ENHANCING THE PERFORMANCE OF SINGLE CYLINDER MOTORCYCLE ENGINE FOR FORMULA STUDENT VEHICLE BY OPTIMIZING INTAKE AND EXHAUST SYSTEM.

[1] Shubhamkumar Mangukiya, [2] Mr. Ripen Shah, [3] Mr. Mazar Shaikh
[1] PG Scholar, [2] Asst. Professor, [3] Asst. Professor
[1] Department of Mechanical Engineering,
[1] Silver Oak College of Engineering & Technology, Ahmedabad, India.

Abstract: This study takes a look in to Optimizing the Design of Intake & Exhaust System of a Single Cylinder Motorcycle Engine for Formula Student Vehicle. The engine and vehicle design in the Formula SAE competition has to comply with a strict regulation. Regarding the engine intake, an air restrictor of circular cross-section no greater than 20 mm must be fitted between the throttle valve and the engine inlet. The design of Intake system for the internal combustion engine depends on many parameters like mass flow rate, turbulence intensity etc. Exhaust system of Formula student car is to be designed with the aim of reducing the noise level of stock engine and restricting it below 110db. The design of an exhaust manifold for the internal combustion engine depends on many parameters such as exhaust gas back pressure, velocity of exhaust gases etc. In this study, the recent research on design of intake system & exhaust system, their performance evaluation using Numerical methods (CFD) are being analyzed.

***Index Terms* – Formula Student, Intake restrictor, Intake runner, Plenum, Exhaust System.**

I. INTRODUCTION

Formula SAE/Formula Student is a competition in which University students design, manufacture and compete in formula student vehicles. These competitions are held all over the world at more than 20 locations. Formula SAE competition has imposed a rule of including a 20 mm restrictor in the intake system allowing all the air flow to the engine through this restrictor whether it may be a single cylinder or multi-cylinder engine. An IC engine requires proper air-fuel mixture for its efficient performance. Due to 20 mm restrictor rule, the designed intake of engine is reduced. This drastic change reduces the air flow to the engine thereby controlling its power output. The objectives behind designing the intake system & exhaust system are to allow maximum possible air flow with minimum pressure drop and reduce sound level below 110db. Engines used in this competition are limited to 710cc. This Research paper deals with optimizing the design of intake system and exhaust system for Formula Student Vehicle of KTM Duke 390cc engine. The engine has a six speed manual gearbox and weights around 35 kg. The engine produces 43 hp power at 9000 rpm and 35 Nm torque at 7000 rpm.

For the Research work the Intake and exhaust system of Car GTM17 of Team GT Motorsports is taken as a reference.

Fig 1 Intake System of GTM 17

Fig 2 Exhaust Pipe of GTM 17

The Intake and Exhaust system of the car GTM17 Shown in the Figure 1 & 2, which dimensions are as follow:
Runner Length: 405 mm, Plenum Volume: 1.8 Litres, Exhaust pipe length: 780 mm, Length of Venturi: 200 mm

II. RESEARCH PROCEDURE

2.1. Intake System

2.1.1. Intake Restrictor

The Intake restrictor is a component mandated by the rules of the FSAE competition, in which all the air entering the engine must go through this 20mm diameter gap. There are two types of instruments which can be used as restrictor 1.Orifice plates 2.Venturi tubes. The Orifice plate is a simple rectangular plate with a hole drilled in it. The Venturi tube is a tube having a converging and diverging section with a throat section of circular shape connecting the both. The choice of restrictor to be used is laid out in below comparison.

Table 1 Comparison of Orifice plate and venturi tube

Orifice plate	Venturi tube
It has coefficient of discharge is between 0.58 to 0.65.	It has coefficient of discharge is between 0.95 to 0.975.
On a scale of high to low the pressure loss is medium.	On a scale of high to low the pressure loss is low.
The manufacturing cost of Orifice plate is low.	The manufacturing cost of Venturi tube is high.
The Process of manufacturing is easy as there is just a hole to be drilled on a plate.	The Process of manufacturing is difficult as there is a conical profile to be made.

As shown in table 1 design of a venturi gives good co-efficient of discharge and minimize pressure loss so, it is preferable as an Intake Restrictor.

From the Various experiments & literature survey, require size of venuri is given below:
Entrance: Diameter: 32mm, Length: 50 mm, Throat : Diameter: 20 mm, Length: 20 mm
Exit : Diameter: 34 mm, Length: 80 mm, Converging & Diverging Angle: 12 degree & 6 degree

2.1.2. Plenum

2.1.2.1. Shape of Plenum

For a basic, non-variable-length, normally aspirated configuration, this usually suggests one of two general shapes, the "spherical" or the "log". Using a single cylinder engine, where only one intake port is there than spherical shape of plenum is most preferable. Spherical shape plenum in a single cylinder engine gives proper path to the air flow.

