DESIGN AND PERFORMANCE ESTIMATION OF AN AUTOMOBILE MUFFLER USING COMPUTATIONAL FLUID DYNAMICS ANALYSIS

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***Abstract*:** Day by day as the number of vehicles are increasing, the noise produce by the exhaust system is also increasing which is affecting the common people. Muffler is one such device used for reducing the noise emitted by this exhaust system of an internal combustion engine or automobile. In this study the aerodynamic performance of muffler is considered for study. Initially performance of an existing muffler used in four-cylinder petrol engine of 91 bhp, 6000 RPM is determined. By keeping the volume of muffler constant, a better optimized muffler is proposed by performing CFD analysis. Four different models are simulated at different velocity of 20m/s, 40m/s, 60m/s and 80m/s and compared with each other to find the best performing muffler design. From the analysis it was observed that model 2 produces around 21%, 11% and 43% increase in pressure drop as compared to model 1, model 3 and model 4 respectively. Thus, from this study model 2 is proposed as the best optimized muffler for use for this petrol engine. Here, Creo Parametric and Ansys Design modeler is used to design these mufflers and Ansys Fluent is used for flow analysis and aerodynamic performance estimation.

***Index Terms*: Muffler, Noise reduction, Automobile, Pressure drop, Maruti Ciaz.**

I. INTRODUCTION

For a vehicle with an internal combustion engine, its exhaust system is the source of majority of noise produced by it. After the combustion stroke of the engine's piston, the exhaust gases inside the combustion chamber are at a very high pressure. And as the exhaust valve opens, these gases expand into the low-pressure region of the exhaust system. These expansions of exhaust gases create very powerful sound waves.

This exhaust noise from vehicles is a major source of noise pollution in urban regions, which leads to adverse health effects in people affected by it. For this reason, the authorities around the world make laws to regulate the noise produced by vehicle. And to comply with these noise regulations the vehicle manufacturers try to come up with new engineering solutions. The most popular method for the reduction of exhaust noise in passenger cars is the use of mufflers [1].

A muffler is a device which is designed to reduce the noise magnitude (in terms of decibels) of sound waves in the exhaust gases flowing through it. A good muffler will also change the note of the exhaust sound to make it more comfortable for the people exposed to it. There are two ways a muffler can reduce or change the noise, which are absorption and reflection. There are three basic type of muffler design, absorptive mufflers or straight-through mufflers, turbo mufflers and chambered mufflers. Different designs use different strategies for noise reduction. [2]

II. MUFFLER PERFORMANCE FACTOR:

A. Transmission loss:

The loss in exhaust noise intensity due to absorption or reflection in the muffler is defined as 'Transmission loss' which can be analyzed using different equations. This transmission loss is used to describe a muffler's performance and the goal of a good muffler design is to maximize this transmission loss without inducing much of an ill effect for the engine's performance. [2]

Calculation of transmission loss,
When the transmission loss is being calculated in a decibel scale, then it is defined as the ten times of the logarithmic ratio of the energy of incident wave to the energy of transmitted wave. In terms of equation, it can be expressed as

$$TL = 10log_{10}\left(\frac{W_i}{W_t}\right) \tag{1}$$

Where, TL= Transmission loss
W_i= Incident energy
W_t= Transmitted energy

From the above equation it can be understood that the lesser the muffler's transmitted sound energy, the higher the transmission loss will be.
In terms of progressive wave components, the equation can be written as

$$TL = 10log_{10}\left(\frac{S_o A_o^2}{2} * \frac{2}{S_n A_n^2}\right) \tag{2}$$

Which can be further simplified as,

$$TL = 20log_{10}\left(\frac{A_o}{A_n}\right) + 10log_{10}\left(\frac{S_o}{S_n}\right) \tag{3}$$

Where, S_o and S_n are the areas of inlet and outlet respectively. A_o and A_n are the acoustic pressure associated with the incident wave and that with the transmitted wave respectively.

B. Backpressure:

Mufflers with achieve good acoustic power loss also generate back-pressure as a side effect, which is exerted on the engine. The drop in stagnation pressure inside a muffler is responsible for the generation of this back-pressure. High amount of back-pressure would result in a reduction of the volumetric efficiency of the engine. The loss in stagnation pressure across muffler is described in terms of dynamic head H of exhaust flow.

$$H = \frac{1}{2}\rho_o U^2 \tag{4}$$

Where, ρ_o = Density of exhaust gases
U = Exhaust flow velocity

Drop in stagnation pressure is directly proportional to this dynamic head.

