DAYANANDA SAGAR UNIVERSITY

SCHOOL OF ENGINEERING

DEPARTMENT OF AEROSPACE ENGINEERING

Calibration and Experimentation of a Vertical Wind Tunnel

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ABSTRACT

At the Department of Aerospace Engineering, Dayananda Sagar University, a low-velocity, open-circuit, vertical wind tunnel was designed, manufactured, and built. The present work describes the first part of the work; that is, the design, the simulation, and the engineering calculations. A second part follows, describing tunnel testing and calibration. The maximum speed is about 8 m/s. The contraction ratio is (2.42). Counter-rotating fans are used in the vertical wind tunnel, and a mesh screen is used to minimize flow disturbances in the tunnel. The design philosophy is discussed and methods for wind tunnel calculation are described. Vertical wind tunnel simulation with ANSYS shows no flow separation in the entire wind tunnel.

Key Words: Vertical Wind Tunnel, Low Speed, Design, Simulation and Construction

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Latin Symbol:

Table 1

Symbol	Terminology
A0	Cross-section area test section
CD	Drag coefficient
DH	Hydraulic diameter
E.R	Energy ratio
E0	Energy at test section
f	Friction factor
Ki	Pressure drop coefficient
L	Length
M	Mach No.
Re	Reynold No.
v0	Velocity at test section
ΔP	Pressure difference

Greek Symbols:

Table 2

δ*	Displacement thickness
η	Efficiency
θ	Divergence angle
μ	Viscosity

Contents

CHAPTER 1

INTRODUCTION

1.1 Introduction

Wind tunnels of many types have long been used to study architectural, mechanical, and structural surveying problems. They have been used to simulate flight conditions for aerospace systems in the laboratory since the 19th century. In principle, these installations include a gas supply system, a nozzle that converts the gas from reservoir conditions to test conditions, the test track, and finally a diffuser and exhaust system.

Vertical Wind Tunnel (VWT) is a wind tunnel that moves air upwards in a vertical column, unlike standard wind tunnels which have test sections that are oriented horizontally, as is the case in level flight. A vertical orientation makes it possible to counteract gravity through air resistance. instead of lifting as experienced in an airplane spin or by a terminal velocity skydiver.We designed a vertical wind tunnel with all the necessary requirements using fusion 360 software and built it. This will help us to conduct experiments that require aerodynamic flow in the vertical direction and to understand the interaction of the flow with the body under test. It also helps to understand roll dynamics much better than testing them in the horizontal wind tunnel. The vertical orientation avoids the large space and floor requirement compared to the traditional horizontal wind tunnel.

Open Circuit Wind Tunnel is a type of wind tunnel that draws air from the atmosphere and blows it through the wind tunnel that runs through the test section where the object under test is manufactured. These types of wind tunnels are inexpensive and much easier to construct. The vertical wind tunnel provides an excellent and realistic prediction of the flight and behavior of the model, helping to identify and validate the various parameters. We've discussed the components used in its construction and the materials used for each of the components. Flow simulation through each component of the wind tunnel was performed and analyzed in Ansys software, and flow simulation of control fans with the new blade design was performed with Ansys software.

The increase in performance by increasing the fan diameter is limited by the space available. Therefore, a higher speed design is carried out, although this causes a deterioration in efficiency and an increase in noise. On the other hand, the lower speed design and performance advantages of counter-rotating fans and pumps are confirmed by experimental results. The introduction of counter-rotating rotors for small fans is helpful in improving performance.With counter-rotating rotors, the axial space is larger than with conventional, small-size axial fans. It is a right choice to adopt the counter rotating rotors for small size fans because the axial space can be secured.

1.2 Theory

Mathematical models describing the flow analysis through all components of a low-speed wind tunnel are made in this article. The flow field is assumed incompressible throughout the tunnel, and the model for each part is then linked to predict power requirements. The chosen tunnel and its components are also investigated. The wind tunnel is to be designed and analyzed for the required dimensions.After the construction the vertical wind tunnel is then needed to be calibarated properly and accurately so that experimentations can be carried out with an accurate results.

1.2.1)Power Consideration

The power required to maintain steady flow through the wind tunnel is equal to the total losses occurring in the flow through the tunnel.These losses are due to kinetic energy being dissipated by vortices and turbulence. The loss in kinetic energy, which appears as a decrease in total pressure must be compensated by pressure rise usually provided by a fan. The power input to the fan is the motor shaft output, and the fan has efficiency (η). The equation balancing the energy input to the stream to the energy losses in the tunnel is:

$$\eta = \sum \text{circuit losses} \qquad \text{Eq 1}$$

As pointed-out previously the tunnel can be divided into sections with energy loss of each section written as a drop in pressure Δp or a pressure drop in coefficient Ki = Δpi / qo, Where qo is the test section dynamic pressure (1/2ρ0v02)

The glide electricity via the take a look at phase is:

$$E_0=1/2\rho_0 v_0^3 A_0 \qquad \text{Eq 2}$$

For subsonic flow with M<0.4, ρ0/ρi=1 (within 1% error):

$$\eta =1/2\rho_0 v_0^3 A_0 \sum_i K \qquad \text{Eq 3}$$

The required power for a given test section size and flow conditions depend on the sum of the pressure drop coefficients (Ki) in various tunnel sections and a reduction in their coefficients improve the tunnel efficiency.

The electricity ratio described as:

$$E.R = (1/2 p_0 v^3_0 A_0)/n = 1/(\sum_i K_i) \qquad \text{Eq 4}$$

1.2.2) The Contraction Section:

It has a square cross section of (265x265) m2 at the inlet with an area ratio of (2.42: 1). The contraction wall shape profile, see Fig.2, consists of two elliptic arcs matching at a point; the position of maximum slope. The dimensions have been scaled so that the width at the entrance is unity.

Once separation is assured not to exist, a simple procedure to predict performance is the regular one-dimensional flow method. The final differential equation which describes this flow affected by area change and friction is given as follows;

$$\boxed{\frac{dM^2}{M^2} = \left[\frac{1 + \frac{(\gamma - 1)M^2}{2}}{1 - M^2} \right] \left\{ -2\frac{dA}{A} + \gamma M^2 \frac{4fdx}{DH} \right\}}$$

Eq 5

The friction factor in this equation will be calculated from the following relation mounted by for the subsonic flow:

$$f = \left[1 - \frac{1.12}{\log_{10}(R_e)}\right]$$

Where:

$$C_D = \frac{0.42}{\log_{10}(R_e)\left[1 - \frac{\gamma - 1}{2} M^2\right]}$$

$$\text{and } Re = \frac{\rho v_{av} D_H}{\mu}$$

$$D_H = \frac{4 y_w z_h}{(y_w + z_h)}$$

$$A = 4Y_w Z_h$$

Eq 6

Also, the Sutherland law of viscosity is used to calculate viscosity:

$$\frac{\mu}{\mu_0} = \left[\frac{T}{T_0}\right]^{3/2} \left[\frac{T_0 + S_1}{T + S_1}\right]$$

Eq 7

Where T0 is reference temperature taken to be equal to (273.6 K) and μ0 denotes the viscosity at reference temperature which is (1.708x10-5 Pa.s), and S1 is constant whose value for air is (110 K).

1.2.3) Contra rotating fans:

The contra rotating fans are used so as to increase the power and the flow rates.The Counter rotating fan (CRF) improves the pressure rise by increasing it and also the isoentropic efficiency are also increased to some extent.This is due to better suction at the bell mouth.When CRF are used there is a less aerodynamic loading on the blades which provides and better stability and pressure gradient.

1.2.4) Blade Element Theory:

Blade detail concept (BET) is a mathematical technique to decide the conduct of propellers. It includes breaking a blade down into numerous small elements then figuring out the forces on every of those small blade elements. These forces are then included alongside the whole blade and over one rotor revolution that allows you to reap the forces and moments produced via the means of the whole propeller or rotor. One of the important problems lies in modeling the brought about speed at the rotor disk. Because of this the blade detail concept is frequently mixed with momentum concept to offer extra relationships vital to explain the brought about speed at the rotor disk, generating blade detail momentum concept.

1.2.5) Settling Chamber:

The one section is used to decrease the turbulence in flow and make it straight by using honeycombs and screens. The velocity at these sections must be low to decrease the pressure losses in the wind tunnel. Screens reduce the axial turbulence more than the lateral turbulence; they have a relatively large pressure drop in the flow direction. Honeycombs have a small pressure drop and this has less effect on the axial velocities but they reduce lateral turbulence. (Pope and Harper 1986) presents a method for calculating these components depending on semi-empirical equations which are used in the coming sections to calculate the pressure drop on the settling section.

1.2.6) Entrance

The entrance may be divided into two components. The first is called (bell mount) and the other is a converged duct as shown in Fig.1. Bell month is an important part in wind tunnel because it improves airflow entrance which decreases the energy losses and increases the amount of air entering the wind tunnel. The design equation of the entrance given by (Bleier 1997) is (r = 0.14 D).Same equations and procedure used in contraction section and diffuser are used for the entrance to find energy losses

CHAPTER 2

LITERATURE SURVEY

2.1 Literature survey table

Table 1 Literature Survey

Sl no.	Author	Title	Year of Publication	Research Findings
1	Alaa A Kareem, Mohamad K Abbas and Farhan A Khammas	Aerodynamic Study of Low-Speed Wind Tunnel Contraction Section: Design and Manufacturing	2021	Contraction profiles generated using polynomials of (6th, 7th, 8th,9th, and 10th) order are suggested to be numerically investigated.The numerical results showed an advantage to the 9th - order profile with an inflection point at 0.65L.
2	Supen Kumar Saht , Anup Ghosh, Chetan S Mistry	Structure and Vibration Analyses of Low Speed Contra-Rotating Fan Stage with High Aspect Ratio	2021	Rotor-2 is aerodynamically highly loaded which causes higher deformation near the leading edge at the tip region and has high Von-Mises stress near the root.
3	Woo-Yul Kim, Santhosh Senguttuvan and Sung-Min Kim	Effect of Rotor Spacing and Duct Diffusion Angle on the Aerodynamic Performances of a Counter-Rotating Ducted Fan in Hover Mode	2020	Comparison of the aerodynamic performance parameters for different rotor spacings revealed that the thrust, thrust coefficient, and FOM slightly increases with an increasing rotor spacing upto 200 mm, regardless of the duct diffusion angle. However, the thrust, thrust coefficient, and FOM start to reduce on further increases in the rotor spacing. Conversely, the power coefficient is at a minimum when the rotor spacing is 120 mm

