Research and optimization of intake restrictor for Formula SAE car engine

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Abstract- This research paper aims to optimize a venturi type restrictor which is to be fitted in the intake manifold of a Formula SAE car engine. 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 research 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 12 degrees and 6 degrees respectively minimum pressure drop can be achieved.

Index Terms- Formula SAE, Intake Restrictor, Flow optimization, CFD.

I. Introduction

Formula SAE is a student competition organized by Society of Automobile Engineers, 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 year and about 80 universities participate every year from over the world. 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 gasoline engines which revs up to 12000 rpm and gives 110 hp of output. An IC engine requires proper air-fuel ratio to work as per its design. Due to 20 mm restrictor rule, the designed intake of 38 mm per cylinder reduces to 20 mm for all four cylinders. This drastic change reduces flow of air mass to engine. When engine is running at low rpm of about 3000 rpm this required mass flow rate is compensated by increase in velocity of air through the venturi. But FSAE engines have to rev maximum time at high rpm of about 7000 to 11000 rpm. At such high speeds engine require much more air for combustion and thus mass flow rate should increase, but due to restrictor area being less air have to pass with very high velocity to compensate or fill the engine with required amount of air. Thus air tries to achieve maximum velocity through restrictor which gives rise to critical flow conditions, where in air reaches its maximum speed of Mach 1 at the restrictor. Thus mass flow rate is fixed parameter for 20 mm restrictor, which is used for calculations further for optimization of venturi. Now according to stated objective to allow maximum possible mass flow from venturi with minimum pressure difference, we work here onwards with reducing pressure drop and causing engine to sufficiently inhale air with minimum pull.

II. Research Procedure

Research procedure consisted of appropriately calculated steps which at every instance provide proper connectivity between the last and next step involved in research of venturi. Following are the steps to ensure efficient working of entire research.

1) Selection of type of restrictor:
We have two options to restrict air flow using a 20mm diameter constriction and these are both a simple orifice and a converging diverging nozzle.

Following is difference between both:

Parameters	Orifice	Nozzle
Coefficient of discharge	0.60	0.975
Pressure loss	Medium	Low
Viscosity effect	High	High
Accuracy(% of full scale)	3	1
Cost	Low	Medium
Manufacturing	Easy	Difficult

As from above differentiation table a converging diverging nozzle looks to be an obvious choice for intake manifold design as we require very high efficiency. Thus a converging diverging nozzle was selected as a type of constriction device. This device will have throat diameter of 20 mm as per rules of the competition. With some basic calculations for throttle body diameter for an engine with 600 cc of displacement and for revolutions per minute of 13000, the diameter of throttle body comes out to be 38 mm, and the same is widely used in competition. This dimension will be the diameter of venturi at inlet and outlet.

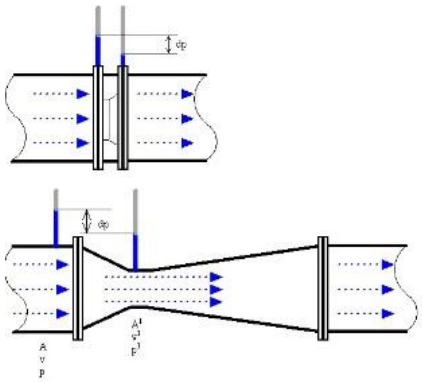
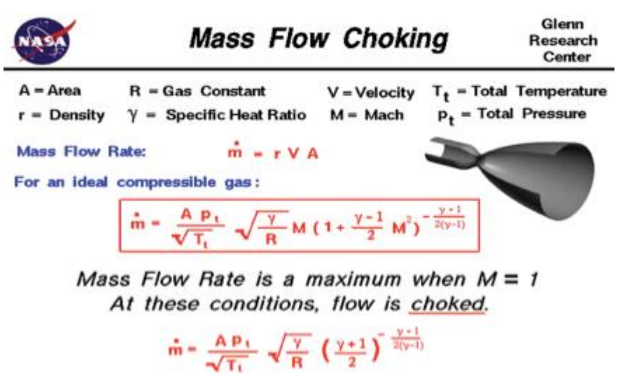


Fig 1: Orifice and Venturi

2) Identifying what are constants and variables in the design of venturi:
To know the parameters which are known and unknown is important for calculating actual flow conditions inside and outside the restrictor. These parameters provides rigid base for boundary conditions to be used in CFD analysis. As from above step we have two dimensions which are fixed, so we have two dimensions on which the venturi will perform and these are converging diverging angles and length of venturi. Thus we have defined two known and two unknown physical parameters for design 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 either pressure, velocity or mass flow rate. Calculating pressure and velocity at outlet of venturi involves complex procedures and thus gives rise to some errors. Mass flow rate at outlet can be easily calculated by using choked flow equation.



