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Development of a Low-Speed Open Circuit Wind Tunnel

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Abstract: *The wind-tunnel test rig is very important for the study or design of airborne structures such as vehicles, quadcopter e.t.c. And this is because it is very difficult to accurately and efficiently predict turbulent flow fields computationally around the moving structure. This is the reason why the development of a laboratory size, the general-purpose low-speed wind tunnel was carried out. The fabrication was carried out at the central workshop of Federal University of Technology, Minna-Niger State. This wind tunnel structure was designed with the test section having 0.2m x 0.2m. The design of the setting section, contraction section, test section and diffusion section were numerically conducted. The power of the blower fan was selected based on the required test section parameters. The tunnel geometry is selected to give the best test section airflow and quality, test section size, and diffuser angle selected to avoid boundary layer separation. The dynamic pressure and mass flow rate of the flow were found to be 55.3 Pa and 0.4655 Kg/s respectively at the maximum test section velocity of 9.5m/s. The test section is 0.04m^2 and has an efficiencv of 63%.*

Key words: *Open Circuit, Wind Tunnel; Low Speed, Test Section, Contraction Section*

INTRODUCTION

A wind tunnel is a tool used in aerodynamic research to study the effect of air moving past solid objects. It is used to simulate echt life wind conditions for aerodynamic analyses of mounted models. (Jameson *et al*, 2011) The knowledge of wind engineering is used to carry out design and analysis of high rise buildings, cable suspension bridges and cable-stayed bridges, electricity transmission towers and telecommunication towers etc. The effects of wind on engineering structures are possible damage, inconveniences or benefits which may result from the wind. (Hussaini *et al*, 2011). Today, wind tunnels are used by the National Aeronautics and Space Administration (NASA), Boeing, Northrop Grumman, and every other organisation that makes aircraft and spacecraft. NASA AMES, in Moffet Field, California, has the most wind tunnels at any one location in the world, and also has the largest wind tunnel on Earth. Wind tunnels are also used for educational research purposes. For instance, schools use them to demonstrate how planes fly or the effect of the wind speed on moving structures, (Dodson, 2005). Also, the automobile industry to improve the fuel efficiency and speed of vehicles, (Fthenakis, 2009). The research aims are to develop a mini, experimental wind tunnel for use in the laboratory, because of the expensive cost of installing commercially available wind tunnels. The development of wind test tunnel requires design analysis, flow analysis, production and performance evaluation of the wind tunnel, and upon the development, it can be used in schools laboratory to carry out experiments on the wind structures.

MATERIAL AND METHODS

2.1 Materials

The material used for the production of the wind tunnel is listed in Table 1.

Table-1 Materials used for the production of the wind tunnel

S/No	Materials	Specifications	Purpose
1.	Mild Steel	1 Sheet, Gauge 22	Wind Tunnel Casing
2.	Plastic sheet	5mm, 4ft x 1ft	For test section
3.	Form	2in thick	For cleaning the inlet air
4.	Plywood	1in thick	To support the test object
5.	Plastics pipes	Diameter 1in	Air inlet
6.	Extraction fan	176 W, AC	For extracting air from the test section.
7.	Mild steel Angle Iron	1in equal angle	For Framing the test section and Wind tunnel support
8.	Test Objects	Plastic Top Car	As test Objects

Some of the important Contents are explained as follows:

A. Test Section

The test section is where objects are placed for testing and it is also the portion of the wind tunnel where the airflow is desired to be most uniform. A square test section with a 0.2m side was used with an air velocity of 15m/s and the length of the testing section was set to 2.3 times its hydraulic diameter (Goldberg 2008).

The Reynolds number is a dimensionless constant used to distinguish laminar from turbulent flow in a pipe or channel or sometimes around an immersed object, with lower values corresponding to laminar flow and higher ones to turbulent flow.

