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FACULTY OF MECHANICAL ENGINEERING

DEPARTMENT OF PROCESS ENGINEERING

WIND TUNNEL DESIGN

BACHELOR THESIS

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MUHAMMAD SULEMAN

BACHELOR'S THESIS ASSIGNMENT

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III. Assignment receipt

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Declaration

I confirm that the bachelor’s work was disposed by myself and independently, under the lead of my thesis supervisor. I stated all sources of the documents and literature.

In Prague 15 January 2021 ……………… ……………………

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Abstract

This thesis proposes a design methodology for a small scale low speed wind tunnel that can be 3D printed in-house. The university currently has a small open circuit wind tunnel but there is a demand for a larger one for experimental measurements of larger test models. Based on the existing wind tunnel, larger dimensions and connections to the existing fan are designed. The designed tunnel should make it possible to measure surface temperatures around objects using various techniques, such as infrared thermography and thermochromic liquid crystals (TLC), by replacing the wall for the required measurement type. Also, Prandtl probes are to be used to measure the velocity in the field as well. The detachable wall, plexiglass or steel or any other material, is designed with a slot so it can slide in and be secured easily within the test section from both sides.

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Nomenclature

Re	Reynolds number [-]
ρ	density [$\frac{m^3}{kg}$]
u	velocity [$\frac{m}{s}$]
L	length [*m*]
μ	kinematic viscosity [$\frac{m^2}{s}$]
β	porosity / angle [-]
d	diameter [*m*]
θ	angle theta [°]
Δp	pressure difference [*Pa, kPa]*
p	pressure [*Pa*, *kPa*]
S	cross-section surface [m^2]
N	contraction ratio [-]
λ	total friction loss coefficient [-]
K_I	Pressure loss coefficient [-]
P	power [*W, kW*]
$\dot{V}$	volumetric flow rate [$\frac{m^3}{s}$]
η	efficiency [-]
Δh	height difference [m]
g	acceleration due to gravity [$\frac{m}{s^2}$]
M	Mach number [-]

Section 1: Introduction

1.1 History of Wind Tunnels

In 1804, George Clay built a whirling arm apparatus for the purpose of testing aerofoil. This was done by lifting the surface or aerofoil which was mounted on the end of a long road and rotated at a speed to produce a flow of air over the aerofoil. In modern engineering, especially the automotive, aviation and architecture industry, these experiments are mostly conducted in the wind tunnel. It has become so vast that there are roughly 1000 wind tunnels all over the world and there is a complete spectrum of them ranging from low subsonic to hypersonic speeds. They include different types, working functions, test section areas, power, and speed. [1]

Experimental techniques via wind tunnels have become easier in the modern era. Major progress in computing technology and software has allowed modelling and testing using computational fluid dynamics (CFD) – in simple cases experimentation is not necessary and computational and simulation methods are acceptable, saving time and money. However, not all aspects are up to par to completely shift to virtual testing, such as drag calculations. Therefore, experiments with complex bodies such as those in aeronautics will likely continue utilizing wind tunnel testing in the near future.

Applications of wind tunnel testing are broad. Automotive researchers may use it to experimentally determine aerodynamic characteristics of cars. It is also used in architecture applications to simulate wind and pollutant conditions around the buildings in a city. It is important in skyscraper designs as the vortices created from the wind can accumulate large enough to cause serious structural damage. [2]

1.2 Wind Tunnel

A wind tunnel is a device that produces a controlled stream of air to study the effects of air flow under varying conditions, within (sometimes) and around the body. Researchers can use the controlled environment of a wind tunnel to safely test and design their models, measuring flow conditions (pressure or airspeed) and forces around them. [3]

The primary purpose and benefit of using a wind tunnel to test miniature prototypes is to gather enough data to produce the full-scale version correctly with the least attempts possible. Relative to free-flight testing, aerodynamic testing can achieve and sustain specified flow conditions such as Mach number and incidence with ease in a wind tunnel. It also is much safer, for example, uncontrollable flight conditions may safely navigate in a wind tunnel. Data acquisition is also much simpler.

There are certain drawbacks in wind tunnels. Almost every model must be scaled down which requires expert model technicians to prepare the model, test the components, and operate it if necessary, during a wind tunnel test. Also, a steady supply of accurate, high quality test components will need to be designed and manufactured to support the program. [4]

Section 2: Principle of a Wind Tunnel

The basic principle of any wind tunnel is to duplicate wind in nature. The fundamental theory is based on that of similarity; the wind field should be equivalent to what an object such as vehicles or aircrafts may experience. The following parameters are important in obtaining accurate representation of the real flow. Geometrical similarity and the forces produced on a small scale need to be in the same relationship with one another. [2]

2.1 Reynolds Number

Reynolds number is the ratio of inertial (resistant to change or motion) forces to viscous forces. They are used to characterize different flow regimes within a fluid, namely, turbulent or laminar flow. It is a dimensionless number. High values (on the order of 10 million) indicate that viscous forces are small and the flow may be assumed as inviscid. Laminar flow occurs at low Reynolds numbers, where viscous forces are dominant, and is characterized by smooth, constant fluid motion. Turbulent flow occurs at high Reynolds numbers and is dominated by inertial forces, which tend to produce chaotic eddies, vortices and other flow instabilities. [1]

Reynolds number is defined as:

$$Re = \frac{\rho u L}{\mu} \tag{2.1}$$

where ρ is density of the fluid, u is velocity of the fluid, L is the characteristic length and μ is the dynamic viscosity of the fluid.

2.2 Mach Number

The Mach number (M) relates the compressibility to the inertia forces. Its similarity is important when noticeable variations of density and temperature occur at high flow velocities. [2]

It is a ratio of velocities: $\frac{actual\ velocity}{speed\ of\ sound}$. This is equivalent as the air speed inside the wind tunnel to the speed of sound. [2]

2.3 Turbulence

Turbulence is defined and characterized by the irregular movement of particles or more commonly labelled as chaotic. It includes swift changes in pressure and velocity, high momentum convection, and low momentum diffusion.

2.4 Bernoulli's Principle

In aerodynamics, the air pressure decreases when the wind speed is increased. "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]

Section 3: Classification of Wind Tunnels

Wind tunnels are categorized by their wind speeds and circulation of air flow. One can easily select the appropriate design based on testing requirements for their prototype. Each design varies in function, dimension, and structure based on these categories.

3.1 Speed Range

Speed range is the most appropriate way of classifying wind tunnels.

In a low speed wind tunnel, inertial and viscous forces are dominant and compressibility effects are negligible. Since the density varies less than 5%, incompressible assumption is made. The cross section of the testing section can reach up to 4 m^2. Maintaining the speed does not cost much because it is low. Overall power is beyond 2000 kW. [1]

A subsonic speed wind tunnel's velocity is much higher than the low speed, and the power required can reach up to 20,000 kW. Power loss during the process generates enough heat to significantly alter test results, thus cooling equipment such as a radiator is necessary. Decreasing energy loss requires greater efficiency of the diffuser section, making the diffusion angle very small and the diffuser section longer than the low speed wind tunnel. [1]

The Mach number of the transonic wind tunnel is approximately 1 with subsonic and supersonic flow regions combined. The reflection of shockwaves from the walls in the test section pose a problem in transonic speed testing, depicted in figure 1. Perforated or slotted walls are solutions used to reduce shock reflection off 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. [1]