2.1.2.2. Size of Plenum

The size of the plenum of Intake system directly affects the performance of the engine. Besides the point of packaging the plenum, arguable the largest component of the air intake system, within the envelope of the FSAE vehicle, it has to satisfy both the steady state and transient requirements of the engine.

The volume of Plenum must not be too small. It is required that the plenum of Intake System be at least the size of the engine capacity, such that it holds enough air to provide for the cylinders during each suction stroke. It is also recommended that the size be at least three or four times to allow the engine to be able to draw air while maintaining a stable pressure in the manifold. From the various tests it is determined that for a steady state analysis, the larger the plenum, the better, as it increasingly approximates to an open atmospheric environment from which the engine can draw air from.

2.1.2.3. Cylinder Runner

The runner of an intake system is the primary tuning tool for modifying volumetric efficiency. Changing the length of the runner is usually the simplest approach with a given engine design, with the cross sectional area, and therefore diameter, already known basis based on the cylinder head cross sectional area prior to the valve. Changing the runner length also has the advantage of being infinitely adjustable, where the diameter is limited to available pipe diameters unless more expensive manufacturing processes such as machining or rapid prototyping are used. For these reasons, runner length modification is practical and the basis for experimentation.

Calculation for Cylinder Runner Length

- Peak Torque of the engine at 7000 rpm and Max Power of the Engine at 9000 rpm but engine remains at 8000 rpm in the dynamic condition.
- The intake valve is open 226 degrees out of 720 degrees in total, so Duration of intake valve closing = 720-226 = 494 degree = 1.3722 rev.
- Speed of sound in air at 30 degrees Celsius is 343 m /sec.
- The engine speed is required to be described in rps (revolution per second) as SI units are preferred: 133.3333 rev/sec.
- Time require for one revolution = 1/133.333 sec = 0.007500 sec.
- The time it takes between when the valve closes and when it opens again is: 1.3722*0.007500 = 0.01029 sec.
- The wave moving at the speed of sound during that time will cover the distance of : 343*.01029 = 3.529 m
- Since the pressure wave has to travel back and forth, the optimum length for the intake runner when it comes to using the

ramming phenomenon at 8000 rpm is half of the calculated length (=1.76 m). A runner length of approximately 1.76 m would be very difficult to fit in the car.

- To address the ungainly size of the intake runner length required to utilize the ramming phenomenon a solution is to shorten the runner length to exactly one sixth of the calculated length. That will provide a runner length of 0.293333 m = 293.33 mm which is conveniently short enough to incorporate the component within car. If the runner length is shorten to one sixth, making it 0.293333 m, the pressure wave will travel up and down the pipe six times before the intake valve opens again. But it still arrives at the valve at the same time. This is a way to shorten the intake runner and still get some benefit from the pressure wave.
- The length of the runner in engine is 100 mm, while the length of throttle body is 85 mm, so for the design of intake system the lengths of runner require is 293.33-185 = **108.33** mm.

2.2. Exhaust System

2.2.1. Exhaust Pipe

Design of exhaust system involves evaluation of pipe diameter, length, and geometry. To control back pressure an ideal length is required to allow for reflected pressure waves to arrive back at the exhaust port in time for the valve overlap period. Changes in exhaust gas temperature throughout the engine revs results in a dynamic speed of sound, c, and therefore the optimum length can only be accounted for at one engine speed and its modes thereafter. Also, any change in geometry within the exhaust system will result in reflected pressure waves, and also significantly affect the length of the exhaust pipes. Because of the complicated nature of the scavenging effects, literature reviews often provide guideline equations which are suited to a specific engine assuming an ideal straight exhaust pipe. Two equations by Smith equation (1972) and Bell equation (1988) give estimates lengths from cylinder characteristics and expected engine speeds and are given by

$$P = \frac{ASD^2}{1400 * d^2} \text{feet}$$

(Equation 1)

$$P = \frac{850(180 + B)}{R} - 3 \text{ inch}$$

(Equation 2)

where P represents pipe length, A is exhaust open period in degrees, S is stroke length in inches, D is cylinder bore in inches, d is exhaust valve port diameter in inches, B is the degree of exhaust opens before BDC (bottom dead centre), and R is the target rpm. Equations (1) and (2) result in pipe length estimates of 533 mm and 763 mm. respectively. So, for better result 615 mm, length of exhaust pipe is finalized.

