken as the square root of $V^2/a^2 = M^2$. The change in gas properties such as density in passing through shock or compression waves depends on the Mach number. If the flow cannot be considered incompressible, the Mach number must be matched. Usually it is not necessary to produce the full-scale Reynolds number, but it must be of a reasonable value. Much low-speed testing involves take off and landing configurations where the Mach number is much less than 1. Both the lift curve slope and maximum lift coefficient are affected by Mach numbers as low as 0.2. This tends to require a tunnel speed approximately equal to the full-scale flight speed. In an unpressurized tunnel using air this means that the Reynolds number ratio of model to full scale is approximately equal to the scale ratio between the scale-model and the aircraft. [5][2]

The question now is what the minimum acceptable value of Reynolds number is. Because much of low-speed testing is at high lift conditions, the effect of Reynolds number on airfoils at high lift must be considered. It is considerably with Reynolds numbers up to a million. There is, in fact, a whole series of airfoils for soaring gliders that are especially designed to operate at Reynolds numbers below 1,000,000. Thus, the lower boundary for Reynolds numbers is in the range of 1,000,000 to 1,500,000 based on chord. At these values of Reynolds number, the model will have an extensive region of laminar flow, and the possibility exists of poor simulation owing to separation of the model's laminar boundary layer. It is assumed that laminar separations do not occur at full scale. Therefore, full scale can be simulated by artificial transition on the model. If the Mach number is taken as 0.2, then the tunnel velocity is about 150mph. For this speed the Reynolds number is a little less than 1,500,000. Although the minimum Reynolds number cannot be rigidly defined, the above rational has been used to define a minimum Reynolds number of between 1,500,000 and 2,500,000 for low-speed tunnels.

For a rectangular tunnel the tunnel width determines the model size and the Reynolds number at a fixed velocity. The cost of the tunnel shell and its required power tend to vary with the square of the test-section width. Since funds for a tunnel are usually fixed, the largest tunnel that the funds will buy is generally built. The size of smaller tunnels is usually determined in the final analysis by the size of the room that will house the tunnel. [2]

The test section should be long enough that flow disturbances resulting from a contraction or screens are sufficiently damped before the reaching the test object. However, care should be taken not to make this section too long as this will lead to detrimental boundary layer growth which can separate when it enters the exit diffuser and create a power loss. This can be prevented by slightly enlarging the tunnel or by partially obstructing the exit end of the tunnel to create an overpressure which allows the use of small vents to control boundary layer growth. [5]

Over the years man shapes have been used for test sections, such as round, elliptical, square, rectangular, hexagonal, octagonal, rectangular with filleted corners, flat ceiling, and floor with half round ends. The cost and power are directly determined by the cross sectional area. [2]

2.7.2 Contraction Cone

Contractions sections are located between the settling chamber and the test sections and serve to both increase mean velocities at the test section inlet and moderate inconsistencies in the uniformity of the flow. There are two problems in the design of the contraction cone. First is the presence of an adverse pressure gradient at the entrance and exit of the contraction. If either of these gradients becomes severe enough for the boundary layer to separate, there can be degradation of the quality of the test section flow, and increase in the power required. Second, the surface streamlines of a rectangular contraction intersect the side walls. This leads to secondary flow in the corners with the attendant lower velocities and possibility of separation. The latter problem is alleviated by making the contraction octagonal. This is done by starting a 45° fillet at the start of the contraction cone and carrying the fillet through the test section and first diffuser. Morel considered uniform flow in the exit as being the basic requirement for a contraction. He also pointed out that as the contraction ratio increases beyond 4 the length will decrease for fixed exit requirements. [22]

Borger recommended a slight expansion near the contraction exit to improve the exit flow uniformity. [23] Mikhail and Rainbird, by controlling the distribution of curvature, were able to control the wall pressures and gradients and flow uniformity at the exit. [24] The length of the exit section was defined on the basis of 0.25% flow uniformity at the centerline at one radius from the exit. The contraction exit length is sensitive to the required length in the test section for a uniform velocity profile. For a contraction ratio of 8 the inlet section length varied from 0.15 to 1.00 times the inlet radius, while the test section settling length varied from 1.5 to 0.5 of the exit radius. Large contraction ratios and short contraction lengths are generally more desirable as they reduce the power loss across the screens and the thickness of boundary layers. Small tunnels typically have contraction ratios between 6 and 9. [12]

For a contraction ratio 8 the inlet section length varies from 0.15 to 1.00 times the inlet radius, while the test section settling length varies from 1.5 to 0.5 of the exit radius. [2]

2.7.3 Settling Chamber

The settling chamber is located between the fan or wide angle diffuser and the contraction and contains the honeycombs and screens used to moderate longitudinal variations in the flow. Screens in the chamber should be spaced at 0.2 chamber diameters apart so that flow disturbed by the first screen can settle before it encounters the second. [5]

Honeycombs

Honeycombs are located in the settling chamber and are used to reduce non-uniformities in the flow. For optimum benefit, honeycombs should be 6-8 cell diameters thick and cell size should be on the order of about 150 cells per settling chamber diameter. [2]

Screens

Screens are typically located just downstream of the honeycomb and sometime at the inlet of the test section. Screens create a static pressure drop and serve to reduce boundary layer size and increase flow uniformity. [5]

The use of screens to improve flow quality in wind-tunnels was first proposed by Prandtl (1932). The screens are very effective in breaking up larger eddies and acts primarily to reduce mean non-uniformities and fluctuations of the stream-wise component. The screens also reduce cross-flow components but less effectively than honeycombs. Hence, the combination of honeycomb and screens provide, in a natural way, a good overall flow quality improvement. [17]

A screen is characterized by its open-area ratio, which is defined in the equation below where d is the wire diameter and L is the length of the screen. Screens in the settling chamber should have an open-area ratio of $.58 < \beta < 0.8$, as screens with lower ratios are known to produced non-uniformities in the flow. This is presumable due to the formation of small vortices created by the random coalescence of tiny jets emitted from the screen. The pressure drop across a screen depends upon the open-area ratio of the screen and the density, kinematic viscosity, and mean velocity of the fluid. [5]

$$\beta = \left(1 - \frac{d}{L}\right)^2 \tag{1}$$

2.7.4 Diffuser

Diffusers are chambers that slowly expand along their length, allowing fluid pressure to increase and decreasing fluid velocity. Since the power losses in the tunnel vary as the velocity cubed, the purpose of the diffusers is to reduce the velocity by expanding the flow and recovering the static pressure. Since it is desired to reduce the velocity in the shortest possible distance to reduce losses, the diffuser is critical to the success of the tunnel. Diffusers are sensitive to design errors that may cause either intermittent separation or steady separation. These separations can be hard to find and can cause vibrations, oscillating fan loading, oscillations in test-section velocities, and increased losses in the tunnel downstream of their origin. Diffusers are described by both their area ratios and an equivalent cone angle. The angle denotes an imaginary conical section with identical length and inlet and exit areas as the actual diffuser. Angles slightly larger than 5 degrees do increase pressure recovery, but can also lead to boundary layer separation and thus flow unsteadiness. The current practice uses an equivalent cone angle of 7° or less; however, the cone angle also depends on the area ratio and the area ratio determines the pressure recovery and pressure gradients, and , hence, the risk of separation. [13] Also thick boundary layers at the diffuser entrance will increase the risk of separation. If a very long 5° diffuser is used to obtain a large contraction ratio, there is danger of a separation. Therefore, the total tends to be limited to area ratios of five or six to one, half of the area ration in each half of the diffuser. This area ratio limits the tunnel contraction ratio. Exit diffusers are located downstream of the test section and are used to recover pressure from kinetic motion of the fluid thereby reduced the power requirement to drive the tunnel. Diffusers are still not very well understood and most of the working knowledge about them comes from experiments. [5]

2.7.5 Fan

Axial fans are popular in open circuit tunnels, and are almost always found in closed circuit tunnels. In larger tunnels, pre-rotation vanes called stators are commonly positioned upstream of the fan, substantially decreasing swirl in the exit flow. Axial fans have a relatively limited effective operating range as the reduction it pressure increase through the fan as the blades approach stall speeds is far more abrupt than in centrifugal blowers. Care must also be given to choosing the proper blade size, shape and spacing in order to prevent shock wave production, stalling, and backflow.

Centrifugal blowers, sometimes called squirrel cage blowers are most often in blower type open circuit tunnels, though they can be used in closed return tunnels if mounted in a corner. Centrifugal blowers have a much larger operating range than axial fans with acceptable levels of unsteadiness. [5]

CHAPTER III

Methodology

3.1 Design Considerations

The design requirements of the wind tunnel were base upon experience gained from the previous research work of Talev et al. (2006). Most of the detailed wind tunnel design work was been described by Barlow et al. (1984), Sætran (1984), and Bell and Metha (1988). The design was a result of the need for obtaining a flow in the test section that is as near as possible to a parallel steady flow with uniform speed through the test section without excessive turbulence. It was judged that constructing an open loop circuit wind tunnel would be the most economical solution to control the boundary condition of the air in order to provide a value of the convective moisture transfer coefficients. The wind tunnel is made of several distinct sections, the settling chamber, the contraction cone, the test/working section, the diffuser and the fan. Several considerations have to be made in order to achieve a wind tunnel with the wanted properties. [10]

The first step in wind tunnel design is related to the shape and main dimensions of the test chamber [2] which depends on the type of intended tests. Generally, wind tunnel dimensions are directly related to the test chamber cross-section. The bigger the test chamber cross-section, the greater the overall wind tunnel dimensions. Test chamber main dimensions and air velocity, as well as wind tunnel type bring to the necessary fan power. These and the wind tunnel's overall dimensions are key factors in its structure and running costs so the best trade-off between costs and tests is necessary. The main goal of wind tunnel design is to have uniform flow within the test chamber. It is best to have a big testing chamber with very high air velocity. The design starts by defining the test chamber dimensions and proceeds counter-stream wise to the design of other wind tunnel components. [11]

A primary aim was to here accommodate experiments that require a large degree of flexibility of the test section geometry. To meet these requirements it was necessary to specify some design criteria. The main design criteria are listed in the table below:

- Open circuit wind-tunnel.
- Good flow quality (mean flow variation, turbulence intensities & temperature variation).
- Contraction ratio, CR, of 8.
- Test section is square and the maximum test section length possible in the available space.
- Maximum flow speed in the test section of 40 m/s.
- Low noise level.
- Low cost.

