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Optimization of Backpressure in Exhaust Muffler for Automobile

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Abstract: The goal of this study is to optimise the exhaust middle box muffler of an automobile by focusing on the design of the perforated pipes. Back pressure and pressure drop in the exhaust are two characteristics that contribute to the various effects of an internal combustion engine. In this study, the pressure distribution of an existing exhaust middle box muffler on the perforated pipe is evaluated using Computational Fluid Dynamic (CFD) software, and the suitable perforated pipe is identified to improve the middle box muffler performance. The simulation of fluid flow inside a passage of perforated pipe with the same diameter and length but different perforation diameters and distance between perforations was carried out in this study. The CFD analysis simulation results showed the flow pattern with pressure contours for each sample. The results also revealed that each sample had a different pressure drop. An optimised design of perforations inside the middle box muffler pipe results in less pressure drop, which improves exhaust system performance. The simulation results are plotted and a comparison of various perforation diameter and distance can be seen. Larger distance between perforations at 20 mm gives large discrepancies in the results which is 15% difference of pressure drop as compared to smaller distance between perforations that gives less than 1% difference of pressure drop for 6mm and 7mm diameter of perforated pipes. The results also shows that 5mm of perforation diameter gives even larger pressure drop as high as 44.66%.

Keywords: Middle box muffler, perforated pipe, computational fluid dynamics, finite element method

1. Introduction

An exhaust system is a piping system that is used to send reaction exhaust gases away from a controlled combustion within an engine or stove. The entire system, which may comprise one or more exhaust pipes, transfers the engine's burnt gases. The exhaust middle box mufflers are situated in the middle of an exhaust system. The intermediate boxes are connected to the catalytic converters through a connecting conduit. There is an exhaust air flow in the pipes in the centre box, which has an effect on temperature and pressure. The current typical design of a middle box may cause inefficient performance. There could be an uneven flow pattern, resulting in undesirable temperature and pressure effects. The current design should be enhanced to improve performance. Additionally, the exhaust manifold, which is connected to the exhaust system, will transport the internal combustion engine's hot exhaust gases to the exhaust pipes. Furthermore, the exhaust system can be employed to reduce engine noise [1]. Numerous studies on the acoustical and flow characteristics of the chamber muffler have been conducted [2, 3, 4]. However, minimal research has been conducted on the perforation porosities of pipe in the chamber.

2. Literature Review

Yao *et al.* [5] studied the performance of a reactive muffler and its effect on engine power loss by considering the muffler's internal flow field. They optimised the design of a reactive muffler by comparing it with experimental data using computational fluid dynamics simulations. Puneetha et al. [6] discussed the critical role of a muffler. It minimises

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noise and backpressure in the engine exhaust manifold by establishing a conduit for exhaust gases, hence improving the engine's fuel economy. They observed the backpressure in their investigation by employing numerical simulation. The model and mesh were generated using the finite element and hyper mesh preprocessors. The performance of the exhaust system was monitored to ensure that exhaust gases created by the engine were disposed of quietly and with minimal impact on the engine's efficiency, life, and maintenance. Mohamad *et al.* [7] investigated the effect of varying diameter holes in the pipe on engine performance. They discovered that different diameter holes with the same porosity influenced engine performance.

2.1 Perforated Tubes

A perforated exhaust tube is normally installed inside the muffler. Perforated exhaust tubes are commonly used in exhaust silencers because they allow exhaust noise to pass through the perforations while still enabling exhaust gas to flow through them, creating backpressure. Although the hole is primarily used for acoustic application, it also helps with engine performance. In other studies, it shows that different patterns of perforations will cause different performance level and different level of backpressure [8, 9].

2.2 Pressure Effect - Backpressure

Backpressure represents a static pressure created by the muffler on the engine through the limitation and restriction in the flow of exhaust gases. In general, a smooth-flowing muffler with a lower noise level generates more backpressure. For performance application, backpressure should be generated and maintained at an optimal level [8]. The pressure is caused by changes in the movement of the exhaust gasses inside the muffler starting from the inlet through resonator chambers and perforated steel pipes. Reducing exhaust backpressure can improve fuel consumption and performance. Exhaust can flow more freely when limitations in the exhaust system are reduced. As a result, the engine may run more efficiently. The total pressure drop considers not just frictional and acceleration pressure losses, but also inflow pressure [10].

