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Optimization of a reactive muffler used in four-cylinder petrol engine into hybrid muffler by using CFD analysis

Ujjal Kalita, Manpreet Singh *

School of Mechanical Engineering, Lovely Professional University, Phagwara, India

A R T I C L E I N F O

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A B S T R A C T

Four-wheeler automotive vehicle is the basic need of people in today's life all over the world. But the noise coming from the exhaust system is highly affecting the human health. Among all the noise produce in vehicle, exhaust system noise is maximum. Muffler is one such acoustic filter used for reducing this exhaust noise. Hybrid muffler is one type of muffler which combines the properties of both reactive muffler and dissipative muffler and it operates at wide frequency range. In this study an already existing muffler (Reactive type muffler) used in 91bhp, 6000 RPM four-cylinder petrol engine was optimized to hybrid muffler. Aerodynamic and acoustic performance parameters were the main performance parameter and were determined by CFD analysis and acoustic analysis. The existing reactive muffler of the four-cylinder petrol engine could be replaced by the hybrid muffler. Here the mufflers were designed in ANSYS design modular and analyses were performed in ANSYS Fluent and COMSOL software. CFD analysis was performed for the existing muffler and three other newly designed muffler by considering inlet velocity boundary condition at inlet velocity 40 m/s and 80 m/s. It was observed that increase in pressure drop (aerodynamic performance) in model 4, model 3 and model 2 is around 38%, 33.2% and 29% respectively. Again, from acoustic analysis the transmission loss (TL) in model 4 was observed to be 47 dB whereas in other models it was around 20 dB. Further it was observed that the sound pressure level from model 1 at the exit is around 75–78 dB whereas in model 4 it was observed to be around 45–50 dB at the exit. Hence from both the analysis it is concluded that model 4 which is hybrid type muffler is the most optimized muffler.

1. Introduction

Four-wheeler automotive vehicle is one of the important and basic needs of people in today's daily life all over the world. The Automotive industry is one of the most developed industries with all the latest techniques implemented on it. The most source of power in an automobile vehicle is internal combustion engine. The engine is operated either by taking in the mixture of air and fuel inside the engine or by compressing the air that is taken inside it. Vehicle composed of either the petrol engine (mixture of air and fuel) or diesel engine (only air is taken inside followed by combustion). The exhaust comes out from these engines at high pressure producing high noise. According to different researches performed on vehicles, it was observed that the noise produce by the exhaust system is maximum around 25% of the total noise produce by the vehicle. This noise is considered as the prime concern as it greatly affects the human health as suggested by the different health organization [1]. From different researches it is observed that different types of acoustic filters are available for reducing this exhaust noise. Muffler is one such device which greatly reduces the exhaust noise. Its tubular metal covering perforated tube, baffles, absorptions materials, tubular pipes are some of the important components present inside the muffler. These components help in reducing the exhaust noise. Depending upon the components present inside the muffler, the mufflers are divided broadly into two types - Reactive muffler and dissipative muffler. In the present scenario these are the two types of muffler which are used in automobile vehicles. Reactive mufflers generally composed of a single chamber or multiple chambers within which a perforated tube, baffles or simple tube could be incorporated. The exhaust gas coming from the engine would enter this chamber through the inlet section of the muffler. This gas would then expand in the chamber and it would cause a significant amount of pressure drop at the

* Corresponding author.
E-mail address: manpreet.20360@lpu.co.in (M. Singh).

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outlet section of the muffler. Incorporation of the perforated tube and baffles help in reduction of pressure to a higher amount. Thus, the backpressure created because of these acoustic elements would help in reducing the noise to a great extent. Dissipative muffler is second type of muffler which composed of absorption material. Absorption material will absorb or dissipate the amount of heat produce by the exhaust system and it would ultimately reduce the exhaust noise. A third type of muffler called the hybrid muffler could also be used in vehicles. Hybrid muffler is the combination of reactive muffler and dissipative muffler. Inside this muffler acoustic elements such as perforated tube, baffles, absorption materials, simple tubes or Helmholtz resonators are used. Unlike the reactive muffler which operates well at low frequency and dissipative muffler at high frequency, this type of muffler can be operated for wide frequency range. Due to the advancement in properties of fibrous material and its characteristics of acoustics dissipation, the absorption materials could be incorporated in mufflers. These materials are found to be more effective when it is combined with reactive muffler, producing hybrid configuration. Different researches are working on it from last few decades. In 1954, Davies et.al. had made the first comprehensive design of muffler and tested it experimentally. They used the transfer matrix method and studied the noise reduction principles [2]. Craggs evaluated the noise reducing capacity of an expansion chamber muffler lined with an absorption material. His work suggested that using the absorption material will increase the magnitude and also increase the transmission loss. Further it is said that increase in thickness of absorption materials would shift the peak frequencies of transmission loss [3]. Peat and Rathi had used Finite element method in the absorption material to determine the effect of non-uniform steady flow in it. He had also used perforated tube in his work [4]. Another researcher Wang worked on single-pass perforated absorbing silencer. He used the one-dimensional decoupled method and through simulation, the performance parameters and material properties are determined [5,6]. Later Liu et al. had worked on transfer matrix method (TMM) and suggested that it is ideally suited for acoustical modeling of the cascaded element in automotive mufflers [7]. The properties of absorption material are important to know the effect of this material while implementing it on muffler. Delany and Bazley had given some empirical expressions for determining the flow resistivity of the material. Flow resistivity is one of the main properties of absorption material. This flow resistivity is determined by using the fiber size and bulk density [8]. Absorption materials are normally combined with perforated tubes for use, so that better performance could be achieved as suggested by Selamet and Lee [9].