C. Size of Muffler:

Drop in stagnation pressure leads to increment in transmission loss but also an increment in back-pressure, but the objective of a good muffler design is high transmission loss and low backpressure. The solution for this is to decrease dynamic head, which requires the increase in muffler size, and hence weight and cost of the muffler. The designer has to compromise between these three muffler performance factors. [1]

II. NOISE STANDARDS IN INDIA:

To regulate the noise produced by automobiles and other sources, and in an effort to keep the noise pollution at a tolerable level, the Government of India implemented Environment (Protection) Amendment Act 2005. According to this Act different vehicle has different noise limit, which are listed in Table 1.

Table 1. Noise limits for vehicles applicable at manufacturing stage from year 2003

Type of Vehicle	Noise limit from 2003 (dB)	Date of Implementation
Two-Wheeler		
i. Displacement up to 80 cm^3	75	1st Jan, 2003
ii. Displacement more than 80 cm^3 but up to 175 cm^3	77	
iii. Displacement more than 175cm^3	80	
Three-Wheeler		
i. Displacement up to 175cm^3	77	1st Jan, 2003
ii. Displacement more than 175cm^3	80	
Passenger Car	75	1st Jan, 2003
Passenger or Commercial Vehicle		
i. Gross Vehicle weight up to 4 ton	80	1st July, 2003
ii. Gross Vehicle weight more than 4 ton but up to 12 ton	83	
iii. Gross Vehicle weight more than 12 ton	85	

III. LITERATURE SURVEY:

Jianhua Fang proposed at constant inlet velocity the punching rate of perforated pipe plays a vital role in the pressure loss of muffler and at the lower punching rate the pressure loss will be higher for gas [3]. Ying-li Shao et al proposed a new concept of exhaust muffler, in which using the chamber with slits located at opposite sides, the flow of exhaust gases is split into two parts with the same magnitude of sound wave intensity but with 180o phase difference. These two flows and the sound waves they carry meet at the centreline of the muffler which results in destructive interference. The proposed concept is compared with a traditional passive muffler in terms of noise attenuation characteristic and specific fuel consumption using computational flow dynamics and engine experiments [4]. Jorge P. Arenas, Malcolm J. Crocker (2010) studied different porous sound absorption materials that can be used for noise control in a variety of applications including mufflers. All materials can absorb some portion of the incident sound, but they defined the term “acoustic material” as the one which absorbs a greater portion of sound waves relative to the portions they reflect and transmit. According to them, all these sound absorptive materials can be classified into three main types of porous absorbing materials based on their microscopic structure, these being cellular, fibrous and granular materials. One of the most innovative sound absorbers they talked about is the micro-perforated panel, which is effectively made up of a large number of individual Helmholtz resonators [5]. S.Bilawchuk, K.R. Fyfe is comparing between FEM (4 pole points method) and BEM (3 pole points method). Because both of these methods are better exclusive for design applications. So, on the basis of performance, 4 pole points method does not perform multiple runs or optimize better than 3-pole points method and the latter is easy to use for baffle spacing, absorptive material properties, or geometrical dimension and impact of multiple small chambers and simulate efficiently.

