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CONCEPT DESIGN AND DEVELOPMENT OF SUPERSONIC WIND TUNNEL

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ABSTRACT

Supersonic vehicles are the future of aerospace. Before using a vehicle, it's important to test whether it works well or not. For the past few years, aerospace engineers have been observing the properties of supersonic vehicles and it's mainly done in two ways: Conducting a test using an actual vehicle and conducting a wind tunnel testing on a scaled vehicle model. As it is dangerous to test in actual vehicles, wind tunnels are widely used for the same. The goal of this research paper is to draw and design a supersonic wind tunnel.

Key Words : Wind tunnel testing , aerodynamics, test facility , supersonic flow

INTRODUCTION

Wind tunnels are primarily used to test aircraft, spacecraft, and nearly any technical application where the effects of wind around a body are important. Supersonic wind tunnels are wind tunnels that produce supersonic speeds between Mach number 1.2 and 5. A supersonic wind tunnel consists of a convergent and divergent section where the velocity goes up from subsonic speed to supersonic speed. In a supersonic wind tunnel, the velocity decreases in the convergent duct and increases in the divergent duct where the cross-sectional area also decreases. If this area is increasing then again the velocity decreases to subsonic. The convergent duct is used to increase and decrease the speed. When running normally, a supersonic wind tunnel is mainly composed of compressible flow effects. The nozzle shape and stagnation factors decide the Mach number in supersonic wind tunnels. The main components of supersonic wind tunnels are a storage tank, gate valve, Plenum chamber, nozzle, test section, and diffuser. To make the air inside the tunnel at a supersonic condition accelerate the flow from zero velocity through a Delaval nozzle. The nozzle section is followed by a diffusing section which is a convergent-divergent type. Two types of nozzles are used in the supersonic wind tunnel, that is either a converging or a diverging nozzle and a converging-diverging nozzle. If the pressures are equal then the flow inside the tunnel is not active but once the pressure varies the air starts moving and the wind tunnel proceeds with its work. Supersonic wind tunnels are more connected with shockwaves. The main two types of shockwaves are normal shocks which are stronger and weaker oblique shocks, which are more efficient. Spikes are used in supersonic vehicles which will convert strong normal shocks into more efficient oblique shocks. To design a supersonic wind tunnel we have to assure that shock waves won't affect the flow speed. More about shockwaves are discussed separately on the further page.

SHOCKWAVES

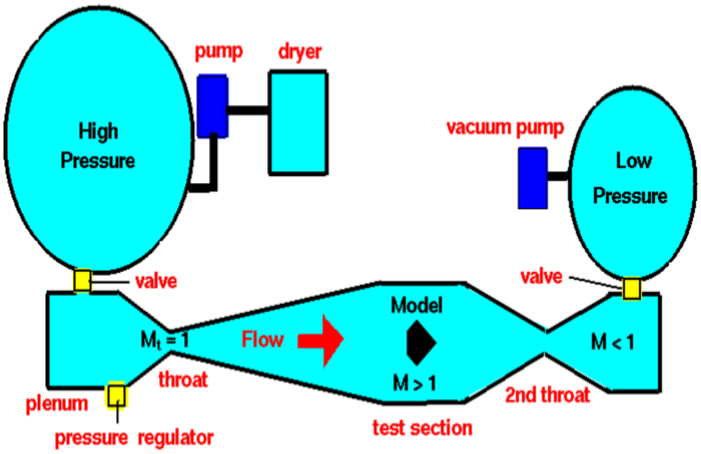
The shockwaves are present in the supersonic flow pattern. Shockwaves will keep the continuity of the boundary. Based on the flow speed and other physical characteristics, these shocks could be oblique or normal shock waves. A normal shock wave is a type of oblique shock wave with a 90-degree wave angle relative to the undisturbed flow direction. Oblique waves are compression waves. Expansion waves are generated by a pressure difference in the flow which also increases the velocity and mach number.

TYPES OF SUPERSONIC WIND TUNNEL

Wind tunnels are built to perform some specific functions in a certain range of velocity. The two types of supersonic wind tunnels are-Intermittent open circuit tunnels and Continuous return circuit tunnels. In an intermittent wind tunnel, the energy to run the tunnel is reserved in the form of pressure. Intermittent tunnels are classified into three types- Blowdown tunnels, induction tunnels, and indraft tunnels. In a continuous wind tunnel, air that travels inside the tunnel doesn't escape into the atmosphere; rather, it comes back through a tube and is constantly circulated through the test portion.