4	Shawn M. Herrington, Jeff T. Renzelman, and Travis D. Fields	Vertical Wind-Tunnel Testing of Steerable Cruciform Parachute System	2019	The vertical wind-tunnel approach to testing the system of steerable cruciform provides the capability to investigate the viability of an untested parachute system rapidly while still providing realistic performance, thereby creating a repeatable and inexpensive alternative to outdoor flight testing.
5	Xiaojing Liu, Yuanchang Guo.	Study on the key structure parameters of a gravity settling chamber based on a flow field simulation.	2019	Simulations are carried to analyse and show the key structural parameters used for the design of gravity settling chamber.
6	Jonathan D.Jaramillo	Design and construction of a low speed wind tunnel	2017	Code was written in Octave to calculate the geometry of each component of the tunnel given a set of constraints and geometry choices. Similarly loss coefficients and efficiency was calculated using code.
7	Toru Shigemitsu, Kensuke Tanaka, atsuhiko Hirosawa, Keisuke Miyazaki	Internal Flow Condition between Front and Rear Rotor of Contra-Rotating Small-Sized Axial Fan at Low Flow Rate	2017	The flow condition and the potential interference between the front and rear rotors are significantly complex. the strong potential and wake interference between the front and rear rotors lead to the separation and stall regions around the front rotor blades.
8	Md. Arifuzzaman	Design , Construction and evaluation of a	2012	A low cost, high efficiency open circuit wind tunnel was designed

		subsonic wind tunnel		and constructed. The test section turbulence level was measured with hotwire and found to be less than 0.26% for free wire.
9	J. H. Bell R. D. Mehta	Contraction Design for Small Low-Speed Wind Tunnel	1988	The wall shape based on a 5th order polynomial was found to perform optimally in terms of avoiding separation and giving minimum Reθand flow nonuniformity.
10	Colin P. Coleman.	A Survey of Theoretical and Experimental Coaxial Rotor Aerodynamic Research	1997	The coaxial rotor required less power than an equivalent solidity single rotor. Vertical spacing gave the greatest gains in performance up to H/D = 0.05, with no practical gains thereafter.
11	I.K. Knight	The Design and Construction of a Vertical Wind Tunnel for the Study of Untethered Firebrands in Flight	2001	Borger contractor profile equation is used to construct the contractor. A tapered working section is created to take care of boundary layer separation. This also allows it to attain terminal velocity without impacting the walls.
12	J.E. Sargison , G.J. Walker and R. Rossi.	Design and calibration of a wind tunnel with a two dimensional contraction	2004	CFD has been used to optimise the design of a wind tunnel contraction. The use of CFD has increased the flexibility of shapes considered, and allowed the use of a sixth order polynomial to define the profile.Physical calibration of the facility has validated the CFD methods used and demonstrated that the technique can be used for future wind tunnel design

13	Toru Shigemitsu , Junichiro Fukutomi , Yuki Okabe and Kazuhiro Iuchi.	Performance and Flow Condition of Contra-rotating Small -sized Axial Fan at Partial Flow Rate	2010	The fan static pressure curve of the tested contra-rotating small-sized axial fan showed the stable gentle slope. The rear rotor upstream flow condition was not good because of the increase of circumferential velocity and the decrease of the axial velocity at the outlet of the front rotor at partial flow rate
14	Ihsan Y. Hussain Makki Hachem Wail Sami Sarsam	Design, Construction and testing of flow speed wind tunnel with its measurement and inspection devices.	2011	An open circuit wind tunnel has been designed, simulated and constructed to the required requirement.
15	B. K. Jones and J. R. Saylor.	Axis Ratios of Water Drops Levitated in a Vertical Wind Tunnel	2009	There is a predominance of particular oscillation modes at discrete d, as well as the onset of oscillations at d ≈ 1 mm. The measurements and observations of these drops have establish a predictable relationship between d and α. Thus improving the accuracy.
16	Ahmed Abdelhameed. Yassen, Mohamed Elsakka	Design optimization of three dimensional geometry of wind tunnel contraction	2014	The best result that produced the most uniform velocity profile at inlet to the working section, and prevented separation of the flow within the contraction, was obtained when the point of inflection was located as far downstream as possible.
17	Shizhai Zhang	Experimental study on performance of contra-rotating axial flow fan	2015	The blade angle 43/26 has the best aerodynamic performance. The blade angle 40/26 is the second and the blade angle 43/24 is the last. The blade angle with the best aerodynamic performance does not necessarily correspond to the

				one with the best match between the motor and fan efficiency
18	América Torres, Roberto Tapia, Antonio Ramo	Generation and control of Turbulences in a Wind Tunnel	2016	Turbulence is generated in a wind tunnel test section and the analysis for it is done using Ansys. CFD analysis is used and control of the laminar and turbulent layer in the wind tunnel is presented.
19	Hoani Bryson , Hans Philipp,Sültrop , George Buchanan , Christopher Hann , Malcolm Snowdon , Avinash Rao , Adam Slee , Kieran Fanning , David Wright , Jason McVicar , Brett Clark , Graeme Harris and Xiao Qi Chen	Vertical Wind Tunnel for Prediction of Rocket Flight Dynamics	2016	Analysis of flow quality including swirl is done . The models were shown to capture the roll flight dynamics in two rocket launches with mean roll angle errors varying from 0.26 to 1.5 across the flight data
20	William T. Eckert, Kemeth K Mort, and Jeau Jope	Aerodynamic design guidelines and computer program for estimation of subsonic wind tunnel performance	1976	The input parameters and output performance values for the several sample cases are compiled. The estimated energy ratios for the seven sample wind tunnels. The corresponding sketches for all these sample tunnel circuits are

				shown.
21	F. steinle , E.Stanewsky	Wind tunnel flow quality and data accuracy requirements	1982	This paper gives an insight to the need of data accuracy and flow quality and the relation between them. It shows the different types of testing to the flows and data accuracy requirements for flows like dynamic pressure, force and moment measures and the flows related to these and also taking into consideration model design tolerances
22	J. B. Barlow, W. H. Rae, Jr, A. Pope	Low Speed Wind Tunnel Testing	1999	This book addresses Design and usage of Low Speed Wind Tunnels. It provides guidelines for methodology and factors to consider while designing a Low Speed Wind Tunnel. It takes different variations of Low Speed Wind Tunnel into consideration.
23	Roy Valentine Smith	The Design, Construction and Calibration of a Small Wind Tunnel	1950	This article addresses Design and Calibration of Small Wind Tunnels. Flow direction is affected by Contra Vanes making it erratic in the Throat. Flow direction, Average Velocity and Energy ratio are affected by the Turning Vanes. Readjustment of Vanes should be taken into consideration. Tunnel characteristics are affected by the number of blades in the fan.
24	Odenir de Almeida,	Low Subsonic Wind Tunnel – Design and	2018	The design and construction details of a closed-circuit, closed

	Frederico Carnevalli de Miranda, Olivio Ferreira Neto1,Fernanda Guimarães Saad	Construction		test section, low subsonic wind tunnel was presented. Analytical models were considered to describe the pressure losses and CFD was also applied to verify the quality of the flow inside the channels.
25	Mauro S.a, Bruscia S.b, Lanzafame R.a, Famoso F.a, Galvagno A.b and Messina M.a..	Small-Scale Open-Circuit Wind Tunnel: Design Criteria, Construction and Calibration	2017	It deals with a study of very small-scale open loop wind tunnel design and test. The designed wind tunnel is composed by a settling chamber, a contraction section, a test section, a diffuser as well as a fan. The test chamber has a squared cross section of 5 x 5 cm and an on -design flow velocity of about 6m/s
26	Sharul Sham Dol	An Improved Design of Low-Cost Wind Tunnel for Educational Purpose in Fluid Dynamics	2018	The wind tunnel performance increased by introducing the settling chamber and a screen straightener.The Velocity magnitude changed from 5m/s to 6.05m/s by having modification to the contraction and test section zone and this has also shown reduction in turbulence intensity present in the wind tunnel.
27	A. Ghenaiet, I. Beldjilali	Improvement of the performance of an axial fan with with counter rotation	2019	The aerodynamic characterization of SRF and CRF increases with particular staggering ange.The flow range of the CRF also improved due to the suction imposed by RR.The configuration with an inter-distance around d=1.5c, gives the best performance.

2.2 Literature summary

2.2.1)Aerodynamic Study of Low-Speed Wind Tunnel Contraction Section: Design and Manufacturing

Alaa A Kareem, Mohamad K Abbas and Farhan A Khammas

- The paper details the improvisation of the visualization of a subsonic open section type smoke tunnel.
- The improvisation of the contraction section plays a very important role in the flow conditions and the use of higher order equations of the order 5 and above.
- The Mesh generation is also being highlighted with hexahedral type elements used , the various studies carried before the meshing and before the modifications help in comparison.
- The use of composites for the construction of the converging section is mentioned.

2.2.2)Structure and Vibration Analyses of Low Speed Contra-Rotating Fan Stage with High Aspect Ratio

Supen Kumar Sah, Anup Ghosh, Chetan S Mistry

- The analysis of the low speed contra-rotating fan was carried out using the Ansys CFX using one way fluid interaction.
- Results from these Ansys analysis were deformation and von-misses stress at stall mass flow rate for two different speeds. Modal analysis and modal pre-stress analysis have also been carried out to obtain the natural frequencies of the contra-rotating fan stage.
- The findings found out to be were the centrifugal forces on the blades, load to structural analysis, asymmetric distribution of stress and finding the natural frequency of the blades.
- These analyses will be helpful to understand the change of flow behaviour due to a rotor deformation.

2.2.3)Effect of Rotor Spacing and Duct Diffusion Angle on the Aerodynamic Performances of a Counter-Rotating Ducted Fan in Hover Mode

Woo-Yul Kim, Santhosh Senguttuvan and Sung-Min Kim

- It shows the aerodynamic performance of a counter-rotating ducted fan in hover mode for different rotor spacing and duct diffusion angle.
- The method used for predicting the performance is the frozen rotor approach for steady-state incompressible flow conditions.
- It showed that the relative angle between the front and rear rotor has extremely low variation with respect to thrust. The thrust, thrust coefficient, and FOM slightly increases with an increasing rotor spacing up to 200 mm.
- The duct diffusion angle of 0◦ generates about 9% higher thrust and increases the FOM by 6.7%, compared with the 6◦ duct diffusion angle. These findings help in

designing more efficient and best aerodynamic performance for the rotor.

2.2.4)Vertical Wind-Tunnel Testing of Steerable Cruciform Parachute System

Shawn M. Herrington, Jeff T. Renzelman, and Travis D. Field

- This paper presents an experimental approach for testing a steerable cruciform parachute system using a vertical wind tunnel.
- The vertical wind-tunnel approach to testing the system of steerable cruciform provides the capability to investigate the viability of an untested parachute system rapidly while still providing realistic performance, thereby creating a repeatable and inexpensive alternative to outdoor flight testing.
- Experiments were conducted in NASA 20 ft. Vertical Spin Tunnel with the parachute system tethered in place. The steerable cruciform was configured to the Vertical Spin Tunnel and experiments were conducted to obtain the VST dataset.

2.2.5)Study on the key structure parameters of a gravity settling chamber based on a flow field simulation

Xiaojing Liu, Yicheng Zhang, Qiangyun Wu, Mingfeng Zhang, Fan Liu and Yuanchang Guo

- A gravity settling chamber plays an important role in improving the effect of the dust removal when it is selected as a dust collector in a pneumatic cleaning system for cleaning a tunnel.
- The height of the inlet duct, and the diameter and height of the outlet duct as the variables of the key structures, a flow field simulation analysis of the gravity settling chamber with different heights of the dust accumulation is carried out.The performance of the settling chamber is studied by using the CFD simulation .
- The maximum velocity of the airflow near the dust accumulation surface and the mean velocity ratio of the airflow near the dust accumulation surface need to be studied. The settling rate of 100% can be expected without any filtering device.
- The inlet duct and outlet duct should stay away from the highest surface of the dust accumulation in order to avoid the secondary blowing, resulting in high settling performance. A reliable and final settling performance can be guaranteed only considering the maximum height of dust-accumulation

2.2.6)Design and construction of a Low Speed Wind Tunnel
Jonathan D.Jaramillo

- This paper talks about how general-purpose low-speed wind tunnels are being designed and built.This paper gives insight about the pros and cons of computational, analytical and experimental approaches to fluid dynamics.
- This wind tunnel was designed to reach test section speeds of up to 44.7 m/s (100 mph). To aid in the initial design, semi-empirical formulas are used to estimate aerodynamic efficiencies and the required fan-blower power as a function of various design choices.
- Tunnel geometry is selected to optimize test section air flow quality, test section size, and diffuser angle (to avoid boundary layer separation). An octave code in MATLAB was used to calculate the geometry of each component of the tunnel given a set of constraints and geometry choices.

