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Design and Fabrication of a Supersonic Wind Tunnel

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Abstract— **This work proposes to design and fabricate a supersonic wind tunnel that can be operated using the compressor and pressure vessel having a capacity of 1000 litres and a maximum storage pressure of 12bar. Test section size and the operating Mach number of the wind tunnel is designed so that the tunnel can operate for 30 sec using the air stored in this pressure vessel. The design is based on the assumptions of 2D in viscid flow and normal shock pressure recovery in the diffuser. The tunnel designed according to these criteria has a design Mach number of 2.5 and an 80mm × 20 mm rectangular test section. Calibration of this facility was also carried out by measuring the static pressure in the test section, which shows a test section Mach number of 2.14.**

Index Terms— **Mach number, Nozzle Throat Area, Stagnation Temperature, Test Section Area.**

I. INTRODUCTION

Wind tunnel is a device for producing a controlled stream of air in order to study the effects of movement through air or resistance to moving air on models of aircraft and other machines and objects. Aerodynamics, propulsion and acoustic testing are some of the main uses of such tunnels. Applications of wind-tunnel research range from routine testing of airframes to fundamental research on the *boundary layer*, the slow-moving layer of air adjacent to any wind-exposed body surface. Measurements of *air pressure* and other characteristics at many points on the model yield information about how the total wind load is distributed. In addition to aircraft and spacecraft, aerodynamic studies in wind tunnels have been highly profitable for solving design problems in automobiles, boats, trains, bridges, and building structures. The wind tunnel is indispensable to the development of modern aircraft.

Despite the heavy dependence on computational fluid dynamics (CFD) for modern aerospace vehicle design, wind tunnels have been improved and are still in continuous use. There are many areas where CFD cannot give accurate solutions, and the Wind tunnel can provide crucial data in such difficult flow fields [3]

1.1 Classification of Supersonic Wind Tunnels

According to the working methods wind tunnels can be divided into two types,

A. Intermittent wind tunnel

- Intermittent blowdown wind tunnel
- Intermittent indraft wind tunnel
- Intermittent Pressure-vacuum tunnel

Because of the high power requirements the high speed wind tunnels are often of the "intermittent" type in which energy is stored in the form of pressure and allowed to drive the tunnel only a few seconds out of each pumping hour. The intermittent wind tunnels can yield higher compression ratios. So starting the intermittent tunnel is not a problem. Intermittent blow down and in draft tunnels are normally used for Mach numbers from 0.5 to 5.0.and the intermittent pressure -vacuum tunnels are normally used for higher Mach numbers.

B. *Continuous Wind Tunnel*

Continuous wind tunnels are capable of operating for longer periods. The testing conditions can be held constant over a long period of time. However, it takes a considerable amount of time to pressurise the tunnel reservoir to the required value resulting in long starting times. In addition, the size of the air supply system required for its operation is much higher when compared to the other types.

1.2 Advantages of Intermittent Wind tunnel

Of the different types of wind tunnels discussed the most commonly employed is the intermittent blowdown type, due to the following advantages.

1. They are simpler to design and less costly to build.
2. A single drive may easily run several tunnels of different capabilities in pumping down the whole circuit and getting the drive motors up to speed.
3. Extra 'power' is available to start the tunnel.
4. Loads on a model during the establishment of high speed flow (starting loads) are less severe because of faster starts.

1.3 Objectives

From the discussions in the previous section, it is clear that a blowdown type wind tunnel is the ideal choice to meet the constraints imposed by the test time requirements and the capacity of the pressure vessel.

Based on these considerations, it was decided to design and fabricate a supersonic wind tunnel with a reasonable run time of 30 seconds, using the pressure vessel available in the laboratory.

II. PRINCIPLE OF SUPERSONIC WIND TUNNEL

There are different techniques by which a stream of supersonic flow can be created, but the most commonly employed technique is to expand the test gas from a high pressure reservoir through a nozzle to the desired Mach number. The test-model with proper instrumentation can be tested in this stream. Supersonic wind tunnels are designed to reproduce the flight Mach number, which is one of the main similarity parameters for compressible flows.

