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OPTIMIZATION OF AUTOMOBILE MUFFLER USING COMPUTATIONAL FLUID DYNAMICS

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Abstract- The muffler is a very important and an indispensable part of an automobile exhaust system. The primary function of a muffler is to reduce noise and vibrations of the exhaust emissions from the engine cylinder. The exhaust gases inside the engine cylinder are at a temperature of around 1200K, while the temperature at which the gases are expelled into the atmosphere is around 300K. The muffler also reduces backpressure. This increases the efficiency of the engine and also the power consumed. In this paper, a CAD model of a laminar flow performance muffler has been designed, which consists of a converging-diverging duct. These ducts contain perforations on their walls through which the exhaust gases scatter after passing in different directions. The material of a muffler should be resistant to corrosion at high temperatures, salt corrosion resistance from the high-temperature exhaust gas, vibration resistance and at the same time it should also possess sufficient strength to withstand high stresses and also be light in weight and affordable at the same time.

Keywords: *Materials study Muffler, Laminar Flow, Ansys Fluent, CFD analysis, Meshing, Yield strength*

I INTRODUCTION

The exhaust system of any automobile is exposed to high temperatures, corrosive exhaust gases like, Carbon dioxide, Nitrous oxides and other Hydrocarbons. The pressure is also very high inside the exhaust system. The most important part of the automobile exhaust system is the Muffler. These factors cause wearing of the inside surface of muffler and considerable deformation also takes place because of excessive pressure [1].

This paper aims at finding the appropriate material and alloying elements which can be used to obviate such consequences. The flow analysis is done using Ansys Fluent. Various materials have been compared based on their mechanical properties to withstand high temperature and high pressure.

Nowadays, the aim is to reduce the weight of the muffler and also reduce its price. The weight and cost analysis presented in this paper is aimed to solve such problems.

The materials used in the fabrication of mufflers include mainly stainless steels and cast steels. Earlier, cast steels were used for manufacturing mufflers, but now the trend has shifted to stainless steels with better corrosion and wear resistance, with the addition of alloying elements [2].

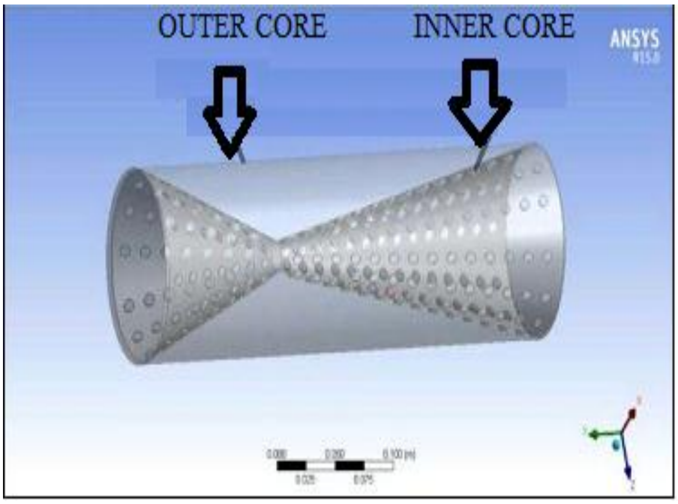


Fig. 1: CAD model of the muffler

The muffler consists of a layer of glass wool between the outer cylinder (not shown in the diagram) and the inner cylinder. This layer of glass wool acts as a sound absorbing medium by absorbing the pressure pulses, while the rest of the wave pulses are cancelled in the inner chamber. The inner chamber acts as an interference chamber, where pressure waves combine with each other destructively. In this way the noise is reduced.
Mufflers used in vehicle exhaust systems can be of various types like [3]:

- Baffle type;
- Resonance type;
- Wave cancellation type;
- Combined resonance and absorptive type;
- Absorber type mufflers.

The muffler discussed in this paper is of the "Combined resonance and absorptive type". Usually, every IC engine is fitted with a muffler in order to cancel the pressure pulses with the purpose of both noise reduction and pollution control. This type of muffler consists of a reflecting chamber, absorption chamber and a resonance chamber. The back pressure is also reduced [4], [5].