Backpressure will be generated every time the flows are forced to change direction. In this circumstance, the geometry must be decreased to minimise the direction change. This is where the reactive and absorptive mufflers differ the most. Absorptive mufflers allow exhaust gases to travel directly through the perforated pipe, whereas reactive mufflers create more backpressure.

2.3 Engine Performance

When exhaust gas leaves the combustion chamber, it creates a pressure that aids the gas to escape, allowing for better combustion. The engine performance is harmed by pressure reductions in the exhaust system. This will cause the engine to lose power and consuming more fuel.

3. Research Methodology

The approach consists of processes that have been completed, starting with the design process, simulation, and data analysis. This part explains the data collection and information, creates perforated steel pipe simulation samples, and analyse the results. The method of designing the samples was done by using Computer Aided Design (CAD) software and Finite Element Method (FEM) for meshing and set the boundary conditions for the perforations. Lastly, the simulation and analyzing process were done by CFD software.

3.1 Finite Element Method

Finite Element Method (FEM) analysis is a method to carry out different analyses on a product design before the development stage, in order to improvise the features and characteristics of a product. This technique is usually used to obtain solutions to the differential equations that describe a wide variety of physical and non-physical problems. This approach of analysis, which was originally created to treat diffusion type problems, could be used to tackle advection-dominated situations, such as incompressible and compressible fluid flow. Advances in the stress-strain equations and heat conduction have forced even more development in solving analytical problems with FEM. In this study, distinct samples were prepared for this investigation to establish different pressure effects. The dimension of the perforation and the density of the perforated portion would be the most important characteristics. Fig. 1 showed the dimensions of the perforated pipe used in the simulation.

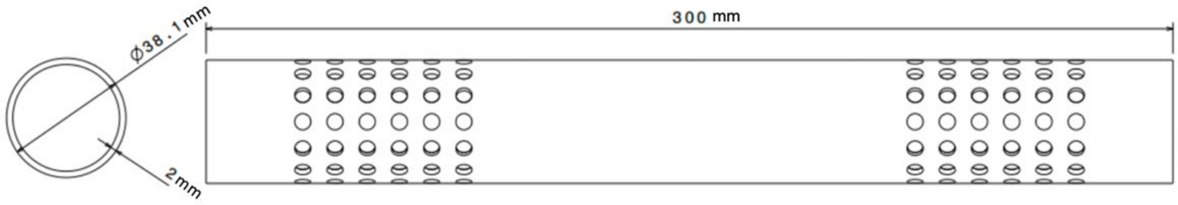


Fig. 1 - Front and side views of the perforated pipe

The geometrical drawing of the perforation pipe was done using CAD software and then exported to a CFD software for pre-processing step. Meshing was done to divide the identified domain into small segments. Hex dominant method was chosen for the perforation pipe. The total number of grids and nodes used in this study was 924,655 and 169,353, respectively. The grid independence test was conducted to ensure optimal grid conditions used in the research.

The simulation of exhaust flow was carried out from one side of the pipe that acted as inlet and the other end as the exit. There were nine samples for the simulation that consist of diameter 5, 6 and 7 mm and distance between each perforation of 10, 15 and 20 mm. The combination of diameters and perforation distances in the steel pipe simulation is shown in Table 1. Three samples were set with 5 mm perforation diameter with perforation distance 10, 15 and 20 mm, another set of three samples had 6 mm perforation diameter with perforation distance from 10, 15 and 20 mm and the last set of three samples had 7 mm perforation diameter with perforation distance 10, 15 and 20 mm, respectively.