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III. SUPERSONIC WIND TUNNEL COMPONENTS

Main components of supersonic wind tunnels are,

1. Settling chamber
2. The convergent-divergent nozzle
3. The test section at the nozzle exit
4. A diffuser located after the test section

The figure below shows the schematic diagram of a supersonic wind tunnel.

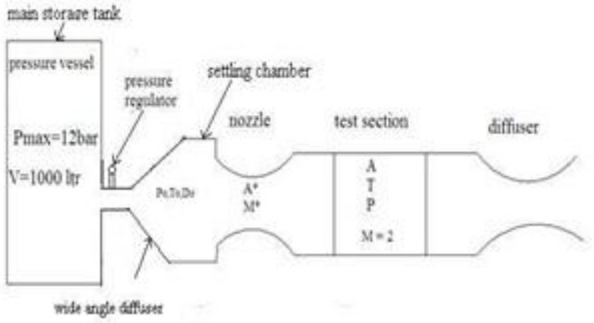

Figure. 1 *Schematic diagram of a supersonic Wind Tunnel*

The main storage tank, having a capacity of 1000ltr is used for storing compressed air at 12bar. Air from the main tank is fed through a pressure regulator to a second reservoir settling chamber) that acts as the constant pressure reservoir for the Laval nozzle. The high-pressure air in the storage tank expands and settles down in a settling chamber, where the air slows down and is kept at a constant pressure. Downstream of the settling chamber is a Converging-Diverging nozzle. It accelerates the flow to a supersonic jet. This supersonic jet passes through the test section and finally the flow is decelerated by a diffuser to low subsonic speed, which helps to reduce the pressure required to start the wind tunnel and thus improve the operating efficiency of the wind tunnel. The diffuser exhausts to the ambient atmosphere.

IV. DESIGN AND FABRICATION OF SUPERSONIC WIND TUNNEL

Based on the discussions it is decided to design a blow down type supersonic wind tunnel, within the constraints imposed by the capacity of the compressor-pressure vessel system. The main design parameters of a wind tunnel are its operational Mach number and test section area. The procedure followed for the estimation of these parameters is described in this section.

The design process starts with the assumption of a reasonable test section size (80mm x 20mm), and an optimum Mach number suited for these dimensions was estimated by maximizing the tunnel run time as a function of Mach number.

First step in the calculation of maximum run time was the assumption of the test section Mach number and test section area. Mach number at any location in the nozzle is a function of the ratio of local area to the sonic throat area. This area Mach number relationship is obtained under the assumption of isentropic expansion in the nozzle.

A^* the throat area, could now be calculated once the Mach number at the nozzle exit/test section and the test section area is known/assumed.

$$\frac{A}{A^*} = \frac{1}{M^2}\left[\frac{2}{\gamma+1}\left(1+\frac{\gamma-1}{2}M^2\right)\right]^{(\gamma+1)/(\gamma-1)}$$

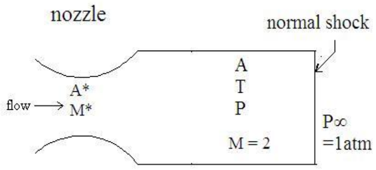

Figure. 2 *Schematic diagram showing normal shock*

A constant area duct serves as the test section and we assume a normal shock stands at the duct exit. Behind the shock flow is subsonic $P_2 = P_\infty$= 1atm, the atmospheric pressure. For a calorically perfect gas for a constant value of γ the pressure ratio across the shock is a function of only the Mach number ahead of the shock

$$\frac{P_2}{P} = 1+\left(\frac{2\gamma}{\gamma+1}\right)\left(M^2-1\right)$$

$$P_0 = \left(\frac{P_0}{P}\right)\left(\frac{P}{P_2}\right)P_\infty$$

In the above equation 'P_2' is the pressure behind the shock, that is the atmospheric pressure and 'P' is the test section pressure. Once 'P_0' is calculated, the properties in the test section can also be evaluated using the test section Mach number.Using continuity equation we can find out the mass flow rate through the system. Mass flow rate throughout the wind tunnel is same as the flow is assumed to be steady. So the mass flow through the tunnel can be evaluated from the flow properties calculated at the test section.