The different acoustic elements available directly affect the performance of the muffler which would ultimately determine the noise reducing capability of the said muffler. Aerodynamic performance parameter and acoustic performance parameter basically determines the noise reducing capacity of the muffler. Pressure drop and back pressure between the inlet and outlet section of muffler is the main aerodynamic performance parameter. Transmission Loss (TL), Insertion loss (IL) and level difference are the acoustic performance parameter which tells the sound pressure level at the exit of muffler. These performance parameters could be determined by finite element method or boundary element method by using simulation techniques [10]. The same properties could also be determined experimentally. Transfer Matrix method is one such method which is used, while determining the performance parameters experimentally. With the advancement in different techniques, it has been observed that Computational Fluid Dynamics (CFD) is greatly used for evaluating the aerodynamic performance parameter of the muffler [12]. Different researchers have worked on it. Munjal in his book had discussed about the different performance parameter and the different constraints that should be considered for implementing the FEM techniques or experimental techniques [13]. Yasuda et al. worked on an automotive muffler. In their work they modeled their muffler by 1D computation fluid dynamics approach and evaluated the tail pipe noise. Their results obtained were compared with measured value and only little deviation was observed with 2nd order of engine rotational frequency. Whereas, deviation with higher order frequency is more [14]. Later Ji and Selamet in 2000 and Hao et al.in 2005 had also worked on FEM techniques [11,15]. Mehdizadeh et al. had worked on packed muffler and also on combined muffler consisting of absorption and perforated tube. Both experimental and numerical technique is used and their result showed a quite increase in transmission loss because of absorption material [16]. Lee in his research work had initially performed analysis on reactive muffler; later on hybrid muffler was constructed. Acoustic performance parameter i.e. transmission loss (TL) is determined for both mufflers and it was observed a considerable increase in TL in hybrid muffler [11]. Saripalli and Sankaranarayana had worked on resistive muffler used in a four-cylinder LCV diesel engine by considering the engine output parameters. Two different models were simulated by using the CFD analysis (ANSYS Fluent) and the results obtained were found to be fruitful [17]. Ujjal et al. has worked on four cylinder diesel engine and performed the CFD analysis for determining the aerodynamic performance parameters [22].Dere et. al. had also performed CFD analysis in their work [18,19].Om Ariara Guhan C P et.al had worked on Three Cylinder LCV Exhaust System. They also performed the CFD analysis and determined the Pressure Drop and Uniformity Index [20,21]. Potente has given about the different aspects of designing the muffler [24]. Further 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 [25].

The main objective of this study is to design an optimized hybrid muffler which could be implemented in a four-cylinder petrol engine. For this study, a muffler used in a Maruti Ciaz is used as the reference muffler. This vehicle composed of a 91bhp, 6000 RPM four-cylinder engine. On this existing engine an elliptical reactive muffler is already in use. The muffler composed of different acoustic elements such as baffles and tubes. Here, in this study without changing the volume of muffler i.e keeping the outer dimension constant an optimized hybrid muffler would be created. This muffler would consist of baffles, tubes and absorption materials inside it for reducing maximum amount of noise. Both the aerodynamics and acoustic performance parameters would be determined through simulation method. From the CFD analysis pressure drop in the muffler from the inlet of muffler to outlet of muffler would be determined. Whereas by using the acoustic analysis, the transmission loss (TL) for the muffler is determined. This performance parameters are obtained by considering the velocity inlet boundary condition where the velocity considered for operation are 40 m/s and 80 m/s.

2. Theoretical approach

2.1. Plane wave propagation theory

This theory is applied to a rigid straight pipe having cross-sectional area (S) and length (L) where an incompressible turbulence mean flow is transported through it which is of velocity (V) as shown in Fig. 1. The sound pressure (p) and volume velocity (v) are represented by the summation of two travelling waves i.e., left and right travelling waves. These sound pressure and volume velocity are related by the equation (1) and (2) at the upstream end (x = 0) and the downstream end (x = L).

$$p_1 = Ap_2 + Bv_2 \tag{1}$$

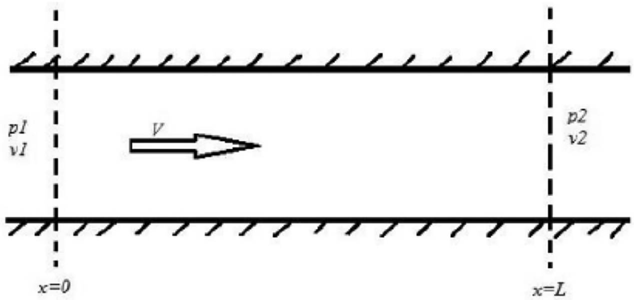


Fig. 1. Plane wave propagation in a rigid straight pipe.

$$v_1 = Cp_2 + Dv_2 \tag{2}$$

Here A, B, C and D are the four pole constants and is dependent on frequency and acoustic properties of pipe [1].

According to M L Munjal, the four pole constants can be determined by

$$A = e^{(-jMk_cL)}\cos(k_cL) \tag{3}$$

$$B = jYe^{(-jMk_cL)}\sin(k_cL) \tag{4}$$

$$C = (\frac{j}{Y})e^{(-jMk_cL)}\sin(k_cL) \tag{5}$$

$$D = e^{(-jMk_cL)}\cos(k_cL) \tag{6}$$

where M = V/c is the mean flow Mach number (M less than 0.2), c is the sound speed (m/s), k_c = k/(1- M^2) is the convective wave number (rad/m), k = ω/c is the acoustic wave number, ω is the angular frequency (rad/s), j is the square root of −1, Y = ρc/S is the characteristic impedance, ρ is the density of fluid (kg/m^3).

2.2. Transfer matrix method

This method is mainly used for calculating the transmission loss of a muffler by noting the required values experimentally by testing the muffler. This transfer matrix used to relate the sound pressure and velocity at the inlet and outlet section of the muffler. According to Munjal [1], for a simple expansion chamber the relation is written in matrix form as

$$\begin{bmatrix} p_1 \\ v_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}\begin{bmatrix} p_2 \\ v_2 \end{bmatrix} \tag{7}$$

Here, p_1= pressure at the inlet, p_2 =pressure at the outlet, v_1= velocity at the inlet, v_2 = velocity at the outlet

2.3. Transmission loss (TL)

It is defined as the ratio of sound pressure incident at the inlet of muffler to the sound pressure transmitted at the outlet of muffler. It is one of the acoustic performance parameters of muffler and is independent of any other element.

$$\mathrm{MathematicallyTL} = 10\log\frac{(\mathrm{incidentenergy})}{(\mathrm{transmittedenergy})} \tag{8}$$

$$\mathrm{i.e.TL} = 20\mathrm{Log}\left(\left|\frac{p_{inc.}}{p_{trans.}}\right|\right) + 10\mathrm{Log}\left(\frac{S_o}{S_i}\right) \tag{9}$$

Here S_i and S_o represent the cross-sectional areas of the inlet and outlet section of muffler respectively.