Table 1 - Type of samples for perforated steel pipe simulation

Sample	Diameter (mm)	Distance between each perforation (mm)
1	5	10
2	5	15
3	5	20
4	6	10
5	6	15
6	6	20
7	7	10
8	7	15
9	7	20

3.2 Computational Fluid Dynamics

The modelling of exhaust gas flow inside a perforated tube is used to determine and improve the design of the perforations. The simulation will focus on the pressure generated by varying the density and diameter of the perforations. Two key parameters have been specified in this simulation to influence the outcomes and to compare between samples, i.e. diameter perforations and density perforations. The simulation's boundary conditions are listed in Table 2.

Table 2 - Simulation boundary conditions

Fluid	Carbon Monoxide, CO
Fluid Temperature	500 °C
Fluid Initial Pressure	10 000 Pa
Turbulence Kinetic Energy	16.822 m^2/s^2
Turbulence Dissipation Rate	9.8564×10^{-3} kg^2/m^2
Iteration	200

Some of the boundary conditions must first be determined. In this simulation, Standard k-epsilon Turbulence Model will be used to determine the turbulence flow characteristics. The Reynolds Number must be determined in order to assess whether or not the flow is turbulent. Two additional boundary conditions, the Turbulence Kinetic Energy, k, and Turbulence Dissipation Rate, ε, must be supplied for the turbulence properties at inlets and outlets, in addition to the two additional transport equations that must be solved when employing a two-equation turbulence model [11, 12, 13]. Before solving these equations, there following parameters need to be specified:

Reynolds Number, Re:

$$Re = \frac{\rho V D}{\mu} \quad (1)$$

Turbulence Intensity, I:

$$I = 0.16\, Re^{-1/8} \quad (2)$$

Turbulence Kinetic Energy, K:

$$K = \frac{3}{2}\,(V\, x\, I\,)^2 \quad (3)$$

Turbulence Length Scale, ℓ:

$$\ell = \dot{m}\, P \quad (4)$$

Turbulence Dissipation Rate, ε:

$$\varepsilon = C_\mu \left[\frac{k^{1.5}}{l}\right] \quad (5)$$

Equations 1 to 5 above are required to determine the properties of the fluid flow inside the perforated pipe. This will ensure that the simulation is done similarly to the real exhaust perforated pipe [14, 15]. The numerical simulation was performed to obtain a detailed view of the flow pattern in terms of pressure and velocity [16]. The simulations were run at 200 iterations, and the solution was found after this number of iterations.

4. Results and Discussion

The simulation using CFD software had been carried out to obtain the pressure contour and pressure drop of the fluid flow inside the perforated exhaust pipe with different perforation diameters and densities. The simulations were performed three times to guarantee the reliability of the results. There were no notable changes in the results after three repetitions, and the error was less than 5%.

4.1 CFD Simulation Results

The simulation had been done for nine different perforated pipe designs with different diameters and densities. The pressure contours of the samples were shown in Fig. 2 to 10. The pressures shown in the diagrams are the local pressure in the perforated pipes. The minimum and maximum pressures for the nine samples are tabulated in Table 3. The maximum pressure values increased when the diameter increased. Sample 1, 2 and 3 with perforation diameter of 5 mm have maximum pressure ranging from 2164.58 to 2221.87 Pa and minimum pressure ranging from -4275.23 to -4044.28 Pa. Sample 4, 5 and 6 with perforation diameter 6 mm have maximum pressure ranging from 4148.3 to 4220.11 Pa and minimum pressure ranging from -1853.26 to -1761.03 Pa. Sample 7, 8 and 9 with perforation diameter of 7 mm have maximum pressure ranging from 4704.29 to 5503.2 Pa and minimum pressure ranging from -2514.3 to -2172.2 Pa.