The tunnel run time is dependent on the air pressure available in the pressure vessel. The supersonic wind tunnel can operate till the pressure inside the pressure vessel becomes less than required reservoir pressure. So, in order to find the maximum run time, the temporal evolution of pressure in the pressure vessel as it is continuously drained during the tunnel operation must be calculated. We can find this by calculating the mass remaining in the pressure vessel as a function of time. Once we know the remaining mass in the pressure vessel we can easily find out the remaining pressure at that time, assuming perfect gas behaviour.

Minimum starting pressure (reservoir pressure) needed for wind tunnel having a Mach number 2.5 to work satisfactorily was found to be $2.4292e^5$ Pa. The tunnel can be operated till the pressure drops below this value and this gives us an estimate of the tunnel run time. The tunnel run time was calculated by this method for a test section area of $0.0016m^2$(80 × 20 mm) and various design Mach numbers. The results from these calculations are shown in fig.2. From the plot it can be seen that the maximum run time corresponds to a test section Mach number of 2.5, which was chosen as the operational Mach number for the tunnel.

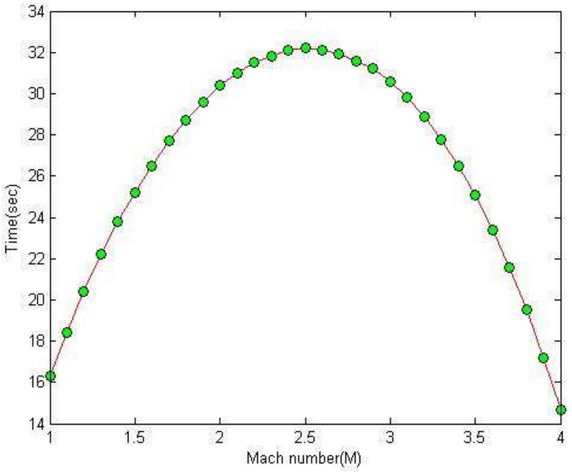

Figure.3 *Mach* number Vs Run time

Having estimated the preliminary design parameters, we can now proceed to the detailed design of the various components of the wind tunnel.

V. DESIGN OF WIND TUNNEL COMPONENTS

a. Design of the Converging Diverging Nozzle

Converging diverging nozzle is designed using the method of characteristics. It is the most frequently used method for defining internal contour of supersonic nozzle. The design is based on isentropic conditions and Prandtl-Meyer expansion. The contoured nozzle can be usually considered to consist of several regions [4].

I. The contraction region, in which flow is entirely subsonic
II. The throat region, in which the flow accelerate from a high subsonic to a low supersonic speed
III. An initial expansion region, where the slope of the contour increases up to its maximum
IV. The straightening or 'Busemann' region in which the cross sectional area increases but the wall slope decreases to zero
V. The test section where the flow is uniform and parallel to the axis.

The nozzle wall profile obtained by this calculation for a design Mach number of 2.5 is shown below.

