Space Advantage Provided by De-Laval Nozzle and Bell Nozzle over Venturi

Omkar N. Deshpande, Nitin L. Narappanawar

Abstract:-The FSAE guidelines state that it is mandatory for each and every car participating in the said event to have a single circular 20mm restrictor in the intake system. All the air flowing to the engine must pass through this restrictor. Conventionally, a Venturi Nozzle is used as a restrictor. In our research, we have proposed two Nozzles: De-Laval Nozzle and Bell Nozzle as an alternative to the Venturi Nozzle. After numerous CFD Simulations; we have inferred that the results of the De-Laval Nozzle and Bell Nozzle are similar to the Venturi Nozzle. Along with providing similar results, the two nozzles provide a space saving of 6.86% over the Venturi Nozzle. The data was gathered from SolidWorks Flow Simulation 2014.

Keywords: - Formula SAE, Intake Restrictor, SolidWorks Flow Simulation, Intake System, Nozzle

I. INTRODUCTION

INTAKE restrictor in an FSAE car is one of the most crucial factors affecting the engine performance. With a restrictor placed early in the intake system, engine performance is greatly compromised, as it is proportional to the volumetric efficiency of the engine system. This in-turn is related to the amount of air which can be drawn in by the cylinders. It is therefore critical to ensure that maximum airflow can be passed through the restrictor, so as to allow the cylinders to take in as much air as possible during suction stroke. This will allow maximum volumetric efficiency across various R.P.M. [5]. At very high R.P.M the flow in the restrictor attains sonic velocities, which give rise to the phenomena of Choked Flow (also known as Critical Flow Condition) [1]. This critical flow condition limits the amount of air passing through the restrictor. The derivation for the choked flow condition is given in 'Section III'. Thus, the pressure difference between the atmosphere and the pressure created in the cylinder should be minimal, so as to have maximum airflow to the engine [2].

Conventionally a venturi-nozzle is used as a restrictor in FSAE cars. Though the venturi-nozzle provides good results, the space occupied by the nozzle is more as it achieves its optimality at a low angle of divergence (12 degrees) as demonstrated in 'Section V part C.)' Space is a major issue in most of the engine compartments, where many crucial components are to be fitted in a very little space. Therefore there is a need to design a new kind of nozzle achieving optimality at a higher angle than that of the venturi nozzle. For this purpose De Laval Nozzle and Bell Nozzle are analyzed as a possible alternative to the venturi. De- Laval Nozzle is used in certain type of steam turbines and also as a Rocket Engine Nozzle [6]. Bell Nozzle is also widely used as a Rocket Engine Nozzle. Both of the nozzles achieve optimality at a higher angle of convergence as demonstrated in 'Section V parts A.); B.).'

Thus, finally it is shown that De-Laval Nozzle and Bell Nozzle at optimal angles show similar results as compared to Venturi Nozzle albeit occupying lesser space in the engine compartment.

II. RESEARCH METHODOLOGY

The first step in our research methodology was to select the parameter, to be optimized. In any restrictor, the inlet conditions are always known. The temperature at the inlet is ambient temperature and the pressure is atmospheric. At the outlet however, for the purpose of analysis, either the velocity of the exit air or the pressure at the outlet needs to be specified. However, there are many errors involved in calculating the pressure and velocity at the outlet of the restrictor. The more accurate method would be to specify the mass flow rate at the outlet.

The mass flow rate of air at choked flow condition should be specified at the outlet instead of max R.P.M. of the engine. This is because the max R.P.M differs from engine to engine.

After the applying the boundary conditions, through simulations, Delta Pressure (Pressure at inlet – Pressure at outlet) is calculated. Singhal et al [3] in their work have selected Delta Pressure as the parameter to be optimized. On the same lines, we have also selected the parameter to be optimized as Delta Pressure.

III. THEORY AND FORMULA

The conservation of mass is a fundamental concept of physics. Within some problem domain, the amount of mass remains constant; mass is neither created nor destroyed. The mass of any object is simply the volume that the object occupies times the density of the object. For a fluid (a liquid or a gas) the density, volume, and shape of the object can all change within the domain with time and mass can move through the domain.

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The conservation of mass (continuity) tells us that the mass flow rate m through a tube is a constant and equal to the product of the density r, velocity V, and flow area A:

$m = r * V * A$ …..... (1)

Considering the mass flow rate equation, it appears that for a given area and a fixed density, we could increase the mass flow rate indefinitely by simply increasing the velocity. In real fluids, however, the density does not remain fixed as the velocity increases because of compressibility effects. We have to account for the change in density to determine the mass flow rate at higher velocities. If we start with the mass flow rate equation given above and use the isentropic effect relations and the equation of state, we can derive a compressible form of the mass flow rate equation.