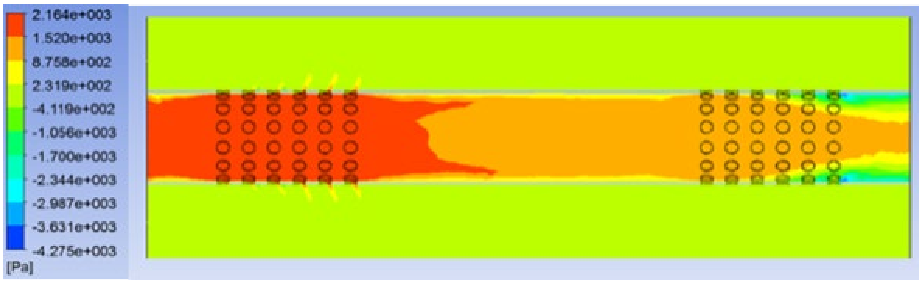


Fig. 2 - Pressure contours for sample 1

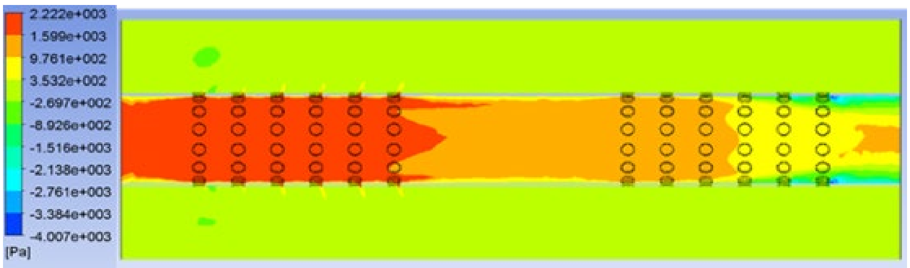


Fig. 3 - Pressure contours for sample 2

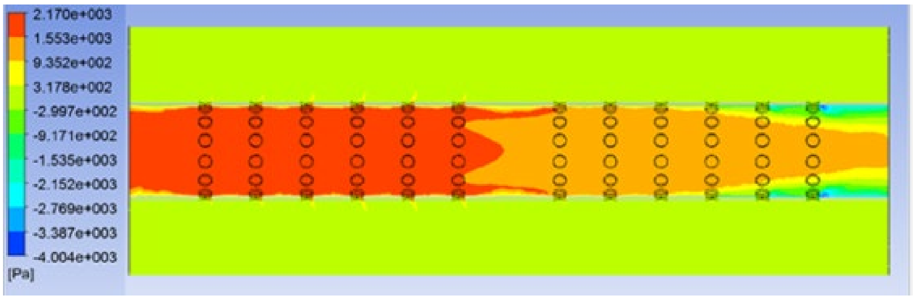
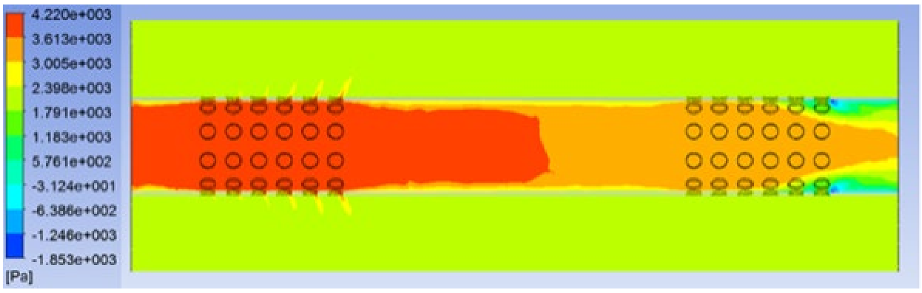
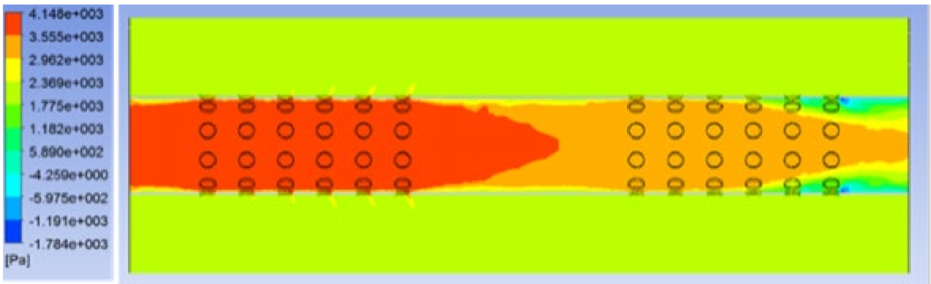