II DESCRIPTION

The 3D CAD model has been made using SOLIDWORKS. Computations have been done to find the dimensions of the muffler. Further, after running numerical simulations, dimensions have been changed to optimize the functioning of the model. This model consists of inner perforated chamber and a covering cylinder.

The inner perforated chamber consists of a convergent duct, a throat and a diverging duct. The converging duct acts as an inlet to the exhaust gases coming out of the engine at high pressure.

Since, the throat has a very small diameter, the velocity of the exhaust gases increase at this section and the pressure significantly reduces in accordance with the Bernoulli's Principle. The Diverging duct acts as an outlet through which the exhaust gases pass out of the muffler into the atmosphere.

Due to a large diverging duct and low-pressure difference between the outlet and the throat, the incoming turbulent flow of exhaust gases turns into laminar flow. This also increases the performance of the muffler and reduces the back pressure at the outlet. As a result of this, the engine works efficiently, and the noise and vibrations are also eliminated, achieving both the objectives of an ideal muffler. An ideal muffler should act as a low pass filter to the incoming exhaust gases. [9]

Exhaust gases flowing into the muffler, also flow through the perforations made in the ducts. The waves flowing through the perforations get scattered from the inner cylinder and combine with other incoming waves to cancel them completely, rather than transmitting the waves through the muffler. The numbers of perforations have been calculated as per the volume of the muffler. Perforated holes are separated at optimal distances on the surfaces of the ducts of the muffler to increase the efficiency and performance of the muffler.

2.1 Design specifications

I. Diameter of inlet= 58.2 mm;

II. Diameter of throat= 9.62 mm;

III. Diameter of outlet= 58.2 mm;

IV. Length of the converging duct= 130 mm;

V. Length of diverging duct= 246 mm;

VI. Diameter of each perforation= 8 mm;

VII. Total length of the muffler= 376 mm.

2.2 Role of CFD in the Analysis of Muffler

This paper uses ANSYS Fluent Package to do numerical simulations and obtain results of CFD analysis. ANSYS is a general- purpose software, used to analyze and simulate interactions of all disciplines of physics, structural, fluid dynamics, vibration, electromagnetic and heat transfer for engineers.

The use of software to replicate the real-life problems provides various advantages like, time and cost saving, repeatedly building the model and analyzing it under practical conditions.

In other words, ANSYS Fluent Package has been used to simulate, visualize and analyze the motion of hot exhaust gas particles flowing at high velocity inside the muffler. ANSYS Fluent Package is a computational fluid dynamics (CFD) software, which delivers reliable solutions to problems involving complex fluid and multi physics applications.

III PROBLEM FORMULATION

The purpose of an exhaust system in an automobile is to act as a passage for the flow of the exhaust gases from the engine to the atmosphere. Muffler is an integral part of any exhaust system. The design of a muffler includes space requirements for the muffler in the vehicle exhaust system, its weight, density and mechanical properties of the material of the muffler. The major should be to select a particular material which would resist corrosion due to the salts present in the exhaust gases and also avoid sticking of particles on the walls of the muffler. The design should be such that pressure distributions throughout the muffler, stress distribution, temperature distribution and velocity distribution of the exhaust gases can be easily found out after doing numerical simulations.

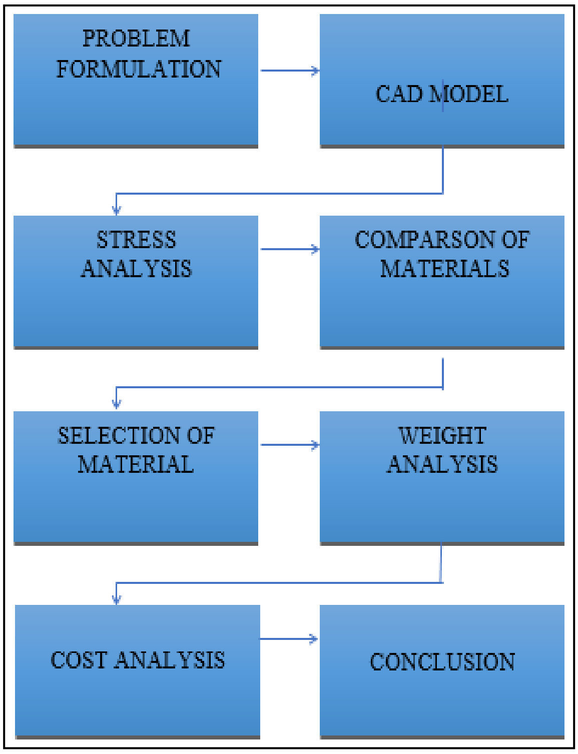
The CFD analysis of this model took several hours to converge due to high subsonic compressible flows and high velocity regions in the muffler.

