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Prediction of Backpressure of Muffler through Results Obtained by Theory and CFD Approach

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A B S T R A C T

The exhaust system being a critical system of any automotive vehicle plays a responsible role of improving the ride quality of the vehicle and fuel economy. The effective design of exhaust system is critical in order to ensure the required exhaust gas is exited from the engine and at the same time, the noise is attenuated. The exhaust system attenuates the noise from the engine without deteriorating the engine performance by ensuring an optimum value of exhaust backpressure. Exhaust backpressure is one of the crucial parameters that are always scrutinized by the automotive manufactures to ensure that the engine delivers a superior performance. This project deals with a practical approach to design, develop and test muffler particularly reactive muffler for exhaust system, which will give advantages over the conventional method with shorten product development cycle time and validation. Traditionally, muffler design has been an iterative process by trial and error. However, the theories and science that has undergone development in recent years has given a way for an engineer to cut short number of iteration.

Keywords

Muffler, Back Pressure, engine, CFD, Noise, efficiency, formula, set up, correlation

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Introduction

The stringent environmental laws demand automotive systems to be produced with superior performance with reduced noise, emissions, maintaining good fuel economy at the same time. The performance of any vehicle is highly depends not only the performance of core engine parts but also on the effectiveness of the sub-systems attached to the engine, like the intake, fuel, engine cooling and exhaust systems(1).

The exhaust system is generally described as composed by two different parts:

The hot end (being the main components the exhaust manifold – with or without a turbocharger – and the catalytic converters)

The cold end (which is located under floor, whose main elements are the main pipe)

The hot end is mainly devoted to the emission after-treatment, while the cold end function is the noise attenuation.

It is well known that, being exhaust line a complex system, a backpressure is generated, which is one of the factors, which negatively affect engine performance, especially in full load conditions and on high performance engines. Therefore, each of the exhaust components must be optimized by the fluid dynamic point of view, in order to improve engine performance. For this reason, during the development phases, it is necessary to know both the total backpressure and the losses generated by each component. The best way to evaluate the exhaust backpressure is of course the direct measurement on the studied engine; unfortunately, this is not possible during the first steps of the engine development process, since even a proto engine could not be available. As a workaround, the backpressure caused by the exhaust system can be evaluated experimentally, measuring it at the flow rig bench at room temperature, or theoretically, estimating it by CFD simulation techniques (2).

Muffler design becomes more and more important for noise reduction and back pressure limitation. Traditionally, muffler design has been an iterative process by trial and error. However, the theories and science that has undergone development in recent years has given a way for an engineer to cut short number of iteration. In today's competitive world market, it is important for a company to shorten product development cycle time. This paper deals with a practical approach to design, develop and test muffler particularly reactive muffler for exhaust system, which will give advantages over the conventional method with shorten product development cycle time and validation. This paper gives prediction of back pressure value during its preliminary stage of design (3). Compression Ignition engine is the most energy efficient power plant among all type of internal combustion engines known today. This high efficiency translates to good fuel economy and low greenhouse gas emissions (4).

Well-designed exhaust systems collect exhaust gases from engine cylinders and discharge them as quickly and silently as possible. Primary system design considerations include:

- Minimizing resistance to gas flow (back pressure) and keeping it within the limits specified for the particular engine model and rating to provide maximum efficiency.
- Reducing exhaust noise emission to meet local regulations and application requirements.
- Providing adequate clearance between exhaust system components and engine components, machine structures to reduce the impact of high exhaust temperatures
- Ensuring it does not overstress engine components such as turbocharger and manifolds (5).

Exhaust system is designed to evacuate gases through muffler from the combustion chamber quickly and efficiently. The faster an exhaust pulse moves, the better it can scavenge out all of the spent gasses during valve overlap. (6).

Objectives and scope

This paper deals with a practical approach to design, develop and test muffler particularly reactive muffler for exhaust system, which will give advantages over the conventional method with shorten product development cycle time and validation. This paper gives prediction of back pressure value during its preliminary stage of design. Main objectives of the project was to calculate back pressure using formula and simulation software and to find out most suitable formula by considering error percentage obtained.