3.1.1 Test Section

The first step in wind tunnel design is defining a priori the test chamber criteria which are dimensions, shape and desired air velocity. In this case, a square testing chamber with a 0.9 m side was used with an air velocity of 40 m/s.

From the testing section dimensions the hydraulic diameter can be calculated as in Eq. (2).

$$D_h = 2\sqrt{A/\pi} \qquad (2)$$

Where, A is the test chamber cross sectional area.

The test chamber length has to be in the range of 0.5 - 3 times its hydraulic diameter [2]. This choice takes into account that the air flow exiting the nozzle needs 0.5 times the hydraulic diameter to become almost uniform. Moreover, a long test chamber (more than 3 times the equivalent hydraulic diameter) could increase boundary layer thickness causing the boundary layer to detach at the test chamber exit.

So, in this study the length of the testing chamber was set to 1.3 times the hydraulic diameter of the testing section. The test section length becomes about 1.35 m.

The test chamber also has flanges and windows to allow sample observations and introduce measuring tools. Figure 3.1 shows AutoCAD design of a test chamber.

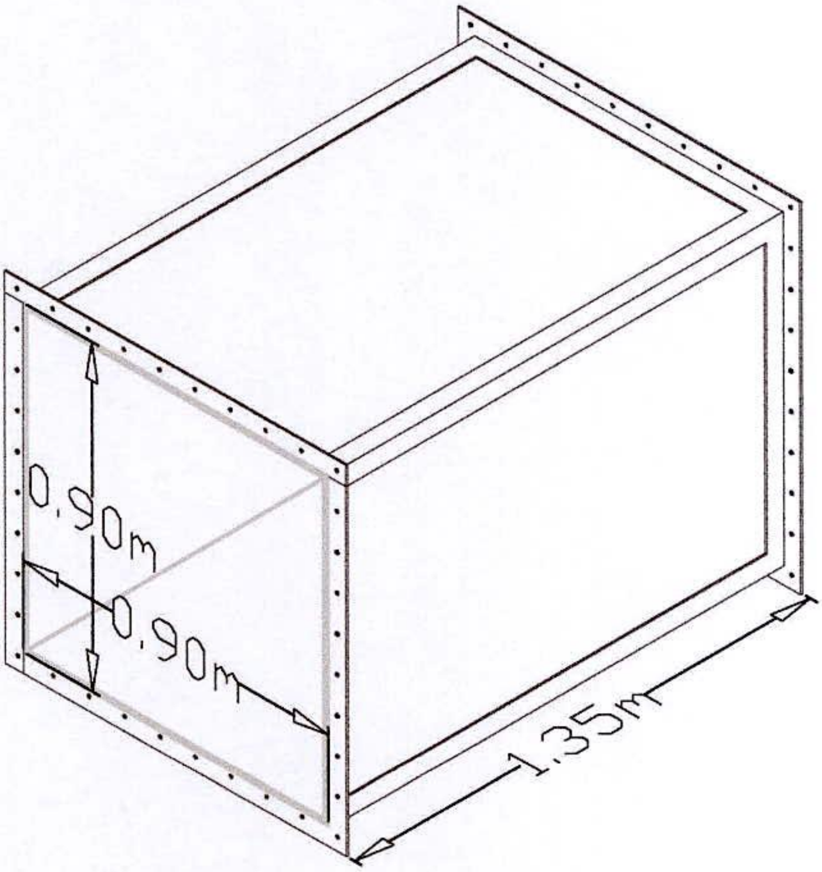

Figure 3.1: Test section

3.1.2 Contraction Cone

The contraction cone accelerates the flow from the settling chamber to the test section, further reducing any variations in velocity. In a wind tunnel, the contraction cone is the most difficult component to design. Flow velocity and its uniformity within the test chamber cross-section depend on the contraction cone design. The contraction cone exit cross-section dimensions and shape are identical to the test chamber ones since they are joined together.

Knowing the contraction cone exit cross-section dimensions and shape, those of its inlet cross section must be determined. The contraction cone area ratio should be 'as large as possible', to reduce the total-pressure loss through the screens mounted between the settling chamber and the cone. Normally, the contraction cone inlet/outlet cross-section area ratio should be in the range 6 - 10 [14]. Area ratios greater than 10 lead to excessive inlet dimensions while area ratios less than 6 lead to high pressure loss through the screens. In this study, an area ratio of 8 was chosen. [2]

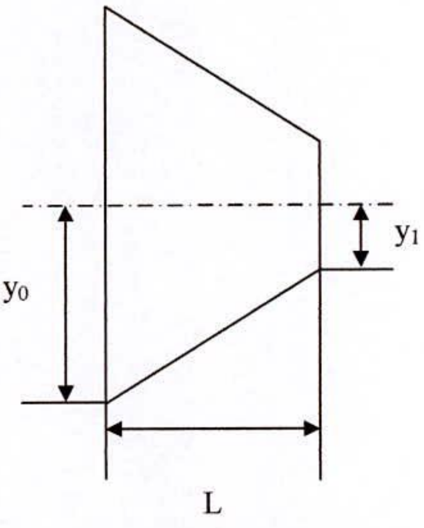

Figure 3.2: Contraction cone

The contraction exit length is sensitive to the required length in the test section for a uniform velocity profile. For a contraction ratio of 8, the contraction section length varies from 0.15 – 1 times the inlet radius, while the test section settling chamber length varied from 1.5 to 0.5 of the exit radius. The length of the contraction is found to be 0.38 m.

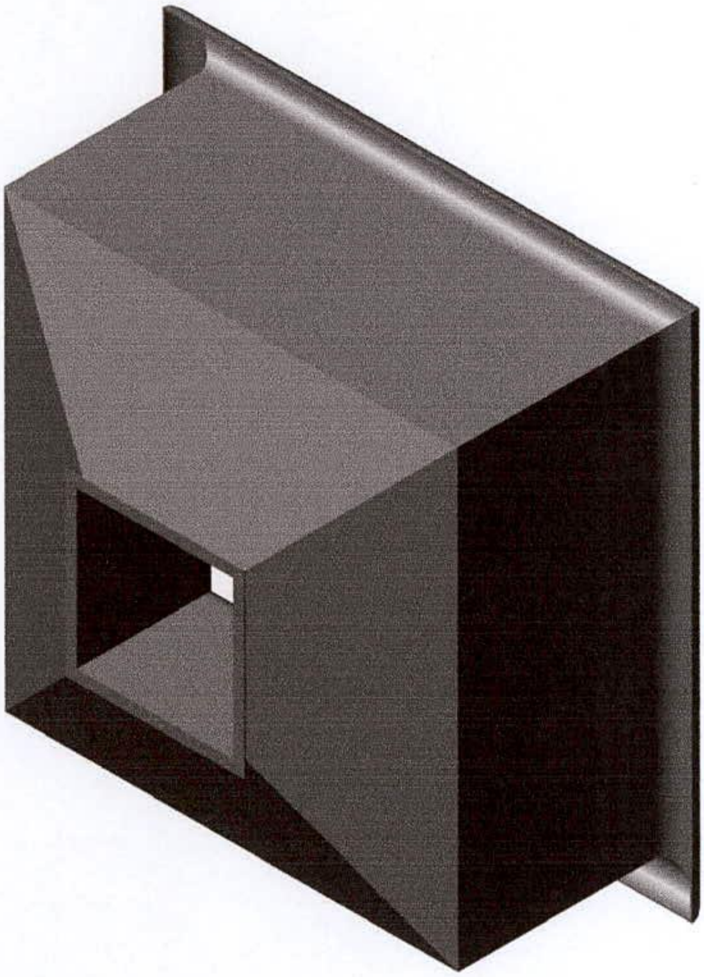

Figure 3.3: Designed contraction cone with settling chamber

3.1.3 Diffuser

The diffuser of a wind tunnel usually extends from downstream end of the test section to the fan. Its main purpose is to reduce velocity in the shortest possible distance to minimize losses. [3] Area ratio of the diffuser should be less than 2.5 and diffuser angle should be 5° – 7° for controlling flow separation. [4] According to these conditions, the diffuser outlet diameter will be 122 cm.

The minimum length of diffuser can be found from equation given below:

$$\vartheta_e = arc\ tan\left(\frac{1}{2}\frac{\sqrt{A_R}-1}{L/D_{h1}}\right) \tag{3}$$

D_{h1} is the inlet section's hydraulic diameter and ϑ_e is the half of the included angle of the diffuser cone.

Solving for L the minimum length of the diffuser is found to be 2.34 m. By adjustment with area ratio and the length of the diffuser is found 3.7 m which satisfy the above criteria. The AutoCAD design of the Diffuser is shown in figure 3.4.

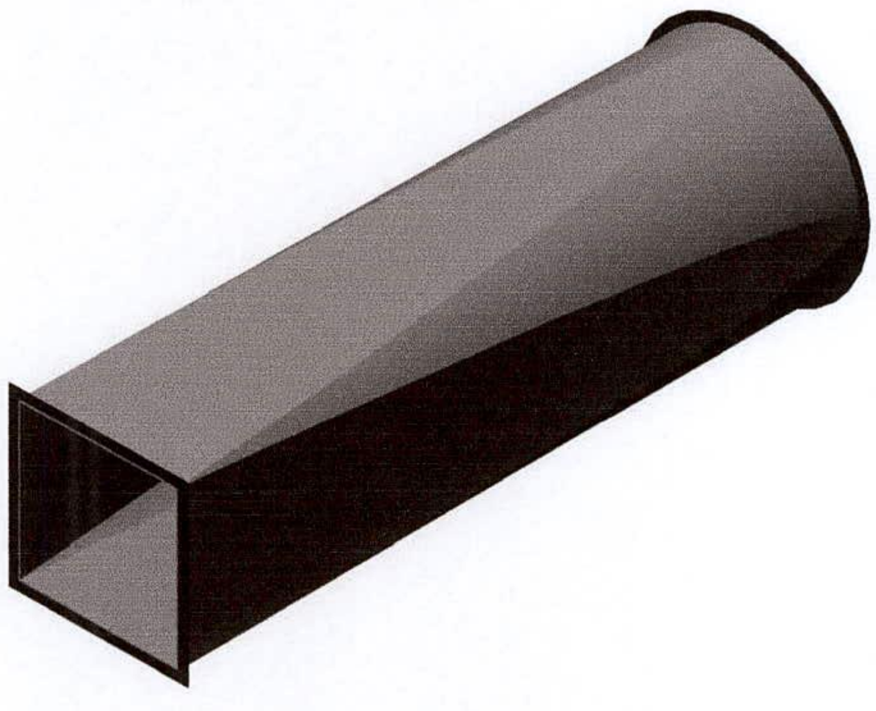

Figure 3.4: Square inlet and circular outlet diffuser section

3.1.4 Fan

The ratio between the fan cross-section area A_f and the test chamber cross-section area A_{ts} can be calculated from the equation given below:

$$R_f = \frac{A_f}{A_{ts}} \quad (4)$$

Taking into account the area ratios and using the mass conservation law, the air velocity at the fan exit can be calculated from the equation given below:

$$c_f = \frac{1}{1.44} c_{ts} \quad (5)$$

From above equation air velocity at the fan outlet is found to be 30 m/s. A fan with 20 kW 3 - phase motor and 10 blades is used to attain this velocity.