At low engine speeds, high exhaust gas velocities are necessary to achieve quick throttle response. By means of conservation of mass, a small diameter exhaust pipe will result in higher gas velocity, conducive to throttle response for acceleration. However, without sufficient cross sectional area, small diameter pipes may limit the mass flow rate needed to expel all combusted gases at higher rpm. Therefore, a compromise must be met to sufficiently provide high velocity flow with proper flow rate at peak engine speeds. Using tabulated data from Bell equation (1988) which accounts for both gas velocity and mass flow rate, a pipe diameter of 1.6 inch. was found to provide sufficient flow for engine speeds up to 8,000 rpm.

$$D^2 = \frac{cc}{(P + 3) * 25}$$

(Equation 3)

Where, D = Diameter of Exhaust Pipe
P = Length of Exhaust Pipe
CC = Cylinder Volume

2.2.2. Exhaust Muffler

A muffler is a device designed to suppress to an acceptable level the noise created by the exhaust gages expelled from an engine's cylinders. Muffler design influences not only the audibility of pressure wave pulsing from an exhaust system, but can also markedly affect power production, according to the amount of restriction offered by the flow path for combustion gases.

Generally, mufflers consist of a perforated tube, enclosed by a muffler body. This body contains packing, or absorption material, usually in the form of fiberglass. The basic operating principle is the exhaust gages flow into the tube and are then forced out through the many perforations, where these gages expand. Muffler design has evolved over a relatively long period of time, resulting in some well developed and well tested designs being available today. There are broadly three muffler types available.

1. Baffle Type:
2. Reverse Flow type:
3. Straight- Through Type

Table 2 Comparison of flow for various muffler types

Muffler Type	% Flow Compared With Equivalent Straight Pipe
Baffle	38
Reverse Flow	59
Straight- Through	92

This testing indicates significantly better flow through a straight-through type muffler compared with the other two designs. In the pursuit of optimized power, all induction and exhaust components must work to produce the best potential for increased power. Therefore, a straight-through muffler, offering minimal flow restriction, is chosen for its anticipated ability to offer superior performance compared with other tested design.

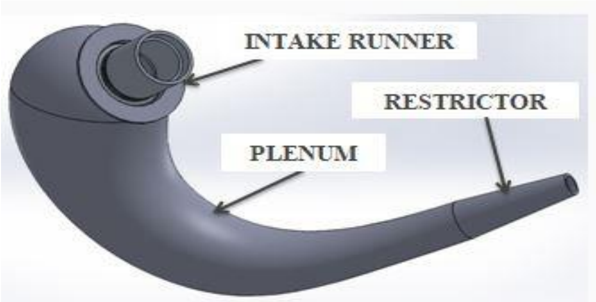

Fig 3 Design of Intake System

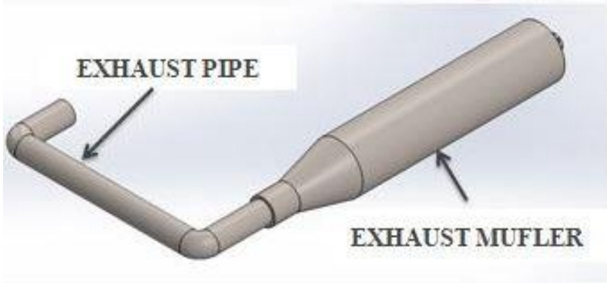

Fig 4 Design of Exhaust System

III. Manufacturing

3.1 Intake System:

3.1.1. Mould Preparation

Moulds fall into two groups – male and female. Glassfibre is laminated on the outside of a male mould and on the inside of a female mould. The desired finish whether it be smooth or textured will be on the side nearest to the mould. A female mould would be used for example to produce car body parts, boat hulls etc. where the finish has to be on the outside. A male mould would be used for example on baths, shower trays etc where the finish has to be on the inside.

3.1.2. Master Mould:

To produce a mould, you need a pattern or former commonly called a “plug” – an exact replica of the finished item. The plug can be made from almost any material as long as it is made rigid, accurate, and dimensionally stable and set on a solid foundation. It is necessary to have slight taper on side walls of your plug so that the mould can be removed easily. Typically, a large mould would need to be a rigid wood frame covered in hardboard, plywood or MDF, clay or plaster can be used and reinforced with wire netting and Hessian, as toolmakers we tend to manufacture from wood, before applying the primer, fill in any grain, holes, dints and joints as any defects will show on your finished mould. Hammer down any nails using a punch and counter sink, any screws or nails cover using polyester body filler, the surface must be smooth and free from blemishes. Seal the wood with a hard varnish such especially if using MDF, a good sand and sealer or shellac varnish can be used. Then sand down with 60 grit sand paper. Plaster of Paris used to give continuous and smooth shape to the mould.