Experimentally by using the two-load method and determining the parameters by transfer matrix method, the TL is calculated by

$$\mathrm{TL} = 20\mathrm{Log}_{10}\left(\left|\frac{1}{2}\left[A + \frac{B}{\rho_o c} + (\rho_o c)C + D\right]\right|\right) + 10\mathrm{Log}_{10}\left(\frac{S_o}{S_i}\right) \tag{10}$$

Here A, B, C and D are the four poles which are calculated as for source method.

3. Design methodology

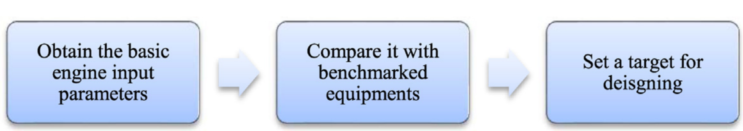
A properly designed muffler must satisfy five basic criteria for application in any type of vehicle [23]. Out of these, two criteria are most important while designing the muffler.

1. Acoustic criterion: It specifies the minimum noise reduced by a muffler concerning frequency.

2. Aerodynamic criterion: It specifies the maximum acceptable average pressure drop in a muffler at a given temperature and mass flow rate [17].

For the good design of a muffler, five broad steps are considered which are followed by practical considerations.

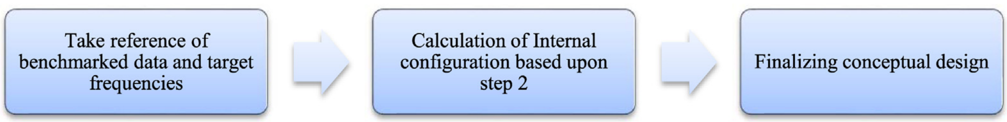
Step 1: Setting objectives and bench marking



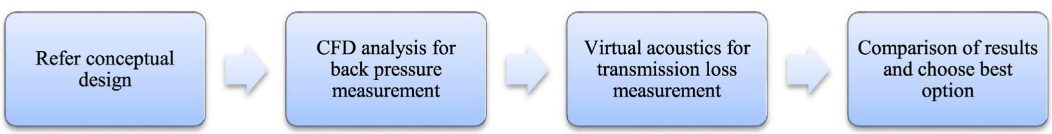
Step 2: Calculation of targetted data or frequencies.

Step 3: Calculation of muffler volume

Step 4: Conceptual design and its internal configuration



Step 5: Virtual Simulation



4. Detail study and problem formulation

In this study different models of muffler are considered for study of pressure drop and velocity variation and transmission loss. Out of this the optimized muffler could be incorporated in LCV petrol engine. While designing this muffler, volume of muffler is the prime property that is taken into consideration.

The existing volume of muffler is considered for study and modification is done in different models considered for study. Here baffles are introduced in to the chamber and its effect on back pressure or pressure drop is take for study. CFD analysis is performed for determining the flow parameters and acoustic analysis is performed for determining transmission loss.

In this work the performance of three muffler models is compared with the performance of an existing proposed muffler model. The different models taken into consideration are shown in Fig. 2, Fig. 3, Fig. 4 and Fig. 5 respectively.

Model 1: Existing Proposed muffler (Four chamber, three baffles and multiple tubes with a hole)

Model 2: Triple chamber with double baffle, tube and angle plates

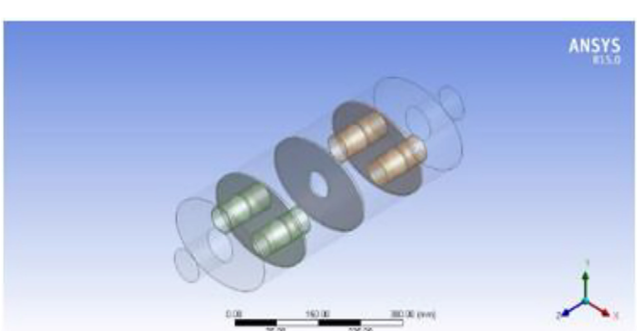


Fig. 2. Model 1.

Model 3: Triple chamber with double baffle, perforated tube and tube

Model 4: Triple chamber with double baffle, double tube and absorption material.

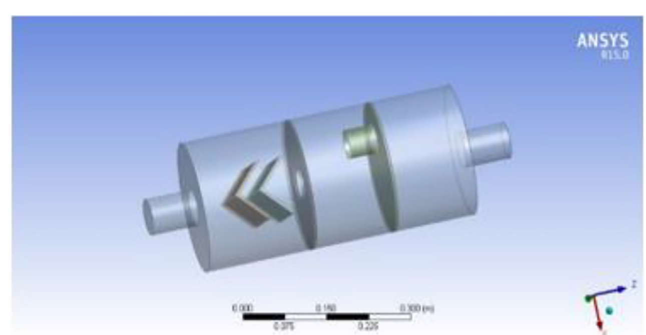


Fig. 3. Model 2.

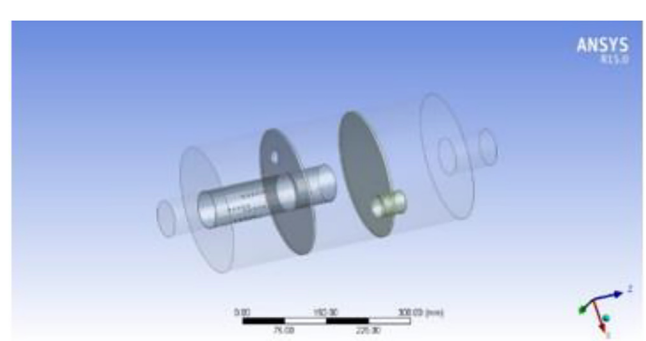


Fig. 4. Model 3.

