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Design and Analysis of Restricted Air Intake for Performance Optimization of Single-Cylinder Engine

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Abstract:
The aim of this paper is to design and analyze a restricted air intake for a single-cylinder engine of 373.2cc displacement. As per, the guidelines of the formula student technical committee, in order to limit the peak performance of an engine, the engine must breathe from a single circular restrictor not more than 20mm in diameter such the single cylinder engine is compatible with the multi-cylinder engine during a race. The goal of this design and analysis procedure is to maximize mass flow rate of air through restrictor keeping the minimum pressure drop across it. This has been achieved by performing a number of iterations on a venturi by altering the normal converging length and normal diverging length. This paper includes a brief comparison of venturi and orifice, brief for venturi and its positioning, need of plenum, the function of a runner, calculative study for mass flow rate and the simulative study of mass flow rate by the strong assistance of pressure drop across the air intake assembly.

Keywords — Single-Cylinder Engine, Restricted Intake, Air Flow, Flow Simulation, Race Car Intake.

I. INTRODUCTION

The naturally aspirated single-cylinder engine used for the study is built for the sole purpose of racing. During a race, the engine always runs at higher revolutions per minute. At such speed to extract the maximum out of an engine is only possible when it does get proper air supply or appropriate air-fuel mixture. The air intake of such engines is designed with a purpose of maintaining a minimum pressure difference between atmosphere and cylinder at any cost. These modern high-performance engines have a sophisticated design of inlet ports, plenum and runners to meet the requirements. The basic function of air intake is to collect air from surrounding atmosphere and transfer it to the cylinder through throttle body with the best air-fuel mixture for that particular throttle input.

In various motorsport events, a wide range of engines is used under the guidelines provided by the technical committee. For formula student event, the engine displacement limit is set to a maximum of 610cc and any engine meeting this rule can be used for engine package of the car; this opens the door for use of single-cylinder engines and multi-cylinder engines based on the purchasing power of the team.

To maintain an ethical competition the 20mm intake restrictor plays a key role. When mostly multi-cylinder engine packages are used a single-cylinder package ideally cannot be compatible in a race, to balance this intake restrictor is introduced, which when placed in the path of engine intake has a great impact on the engine in terms of performance. In order to restore the performance of the engine, the intake restrictor must be designed in such a manner that the engine breathes with the restrictor in the same manner as it was breathing without the restrictor. It is possible only when the maximum mass flow rate of air through the restrictor occurs with the minimum pressure drop across it, this is a challenge.

In this paper the design and analysis of the restricted intake for a single-cylinder four-stroke engine with the following specification is performed:

TABLE I
STOCK ENGINE SPECIFICATION

Engine	KTM 390
Displacement	373.2cc
Torque	35 N-m @7250 rpm
Power	32 kW @9500 rpm
Throttle Body Diameter	48 mm

In general, restricted intake should have the arrangement of parts in order of Throttle > Restrictor > Engine Intake. Ideally, after restrictor plenum and runner are used which act as air storage pack as well as they reduce the velocity of air. For our intake system, we are using the venturi profile restrictor having converging and diverging ends on each side of the 20mm restrictor.

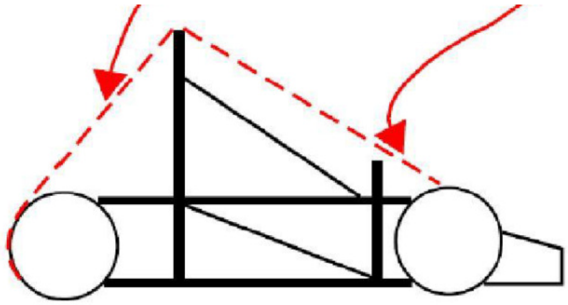

Fig. 1 Side view surface envelope

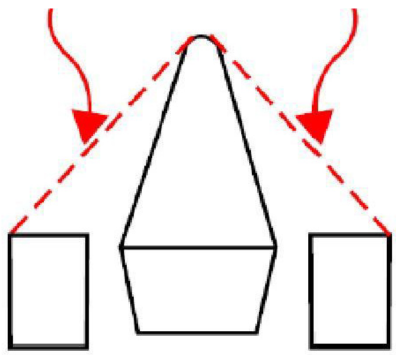

Fig. 2 Rear view surface envelope

All assembly parts of engine intake including throttle body, restrictor, and runner, including air filters must lie within the surface defined by the top of the main roll hoop and outside edges of all four tires as shown in fig. 1 and fig. 2.