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

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

Fig: 2 Mass flow choking

Calculating maximum mass flow rate from above equation using available data values as stated below:

M = 1 (choked flow)
A = 0.001256 m^2 (20 mm restriction)
R = 0.286 KJ/Kg-K
γ = 1.4
Pt = 101325 Pa
T = 300 K

Mass flow rate = 0.0703 kg/s

This is second boundary condition which will be applied at the exit of venturi. Thus we are ready all our known and unknown parameters to proceed for calculations.

3) Understanding compressible fluid flow 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.
Compressibility is around 47 % at supersonic flows.

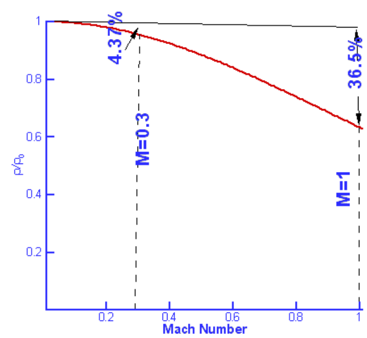


Fig 3: Density change vs Mach number

Applying above basic knowledge to a diverging converging nozzle we can understand clearly 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 availaible 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.

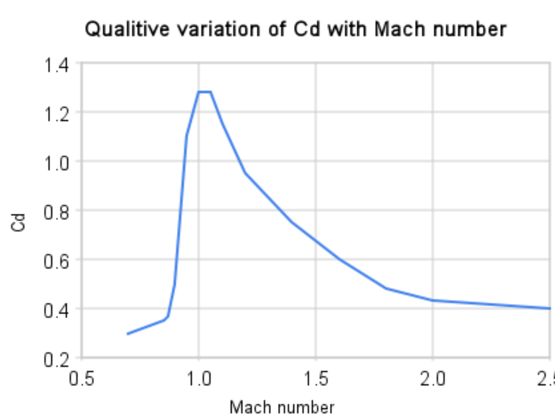


Fig 4: Cd vs Mach number

4) CFD analysis:
A very appropriate software package like Ansys Fluent and Solidworks were simultaneously used to verify and check results for CFD simulation. These software’s help in optimization of restrictor to attain maximum possible mass flow rate at minimum pull from engine. Primary software used is Solidworks Flow Simulation 2014. While performing CFD analysis different converging and diverging angles were taken into consideration and with numbers of iteration it was tried to achieve minimum pressure drop across constriction.

5) Manufacturing of venturi:
Manufacturing is also an important step to provide results as per simulation. Manufacturing defects can be improper angles of converging and diverging nozzle, rough surface and inaccurate dimensions. Manufacturing had two options weather to go for sheet metal or Rapid prototyping. Rapid prototyping was the most appropriate way to manufacture venturi, as it gives a very smooth finish to the final object, which in our case is essential. Even rapid prototyping gives accurate dimensions which ensures accuracy in restriction diameter and uniform angles of converging and diverging cones over its entire length. This manufacturing process is costly as compared to others, thus we searched for help and D B Designs sponsored us.

III. 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 modeling was done using Solidworks 2014 and then analyzed in Flow Simulation for following boundary conditions:

Inlet: Total Pressure = 101325 Pa
Outlet: Mass flow rate = 0.0703 kg/s

Iterations carried out on converging and diverging angles are as indicated in below table:

Iteration no	Converging angle	Diverging angle
1	12	6
2	14	6
3	16	6
4	18	6

The above iterations were solved in Flow simulation by constructing a volume mesh of fine quality. The results from CFD are tabulated below for all above iterations.

