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Analysis of Air Intake for Formula SAE Vehicle

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Abstract: *This paper aims to the design and manufacture of an intake system for a 600cc Formula SAE engine by optimizing a venturi type restrictor which is to be fitted in the intake manifold of a Formula SAE car engine. The engine analyzed for intake manifold was Honda CBR 600rr. The main purpose of 20mm restrictor in intake manifold is to restrict mass flow passing to the engine thus reducing its maximum power. Objectives of this paper is to optimize a venturi type design to allow maximum possible mass flow rate to the engine from 20 mm restrictor buy reducing the difference in pressure across venturi at all speeds. Analytical calculations are done based on standard results to get maximum mass flow rate and CFD tool is used to calculate minimum pressure drop across the restrictor buy varying converging and diverging angles of venturi. It can be observed from CFD results that for converging and diverging angle of 14 degrees and 6 degrees respectively minimum pressure drop can be achieved.*

Keywords: *Formula SAE, Intake Restrictor, Flow optimization, CFD.*

1. INTRODUCTION

Formula SAE is a student competition organized by Society of Automotive Engineers (SAE), where in students are supposed to design, manufacture and run a prototype of open wheel racing car. This competition is conducted in various parts of world every. Formula SAE rules committee has imposed a rule of adding a 20 mm restrictor to intake manifold and also states that all air flowing to the engine should pass through this single restrictor bet it a single cylinder or multi cylinder engine. This rule limits the maximum power of engine by reducing mass flow rate flowing to engine. Thus a restrictor should be efficiently designed and validated to allow maximum possible air flow and maintain minimum pressure difference across the restrictor.

Engines used in this competition are majorly 600cc engines which revs up to 14000 rpm and gives 110 hp of output [1].It is beneficial to design an intake manifold that best utilizes the available airflow for increased performance.Based on FSAE competition rules, the following major design specifications were developed:

- Conform to FSAE regulations: The main restrictions on the air intake manifold are that it has to have a 20mm restrictor and no throttling downstream of the restrictor.
- Fits into the current chassis of the car:The air intake manifold must fit into the current chassis without obstructing other main components of the car.

2. INTAKE MANIFOLD

The purpose of intake manifold is allowing mass flow of air passing to the engine thus improving the performance of engine with consideration of all the FSAE rules and regulations. This intake manifold is thereby connected with the cylinder head of engine which is guided by the air flow passing through 20mm restrictor.

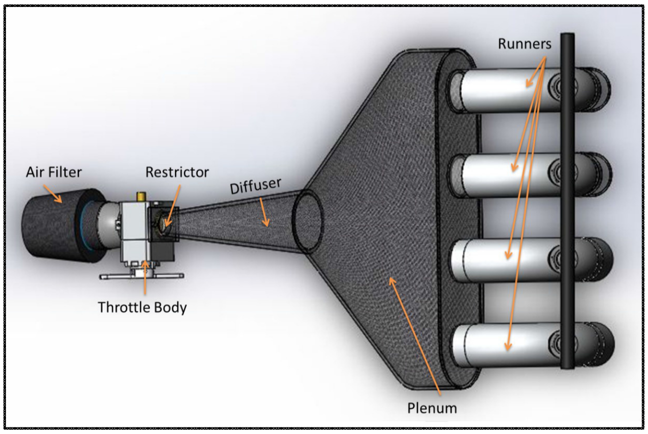


Fig. 1. Intake Manifold with its part

The fluid element enters into the air induction system by first passing through the air filter. This is to ensure that the air is free from particulates that could potentially harm the internal components of the engine. The fluid element then enters the throttle body, which is a throttling device responsible for regulating the mass flow rate of air into the engine using a butterfly valve. Once passing through the throttle body, the fluid element enters into a converging/diverging nozzle, with the throat diameter that of the 20.0 mm restrictor regulated by the Formula SAE rules. The fluid element increases and decreases its velocity in the converging and diverging sections.

The diffuser represents the trumpet-styled inlet tube that connects the throttle body and the plenum. It is comprised of a flange attachment to the throttle body with the inlet diameter matching that of the inner diameter of the throttle body. The inlet then converges to the restrictor diameter. After the restrictor, the airway then diverges until meeting the inner diameter required for attachment to the plenum.

A plenum is a relatively large chamber between restrictor and primary runners. The plenum is designed to deliver equal flow to all cylinders and to damp out pulsation caused by intake stroke of the engine. The plenum also allows the gases to slow down and gain density. If the plenum volume is too high then throttle response is very poor and if plenum volume is very low then it will create negative pressure inside plenum which will affect efficiency of engine.