2.2.7)Internal Flow Condition between Front and Rear Rotor of Contra-Rotating Small-Sized Axial Fan at Low Flow Rate
Toru Shigemitsu, Kensuke Tanaka, Katsuhiko Hirosawa, Keisuke Miyazaki

- Internal Flow Condition between Front and Rear Rotor of Contra-Rotating Small Sized Axial Fan at Low Flow Rate-The use of contra rotating fan used in small scale electrical cooling apparatus such as electronic devices such as GPU and hard disks
- By knowing the static pressure and flow analysis between the two fan disks we can create an efficient configuration of the blades based on the distance between the two fans such as 10mm and 30mm.
- The measurement of the vortices intensity helps in the determination of the wake region and thus is useful for efficiency.

2.2.8)Design , Construction and evaluation of a subsonic wind tunnel
Md. Arifuzzaman

- An open circuit wind tunnel was designed and constructed with a magnetic suspension system. The aim was to create a low cost, high efficiency wind tunnel with the reduction in turbulence.
- The factors taken in consideration were power requirement, different types of losses and the boundary layer. It gives a brief description of the components and the construction of the wind tunnel.
- Then the evaluation of the tunnel is done to check for losses and the performance of each component of the wind tunnel. The calibration of the test section was done which showed maximum dynamic pressure that was in agreement to the calculations done.
- The turbulence was found to be less at a particular Reynolds number using hot wire measurements.

2.2.9)Contraction Design for Small Low-Speed Wind Tunnel
J. H. Bell R. D. Mehta

- The paper gives an idea to the designing of the two or three dimensional contraction that is installed on low speed wind tunnels. It also calculates the wall pressure distributions, and hence the wall velocity distributions, using a 3-D potential flow method.
- It also accounts for the boundary layer behaviour from these potential flow methods. The values that were obtained were well within the 10% predicted values. From the designs of contraction, the wall shape based on a 5th order polynomial was found to perform optimally in terms of avoiding separation and giving minimum Re number and flow nonuniformity.

2.2.10)A Survey of Theoretical and Experimental Coaxial Rotor Aerodynamic Research
Colin P. Coleman

- A Survey of Theoretical and Experimental Coaxial Rotor Aerodynamic Research-The aerodynamic performance of the coaxial rotor and the survey conducted in order to find out the use of coaxial rotors for hovering and low level flight and use of different convection and contraction rates which is used to model the blades of the rotors.
- The contraction of the upper rotor helps in improving the hovering performance by reducing the wing tip vortices. The rotor with higher collective settings in which the wake structure is prevalent .The biggest advantage in the use of coaxial rotor is the lack of a tail rotor.

2.2.11)The Design and Construction of a Vertical wind tunnel for the Study of Untethered Firebrands in Flight
I.K. Knight

- This paper speaks about the construction of a vertical wind tunnel used for the successful study of untethered firebrands at terminal velocity.
- It has been constructed using plywood, timber and sheet metal and the supported structure is made of iron and this wind tunnel has achieved uniform airflow.
- They used the borger contractor profile equation to construct the contractor. They created a tapered working section to take care of boundary layer separation and gave practical observation.
- This also allows it to attain terminal velocity without impacting the walls.

2.2.12)Design and calibration of a wind tunnel with a two dimensional contraction
J.E. Sargison , G.J. Walker and R. Rossi

- A low speed open circuit wind tunnel has been designed with the two dimensional contraction which was designed.
- The designing of contraction was done using the CFD since it has increased

flexibility of shapes. The point of inflection in the contraction section and the curvature of contraction were also considered.

- The result was that the most uniform velocity profile at inlet to the working section, and preventing the separation of the flow within the contraction, was obtained at the point of inflection when it is located as far downstream as possible.
- At the end the physical calibration was done of the test section with respect to mass air flow and direction of flow.

2.2.13)Performance and Flow Condition of Contra-rotating Small-sized Axial Fan at Partial Flow Rate

Toru Shigemitsu , Junichiro Fukutomi , Yuki Okabe and Kazuhiro Iuchi

- It gives an insight to the performance curves of the contra-rotating small-sized axial fan with 100mm diameter and the velocity distributions at a partial flow at the inlet and outlet.
- The performance and the internal flow conditions at the partial flow rate of the contra-rotating small-sized axial fan were experimented and analysed .
- The static pressure curve of the fan showed stable gentle slope and the back flow occurred at the inlet tip of each rotor and it gave swirl flow at the outlet and could not be controlled.
- These can deteriorate the rear rotor performance and efficiency.

2.2.14)Design, Construction and testing of low speed wind tunnel with its measurement and inspection device

Prof. Dr. Ihsan Y. Hussain, Asst. Lect. Maki H. Majeed, Lect. Anmar H. Ali, Lect. Wail S. Sarsam

- An open wind tunnel was designed and constructed with the desired value of speed of 70m/s at the test section with a particular dimension of it.
- The design of it has shown 0.25 losses with respect to dynamic pressure. Screens were used to minimize the flow disturbance towards the test section.
- The simulation of it was done using the software Ansys to obtain the flow simulation in the wind tunnel.

2.2.15)Axis Ratios of Water Drops Levitated in a Vertical Wind Tunnel

B. K. Jones and J. R.Saylor

- The literature identifies a predominance of particular oscillation modes at discrete d, as well as the onset of oscillations at d ≈ 1 mm.
- The measurements and observations of these drops have established a predictable relationship between d and α. Thus improving the accuracy.
- It also gives data to the oscillation of drops with varying d .

2.2.16)Design optimization of three dimensional geometry of wind tunnel contraction
Ahmed Abdelhameed. Yassen, Mohamed Elsakka

- The design of a contraction in a wind tunnel plays a very important role as the velocity and pressure through the wind tunnel can be influenced by these parameters.
- The paper helps in achieving the recommended contraction ratio and the maximum uniformity along the working section of the plane and the use of cfd which helps in getting the necessary boundary layer characteristics based on the performance of the wind tunnel .

2.2.17)Experimental study on performance of contra-rotating axial flow fan
Shizhai Zhang

- The study of the contra-rotating fan is important to understand its performance and efficiency. It focuses on the fan performance, the shaft power and the match between the motor and fan efficiency at different blade angles.
- Study was conducted for the fan with different angles of blades and different shaft power and it shows that the best blade angle is 43degree/26 degree and gives best aerodynamic performance. It also finds out the best match between the motor and the fan efficiency.

2.2.18)Generation and control of Turbulences in a Wind Tunnel
América Torres, Roberto Tapia, Antonio Ramo

- The following research paper talks about the generation of turbulence in a wind tunnel test section and the analysis of the following by using ANSYS. In the introduction the author speaks mostly about the basics of the wind tunnel and its applications.
- The use of cfd analysis is also shown in the introduction and the control of the laminar and turbulent layer in the wind tunnel is one of the features shown in this paper.
- The wind tunnel used in the experiment is a open circuit wind tunnel and has a maximum velocity of 20m/s and has a closed test section with a test section 0.80m*0.80m.the paper.

2.2.19)Vertical WindTunnel for Prediction of Rocket Flight Dynamics
Hoani Bryson , Hans Philipp,Sültrop , George Buchanan , Christopher Hann , Malcolm Snowdon,Avinash Rao , Adam Slee , Kieran Fanning , David Wright , Jason McVicar , Brett Clark , Graeme Harris and Xiao Qi Chen

- This paper gives details of a wind tunnel that has been critical for the success of UC Rocketry. It outlines the construction of the wind tunnel and includes an analysis of flow quality including swirl.
- The models were shown to capture the roll flight dynamics in two rocket launches with mean roll angle errors varying from 0.26 to 1.5 across the flight data.

2.2.20)Aerodynamic design guidelines and computer program for estimation of subsonic wind tunnel performance

William T. Eckert, Kemeth K Mort, and Jeau Jope

- This talks about the simplified techniques for the aerodynamic design and loss prediction of the components of subsonic wind tunnels. General guidelines are given for the design of diffusers, contractions, corners, and the inlets and exits of non-return tunnels.
- A system of equations, reflecting the current technology, has been compiled and assembled into a computer program for determining the total pressure losses.
- The formulation presented is applicable to compressible flow through most closed- or open-throat, single-, double-, or non-return wind tunnels. A comparison of estimated performance with that actually achieved by several existing facilities produced generally good agreement.

2.2.21) Wind tunnel flow quality and data accuracy requirements

F. steinle, E. Stanewsky.

- Database for computer program assessment has shown that there is a scarcity of reliable information on flow quality and data accuracy in existing subsonic and transonic wind tunnels.
- The effect of flow quality on data accuracy was not in all instances well understood and that there was only limited information on the data accuracy - and hence on the flow quality - actually required for a specific test.
- In recognition of these problems, of the necessity for future improvements of existing wind tunnels.

2.2.22) Low Speed Wind Tunnel Testing

J. B. Barlow, W. H. Rae, Jr, A. Pope

- This book talks about design, construction, calibration, testing and corrections that need to be made in a wind tunnel.
- In the Wind tunnel design section of the book, it talks about different types of wind tunnels and the parameters to be chosen for different requirements, the aerodynamic coefficient considerations for designing different components are thoroughly explained along with equations supporting it.
- This section also talks about flow quality required and different corrections that can be made for improvement for the flow.

2.2.23) The Design, Construction and Calibration of a Small Wind Tunnel
Roy Valentine Smith

- The development of the wind tunnel's primary objective was to construct a low cost wind tunnel of comparable size for the laboratory testing and not for commercial testing. It gives a brief introduction to each different type of wind tunnel and also the balance system and method of support.
- It also describes the components of the wind tunnel and also the specification used for the designing and for the construction of it
- .It also gives the problems encountered during the construction and what modification was done to overcome it. The instruments that are required for the measurements are also specified with different types of flow present in it.

2.2.24)Low Subsonic Wind Tunnel – Design and Construction
Odenir de Almeida, Frederico Carnevalli de Miranda, Olivio Ferreira Neto1,Fernanda Guimarães Saad

- This paper describes the design and the construction details of a medium size subsonic low-speed wind tunnel, which has been designed to achieve 90 m/s in the working section with expected low intensity turbulence level.
- A detailed design was carried on using theoretical analyses, CFD simulations and semi-empirical methods. A detailed design of the blades was also done.
- The Flow control and stabilization also took place using screens, honeycombs and corner vanes, all of them optimized to induce low turbulence levels in the working section. It has given an design to each component section of the wind tunnel and also the manufacture guidance for low subsonic wind tunnel

2.2.25) Small-Scale Open-Circuit Wind Tunnel: Design Criteria, Construction and calibration Mauro S.a, Bruscia S.b, Lanzafame R.a, Famoso F.a, Galvagno A.b and Messina M.a.

- In order to test the design procedure and measurement technique, a very small-scale open-loop wind tunnel was designed and built. A Particle Image Velocimetry experimental setup was implemented and used to qualify the built wind tunnel.
- The designed wind tunnel is composed of a settling chamber, a contraction section, a test section, a diffuser as well as a fan. The test chamber has a squared cross section of 5 x 5 cm and an on-design flow velocity of about 6 m/s.
- A preliminary test on a NACA 0012 aerofoil was carried out. The result proved to be compatible with the aerodynamics theory as well as the scientific literature. Thus, the wind tunnel results may be used to calibrate and verify Computational Fluid Dynamics mathematical models.
- In conclusion, the experimental data demonstrate that a small-scale wind tunnel may be more easily used to measure the flow field and its characteristics around low Re airfoils than the large wind tunnel.