The 3-points computation method gives a better correlation between theoretical or experimental results [6]. Ahmed Elsayeda, Christophe Bastienb, Steve Jonesa et al presented the transmission loss and backpressure changes due to different sizes of the baffle in the muffler. The increase in baffle size leads to an increase in the backpressure. According to the authors, multiple holes are preferred to reduce backpressure, and a centre hole is more effective than distributed holes on the baffle surface in terms of noise reduction [7]. Ji Et Al., used the GT Power software for the design and simulation of muffler. In his works he incorporated the mass flow rate at an elevated temperature from this it was found that there was frequency shift in the transmission also there was variation in amplitude. The amplitude variation was unpredictable although the overall amplitude remains consistent with frequency [8]. Z.Tao and F.Seybert proposed a two-source method for measuring the four-pole parameters of an acoustic element. As it is difficult to measure the incident sound power due to the sound reflection from the muffler if the decomposition method is used. They observed that the two-source method measures accurately even in the absence of good anechoic termination [9]. Sudershan Deelip has described the influence on backpressure due to keeping some measurements constant while increasing the porosity of the muffler and diameter of holes. It results in sharp decrease in backpressure and this backpressure is difficult to forecast by any equation and to perform experimental action on muffler and CFD analysis which gives better co-relation to each other [10]. Omid Z.Mehdizadeh and Marius Paraschivoiu, have described a three-dimensional finite element method to find the transmission loss in mufflers and silencers. They chose the iso-parametric quadratic tetrahedral element because of its flexibility and accuracy. The previous methods don't fulfill specific resolution requirements and have a higher error percentage [11]. Xu Et Al., has used the two-dimensional analytical approach to estimate the effect of chamber diameter, fiber thickness and material properties on the acoustic performance of dissipative muffler. This approach was proposed and based on the solution of Eigen equations for a circular dissipative expansion chamber [12, 19]. Potente has given about the different aspects of designing the muffler [16]. Further Chiu Et. Al had worked on both reactive and dissipative mufflers and performed the CFD analysis [17]. Arslan Et Al. worked on performance of multi-chamber reactive silencer. According to them silencer performance depends on baffle geometry, position and number. Changing baffle position increases the sound transmission loss [18].

IV. PROBLEM FORMULATION:

Four muffler designs are proposed, simulated and compared. These are designed as per the engine output of Maruti Suzuki Ciaz [13].

Case study for LCV Petrol engine (Maruti Suzuki Ciaz):

A. *Engine Data:*

Bore (D) = 73mm
Stroke (L) = 82 mm
No. Cylinders (n) = 4
Engine power (P) = 91 bhp at 6000 RPM

B. *Muffler Volume Calculations:*

Swept volume per cylinder = $0.25\ (\pi \times D^2 \times l) = 0.25\ (3.14 \times 73^2 \times 82)$
(V_s) = 0.343201lit.
Total swept volume in litres = 4x0.343201= 1.3728 Lit.
Volume to be considered for calculation = 0.5 x Vs x n= 0.686402 Lt
Silencer volume: Volume of silencer must be at least 12 to 25 times the volume considered [12]. Volume can be adjusted depending on the space constraint.
Factor considered is = 20
Silencer volume = factor x consider volume = 13.728 Lit

C. *Diameter of inlet pipe Calculations:*

Hypothetical cylindrical diameter for muffler of calculated volume.
$Vm = 0.25\times \pi \times d2 \times l$
$0.013728 = 0.25\times \pi \times d^2 \times 0.5$
d = 0.187 m= 187 mm

As per the standards of the supercritical grade of mufflers, the diameter of the body should be about three times than the exhaust pipe diameter [15].

d = 3* d exhaust
187= 3* d exhaust
d exhaust = 62.33 mm

The muffler diameter calculated is for a muffler with cylindrical cross-section which can handle exhaust flow from the given engine. These proposed muffler designs have similar volume and therefore can cope with the exhaust gas flow from this engine, but their outer shell have an elliptical cross-section and its dimensions are given in Table 2.

Table 2. Dimensional data

Entity	Dimension(mm)
Semi major axis(a)	112
Semi minor axis(b)	78
Length	500
Exhaust Pipe diameter	62.33

Steel is taken as the material of choice for these mufflers, while the fluid which is simulated inside the muffler is considered to be air. The material properties data fed in the software simulation are mention in Table 3.

Table 3. Material properties

Material	**Density (kg/m^3)**	**Specific heat (J/[kg*k])**	**Thermal conductivity (W/[m*k])**
Steel	7900	502.48	16.27
Air (at 500k)	0.696	1029.5	0.0379

The exhaust flow simulation is done on Ansys fluent using k-ε (k-epsilon) turbulence model in the Computational Flow Dynamics. Different cases of exhaust flow velocity are simulated, which are 20 m/s, 40 m/s, 60 m/s and 80 m/s. The boundary conditions used are given in the Table 4.

Table 4. Boundary conditions

Entity	**Dimension**
Temperature (K)	470
Viscosity (kg/m.s)	2.7e-05
Enthalpy (J/kg)	749575.3
Density (kg/m3)	0.696
Ratio of specific heats	1.4

For the engine type taken under consideration, the maximum back pressure allowed is 20kPa. Therefore, any model in which pressure drop exceeds this limit, that model will not be considered fit for use with this engine.