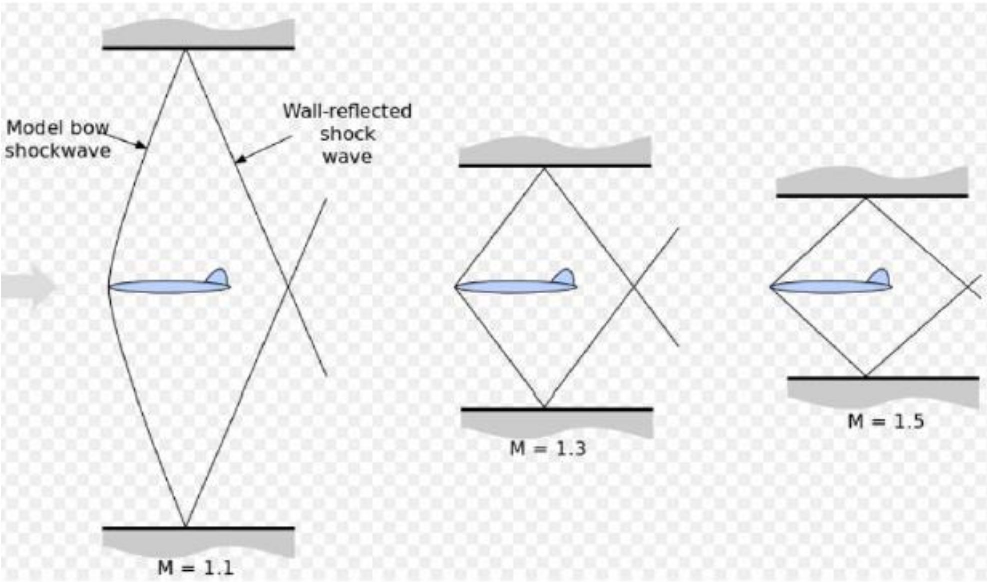


Figure 1. Reflection of shockwaves from the walls inside the testing section of a transonic wind tunnel [1]

In a supersonic wind tunnel, the nozzle geometry determines the Mach number and flow. Reynolds number varies by changes in density level due to the pressure in the settling chamber. Thus, a high pressure ratio is required. Generally, supersonic wind tunnels require a drying or preheating facility due to a cold static temperature caused by gas liquefication or condensation of moisture. The power demand is extremely large, and most supersonic wind tunnels run intermittently rather than continuously. [1]

Hypersonic wind tunnels have a large Mach number and it is desired in such cases to allow real gas effects to occur. This requires that besides the high Mach number in test section also high total temperatures are provided. The high temperatures, which are linked with high pressures, yield vibration of the gas molecules, possibly causing dissociation and ionization. These are dominant features of hypersonic flows where the gas can no longer be treated as an ideal gas. [2]

Wind tunnel types and their respective Mach numbers are provided in the table below.

Table 1. Mach numbers of various wind tunnels [1]

Wind Tunnel Type	**Velocity Limits at Test Section**
Low speed wind tunnel	$0 < u < 135$ 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	10 (or 12) $< M$

As the Mach number increases, energy requirements to operate increase as well and it tends to switch from continuously operating to intermittent.

3.2 Types of Wind Tunnels

3.2.1 Open Return Wind Tunnel

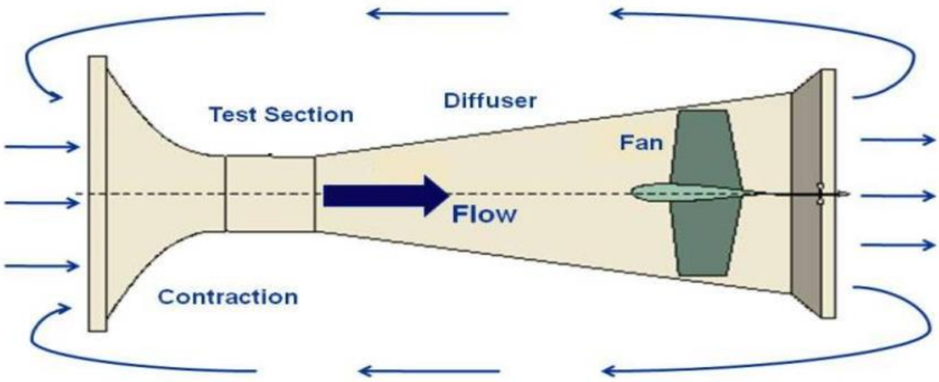


Figure 2. Schematic drawing of an open return wind tunnel [5]

The open return wind tunnel, also known as Eiffel Tunnel named after the French engineer, the Open Return Wind Tunnel is the first type of wind tunnel that was built. The working principle of this type is direct air-intake from the atmosphere drawn into the contraction area where there can be honeycomb filters used to straighten the airflow to achieve desired uniformity in the test section. The desired uniform air flows through the test section where the testing prototype is located; it is important that the test section conditions are controllable. Finally, the air continues to the end of the wind tunnel via a driving unit and the air returns to the atmosphere. The arrows on figure 2 show the direction of air flowing through the wind tunnel. This type of wind tunnel can only operate in subsonic speeds. [6]

Open and closed return wind tunnels can be further categorized as "suck-through" or "blow-down." They are based on the location of the fan relative to the test section. If the fan is located after the test section and is pulling air through the flow straighteners and test section, it is a suck-through type of wind tunnel. The opposite is true for the blow-down – if the fan is located before the flow straighteners and test section, and the air is pushed through the flow straighteners and test section, it is a blow-down type of wind tunnel. [7]

"Blow-down type wind tunnels tend to cause twist in the flow that is significant enough to exist past the flow conditioning sections and into the test section. Suck-through type wind tunnels pull air with significantly less twist through the flow conditioners and have negligible twist in the test section." [7]

3.2.2 Closed Return Wind Tunnel

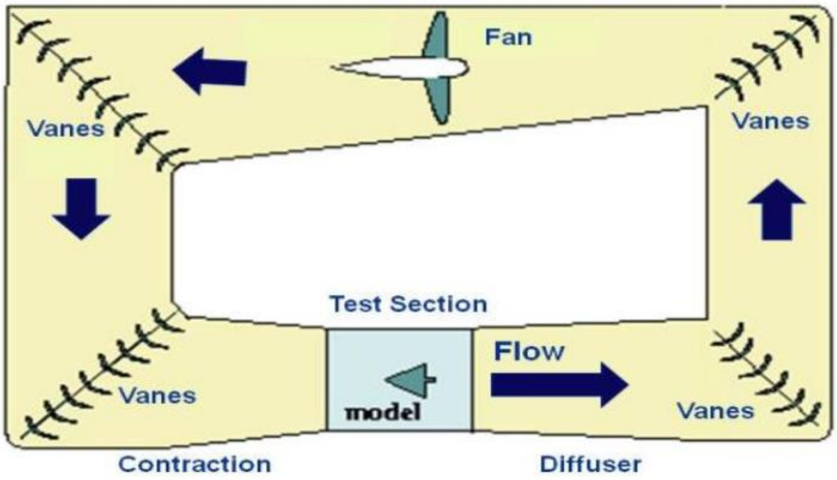


Figure 3. Schematic drawing of a closed return wind tunnel [8]

The closed return wind tunnel is also known as a Prandtl Tunnel, named after the German engineer Ludwig Prandtl. The working principle is based on air returning from the exit of the test section back to the fan via turning vanes. From the fan, the air is returned to the contraction section and back again to the test section. Energy is more conserved in this type of wind tunnel as the air is recirculated. The arrows on figure 3 show the direction of air flowing through the wind tunnel. This type of wind tunnel may operate in subsonic or supersonic speeds. [8]

3.3.3 Blowdown Wind Tunnel

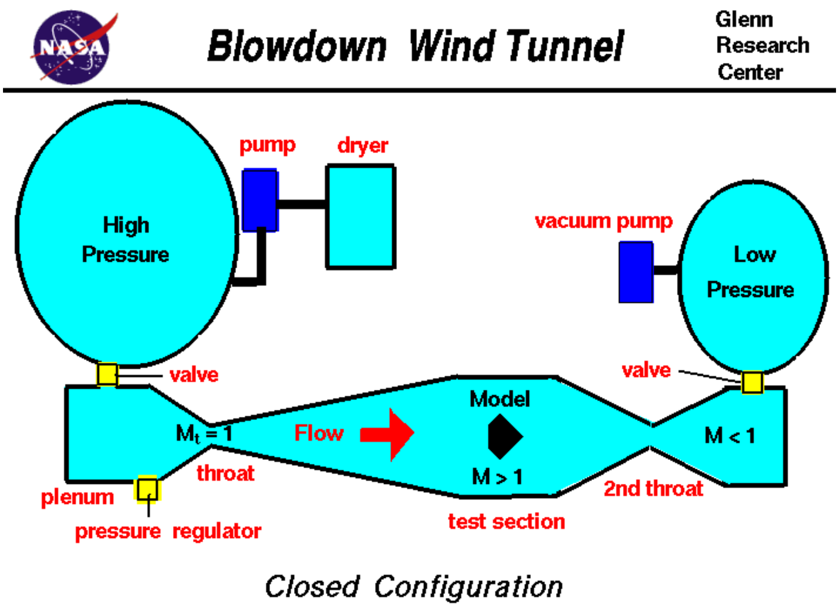


Figure 4. Schematic drawing of a blowdown wind tunnel [9]