2.2.26) An Improved Design of Low-Cost Wind Tunnel for Educational Purpose in Fluid Dynamic
Sharul Sham Dol

- A model was designed consisting of a settling chamber, curved-wall aluminium contraction cone with trip wire, plexiglass test section, circular aluminium diffuser fan, and settling chamber and screen.
- The cross-sectional area of a contraction decreases towards upstream of the test section. The designs of the wind tunnel was verified and improved using the ansys fluent CFD simulation.
- The results are validated by the anemometer probe measurements for both instantaneous velocity and time-averaged velocity for turbulence statistical data.
- These velocity vectors shows the speed of air at each different region of the wind tunnel . it also shows the turbulence intensity at various points.
- .The turbulence and velocity profile were recorded and a comapriosn were done showing the second model having better efficiency of air flow compare to the first model. Thus, the implementation of new design in the final tunnel construction is more effective as it yields better flow quality.

2.2.27)Improvement of the performance of an axial fan with with counter rotation
A. Ghenaiet, I. Beldjilali

- Test rig was built to test both SRF and CRF composed of venturi nozzle. The pressure was measured at the inlet , in between the SRF and CRF and also towards the outlet. The performance are measured with two different stagger angle .T
- The Reynold averaged navier stroke equation is solved by using Ansys CFX. The model k- is adopted. The mixing plane is also used for aerodynamics performance.
- The results are validated for different stagger angle for SRF for efficiency and the pressure rise. These shows there is a strong dependency on the stagger angle .
- The computed performance for CRF with different inter-distances, depicting gains in the pressure rise and isentropic efficiency compared to SRF. The CRF operates at a wider range of high efficiency compared to SRF since the RR provides a better suction.
- The blade staggering has a significant effect on aerodynamic loading due to higher suction of blades. There are improvements in the flow range due to better suction imposed by RR and lesser aerodynamic loading in CRF compared to SRF.

CHAPTER 3

AIM, OBJECTIVE, METHODOLOGY

3.1 Aim

To calibrate and conduct experimentation of the vertical wind tunnel

3.2 Objective

Understanding the working of a Vertical Wind Tunnel:

1. Reconfigurations of the fans
2. Designing of blades
3. Correcting out the errors present in the vertical wind tunnel
4. Carrying out experiments

3.3 Methodology

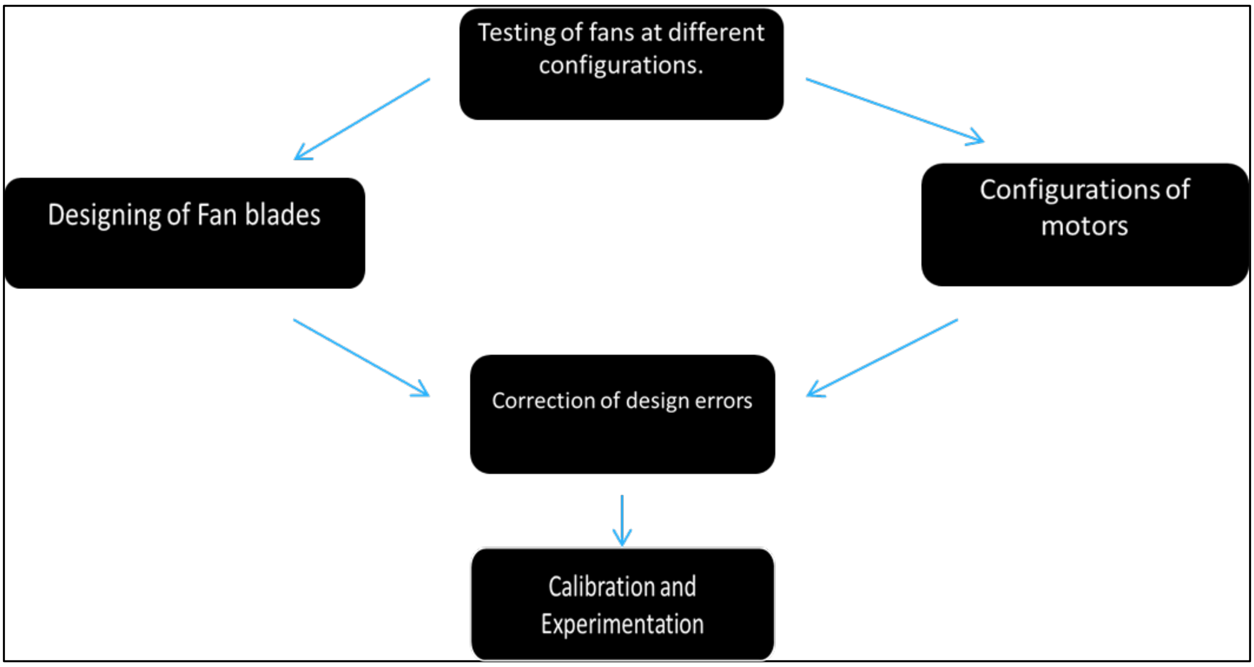

Figure 1.Methodology Flow chart

CHAPTER 4

DESIGN, SIMULATION, EXPERIMENTATION

4.1 Design

4.1.1)Engineering Drawing

The conditions at the test section are;

• Square inlet area (170*170 mm^2)

• The dynamic pressure (3000 Pa) and velocity (10 m/s)

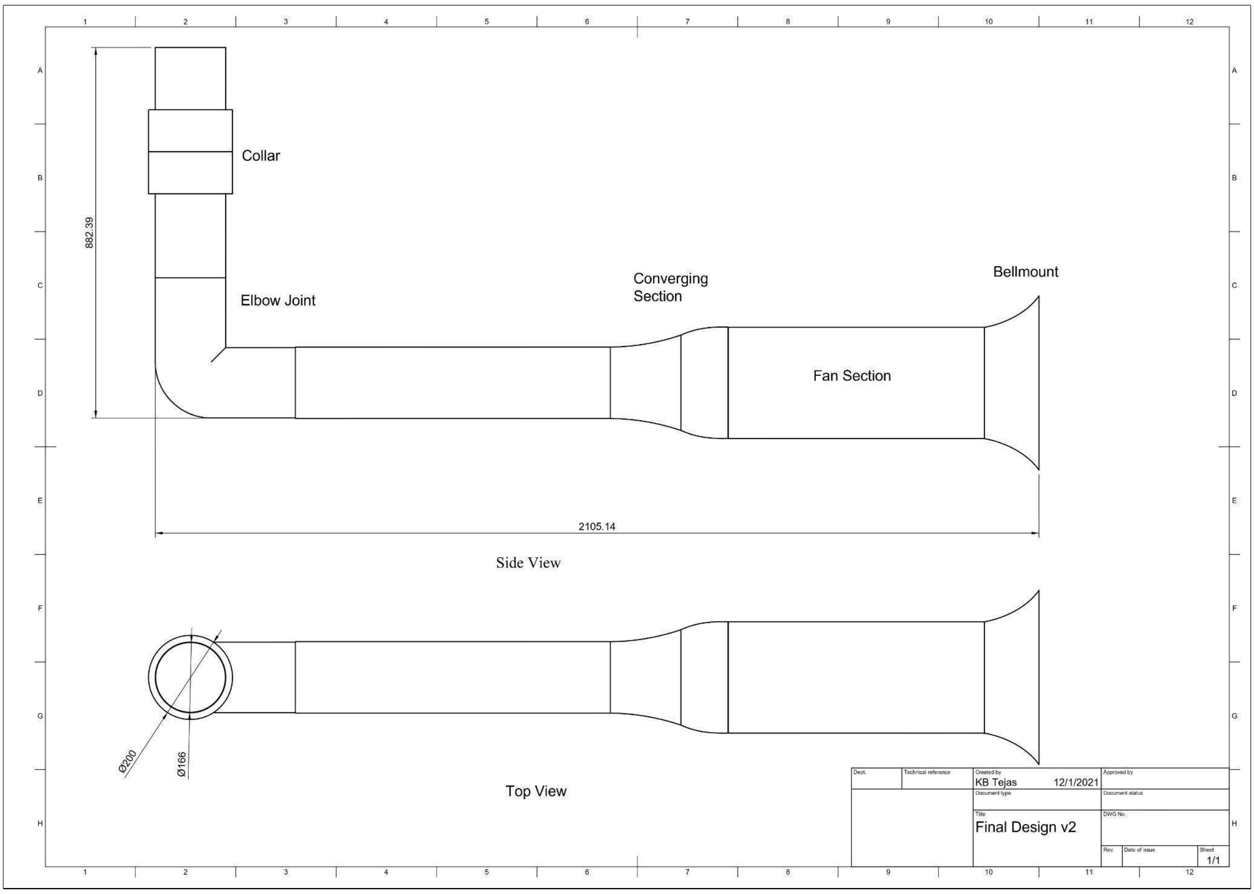

Figure 2 - Engineering Drawing of the Vertical Wind Tunnel

4.1.2)Inlet

For the contraction ratio (8.16: 1) where

Inlet area is (265x265 mm^2) and exit area equal to (π/4x170mm^2)

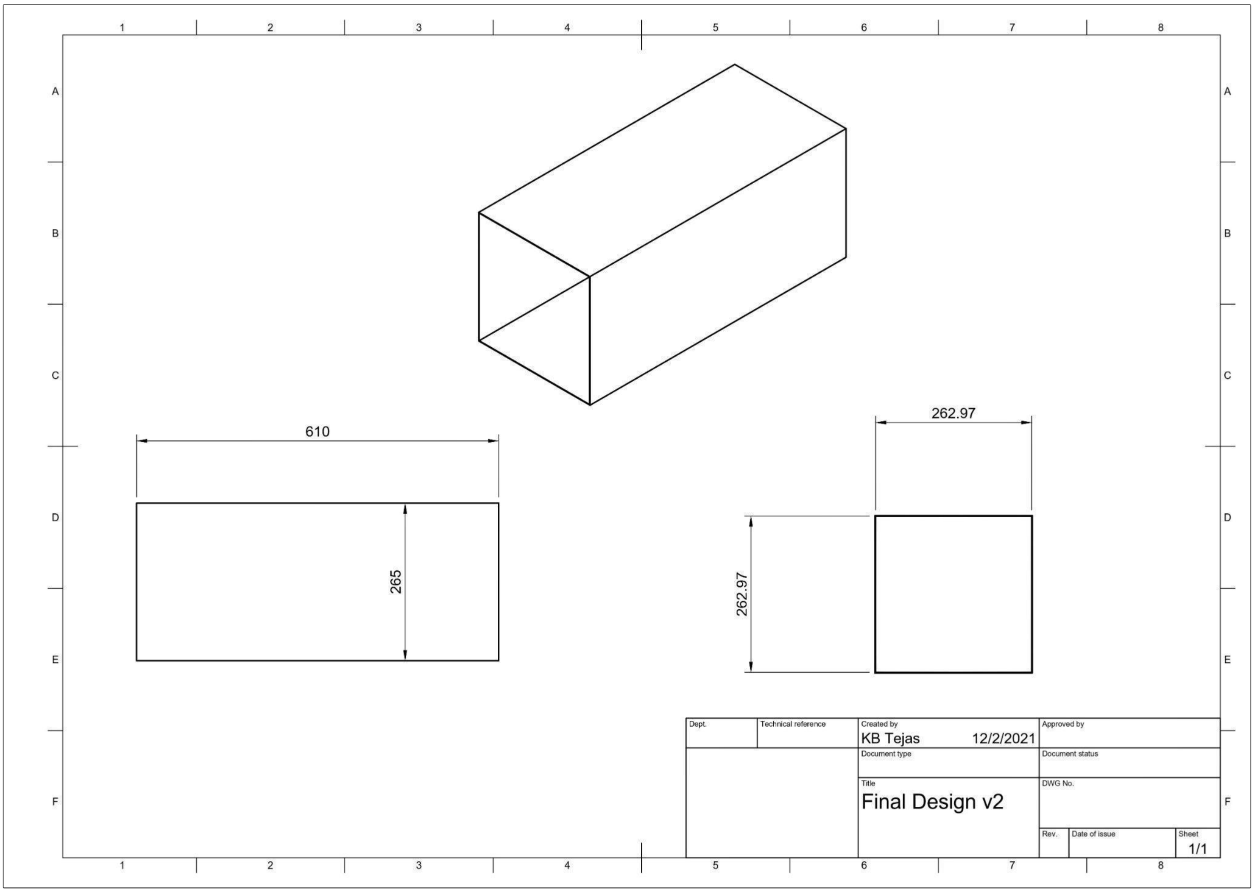

Figure 3- Dimensions of the inlet section

4.1.3)Bell Mount

The bell Mount conditions are:

1) inlet dimensions -

2 outlet dimensions of (265 *265) and 15 cm radius arc of circumference.