The focus was also to reduce the weight and cost of the muffler to make it more efficient and cost effective, without compromising the mechanical properties like, strength of the material and its wear resistance. These problems have been solved in this research paper by undertaking a robust methodology.

IV PROBLEM SOLUTION

The model of the muffler is designed using weldments in SOLIDWORKS, after which the model is simulated and its CFD analysis is done using ANSYS Fluent.

We considered the burning gases to enter the muffler at a velocity of 50 m/s. The outlet pressure is taken to be 1 Bar. The pressure distribution in Fig. 6 shows gauge pressure distribution throughout the muffler. The CFD analysis of this model was carried out on I5 5th generation Intel core system with a ram of 8 GB. The solution for this model converged after 100 iterations.



V SIMULATION AND ANALYSIS (ANSYS FLUENT)

A. Meshing

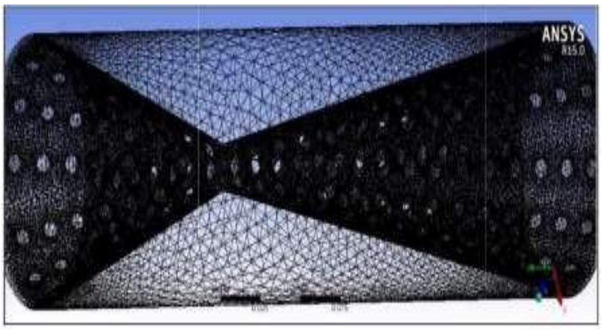


Fig. 2: Meshing of the muffler model

To carry out the CFD analysis the model is extracted and divided into finite elements. To get satisfactory results, the fluid volume has been divided into many elements. The mesh consists of tetrahedral elements and the number of elements is 1.814652 million

Boundary Conditions

Inlet velocity of exhaust flow = 50 m/s [2]

Outlet pressure = 1.01325*105 Pa

Inlet flue gases temperature = 773K

Base temperature = 298 K

Velocity Distribution

The velocity distribution of the exhaust gases flowing in the muffler is shown in figure 3.

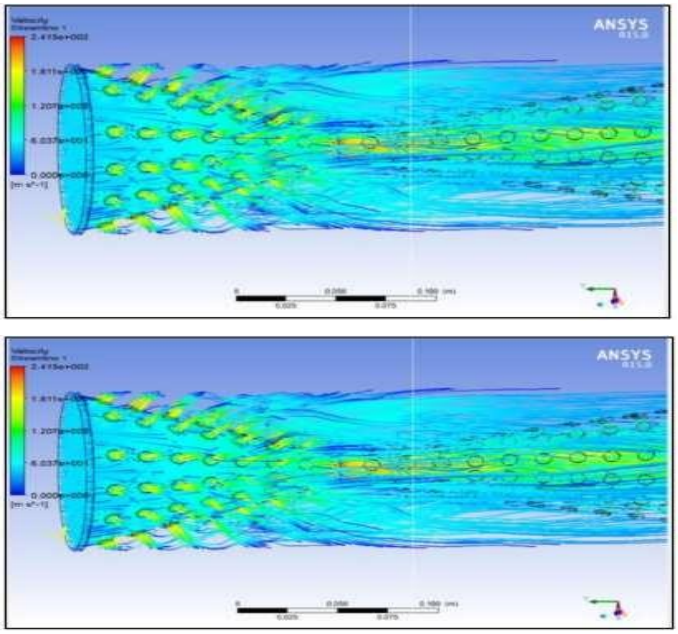


Fig 3.Velocity distribution of exhaust gases in the muffler and Distribution of velocity streamlines through the ducts.