The main function of the intake system is to direct air from surrounding to the combustion chamber of the engine. The design of the intake system will have a significant effect on how the engine runs. The key of making power is to fill the combustion chamber with maximum amount of air and fuel mixture.

The general rule is that you should begin with a runner length of 17.8 cm for a 10,000 rpmpeak torque location, from the intake opening to the plenum chamber.

3. DESIGN EXPLORATION

Design consistedofappropriately calculated steps which at every instance provide proper connectivity between the last and next step involved in research of venturi.

3.1 SHAPE OF RESTRICTOR

The shape of a restrictor can be as simple as a plate with the mandated dimensions machined into it, and placed anywhere along the air intake system. But a simple orifice plate would create a lot of pressure loss downstream of the restrictor, and the resultant effect would decrease the efficiency of the line of airflow. There were some other factors also which forced us to switch from simple orifice plate to Convergent-Divergent Nozzle this includes the co-efficient of discharge which is higher for the Convergent-Divergent Nozzle. Therefore it was decided to design Convergent-Divergent Nozzle that replaced the orifice plate as an air intake restrictor.

This device will have throat diameter of 20 mm as per rules of the competition.With the basic information for throttle body diameter for an engine with 600 cc of displacement and for revolutions per minute of 14000, the diameter of throttle body is taken to be 40mm; the same is widely used in competition. This dimension will be the diameter of venturi at inlet and outlet.

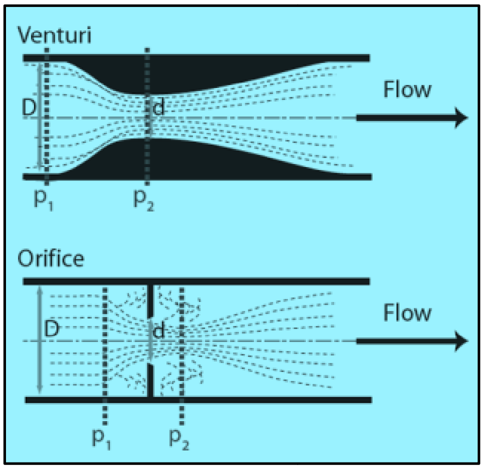


Fig. 2. Orifice and Venturi

3.2 CONSTANTS AND VARIABLRS IN DESIGN OF VENTURI

We have two dimensions on which the venturi will perform and these are converging diverging angles and length of venturi. We also know that temperature at inlet is ambient and pressure at inlet is atmospheric. For boundary conditions at outlet of venturi we can have pressure, velocity or mass flow rate. According to the laws governing fluid dynamics, a fluid's velocity must increase as it passes through a constriction to satisfy the principle of continuity, while its pressure must decrease to satisfy the principle of conservation of mechanical energy. Thus a drop in pressure negates any gain in kinetic energy a fluid may accrue due to its increased velocity through a constriction. An equation for the drop in pressure due to the Venturi effect may be derived from a combination of Bernoulli's principle and the continuity equation. The parameters are important for calculating actual flow conditions inside and outside the restrictor [2]. These parameters also provides rigid base for boundary conditions to be used in CFD analysis.

Calculations:

The values taken for substitution in Equation are:

P_t = 101325 Pa

T = 300K

γ = 1.4

R (air) =0.286 kJ/Kg-K

A = 0.001256 m2

M = 1 (Choking Conditions)

Result**: Mass Flow Rate at Choking = 0.0703 kg/s**

3.3 DATA ANALYSIS

A. Aim to maximize pressure recovery at outlet

B. Variables

a. Dependent Variables: Delta Pressure (= Inlet Pressure – Outlet Pressure)

b. Independent Variables: Converging angle and Diverging angle

c. Constants: Inlet, Outlet and Throat diameter, Type of Fluid -Air, Temperature - 300K

