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Investigation of Modern Muffler Acoustic Characteristics using Transfer Matrix Method

Vijayaraj V T[1], Bhuvaneshwaran M[2]

[1]Assistant Professor, Department of Mechanical Engineering, Karpagam Institute of Technology, Coimbatore, India.

[2]Assistant Professor, Department of Mechanical Engineering, K S R College of Engineering, Tiruchengode, India.

Abstract - *This present work aims to evaluate a comparative work of reduce the exhaust noise level of IC Engine Mufflers. The suitable design and development will help to reduce the noise level. The exhaust noise in terms of pressure is about ten times all the other noises combined. Exhaust noise in the multi cylinder IC engine is known to be one of the most harmful to the mankind. The long-time noise would to harm the workers physically and mentally. That's why reduction of noise in the multi cylinder IC engine exhaust is more important one. So the problem of reducing engine noise consists, mainly, in attenuating exhaust noise. According to correlative measurement standards, a set of exhaust noise measurement system for multi cylinder IC engine was designed.*

A muffler for stationary multi cylinder engine has been designed. The newly designed muffler was fixed in the engine exhaust and analyzed. After analyzing different muffler configurations and the numerical predictions are compared with the results obtained by means of an experimental. The use of these results in the overall reduction in exhaust noise of the muffler is described.

Keywords - *Acoustics, noise control, transmission loss.*

I. INTRODUCTION

It is often desirable to evaluate mufflers experimentally, especially when either complex configurations are involved or flow effects are of interest. The present work aims to reduce exhaust noise level by designing different types of mufflers. The suitable design and development will help to reduce the noise level, but at the same time the performance of the engine should not be hampered by the back pressure caused by the muffler. By tuning the lengths and associated physical parameters to the in-suitcase of various perforated tubular elements, one can achieve rapid and economical modeling of those that are frequently used in many commercial reactive mufflers. In order to guarantee good attenuation at the firing frequency (or any of its multiples), where the unattenuated pulsating noise resulting from internal combustion engine is a maximum, various geometrical configuration of perforated muffler elements (eccentric tube resonator) have been developed. This configuration may be one of the straight-through types or the reversed flow types. Straight-through types are normally preferred because they result in broadband frequency attenuation without a significant increase in resistance, whereas reversed flow types are used when an exhaust system is being designed to archive large amplitude, narrowband frequency attenuation as in the case of an internal combustion engine that runs at constant speed. Generally, straight-through type muffler offer low resistance to the flow of gases acoustically not very effective. Mufflers with flow reversals, on the other hand, offer increased attenuation. In practice, mufflers with fully perforated intruding tube components are widely used nowadays as an effective acoustical element in view of their greater effectiveness in noise attenuation with concentric-tube resonator, and reasonable pressure drop with cross- flow elements. Hitherto, through the transfer matrices of various tubular elements have been

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developed and utilized. The transfer matrices of a fully perforated intruding tube muffler (FPITM) were not yet found. Thus to predict the acoustical performance of FPITM is a challenging subject for the design of commercial reactive muffler1. The present investigation deals essentially with development of a new approach, with the help of 'perforated-end plate' side boundary condition of intruding tubes and, in the case of zero mean flow, to model FPITM, and then discusses some of their practical implication for design.

I. Functional Requirements of an Engine Exhaust Muffler

There are numerous functional requirements that should be considered when designing a muffler for a specific application. Such functional requirements may include adequate insertion loss, size, durability, desired sound, cost, shape and style. These functional requirements detailed below focusing an automotive muffler's functional requirements. The main function of the muffler is to muffle or attenuate sound. An effective muffler will reduce the sound pressure of the noise source to the required level in the case of an automotive muffler the noise in the exhaust system, generated by the engine is to be reduced. A muffler performance or attenuating capability is generally defined in terms of insertion loss (IL) or transmission loss (TL). Insertion loss is defined as the difference between the acoustic powers radiated without and with a muffler fitted.

The available space has a great influence on the size and therefore type of muffler that may be used. A muffler may have its geometry designed for optimum attenuation however if it does not meet the space constraints, it is useless. Generally the large muffler is, the more it weighs and the more its costs to manufacture. For a performance vehicle every gram is saved crucial to its performance/acceleration, especially when dealing with light open wheeled race vehicles. Therefore a small light weight muffler is desirable.