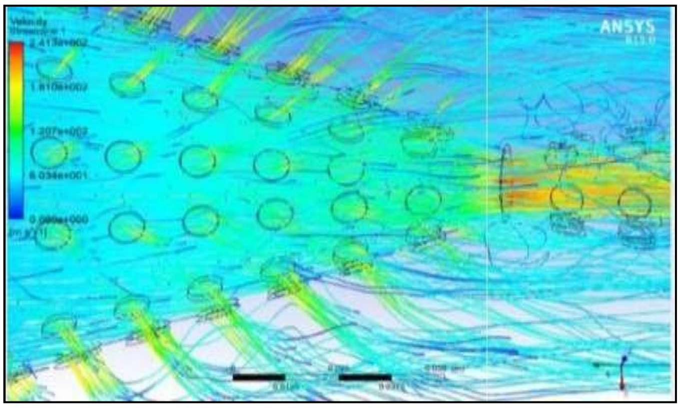


Fig.4.Velocity of scattered exhaust particles through the ducts

A closer look at the velocity of the turbulent exhaust gases through the holes can be seen in figure 4. The velocity of Fig 1

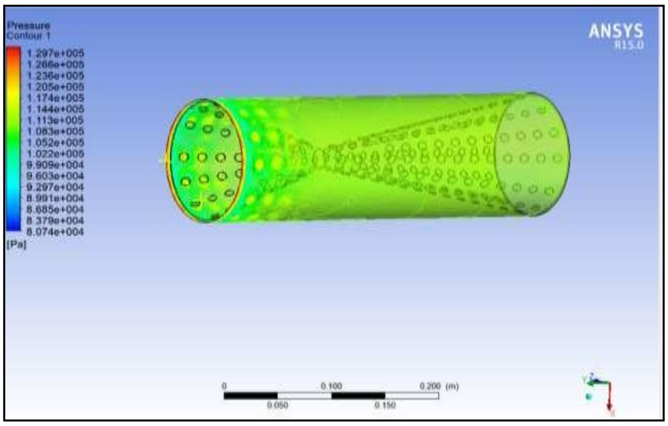


Fig 5.Pressure contour 1

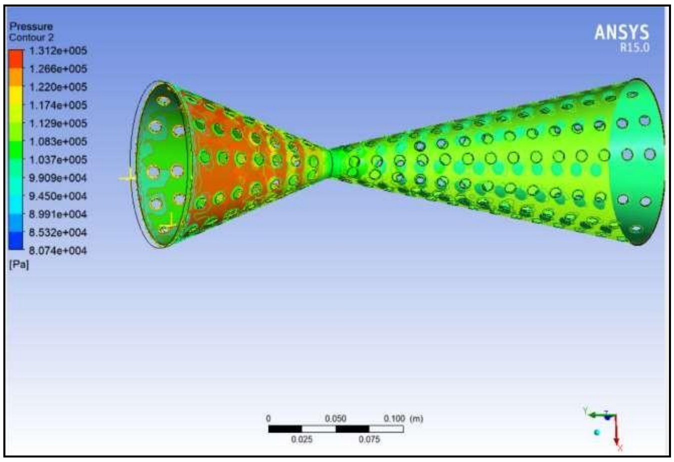


Fig.6 Pressure contour 2

exhaust gases from the perforated holes is very high and the particles get deflected from the outer cylinder which acts as a cove ring of the ducts.

C.Pressure Distribution

From the above figures, the pressure distribution throughout the muffler can be well observed. The pressure at the inlet section of the muffler, through which the hot exhaust gases enter the muffler, is around 20,000 Pa, while the pressure at the throat is well below the atmospheric pressure. The pressure at the outlet is taken to be 0 Pa (Gauge pressure) or 1 atm (Absolute pressure). This implies the pressure is minimum at the throat.

Apart from this, due to vast pressure difference between the inlet and throat, a scavenging effect comes into play. The gases get sucked in more due to this effect and hence quicker exhaust of gases increasing performance.