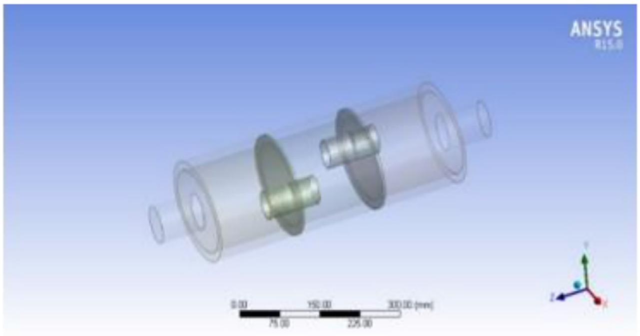


Fig. 5. Model 4.

4.1. Engine data

Engine Power (P) = 91 bhp at 6000 RPM = 67.86 kW
Bore (D) = 73 mm, Stroke (L) = 82 mm, Number of cylinders (n) = 4

4.2. Calculation of volume of muffler

As per theory of acoustics, the volume of muffler is calculated as follows.

Swept volume per cylinder (V_s) = 0.25 ($\pi \times d^2 \times l$) = 0.25 ($3.14 \times 73^2 \times 82$) = 0.343201lit.

Total swept volume in litres = 4 $\times$ 0.343201 = 1.3728 Lit.

Volume to be considered for calculation = 0.5 $\times$ V_s $\times$ n = 0.68 6402 Lt

Silencer volume: Volume of silencer must be at least 12 to 25 times the volume considered [6]. Volume can be adjusted depending on the space constraint.

Factor considered is = 20

Silencer volume = factor $\times$ considered volume = 13.728 L = 0.01372 m^3.

Volume can be varied depending on the space constraint.

4.3. Internal configuration and concept designs

Diameter of inlet pipe Calculations: Hypothetical cylindrical diameter for muffler of calculated volume.

Volume of muffler (V_m) = 0.25x $\pi \times d^2 \times l$

0.013728 = 0.25x $\pi \times d^2 \times 0.5$

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.

d = 3* $d_{exhaust}$ or 187 = 3* $d_{exhaust}$ i.e. $d_{exhaust}$ = 62.33 mm

For designing a muffler, the dimensions of muffler are the important parameters.

By considering the dimension of existing muffler

Semi-major axis = 112 mm = 0.112 *m*

Semi-minor axis = 78 mm = 0.078 *m*

Length of muffler = 500 mm = 0.5 *m*

Volume of muffler (V_m) = (πabh) = 3.14 $\times$ 0.112 $\times$ 0.078 $\times$ 0.5 = 0.01372 m^3

By taking reference with existing proposed muffler in Ciaz, length considered is 0.5 m or 500 mm. Other internal design concepts should also be used according to the design considered.

4.4. Material Properties:

For construction of muffler and its solid components, the material considered is steel, while the fluid which is simulated inside the muffler is considered to be air at 500 K. According to the material the properties used during simulation is shown in Table 1.

Table 1
Properties of material.

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

Here the exhaust flow simulation is done on ANSYS Fluent using k-ε (k-epsilon) turbulence model in the Computational Flow Dynamics [17,23]. The transmission loss and the sound pressure level are determined by using COMSOL software. Two types of boundary conditions can be implemented for evaluation this performance parameters. Velocity inlet boundary condition and the pressure outlet boundary conditions. The different values considered for implementing the velocity inlet boundary condition is given in Table 2. The performance of the muffler is determined at two different inlet velocities. Once at inlet velocity 40 m/s and once at 80 m/s.

Table 2
Boundary Conditions.

Properties	Values
Temperature (K)	500
Viscosity (kg/ms)	2.7e-05
Enthalpy (J/kg)	749575.3
Density (kg/m^3)	0.696
Ratio of specific heats	1.4

5. Results and discussion

From different literature survey and according to the works performed by different researchers it was observed that increase in restriction to the flow inside muffler lead to increase in back pressure and it also affects the efficiency of the engine. The maximum permissible back pressure for different type of engine is shown in Table 3.

Applying the boundary conditions to all the models, the CFD analysis for different models is shown in below figures. Initially aerodynamic performance parameters are evaluated. The pressure and velocity variation inside the muffler is determined. The inlet velocities considered for study are 40 m/s and 80 m/s. The models are created in ANSYS design modular and analysis is performed in ANSYS Fluent.

Mesh or Grid convergence test: The size of mesh plays an important role in simulation results. So, for getting accurate mesh size, mesh convergence test was performed on models varying mesh sizes between 2 mm and 3.5 mm. It was observed that there was not much variation in total pressure and acoustic power level between this ranges. Total pressure varying from 840 Pa to 843 Pa whereas acoustic power level varying between 54.54 dB and 55.86 dB. Thus, for reducing the simulation time, a suitable mesh size of 2.5 mm is considered for performing the simulations.

Table 3
VERT maximum recommended exhaust back pressure.

Engine Size	Back Pressure Limit
Less than 50 kW	40 kPa
50–500 kW	20 kPa
500 kW and above	10 kPa

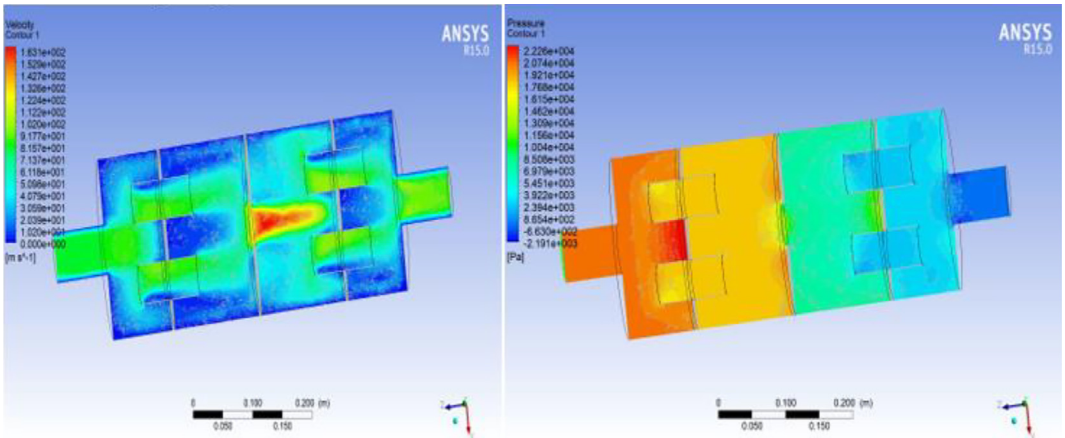


Fig. 6. Velocity variation and pressure variation inside model 1 at velocity 80 m/s.