Reynolds number is given by (Singh *et al, 2013*) as:

$$R_e = \rho v d/\mu \tag{1}$$

Where,

R_e = *Reynolds number*
ρ = *density of air*
v = *velocity of air in the testing section*
d = *diameter of the test section*
μ = *kinematic viscosity of air*

The equation to obtain the dynamic pressure in the test section is given by (Coggan, 2011) as:

$$q_0 = {}^1/_2\, \rho_0\, v^2 \tag{2}$$

Where,

$q_{0\,=}$ *Dynamic pressure in the test section*
$\rho_{0\,=}$ *The density of air in the test section*
v= *Velocity of air in the test section*

B. *Diffuser Section*

The diffuser section reduces the power losses due to high flow velocity. According to Hussain *et al* (2011), the velocity must decrease as the air travels the distance without any separation of the boundary layer at the walls. One of the consequences of separation is the vibration of the fan which causes a change in velocity at the test section. The divergence angle is given as:

$$\theta \;=\; \tan^{-1}\left(\frac{1}{2}\,\frac{\sqrt{A_R-1}}{L/D_{h1}}\right) \tag{3}$$

Where,
θ = *Half of the included angle of the diffuser cone*
A_R = *The aspect ratio of diffuser* $\left(\frac{A_2}{A_1}\right)$
L = *Length of diffuser*
D_{h1} = *Inlet section hydraulic diameter of the diffuser*

To obtain the minimum length of the diffuser, equation 4 was used.

$$L_d \;=\; (R_i)\left[\frac{\sqrt{A_R-1}}{\tan(\theta_d)}\right] \tag{4}$$

Where,
R_i = *Inlet hydraulic radius*
L_d = *Diffuser minimum length*
A_R = *The aspect ratio of diffuser* $(\frac{A_2}{A_1})$
(θ_d) = *Diffuser expansion angle*

C. *Contraction Section*

The contraction section designed to increases the mean velocity which allows the honeycomb and screens to be placed in a low-speed region, thus reducing pressure losses and it reduces both mean and fluctuating velocity variations to a smaller fraction of the average velocity (Mehta and Bradshaw, 1979). The contraction ratio of the wind tunnel is the ratio of the entry cross-section area to the exit cross-section area of the contraction cone.

D. *Settling Chamber*

The settling chamber has a constant cross-sectional area which consists of honeycombs and screens, the function of the settling chamber is to reduce the flow turbulence before it enters the cone. The settling chamber cross-section area matches the dimensions of contraction cone inlet (0.6m x 0.6m). A settling chamber length 0.5 times the inlet diameter is often used (Arifuzzaman and Mashud., 2012).

E. *Honeycomb*

Honeycombs are located in the settling chamber and are used to reduce non-uniformities in the flow. A honeycomb with its cell aligned in the flow direction can reduce fluctuating variations in transverse velocity (Welsh., 2013)

$$L_h = 10 \times D_h \tag{5}$$

Where,
$L_{h=}$ *Length of honeycomb*
$D_{h=}$*Cell hydraulic diameter*

Their criteria to be verified in wind tunnel honeycomb design. The first one is;

$$6 \;\le\; \frac{L_h}{D_h} \le 8 \tag{6}$$

And, the second one is;

$$\beta_h \;\ge 0.8 \tag{7}$$

$\beta_{h} = \frac{A_{flow}}{A_{total}}$ (8)

Where,

$\beta_h =$ *Honeycomb porosity*

$A_{flow} =$ *Actual flow cross-section area*

$A_{tot} =$ *Total cross-section area*

F. Screens

Screens create a static pressure drop and serve to reduce boundary layer size and increase flow uniformity. For a screen to be effective in reducing turbulence, it must have porosity in the ranges 0.58 - 0.8. Screen porosity values over 0.8 are not suitable for good turbulence control, while values below 0.58 lead to flow instability (Arifuzzaman and Mashud., 2012). The design formulas are as follows:

The area occupied by the screen = $n_w\, l\, d_w + n_w\, l\, d_w - n_w \left(n_{w\, d_w{}^2}\right)$ (9)

Screen porosity, $\beta_s = \left(1 - \frac{n_{w\, d_w}}{l}\right)^2$ (10)

Screen mesh density, $\rho_m = \frac{n_w}{l}$ (11)

Screen mesh division, $w_m = \frac{1}{\rho_m}$ (12)

Where,

$d_w =$ *Screen wire diameter*

n_w =*Generic wire number in the mesh* (200)

l =*Settling chamber cross-section side* (Arifuzzaman and Mashud., 2012)

G. Power Requirements

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 pressure of the wind tunnel component and the energy ratio is given by equations 13 - 14;

The pressure loss, $\Delta P = K_T \times 0.5 \times \rho_0 V^2$ (13)

E. R = $\frac{{}^1/_2 \rho_o V^2 A_o}{\eta} = \frac{1}{\sum K_i}$ (14)

Where,

$K_i = \frac{\Delta P_i}{{}^1/_2 \rho_i c^2}$ (15)

where,

c_i = mean flow velocity

K_i = Pressure drop coefficients

$K_T =$ The summation of the pressure drops in the various tunnel sections $K_T = (K_{sc} + K_n + K_{ts} + K_d)$ (16)

$\rho_0 =$ The density of air at the test section

v =Velocity of air at the test section

The total pressure loss, $\Delta P_T = \Delta P + P_f$ (17)

Where,

$P_f = 0.5\, \rho_0\, v_{fan}^2$ (18)

$V_{fan} = \frac{A_{bs} \times V_{ts}}{A_{fan}}$ (19)

where,

$A_{bs} =$ *Area of the contraction cone*

$V_{ts} =$ *The velocity at the test section*

$A_{fan} =$ *The area of the fan*

The power required was given by (Almazo, Rodriguez, & Toledo, 2013) as:

Power required =Air volume × ΔP_T

where,

Air volume = Area of the test section × Velocity of the test section

ΔP_T = Static Pressure losses + Dynamic Pressure

H. Pressure Losses in the Diffuser Section

Onyenanu *et al.* (2013) gave the losses in the diffuser section by equation 20:

$$\frac{\Delta P}{1/2\rho_0 V_0^2} = 3.14\,\lambda + 0.0262\left\{1 - \frac{D_0^4}{D_1^4}\right\} + \left\{\frac{D_0}{D_e}\right\}^2 \tag{20}$$

Where,

$D_0 =$ *Test section diameter*

$\lambda = 0.01$

$D_e =$ *Diffuser exit diameter*

$D_1 =$ *Diffuser inlet diameter*

J. Pressure Losses

The pressure loss at a different section of the wind tunnel is given by equations 20 – 23. According to Hussain *et al*, 2011, the only loss in the test section is the friction losses.

$$\frac{\Delta P}{1/2\,\rho_0\,v^2} = K_{ts} = f\,\frac{L_0}{D_0} \tag{21}$$

where,

$D_0 =$ *The hydraulic diameter of the test section*

f =*Friction factor. It is assumed constant along the test section and approximately equals* to($f = 0.01$).

$L_0 =$ *Test section length.*

The design formula for the pressure losses in the contraction section is given by Onyenanu *et al*, (2013) as:

$$\frac{\Delta P}{1/2\,\rho_0\,v^2} = \frac{\lambda}{4}\left\{\frac{L_{cc}}{D_i - D_0}\right\}\left\{1 - \frac{D_0^4}{D_1^4}\right\} \tag{22}$$

Where,

L_{cc} =*Length of the contraction cone*

$D_0 =$ *Test section diameter*

$D_i =$ *Inlet cone diameter*

$\lambda = \approx 0.01$

$D_1 =$ *Outlet cone diameter*

Screens reduce the axial turbulence more than the lateral turbulence; they have a relatively large pressure drop in the flow direction. Honeycombs have small pressure drop and thus have less effect on the axial velocities, but they reduce lateral turbulence (Hussain *et al*, 2011).