So, it can be inferred that the flow between the throat and the outlet is not only due to pressure difference, but also due to the kinetic energy possessed by the flow particles.

This causes the flow to be laminar instead of turbulent flow.

D.Stress Distribution

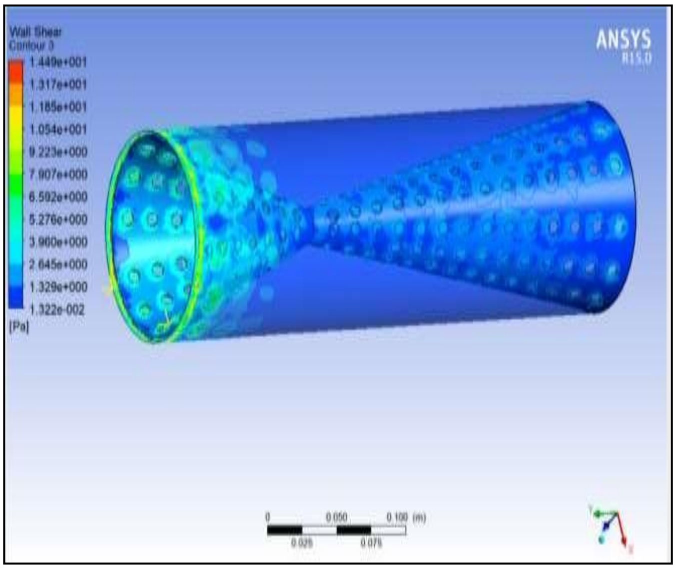


Fig.7. Shear stress distribution in the (a) Outer core and (b) Inner core walls of the muffler

The shear stress distribution is shown in the above figures. The stress at the inlet cross section is highest with a value of 9 Pa. Its value at the throat and the outlet cross section is about 0.01 Pa. The shear stress does not change much between the throat and the outlet.

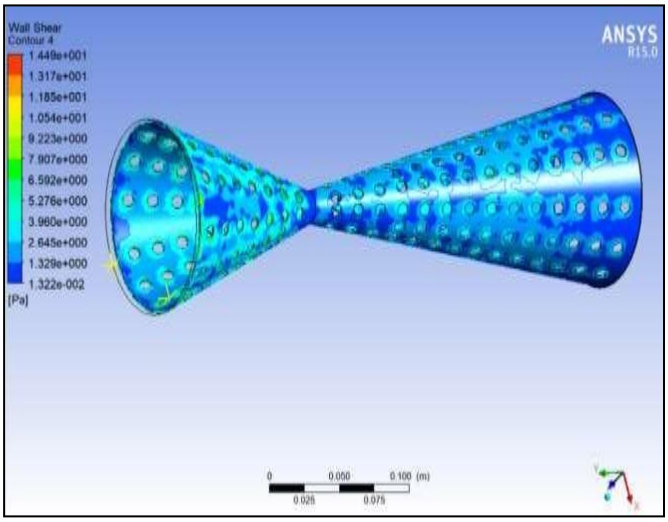


Fig.8. Shear stress distribution in the (a) Outer core and (b) Inner core walls of the muffler

VI SELECTION OF MATERIALS

There's no definite material used for manufacturing industrial mufflers. It can be anything from mild galvanized steel to stainless steel or mild steel, depending upon different heating temperatures in different types of vehicles.

A variety of stainless steels along with their properties are given in this section to compare their properties and suitably select the proper material for muffler. Principally, the muffler of an exhaust system is exposed to chemical attacks that must be accounted for while designing the muffler. At the same time, it is also subjected to vibrations and unwanted knockings. The particulate matter of the unburned exhaust gases sticks on the walls of the muffler and this is known as condensate corrosion [2]. The condensate usually consists of salts of various compounds like Cl-, NO3-, and other inorganic as well as inorganic compounds.

To account for these factors, stress corrosion cracking (SCC) and inter-granular cracking, it is advisable to use stainless steel as a base material [6]. It has good wear resistance and thermal resistance to high temperatures. Stainless steels along with other alloying materials yield good results. Two varieties of stainless steels are commonly used; Austenitic and Ferritic [5], [6], [7].