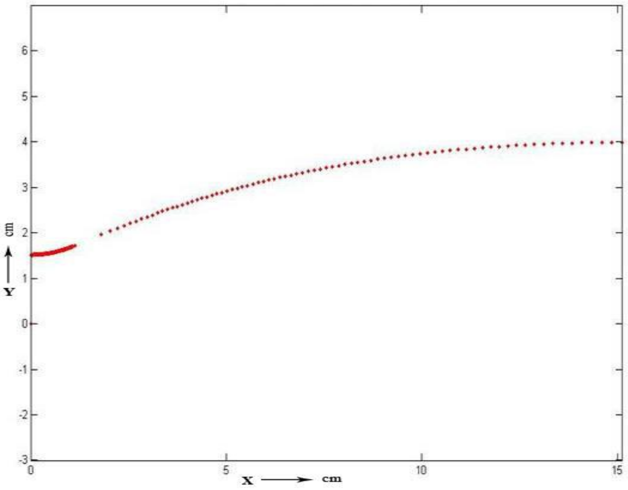

Figure.4 *Mach* 2.5 contour nozzle

So far, only the supersonic section of the nozzle has been designed. The subsonic, convergent section is chosen arbitrarily by joining the nozzle throat to the inlet (65mm) by a smooth curve.

The converging diverging nozzle was fabricated in aluminium using the WIRE EDM process out of two aluminium blocks of dimension 100mm × 25mm × 530.

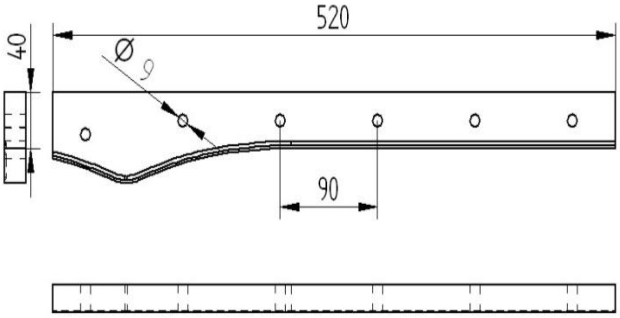

Figure.5 *Mach* 2.5 contour nozzle

b. Design of the Settling Chamber

The settling chamber should be designed for flow velocities no greater than 80 to 100 feet per second (30.48 m/s) to ensure uniformity as recommended by Pope and Goin [2]. A lowest velocity in the settling chamber should be no less than about 10 feet per second (3.048 m/s). A low limit on velocity is desirable to prevent convection currents from causing a non uniform temperature distribution.

To find the velocity of flow inside the settling chamber

Diameter of the chamber = 200mm
Length of the chamber = 600mm
Area of cross section,

$$A = \pi r^2$$

We know the mass flow rate M_f = 0.3428 kg/sec

$$\rho A V = M_f$$

$$V = 3.893 \text{m/s}$$

Since this velocity is within the acceptable limits, the pipe of 200mm diameter can be used for the settling chamber.In order to find the wall thickness, we consider the settling chamber as thin cylinder so the circumferential stress should be the criterion for determining the wall thickness.

$$t = \frac{P \times D}{2\sigma}$$

Where,

t= Thickness of the chamber wall
P= Maximum pressure inside the chamber
D= Diameter of the cylinder
σ= Allowable stress

We took a factor of safety of 5, and found out the allowable stress.

$$\sigma = S_{ut} / F_s$$

S_{ut} = 340N/m^2 for mild steel

For these calculations the maximum chamber pressure *P* was taken as 12 bar which corresponds to the maximum pressure attainable by the compressor used. These calculations show that a minimum of 1.76mm thickness is required for the for the settling chamber wall. A 6mm thickness tube was chosen for fabrication as it was readily available in the same dimension as we calculated for settling chamber.

The figure shows the draft view of settling chamber. A 200mm × 600mm MS tube was taken and MS flanges of same diameter 200mm was welded at both ends.

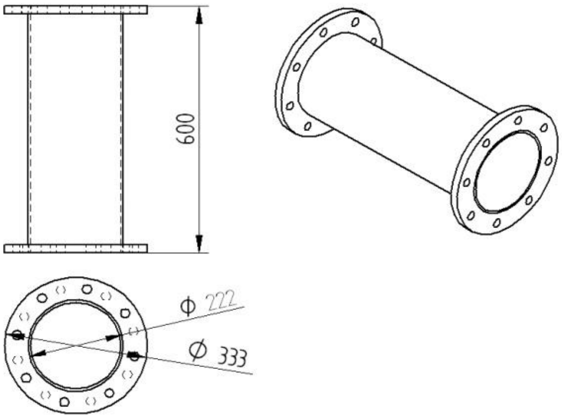

Figure.6 *Settling chamber*

A wide angle diffuser was designed to decelerate the flow entering the settling chamber. This also serves as a connector for connecting the settling chamber to the 1.5 inch diameter pressure pipes from the pressure vessel. A 6mm thick MS plate was rolled to the shape of a cone with an included angle of 40^0. An 8 inch MS flange was welded to the larger diameter end of the cone.