3.1.3. Finished Intake

The component-making process involves building up a component on the fiberglass mold. The mold is a negative image of the component to be made, so the fiberglass will be applied inside the mold, rather than around it.As in the mold-making process, release agent is first applied to the mold. Colored gelcoat is then applied. Layers of fiberglass are then applied, using the same procedure as before. Once completed and cured, the component is separated from the mold using wedges, compressed air or both.

Fig. 5 Mould of Intake System

Fig. 6 Intake System

3.2. Exhaust System:

3.2.1. Welding:

Welding is the main focus of steel fabrication. The formed and machined parts will be assembled and tack welded into place then re-checked for accuracy. A fixture is used to locate parts for welding if multiple weld elements have been ordered.

Exhaust Pipe is made by welding various parts of requires length to give proper flow to the exhaust gases.
A Straight through muffler is bolted with exhaust pipe, which gives minimum backpressure.


Fig 7 Exhaust pipe


Fig 8 Exhaust System

IV. Experiment Result:

4.1. Idling Speed (Idle RPM):
Idling speed is the rotational speed an engine runs at when the engine is uncoupled from the drive train and the throttle pedal is not depressed.

Table 3 Idling Speeds of Various Engine Types

Sr. No.	Engine Type	RPM
1.	Stock Engine	1300
2.	Engine with Reference design	2100
3.	Engine With New Design	1500

4.2. Throttle Position sensor:
The throttle position sensor (TPS) is mounted on the throttle body and monitors the position of the throttle opening. The TPS sensor is a potentiometer, providing a variable resistance depending on the position of the throttle valve. The sensor signal is used by the engine control unit (ECU) as an input to its control system. The ignition timing and fuel injection are altered depending on the position of the throttle valve, and also depending on the rate of change of that position. The TPS value is displayed on a scan tool as percentage of throttle opening. The ECU uses this information to estimate air flow and engine load.

Table 4 Test Reading of Throttle Position Sensor

Sr. No.	RPM	Stock Engine (%)	Engine with Reference Design (%)	Engine With New Design (%)
1.	Idle	20	28	23
2.	4000	34	39	36
3.	6000	48	56	49
4.	7000	59	69	60
5.	8000	71	82	72
6.	9000	82	91	84

4.3. Manifold Absolute Pressure Sensor:
Manifold Absolute Pressure Sensor (MAP) is connected to the intake manifold through a vacuum hose. The vacuum in the intake manifold actuate the MAP sensor's diaphragm. The ECU calculates the fuel mixture composition depending on the signal of MAP and engine speed. When there is a high level of vacuum in the intake manifold (e.g. Idling), MAP output signal is relatively low and the onboard controller provides less fuel. (1 bar = 29 hg (inches of mercury).

Table 5 Test Reading of Manifold Absolute Pressure Sensor

Sr. No.	Rpm	Stock Engine (hg)	Engine with Reference Design ((hg)	Engine With New Design (hg)
1.	Idle	18.2	19.3	18.3
2.	4000	18.8	20.1	18.9
3.	6000	19.4	21.5	19.5
4.	7000	20.2	22.1	20.4
5.	8000	21.6	23.2	21.8
6.	9000	22.4	24.1	22.6

4.4. Lambda Sensor:
Lambda sensor is mounted on the exhaust manifold so that exhaust gases can be on the streamline of its working surface. Lambda sensors are essentially chemical generators. They work like a miniature generator and produce its own voltage. For example, by constantly measuring the oxygen content inside the exhaust manifold and comparing it to the air outside the engine, a voltage is generated if the comparison shows little or no oxygen in the exhaust manifold. If the oxygen sensor measures the correct mixture, the voltage drops and an appropriate signal is sent. The ECU receives the voltage and responds by making necessary adjustments

of the overall fuel-air mixture in the engine based on it. The non-stop exchange of signals between the sensor and the ECU ensures that the constant adjustments depending on the needs of the engine are made.

Table 6 Test Reading of Lambda Sensor

Sr. No.	Rpm	Stock Engine	Engine with Reference Design	Engine With New Design
1.	Idle	0.720	0.650	0.700
2.	4000	0.710	0.670	0.690
3.	6000	0.700	0.660	0.685
4.	7000	0.710	0.630	0.690
5.	8000	0.700	0.640	0.695
6.	9000	0.720	0.650	0.700

V. Conclusion:

For a single cylinder, non variable length intake system Runner length & Plenum volume are most important factors for optimum design of Intake system. Ram theory is very helpful to decide accurate runner length according to Engine speed. Minimum bends in the geometry of exhaust system and straight through muffler helps to reduce backpressure and noise of exhaust gases.

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