The two most important constituents of stainless steels is Nickel and Chromium. Nickel stabilizes the austenitic phase and also shifts the eutectoid point towards the left.

One of the most common and lower cost austenitic stainless steel used for exhaust systems is SS(304), but the residual stresses in the material and poor resistance to corrosion to road salts make it susceptible to SCC [8].

Contrary to this, SS(316) gives more resistance to stress corrosion cracking due to its higher Ni contents. Its another variant, SS(316L) is highly resistant to stress corrosion cracking and inter granular cracking but it has lower strength as compared to SS(304). Type 316Ti has same strength as Type 316 with increased corrosion resistance. This research paper presents a quantitative comparison of various materials.

The table given below gives the mechanical properties, cost and the resulting thickness of the portions of the muffler for some of the materials:

Table – 1

Physical and Mechanical Properties of stainless-steel varieties

Material	*Inner core weight (grams)*	*Outer core weight (grams)*
SS(316H)	*374.52*	*696.00*
Al alloy	*122.62*	*240.85*
SS(304)	*324.49*	*626.80*
Mild Steel 6061	*186.12*	*368.52*
SS(30L)	*265.80*	*512.12*
SS(316)	*332.12*	*629.90*
SS(202)	*272.16*	*504.42*

Table – 2

Weight of inner and outer core corresponding to different material

Material	*Inner core weight (grams)*	*Outer core weight (grams)*
SS(316H)	*374.52*	*696.00*
Al alloy	*122.62*	*240.85*
SS(304)	*324.49*	*626.80*
Mild Steel 6061	*186.12*	*368.52*
SS(30L)	*265.80*	*512.12*
SS(316)	*332.12*	*629.90*
SS(202)	*272.16*	*504.42*

VII FORMULA USED

The formula used to calculate the thickness of inner and outer core in table 2 is:

σ= p*d/(2*t)
where, σ= circumferential hoop stress (Pa)
p= pressure acting in a direction normal to the cross section (Pa)
t= thickness of the part considered (m)
d= The diameter of the pipe where stress is calculated (m)
Here, σ= Maximum allowable stress= Yield strength of the material/ F.O.S
Yield strength values were taken from table 1 for different materials.
and, F.O.S (Factor of Safety)= 10.
Also, the pressure value taken, p = maximum pressure values from figure 6 (for outer core) and figure 7 (for inner core) respectively.

VIII CONCLUSION

This paper presents the weight and the cost analysis of the inner and outer core of the muffler to select the most suitable material for its manufacturing. A CAD model of the muffler has been developed and simulated with practical boundary conditions to find the pressure, velocity and shear stress distributions in the muffler. The comparison of different stainless steels has been done.

From the results, clearly, the Mild steel is the least costly material and the Al alloy material is the lightest.

But Aluminium and Mild steel has higher thermal conductivity than Stainless steel. This leads to elevated temperature of the muffler body and easy deformation. Stainless steel can be used at much higher temperatures than Aluminum (which can become very soft above 400 degrees).

Stainless steel is highly corrosion resistant unlike Mild steel and has higher strength to weight ratio.

Hence Stainless steel is more preferred for automotive industry even though it is available at a higher cost.

This study was carried out for the purpose of building our in-house performance muffler in lowest cost and weight possible for use in the Formula Student car of the college.

The study gave us the idea of thickness of the sheets to be bought keeping in factor of safety as well as the weight constraints of the car in mind.

Table – 2
Table showing thickness and cost of material of inner and outer core

Material	Inner core thickness (mm)	Outer core thickness (mm)	Inner core volume(mm^3)	Outer core volume(mm^3)	Inner core cost in Rs	Outer core cost in Rs
SS(316H)	0.584	0.625	46095	88955.03	110.628	213.492
Al alloy	0.795	0.668	47546	92011	32.090	62.100
SS(304)	0.511	0.552	40952	79244	54.650	105.616
Mild Steel 6061	0.300	0.340	25412	49000	10.760	22.751
SS(30L)	0.428	0.456	34955	67000	60.597	116.151
SS(316)	0.518	0.600	44305	81618	88.913	163.79
SS(202)	0.202	0.495	34948	66512	46.340	88.194

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