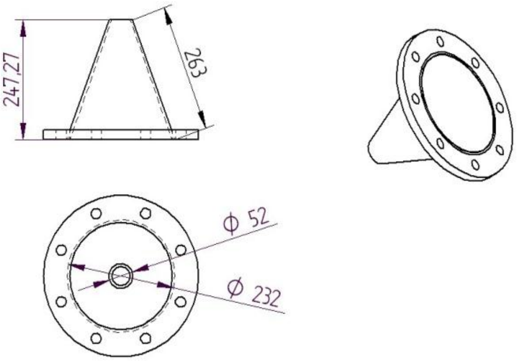

Figure.7 *Mach* 2.5 contour nozzle

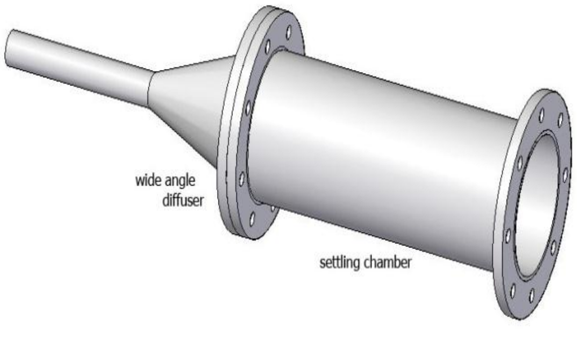

Figure.8 *Mach* 2.5 contour nozzle

C. Design of the Diffuser

The minimum area of diffuser throat corresponds to the minimum possible strength of the shock at the test section. P_{0x}, P_{0y} are stagnation pressures and for $M_x = 2.5$, test section Mach number,

$P_0y/P_{0x} = 0.4990$
$A_x^* = 6.0682e^{-4}m^2$
$A_y^* = (P_{0x}/P_{0y}) \times A_x^*$
$A_y^* = 12.\ 16072e^{-4}\ m^2$

Area of diffuser throat was $12.16072e^{-4}\ m^2$, so the height of the throat will be $6.08e^2$m. But, as the test section height was already $8e^{-2}$m, we opted for a conservative design and decided to do away with the CD diffuser. We have chosen a straight duct with a diverging section at the end as diffuser instead. This was fabricated using an MS plate of thickness 3mm.