Fig. 4 - Pressure contours for sample 3





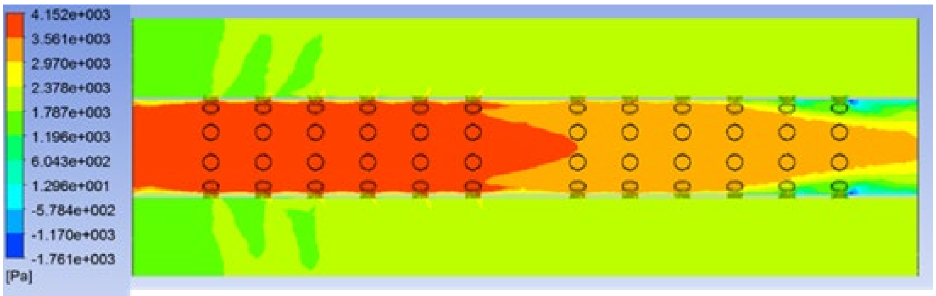


Fig. 7 - Pressure contours for sample 6

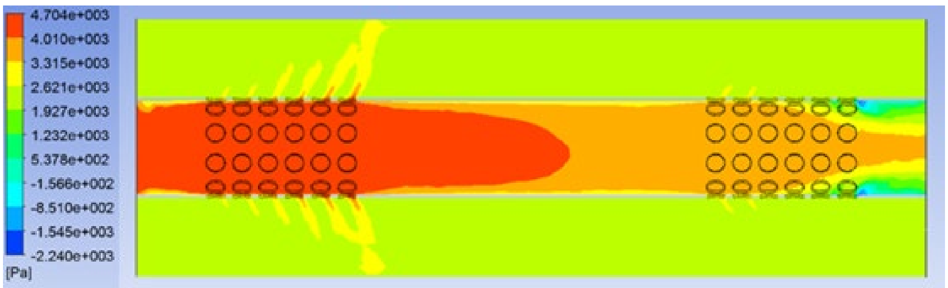


Fig. 8 - Pressure contours for sample 7

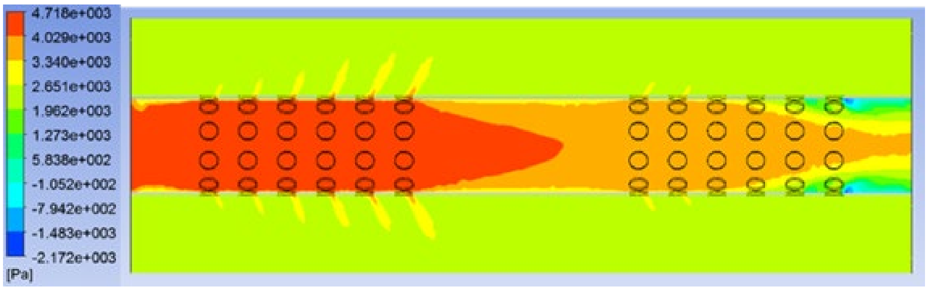


Fig. 9 - Pressure contours for sample 8

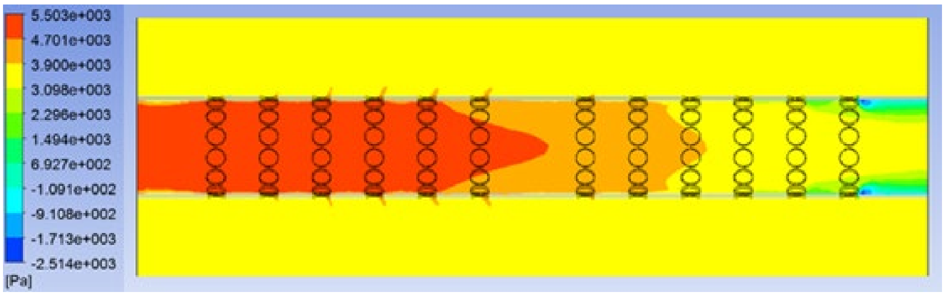


Fig. 10 - Pressure contours for sample 9

Sample No.	Max Pressure (Pa)	Min Pressure (Pa)
1	2164.58	-4275.23
2	2221.87	-4007.13
3	2170.06	-4004.28
4	4220.11	-1853.26
5	4148.3	-1783.93
6	4152.26	-1761.03
7	4704.29	-2239.86
8	4717.9	-2172.2
9	5503.2	-2514.3