We begin with the definition of the Mach number M and the speed of sound a:

$V = M * a = M * \mathrm{sqrt}(\gamma * R * T)$ …... (2)

Where **γ** is the specific heat ratio, R is the gas constant, and **T** is the temperature. Now substitute (2) into (1):

$m = r * A * M * \mathrm{sqrt}(\gamma * R * T)$ …….. (3)

The equation of state is:

$r = P / (R * T)$ ……. (4)

Where, P is the pressure. Substitute (4) into (3):

$m = A * M * \mathrm{sqrt}(\gamma * R * T) * P / (R * T)$ ……. (5)

Collect terms:

$m = A * \mathrm{sqrt}(\gamma / R) * M * P / \mathrm{sqrt}(T)$ …….(6)

From the isentropic flow equations:

$P = Pt * (T / Tt) \wedge (\gamma/(\gamma-1))$ …….(7)

Where Pt is the total pressure and Tt is the total temperature. Substitute (7) into (6):

$m = (A * Pt)/\mathrm{sqrt}\ Tt)*\mathrm{sqrt}(\gamma / R) * M * (T / Tt)\wedge((\gamma+1) / (2 * (\gamma -1)))$ …….(8)

Another isentropic relation gives:

$T/Tt = (1 + .5 * (\gamma -1) * M\wedge 2) \wedge -1$ ……. (9)

Substitute (9) into (8):

$m = (A * Pt/\mathrm{sqrt}[Tt]) * \mathrm{sqrt}(\gamma/R) * M * [1 + .5 * (\gamma-1) * M\wedge 2]\wedge-[(\gamma + 1)/(\gamma - 1)/2]$ …….(10)

This equation is shown relates the mass flow rate to the flow area A, total pressure Pt and temperature Tt of the flow, the Mach number M, the ratio of specific heats of the gas γ, and the gas constant R [4].

- CALCULATIONS

Values taken in (10) are referenced from [3] as they are applicable in our case: -

Pt= 101325 Pa
T= 300K
γ= 1.4
R (air) = 0.286 kJ/Kg-K
A= 0.001256 m^2
M=1 (Choking condition)

IV. GATHERING THE DATA

1.) SOFTWARES USED: -
A.) CAD Modelling: - SolidWorks 2014
B.) CFD : - SolidWorks Flow Simulation 2014
C.) Data Tabulation: - Microsoft Excel
D.) Data Compilation: - Microsoft Word

2.) BOUNDARY CONDITIONS: -
a.) Inlet: -Total Pressure= 101325 Pa
b.) Outlet: -Mass Flow Rate= 0.0703 Kg/s

V. RESULTS AND DISCUSSION

The data has been obtained by performing simulations for different angles of convergence and divergence under the boundary conditions mentioned in Section IV Part 2.).

The converging angles selected are from 12 degrees to 16 degrees with an increment of 2 degrees. The diverging angles selected are 4 degrees and 6 degrees.

TABLE I DATA TABULATION FOR DE-LAVAL NOZZLE

Converging Angle	Diverging Angle	Delta Pressure
12	4	4886.12 Pa
14	4	4091.31 Pa
16	4	3605.22 Pa
12	6	7909.73 Pa
14	6	8265.28 Pa
16	6	9782.47 a

TABLE II DATA TABULATION FOR BELL NOZZLE

Converging Angle	Diverging Angle	Delta Pressure
12	4	11051.03 Pa
14	4	9228.34 Pa
16	4	4715.36 Pa
12	6	8869.79 Pa
14	6	9766.33 Pa
16	6	8119.83 a

TABLE III
DATA TABULATION FOR VENTURI

Converging Angle	Diverging Angle	Delta Pressure
12	4	3452.52 Pa
14	4	4311.63 Pa
16	4	4480.61 Pa
12	6	10391.7 Pa
14	6	9880.541 Pa
16	6	10512.277 Pa

- DISCUSSION

As the De-Laval Nozzle and Bell Nozzle have different geometries than the Venturi Nozzle, their angle of optimality differs from each other. Therein lays our advantage. Least amount of delta pressure in De-Laval Nozzle and Bell Nozzle occurs at 16 degrees of convergence and 4 degrees of divergence. On the other hand, Venturi Nozzle shows minimum delta pressure at 12 degrees of convergence and 4 degrees of divergence. Therefore, the space occupied by the De-Laval Nozzle and Bell Nozzle is lesser than Venturi Nozzle due to sharper angle of convergence. This is a major advantage in the engine compartment as space is a very limited commodity.

That narrows down our choice to the two nozzles in question: De-Laval Nozzle and Bell Nozzle. Choice between the two nozzles is made on the basis of the velocity plots of the two nozzles as shown in 'Section A.) Part 2) and Section B) part 2)'. Even though the pressure plots of the two nozzles are similar, there is a drastic difference in their velocity plots. The velocity plot of De-Laval Nozzle is much more uniform than that of the Bell Nozzle. Hence, to take an overview, De-Laval Nozzle should be preferred over Bell Nozzle, as it not only provides a lesser Delta Pressure but also a more uniform flow distribution.

With the advent of 3-D Printing technology, De-Laval Nozzles can be fabricated with ease.