$$K_m = (K_{mesh})(Re_s)(\sigma) + \left(\frac{\sigma^2}{\beta^2}\right) \tag{23}$$

Where,

$K_m =$ *Mesh loss coefficient*

$K_{mesh} =$ *Screen mesh factor =1.3*

$Re_s =$ *Mesh screen Reynolds number*

$\sigma =$ *Screen solidity = 0.40*

$\beta =$ *Screen porosity*

RESULTS AND DISCUSSIONS

A. Specifications of the Newly Fabricated Wind Tunnel

Table- 2 Specifications of the Newly Fabricated Wind Tunnel

Parameters	Value
Type	Open circuit
Test section cross section	0.2m × 0.2m
Mean air velocity	9.5m/s
Overall length	2.11m
The effective region in the test section	73% of width or height
Boundary layer region	13.5% of width or height from every wall
Contraction ratio	9
Honeycomb cell diameter, length	0.02m, 0.12m
Test section length	0.46m
Number of screens	2
Settling chamber cross section	0.6m × 0.6m
Mach number	0.03
Motor and fan	Single-phase 176W, 4 blades

From Table 2, it can be seen that the newly fabricated wind tunnel have a free stream velocity of 9.5m/s.

B. *Experimental Results of Wind Tunnel*

The experimental results are presented in Table 3. This includes the measurements of velocities, pressure, mass flow rate and Reynolds number at different test velocities.

Table -3 Experimental Results

Speed of fan (rpm)	Linear velocity (wr) (m/s)	Air velocity (m/s)	Relative velocity (m/s)	Reynolds number, R_e	Dynamic pressure (Pa)	Mass flow rate (kg/s)
90	1.607	0.3	1.307	9.2×10^2	0.0549	0.01464
150	2.6786	0.9	1.7786	2.8×10^3	0.4941	0.04392
550	9.821	1.8	8	5.5×10^3	1.976	`0.08784
800	14.3	4.8	9.5	1.5×10^4	14.0544	0.23424
1400	24.999	9.5	15.499	2.9×10^4	55.278	0.4655