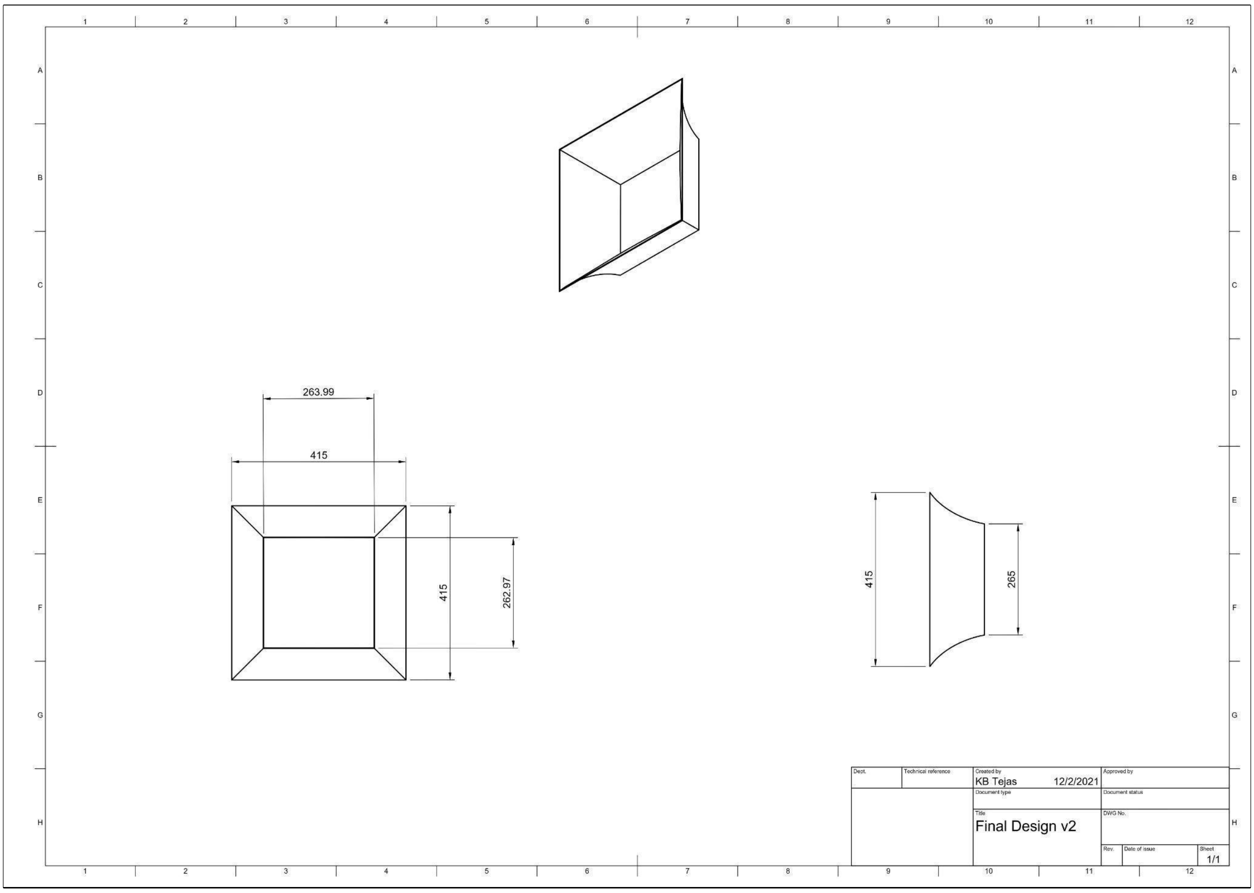

Figure 4 - Dimensions of Bell Mount

4.1.4)Converging Section

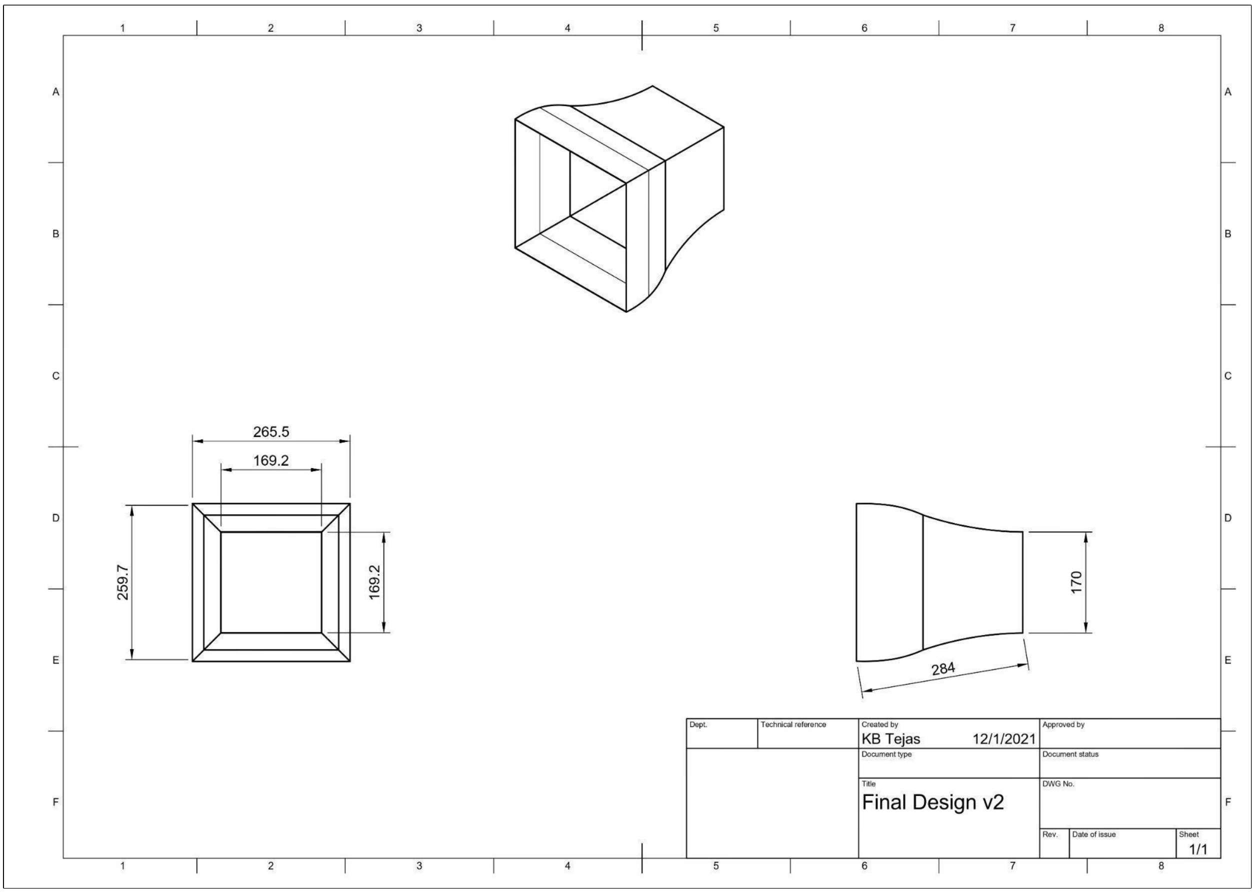

Figure 5.Dimensions of Converging section

The contraction profile for the converging reason was plotted using y/h and x/l ratio of our given wind tunnel. With a= 2.65 in y direction, b= 6.3 in y direction and c= 112 in x direction.

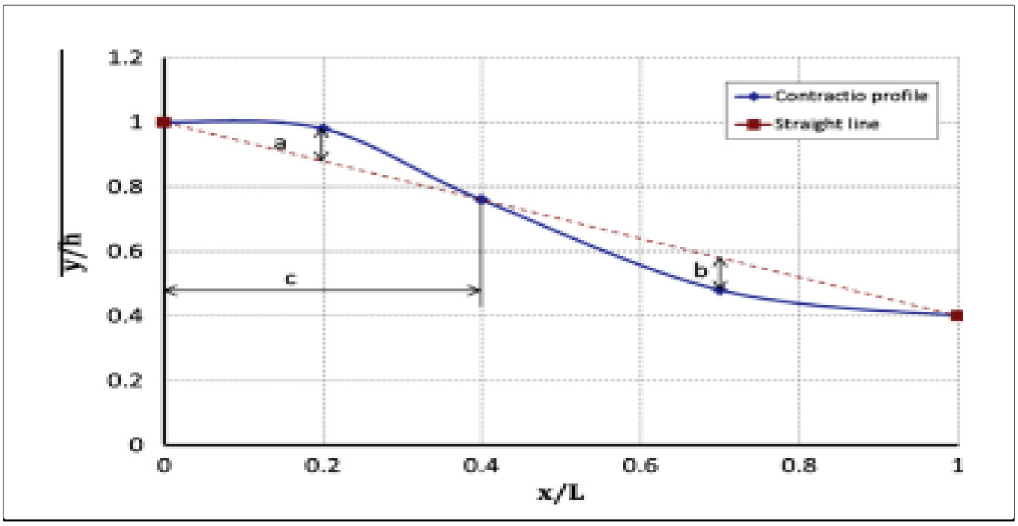

Figure 6. Contraction Profile Graph

4.1.5) Pipes

Six inch pipes were taken for the construction, there are two pipes of length 0.8 and 0.75 m used vertically/ horizontally