The life expectancy of a muffler is another important functional requirement especially when dealing with hot exhaust gases and absorptive silencers that are found in performance vehicles. Reactive type mufflers with no absorptive material are very durable and their performance does not diminish with time. Generally mufflers are made from corrosion resistive materials such as ferrous alloys and aluminium alloys.

Generally a muffler is used to reduce the sound of combustion engine to a desired level that provides comfort for the driver and passengers of the vehicle as well as minimizing sound pollution to the environment. Muffler designs generally reduce any annoying characteristics of the untreated exhaust noise such as low frequency rumble.

Automotive mufflers come in all different shapes, styles and size depending on the desired application. The inside detail of the large chamber may be one of numerous construction. The end user of the usually does not care what is inside this chamber so long as the muffler produces the desired sound and is aesthetically pleasing.

II. Types of Mufflers

Two different physical principles are used for sound reduction in mufflers. Sound can be attenuated by the use of sound-absorbing materials in which sound energy is converted into heat mainly by viscous processes. Typical sound-absorbing materials used are rock wool, glass wool, and plastic foams. To force the exhaust flow through the absorbing material would create a large pressure drop so the material is usually placed concentrically around the main exhaust pipe. To protect the absorbing material and prevent it from being swept away by the flow, a perforated pipe is usually inserted between the main pipe and the absorbing material. Sometimes a thin layer of steel wool is included for additional protection. In some cases the outer chamber containing the absorbing material is flattened because of space limitations in fitting the muffler under a car. These types of mufflers are called reactive. If the acoustic energy is reflected back toward the source, then the question is what happens with it once it reaches the source2. It could of course be that the source is more or less reflection free, but this is not usually the case. If multiple reflections in between the source and the reactive muffler occur, the sound pressure level should build up in this region and cause an increase further downstream too. The answer to this apparent paradox is that a reactive muffler when properly used causes a mismatch in the acoustic properties of the exhaust system and the source to actually reduce the acoustic energy generated by the source. There are also cases where resistive and reactive properties are combined in the same muffler element. All reactive muffler elements do, in fact, cause some loss of acoustic energy in addition to reflecting a significant part of the acoustic energy back toward the source. The losses can be increased, for instance, by reducing the hole size of perforates, especially if the flow is forced through the perforates.

Absorption Mufflers

Absorption mufflers are effective over a broad range of frequencies. The simplest form of absorption muffler is a duct with sound-absorbing material on the walls. Thicker material can reduce the sound and lower the frequency noise. For higher frequencies, the space between the absorbing walls must be made smaller. A large duct must therefore be subdivided into many smaller ones.

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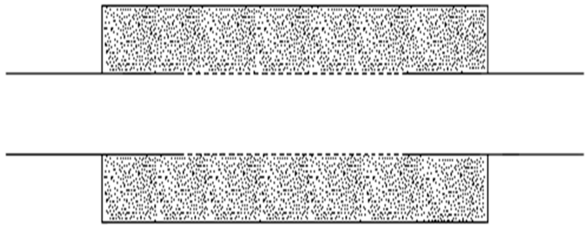

Fig 1.Absorption muffler, Schematic diagram

Reactive Mufflers

Reactive mufflers are expansion chambers. The jackhammer is an example of this type of muffler. They are useful for reducing all frequency noise. If a duct is provided with an expanded section or chamber, the low frequency pressure variations in the duct are reduced. The greater the space in the chamber lowers the sound frequencies. At the same time the perforated holes present on the circumference of the induct pipe will reduce all type frequencies. The sound waves will colloid each other when these are passed in the perforated pipes.

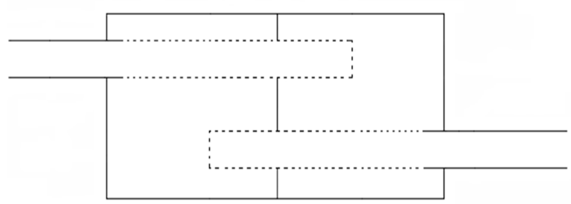

Fig. 2.Reactive muffler, Schematic diagram

III. Definitions of Muffler Performance

To assess the success of a new muffler design, there is a need for measures to quantify the sound reduction obtained. There are at least three such measures in common use: transmission loss, insertion loss, and noise reduction.