Blowdown wind tunnels

This type of wind tunnel is generally utilized in a situation, where the mach number will be between high subsonic to high supersonic. A blowdown tunnel can be designed in different ways. We added a completely closed supersonic setup in the diagram (refer to next page). The test section, in which the model is kept is terminated by a nozzle. The pressure and temperature in the plenum, as well as the area ratio between the test section and the nozzle throat, define the Mach number in the test section. As the flow expands in the nozzle the pressure decreases and if any moisture is present in the tunnel, it will go under condensation and ultimately liquefies in the testing area. A drier bed is used to reduce condensation. Upstream of the plenum, the air is pushed into a closed high-pressure chamber. Air is blasted out of a covered low-pressure chamber downstream of the test portion at the same time.



Air is blasted out of a covered low pressure chamber downstream of the test portion at the same time. In blowdown wind tunnels, test times are limited. Valves upstream and downstream of the test section are opened at the start of the running of the test. In the test portion, the pressure ratio creates a supersonic flow, and air moves from the high-pressure chamber to the low-pressure chamber. The pressure in the high-pressure chamber lowers as the air leaves the chamber. When the air enters the low-pressure chamber, it increases the pressure in the high-pressure chamber. The pressure in the two compartments eventually equalizes, the flow ceases, and the test is completed. A valve (which limits pressure) is placed in the plenum to avoid inconstant situations in the test area.

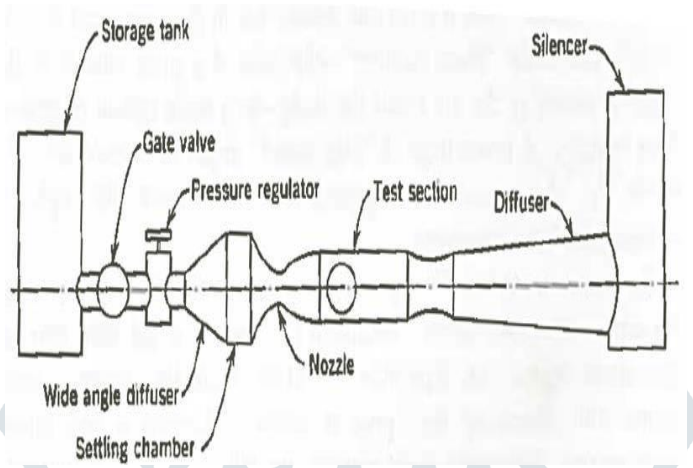
Continuous wind tunnels

A continuous supersonic wind tunnel is used to examine subsonic and supersonic airflow. It enables students to investigate two-dimensional airflow around small-scale aerodynamic models. A remote control unit with a large capacity vacuum pump is mounted in an equipment frame. To suck air into the tunnel the pump generally releases a downstream with less pressure in the working part. The worker can reduce the airflow using a bypass tube with a valve that can be operated by hand without affecting the main airflow. A convergent-divergent nozzle with a detachable top component called a liner functions as the operating section of the tunnel. Maximum airspeed at the divergent part of the working area is limited by the shape of the liner. For two-dimensional flow research, the instrument comes with different types of models with pressure tappings. These are joined with the working area and both windows are flushed. We can use a geared mechanism to change the incidence angle of the scaled model. A pressure displaying unit and a ‘mimic’ screen is connected along the working area. It will display the pressures at the tappings. The display has regulated pressure sensors to monitor pressure compared to the atmosphere. It also displays the pressures acting on the model.

SUPERSONIC WIND TUNNEL COMPONENTS

The main components of supersonic wind tunnels are,

1. Settling chamber
2. Converging-diverging nozzle
3. Test section
4. Diffuser



Settling chamber:

A perforated transition cone, multiple damping panels, and probes measuring stagnation pressure and temperature are all found in the settling chamber. The nozzle chamber can be replaced with two-dimensional shaped steel nozzle blocks. The tunnel has three complete nozzle chambers, each of which is currently equipped with nozzles for Mach numbers ranging from 2.4, 3, and 4.

Converging-Diverging nozzle:

The supersonic vehicle's nozzle is normally designed with a convergent section succeeded by a divergent section(CD nozzle). In the supersonic wind tunnel, we use either a converging or diverging nozzle and a converging-diverging nozzle. The flow at the end of a convergent-divergent nozzle in a supersonic wind tunnel is influenced by the contact between the nozzle and the test section. The flow accelerates in the diverging section of the nozzle. The nozzle geometry decides the mach number and the flow.

Test section:

The test section is the part of the wind tunnel where the testing model is placed and tested. The test section is located near the diffuser. The entire performance of a wind tunnel is represented by the quality of the flow of air in the test segment. Depending on the test section's area and conservation of mass of compressible flow, we can construct a test section to obtain a particular velocity.