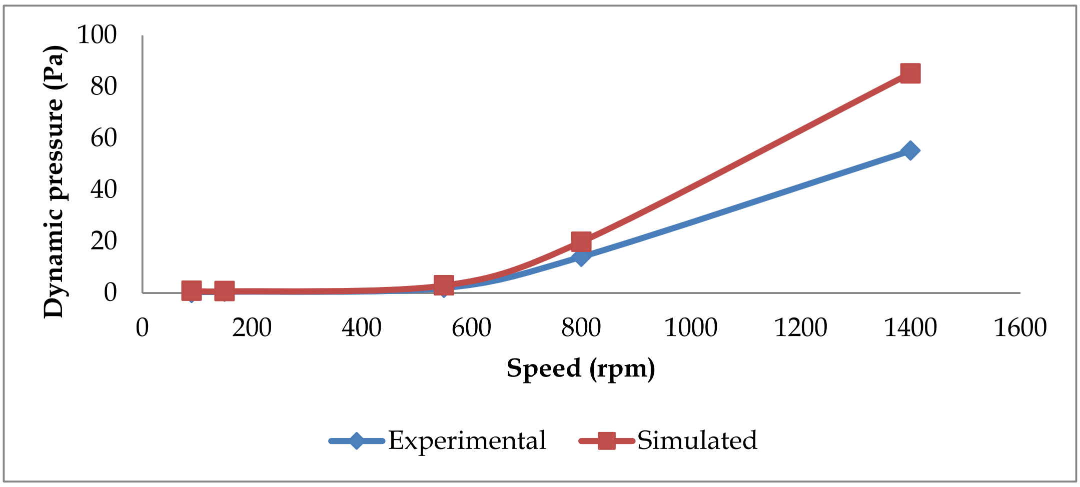

Fig. 1 Variation between dynamic pressure and speed of fan

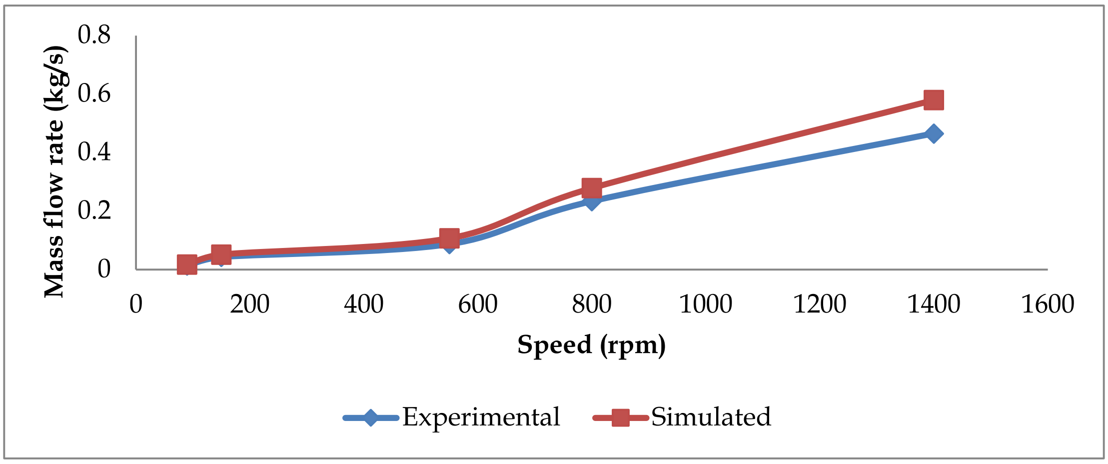

Fig. 2 Variation between mass flow rate and speed of fan

From Table 3, the wind tunnel maximum velocity of 9.5 m/s was attained at a fan speed of 1400rpm and the minimum velocity of 0.3 m/s was also attained at a fan speed of 90 rpm. As depicted in Fig. 1, the dynamic pressure increases as the speed of the fan increases, which shows that the simulated dynamic pressure increases more in magnitude than the experimental dynamic pressure due to higher velocity value. They both have similar behaviour. From Fig. 2, the relationship between the mass flow rate of the experimental/simulated result and the speed of the fan. It shows that the mass flow rate of the experimental result and simulated results have the same behaviour when subjected to the same fan speed. It also shows that the simulated result validates the experimental result. Therefore, the newly fabricated wind tunnel is a good device to provide parallel steady flow with uniform speed through the test section without excessive turbulence and can be used effectively in different aerodynamic researches. As depicted in Table 4, it can be seen that data were collected from five (5) different distances to construct the horizontal velocity profile in the test section.

Table -4 Wind Tunnel Horizontal Velocity Profile

Distance (cm)	**0.4**	**1.27**	**2.49**	**3.4**	**4.6**
Velocity (m/s)	**6.8**	**9.2**	**9.3**	**9.5**	**9.35**

From the horizontal velocity profile in Fig. 3, it can be seen that the flow is almost linear from 1.27cm up to 3.4cm. The velocity in the tunnel from distance 1.27cm to 3.4cm progresses gradually to the maximum velocity of 9.5m/s. The maximum boundary thickness is found to be 1.27cm and the effective airflow velocity is found in a length 3.4cm which is located approximately 1cm from both walls. In percentage, the effective flow length is about 73% and the boundary layer region in each wall is 13.5% of the total width of the tunnel. The mean free stream velocity is found to be about 9.5m/s.