The transmission loss (TL) is defined as the ratio between the sound power incident to the muffler (Wi) and the transmitted sound power (Wt) for the case that there is a reflection-free termination on the downstream side

$TL = 10 \log (Wi/Wt)$ -- (1)

This makes it difficult to measure transmission loss since an ideal reflection-free termination is difficult to build, especially if measurements are to be made with flow. There are measurement techniques that can be used to determine transmission loss by using multiple pressure transducers upstream and downstream of the test object. It is also necessary to make two sets of measurements either by using two acoustic sources, one downstream and one upstream of the test object, or by using two different downstream acoustic loads. The advantage of using transmission loss is, on the other hand, that it only depends on the properties of the muffler itself. It does not depend on the acoustic properties of the upstream source or the downstream load. Transmission loss can, therefore, also be calculated if the acoustic properties of the muffler are known without having to consider the source or load characteristics. Since the transmitted sound power can never be larger than the incident, the transmission loss must always be positive. A high transmission loss value tells us that the muffler has the capacity to give a large sound reduction at this frequency. It will not tell us how big the reduction will be since this depends on the source and load properties3.

Insertion loss (IL) is defined as the difference in sound pressure level at some measurement point in the pipe or outside the opening when comparing the muffler element under test to a reference system:

$IL = 20 \log (pm/pr)$ -- (2)

Where pm is the root-mean-square (rms) value of the sound pressure for the muffler under test, and pr is the rms value of the sound pressure for the reference system. It is common that the reference system is a straight pipe with the same length as the muffler element under test, but it could also be a baseline muffler design against which new designs are tested. Insertion loss is obviously easy to

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measure, as it only requires a sound pressure level measurement at the chosen position for the two muffler systems. It does, however, depend on both upstream acoustic source characteristics and downstream acoustic load characteristics. Insertion loss is, therefore, difficult to calculate since especially the source characteristics are difficult to obtain. Insertion loss has the advantage that it is easy to interpret. A positive value means that the muffler element under test is better than the reference system while a negative value means that it is worse.

Sound reduction (SR) is defined as the difference in sound pressure level between one point upstream of the muffler and one point downstream:

$$SR = 20 \log (pu / pd) \qquad \text{-- (3)}$$

Where pu is the rms value sound pressure upstream of the muffler and pd is the rms value of the sound pressure downstream of the muffler. Just as insertion loss, sound reduction is easy to measure but difficult to calculate since it depends on source and load properties. The interpretation is less clear compared to transmission loss and insertion loss. It does tell us the difference in sound pressure level over the muffler for the test case, but the result may depend heavily on where the measurement positions are placed.

IV. Transfer Matrix Method

The transfer matrix method is an effective way for the analysis of sound propagation inside a duct network, especially if most of the acoustical elements are connected in cascade. The exhaust system of an internal combustion engine does in many cases have this kind of transmission line character. The method, which is often referred to as the four-pole method, was originally developed by the Munjal et al2. To get a complete model accurate for analysis and design of exhaust systems, we must also take the influence of the sound source and the termination of the system into account. That is the sound generation and acoustic reflection characteristics of the engine as an acoustic source and the sound reflection and radiation characteristics of the termination. Using the assumptions of linearity and plane waves, the actual physical system with engine, exhaust system, and outlet can be described by a sound source, transmission line, and acoustic load.

