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Designing & Validating a New Intake Manifold for a Formula SAE Car

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***Abstract*— This paper gives the importance of the intake system in a car and how it affects the performance of the car, designs and then validates a new intake system by computational & analytical analysis used by the Formula SAE Car of Daksh Racing Team, which participated in FSAE Italy2010. The new air intake system was developed according to the rules of formula student competition, which requires a restriction of 20mm to be placed before the air intake system with all engine airflow passing through the restrictor. The major results obtained are discussed and listed.**

***Keywords*— CFD Analysis, Formula SAE, Intake Manifold (Plenum), Manifold Design Calculations**

I. INTRODUCTION [3][4][10]

The intake manifold is just a series of cylinders that distributes air evenly to each of the engine cylinders, which enables right amount of air to mix with right amount of fuel. Internal combustion engines mostly have a four-stroke process; the first stroke (known as the suction stroke) air is sucked from plenum into each cylinder from inlet valves. Intake valves then gets closed for the compression, combustion and exhaust strokes (exhaust valves used during exhaust stroke) and intake opens only when the cycle is repeated. Intake manifold is responsible that whenever the valve opens for each intake stroke each cylinder gets the same amount of air. The basic function of an air intake system is to provide the throttle body with air where it is then mixed with the fuel and then sent to combustion chamber. The intake system controls how the engine will perform at various Rotations per minute (RPM)'s.

An intake system consists of four main parts:

1) Filter which is normally a special paper element, conical in shape and provides filtered air from dust and dirt particles to the engine.

2) Then from Filter to Plenum Runner is the tube (pipe) which provides the air from filter to the plenum.

3) And then the Plenum, it is the reservoir of air that supplies the engine with equal amount of air. The Intake Runners are the tubes that take the air from plenum to the throttle bodies. Long runners are basically used to give good top end speed while on the other hand when good low end torque is required short runners are used.

Most of the cars will require most of their power certain RPM range, which is known as the 'Peak Torque Location'. The range of which is dependent on the kind of track the car is driven on. Tracks with short straights and sharp turnings will require its engine adjusted for low end torque to easily counter out of the corners and therefore will have a low peak torque. On the other hand open tracks with long straights and fewer curves will require engine adjusted for good top end speed and thus subsequently will have a higher peak torque location.

Peak torque location is explained by the three main features of the intake system 1) plenum volume 2) runner length 3) runner area.

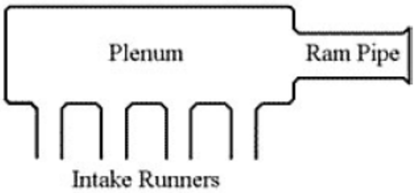

Figure 1: Features of the intake system

II. CALCULATIONS [1][6][7][3]

Tunnel Ram intake runners with bell mouth ends were chosen for easy manufacturing and also for their extensive use in race applications. The runner lengths were chosen for effective 3rd order reflections of the reflected wave from the bell mouths, for 9000 rpm (which is on the lower side) considering that the maximum engine rpm was near 16000 rpm. The method of ram charging is very efficient in increasing power by about 15 to 20%. The lower rpm was again designed for good low speed acceleration.

Intake manifold design at 9000 rpm

Intake valve opens = *22BTDC (Before top dead cycle)*
Intake valve closes= *43ABDC (After bottom dead cycle)*
Crank angle *(inlet valve is open) = 245 degrees*
Crank angle *(inlet valve is closed) =475 degrees.*
Time *(inlet valve is closed) =0.008796 s= EVCD (Effective valve closed duration)*

Using david vizerds formula*;*
L= *221mm* (1)

Diameter of Intake Runners*:*

$$\sqrt{(target\ rpm \times displacement \times percent\ volumetric\ efficiency) \div 3330)} = 1.20737\ inches = 30.6mm \quad (2)$$

As the throttle body bore in the Honda cbr engine (stock) is 38mm; we keep intake runner diameter as 38mm.