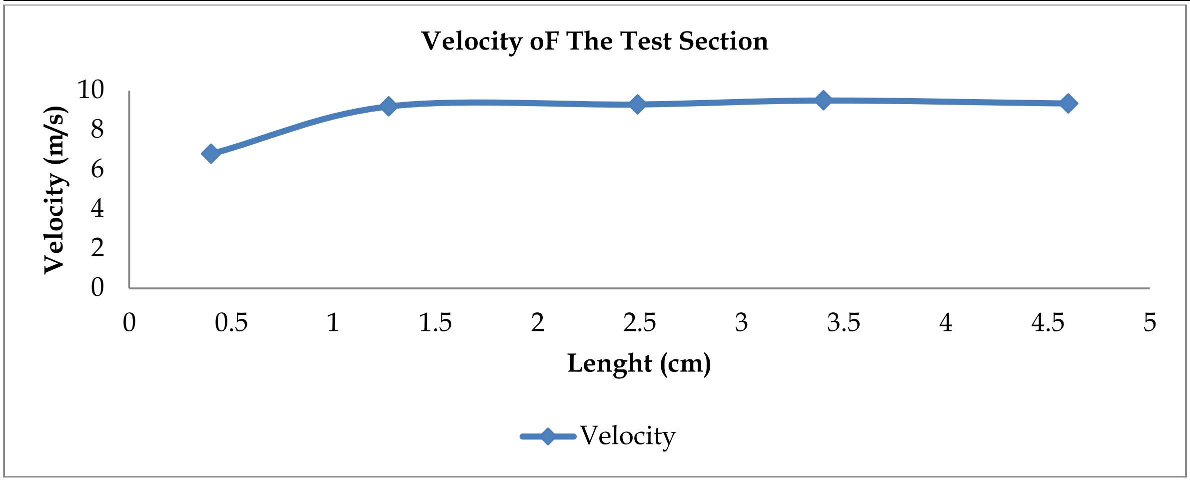

Fig. 3 Horizontal velocity profile

Table 5 shows the data collected from five different distances in the test section to construct the vertical velocity profile.

Table -5 Vertical Velocity Profile

Distance (cm)	**0.2**	**0.7**	**1.2**	**1.6**	**2**
Velocity (m/s)	**6.8**	**9.2**	**9.3**	**9.5**	**9.35**

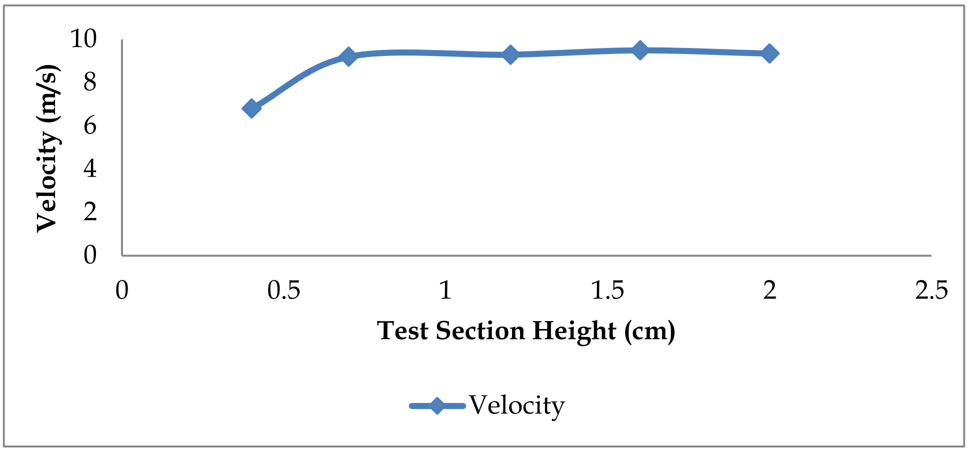

Fig. 4 Vertical Velocity Profile

From Table 6, it can be seen that the force of drag of five selected models was determined with varying flow velocities from the experiment of the wind tunnel.