VI. PLOTS

A.) DE-LAVAL NOZZLE (16 DEGREES CONVERGING ANGLE AND 4 DEGREES DIVERGING ANGLE)

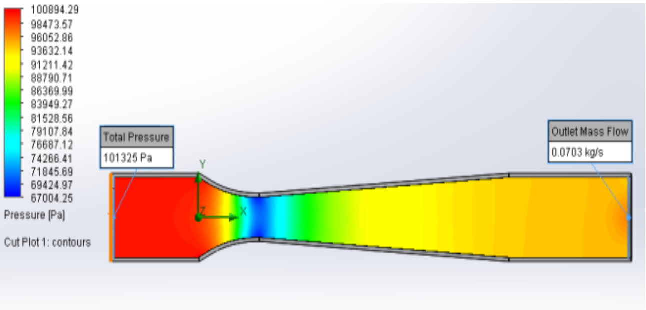

Fig 1 PRESSURE VARIATION

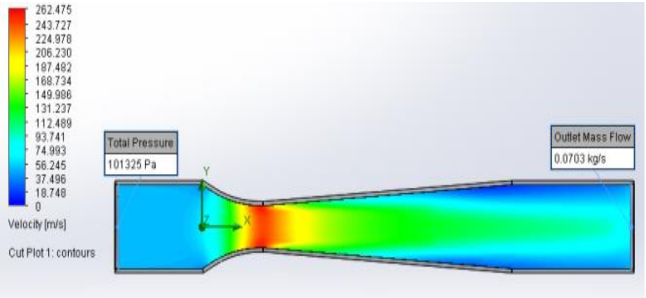

Fig 2 VELOCITY VARIATION

B.) BELL NOZZLE (16 DEGREES CONVERGING ANGLE AND 4 DEGREES DIVERGING ANGLE)

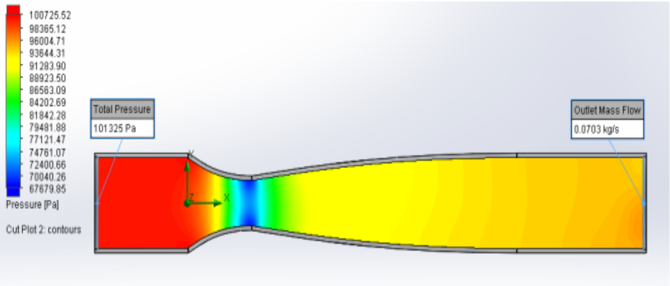

Fig 3 PRESSURE VARIATION

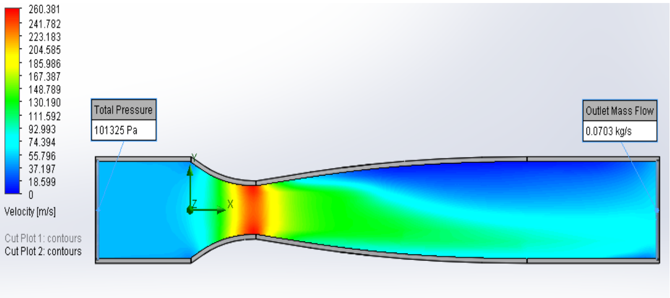

Fig 4 VELOCITY VARIATION

C.) VENTURI (12 DEGREES CONVERGING ANGLE AND 4 DEGREES DIVERGING ANGLE)

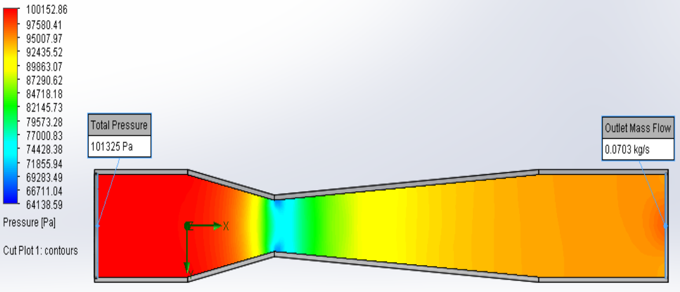

Fig 5 PRESSURE VARIATION

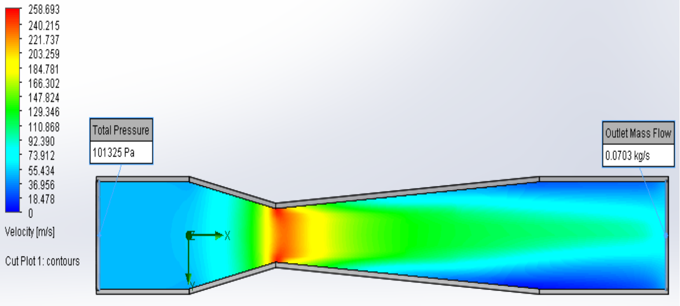

Fig 6 VELOCITY VARIATION

VII. INFERENCE

From the data tabulated in Section V, it can be seen that the De-Laval Nozzle and Bell Nozzle provide minimum delta pressure at 16 degrees angle of convergence and 4 degrees angle of divergence. Venturi Nozzle on the other hand provides minimum delta pressure at 12 degrees of convergence and 4 degrees of divergence.

Thus, we conclude that out of the three nozzles: De-Laval, Bell and Venturi, the De-Laval Nozzle is the better on the count of compact design. A space saving of 6.86% over venturi is provided by the De-Laval and Bell Nozzle. Due to the non-uniformity of flow through the Bell Nozzle, De-Laval Nozzle is preferred over it.

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