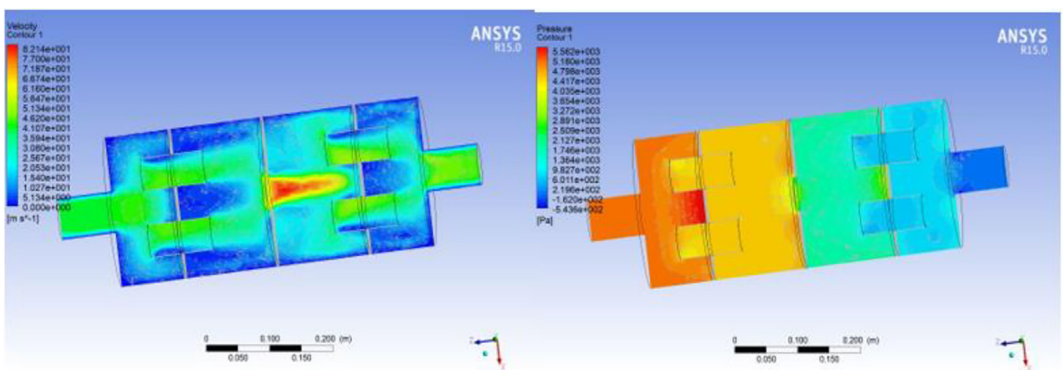


Fig. 7. Velocity variation and pressure variation inside model 1 at velocity 40 m/s.

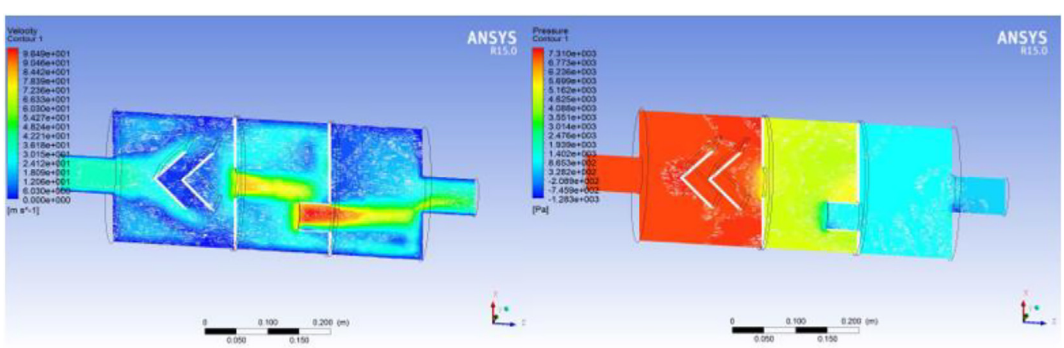


Fig. 8. Velocity variation and pressure variation inside model 2 at velocity 40 m/s.

5.1. Aerodynamic performance analysis

5.1.1. Model 1: existing proposed muffler

Fig. 6 shows the velocity and pressure variation at 80 m/s whereas Fig. 7 shows the velocity and pressure variation inside the proposed existing muffler at 40 m/s. From the velocity variation it was found that near the hole of second baffle the velocity increases drastically to a higher value. The pressure is maximum at the inlet of muffler but as it moves through the baffles and tubes the level of pressure decreases and towards the outlet it is minimum.

5.1.2. Model 2: triple chamber with double baffle, tube and angle plates

Fig. 8 and Fig. 9 shows the velocity and pressure variation at 40 m/s and 80 m/s when an angle plate is placed inside the muffler by replacing the already existing baffles. It shows an increase in pressure drop by about 29% then the existing proposed model i.e. model 1.

5.1.3. Model 3: triple chamber with double baffle, perforated tube and tube.

Fig. 10 shows the variation of velocity and pressure at 40 m/s and it was observed that on using a perforated tube with baffle the pressure drop increased by 33.2% as compared to model 1 and 5.42% as compared to model 2.

5.1.4. Model 4: triple chamber with double baffle, double tube and absorption material.

Fig. 11 and Fig. 12 show the variation of velocity and pressure at 40 m/s and 80 m/s. It was observed that on using two tubes with

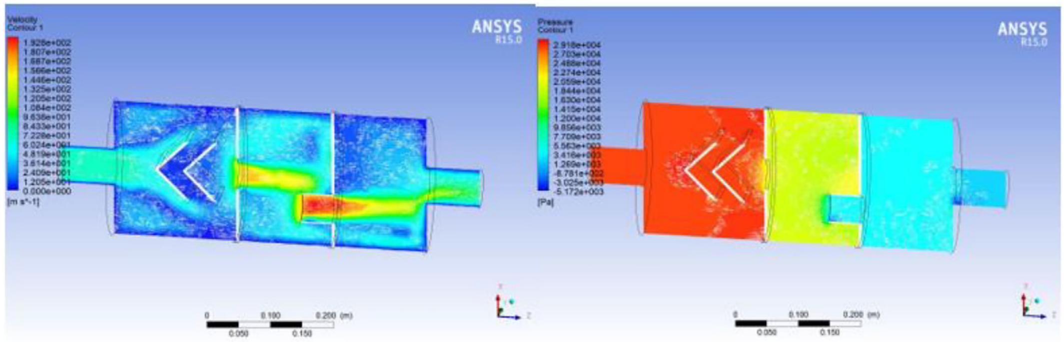


Fig. 9. Velocity variation and pressure variation inside model 2 at velocity 80 m/s.

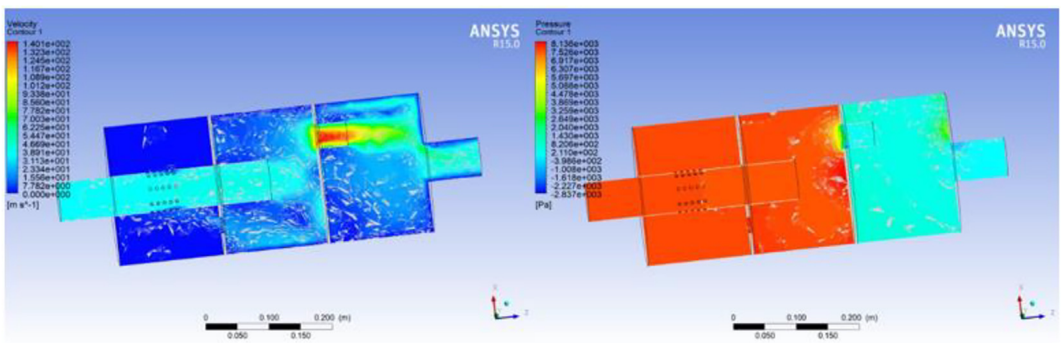


Fig. 10. Velocity variation and pressure variation inside model 3 at velocity 40 m/s.