V. PROPOSED MODEL DESIGN:

All the models have same external shell with dimensions as mentioned in the table above, but they differ in their internal structures. Model 1 and Model 2 has holes and circular tubes in its baffles which have a diameter of 50mm. Model 3 and Model 4 are a type of turbo mufflers in which flow reversal takes place. They have two pipes of which one with a diameter of 62.33 mm and a length of 460 mm is connected to the inlet, while the one with a diameter of 50mm and length of 450 mm is connected to the outlet. They also have a hole on their baffle whose diameter is 50mm. Model 4 also have perforations on either sides of its pipe, and the perforation holes have a diameter of 3mm to 5mm.This models are shown in figure 1, figure 2, figure 3 and figure 4 respectively.

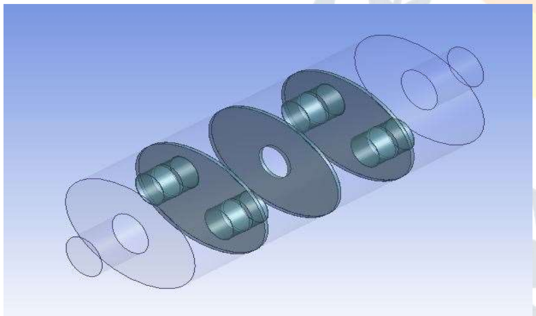

Figure 1. Design of model 1

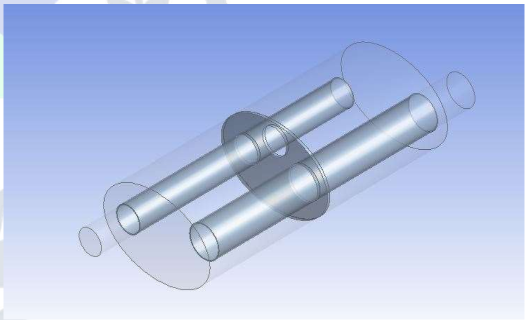

Figure 3. Design of model 3

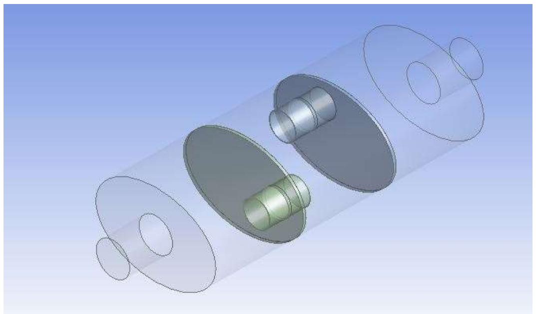

Figure 2. Design of model 2

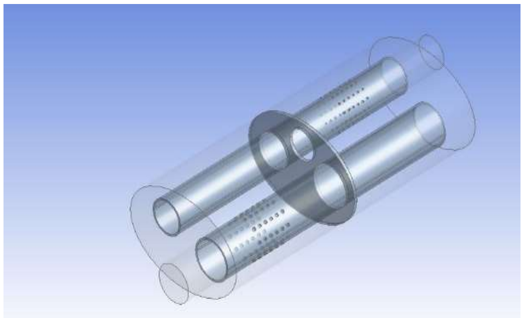

Figure 4. Design of Model 4

VI. RESULT AND DISCUSSION:

Table 5. Pressure drop for all the models at different inlet flow velocities

	Pressure drop in proposed models (Pa)			
Inlet-Velocity (m/sec)	**Model 1**	**Model 2**	**Model 3**	**Model 4**
20	1436.15	1821.054	1625.96	1034.41
40	5695.83	7257.123	6425.45	4102.25
60	13361.9933	16308.675	14442.6	9190.36
80	22641.23	29166.98	25584.8	16292.3

From the above-mentioned table 5 we can observe that the pressure drop by the model 2 is best among all other models including the existing model and the pressure and velocity contour of the existing model or Model 1 are given in Figure 5 to 12, Model 2 are given in Figure 13 to 20 and Model 3 is given from Figure 21 to 28.