II. Procedure

A. Selection of Restrictor Structure

The two options for a device which can act as restrictor are:

- Orifice
- Venturi

TABLE II
COMPARISON BETWEEN ORIFICE AND VENTURI

Factors	Orifice	Venturi
Coefficient of Discharge	Low	High
Pressure Drop	Huge	Small
Cost	Cheap	Expensive
Manufacturing	Easy	Difficult
Ease of Installation	Easy	Not Easy

Considering the above-mentioned factors only the best option between these two is selected and that is venturi because it is very efficient as compared to an orifice. Though the manufacturing is difficult and expensive it can be compensated.

B. Venturi Structure and its Positioning in Car

A venturi is a structure having a narrow throat section in between two wider sections contributing to the converging and diverging effects in the flow path.

As per norms of air intake restrictor, the throat diameter of venturi is set to 20mm; both converging and diverging ends opening would be of 48mm internal diameter similar to the internal diameter of the throttle body.

The two available options for positioning of air feeding of intake system:

- Top of the car
- Side of the car

TABLE III
COMPARISON BETWEEN TWO POSITIONS OF AIR FEEDING

Factors	Top of the Car	Side of the Car
Impurities in Air (like dust)	Less	High
Damage from Debris	Low	High
Turns in Intake Structure	Small	Sharp
Assembly	Easy	Difficult

Considering, the above-mentioned factors, the top of the car position for air feeding of intake system is a very healthy choice for an engine.

According to the roll-cage design of the car, a venturi of length more than 400mm cannot be accommodated; this became one more constraint for the design.

C. Plenum

A plenum is basically an air reservoir and functions to reduce the velocity of air, which is very high just after exiting venturi throat. It is used mostly in multi-cylinder engine to maintain the balance of air supply among cylinders due to different valve opening time. The size of plenum should ideally be 1.5 times the displacement of the engine.

But, using plenum is not a considering option because:

- This intake restrictor design and analysis is for a single-cylinder engine, for which it is not necessary to use a plenum.
- Since it is not necessary, use of this part adds to the extra cost.

D. Runner

A runner is the path guide of air flow to the engine cylinder. For the top of the car air feeding of intake system the runner would be bent at a radius so as to connect the venturi outlet and engine intake; also to avoid the sudden sharp turn in air flow. The internal diameter of runner would be set to 48mm similar to that of throttle body internal diameter.

E. Design Calculations

From the above discussion, the assembly order of various parts in air intake system would be:

Air Filter > Throttle Body > Restrictor (Venturi) > Runner > Engine Intake.

For flow simulation the boundary condition parameters for inlet assembly are sufficient that is the total pressure at the inlet, but we don’t have boundary condition parameters for the outlet of assembly. The following chocked flow equation was used to calculate mass flow rate at the outlet of assembly:

Mass flow rate: [9]

$$\dot{m} = r\,V\,A \qquad \text{- (a)}$$

For an ideal compressible gas,
Mass flow rate:

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

Since the restrictor diameter is very small that is 20mm.
Therefore, mass flow rate is at maximum when,
M = 1

At these conditions, flow is choked.

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

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

On substituting the following standard data values in equation (c):
A = 3.14×10^{-4} m^2 (20mm restrictor)
R = 0.286 kJ/kg-K
γ = 1.4
T_t = 300 K
p_t = 101325 Pa
Mass flow rate:

$$\dot{m} = 0.072 \text{ kg/s}$$

Now, all the necessary boundary conditions are at inlet total pressure is 101325 Pa, at outlet mass flow rate is 0.072 kg/s and surface goal is total average pressure at the outlet.

F. Design Analysis (Flow Simulation)

Since this analysis for air intake so, therefore, internal flow simulation was performed keeping the air as the fluid substance. The working of venturi and all the boundary conditions are known. This air intake analysis has one single goal that is to minimize the pressure drop across it and to start analysis began by assuming dimensions i.e. normal length of converging part as well as diverging part of venturi keeping its working principle in mind.