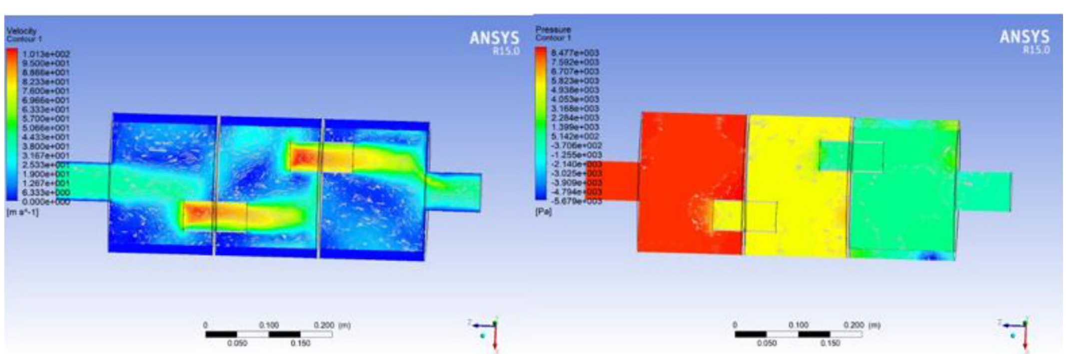


Fig. 11. Velocity variation and pressure variation inside model 4 at velocity 40 m/s.

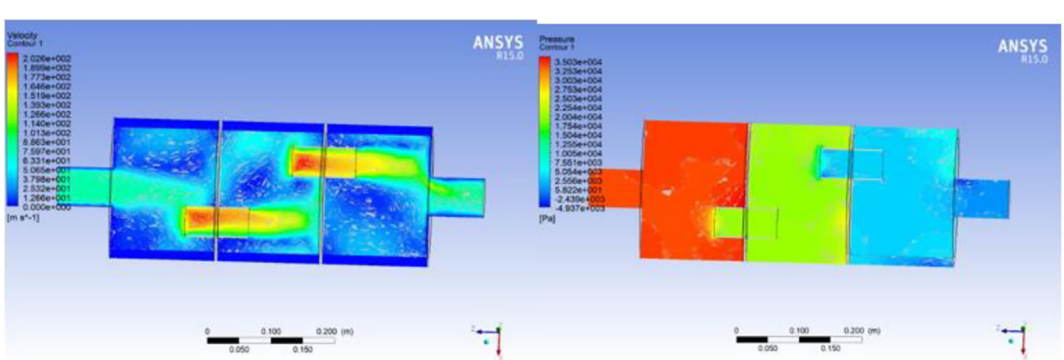


Fig. 12. Velocity variation and pressure variation inside model 4 at velocity 80 m/s.

Table 4
Pressure drop in different models at velocity 40 and 80 m/s.

	Velocity	Pressure Max. Pressure [Pa]	Min. Pressure [Pa]	Inlet Pressure [Pa]	Outlet Pressure [Pa]	Pressure Drop [Pa]
Model 1	80	22773.3	−2191.49	20695.8	31.59	20664.2
	40	5688.7	−543.6	5160.28	9.79	5150.49
Model 2	80	30251.7	−3445	29143.7	51.47	29092.2
	40	7578.67	−1283.01	7303.31	12.71	7290.6
Model 3	80	32857.2	−11433.8	30734.5	−0.35	30734.8
	40	8237.46	−2837.48	7708.56	0.11	7708.45
Model 4	80	36274.4	−4937.12	34152.5	52.07	34,100
	40	8919.82	−5678.95	8423.35	13.34	8410.01

Table 5
Comparison of pressure drop in different models.

Models	Pressure Drop	Percentage increase in pressure drop as compared to model 1(existing muffler)
Model 1	5150.49	–
Model 2	7290.6	29.35
Model 3	7708.45	33.2
Model 4	8410.01	38

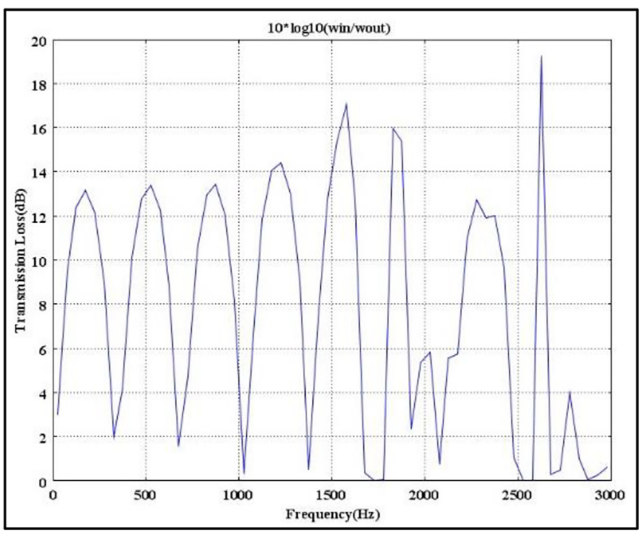


Fig. 13. Transmission loss (TL) for existing proposed muffler.

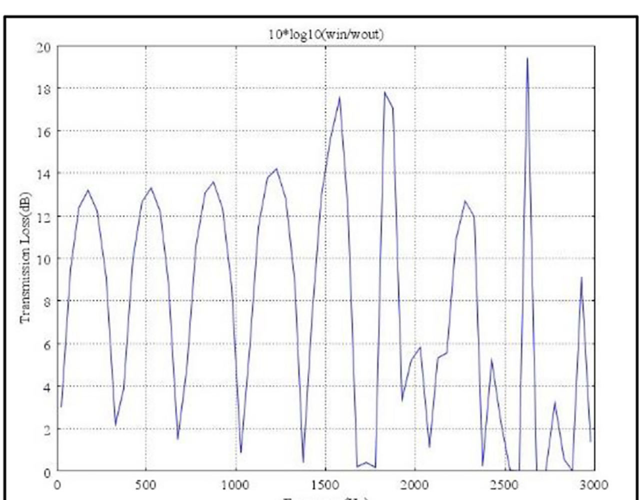


Fig. 14. Transmission loss for model 2.