Based on the tabulated results, it is clear that the hole diameter influences the maximum pressure inside the pipe. The maximum pressure is higher the larger the perforation diameter. Furthermore, the results show that the hole diameter affects the lowest pressure, although not in a proportional way. Simulations were run three times to check the validity of the results, and there were no major changes in the results, and the error was less than 5%. These findings have particular relevance for future researchers conducting experimental validation testing.

4.2 Comparison of Pressure Drop Percentage

The pressure drop between the pipe's inlet and outlet is shown in Fig. 11. To calculate the pressure drop, the recorded pressure at the intake is compared to the recorded pressure at the outlet. The pressure drop between samples can be seen as a percentage of the total pressure loss. Sample 1 had the greatest pressure decrease percentage of 44.66 percent while Sample 6 shows the lowest pressure drop at 21.36 percent.

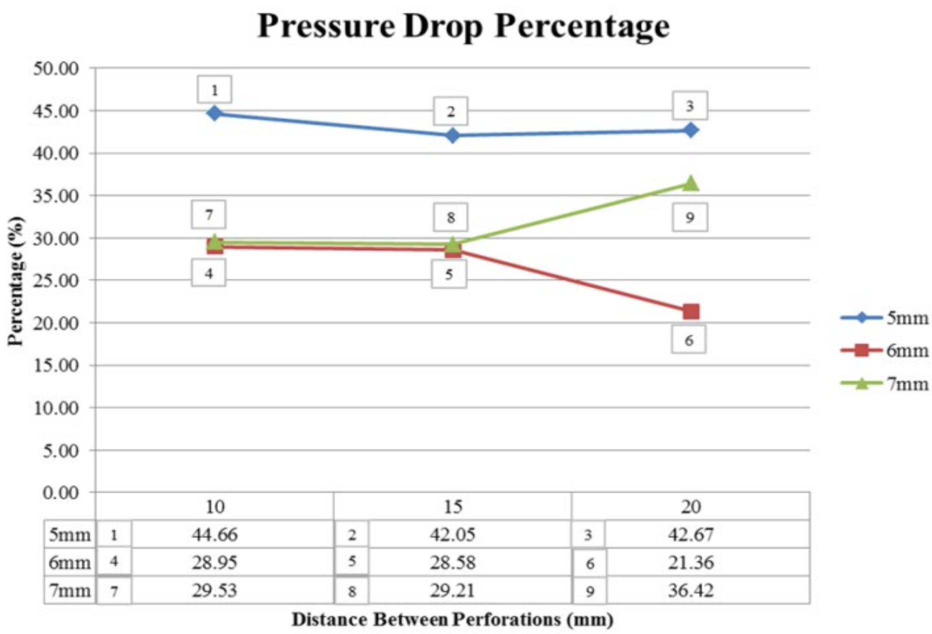


Fig. 11 - The percentage of pressure drop between the samples

5. Conclusion

This study focuses on the modelling of perforated pipes with varying perforation diameters and densities. The goal of the analysis and simulation is to provide local pressure information inside the perforated pipe in the middle box muffler. The finite element method and the computational fluid dynamics approach were successfully employed to model the problem. The lowest pressure drop percentage recorded in this study is 21.36% for Sample 6. This shows that Sample 6 is the best perforation design. The appropriate design should cause a lower pressure drop rate, resulting in a lower backpressure effect throughout the exhaust system. The perforated pipe inside a middle box muffler of an exhaust system is found to have a vital role in ensuring that the backpressure and pressure drop are optimised and the exhaust system is functioning as intended by the manufacturer.

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