3.1.5 Settling Chamber

Before the contraction cone there is a settling chamber with a constant cross-sectional area. The aim of a settling chamber which contains honeycombs and screens is to reduce the flow turbulence before it enters the cone. The settling chamber cross-sectional area matches the dimensions of contraction cone inlet diameter. A settling chamber length of 0.5 times the inlet diameter is often used. Thus, the length of the settling chamber becomes 1.105 m.

3.1.5.1 Honeycombs

A honeycomb with its cells aligned in the flow direction is able to reduce fluctuating variations in transverse velocity. The honeycomb has little effect on stream-wise velocity due to the fact that the pressure drop through a honeycomb is small. [15]

The primary reason to use a honeycomb is that, with a sufficient length of about 10 cell diameters, it is a very effective flow straightening device. The relatively low pressure drop of a honeycomb makes it rather ineffective in reducing non-uniformities or fluctuations in the stream-wise component but it is very effective in reducing cross-stream components. [16]

In the honeycomb design procedure, its length (L_h), cell hydraulic diameter (D_h), and the porosity (β_h) are key factors [12]. Honeycomb porosity is defined as the ratio of actual flow cross-section area over the total cross-section area.

$$\beta_h = \frac{A_{flow}}{A_{total}} \tag{6}$$

Two main criteria have to be verified in wind tunnel honeycomb design. The first one is;

$$\mathbf{6 \leq \frac{L_h}{D_h} \leq 8} \tag{7}$$

and the second one is;

$$\beta_h \geq 0.8 \tag{8}$$

For optimum benefit, honeycombs should be 6-8 cell diameters thick and cell size should be on the order of about 150 cells per settling chamber diameter. [5]

The parameters of the honeycomb in this study are shown in the table below;

Table 3.1: Parameters of honeycomb in this study

Parameters	Symbols	Value	Units
Cell hydraulic diameter	D_h	2.12	cm
Length of honeycomb	L_h	12	cm
Number of cells	N	38000	
Length to diameter ratio	L_h/D_h	6	
Honeycomb porosity	β_h	0.8	

3.1.5.2 Screens

It is well known that screens mainly reduce stream-wise velocity fluctuations, with little effect on flow direction. Moreover, it has been demonstrated that a series of screens with different mesh qualities (coarse, medium and fine) is more efficient than only one fine mesh screen. To be effective in reducing turbulence a screen must have a porosity in the range 0.58 – 0.8. [15]

$$0.58 \geq \beta_s \leq 0.8$$

Screen porosity values over 0.8 are not suitable for good turbulence control, while values below 0.58 lead to flow instability. Screens could also be installed on a removable frame for cleaning and maintenance. Since the screens are inside the settling chamber (square cross-section side $l = 2.55$ m in this study) and have a square mesh (commonest), the area occupied by the screen wire can be calculated with the following equation;

$$n_w l d_w + n_w l d_w - n_w(n_w d_w^2) \quad (9)$$

where d_w is the wire diameter, n_w is the generic wire number in the mesh and l is the settling chamber cross-section side. The last term in above equation takes into account the areas where the wires cross (black areas in Figure 3.5).

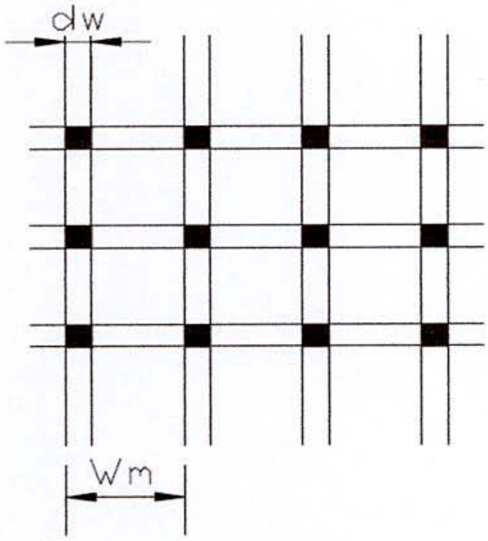

Figure 3.5: Screen mesh sample

As in the honeycomb case, it is possible to calculate screen porosity using the following equation;

$$\beta_s = \frac{A_{flow}}{A_{total}} = \frac{l^2 - 2n_w l d_w + n_w^2 d_w^2}{l^2} = 1 - 2n_w \frac{d_w}{l} + \frac{n_w^2 d_w^2}{l^2}$$

Simplifying the equation produces

$$\beta_s = \left(1 - \frac{n_w d_w}{l}\right)^2 \tag{10}$$

Screen mesh density is defined as the ratio between the mesh wire number and the cross section side of the chamber into which the screens are inserted [2]. The following equation defines the mesh density;

$$\rho_m = \frac{n_w}{l} \tag{11}$$

The mesh density inverse represents the screen mesh divisions (w_m) as shown in Figure 3.5 and the following equation;

$$w_m = \frac{1}{\rho_m} \tag{12}$$

Taking screen mesh density into account, porosity can be written as-

$$\beta_s = (1 - d_w \rho_m)^2 \tag{13}$$

Table 3.2 shows the main screen characteristics for the case study. It also shows that the screen porosities for the two screens (M_1 and M_2) verify the criterion $0.58 \geq \beta_s \leq 0.8$.

Table 3.2: Screen characteristics

Description	Symbol	Unit	M_1	M_2
Mesh wire diameter	d_w	mm	0.58	0.45
Mesh divisions	w_m	mm	2.50	1.95
Screen porosity	β_s	-	0.59	0.59

3.2 Pressure Losses

In a wind tunnel, pressure losses occur as consecutive pressure losses in the different sections. Overall pressure loss *(Δp_{global})* equals the pressure gain due to the fan. In a wind tunnel component, *i*, pressure loss *(Δp_i)* can be written as the product of constant K_i and the dynamic pressure at the entrance of the component as shown in the following equation;

$$K_i = \frac{\Delta p_i}{\frac{1}{2}\rho_i c_i^2} \tag{14}$$

where c_i is the mean flow velocity in the concerned section at the entrance of component i. [11]

3.2.1 Pressure Losses in Test Section

Considering a constant-area section, the pressure loss (Δp) along the duct is proportional to its length (L), hydraulic diameter (D_h), fluid density (ρ), and the square of mean flow velocity c. The constant of proportionality is the friction factor (f).

$$\frac{\Delta p}{\rho} = f\frac{Lc^2}{2D_h} \tag{15}$$

Combining Eqs. (14) and (15), the loss coefficient can be related to duct geometry producing Eq. (16).

$$K_l = f\frac{L}{D_h} \tag{16}$$

For smooth pipes at high Reynolds numbers, Shames [18] uses the Prandtl universal law of friction to determine the friction factor:

$$f_{i+1} = \left[2log_{10}\left(Re\sqrt{f_i}\right) - 0.8\right]^2 \tag{17}$$

where

$$Re = \frac{\rho c D_h}{\mu} \tag{18}$$

Eq. (18) can easily be solved iteratively starting from a tentatively chosen friction factor value. A starting value as distant as $f = 1$ will lead to convergence within four to six iterations. Friction factor can also be found from Moody diagram.

3.2.2 Pressure Losses in Diffuser

To calculate pressure loss in a diffuser, the energy loss due to friction must be considered. The main parameters are the equivalent conical expansion angle (Eq. 3) and the ratio between inlet and outlet cross-section areas ($A_R=A_2/A_1$).

The loss coefficient is the sum of the two. The first relates to friction and the second to expansion as shown in the following equation;

$$K_d = K_f + K_{exp} \tag{19}$$

For one-dimensional flow, constant friction factor and constant density with the stream, Eq. (20) is produced.

$$K_f = \left(1 - \frac{1}{A_R^2}\right)\frac{f}{8sin\vartheta_e} \tag{20}$$

The expansion loss coefficient can be calculated with the empirical expression in Eq. (21).

$$K_{exp} = K_e(\vartheta_e)\left(\frac{A_R-1}{A_R}\right)^2 \tag{21}$$

The term $K_e(\vartheta_e)$ can be expressed as a geometrical function. W.T. Eckert proposed the expressions in Eqs. (22) and (23) for circular and square cross-sections. [19]

The lower the equivalent conical expansion angle, the lower the losses.

$$K_{e(circular)} = A_2 + B_2\vartheta_e + C_2\vartheta_e^2 + D_2\vartheta_e^3 + E_2\vartheta_e^4 + F_2\vartheta_e^5 + G_2\vartheta_e^6 \ \ if\ 1.5° \le \vartheta_e \le 5° \tag{22}$$

$$K_{e(square)} = A_2 + B_2\vartheta_e + C_2\vartheta_e^2 + D_2\vartheta_e^3 + E_2\vartheta_e^4 + F_2\vartheta_e^5 + G_2\vartheta_e^6 \ \ if\ 1.5° \le \vartheta_e \le 5° \tag{23}$$

Table 3.3: Eckert's K_e parameters for circular and square cross-sections

Parameter	Circular	Square
A_2	0.1709	0.1222
B_2	-0.1170	0.04590
C_2	0.03260	0.02203
D_2	0.001078	0.003269
E_2	-0.0009076	-0.0006145
F_2	-0.00001331	-0.0000280
G_2	0.0001345	0.00002337

3.2.3 Pressure Losses in Honeycombs

To determine the pressure loss in honeycombs, the three main parameters of stream-wise length to cell hydraulic diameter ratio, porosity and Reynolds number based on cell hydraulic diameter must be accounted for. W. T. Eckert, K. W. Mort, and J. Jope [19] proposed the relation reported in Eq. (24).

$$K_h = \lambda_h\left(\frac{L_h}{D_h} + 3\right)\left(\frac{1}{\beta_h}\right)^2 + \left(\frac{1}{\beta_h} - 1\right)^2 \tag{24}$$

where:

$$\lambda_h = \begin{cases} 0.375\left(\frac{\Delta}{D_h}\right)^{0.4} Re_\Delta^{-0.4} & \mathrm{Re}_\Delta \leq 275 \\ 0.214\left(\frac{\Delta}{D_h}\right)^{0.4} & \mathrm{Re}_\Delta > 275 \end{cases} \quad (25)$$

In Eq. (25) Re_Δ is the Reynolds number based on material roughness Δ and D_h is the cell hydraulic diameter.