Iteration no	Converging angle (degree)	Diverging angle (degree)	Pressure difference (Pa)
1	12	6	8560.24
2	14	6	9161.78
3	16	6	9256.88
4	18	6	10009.65

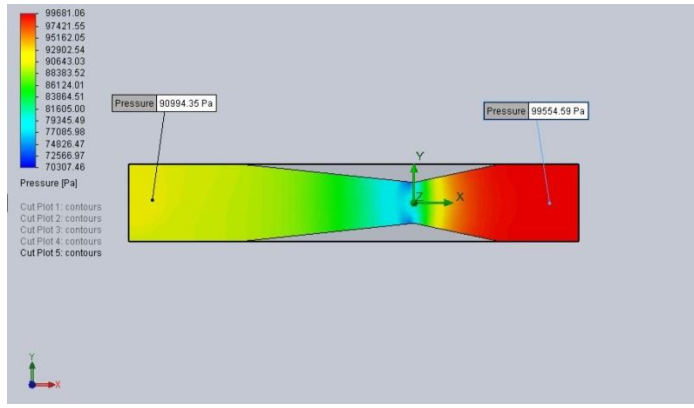


Fig 5: Pressure plot for iteration 1

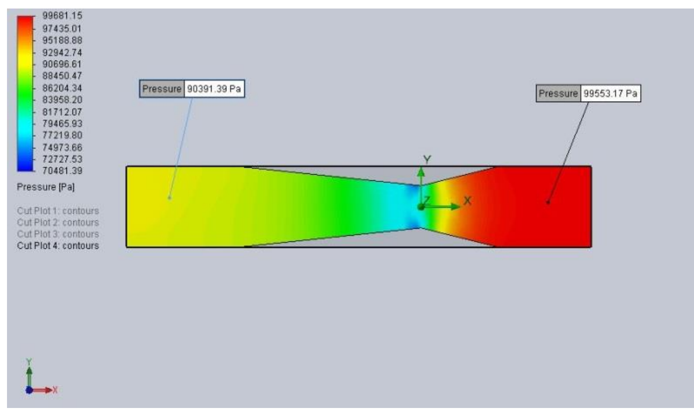


Fig 6: Pressure plot for iteration 2

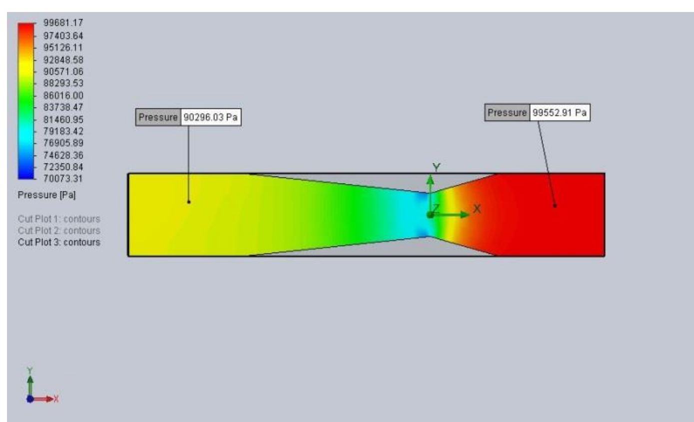


Fig 7: Pressure plot for iteration 3

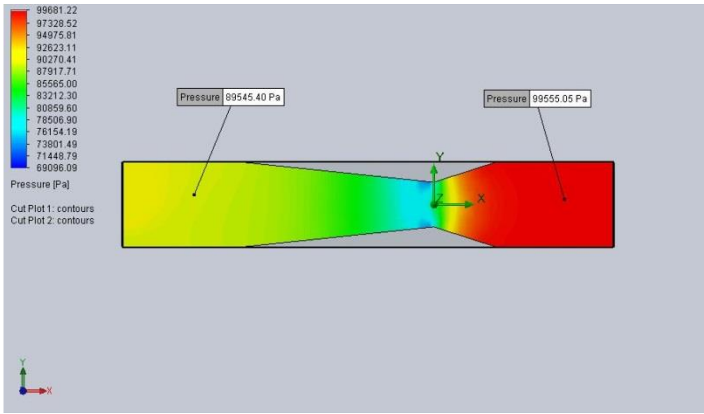


Fig 8: Pressure plot for iteration 4

After understanding all the above master iterations, many iterations were 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 12 degree and diverging is 6 degree.