Table-6 Experimental Result of Force of Drag of Five Selected models

Velocity (m/s)	**Vehicle (Audi RA) (N)**	**A rectangular shape (N)**	**Circular Shape (N)**	**Square Shape (N)**	**Triangular Shape (N)**
0.3	0.0043	0.000752	0.000077	0.000413	0.000247
0.9	0.0389	0.00677	0.00069	0.00371	0.0022
1.8	0.1556	0.0271	0.00645	0.01486	0.00890
4.8	1.106	0.1926	0.01976	0.105671	0.06322
9.5	4.3	0.75	0.08	0.4139	0.247

From the vertical velocity profile at Fig. 4, it is clear that the mean velocity in the test section is almost linear. At 0.2cm from the test section inlet, air velocity close to the wall is much less than the other positions (0.7cm, 1.2cm, 1.6cm and 2cm). The maximum velocity is found in 1.6cm position. The velocity gradually increases near the wall because of the boundary layer formed. The boundary layer region is found to be 10% of the total height of the test section in each side. The effective flow height is found to be 80% of the total height of the test section. The effective flow region is approximately 0.5cm from the bottom wall to 0.5cm below the top wall. The mean flow velocity for vertical measurement is about 9.5m/s.

C. *Comparison of Newly Fabricated Wind Tunnel with Existing Wind Tunnels*

The result of the design and testing is been compare with other wind test rig and shown in Table 7.

Table-7 Comparison of Newly Fabricated Wind Tunnel with Existing Wind Tunnels

Parameters	**Newly fabricated wind Tunnel**	**Review Low-speed Tunnel**	**NASA (Small) Tunnel**	**MIT (USA) Tunnel**
Test section area	0.2m × 0.2m	0.3m × 0.3m	0.9m × 0.9m	0.85m × 0.85m
Mean velocity	9.5m/s	5.7m/s	25m/s	40m/s
Test section length	0.46m	0.5m	3m	2.8m
Overall length	2.11m	3m	13m	11m

From Table 7, above, the newly fabricated wind tunnel was compared with existing wind tunnels. The existing wind tunnels were Review of design and construction of an open circuit low-speed wind tunnel by (Singh *et al, 2013*) in India, Constructed small wind tunnel by National Aeronautics and Space Administration (NASA) the USA, and design, construction and evaluation of subsonic wind tunnel by (Vilaginac, M, 1970) in Massachusetts Institute of Technology (MIT), USA.

CONCLUSIONS

The wind tunnel has been designed, fabricated and tested with the maximum air velocity of 15m/s in the test section. The length of the fabricated wind tunnel is 2.11m and a free stream velocity is found to be 9.5m/s. A comparison between the newly fabricated wind tunnel and the wind tunnels constructed in India by NASA (USA) and MIT (USA) shows that the newly fabricated wind tunnel conforms to global standard having a free stream velocity of 9.5m/s with the test section cross-sectional area of 0.04m^2 and efficiency of 63%. Therefore; it is adequate for aerodynamic research. Models of aeroplanes, spacecraft, air foil, vehicles and other solid objects can be tested in the newly fabricated wind tunnel to determine the aerodynamic forces that would be used to improve the design. In this study, a vehicle (Audi R8) and four other shapes were used as test models. The dynamic pressure and mass flow rate of the flow were found to be 55.3 Pa and 0.4655 Kg/s respectively at the maximum test section velocity of 9.5m/s.

CONFLICT OF INTEREST

We hereby state that no conflict of interest will arise in any form from the publishing of this study.