3.2.4 Pressure Losses in Screens

W. T. Eckert proposes an empirical relation for the screen loss coefficient based on three main parameters: porosity or its complement solidity, the Reynolds number calculated with wire diameter Re_w, and mesh factor K_{mesh}. [19] The latter was studied by I. E. Idel'chik who assigned it a value of 1.0 for new metallic wires, 1.3 for circular metallic wires, and 2.1 for silk fibres. [20] An average value of 1.3 for K_{mesh} is a good choice in most of cases. σ_s is the mesh screen solidity which is taken as less than 0.44 for almost all the cases.

Eckert's empirical equation for calculating the screen loss coefficient is reported in Eq. (26).

$$K_m = K_{mesh} K_{Rn} \sigma_s + \frac{\sigma_s^2}{\beta_s^2} \quad (26)$$

$$K_{Rn} = \begin{cases} 0.785\left(1 - \frac{Re_w}{354}\right) & 0 \leq Re_w < 400 \\ 1.0 & Re_w \geq 400 \end{cases} \quad (27)$$

3.2.5 Pressure Losses in Contraction Cone

The pressure loss in a contraction cone is considered only due to skin friction. Since pressure loss in the contraction cone is about 3% of total loss, errors evaluating K_{nt} are less significant than those made in the high velocity wind tunnel sections so the approximated expression proposed by F. L. Wattendorf [21] (Eq. 28) can be used.

$$K_n = 0.32 f_{av} \left(\frac{L_n}{D_{sc}}\right) \tag{28}$$

where L_n is the nozzle length, D_{sc} is the settling chamber hydraulic diameter, and f_{av} is the average friction factor between contraction cone inlet and outlet sections. The average friction factor f_{av} can be evaluated by Eq. (17), with *Re* equal to the mean value between *Re* evaluated at the inlet and outlet of the contraction cone.

3.2.6 Overall Pressure Losses in the Wind Tunnel

With the above criteria, the loss coefficients for each wind tunnel component can be calculated. Table 3.4 shows pressure drops for each wind tunnel component. Summing all the wind tunnel section pressure drop values produces the total pressure drop. This pressure drop has to be compensated by the wind tunnel fan.

Table 3.4: Component pressure loss at c_{ts} = 40 m/s (c_{ts} = test section air speed)

Components	Pressure loss, Δp [Pa]
Test section	9.76
Diffuser	61.42
Honeycomb	3.1
Screen 1	7.65
Screen 2	9.46
Contraction cone	2.05
Total Pressure loss	93.44

Based on the loss coefficients and wind tunnel section pressure drops, and assuming a null relative pressure value in the testing section, the relative pressure values in the wind tunnel sections can be calculated (*ideal,* without energy loss see Eq. (29); *real*, with energy loss see Eq. (30)).

$$P_{out} - P_{in} = \frac{1}{2}\rho(u_{in}^2 - u_{out}^2) \tag{29}$$

$$P_{out} - P_{in} = \frac{1}{2}\rho(u_{in}^2 - u_{out}^2) - \Delta P_{loss-in-out} \tag{30}$$

where $\Delta P_{loss\text{-}in\text{-}out}$ is the pressure loss between inlet and outlet cross-sections of the component correlated to the K_i factors.

Static pressure variation within the wind tunnel in ideal and real cases is reported in Figure 3.6, while Figure 3.7 shows incremental pressure loss.

Figure 3.6 clearly shows lower pressure values in the real case compared to the ideal case up from test section to the fan section. From inlet to the honeycomb, the real pressure curve is always smaller than the ideal one which is due to the pressure losses throughout the wind tunnel.

The wind tunnel sections' contribution to pressure loss is shown in Figure 3.8. Clearly most occurs in the diffuser section and minimum occurs in the contraction cone.