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Using formula from GRAPE APE racing,

$$L = \left((EVCD \times 0.25 \times V \times 2) \div (RPM \times RV)\right) - (0.5 \times diameter\ of\ runner\ inches) \quad (3)$$

Table 1: Results of calculation for Equation 2

RV(Reflective Value)	L (mm)
2	416.68
3	271.45
4	198.84
5	155.272
6	126.22

As the data matches for Equation 3 and Equation 2 at RV=3, thus this value is selected.

Plenum Volume [8]

With suggestions from 92TypeR racing, we select; plenum diameter = 1.5 to 1.7 × *(diameter of runner)* = 57mm to 64.6 mm. Therefore taking plenum diameter as 58 mm will ensure good initial acceleration. According to the research & technical suggestions, *plenum volume is 1.5 × volume of a runner*. Thus the data obtained is shown in Table 2.

Table 2: Results obtained for plenum geometry

Parameters	***Value***
Volume of the runner	3.3929e-04 mm^3
Plenum volume	5.08935e-04 mm^3
Length of plenum to accommodate runners	310 mm
Diameter of plenum	45.7 mm

We choose the plenum diameter as 45mm. Because at CFM (maximum RPM) of 10000 the volumetric efficiency comes out to 95%.

RAM Tube Diameter

$$D\ (inches) = \sqrt{((Cubic\ inch\ displacement \times volumetric\ efficiency \times rpm) \div (V \times 1130))} \quad (4)$$

Designing at the velocity of pressure wave (V) of 180 ft./s, RPM of 8000, D can be estimated to 28.89mm.

III. PLENUM (INTAKE MANIFOLD) [5][9]

After the restrictor the air then flows into the plenum. Anytime a fluid exits a pipe into large volume there will be an associated pressure loss. This loss is proportional to the velocity of the fluid exiting the pipe. The air will have a very high velocity as it passes through the restrictor so it is advantageous to slow down the air before it enters the plenum. This will be accomplished by using a conical diffuser between the restrictor and the plenum. Both the angle of expansion and the final diameter of the diffuser will affect the losses in this section. Decrease in losses starts to level off when the exit diameter exceeds 40 mm and reaches an absolute minimum at approximately 60 mm. Another approach to sizing the diffuser is to maximize the pressure recovery.

The plenum acts to smooth out turbulence in the flow and assure that each runner "sees" the same flow area. Through correspondence with a technical specialist at Honda, it was decided that a plenum volume of twice the displacement of the engine. The plenum was designed to be close to this volume to its complex geometry.

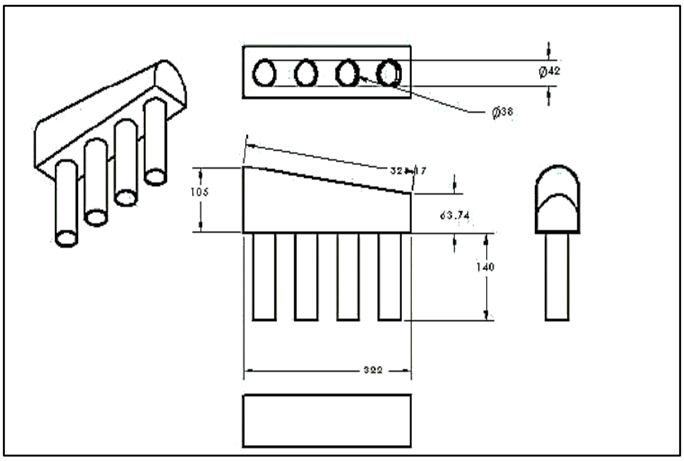

Figure 2: Intake Manifold Geometry

Figure 3: Intake manifold manufacture and installed over the Car

IV. CFD TESTING DATA & RESULTS [2]

To ensure that the designed geometry equally distributes the flow through each runner, we performed CFD (Computational Flow Dynamics). The IGES model of the plenum manufactured on solid works was imported in Gambit, where

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it is meshed and then the meshed plenum was solved on Fluent with the inlet and operating conditions in hand.