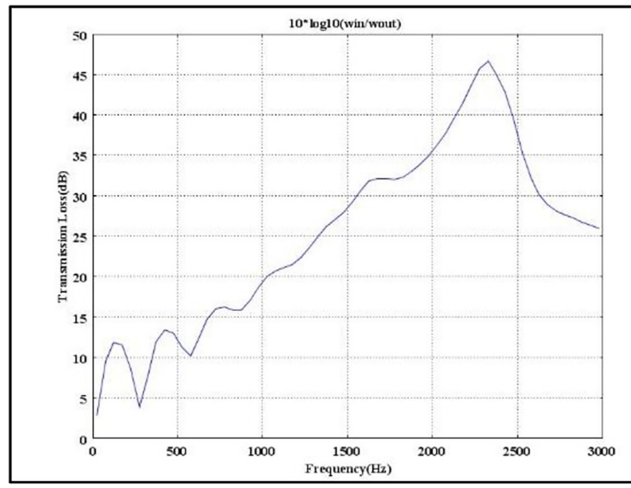


Fig. 15. Transmission loss for model 4.

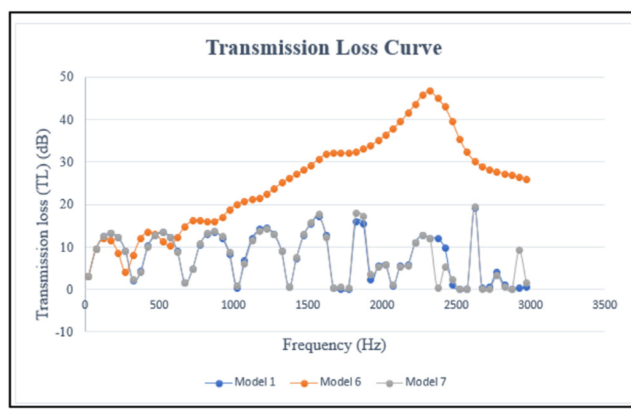


Fig. 16. Comparison of TL for the existing model with optimized model.

baffle and 15 mm absorption lining the pressure drop increased by 38%, 13.3 % and 8.34% as compared to model 1, model 2 and model 3 respectively.

The contours of pressure variation and velocity variation from the simulation are shown from Figs. 6–12. It was observed that the amount of pressure drop in more in model 4 than the other models. In the existing proposed muffler i.e. model 1, three baffles and four internal tubes were used due to which the restriction to the flow increased. The resistance produced by this elements increased the back pressure as shown in Fig. 6 and Fig. 7. This is due to the turbulence and eddy currents produced near the holes and the tubes. Whereas in model 2 the restriction inside the flow or resistance produced by the components is reduced on applying an angular plate as show in Fig. 8 and Fig. 9. This was because of

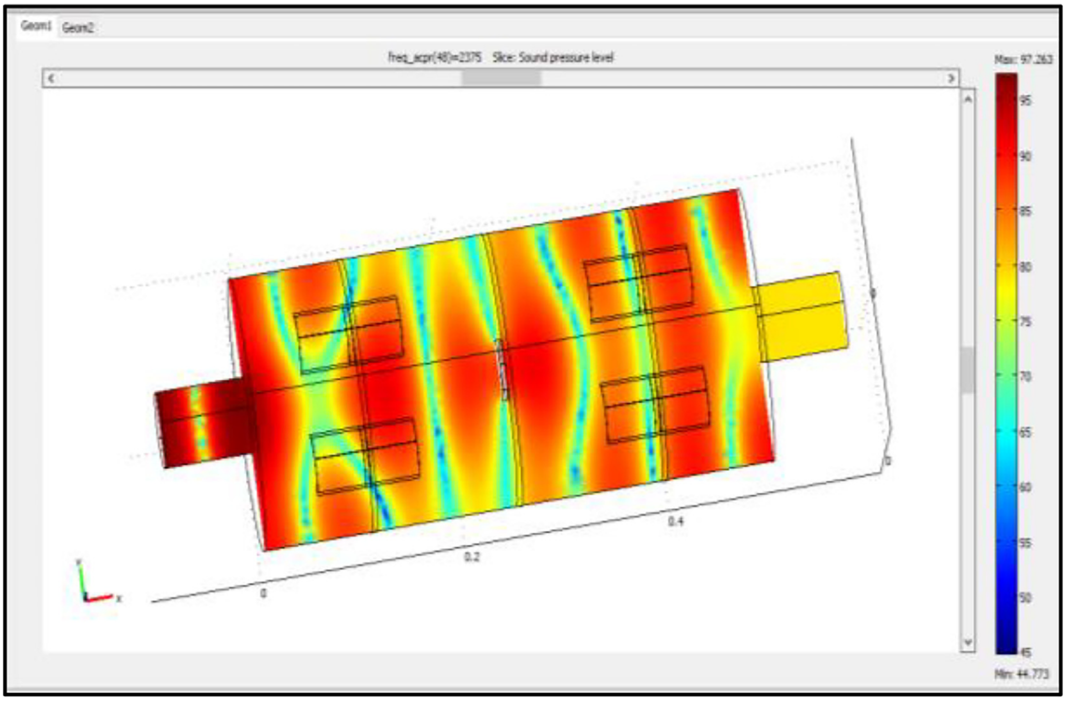


Fig. 17. SPL at 2375 Hz for Model 1.