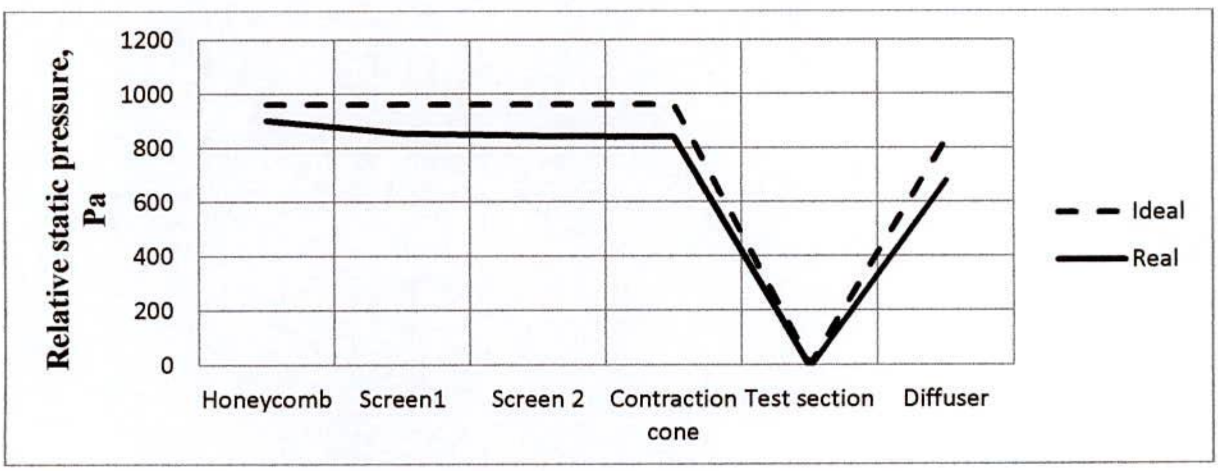

Figure 3.6: Relative static pressure in the wind tunnel

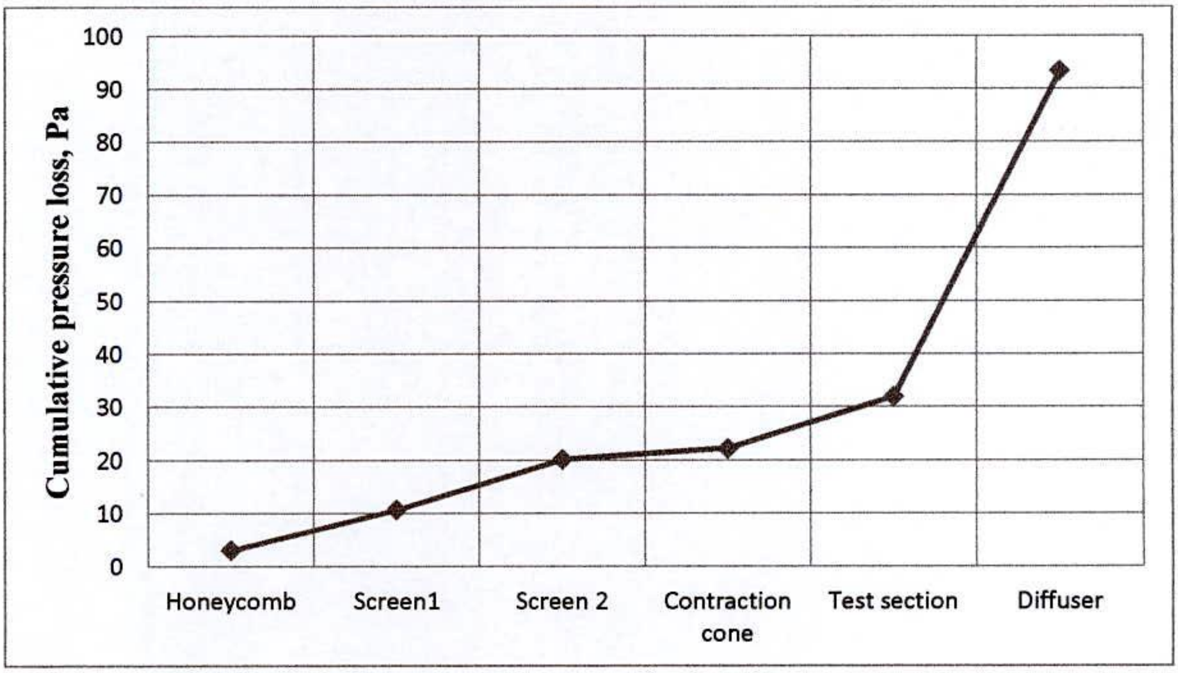

Figure 3.7: Cumulative pressure loss in the wind tunnel

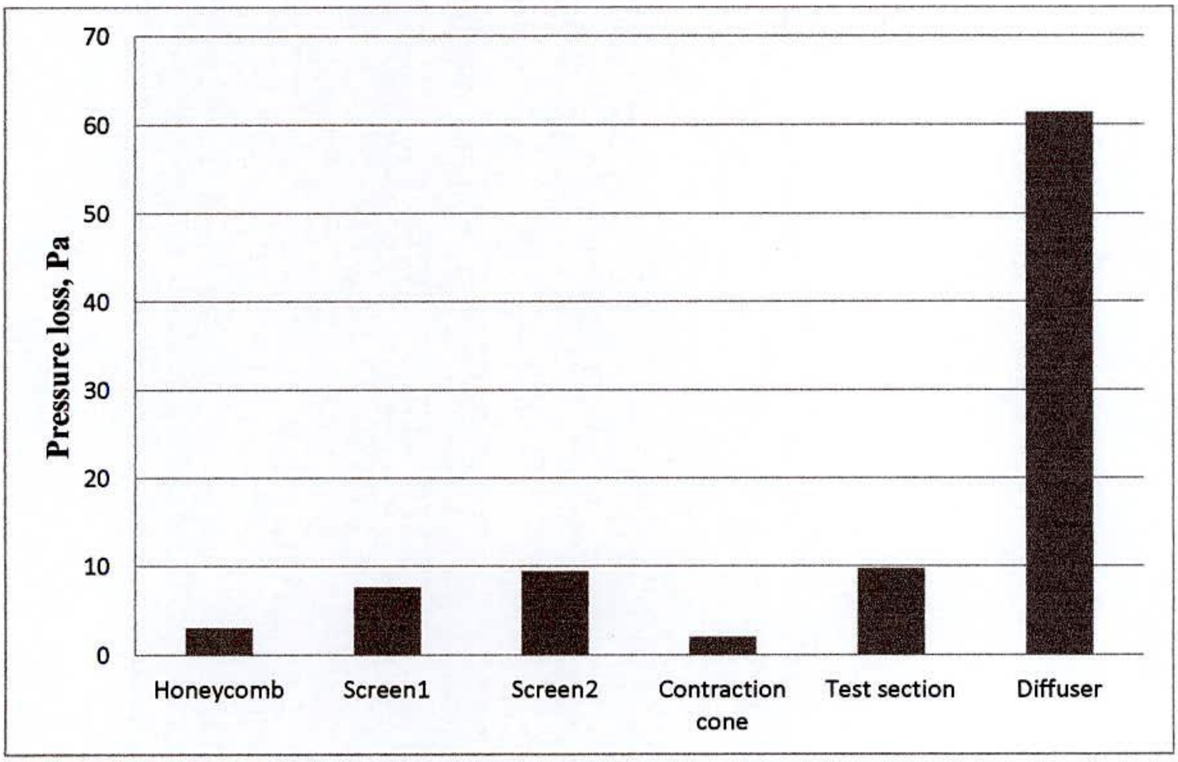

Figure 3.8: Pressure losses in the wind tunnel

CHAPTER IV

Construction

4.1 Test Section

The test section of the wind tunnel is constructed according to the design. The test section can be seen from the three sides i.e. front, back and top sides. For making the test section visible, acrylic sheet was used which is bolted to fix to the test section frame. An opening at the front side is provided to place the models into the test section easily. The leakages have been sealed with M-seal materials. Figure 4.1 shows the constructed test section from front side.

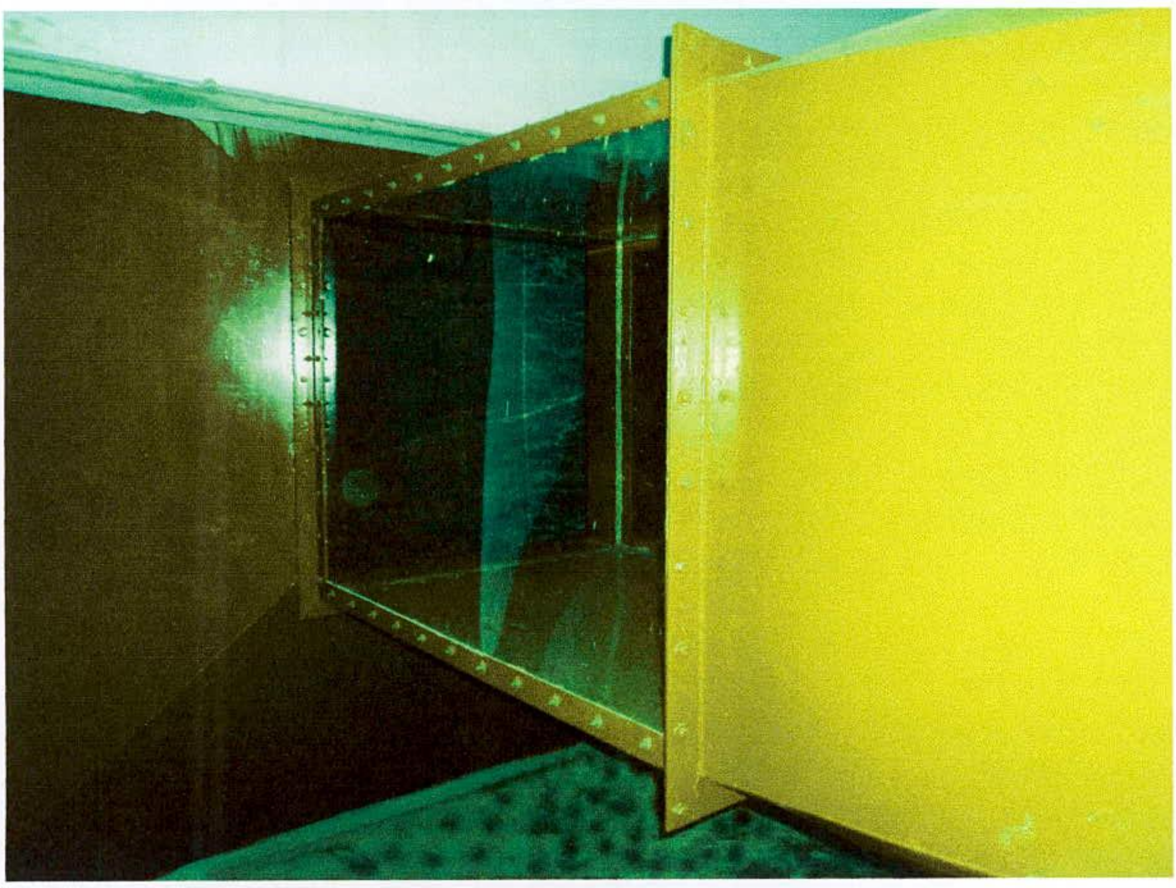

Figure 4.1: Constructed test section with window closed

4.2 Construction of Contraction Cone, Settling Chamber and Diffuser

Contraction cone, settling chamber and diffuser have been constructed by 3 mm thick mild steel plate to minimize the construction costs. The most important thing is to fabricate the diffuser section since it has one end rectangular and other end circular. Figure 4.2 shows constructed contraction cone with settling chamber and test section, figure 4.3 shows the diffuser section with fan section and figure 4.4 shows the fan used to facilitated the air flow through the wind tunnel.