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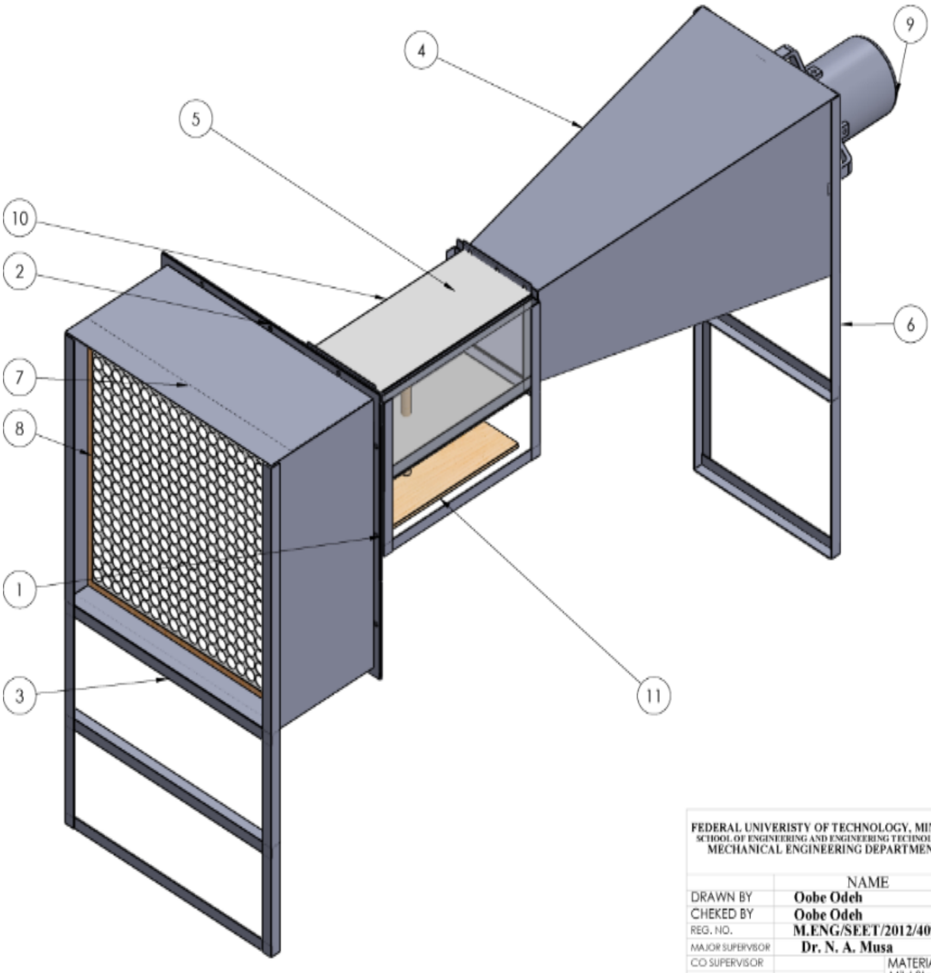
Appendix A: Drawings and Picture



ITEM NO.	PART NUMBER	QTY.
1	Contraction Cone	1
2	Settilng Chamber	1
3	Leg	1
4	Diffuser	1
5	Test Chamber	1
6	Diffuser Stand	1
7	Plywood	1
8	Plastic Pipes (PVC)	921
9	Fan sub assembly	1
10	testing center cover	4
11	Base Plywood	1

FEDERAL UNIVERISTY OF TECHNOLOGY, MINNA, SCHOOL OF ENGINEERING AND ENGINEERING TECHNOLOGY MECHANICAL ENGINEERING DEPARTMENT		All Dimension in mm	REVISION
	NAME	Part Name: Isometric Projection	
DRAWN BY	Oobe Odeh	TITLE: Design and Fabrication of Low Speed Open Circuit Wind Tunnel	
CHEKED BY	Oobe Odeh		
REG. NO.	M.ENG/SEET/2012/4096		
MAJOR SUPERVISOR	Dr. N. A. Musa		
CO SUPERVISOR	MATERIAL: Mild Steel an	DWG NO.	A4
APPROVED BY	Dr. N. A. Musa		
DATE	July, 2015	SCALE 1:10	SHEET 1 OF 6

Plate 1. Fabricated low-speed open circuit wind tunnel