The meshed plenum as shown is achieved by doing a structured mesh for most of the geometry. The plenum was meshed without considering the elbow because we are just concerned with the flow pattern inside the plenum once it inflows from the Elbow, we mark this the inlet condition for solving the problem in fluent giving the mass flow rate

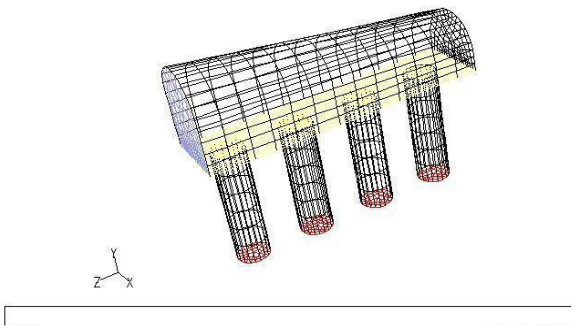

Figure 4: Manifold Meshed

Pathlines of Velocity shows exactly the velocity variation, it can be seen that the pathlines shows the highest velocity magnitude in the four outlet cylinders, which is because of the reason that due to decrease in area velocity gets decreased. This also depicts the recirculation happening at the end of the plenum which results in the turbulence as a result will also account for the factor of the increase in velocity magnitude.

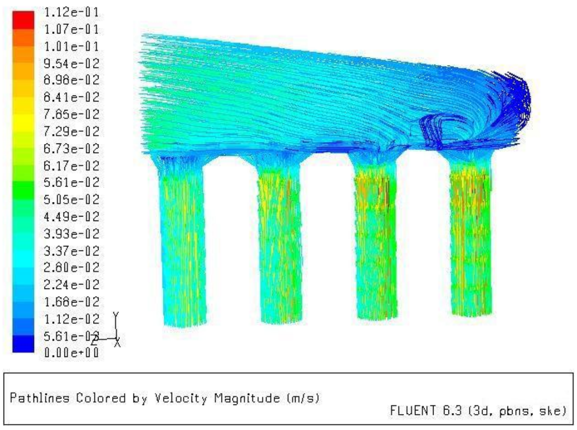

Figure 5: Pathlines of Velocity Magnitude

By Bernoulli's equation pressure and velocity are inversely dependent upon each other, so the depicted analysis result the dark red region denotes the region of highest pressure and to mind you it is the region of lowest velocity happening when the flow strikes the wall and so the velocity at wall becomes zero due to no-slip condition. While it is seen that the pressure in the outlet cylinders becomes lesser as it moves deeper, it is because the velocity in this region is pretty high due to sudden decrease in area.

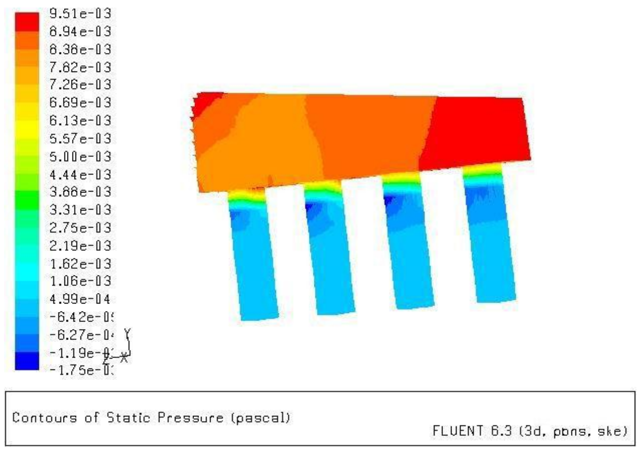

Figure 6: Contours of Static Pressure

Contours of velocity magnitude show the variation of velocity magnitude in various areas of the plenum. Like at the wall portion the velocity ceases to exist as the wall acts as the boundary layer for the flow and no slip condition causes the velocity to be zero in magnitude. It can be seen as the flow moves away from the wall section the magnitude of velocity increases to an extent. But the highest/maximum velocity regions can be seen to be inside the outlet cylinders which are acting as pressure outlets for the mass flow through the inlet. It is because of the reason that the flow while entering the outlet cylinders becomes turbulent from the low speed mainly laminar after getting recirculating at the end wall section and also due to sudden decrease in the area which causes the flow to become turbulent and hence increasing the velocity.