Methodology

This review was carried out for complete understanding of exhaust backpressure and its positive as well as negative effects on engine performance and to understand and minimize product develop cycle time. Good design of the muffler should give the best noise reduction and offer optimum backpressure for the engine (3).

The scope of this study is to establish a design methodology to make design process simpler and less time consuming by finding most suitable formula for exhaust backpressure value and approach to get better design. In addition, this approach will predict design quality at earlier stage of muffler design, evaluate quality of design, set targets for proto design, improves the same throughout the product design steps, and reduce cost of proto development. In this study, we were calculated the backpressure by three different formulas than compare it with back pressure obtained from CFD and actual experiment. Formula, which gives the backpressure most near to CFD and Experiment, was selected for further design study.

Exhaust back pressure calculation using formula I

There is no direct formula to calculate backpressure; although there is numerous solution and formula are available to predict the back pressure value.

From the literature survey, the book called, "Diesel Generator Auxiliary Systems and Instruments by Mohammad Abdulqader" has given formula of back pressure with input value as basic engine data.(10)

Input Data

FA – flow area required, square feet, C – Silencer pressure drop coefficient, T- exhaust gas temperature,ºF, CFM – gas flow rate, cubic feet per minute, ΔP – back pressure, inches of water

$$FA = \frac{\pi}{4} * D^2$$

Hence, area and diameter can be directly calculated if any of the value is known which boundary condition is.

$$FA = \sqrt{\frac{530 * C * CFM^2}{4005^2 * (T + 460)\Delta P}}$$

So, after getting the internal dia D from above 2 equations back pressure can be calculated from below formula Qby using another input data i.e.

L – total equivalent length of the pipe
Q – exhaust gas flow rate (cfm)
D – internal diameter of the pipes in inches
S – specific weight of gas

$$P = \frac{L * S * Q^2}{5184 * D^5}$$

Exhaust back pressure calculation using formula II

From the literature survey, the installation guide for exhaust system of benchmarking (11) has suggested another formula for backpressure. Given formula of back pressure with input value as

P = Back pressure (kPa), (in. H2O) {psi = 0.0361 x in. water column kPa = 0.00981 x mm water column}
L = Total Equivalent Length of pipe (m) (ft)
Q = Exhaust gas flow (m3 /min), (cfm)
D = Inside diameter of pipe (mm), (in.)
S = Density of gas (kg/m^3), (lb/ft^3)
Ps = Pressure drop of silencer/raincap (kPa), (in. H2O)

$$P\ (kPa) = \frac{L * S * Q^2 * 3.6 * 10^6}{D\text{^}5} + P_s$$

$$P\ (in. H_2O) = \frac{L * S * Q^2}{187 * D^5} + P_s$$

Exhaust backpressure calculation using formula III

From literature survey another formula is given by Sherekar V, Dhamangaonkar PR.et.al for Pressure drop(12) Theoretically it is very difficult to calculate exact pressure drop because of complex inner structure of silencer but following equations gives approximate pressure drop and it should not exceed by the specify limits.

$$Exhaust\ flow\ rate\ (CFM) = \left(Engine\ Displacement\ (cu\ in) * RPM * Eff. * \frac{(exh.temp. + 460)}{C * 641760}\right)$$

Where,
Efficiency = .85 for naturally aspirated, 1.4 for turbocharged engine
C = 1 for two stroke engine, C = 2 for 4 stroke

$$Exhaust\ gas\ velocity\ (V) = \frac{Exhaust\ flow\ rate\ (CFM)}{Silencer\ inlet\ pipe\ area\ (ft^2)}$$

$$Pressure\ drop\ (\Delta P) = C * \left(\frac{V}{4005}\right)^2 * \left(\frac{530}{T^{\circ}F + 460}\right)$$

C = Pressure drop coefficient
ΔP = Pressure drop inches of water

CFD analysis of exhaust system

Predication of pressure drop is very useful for the design and development of muffler. To predict the pressure drop associated with the steady flow through the muffler, CFD has developed over the last two decades. In this analysis, steady airflow passes through mufflers. Pressure drop in an exhaust muffler plays an important role for the design and development of mufflers