A. Model 1:

Pressure contour diagrams for this design:

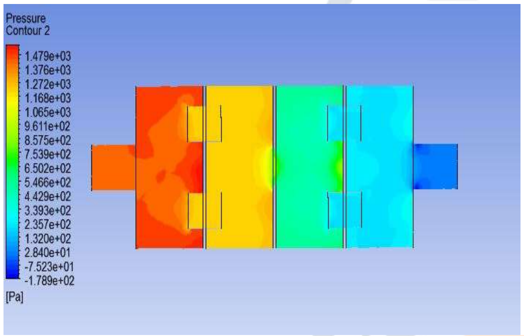

Figure 5. Inlet flow velocity at 20m/sec

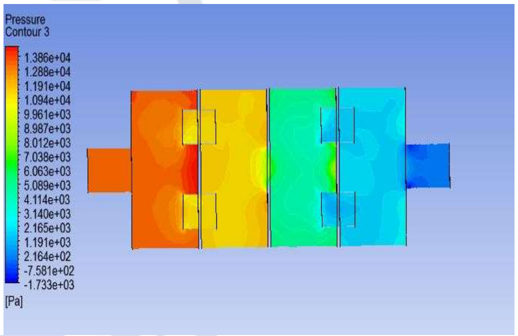

Figure 7. Inlet flow velocity at 60m/sec

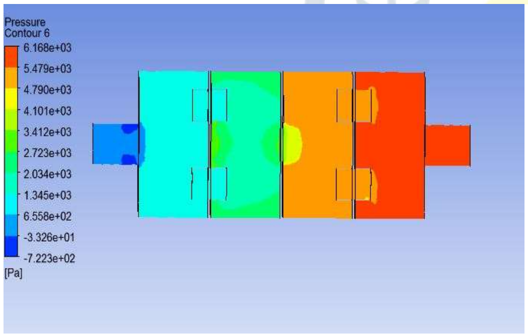

Figure 6. Inlet flow velocity at 40m/sec

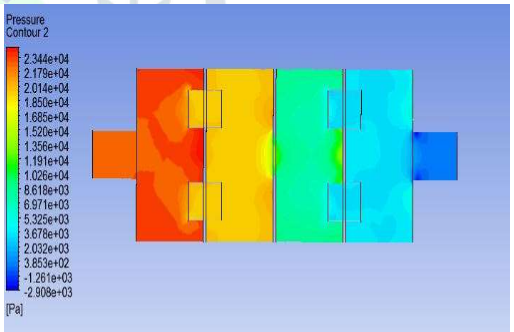

Figure 8. Inlet flow velocity at 80m/sec

Velocity contour diagrams for this design:

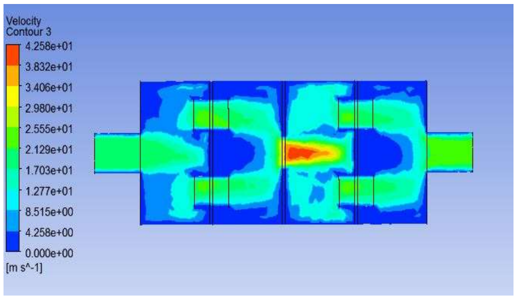

Figure 9. Inlet flow velocity at 20m/sec

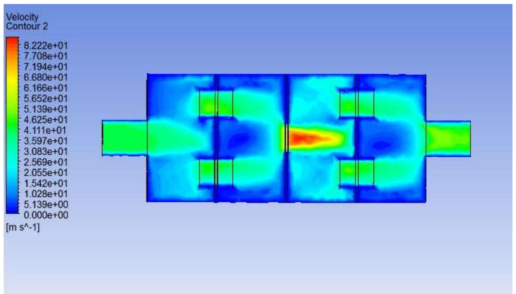

Figure 10. Inlet flow velocity at 40m/sec

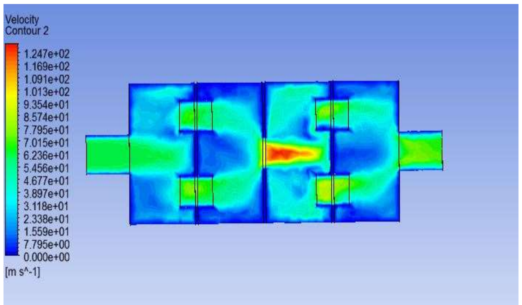

Figure 11: Inlet flow velocity at 60 m/s

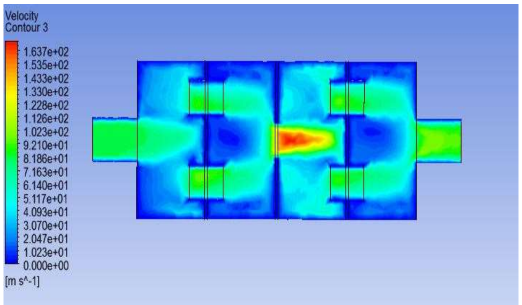

Figure 12. Inlet flow velocity at 80m/s

Here figure 5 to figure 8 shows the pressure variation inside model 1 at different inlet velocities whereas figure 9 to figure 12 shows the velocity variation inside model 1 at different inlet velocities.