There are several configurations possible for a blowdown wind tunnel. Figure 4 shows a completely closed supersonic configuration. These type of wind tunnels are designed for high subsonic to high supersonic airflow speeds. The test section is located at the end of a supersonic nozzle. Mach number in the test section is determined by pressure and temperature in the plenum as well as the area ratio of the test section to the nozzle throat. Pressure decreases as the flow expands in the nozzle and moisture in the tunnel, if there is any, may condense and liquefy in the test section. Air is brought into the tunnel via a dryer bed to prevent condensation. Air is then pumped into a closed high pressure chamber upstream of the plenum. Simultaneously, air is pumped out of a closed low pressure chamber downstream of the section. Test times are generally limited and operates intermittently. [9]

3.3.4 Comparison Summary

Table 2. Summary of different constructions of wind tunnels.

Wind Tunnel Type	Advantages	Disadvantages
Open Return	• Low construction cost. • Better design for propulsion and smoke visualization. • No accumulation of exhaust products. • Subsonic airflow speed.	• High operating costs – fan must continuously accelerate airflow. • Noisy operation.
Closed Return	• Low operating costs – fan only has to overcome losses on the wall and through the turning vanes (does not need to accelerate airflow). • Quiet operation, relatively. • Subsonic to supersonic airflow speed.	• Higher construction cost • Hotter running conditions – may require heat exchangers or active cooling. • Tunnel needs to be designed to reject exhaust products that may accumulate.
Blowdown	• Lower construction and operating cost compared to closed return. • No accumulation of exhaust products. • High subsonic to high supersonic airflow speed.	• Shorter test times require faster, generally more expensive, instrumentation. • Requires pressure regulators. • Noisy operation.

Section 4: Research Background

4.1 Wind Tunnel Components

The research of this paper is focused on a low speed open circuit wind tunnel, therefore the parts to be discussed will be solely of those found in an open circuit low speed tunnel. The main components are:

1. Contraction
2. Settling Chamber
3. Test Section
4. Flow Straighteners
5. Diffuser
6. Drive System

The placement of the components differs based on driving unit and required outcomes. Besides budget as a limiting construction factor, test section conditions must be defined. The rest of the components in the wind tunnel are built around it, starting with the contraction, then choice of fan, followed by the diffuser, and finally the settling chamber which may include the honeycombs and screens. Examples of different layouts are shown in figure 5 and 6 respectively.

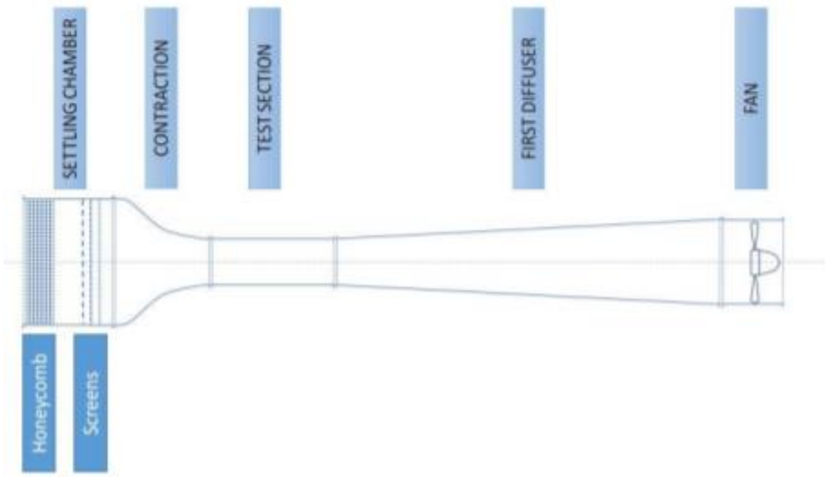


Figure 5. Open Circuit Wind Tunnel [10]

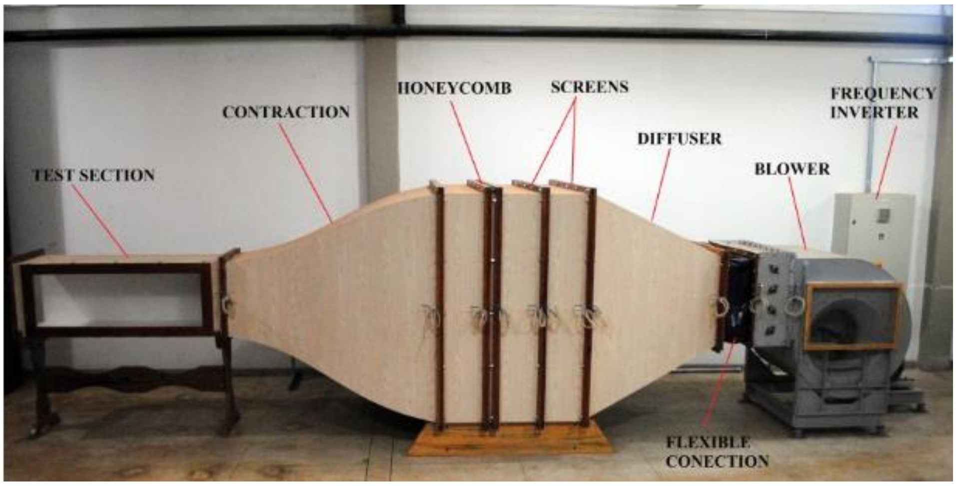


Figure 6. Open Circuit Wind Tunnel [11]

4.1.1 Contraction

The contraction is considered one of the most important part in the design of a wind tunnel due to its significant impact on the flow quality in the test section. Its purpose is to accelerate and supply the incoming flow of air from the settling chamber to the test section at preferred velocity. A highly accepted design condition is that the velocity at the end of the cone must be fairly uniform. [12] Basically, this segment reduces the cross-sectional velocity variance and preserves flow uniformity. The size and shape of the contraction in the test section determine the final turbulence strength levels. The flow acceleration and non-uniformity attenuations mainly depend on the so-called contraction ratio, N, between the entrance and exit section areas. [13] 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. [1]

Contraction ratios defer based on application. For civil or industrial applications, contraction ratios between 4 and 6 are suitable. If the shape is designed well, turbulent and non-uniform flow levels may reach 2% – suitable for many applications. However, this can be reduced further down to 0.5% (suitable for some aeronautical purposes) with the help of a screen placed in the chamber. When more precise measurements are required, like 0.1% in non-uniform average speed and turbulence levels, a contraction ratio between 8 to 9 is recommended. [13]

The shape of the contraction is a significant design criterion as well. Many profiles have been developed, however, a commonly accepted one by Bell and Mehta [11] is suggested for a low-speed open wind tunnel, as shown in figure 7. Their 5th order polynomial method does not allow flow separation in the centre line nor the contraction corners. It meets the minimum criteria for Reynolds number and offers excellent flow uniformity.