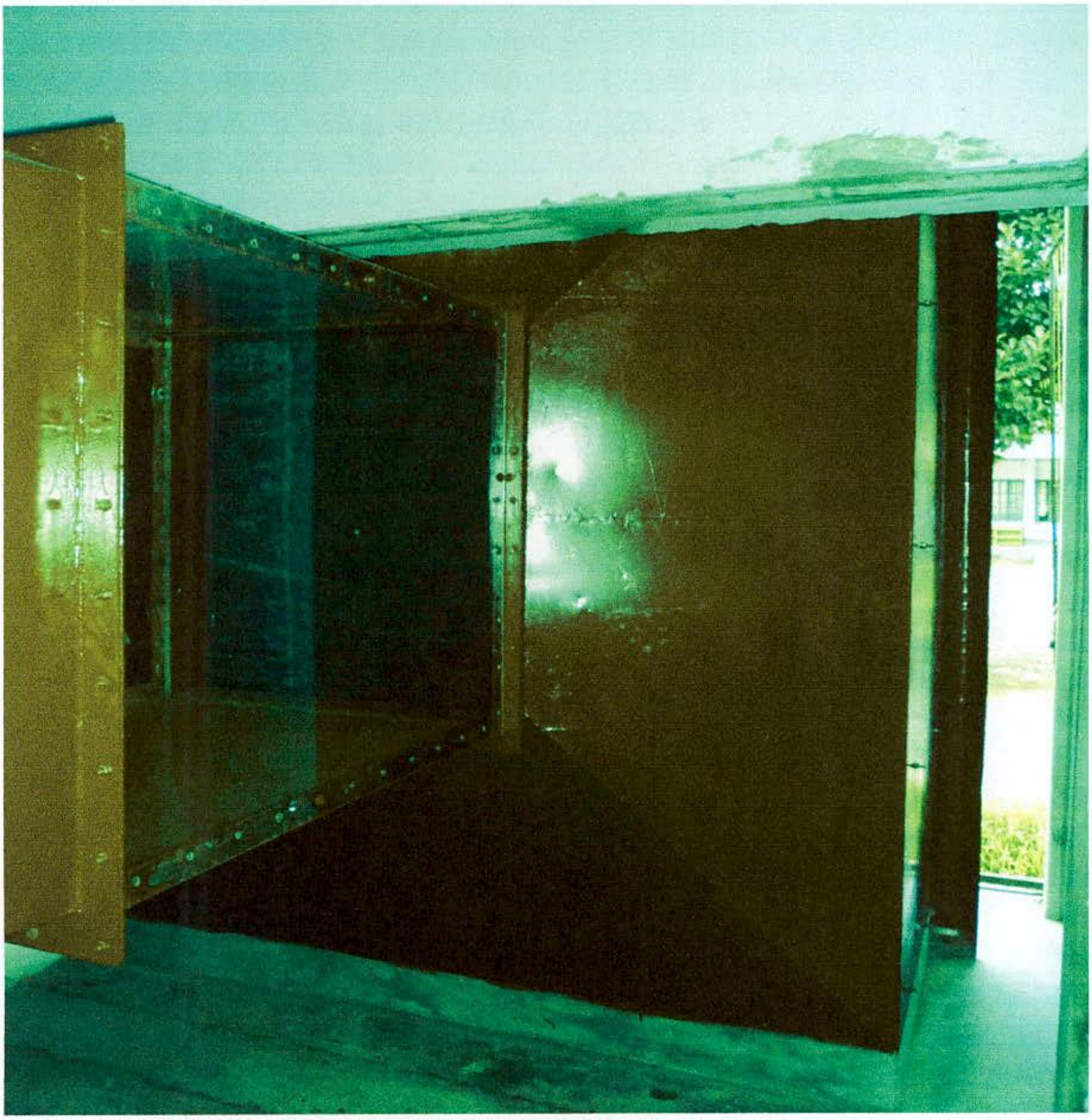

Figure 4.2: Constructed contraction cone with settling chamber and test section

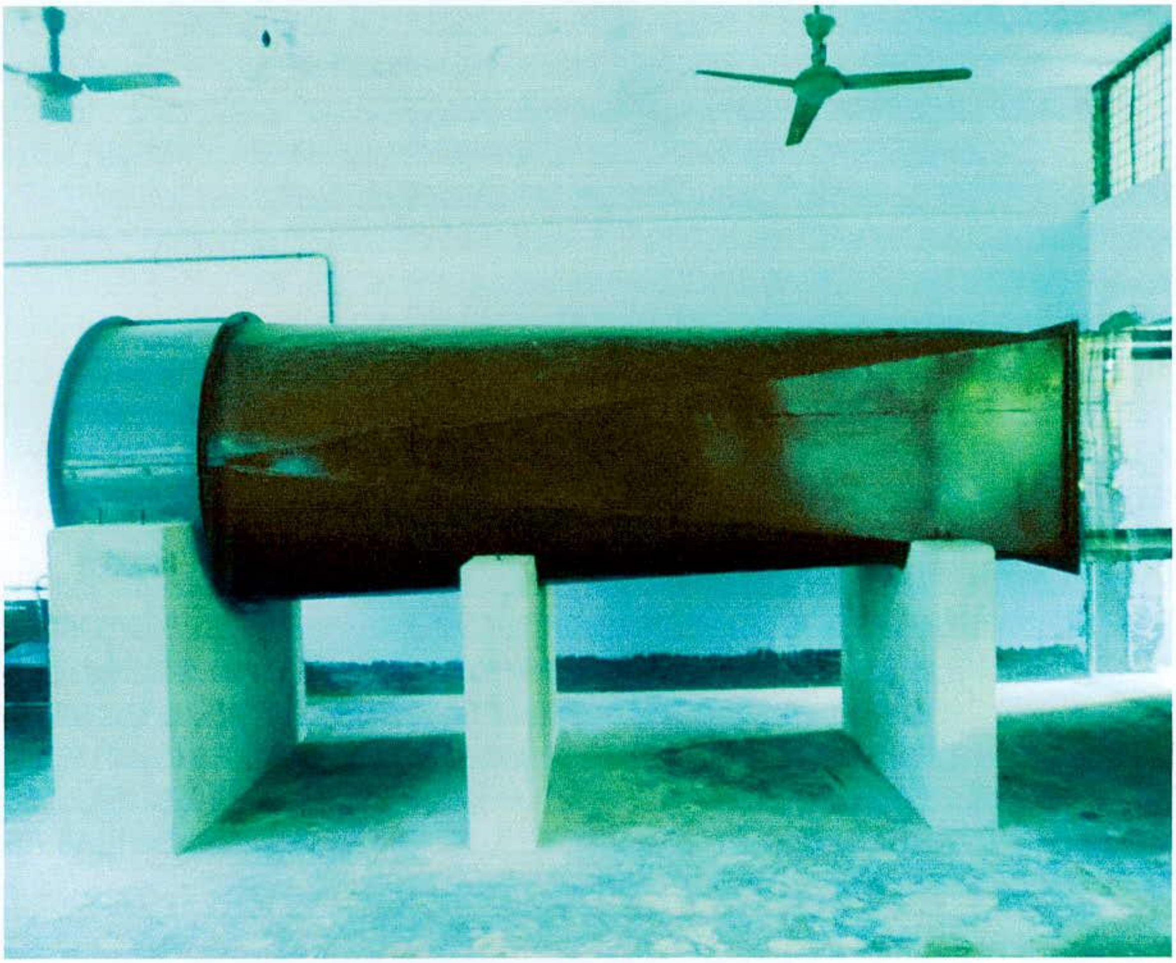

Figure 4.3: Constructed diffuser with fan section

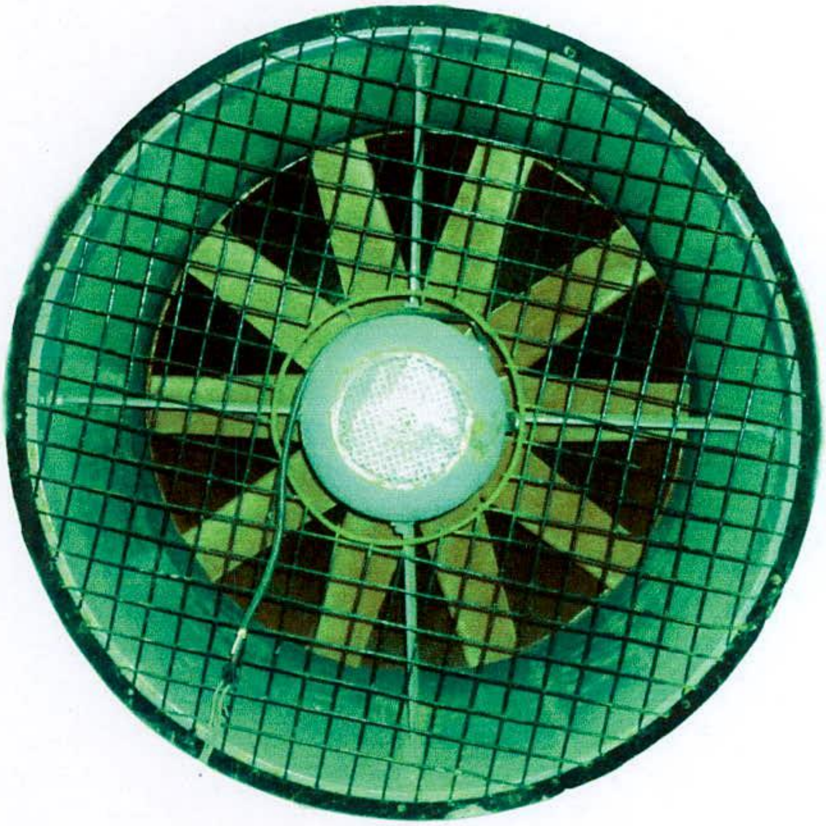

Figure 4.4: Fan used to facilitate air flow through the tunnel

4.3 Construction of Honeycomb and Screens

Two screens have been used in this wind tunnel to minimize the air turbulence and increase flow uniformity. Readymade screens were purchased from local market with necessary requirements. Honeycomb was made in the lab manually. For construction of honeycomb class-A PVC pipe was used. Figure 4.6 shows the constructed honeycomb.

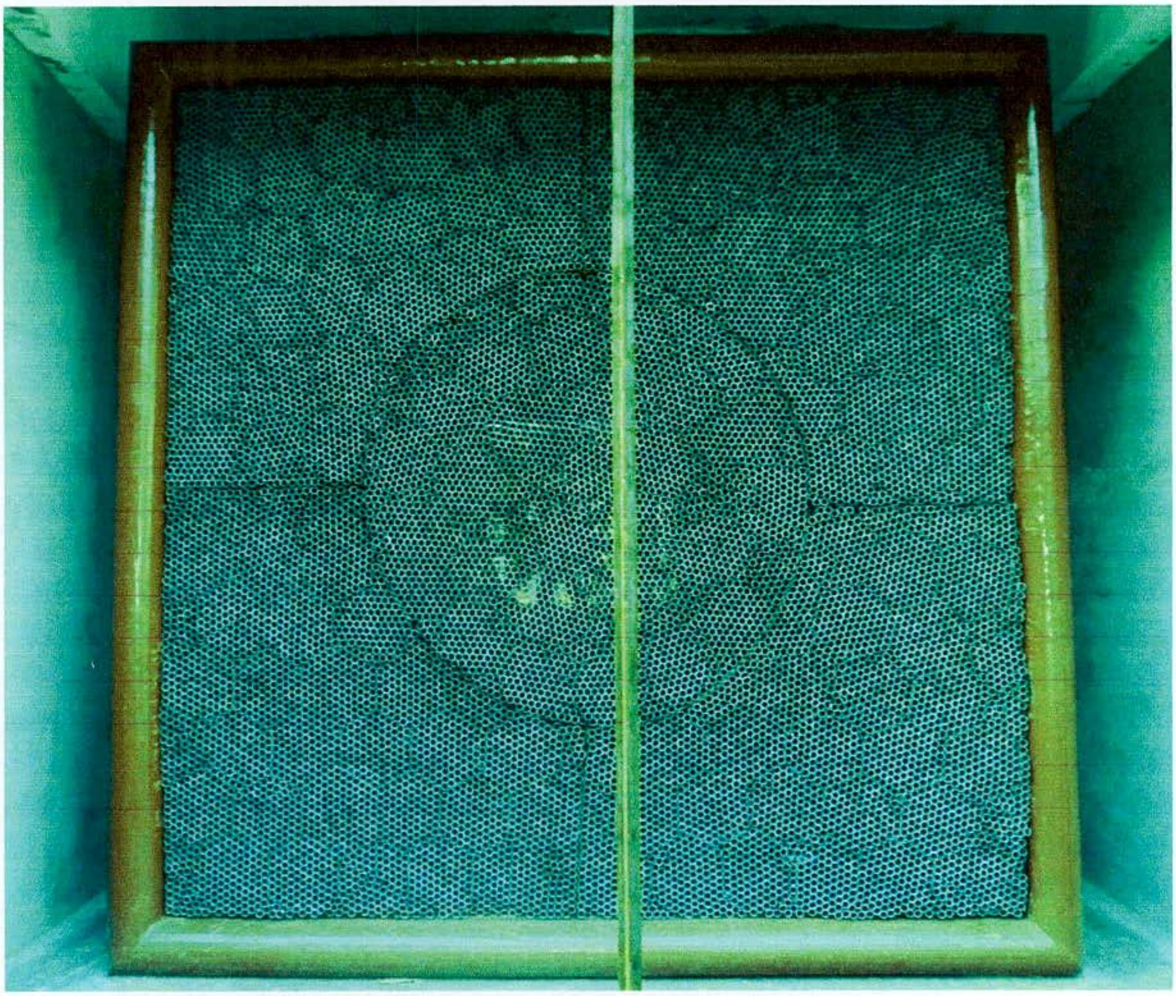

Figure 4.5: Constructed honeycomb

4.4 Assembled Wind Tunnel

All sections of the wind tunnel were assembled and installed in the mechanical engineering workshop. Figure 4.7 shows the installed full wind tunnel after assembly.