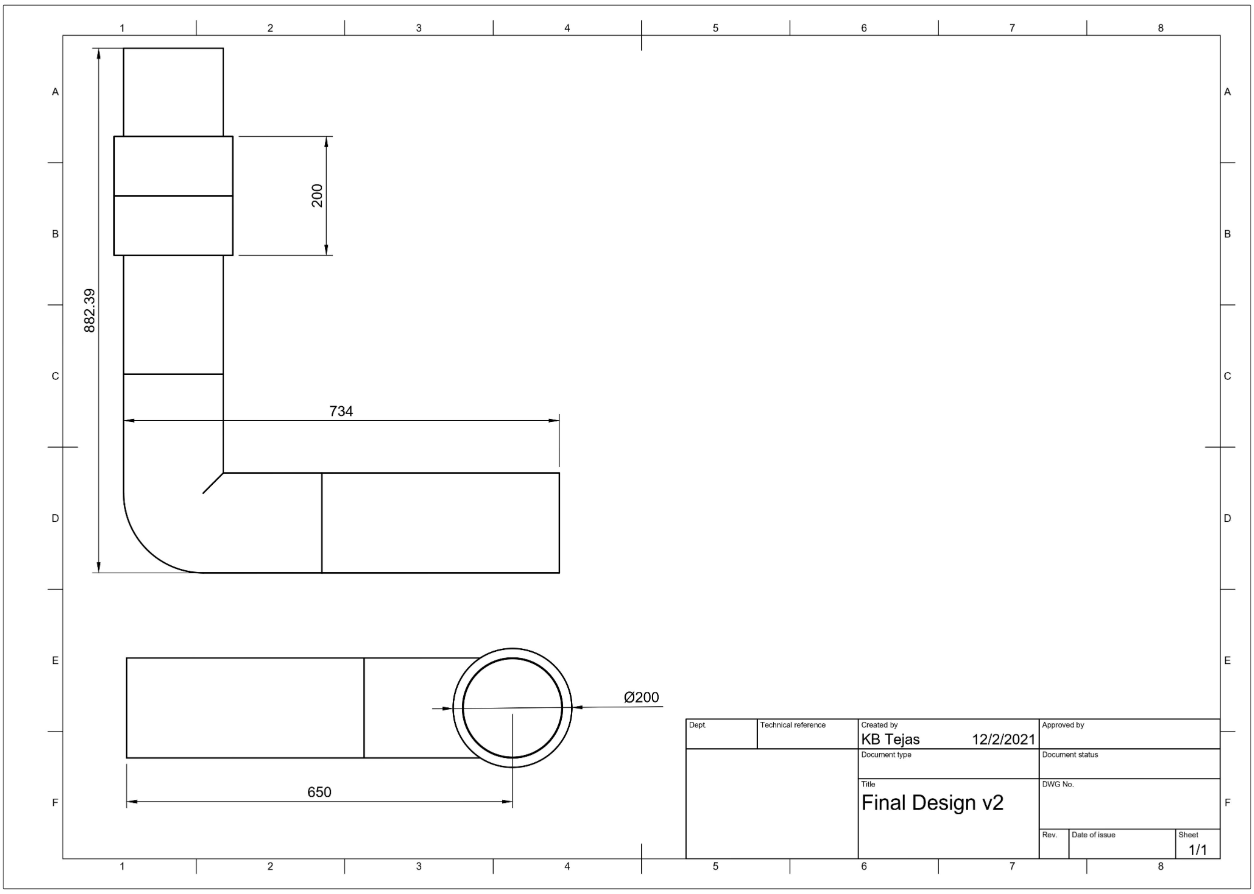

Figure 7.Dimensions of the pipes

4.2 Simulation

The simulation was conducted through ANSYS 19.2. Fluid Flow through Fluent solver was utilized to solve for the simulation. We used the Laminar (Viscous) model as the boundary condition.

Mesh:

The mesh utilized for the simulation of vertical wind tunnel is displayed as follow.This an unstructured mesh generated deafault by the software ANSYS 19.2

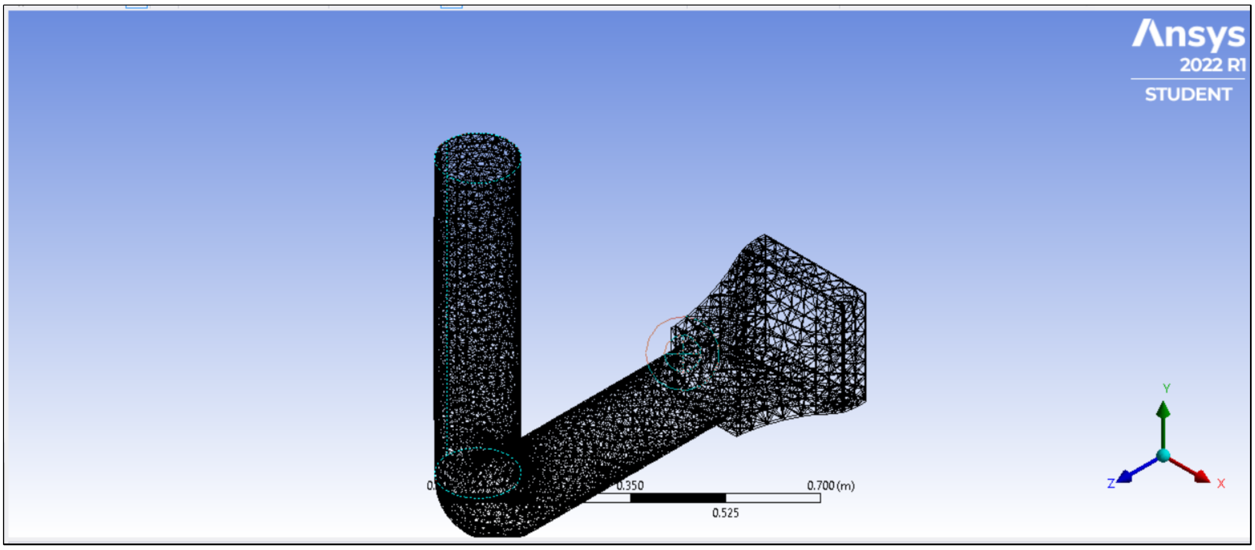

Figure 8. Unstructured Mesh of vertical wind tunnel

Case1 Boundary condition:

Laminar flow model.

Inlet type: Mass flow rate (0.32 kg/s)

Outlet type: Velocity (4 m/s)

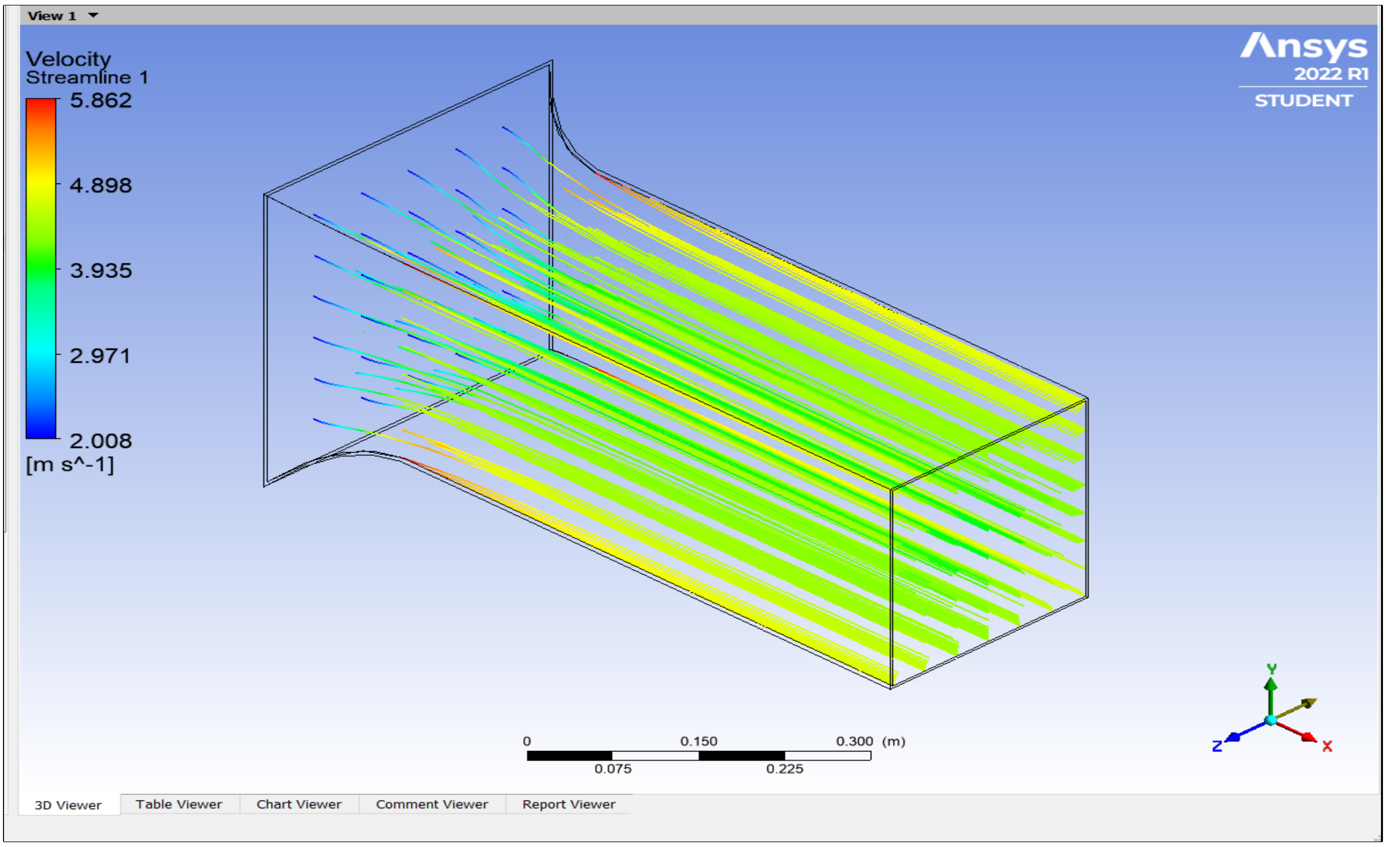

Figure 9.Velocity streamline of Fan section (isometeric view)

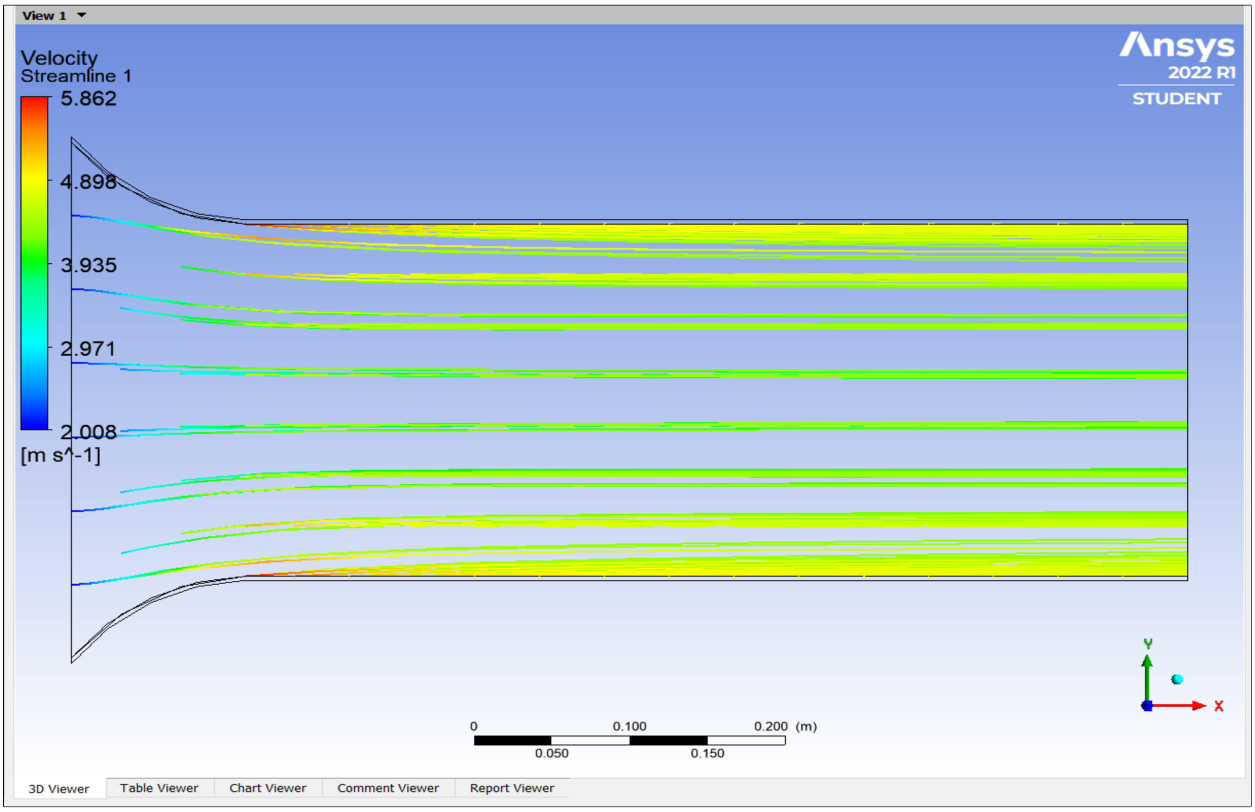

Figure 10.Velocity streamline of Fan section(side view)

Case2 Boundary condition:

Laminar flow model.