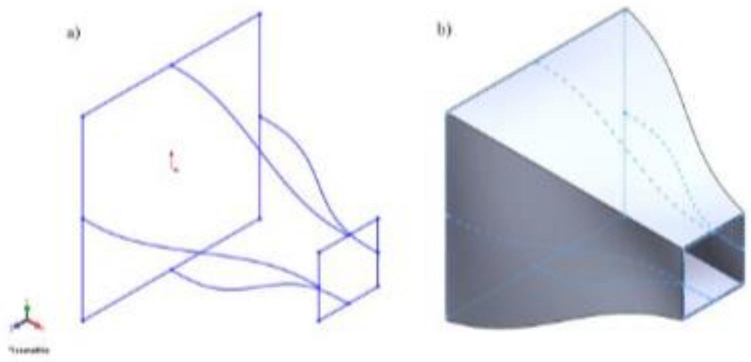


Figure 7. Generation of profile through medium lines (a) and completed profile of the contraction [11]

4.1.2 Settling Chamber

The settling chamber is the most significant component of the wind tunnel primarily due to its influence on flow quality prior to entering the contraction section. This occurs because of the high local pressure drop caused by the honeycombs and screens. The purpose of the settling chamber is to slow down the velocity of the flow, decrease flow turbulence, and smoothen out irregularities caused by the fan before the flow enters the contraction. Flow speed is the smallest in this section. When flow quality requirements are low, the settling chamber is merely a simple duct of constant section. On the other hand, when high quality flow is required, flow straighteners such as honeycombs and screens are used. [11]

4.1.3 Test Section

The size of test section is confined by operating speed and desired flow quality. These factors determine the maximum size of the test models and the maximum achievable Reynolds number. [13] The test section may be of various shapes such as rectangle, circular, hexagonal, octagonal etc. The height to width ratio is determined by the intended purpose of the wind tunnel. For instance, a wind tunnel for wing testing is usually wider than tall – generally 3:2 ratio and architectural models are generally taller than wide. It is common to determine the test section velocity as a variation percentage from the average of the cross-section. Ideally, the test section has steady uniform velocity with little to no turbulence. [14]

When designing the test section, ease of accessibility is fundamental to the installation of test models as well as instrumentation (velocity, temperature etc. measurements). A common rule of thumb in test section sizing is to have rectangular dimensions with a ratio of about 1.4 – 1. [15]

According to Mehta [16], the minimum length of the test section should be 0.5 – 3 times the hydraulic diameter due to the flow in the contraction outlet requiring 0.5 times the hydraulic diameter of the test chamber; non-uniformities in the flow are consequently reduced to an acceptable level. The recommended maximum length is no greater than 3 times the hydraulic diameter – this would lead to an increase in the boundary layer thickness along this section which can detach the boundary layer at the exit of the test section. [11]

4.1.4 Flow Straighteners

Flow straightener devices are placed to improve flow uniformity and reduce turbulence levels at the contraction inlet. The most used devices are honeycombs and screens. [13]

4.1.4.1 Honeycombs

Flow straighteners, or honeycombs, are generally the first component encountered by the flow in an open circuit wind tunnel. It is mainly used for straightening the air flow from the inlet. The most common are three types – rectangular, circular, and hexagonal – shown in figure 8.

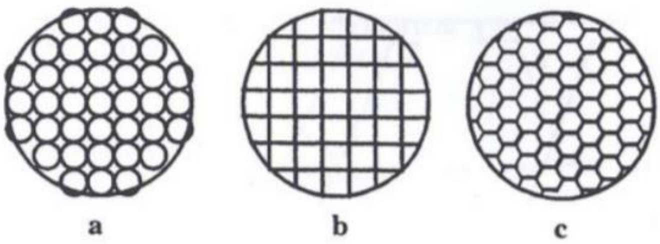


Figure 8. Honeycomb types [7]

Table 3. Typical values of pressure loss coefficients [7]

Honeycomb Type	Pressure Loss Coefficient (K_I)
a	0.3
b	0.22
c	0.2

Table 3 lists the pressure loss coefficients K_I for each of the honeycombs shown in figure 8. This coefficient is the ratio of the pressure loss in the wind tunnel section to the dynamic pressure at the inlet. Evidently, the lowest incurred pressure loss is from hexagonal honeycombs.

Honeycomb sizes vary. As determined by Bradshaw and Mehta [15], the minimum number of hexagon cells are proportional to the inlet diameter of the wind tunnel. The minimum number of recommended cells is roughly 150 cells per inlet diameter. They also found that the length of each cell should be 6-8 times the cell diameter. [7] A more recent experimental finding recommends the optimum length-to-diameter ratio between 8-10. [17]

Impregnated paper honeycombs can be used when for small wind tunnels with low precision requirements and aluminium honeycombs are recommended for greater performance. [15]

Honeycombs alone reduce lateral turbulence more than axial turbulence, and screens alone reduce axial turbulence more than lateral turbulence. As suggested by Kulkarni [17], "Configuration of relatively short honeycomb preceded by a coarse screen and followed by one or more fine screens was found to be an effective arrangement in turbulence reduction." In his experiment, it was found that turbulence reduction by honeycomb alone was insignificant but lateral flow uniformity was effective. A combination of honeycombs and screens are recommended for uniform flow and reduced turbulence.

4.1.4.2 Screens

The addition of screens further help reduce turbulence in the flow by breaking up large scale turbulent eddies into more small-scale eddies that subsequently decay. Scheman and Brooks [18] recommend using a series of turbulence reducing screens. The screens create a blockage effecting the flow quality; hence design parameters are their wire diameter and mesh size. They can be related by the porosity β – ratio of projected open area and the total area of the screen, given by:

$$\beta = \left(1 - \frac{d}{L}\right)^2 \tag{4.1}$$

Where d is the wire diameter, and L is the length of the screen.

Mehta and Bradshaw [15] found screens with porosity in the range 0.58 – 0.8 most effective in reducing turbulence. [11] Recommended sizes are low mesh for the first screens to high mesh for the final screens, meaning, a less dense mesh at the inlet of the series of screens and more mesh at the outlet. [7]

Flow quality requirements in the test section determine the number of screens required. When placing more than one screen, spacing recommended by Mehta and Bradshaw [15] should be enough that the static pressure recovers completely from deviations before reaching the next screen. Distance between screens and between the last screen and contraction inlet should be about 0.2 times the settling chamber diameter.

With the increasing number of screens, the power requirement increases as well. To effectively maintain turbulence reduction, great care must be taken when installing or maintaining honeycombs or screens as they are significantly affected by relatively minor physical damage. [14] A good design will allow simple access to the screen for cleaning and maintenance.

4.1.5 Diffuser

The diffuser's function is to decelerate the velocity leaving the test section and to achieve static pressure recovery, which helps decrease the load on the drive system. The design should be gradually increasing area from its inlet to outlet to avoid flow separation.

As suggested by Mehta and Bradshaw [15], important parameters for diffusers are the area ratio (A), diffuser angle (2θ), wall contour and cross-sectional shape of the diffuser. The two main types are the exit diffuser fitted downstream as shown in figure 5 and wide-angle diffuser fitted between the blower and settling chamber as seen in figure 6. Design recommendations of the diffuser by Mehta and Bradshaw [15] is not exceeding 5° angle for the best flow steadiness, however, best pressure recovery is achieved at around 10°. Wide-angle diffuser is a means of reducing length for a given area ratio instead of influencing pressure recovery. Detailed explanation can be found in their report. An example of the diffuser angle is shown in figure 9.

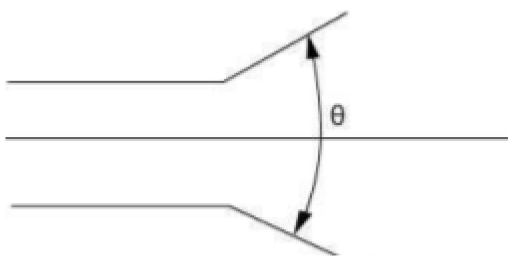


Figure 9. Example of diffuser angle [6]

The importance of a well-designed diffuser can be seen in figure 10, which compares different pressure profiles; a gradual profile is better than a sharp or no profile.