Diffuser:

A supersonic diffuser lowers the velocity and raises the fluid pressure traveling at supersonic speeds. It is a duct that is intended to slow down an entering gas flow to a lower velocity. The airflow from the test section is collected by the diffuser. A diffuser is constructed in such a way that the total pressure loss is lowest when the flow is slowed significantly. The convergent portion and the throat of an actual supersonic diffuser slow down an entering flow with a sequence of reflected oblique shocks. When shock waves come in contact with viscous flow close to the wall, weaken the reflected shock patterns which result in the formation of weak normal waves at the end of the throat area.

PRINCIPLE OF SUPERSONIC WIND TUNNEL:

Supersonic wind tunnels work by propelling high-pressure gas through a nozzle and into a testing section where the scaled model of the vehicle is placed. Continuous and blow-down (also referred to as impulse) facilities are the two types of supersonic wind tunnels. Continuous operation facilities work in a similar way to subsonic tunnels in that the gas is compressed, then accelerated through a nozzle, passed through the test section, decelerated through a diffuser, and then returned to the compressor.

Blow-down facilities use a diaphragm or valve to separate the nozzle and test portion from a pressurized section, then break the diaphragm or open the valve. As long as the pressure in the driving chamber stays high enough, the resulting pressure differential propels gas through the nozzle and across the test section, resulting in supersonic flow.

Each type has its benefits and drawbacks. Because they may often function under constant circumstances indefinitely, continuous operation tunnels can conduct long-term research. The energy consumption of a continuous supersonic wind tunnel is normally very significant due to the high speeds obtained in supersonic tunnels. Because of mechanical components such as the compressor, continuous wind tunnels are often expensive to maintain.

By comparison, blow-down tunnels are very inexpensive since they usually have no moving parts, and the cost of an experiment is restricted to the cost of gas and single-experiment components because maintenance is rarely required. Furthermore, some blowdown facilities, such as shock tunnels and expansion tubes, can create hypervelocity test flow, which is impossible to achieve in continuous operation wind tunnels due to the high reservoir enthalpies required for hypervelocity flow, which can only be achieved through non-steady processes.

Due to the quick transients associated with high-speed flow, blow-down facilities have a limited test period, which is often very brief (less than 1 second). The impact of this disadvantage has been greatly reduced thanks to the introduction of high-speed cameras and transducers. A common high-speed camera, for example, may take several hundred to tens of thousands of high-quality photographs in the time it takes to test ordinary blow-down facilities, making it well-suited to nearly any high-speed flow experiment.

DESIGN OF SUPERSONIC WIND TUNNEL

The operating Mach number and test section area are the two most significant design criteria for a wind tunnel. To start the designing process we have to assume a proper test section and mach number for these wind tunnel dimensions by increasing the tunnel run time. The first step in determining maximum tunnel run time is calculating mach number and area of the test section. We can find mach number at any point in the nozzle by the equation,

$$Mach\ number = \frac{Local\ area}{Sonic\ throat\ area}$$

This area-mach number relationship is based on the assumption of isentropic nozzle expansion. We can calculate the area of throat A∗ with the nozzle exit mach number and test section area. The test segment is a constant area duct, and consider that a normal shock wave is present at the exit of the duct.

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

In the below equation, P is test section pressure and P2 is atmospheric pressure. Before the shock, the flow is subsonic so P2 = P∞= 1atm where P∞ is back pressure. The pressure ratio depends only on mach number when γ is constant. The test section properties can be analysed by using the test section mach number after stagnation pressure "P0" has been computed. We can determine the mass flow rate which is constant everywhere in the tunnel as the flow is steady by using the continuity equation.

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

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

The run time of the supersonic wind tunnel is determined by the pressure of the air in the pressure vessel. This tunnel can run until the pressure drops below the reservoir pressure requirement in the pressure vessel. To determine the highest possible run time, we have to compute the temporary variation of the pressure in the pressure vessel as it is reduced throughout the tunnel testing, by calculating the mass left in the pressure vessel as a time-dependent quantity. If we know the leftover mass, we can find the remaining pressure in the vessel. 2.4292e5 Pa was found to be the least beginning pressure required for a wind tunnel with a Mach number of 2.5 to function successfully.

DESIGN OF SUPERSONIC WIND TUNNEL COMPONENTS

Design of Converging-Diverging nozzle :

The method of characteristics is used to build a converging-diverging nozzle. Isentropic conditions and the Prandtl-Meyer's equation are used to design the nozzle. This is the most common way of designing a supersonic nozzle's internal contour. Different regions in the CD nozzle are as follows:

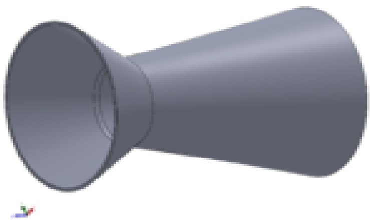
Contraction region: In this region, the flow is fully subsonic.