B. Model 2

Pressure contour diagrams for this design:

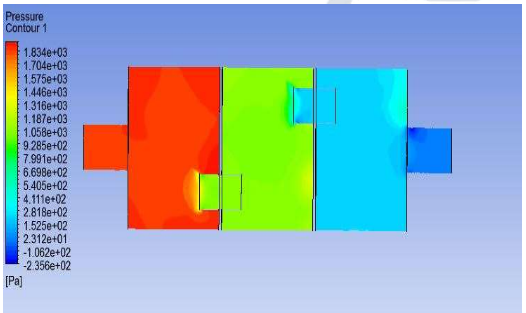

Figure 13. Inlet flow velocity at 20m/sec

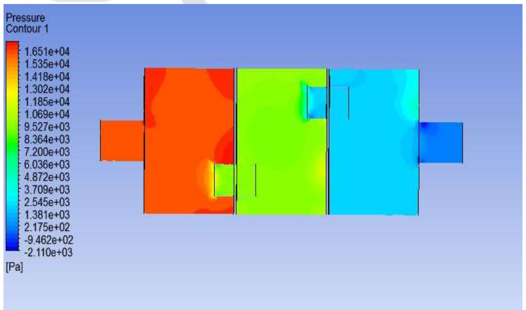

Figure 14. Inlet flow velocity at 40m/sec

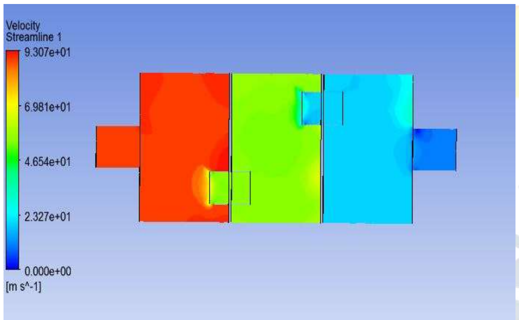

Figure 15. Inlet flow velocity at 60m/s

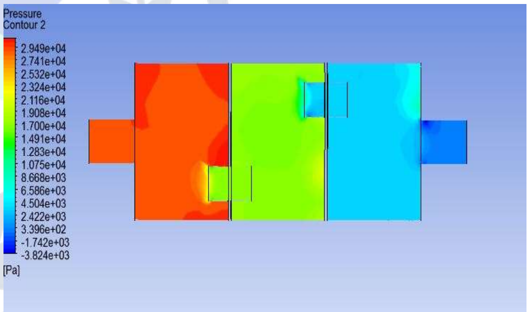

Figure 16. Inlet flow velocity at 80m/sec.

Velocity contour diagrams for this design:

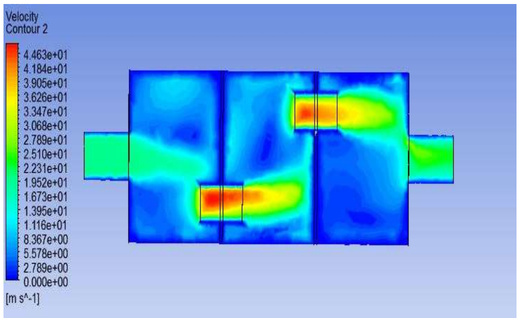

Figure 17. Inlet flow velocity at 20m/sec

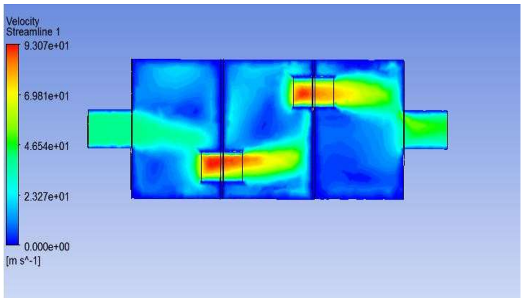

Figure 18. Inlet flow velocity at 40m/sec

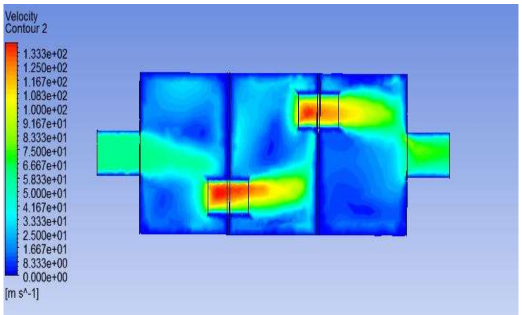

Figure 19. Inlet flow velocity at 60m/sec

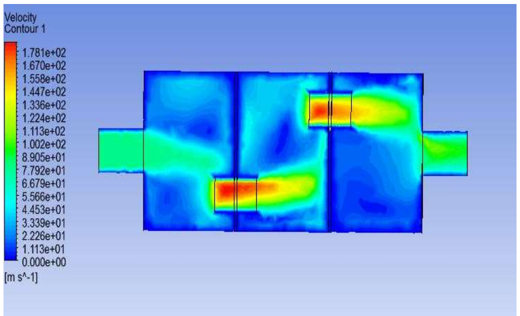

Figure 20. Inlet flow velocity at 80m/sec

Here figure 13 to figure 16 shows the pressure variation inside model 2 at different inlet velocities whereas figure 17 to figure 20 shows the velocity variation inside model 2 at different inlet velocities.

C. Model 3

Pressure contour diagrams for this design:

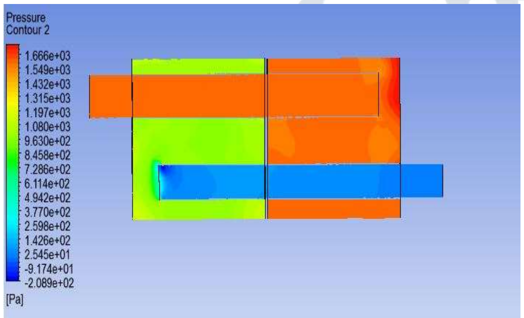

Figure 21. Inlet flow velocity at 20m/sec

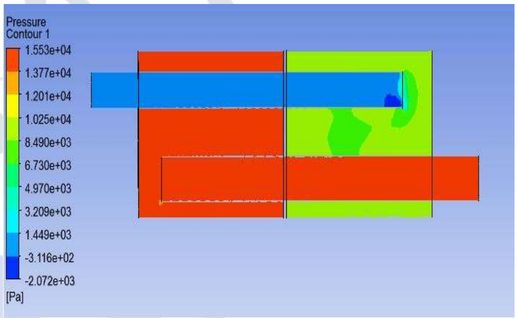

Figure 23. Inlet flow velocity at 60m/sec

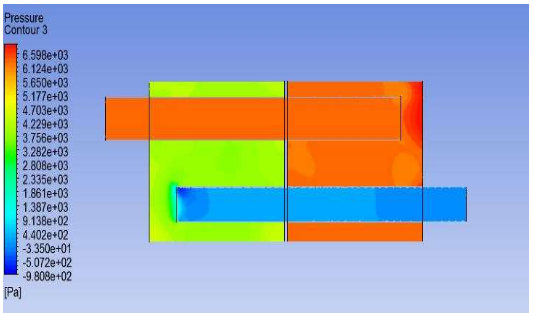

Figure 22. Inlet flow velocity at40m/sec

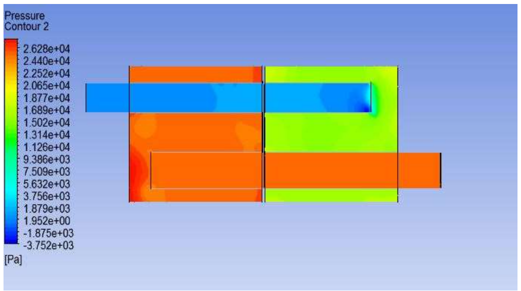

Figure 24. Inlet flow velocity at 80m/sec

Velocity contour diagrams for this design:

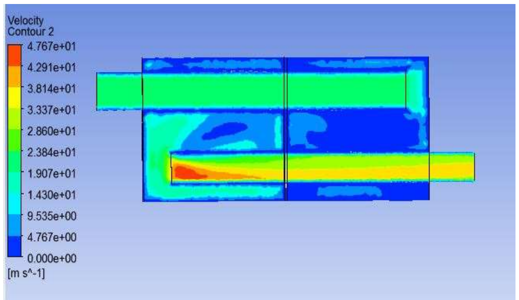

Figure 25. Inlet flow velocity at 20m/sec

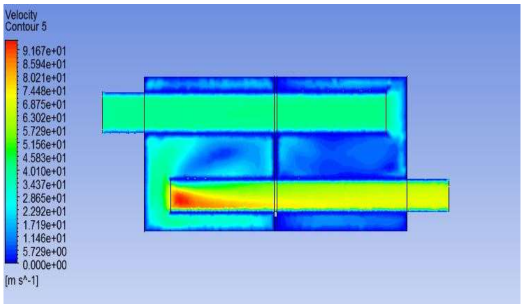

Figure 27. Inlet flow velocity of 40m/sec

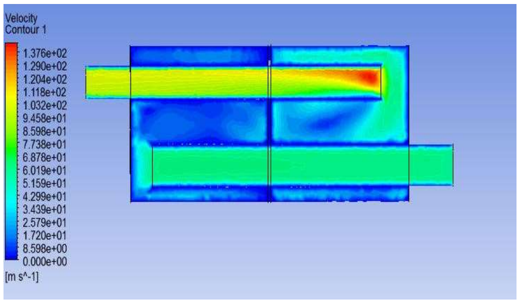

Figure 26. Inlet flow velocity at 60m/sec

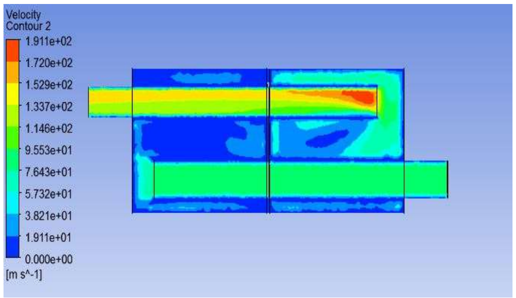

Figure 28. Inlet flow velocity of 80m/sec

Here figure 21 to figure 24 shows the pressure variation inside model 3 at different inlet velocities whereas figure 25 to figure 28 shows the velocity variation inside model 3 at different inlet velocities. These graphs shown in figure 29 represent the concerned data collected from simulations and we can observe that Model 2 is showing better performance than other models.

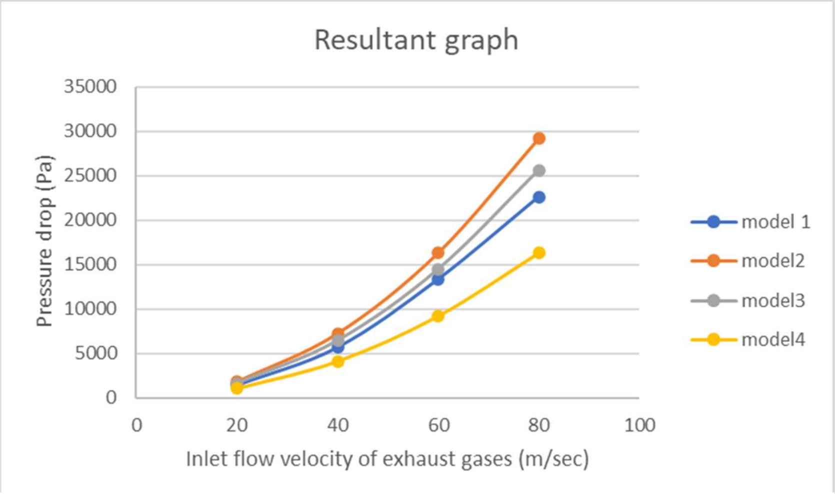

Figure 29. Inlet flow Velocity VS Pressure drop curve for each muffler

VII. CONCLUSION:

The pressure drop inside a muffler is related to the back pressure generated inside that muffler. So, Aerodynamic performance analysis was carried out and from the analysis result, it can be concluded that Model 2 has highest pressure drop for every inlet velocity considered. Model 3 gives the second highest pressure drop while the Model 4 gives the least amount of pressure drop among these proposed models. At different inlet velocity Model 2 provide 18% to 22% better pressure drop than the existing model i.e. Model 1 whereas model 3 and model 4 provides 7-11% and no increase in pressure drop respectively. Hence, Model 2 is expected to provide better noise reduction in physical application.

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