Three basic assumptions concerning the sound field inside the transmission line are made in the transfer matrix method. First, the field is assumed to be linear, that is, the sound pressure is typically less than one percent of the static pressure. This allows the analysis to be carried out in the frequency domain, and transfer function formulations can be used to describe the physical relationships. The assumption of linearity does not, however, mean that no nonlinear acoustic phenomena inside the system can be modeled. Some local nonlinear problems can, for example, be solved in the frequency domain by iteration techniques. The second assumption requires that the system within the black box is passive, that is, no internal sources of sound are allowed. Finally, only the fundamental acoustic mode, the plane wave, is allowed to propagate at the inlet and outlet sections of the system. Provided the above-mentioned assumptions are valid, there exists a complex 2 × 2 matrix T, one for each frequency that completely describes the sound transmission within the system:

$$\begin{bmatrix} p_1 \\ v_1 \end{bmatrix} = \begin{pmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{pmatrix} \begin{bmatrix} p_2 \\ v_2 \end{bmatrix} \qquad \text{-- (4)}$$

Where P1 and P2 are the temporal Fourier transforms of the sound pressures, and V1 and V2 are the temporal Fourier transforms of the volume velocity at the inlet and the outlet, respectively. The major advantage with the transfer matrix method is the simplicity with which the transfer matrix for the total system is generated from a combination of subsystems, each described by its own transfer matrix.

The division of the total system into more easily analyzed subsystems can be done in many different ways as long as the coupling sections between the elements fulfill two conditions. First, there must be continuity in sound pressure and volume velocity. This is achieved by choosing a suitable formulation of the transfer matrix, where the effects of discontinuities are included within the described element. Second, the coupling sections must not allow any higher order modes to propagate. This condition implies that the allowed frequency range for the classical transfer matrix method has an upper limit that coincides with the cut-on frequency for the first higher order mode in the coupling section. With modal decomposition the number of modes can easily be extended by increasing the dimension of the transfer matrix and accordingly the frequency range. Once the division of the system into acoustical elements has been done, the final task is to generate the total transfer matrix. This is done in analogy with the theory of electric circuits, that is, by regarding the system as a network of cascade or parallel-coupled elements. In exhaust systems, most of the elements are usually connected in cascade, and the transfer matrix formulation is, therefore, especially powerful for this application.

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V. Perforated end Plate Muffler Elements

Perforated tubes are commonly found in automotive mufflers. In a commercial muffler the configuration is usually much more complicated, as illustrated in Fig.3. Perforates can be used to confine the mean flow in order to reduce the back-pressure to the engine and the flow generated noise inside the muffler, such as in the through-flow configuration. Ideally, perforates are then acoustically transparent and permit acoustic coupling to an outer cavity acting as a muffler. Perforates can also be used to create losses when the flow is forced through the perforates such as for the plug flow configuration. Being able to theoretically model these mufflers enables car manufacturers to optimize their performance and increase their efficiency in attenuating engine noise. Therefore, there has been a lot of interest to model the acoustics of two ducts coupled through a perforated plate or tube. Generally, the modeling techniques can be divided into two main groups, the distributed parameter approach and the discrete or segmentation approach. In the distributed approach, the perforated tube is seen as a continuous object, and the local pressure difference over the tube is related to the normal particle velocity via surface-averaged wall impedance. The main challenge facing this approach is the decoupling of the equations on each side of the perforate. Using this approach results in closed-form expressions for the acoustic transmission, and therefore the calculations are very fast. Sullivan and Crocker4 presented the first analysis of this approach. They only considered through-flow concentric resonators with the flow confined in the main duct. They did not have the decoupling problem because the flow inside the cavity was assumed to be zero. Therefore, their model cannot be applied to situations with cross flow. Moreover, it does not work for non rigid boundary conditions at the side plates of the muffler.

The discrete or segmentation approach was first developed by Sullivan. In this approach; the coupling of the perforate is divided into several discrete coupling points with straight hard pipes in between. Each segment consists of two straight hard pipes and a coupling branch. The total 4 × 4 transmission matrix of the perforated element is found from successive multiplication of the transmission matrices of each segment. Luo and Chen1 used this concept and presented, for the case of two waveguides communicating via single holes, a model for wave transmission in a periodic system. Here fully perforated eccentric pipe with perforated end plate was taken.