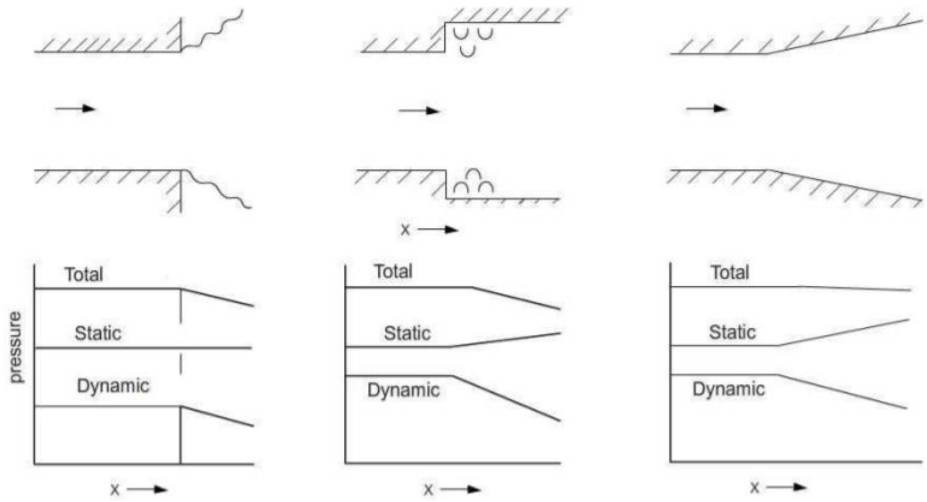


Figure 10. Effect of diffuser shapes on pressure profiles [6]

4.1.6 Drive System

The driving system determines how the working fluid flows through the wind tunnel and vary based on operational modes. Fans and compressors are most used. Axial and centrifugal fans or blowers push or pull air through the wind tunnel. Both can be shaft or belt driven, based on budget and required performance. Compressors can provide large pressure ratios for a relatively low budget and are usually the prime choice for high-speed tunnels that require high stagnation pressure while fans are often used in low-speed wind tunnels. [19]

Fans can operate continuously however the operating costs increase rapidly with power and flow rate requirements. Compressors are limited by the quantity of air available because they cannot supply the necessary mass flow continuously, and thus the operation and testing can function for a limited time like a couple of minutes or less. Influencing factors are initial pressure, storage tank volume, and mass flow rate. [19]

Fan rating is given by the static pressure drop they can overcome and volumetric flow rate. The performance is determined by fan load curves which plot fan efficiency and pressure loss against flow rate, shown in figure 11. Operating point of the fan is where pressure loss curves insect tunnel performance curve. Optimum performance is achieved when the tunnels operating points are close to the maximum efficiency. [19]

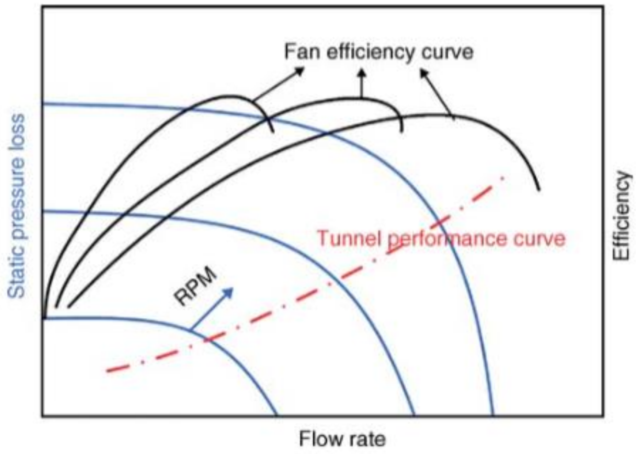


Figure 11. Fan load curve [19]

Pressure drop *p* can be calculated once certain parameters are defined, such as total pressure loss coefficient λ given by local and pressure loss coefficient, determined experimentally or through given tables, length L, diameter *d*, density of air ρ_A and required velocity *u* in the test section.

$$\Delta p = \lambda \times \frac{L}{d} \times \frac{u^2}{2} \times \rho_A \quad (4.2)$$

Alternatively, if the fan has already been chosen and the pressure drop is known from the manufacturer, the equation can be arranged to find maximum velocity in the test section. Required power *P* of the fan can also be calculated as:

$$\dot{V} = u \times S \quad (4.3)$$

$$P = \Delta p \times \frac{V}{\eta} \quad (4.4)$$

where $\dot{V}$ is volumetric flow rate, S is the cross-section surface, and η is the fan's efficiency.

4.2 Manufacturing Methods

Many wind tunnels are constructed based on need for educational and research purposes with varying budgets and testing outcomes, which are ultimately the leading factors that influence construction materials necessary to get the job done.

General construction material choices are wood, plywood, thin metal, heavy metal (pressure tunnels), cast concrete, gunnite, and plastics.

4.2.1 Plywood

Plywood is a highly favorable choice for construction when building in-house for research or instruction due to its low cost and ease of machinability. Holes cut in the wood for measurements or joining components can be patched easily and epoxy fillers used to smoothen the interior surface. Components are usually constructed individually and bolted together. A considerable factor for wooden tunnels is humidity, causing a change in flow quality. [20]

4.2.2 Metal

Material selection is not limited to a single type but multiple can be used together. Almeida et. al [21] constructed a wind tunnel where the main structure was made of steel covered by a skin of naval wood which was treated for humidity and conducted a high level surface finishing, shown in figure 12. Aluminium and plywood can also be combined for different components in the wind tunnel; an example is shown in figure 13. The parts are then welded together depending on the chosen metal; metal inert gas (MIG) or tungsten inert gas (TIG) welding methods are used. Plexiglass is usually used in the test section to observe the experiment and polycarbonate can also be utilized.

Figure 12. Steel frame and naval wood wind tunnel [21]

Figure 13. Aluminium frame and plywood wind tunnel [13]

4.2.3 Additive Manufacturing

Additive manufacturing processes such as fused deposition modeling (FDM) and selective laser sintering (SLS) can also be used for manufacturing a wind tunnel. FDM is a 3D printing process that melts and fuses thermoplastic polymers in filament form and deposits them in a pre-determined path, creating the desired object. SLS uses a carbon dioxide laser and thermoplastic polymer in granular form to build parts layer by layer.

The three main materials used in FDM are PLA (polylactic acid), ABS (Acrylonitrile Butadiene), and PETG (Polyethylene Terephthalate Glycol). A comparison of the materials is shown in table 4. The most common SLS material used is Polyamide 12 (PA 12) for its good mechanical properties: lightweight, strong, and flexible, as well as stable against impact, chemicals, heat, UV light, water, and dirt. [22]

Table 4. Summary comparison of FDM materials [23]

	PLA	**ABS**	**PETG**
Advantages	• High strength • Most versatile • Easy to print • Lowest cost • High visual quality	• Good impact resistance • High temperature resistance • Highly durable	• Chemical and moisture resistance • Good strength • High flexibility • Good temperature resistance • No odor • Suitable for transparent parts
Disadvantages	• Susceptible to deformation and warping under high temperatures • Print layers are likely to be visible • Low humidity resistance • Brittle	• Emits toxic odor • Warping – shrinks significantly as it cools • Ultraviolet light sensitive	• Denser (heavier) than PLA and ABS • Ultraviolet light sensitive

FDM is a quicker and cheaper method of manufacturing a wind tunnel. However, the dimensional accuracy in SLS is greater; ± 0.3% (lower limit of ± 0.3 mm) versus FDM's ± 0.5% (lower limit ± 0.5 mm). SLS also has greater resolution, surface finishing, and mechanical properties over FDM. A recommended choice is FDM if precision, surface finish, and complexity of the model is not crucial.

4.3 Measurement Techniques

A wind tunnels primary purpose is to investigate aerodynamic characteristics of models experimentally. This refers to measuring the behavior of velocity, pressure, temperature, viscosity, and density around an object as functions of position and time. Reliable results not only depend on the quality of the wind tunnel construction but also the techniques used during the measurements. A major challenge in any of these measurements is finding a minimally invasive way of placing the instruments in the flow field. Any instrument inserted within the flow field will disturb the flow quality around the object; more rigid designs are necessary to obtain more accurate, precise, and reliable results.

This section overviews some of the methods used today.

4.3.1 Pressure Measurement

Measuring pressure is a critical parameter in wind tunnel testing. It is defined as force per unit area. Jaramillo [24] explains "In the context of aerodynamics, this force is exerted on an area element due to a time rate of change of momentum of the gas molecules impacting that surface. Pressure is a function of both time and position."

