Optimizing the Design of Intake & Exhaust System of a Single Cylinder Motorcycle Engine for Formula Student Vehicle

Shubhamkumar Mangukiya
Research Scholar, Department of Mechanical Engineering, Silver Oak College of Engineering & Technology, Gota Ahmedabad, Gujarat, India.

Mr. Ripen Shah
Assistant Professor, Department of Mechanical Engineering, Silver Oak College of Engineering & Technology, Gota Ahmedabad, Gujarat, India.

Mr. Mazar Shaikh
Assistant Professor, Department of Mechanical Engineering, L.D. College of Engineering, Navarangpura Ahmedabad, Gujarat, 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.

Keywords: Formula Student Vehicle, Intake Restrictor, Intake runner, Plenum, Exhaust Muffler.

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 entering the engine through this 20mm diameter gap. 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.

Research Procedure
Intake System

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

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

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

2 Plenum

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.

2.2 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.

Fig. 1 Design of Venturi with 20mm Intake Restrictor

Fig. 2 Design of Plenum shape and size
Plenum Shape: Spherical shape
Plenum Volume: 3.5 litres

1.3 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: 133.333 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*0.01029 = 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 the car. If the runner length is shortened by 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 the engine is 100 mm, while the length of the throttle body is 85 mm, so for the design of the intake system the lengths of runner required is 293.33 - 185 = 108.33 mm.

![Fig. 3 Design of Intake Runner](image)

**Length of Runner: 108 mm**

### Exhaust System

#### 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:

\[
P = \frac{850(180 + B)}{R} - 3 \text{ inch} \quad \text{(Equation 2)}
\]

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.

\[
P^2 = \frac{1400AS^2}{d^2} \quad \text{feet} \quad \text{(Equation 1)}
\]

\[
P = \frac{CC}{(P + 3) \times 25} \quad \text{(Equation 3)}
\]

Where, D = Diameter of Exhaust Pipe

P = Length of Exhaust Pipe

CC = Cylinder Volume

![Fig. 4 Design of Exhaust Pipe](image)

**Length of Exhaust Pipe: 40.64 mm**

#### 2 Exhaust Muffler

A muffler is a device designed to suppress to an acceptable level the noise created by the exhaust gases 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 gases flow into the tube and are then forced out through the many perforations, where these gases 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

<table>
<thead>
<tr>
<th>Muffler Type</th>
<th>% Flow Compared With Equivalent Straight Pipe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baffle</td>
<td>38</td>
</tr>
<tr>
<td>Reverse Flow</td>
<td>59</td>
</tr>
<tr>
<td>Straight-Through</td>
<td>92</td>
</tr>
</tbody>
</table>

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.

Analysis

To validate design an analysis of CAD model of the systems are carried out and the results of analysis are as shown in Fig. 6 & Fig. 7. Velocity vectors show the direction of flow takes inside of intake and exhaust system. The analysis shows the values of velocity of air and exhaust gases at the inlet and outlet of the systems. At the inlet of intake system the velocity of air is around 475 m/s which decrease to 100 m/s in the plenum. Velocity of exhaust gases at exhaust port is around 290 m/s and decreases to 50 m/s at the end.

Conclusions

For a single cylinder, non variable length intake system the plenum volume should be 3 – 3.5 Litres. Ram theory is very helpful to decide accurate runner length according to speed. Minimum bends in the geometry of exhaust system and straight through muffler helps to reduce backpressure and noise of exhaust gases.

References