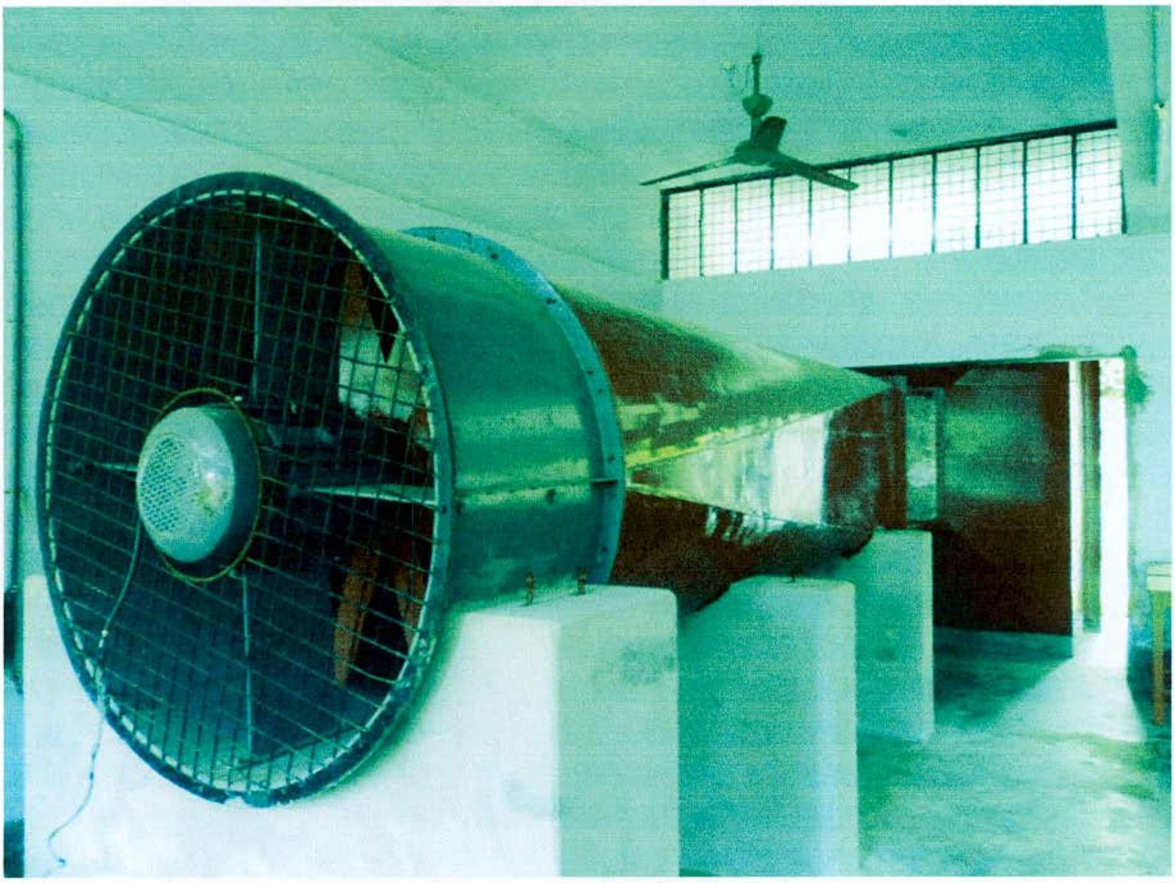

Figure 4.7: Wind tunnel after assembly

CHAPTER V

Results and Discussion

After the construction of the wind tunnel component sections according to the design, the tunnel has been assembled and erected in the mechanical engineering workshop. Different data have been taken to construct the velocity profile in the test section and also the pressure readings at different point have been recorded. All data have been taken at maximum air velocity. Figure 5.1 shows the horizontal velocity profile at different distance from the test section front wall while the data were taken midway of the test section.

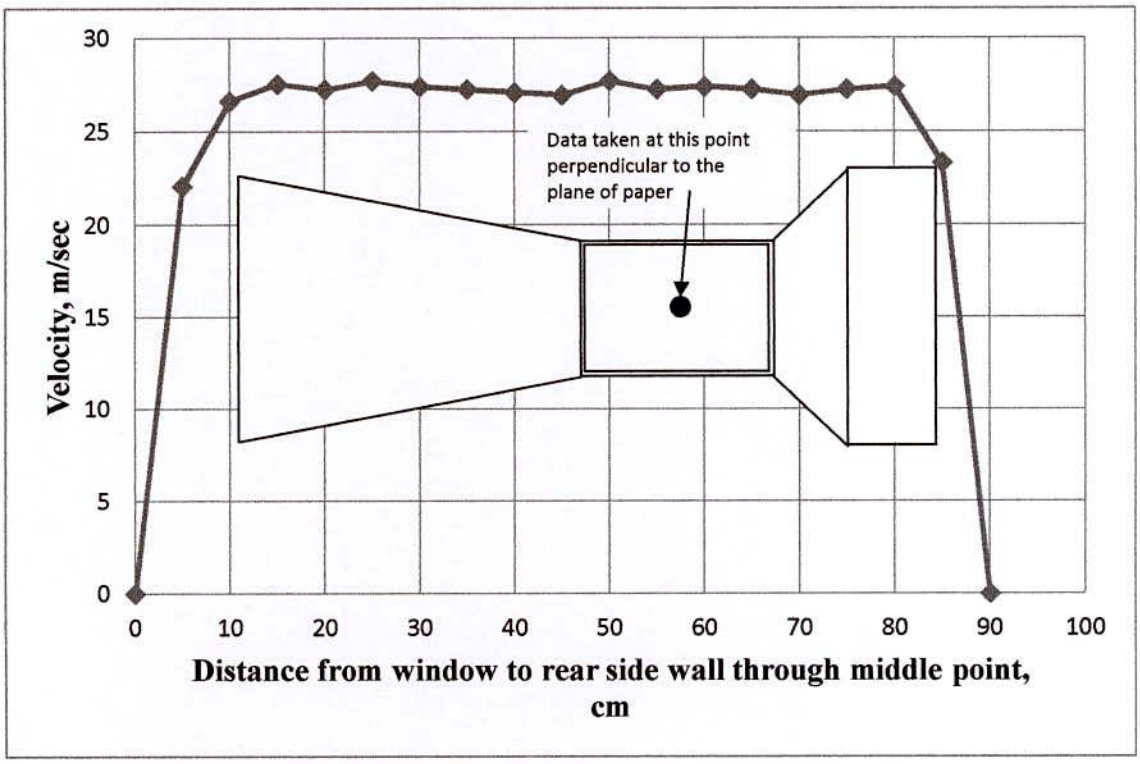

Figure 5.1: Horizontal velocity profile

From horizontal velocity profile it can be seen that 10 cm from the rear front wall the velocity of flow is almost linear up to 80 cm. Velocity near the wall is of gradually increasing nature this is because of the boundary layer. So, the maximum boundary layer thickness is found to be 10 cm and the effective air flow velocity is found in a length of 70 cm which is located 10 cm from the both wall. In percentage, the effective flow length is about 76% and boundary layer region in each wall is about 12% of the total width of the tunnel. The mean free stream velocity is found to be about 30 m/s.

Figure 5.2 shows the vertical velocity profile at different distance from the bottom to top wall of the test section while the pressure difference reading was taken at a distance 5 cm from the test section inlet. Figure 5.3 and 5.4 shows the same while data were taken at a distance 60 cm and 115 cm from the test section inlet.

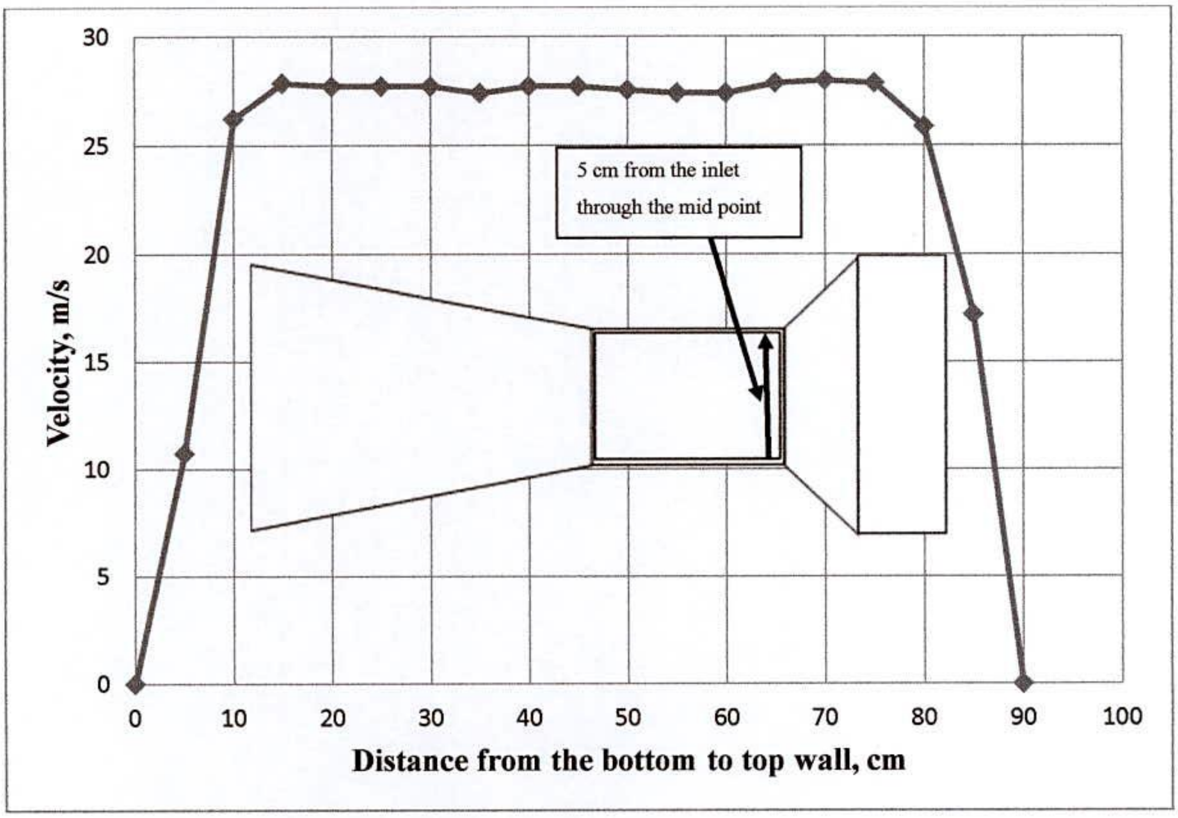

Figure 5.2: Vertical velocity profile at a distance 5 cm from the test section inlet