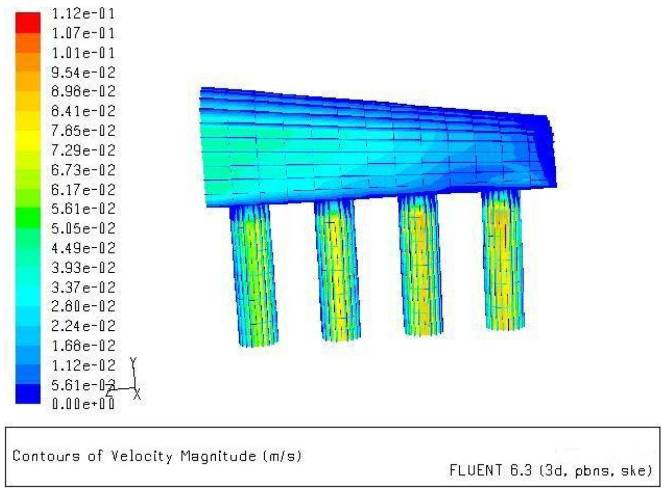

Figure 7: Contours of Velocity Magnitude

Velocity vectors show the direction the flow takes inside the plenum, it is seen that the high magnitude vectors are in the outlet cylinders and the lowest magnitude vectors are at the end of the plenum. The above analysis also shows how the velocity vectors are getting distributed to the outlet cylinders from the main plenum volume, which the last outlet getting the flow with the highest velocity because of the circulation happening and the flow reversal from the wall as explained by the vector directions in the above analysis result.

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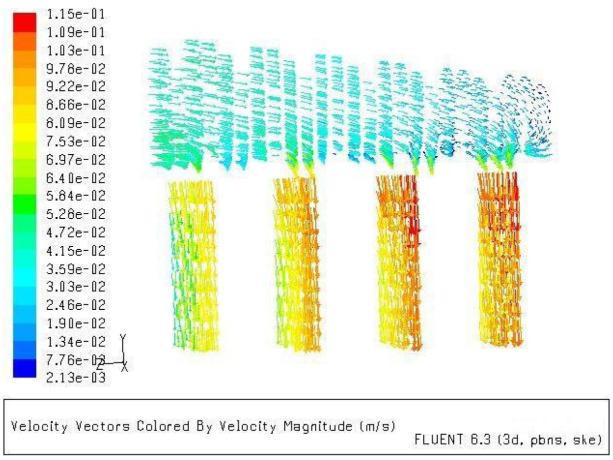
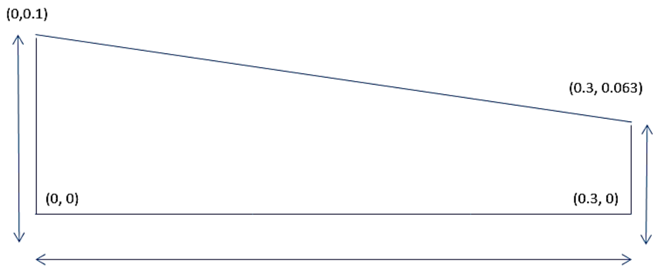


Figure 8: Velocity Vectors by Velocity Magnitude

V. ANALYTICAL TEST

To test the flow/velocity analytically a 2D shape of the plenum considered as shown, we are just testing the variation of velocity in X-direction and if finally it does become finally zero at the wall/end surface of the plenum. To do that we are not considering the outlet pipes, we are just trying to figure if the velocity decreases as the air moves in the plenum and become zero at the wall, where circulation happens and the fluid becomes turbulent so we are not going till that happens, so we are just considering till fluid hits the wall.

We are considering the flow nearly steady until it hits the wall as can be shown by the pathlines plot of the velocity generated by the CFD testing.