The study was performed to design a muffler for a four-stroke three-cylinder engine. The muffler under consideration was a two chamber muffler with perforated internal tubes, wherein the two chambers are separated by a perforated baffle plate. The exhaust gas flow through the muffler is as illustrated in the Figure.1

Modeling and meshing

The model for CFD analysis consists of two types of mesh, a structural mesh defining the boundary area of the flow and a cavity mesh defining the fluid area. The structural meshing of the muffler was done using 2D shell elements. Fluid mesh generation can be performed directly by importing the CAD geometry; however, in order to control the element size at the perforated holes the muffler 2D mesh model was used. This acts as a reference for the fluid cavity mesh and hence the model was imported into the preprocessor as a water-tight volume after closing the inlet and outlet ends with a mesh.

Boundary condition

Deviation of simulation results from actual entirely depends on how well the inputs are defined, and the assumptions involved. This study simulates internal flow, and hence the inlet pipe, baffles, shell, outlet pipe and tail pipe were defined as ‘wall function’.

The surface on the inlet pipe cross-section through which exhaust gases enter the muffler was defined as 'inflow'. Neumann (element) boundary conditions were assigned at the inflow wherein the mass flow rate was defined. The mass flow rate was calculated from the engine test data.

The maximum backpressure of an engine is at rated speed condition, hence the input flow rate of 500 kg/h was considered for analysis. The surface on the tail pipe outlet cross-section is defined as 'outflow' where ambient pressure conditions are considered. The fluid was considered as air. The temperature measured at the exhaust manifold is about 600ºC and hence the density of the exhaust gases at this condition (0.6119 kg/m3) was assigned to the fluid properties.

Experiment setup for measuring backpressure

Exhaust backpressure was measured as the engine is operating under full rated load and speed conditions. Either a water manometer or a gauge measuring inches of water may be used.

Some engine installations are already equipped with a fitting in the exhaust discharge for measuring backpressure. If the system is not equipped with such a fitting, by using the following guidelines to locate and install a pressure tap.

Locate the pressure tap in a straight length of exhaust pipe as close to the turbocharger as possible.
Locate the tap three pipe diameters from any upstream pipe transition.
Locate the tap two pipe diameters from any downstream pipe transition.

For example, in a 100 mm (4 in) diameter pipe, the tapping would be placed no closer than 300 mm (12 in) downstream of a bend or section change. Hence, the experimental back pressure value found to be 25 mbar.

Results and Discussion

Results of CFD of muffler

Back pressure calculated = 23.92 mbar

Back pressure acceptance value = Less than 60 mbar

Correlate error percentage for exhaust back pressure analysis

The main motive of this project work is to predict the backpressure value in the design stage itself, to cut short the product development cost. Muffler design has been an iterative process by trial and error. However, the theories and science that has undergone development in recent years has given a way for an engineer to cut short number of iteration.

To minimize number of iteration, theoretical formula and calculation were validated with CFD and experimental results with minimum error percentage. There is difference between the result of the back pressure values, calculated by using formulas, CFD analysis and experiment.

Also, there were three number of formulas for back pressure. So, to finalize any one of the back pressure formula, CFD analysis was performed. By comparison of all three result with CFD analysis and experiment value have been tabulated to find error percentage.

Table.1 Backpressure Calculation by Formula I

Exhaust flow rate (kg/hr)	Temperature °F	CFM	Internal DIA. of Pipe (inches)	Total EQ. Length (inch)	SP. Weight of Gas (lb-ft$^{3)}$	Back pressure (mbar)
500	1112	248.364	9.760705	24.401763	0.04125	2.843775

Table.2 Backpressure Calculation by Formula II

Exhaust flow rate (kg/hr)	Temp (˚C)	Density (S)	Exh. flow rate (Q)	Dia. (D) (mm)	Total eq. length (L)	Back pressure P (inch of water)	Back pressure P in (mbar)
500	600	0.037358	248.364	50.8	139.7	11.43	3.57

Table.3 Backpressure Calculation by Formula III

Exhaust flow rate (kg/hr.)	Temp. (°C)	Temp. (°F)	Inlet dia. (ft.)	Area at inlet (ft^2)	Density (kg/m^3)	Exhaust flow rate CFM	Velocity (ft/min)	ΔP
500	600	1112	3.64736	10.44304	1.184	248.36	11395.77	5.45