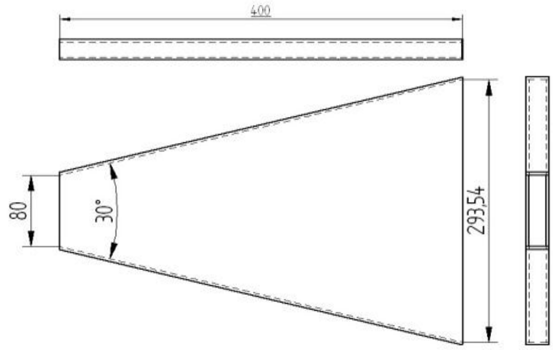

Figure.9 *Wide Angle Diffuser*

The assembled view of the tunnel is shown in figure below

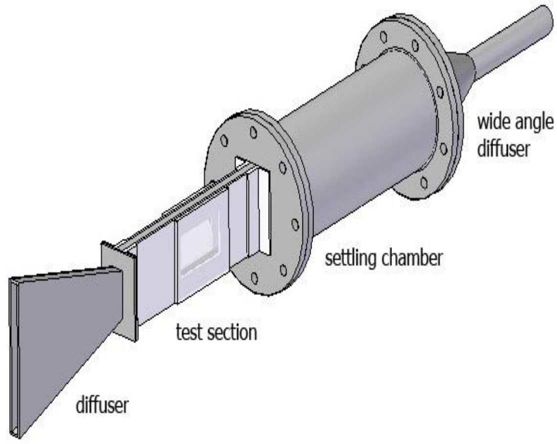

Figure.10 *Settling Chamber – Wide Angle Diffuser Assembly*

VI. RESULT AND DISCUSSION

Initially the calibration was done along with the diffuser. During this test, it was observed that the pressure in the settling chamber could not be maintained constant and showed significant fluctuations about a mean value. In addition, while operating at the designed settling chamber pressure, the pressure ratio developed across the nozzle was much lesser than that corresponding to the design Mach number. The pressure in the test section was nearly equal to the ambient pressure indicating a subsonic flow in the test section. On inspection, it was observed that there was a significant mis-alignment between the nozzle and the diffuser segments resulting in a highly separated flow in the diffuser which in turn affected the upstream conditions. So the diffuser was removed and calibration was performed, with the constant area duct of the test section itself acting as a normal shock diffuser. The results obtained are tabulated in Table 4.1. During these tests, all the pressures were monitored manually using Bourdon-type pressure gauges and the settling chamber pressure was maintained steady at the required value by manually adjusting the ball valve provided.

Reservoir pressure (bar)	Pressure in the test section (bar)	
3.6	1	0.346
	2	0.333
	3	0.320
3	1	0.306
	2	0.306
	3	0.306
2.5	1	0.746
	2	0.746
	3	0.746
2	1	0.986
	2	0.986
	3	1
1.6	1	0.906
	2	0.906
	3	0.906

The tests were carried out for different reservoir pressures ranging from 1.6 – 3.6 bar, and it was observed that only above at pressures 3 bar and above does the tunnel operate at Mach numbers close to the design value.

Reservoir pressure, P_0 = 3bar
Pressure inside the test section, P = 0.306 bar
P_0 / P = 10.22
Corresponding Mach number M = 2.14

It has been found that the initial pressure needed to operate the wind tunnel for the required Mach number was 20% higher than the calculated value and also the nozzle with a design Mach number of 2.5 is only producing a Mach number of 2.1. The differences might be attributed to viscous effects, which were neglected during the nozzle design.

CONCLUSION

The calibration of the supersonic wind tunnel was carried out by measuring static pressure in the test section using the pressure taps provided. Even though it was observed that the tunnel operates satisfactorily at pressures above 3 bar, it is not clear what happens at lower pressures. Especially at a reservoir pressure of around 2 bar the pressure in the test section was highly transient this might be due to the formation of shock waves in the nozzle.

In order to verify these speculations it is required to measure pressure at more locations along the wind tunnel circuit. In addition, the uniformity of flow in the tunnel also needs to be verified by taking surface pressure measurements on a test model placed in the test section.

REFERENCES

[1] Anderson J. D., *Modern Compressible Flow with Historical Perspective*, McGraw- Hill Inc., New York, 1990
[2] Pope, A. and Goin K., *High-Speed Wind Tunnel Testing*, Wiley, New York, 1965
[3] Design and testing of a subscale supersonic Aero propulsion wind tunnel, joji matsumoto, Presented to the Faculty of the Graduate School of The University of Texas at Arlington
[4] Design of a supersonic nozzle by A.McCABE.Ph.D. the Mechanics of fluid Department, University of Manchester, Aeronautical Research Council Reports and Memoranda.
[5] High speed wind tunnel and test systems design hand book, Lockheed Martin Misiles And Fire Control, Publication number Aer-Eir-13552-E
[6] H. W. Liepmann, A. Roshiko , *ELEMENTS OF GASDYNAMICS* California Institute of technology, John Wiley & sons ,New York 1957

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