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

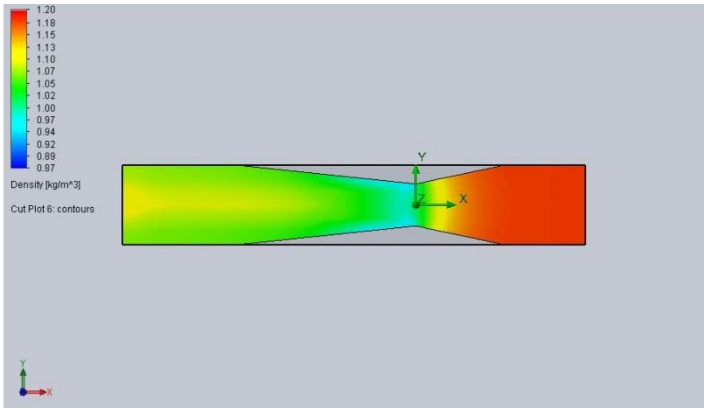


Fig 9: Density plot for final design

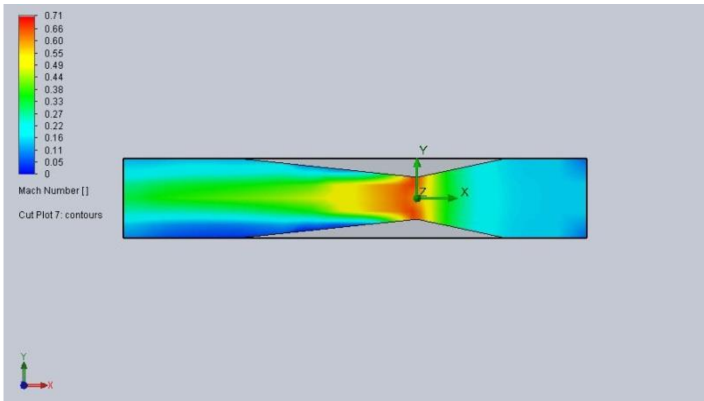


Fig 10: Mach number plot for final design

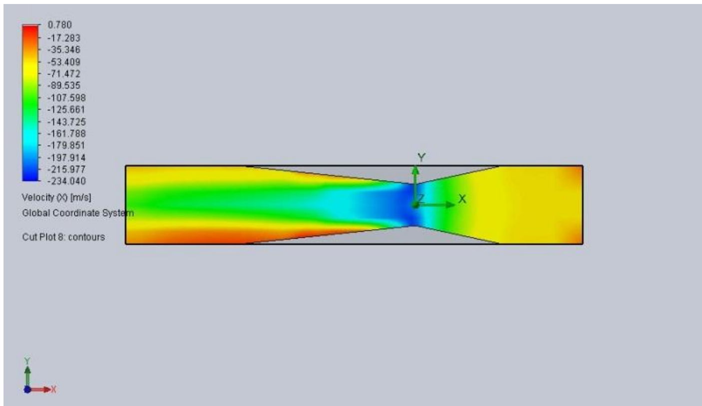


Fig 11: Velocity plot for final design

IV. CONCLUSION

A venturi, generally is used in diverse purpose for various applications in fluid dynamics involving either liquid or gas. In this project it is brilliantly used in reducing power of engine. As in this competition all the 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. One such technology used is supercharging of air downstream the venturi to increase the pressure on engine side. A venturi in itself can allow a maximum of 0.0703 kg/s of air flow to engine, considering no losses in friction and turbulence.

From all the research done till now it is clear that at converging angle of 12 degree and diverging angle of 6 degree we get maximum recovery of pressure. Computational fluid dynamics played important role in all analysis.

ACKNOWLEDGMENT

I would like to express my sincere thanks to all my friends who helped me to bring up this paper from nowhere to its publication. My sincere thanks to Prof. Bansode of Mechanical department who helped me out in performing computational fluid dynamics accurately, after lots of practice and hours put into it.

I would like to extend my gratitude towards Prof Joglekar of Mechanical Department who taught me basics of fluid dynamics and made me understand accurately what I was doing in every single stage of this project.

Finally I would like to thank D B Designs Pvt Ltd for sponsoring Rapid Prototyping Service which manufactured our venturi.

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