4.3.1.1 Manometer

A manometer is one of the techniques used to measure pressure and is based on the pressure differences within. Many types of manometers exist but the simplest is the u-tube manometer. The principle of it is measuring the height differences of a liquid in the manometer with both ends connected to the reference and testing points. An example is shown in figure 14. the relation between and height difference in the liquid is:

$$\Delta p = p_1 - p_2 = \Delta h sin(\beta)(g)(\rho_f - \rho_a) \quad (4.5)$$

Where Δh is the height difference of the liquid in the columns, β is the angle between the horizontal and the plane made by the two columns, g is the acceleration due to gravity, ρ_f is the density of the liquid in the tubes, and ρ_a is the density of the fluid in the wind tunnel. [24]

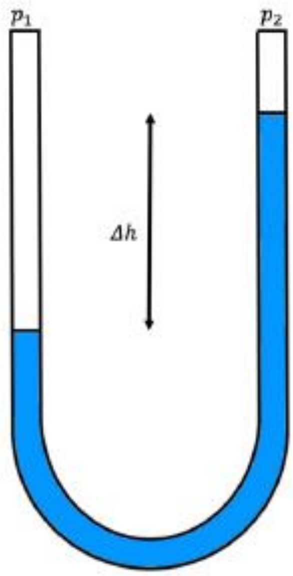


Figure 14. Simple depiction of U-tube manometer [24]

4.3.1.2 Pressure Transducer

A pressure transducer is a device that provides an electrical potential or current in response to pressure or a change in pressure. The most common pressure transducers are the diaphragm ones. A thin sheet of metal deforms when a differential pressure is applied to it. Sensors measuring the diaphragm deformation are strain gauges are attached directly to the diaphragm, circuits to sense the change in capacitance due to the geometric change, and circuits to sense the change in inductance due to the geometric change. They can be constructed cheaply and relatively small but must be calibrated frequently. [24]

Another type of pressure transducer is the piezoelectric transducer. They produce an electric field in response to applied pressures. Barlow et al. [20] explains this in detail. Limitations with these pressure measurements are their disturbances to the flow in the wind tunnel as the instruments need to be inserted through a port and the time response of the measurement is constrained by the presence of a tubing for transferring data to the sensor.

4.3.1.3 Pressure-Sensitive Paint (PSP)

The benefits of pressure-sensitive paint are its high special density of measurements. The principle of it as stated by Gregory et al. [25] "oxygen quenching of luminescence from the paint. Light intensity emitted by the paint is measured by a photodetector and is inversely proportional to the local air pressure." For a thorough review about PSP's, see [25]

4.3.2 Velocity Measurement

By measuring total and static pressure, one can determine the velocity in the flow by measuring the total pressure in the settling chamber and static pressure on the walls of the wind tunnel simultaneously. The relationship between velocity, static and stagnation pressure is given by:

$$u = \sqrt{\frac{2(p_t - p_{st})}{\rho}} \qquad (4.6)$$

where p_t is total pressure, p_{st} is static pressure and ρ_{st} is the density of fluid. [26]

4.3.2.1 Pitot-Static Tube

One of the most common ways of measuring velocity in a wind tunnel is using a pitot-static tube. It is an instrument that yields total pressure and static pressure difference in the flow. The Pitot probe is a cylindrical tube with a front hole, placed parallel to the flow. Measurement error is low at about 0.2% up to Mach = 1. The shape of the tube does not affect the measurement accuracy. [26]

A pitot-static tube comprises of two tubes where one is inside the other tube. One orifice is in the direction of the flow and the other orifice is perpendicular to the flow. Figure 15 is an example of a simple pitot-static tube where the total pressure is measured at orifice A (p_t), as it brings the air to a halt, and static pressure is measured at orifice B (p_{st}) where the air moves past it. The pressures from both orifices are connected to a manometer or pressure transducer. The pressure difference is approximately $\frac{1}{2}\rho u^2$. Velocity can then be calculated from this with the equation above. [24]

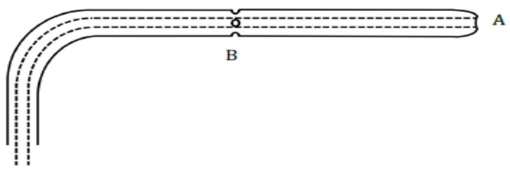


Figure 15. Simple pitot-static tube [24]

4.3.2.2 Thermal Anemometry

This method takes advantage of the thermal and electrical properties of a thin wire or film. Its principle is based on heat exchange between the wire or film and the fluid. The thermal energy transferred from it can be used to measure the velocity. The rate of energy transfer to the fluid is a function of velocity because the wire or film is not in equilibrium with the fluid. An electronic device is used to monitor and adjust the temperature of the wire or film to keep it constant. The fluid's velocity is a function of the power provided by the electronic device. [24]

4.3.2.3 Particle Image Velocimetry (PIV)

Particle image velocity (PIV) uses cameras and lasers to measure the velocimetry. The fundamental idea includes the photographic recording of the motion of microscopic particles that follow the fluid. The particles are illuminated by a two-dimensional laser light sheet and two images of the particles are captured. The velocity of the field can be calculated either from determining the average displacement of the particles over a small interrogation region in the image or individual particle displacement between pulses of the light sheet. Knowing the time interval between the light sheet pulses allows the flow velocity to be computed. The benefits of PIV is it is non-intrusive to the flow field which means the flow is not disturbed by instruments, hence the results are highly accurate. [26]

4.3.2.4 Laser Doppler Anemometry (LDA)

Another non-invasive method of measuring velocity of the fluid is called laser doppler anemometry (LDA). Several factors such as temperature, pressure, humidity etc. do not influence results in LDA testing, however the fluid must be transparent for the laser light. Kamil et al. [27] best explains the principle as “A light ray, which has a definite wavelength, comes out of the laser, meets a track part and changes its wavelength by the Doppler principle. This changed ray is recorded by the receiver and evaluated. If there are a lot of measured changes of the wavelength by many track parts in different points in space and different times, we can make velocity profiles. The condition of this method is using the laser rays, because it is coherent unlike light from the sun or a bulb. This means that the rays have the same phase, amplitude and phase difference. If the wave did not have permanently same and very short difference between frequencies of various rays, we would not record the difference between the original and changed ray.”

A summary comparison of different methods used to measure velocity is shown in table 5.

Table 5. Comparing different velocity measuring methods [26]

Method	Pitot-static Tube	Thermal anemometry	Particle Image Velocimetry (PIV)	Laser Doppler anemometry (LDA)
Intrusiveness	Intrusive	Intrusive	Non-Intrusive	Non-Intrusive
Price	Relatively inexpensive	Relatively inexpensive	Moderately expensive	Very expensive
Frequency response	Good	Excellent	Limited by camera	Good
Ease of calibration and positioning	No calibration required	Difficult to calibrate in water	Easy to calibrate	No calibration required
Multi sensor capability	One sensor location per probe	One sensor location per probe	Numerous sensor location	One sensor location per unit

4.3.3 Temperature Measurement

4.3.3.1 Thermocouples

Thermocouples can be used to measure temperatures of the flow and testing model. It is extremely easy and cheap to make. It is not the most favorable for measuring temperature field around an object as many thermocouples would need to be attached to or placed in the model for better results, but it would be at the cost of reduced flow quality. The material of the model must have the same thermal characteristics as that of the external thermocouple material. The model thickness must be several millimeters in order to measure correct temperatures. [28]

4.3.3.2 Infrared Thermography

This method is a non-invasive temperature measurement technique and is used to visualize the surface temperature around a model. Thermography cameras detect radiation in the infrared range of the electromagnetic spectrum and produce images of that radiation. Infrared radiation is emitted by all objects based on their temperatures, according to the black body radiation law, thermography makes it possible to "see" one's environment with or without visible illumination. The amount of radiation emitted by an object increases with temperature, therefore thermography allows one to see variations in temperature. For this to work thermal characteristics and emissivity need to be known. [28]

4.3.3.3 Thermochromic Liquid Crystals (TLC)

Like infrared thermography, thermochromic liquid crystal (TLC) is another temperature visualization technique and non-invasive as well. TLC fluids reflect different colors as a function of their temperature. When a thin layer of it is applied to a black surface, TLCs selectively reflect the light based on the temperature on the surface. The color and temperature relationship can be utilized to quantitatively map surface a model or see the flow-field temperature distribution with high spatial resolution and accuracy. The only equipment required is a coated TLC plate and a light source. [29]

Section 5: Wind Tunnel Specification

Currently, a small wind tunnel exists in the laboratory. However, a larger test section to investigate bigger models that can withstand larger velocities in the test section is required. Additionally, the wind tunnel will be used for experimental measurements to scan the velocity field around the test objects based on the heat transfer coefficient measurement. This section covers the designs chosen for the new wind tunnel.