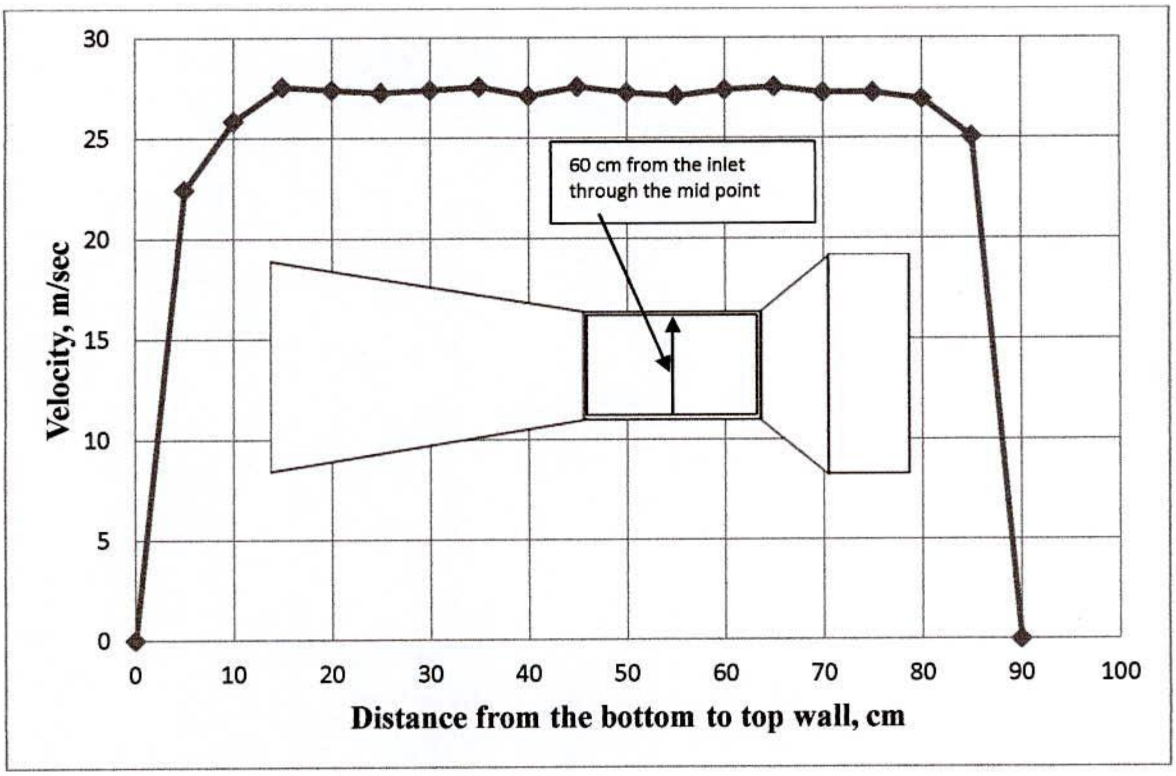

Figure 5.3: Vertical velocity profile at a distance 60 cm from the test section inlet

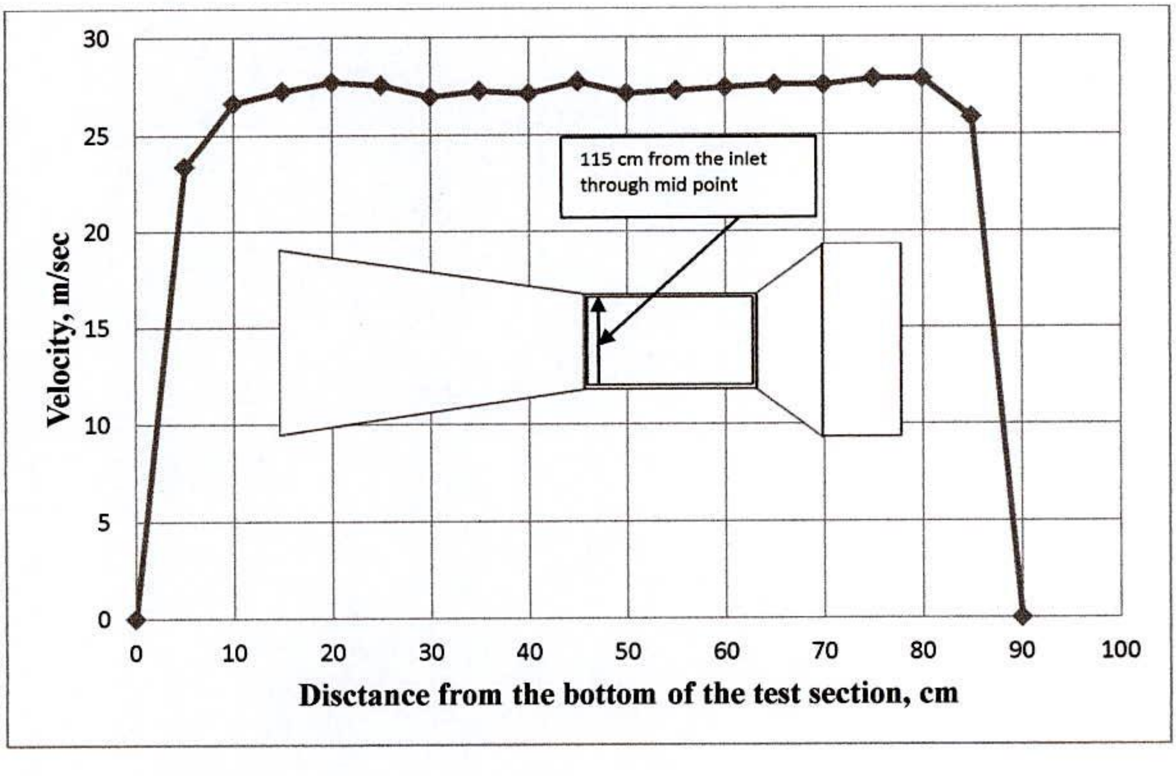

Figure 5.4: Vertical velocity profile at a distance 115 cm from the test section inlet

A plot was build up to show the vertical velocity profiles in combined form which is shown in figure 5.5.

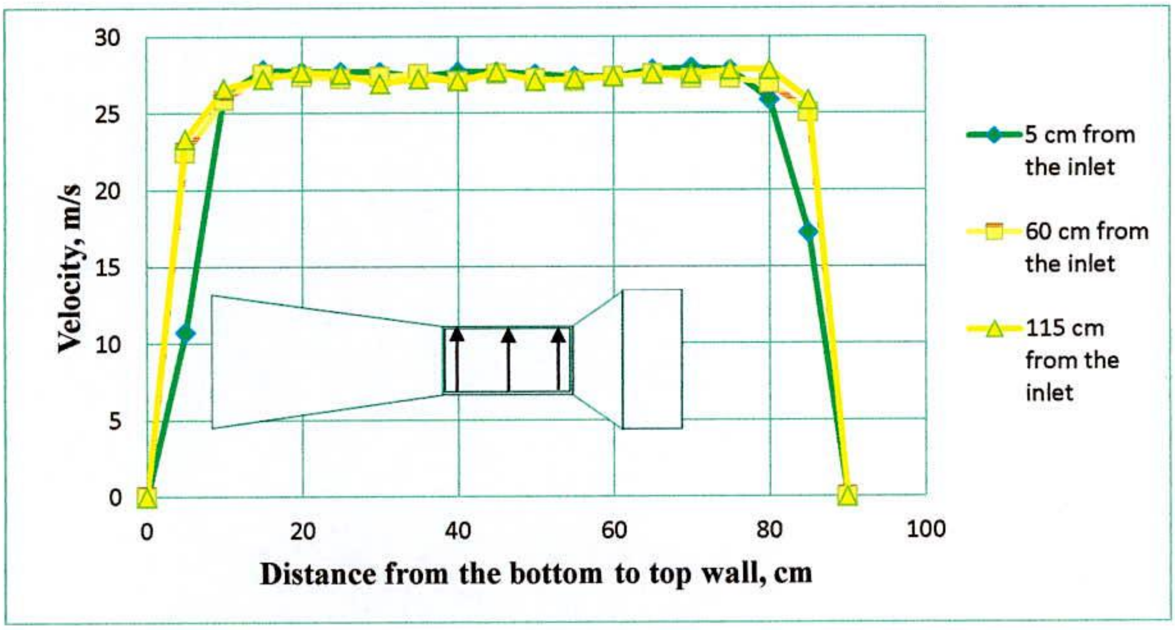

Figure 5.5: Vertical velocity profile at three positions

From the velocity profiles it is clear that the mean velocity in the test section is almost linear. At 5 cm from the test section inlet, air velocity close to the wall is much less than the other positions (at 60cm and 115 cm). The maximum velocity is also found at 5 cm position. These happen because of the effect of the contraction outlet due to which vena contracta is formed. In case of 60 cm and 115 cm positions, velocity profile is almost similar which indicates that mean flow velocity throughout the test section is identical. For all cases, velocity is gradually increasing near the wall because of the boundary layer formed. This boundary layer region is approximately 12% of the total height of the test section in each side.

So, the effective flow height is found to be approximately 76% of the total height of the test section. The effective flow region is 10 cm from the bottom wall to 10 cm below the top wall. In case of vertical measurements, the mean flow velocity in the effective flow region is about 30 m/s.

CHAPTER VI

Conclusions and Recommendations

6.1 Conclusions

The purpose of this research work was to design, construct and performance test of a short length subsonic wind tunnel to verify its adequacy for aerodynamic analysis applications as well as to simulate the velocity profile at different position of the test section. The wind tunnel is designed considering a mean test section speed 40 m/s and all factors are considered to make it as short as possible. Then, it is fabricated as accurately as possible.

The length of the constructed wind tunnel is about 7.35 m and a free stream velocity is found approximately 30 m/s. A comparison between the newly constructed wind tunnel and the wind tunnel built at NASA and MIT (USA) of approximately same test section is shown in table 6.1. From the comparison it is clear that the overall length of newly designed wind tunnel is much shorter than the other two.

Table 6.1: Comparison of newly designed wind tunnel with existing tunnels

Parameters	**New Tunnel**	**NASA(Small) Tunnel**	**MIT (USA) Tunnel**
Test section	0.9 m × 0.9 cm	0.9 m × 0.9 m	0.85 m × 0.85 m
Mean velocity	30 m/s	25 m/s	40 m/s
Test section length	1.35 m	3 m	2.8 m
Overall length	7.35 m	13 m	11 m

Measurements of the velocity in the empty wind tunnel showed a uniform field which is essential for using it for aerodynamic researches. The detailed specifications of the constructed wind tunnel are shown in table 6.2.

Table 6.2: Specifications of the newly designed wind tunnel

Parameters	Value
Type	Open circuit
Test section length	1.35 m
Test section cross section	0.90 m × 0.90 m
Mean air velocity range	30 m/s
Discharge	1440 m^3/min
Overall length	7.35 m
Effective region in the test section	76% of width or height
Boundary layer region	12% of width or height from every wall
Contraction ratio	8
Honeycomb cell diameter, length	0.02 m, 0.125 m
Number of screens	2
Settling chamber cross section	2.55 m × 2.55 m
Motor and Fan	3-phase 20 kW, 10 blades

The new designed tunnel is, therefore, a very good device to provide parallel steady flow with uniform speed through the test section without excessive turbulence and can be used effectively in different aerodynamic researches.

6.2 Recommendations

Future work will consider the evaluation of the flow condition on the value of the convective moisture transfer coefficients and their application in the buffering moisture effects of the building materials. In addition, the turbulence intensity profile will be also subject of further work after installation of a hexagonal cell-aluminum honeycomb and screens in the settling chamber.

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