Inlet type: Velocity Intelt(4m/s)

Outlet type: Pressure outlet (0 bar)

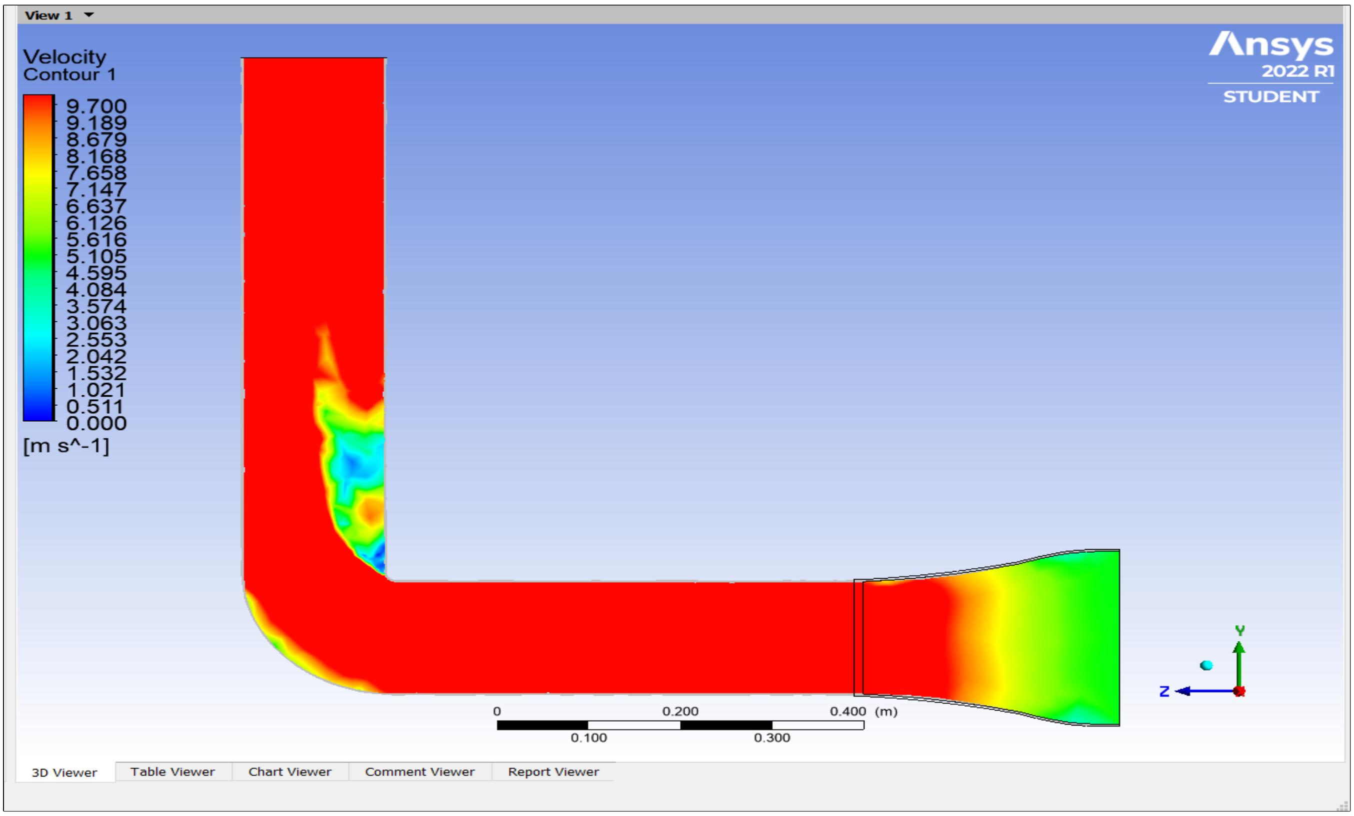

Figure 11. Pressure contour of contraction and test section

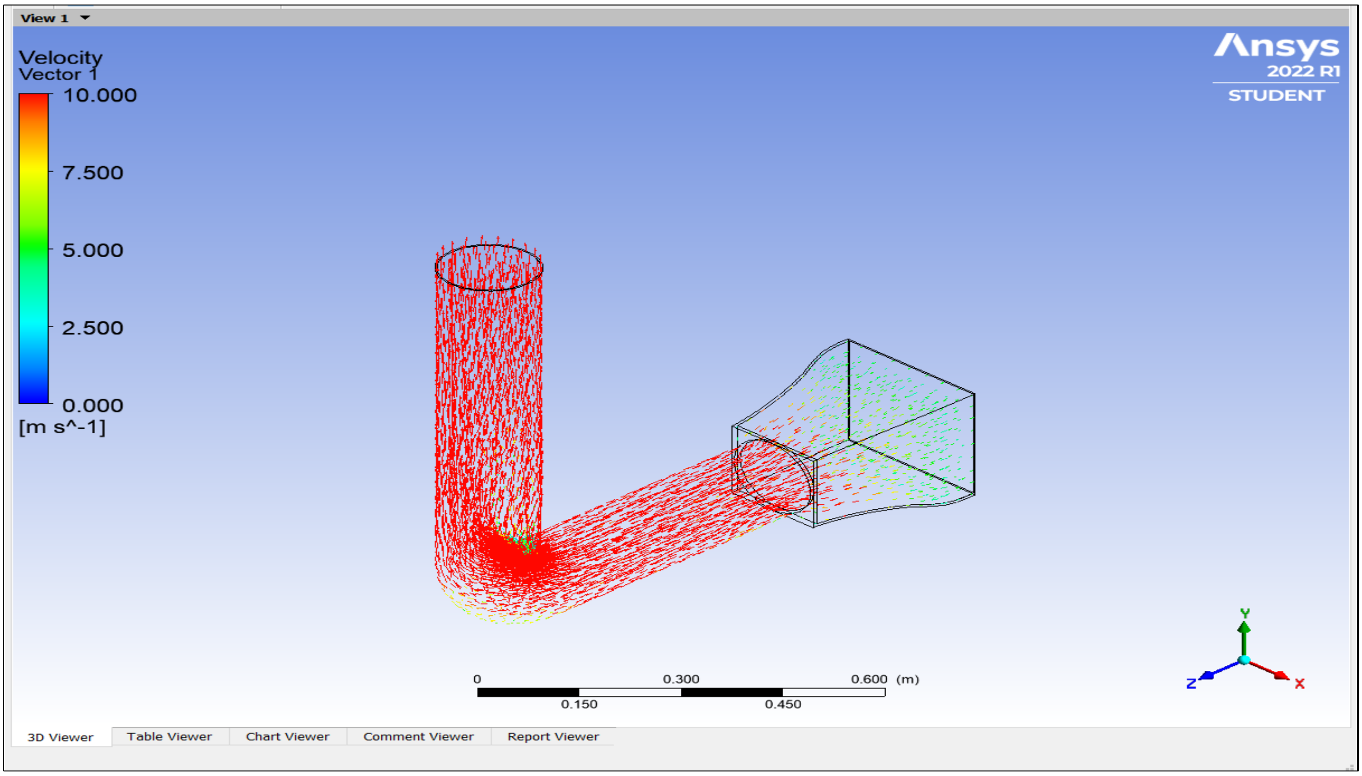

Figure 12. Velocity vectors of contraction and test section (isometric view)

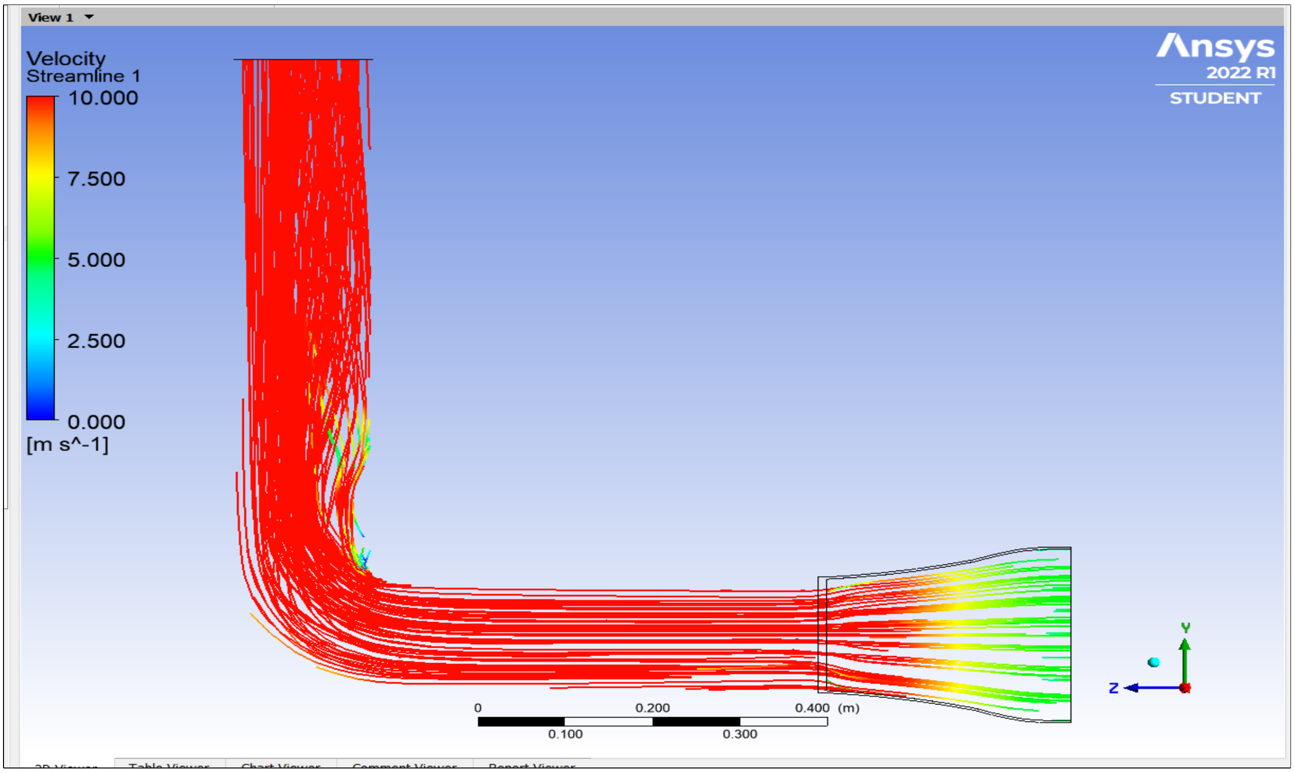

Figure 13.Velocity vectors of contraction and test section (side view)