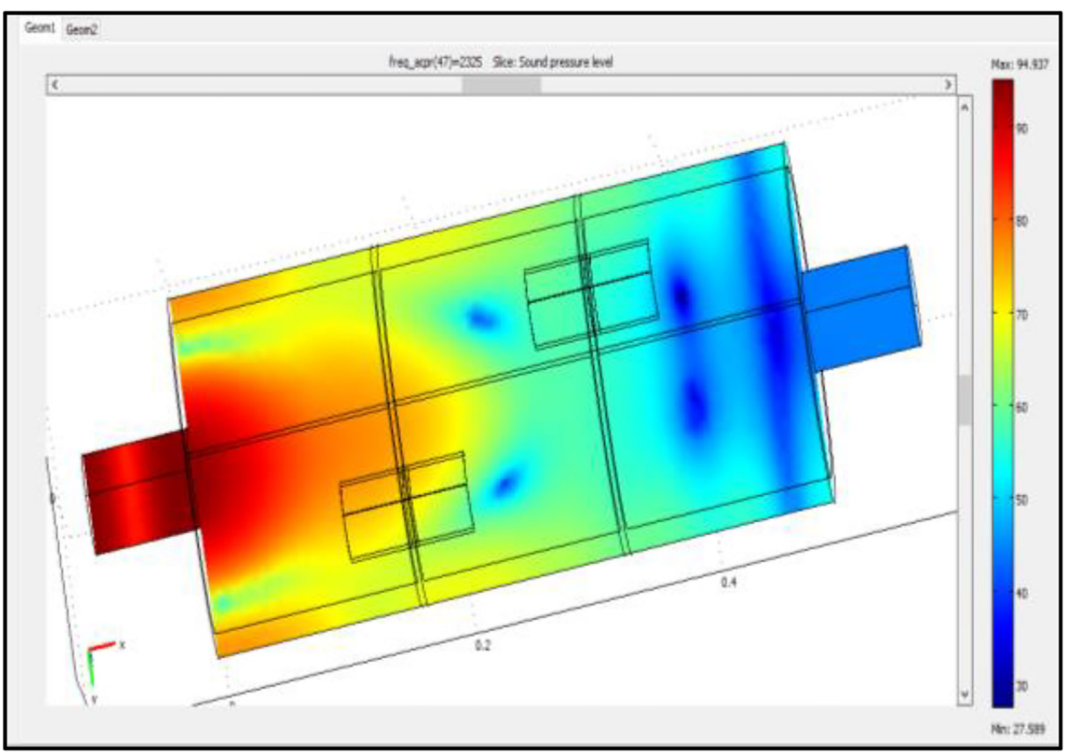


Fig. 18. SPL at 2375 Hz for optimized model i.e. Model 4.

the direction of flow near the angle plate where the flow smoothly passes reducing the resistance. This leads to decrease in back pressure and efficiency of engine increases. Further from Fig. 10 it could be observed that on using a perforated tube instead of angle plate the flows were now dispersed through the holes. Due to this the pressure drop increased further because the flow through the holes were spread inside the muffler reducing the resistance. Ultimately on using absorption material and tubes inside muffler the flow restriction reduced to a high amount as shown in Fig. 12. The sound absorption material absorbs the acoustic energy and it reduces the turbulence by absorbing the vibration of the air which is present in the pores or reduces it by friction against the edges. Due to this maximum pressure drop was attained by this muffler which helps in reducing noise to maximum amount. Thus, the proposed design i.e. model 4 is the most effective optimized muffler for use in this four-cylinder petrol engine.

Table 4 shows the different pressure variation occurred inside the muffler for all the models. The maximum and the minimum pressure as well as the pressure at the inlet and outlet section of the muffler is determined. All the results are obtained by using ANSYS Fluent software.

From the above Table 5 it can be concluded that by performing the aerodynamic performance analysis of all the models, model 4 is found to be best optimized model for use. As compared to existing proposed muffler, pressure drop increase by 29.35 % in model 2, 33.2 % in model 3 and 38 % in model 4 respectively.

5.2. Acoustic performance analysis

5.2.1. Determination of transmission loss (TL) for models

Fig. 13, Fig. 14 and Fig. 15 shows the transmission loss curve for model 1, model 2 and model 4 respectively. Whereas Fig. 16 gives us the comparison of the TL in those models. It is observed that model 4 produces the maximum transmission loss, i.e., maximum amount of noise coming from exhaust system would be reduced by this muffler. Thus, model 4 is the most optimized model for use.

5.2.2. Sound pressure level (SPL) comparison

Here the Sound pressure level produced at the inlet and outlet sections of the mufflers are compared. The comparison is made between model 1 (existing proposed model) and model 4 (optimized model). As from CFD analysis, model 4 is found to be best suited muffler, so comparison of SPL is made with model 4 only. The sound pressure level of the models is shown in Fig. 17 and Fig. 18 respectively.

From Fig. 17 and Fig. 18 it could be observed at sound pressure level (SPL) at the exit of muffler for model 4 is less than the SPL at the exit of model 1. So, noise reduction by model 4 is better than model 1.

Finally, from the above analysis it is observed that hybrid muffler reduces maximum amount of noise coming out from the exhaust of that engine.

6. Conclusion

From the work performed by different researchers, it was observed that increase in back pressure reduces the noise at the exit of muffler. By increasing the pressure drop from the inlet to the outlet of muffler, the backpressure is increased which ultimately reduces the noise coming out from the exhaust system. For determining this pressure drop, CFD analysis is performed. From the analysis, it was observed that the optimized muffler i.e. model 4 is producing more pressure drop than the existing proposed model i.e. model 1. Instead of using three baffles and four tubes with a hole in model 1, model 4 in reduced to two baffle and two tube with an absorption material lining 15 mm. This increased the pressure drop by 38% as compared to model 1. Whereas model 2 and model 3 had produced 29% and 33.2% rise in pressure drop as compared to model 1.

Acoustic analysis was also performed and it was observed that the maximum transmission loss in model 4 is around 47 dB and in model 1 it is around 20 dB. The sound pressure level at the outlet section of muffler in model 1 is around 75–78 dB, whereas for model 4 it is around 46–49 dB. Hence, from both the analysis i.e. aerodynamic and acoustic performance analysis it could be concluded that model 4 is the best optimized model and it could be implemented in the four-cylinder petrol engine. It is a hybrid type of muffler which possesses the properties of both reactive and dissipative muffler.

CRediT authorship contribution statement

Ujjal Kalita: Data curation, Software, Methodology, Writing – original draft. **Manpreet Singh:** Supervision, Writing–review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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