5.1 Requirements

A simple small-scale low-speed wind tunnel was designed based on the fan size available in the laboratory. The prerequisites for the design are:

- Inner size of test section limited to 120x120 mm cross-section and length limited to 1000mm.
- Two flow straighteners at the inlet and outlet of the test section.
- A detachable wall for testing with different temperature measurements, specifically with an IR camera and TLCs.
- All components designed for FDM 3D printing technology.
- A minimum of two walls to be attached. One made of plexiglass and the other made of steel.

5.2 Completed Design

Each of the components will be 3D printed in the facility using the FDM method and PLA material. A Prusa i3 Mk3 printer will be used. Figure 16 shows what the wind tunnel will look like once the components are printed and assembled with bolts; the exploded view of the assembly is shown in figure 17.

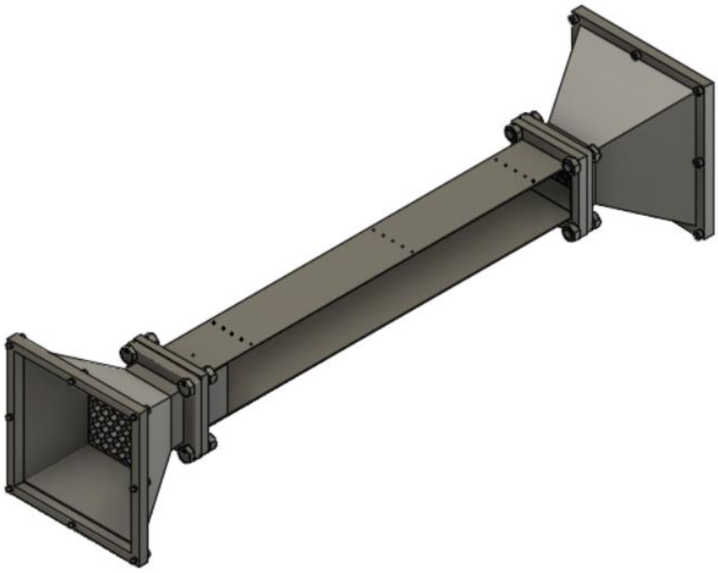
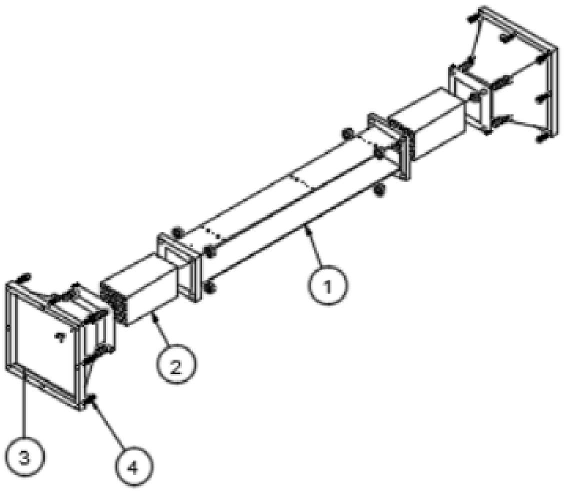


Figure 16. Assembled view of wind tunnel



Parts List			
Item	Qty	Description	Material
1	1	Wind Tunnel Test Section	PLA
2	2	Honeycomb	PLA
3	2	Contraction Chamber	PLA
4	24	Bolts: 16 M10, 8 M20	Steel

Figure 17. Exploded view of wind tunnel assembly

5.3 Contraction Chamber

The chosen dimensions of the contraction chamber are based on the maximum fan outlet dimensions 350x350 mm. The contraction will be connected to the fan with 8 of M10 bolts. The contraction ratio is approximately 2.6. The corners of the contraction were chamfered 2 mm. For simplicity, the same contraction will be used at the inlet and outlet of the test section. Figure 18 shows the 3D model of the contraction and figure 19 shows the dimensions of it.

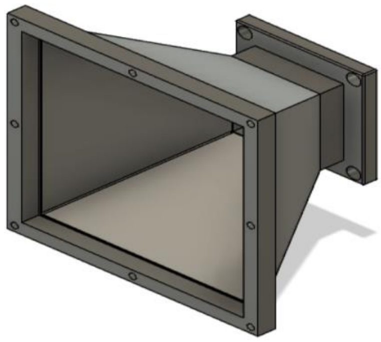
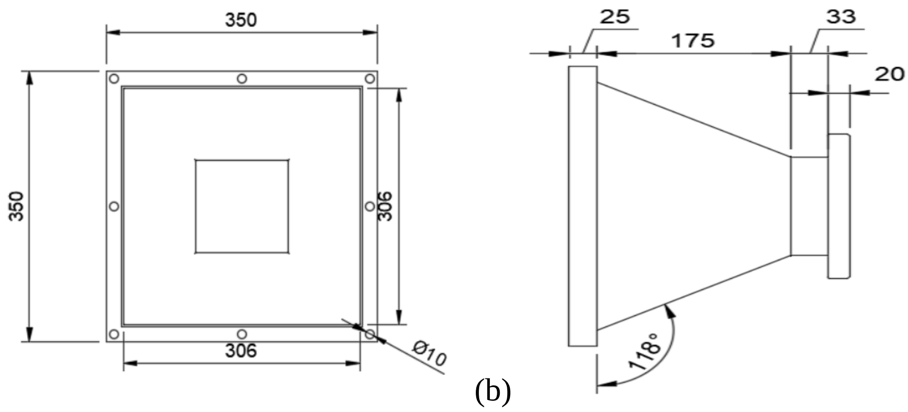


Figure 18. 3D view of contraction



(a) (b)

Figure 19. Dimensions of front view of contraction (a) and side view (b)

5.4 Honeycomb

The selected flow straightener was of the honeycomb design and will be placed at the inlet and outlet of the test section. The model can be seen in figure 20 and its dimensions are shown in figure 21.

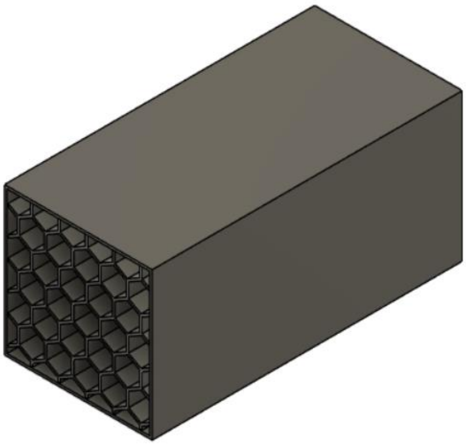
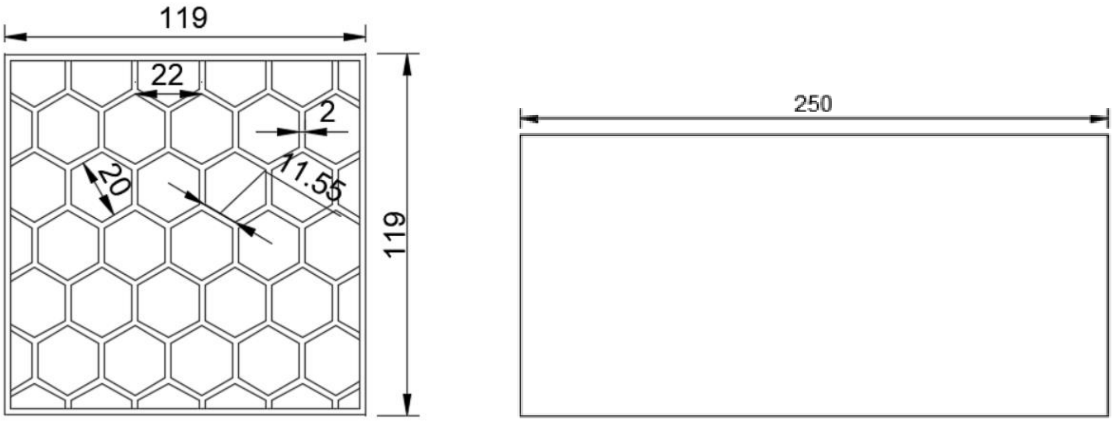