INTAKE IN 2D WITH COORDINATES W.R.T ORIGIN AT ONE POINT OF THE INTAKE

The geometric dimensions of the plenum are taken considering one vertex as the origin itself. Since we are considering a steady flow, we can use Laplace equation for 1D to compute for the variation in x direction (for x varying from $0 < x \leq 0.3$).

We can use laplace equation to compute for velocity in x − direction:

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} = 0 \qquad (5)$$

Laplace equation in 1D gets reduced to

$$\frac{\partial^2 u}{\partial x^2} = 0 \qquad (6)$$

Now integrating equation, we get

$$\frac{\partial u}{\partial x} = C_1 \qquad (7)$$

Integrating again we get

$$u = C_1\, x + C_2 \qquad (8)$$

Now using B.C as:

$x = 0, u = 0.7$ [*we know mass flow rate at the inlet*]
$x = 0.3, u = 0$ [*wall*]

Using them in equation (8)

$$\boldsymbol{C_1} = \frac{-0.7}{0.3} \ \& \ \boldsymbol{C_2} = \mathbf{0.7}$$

So eq. (4) *becomes*

$$u = 0.7 - \frac{0.7}{0.3}x \qquad (9)$$

Now using equation (9), we can calculate the variation of velocity(x) at different points long a line varying in x;
Using the values of x from 0 to 0.3: x ∈(0, 0.3)
We get,

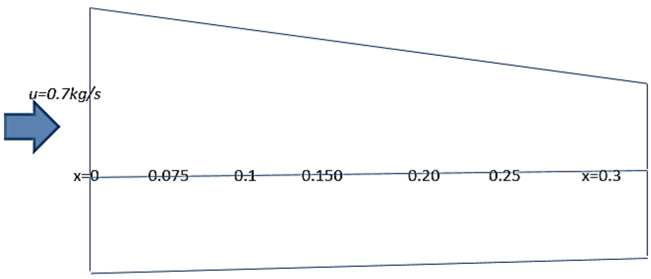


Table 3: Variation of velocity with x as mentioned above

x	*u (Kg/s)*
0	0.7
0.075	0.525
0.1	0.467
0.150	0.35
0.20	0.233
0.25	0.1167
0.3	0

We are not considering the 4 outlets in this test with x = 0 and x=0.3 marks the inlet and wall points respectively. Hence the velocity can be shown from the above analysis to decrease as we move forward into the manifold and finally becoming zero (0) at the wall.

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CONCLUSION

It was seen that the intake plenum designed provides each cylinder with somewhat equal amount of air, which is the most important task to be performed by the intake to facilitate the proper performance of the engine by improving the air fuel mixture.

Analysis of plenum: *Boundary Conditions*:

Mass flow at *Inlet 0.7 kg/sec*

Pressure outlet at the four ends of pipes

Operating Pressure taken as 1 atm = (*101325 Pa)*

Mass flow at outlet 1 is *0.1428 kg/s*

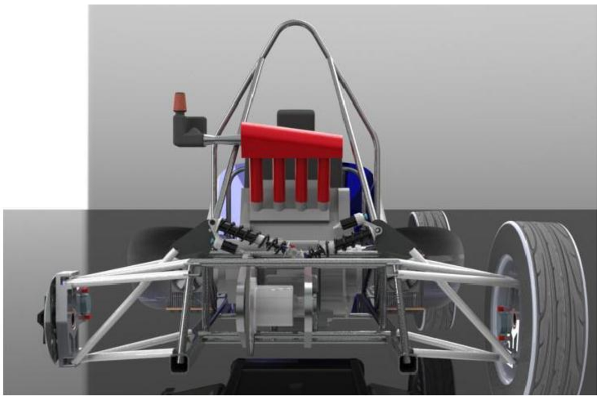
Mass flow at outlet 2 = *0.1739 kg/s*

Mass flow at outlet 3 = *0.1886 kg/s*

Mass flow at outlet 4 = *0.1946 kg/s*

Numbered from inlet i.e., outlet 1 is near inlet

But the recommendation could be given to test more intake plenum to increase the performance of efficiency of the engine. The intake system mounted over the engine of the Formula SAE car [1] can be shown by the following Solid works figure:



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