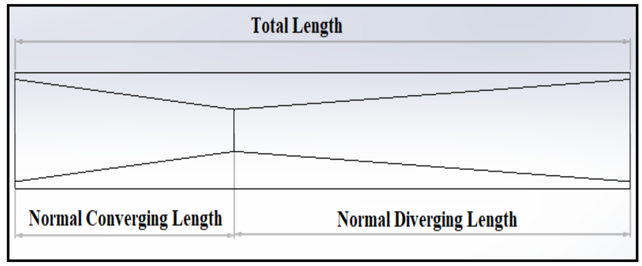

Fig. 3 Venturi Structure Diagram

The following is the table of the normal length of converging part and diverging part for iteration:

TABLE IV
ITERATIONS TO BE PERFORMED

Iteration Number	Normal Converging Length	Normal Diverging Length
1	120	280
2	125	275
3	140	260
4	142.5	257.5
5	145	255

All the iterations mentioned in Table IV were performed and the standard mesh quality was used for complete volume; the following CFD results were obtained for the number of iterations:

TABLE V
CFD RESULTS OF ITERATIONS

Iteration Number	Normal Converging Length	Normal Diverging Length	Pressure Drop
1	120	280	9162.24
2	125	275	6503.29
3	140	260	5964.28
4	142.5	257.5	5609.41
5	145	255	6462.36

The pressure cut plots for CFD analysis of above-mentioned iterations are as follows:

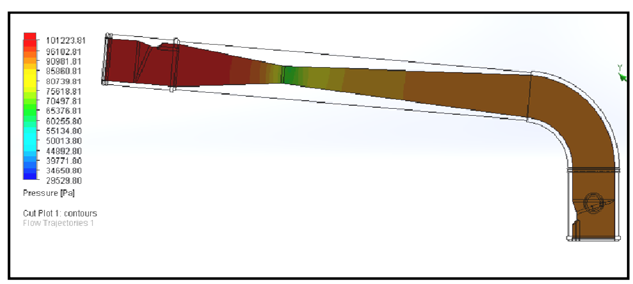

Fig. 4 Pressure Cut Plot of Iteration Number 1

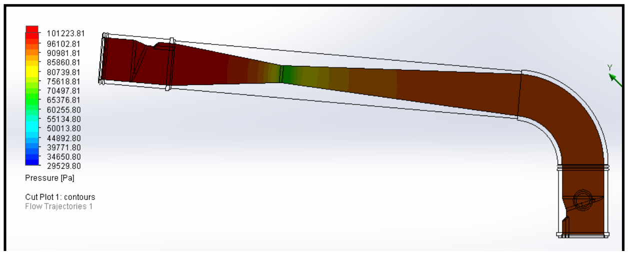

Fig. 5 Pressure Cut Plot of Iteration Number 2

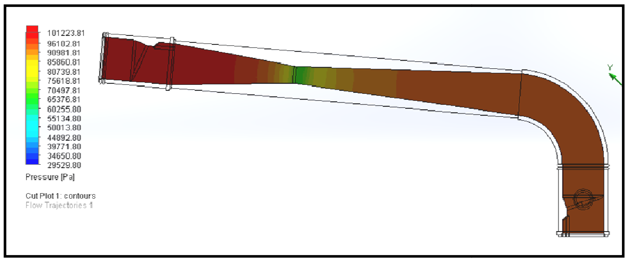

Fig. 6 Pressure Cut Plot of Iteration Number 3

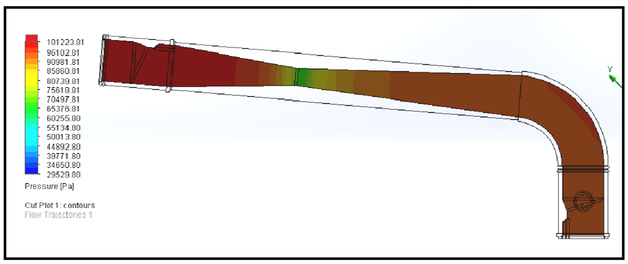

Fig. 7 Pressure Cut Plot of Iteration Number 4

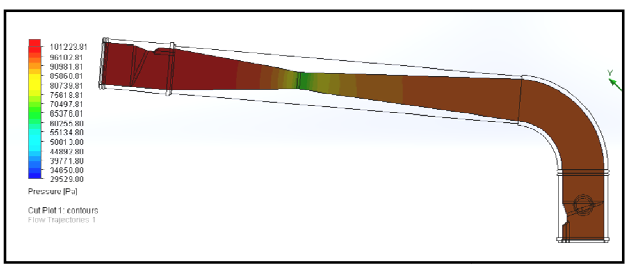

Fig. 8 Pressure Cut Plot of Iteration Number 5

These iterations are few out of many iterations that were performed. During the CFD it was observed that with a slight change is the normal length of converging part could create the drastic variation in pressure difference.

From iteration results in Table V, an observation that the pressure drop across the restricted air intake is minimum (5609.41Pa) when venturi is designed having a normal converging length of 142.5mm and normal diverging length of 257.5mm.

III. CONCLUSION

The purpose of maximizing the mass flow rate through restrictor by minimizing the pressure drop across it is to maintain the peak performance of an engine.

As summarized in section II-A, due to numerous advantages, the venturi can be preferred as an air intake restrictor over the orifice. Because of the restrictor, the resulting losses in power has been minimized by design and optimization of venturi in such a manner that there is the mass flow rate of 0.072kg/s through 20mm throat with a minimum pressure drop across it; considering that the throttle is wide-open for air intake.

The venturi of following design specification can be used for extracting the best performance from the engine:

- Total Length = 400mm
- Normal Converging Length = 142.5mm
- Normal Diverging Length = 257.5mm
- Throat Diameter = $20_{-0.2}$mm

The manufacturing of venturi and runner could be done by 3-D printing; this is because 3-D printing is fast, most precise and accurate manufacturing process for such sophisticated venturi- runner designs.

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REFERENCES

[1] *D. Kennedy, G. Woods and D. Forrest, "Development of a New Air Intake and Exhaust System for a Single Seat Race Car," in Irish Transport Research Network, Cork, 2011.*

[2] *A. Singhal and M. Parveen, "Air Flow Optimization via a Venturi Type Air," in World Congress on Engineering, London, 2013.*

[3] *O. N. Deshpande and N. L. Narappanawar, "Space Advantage Provided by De-Laval Nozzle and Bell Nozzle over Venturi," in World Congress on Engineering, London, 2015.*

[4] *P. V. Wable and S. S. Shah, "Air Flow Optimization of Venturi Type Intake Restrictor," International Journal of Engineering Development and Research, vol. 5, no. 4, pp. 483-489, 2017.*

[5] *P. Nallawar, V. Narwade, P. Patole, V. Lokhande and A. Apte, "Design and Analysis of Intake Manifold using 3-D CFD Analysis," International Journal of Mechanical and Production Engineering Research and Development, vol. 5, no. 5, pp. 115-122, October 2015.*

[6] H. K. Versteeg and W. Malalasekera, An Introductioon to Computational Fluid Dynamics, England: Longman Scientific and Technical, 1995.

[7] A. Sayyed, "Air Flow Optimization through an Intake System for a Single Cylinder Formula Student (FSAE) Race Car," International Journal of Engineering Research & Technology, vol. 6, no. 1, pp. 183-188, January 2017.

[8] SAE India, "Rulebook of Student Formula," January 2018. [Online]. Available: http://suprasaeindia.org/.

[9] N. Hall, "Mass Flow Choking," NASA Glenn Research Center, [Online]. Available: https://www.grc.nasa.gov/www/k-12/airplane/mflchk.html#.

[10] V. D. Ravindra and P. K. AV, "Design and Optimisation of an FSAE Restrictor with Structured Mesh," International Journal of Science and Research, vol. 4, no. 10, pp. 1995-1997, October 2015.

[11] S. N. Waghmare, N. S. Karekar and P. P. P. Kara, "Design & Analysis for Intake System of Formula SAE Car," International Journal of Engineering Technology, Management and Applied Sciences, vol. 4, no. 2, pp. 116-121, February 2016.

[12] P. A. Shinde, "Research and Optimization of Intake Restrictor for Formula SAE Car Engine," International Journal of Scientific and Research Publications, vol. 4, no. 4, April 2014.