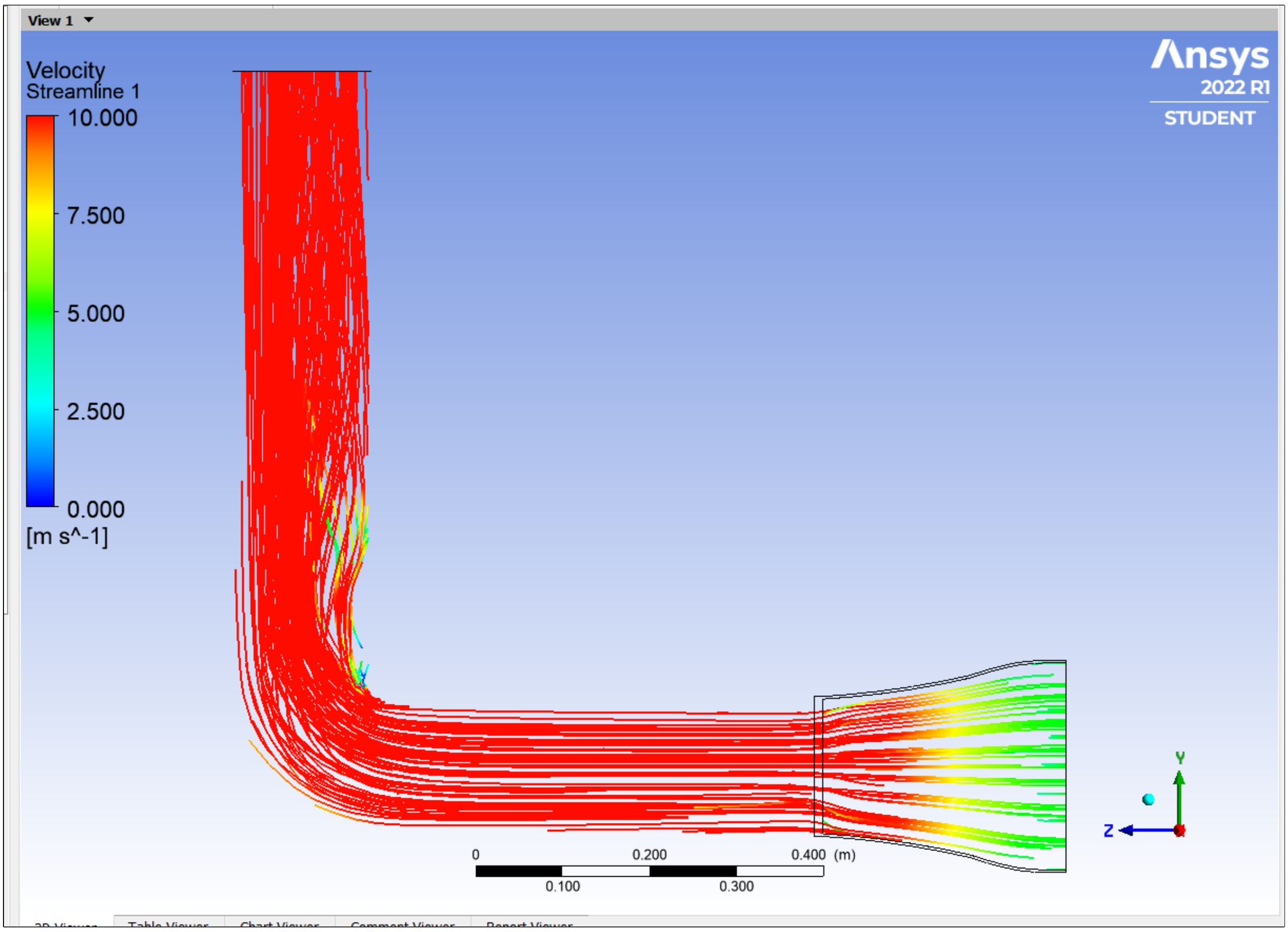

Figure 14.Velocity Streamline of contraction and test section (side view)

4.3 Construction of prototype

An open circuit Vertical wind tunnel was designed and constructed incorporating features discussed in the references. The following group figures show the construction of parts of the wind tunnel and its final shape.

4.3.1) Test Section(Exit Section)

An exit section was designed to give a velocity of 10m/s and size equal to (170x170) mm^2 outlet area.. PVC pipe was used entirely in its construction of the exit section.. A circular cross section with upper and lower surface diverges along the section to balance the boundary layer growth. This may provide a constant pressure along the test section and prevent error in measurements.

Figure 15.PVC Pipes of the test section

Figure 16.Mesh inside the pipes

4.3.2)Contraction

The contraction shape was made of 3mm sheet metal and it's strong enough to give safety work with velocity 10m/s.It has square inlet and circular outlet . The contraction ratio is (2.42:1). The wall shape was designed using the previous equations.

Figure 17.Contraction section side view

Figure 18.Elbow Joint

4.3.3)Inlet section

Inlet section and bell mouth are made of 3mm sheet metal. The bell mouth increases the efficiency of air inlet and prevents what is called vena contracta. All the wall plates of the inlet section made a pyramid shape with inlet and outlet area. The inlet section is welded to the bell mouth and connected to the contraction region through nuts and bolts.

Figure 19.Bell Mount front view

4.3.4)Power

An axial fan driven by a (75hp) (2800rpm) amplitude lament motor provides the power to the tunnel. The fan is mounted at the beginning of the tunnel and blows the flow from the tunnel inside and discharges it to outside. The second fan is mounted in the rear end of the wind tunnel which provides the required airflow through the wind tunnel. The power plant section is in the inlet section. The fan is manufactured by steel of 3mm thickness and 3 blades for each fan.

CHAPTER 5

RESULT AND DISCUSSION

5.1 Results

Approach to designing a Vertical Wind Tunnel of our requirements was followed and an open circuit vertical wind tunnel has been designed, simulated and constructed to obtain an exit velocity of around 10m/s with an exit area of 113.09734m^2 . The designing of the vertical wind tunnel was done using the software autodesk fusion 360. The design procedure shows the wind tunnel losses are approximately equal to 0.25 with respect to the dynamic pressure at the test section.

Two exhaust fans driven by 230 Volt motors with a regulator which are contra-rotating are used to control the velocity of flow in the test section from 0-10 m/s.There is one layer of perforated mesh present to avoid the vortices and eddies formed from the fan. This not only helps in reducing the vortices and eddies, but also helps in straightening the incoming flow towards the test section and hence a uniform velocity is maintained at the test section .The contraction ratio of the convergent part is 2.42. At the corners there is a possibility of losses of air due to the separation of air in the elbow joint but these losses seem insignificant. The test section of the vertical wind tunnel is kept open so a better aerodynamic interaction is encountered and better visualization is seen.

The wind tunnel was simulated and solved using ANSYS commercial program. The results show that the test section has a constant velocity along it. Multiple iterations of simulation was run to see the various flow patterns and different areas of loss which was all noted and changed in the final version of the model.

5.2 Prototype of the vertical wind tunnel

Figure 20.Prototype View 1

Figure 21.Prototype View 2

Figure 22.Prototype View 3

Figure 23.Prototype View 4

Figure 24.Prototype View 5

5.2 Discussions

The vertical wind tunnel has been designed and constructed.

1)We calibrated the wind tunnel and improved its aerodynamic performance
2) The results of the vertical wind tunnel simulation were compared with the experimental results.

The future outlook of the project is:

1)To experiment and study the aerodynamic characteristics of the mangrove seeds and then to design the rotor.

2) To conduct and test models of different types and record the observations made from it.

3)To check the stability and the performance of these models with respect to airflow and determine their characteristics.

4) Interpret those observations and data and to see if it matches the calculation done.

5) To tabulate the calibration parameters, check if the vertical wind tunnel can be constructed of bigger scale and higher performance.

CHAPTER 6

CONCLUSION

We decided to build a prototype vertical wind tunnel. The design studies were conducted after researching articles and research papers that helped us understand the components of the vertical wind tunnel and the design approach. Using the contours provided by the references, we then designed the vertical wind tunnel of our project using Autodesk Fusion 360 software for prototyping and then built the vertical wind tunnel.

Each of the wind tunnel components was designed using this software with details of our requirements and needs. The technical drawing of each component of the vertical wind tunnel is made.The materials used in construction were readily available and they were built using PVC pipes, sheet metal and exhaust fans. Modification and modeling of the materials were done and then the components were created.

We use perforated mesh as a stilling chamber in our vertical wind tunnel and use it as a screen to ensure an even flow rate. We then reconfigured the fans to achieve the required airspeed, which was not achieved in the previous test. The leaf design was also created with Autodesk Fusion 360. These newly designed contra-rotating engine blades were simulated in Ansys software using Fluent. The previously existing design errors have been corrected and the vertical wind tunnel is also simulated for the vertical wind tunnel.

The results obtained were in agreement with the required expectation. The end result was a smooth airflow, which was simulated using numerical flow simulation with ANSYS software. Therefore, prototyping of a vertical wind tunnel will be completed and built as needed. Vertical wind tunnel calibration and experiments are successfully calibrated and completed.

APPENDIX

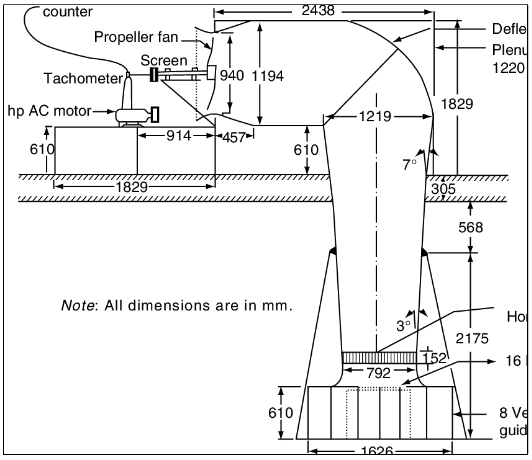

Figure 25.Diagram of Theoretical Vertical Wind tunnel

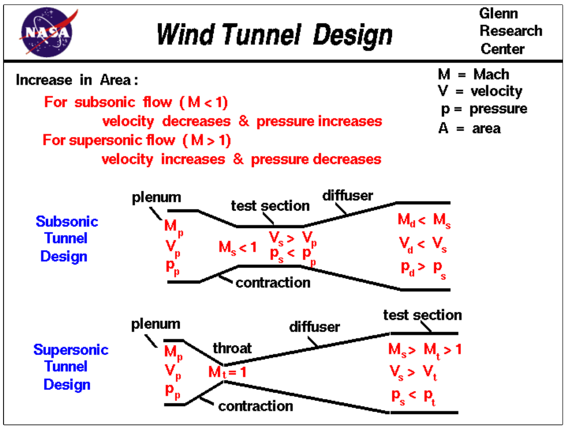

Figure 26.Design of NASA’s Converging Section

Vertical wind tunnel used for SkyDiving

Figure 27.Vertical wind tunnel used for SkyDiving

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