Figure 20. 3D view of honeycomb

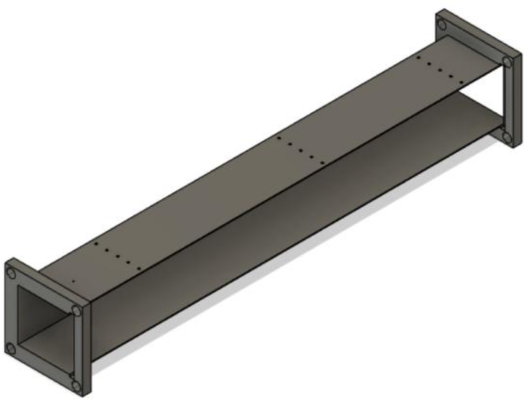


(a) (b)

Figure 21. Front view honeycomb dimensions (a) Side view honeycomb dimensions (b)

5.5 Test Section

The test section was redesigned to make measurement installations like TLC easier. The current wind tunnel in the lab uses clamps to attach the plexiglass to it. In this design, the plexiglass will slide into the test section from one side only to the other end where there is 8mm space to lock against for a tight fit, shown in figure 23. The contraction chamber will be fitted and the plexiglass need not any further devices to hold it in place. A thin sheet of silicon will be inserted with the plexiglass to secure it with the inner section of the wind tunnel. 5 holes at 3 locations are placed 50mm apart on the top and side of the test section for flow velocity measurements with 5mm diameter, a single hole measuring 3mm diameter placed at the entrance of the test section for temperature measurement with a thermometer, and a single 6mm hole placed in the center to hold an object in the wind tunnel. The model is shown in figure 22 (a). In figure 22 (b), dimensions of the slot for plexiglass insertion is shown. The holes placement for velocity measurements is shown in figure 24 and 25; in the middle of figure 24 is the location of the hole for holding an object and the thermometer location will be placed 52mm from the entry (right side of the image) shown in figure 25.

(a) 

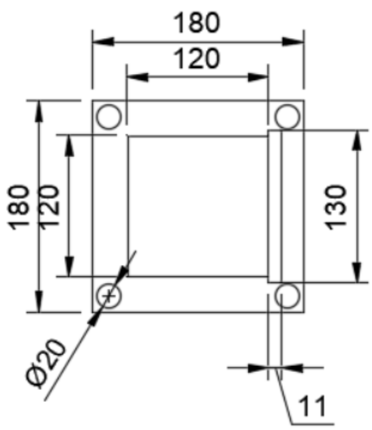
(b) 

Figure 22 (a) 3D view of test section (b) Front view of test section dimensions

Figure 23. Section view of measurement wall locking space. 8 mm distance between blue lines 1 & 2

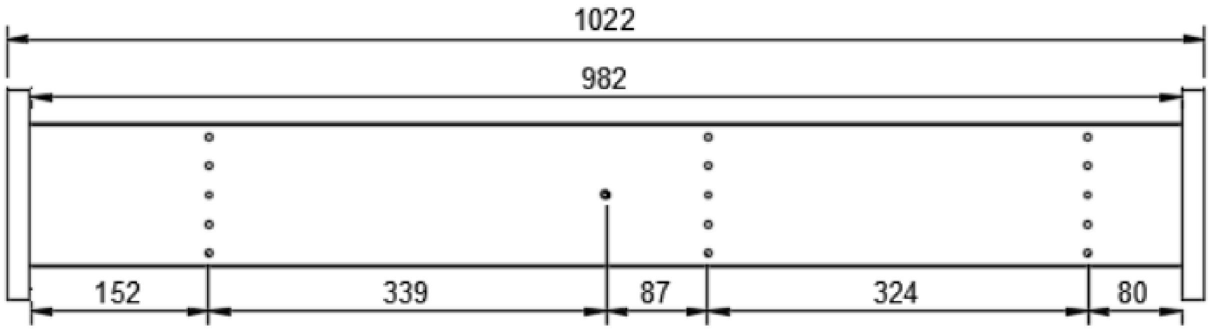


Figure 24. Left side view of test section dimensions

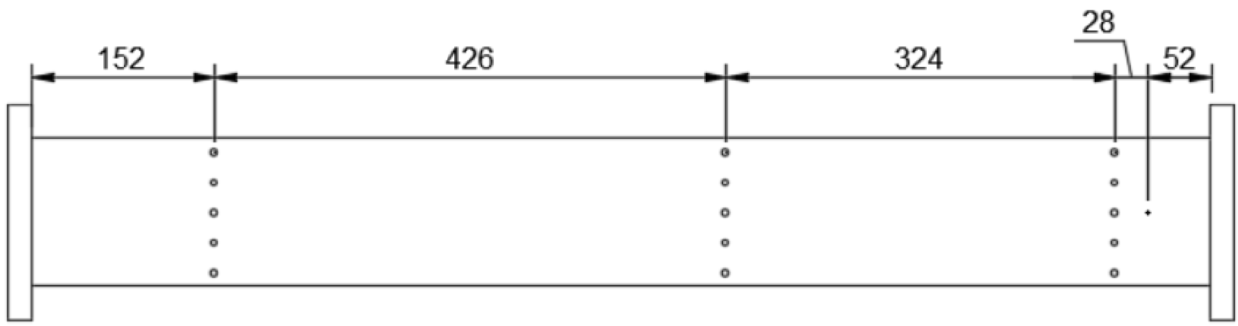


Figure 25. Top view of test section dimensions

Given that the fan specifications were mentioned, theoretical value of the maximum velocity in the testing section was calculated and is equal to approximately 32 m/s. The pressure drop *Δp* given by the fan was 5.4 kPa, internal diameter *d* of the test section 0.12m, density of air at room temperature ρ_A 1.2 kg/m^3, length L of the wind tunnel 1m, and total friction factor λ determined experimentally by researchers in the lab as 1.08. Reorganizing equation (4.2):

$$u = \sqrt{\frac{2(\Delta p)(d)}{(\lambda)(L)(\rho)}} = 31.62\ m/s \qquad (5.1)$$

Section 6: Results

Note: Due to the ongoing coronavirus pandemic, all laboratory work has been suspended and therefore the designed wind tunnel could not be fabricated, and testing could not be performed.

The small wind tunnel is designed based on the lab one. So, modifications are done to accommodate larger test models. The contraction chamber is designed to achieve the recommended contraction ratio, maximum uniformity at the working section mid-plane, without separation, no vortices in the contraction, and minimizing the boundary layer thickness at entrance to the test section. Also, the honeycomb is designed to have a uniform flow. The test section is designed to accommodate larger test models.

Once the wind tunnel is printed and ready for use, instrumentation can be added. Multiple Prandtl probes and PT1000 thermometer (temperature sensor) will be used, positioned in different sections at the inlet, before the model, and after the model. TLC detachable wall and IR thermography with plexiglass will be used for temperature measurements to plot the field around the model. Once all the data has been collected and compiled as a matrix of velocity and temperature fields the results are then analyzed and compared with data from other tests. If the data proves to be unreliable, the design of the wind tunnel can be modified to improve fluid flow in the wind tunnel.

Section 7: Conclusion

The objective of this thesis was to design a custom low-speed small-scale wind tunnel for 3D printing, for the purpose of testing velocities and temperatures around an object using an IR camera, TLCs, Prandtl probes, and thermometer; analyze the results and modify the wind tunnel for minimizing the errors. The research covers the design procedure and measurement techniques of a low speed wind tunnel and a new design, with the intention of simplifying and improving the existing one in the laboratory, was presented.

The design of a custom low-speed small-scale wind tunnel for 3D printing is completed. It measures 120x120 mm internally with a total length of 1 meter without the honeycombs. The components are to be 3D printed with a Prusa i3 Mk3 printer via the FDM method and PLA material. Two honeycombs are to be placed at the inlet and outlet of the wind tunnel. A detachable wall is designed to measure the temperature field around a model using an IR camera and TLC. Also, Prandtl probes are used to measure the velocity in the field as well. The detachable wall, plexiglass or steel or any other material, is designed with a slot so it can slide in and be secured easily within the test section from both sides.

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