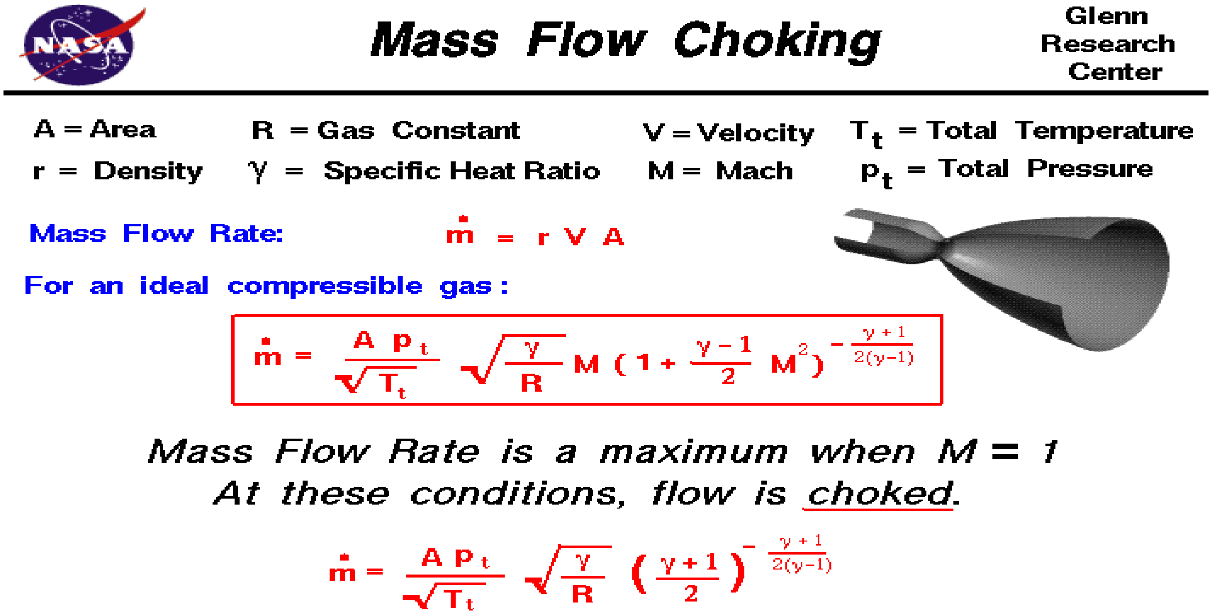
C. Boundary Conditions

a. Inlet Face: Total Pressure = 1 bar

b. Outlet Face: Mass Flow Rate = 0.0703kg/s [4]

3.4 UNDERSTANDING COMPRESSIBLE FLUID DYNAMICS

The most important parameter in compressible flows is Mach number Ma=V/C where V is flow velocity and C is speed of sound. If Mach number is less than 0.3, compressibility effects can be neglected as there is around 3 % change in density. Whereas if Mach number is from 0.3 to 1 flow is called subsonic and if Ma>1 flow is supersonic, in this regions compressibility increases and its effects are considerable. And also a great discharge is observed in this region [5-6].



Mass Flow Choking

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A = Area
R = Gas Constant
V = Velocity
T_t = Total Temperature
r = Density
γ = Specific Heat Ratio
M = Mach
p_t = Total Pressure

Mass Flow Rate: $\dot{m} = r\ V\ A$

For an ideal compressible gas :

$$\dot{m} = \frac{A\ p_t}{\sqrt{T_t}} \sqrt{\frac{\gamma}{R}}\ M\ \left(1 + \frac{\gamma - 1}{2}\ M^2\right)^{-\frac{\gamma+1}{2(\gamma-1)}}$$

Mass Flow Rate is a maximum when M = 1
At these conditions, flow is choked.

$$\dot{m} = \frac{A\ p_t}{\sqrt{T_t}} \sqrt{\frac{\gamma}{R}} \left(\frac{\gamma+1}{2}\right)^{-\frac{\gamma+1}{2(\gamma-1)}}$$

Fig.3. Formulae for Mass Flow Choking [3]