Throat region: The region where the flow will accelerate from high subsonic to low supersonic.

Expansion region: In this region, the contour's slope increases to its peak level.

Busemann region: The area of cross-section and slope of the wall decreases to zero in this region.

Test section: In this region the flow is uniform.



Design of Settling chamber :

The settling chamber is used to keep the wind tunnel's velocity consistent. The settling chamber is constructed in a flow velocity range of 80 to 100 to maintain uniformity.

The velocity of flow inside the settling chamber can be calculated using the below equations.

Area of cross-section,

$$A = \pi r^2$$

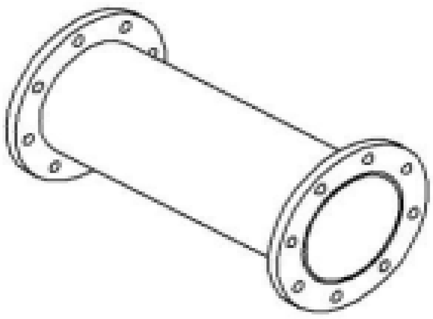
As we know mass flow rate Mf, we can find velocity with the equation,

$$\rho AV = Mf$$

If this velocity is within the permissible velocity, then we can use a pipe with this diameter in the settling chamber.

To find wall thickness needed for designing settling chamber, we can use the below mentioned equation

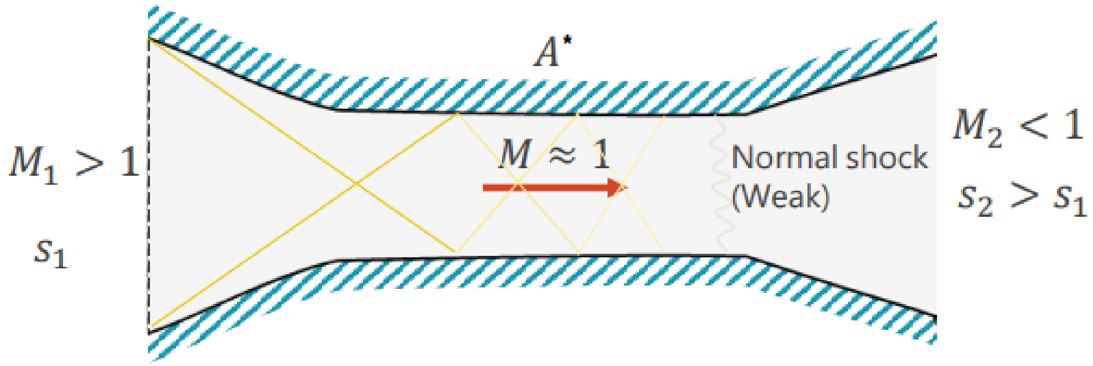
$$t = \frac{P \times D}{2\sigma}$$



Design of Diffuser :

The test section's minimal diffuser throat area corresponds to the shock's smallest feasible strength. Initially, the calibration was carried out in conjunction with the diffuser. A supersonic wind tunnel diffuser is designed in such a way that, when the flow is dropping down, the total pressure is minimum.

The diffuser in the supersonic wind tunnel actually decreases the velocity of the incoming air flow by continuous reflection of oblique shock waves at the site of convergent section and throat section. When the shock waves interact with the viscous flow, it weakens near the wall and the backscattered shock waves are diffused, which ultimately results in the formation of normal weak shock waves and it happens at the exit of the throat area. By the diverging duct, the subsonic flow towards the throat area is reduced. At this part the entropy of the flow is not constant, so the exit entropy is more and total pressure is less. We have to design the convergent, divergent and the constant area in such a way that the total pressure loss is minimum.



Let us assume that we want to build a supersonic wind tunnel with an uniform flow of mach number 2.5, As discussed previously, for this range of mach number we need a convergent-divergent nozzle with ration between test section area to throat area A/A^* = 2.63, and ratio of atmospheric pressure to test section pressure P_2/P = 17 (Approximate value), so that we can maintain a shock free expansion throughout the experiment.

CONCLUSION:

By using the above mentioned equations, we can design some of the basic parts of a supersonic wind tunnel. It has been observed in this research that the supersonic speed is achieved from the subsonic level, which is undergone in the nozzle section. The components of the supersonic wind tunnel are designed by keeping some limitations in mind. The supersonic wind tunnel, which is with mach number ranging from 1.2 to 5 will run at a certain period of time. It has been noticed that the pressure is maximum at the nozzle, so as the velocity is less, it will increase when the pressure drops. Designing a supersonic wind tunnel is not an easy task, a lot of mathematical equations and technical components have to be worked simultaneously, to get the required data of the test piece.

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