Conclusion from all three formulas applied for back pressure

Table.4 Comparison of all Three Result with CFD Analysis and Experiment Value

	Theoritical	CFD	Experiment	Error% (Theoritical and Analytical)
FORMULA I	28.44	23.92	25	15.77
FORMULA II	27.78	23.92	25	13.89
FORMULA III	30.52	23.92	25	21.62

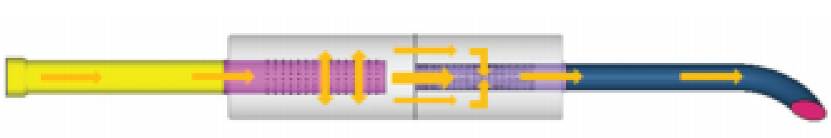

Fig.1 Schematic Flow in the Muffler

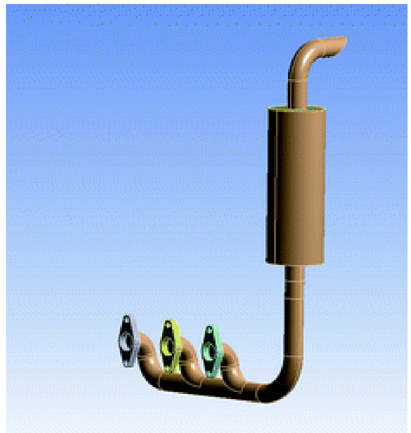

Fig.2 CAD Model of Exhaust System

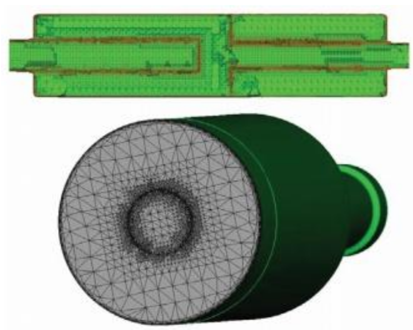

Fig.3 Vertical and Horizontal Cut Section of Meshed Model

INLET:
Mass flow rate = 500 Kg/hr
Temperature = 600ºC

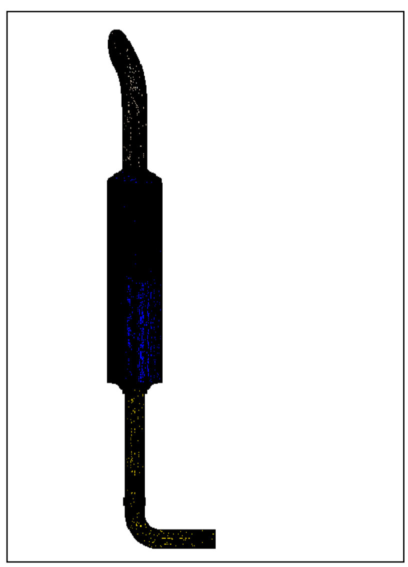

Fig.4 Meshing of Exhaust System

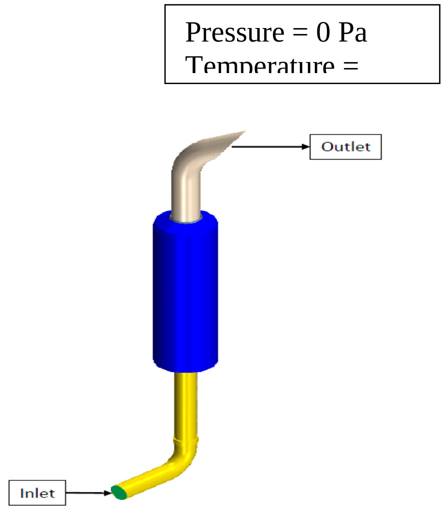

Fig.5 Boundary Condition of Exhaust System

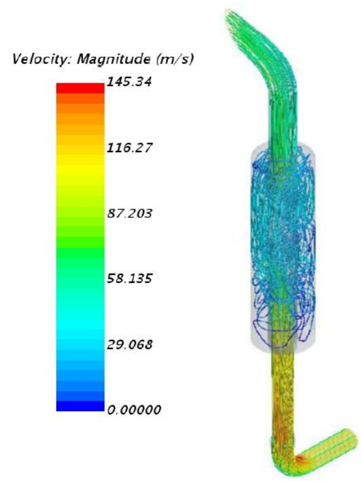

Fig.6 Velocity Magnitude of Exhaust System

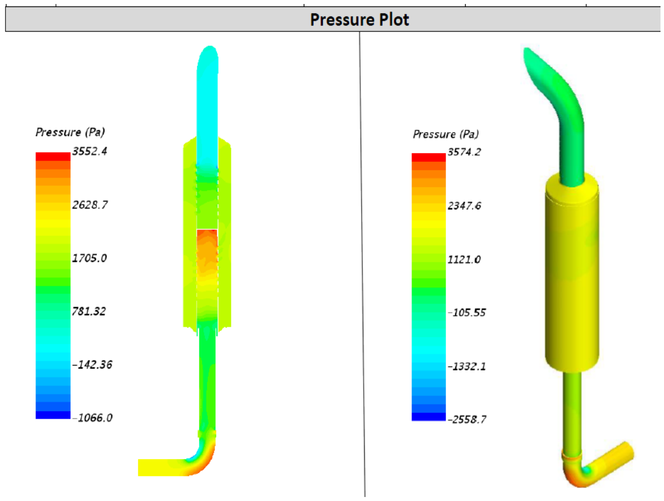

Fig.7 Pressure Plot for Exhaust System

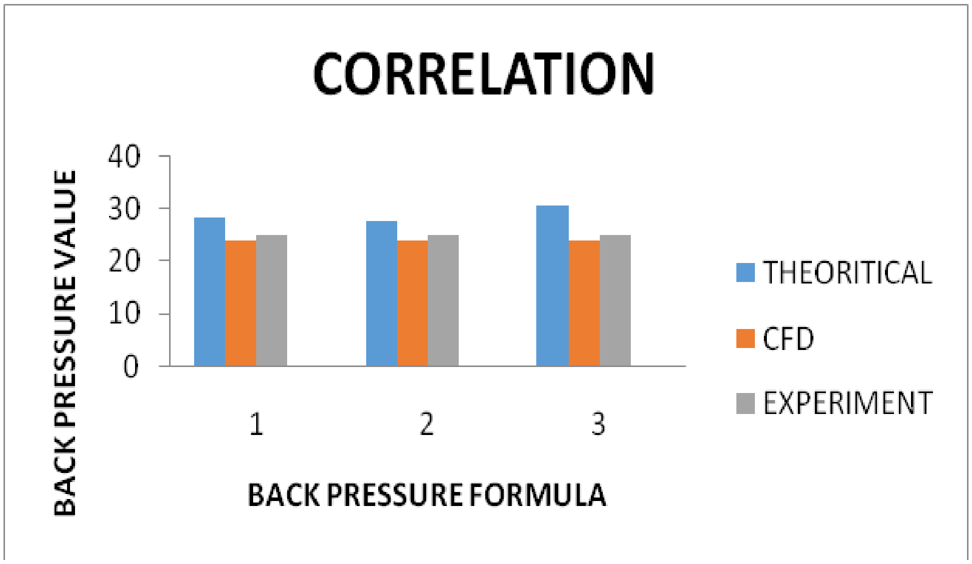

Fig.8 Correlation of Theoretical, CFD and Experiment results

The main motive of this project work was to predict in the design stage itself, to cut short the product development cost. Muffler design has been an iterative process by trial and error. However, the theories and science that has undergone development in recent years has given a way for an engineer to cut short number of iteration.

To minimize number of iteration, theoretical formula and calculation are validated with CFD and experimental results with minimum error percentage. There is difference between the result of the back pressure values, calculated by using formulas, CFD analysis and experiment. Also, there were three number of formulas for back pressure. So, to finalize any one of the back pressure formula, CFD analysis has been performed.

The target of the project work is to get error % of CFD and Theoretical formula is to get below 20% and after calculation it is found that all the values are coming under targeted value. The minimum and the best result came for formula II that is taken up by benchmarking installation guide of exhaust system for which error % is 13%. Hence, formula 2 was finalized for further study.

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