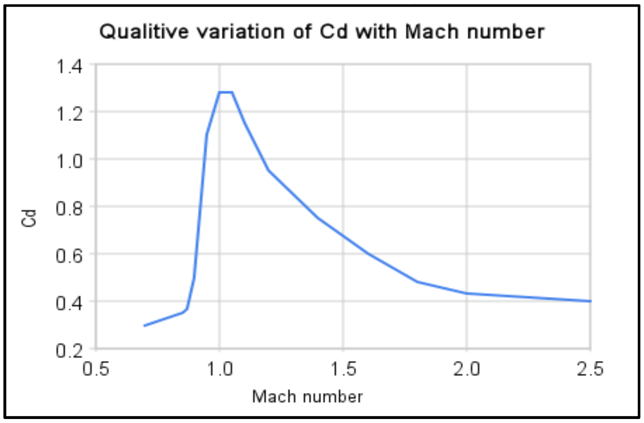

Fig. 4. Variation of C_d with Mach number

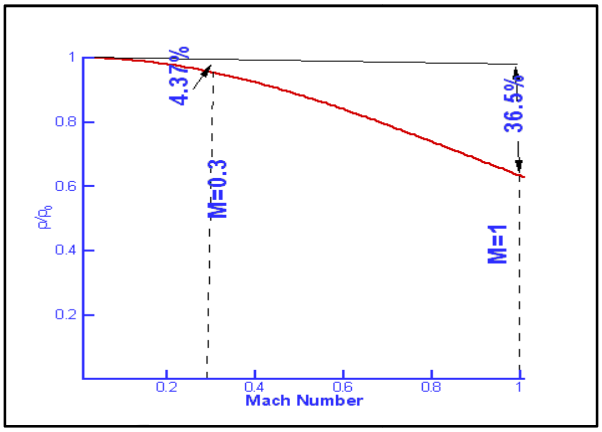

Fig. 5. Density change vs. Mach number

Applying the knowledge above to a converging-diverging nozzle we can easily analyze that density of air is reduced drastically when passing through the restriction. It means that pressure on downstream side is reduced. As all the air to engine will be passed through this single venturi, pressure available at inlet to engine will be very less. Thus engine work is increased to high levels and it is forced to pull more air from venturi so that there is enough air available inside combustion chamber to burn fuel completely. This situation occurs usually at high rpm around 6000 and more. This is not good for engine as it cannot squeeze out maximum power that is available and the car moves slowly. Thus our aim is to reduce this pull from engine and recover maximum amount of pressure at outlet of venturi [7-8].

4. STUDIES AND FINDINGS

Once we have found out all data that we have for solving our problem, we now move towards studying the problem and finding out dimensions of venturi which will provide us minimum pressure drop across the venturi. So to do the study we have started with assuming some dimensions of diverging and converging angles by basic knowledge of functioning of venturi. CAD modelling was done using Autodesk Inventor 2014 and then analysed in Flow Simulation for following boundary conditions:

Inlet: Total Pressure = 101325 Pa

Outlet: Mass flow rate = 0.0703 kg/s

Iterations have been carried out with set of converging and diverging angles. These iterations were used for the flow simulation of venturi also at different angles. ANSYS 13.0 was used for CFD analysis of the venturi.

These iterations have been tabulated as follows-

TABLE 1.

S.No(Iterations)	Converging Angle	Diverging Angle	Pressure difference (Pa)
1.	16^0	6^0	9256.68
2.	14^0	6^0	9161.78
3.	18^0	8^0	10009.65

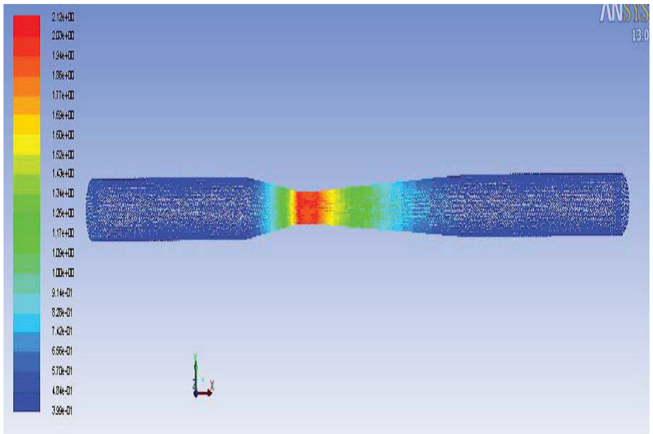

Fig. 6. CFD analysis of venturi with 14^0 and 6^0 as its converging and diverging angle respectively

After understanding all the above master iterations, much iteration was performed to see for other valves of converging cone. Diverging cone angle was set to 6 degree as it was found that any increase or decrease in angle caused streamline disturbance and drop in pressure at downstream side. It was finally observed from various simulations that pressure recovery was maximum when converging angle is 14 degree and diverging is 6 degree.

Following are the images which show other operational parameters for final design of venturi.

5. CONCLUSIONS

The optimum solution to achieve maximum possible mass flow rate of air as quickly as possible is to minimize the pressure loss through the flow restriction device. The best way to achieve it is by passing it through a venturi design. In this project venturi is brilliantly used in reducing power of engine. As in this competition teams are busy trying to squeeze almost all single horse power available even with the restrictor attached, this gives rise to increasing research in optimization and finding out alternative technology for increasing mass flow rate to engine. From the collected data and gathered information from various simulations one has reached to this conclusion that the Venturi with 14^0 and 6^0 as its converging and diverging angle respectively will perform the optimized flow.

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