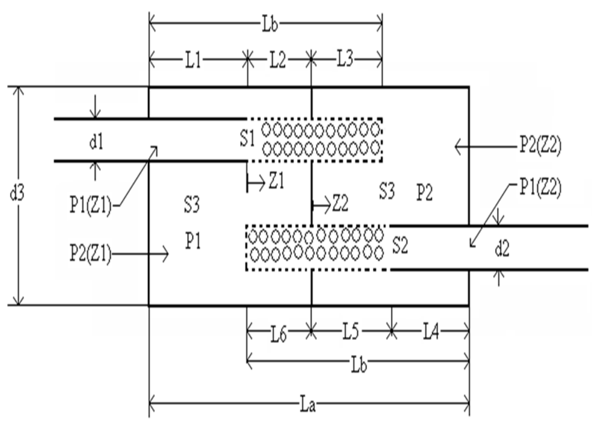

Fig. 3.Basic muffler configurations.

VI. Assumptions

1. Amplitude of pressure and density perturbations in ducts is negligible compared to their mean values2.
2. Temperature variation and viscous effect of the medium are negligible.
3. Perforation along the entire length of the tube is uniform.
4. Wall thickness of the ducts is negligible as compared to their radii.
5. Sudden cross sectional change5(expansions or contractions)

VII. Notation

c	Local speed of sound, velocity of wave propagation
d	Inside diameter of tube, annular cavity or buffer zone
dB	Sound pressure level unit decibel
L	Axial distance between stations
m	Area expansion ratio
M	Mach number of undisturbed flow
n	Number of holes in row

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P	Acoustic pressure, fluctuating pressure
s	Spacing between centre of holes
S	Area of cross section
t	Thickness of perforated plate
T	Four pole parameters
TL	Transmission loss
W	Fluctuating particle velocity in axial direction

VIII. Experimental SET-UP

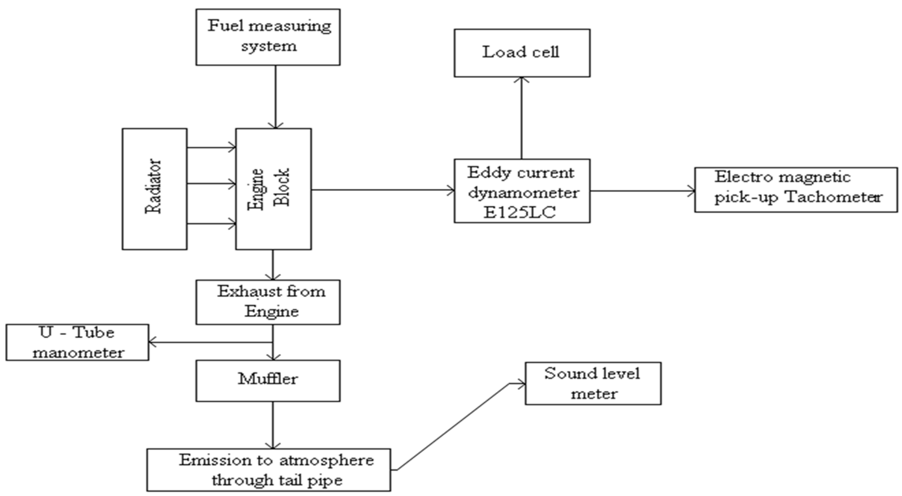

Fig. 4. Experimental Setup

The block diagram of the set-up is shown in Fig. 4. The diagram is self-explanatory. The experiment was conducted in the Automobile Laboratory of the Automobile Engineering Department at I.R.T.T., Erode. All noise data were taken on a relative basis in the closed base of the laboratory and in the presence of other engines and instruments in the close vicinity of the muffler exit. The background noise was recorded before experimentation. In order to keep background noise to minimum, all other engines and machines in the laboratory were shut down during recording of the background noise. The engine was mounded on a test cell.

The E125LC eddy current dynamometer used to set the load and rpm. In order to carry out the related experiments precision sound level meter was used. The sound level meter was placed at an angle of 450 to the centre line of the tail pipe of the muffler at a distance of 1m from the tail pipe exit. The engine speed and torque were set to the appropriate values simultaneously. Data were taken for speeds of 1000rpm, 1400rpm and 1800rpm and loads of 32Nm, 65Nm, 97Nm, 130Nm, and 162Nm corresponding to each rpm. The Fig. 5, 6, 7 states the performance of the engine under three cases: (a). without muffler, (b). Existing muffler, and (c). New muffler.

IX. Graph

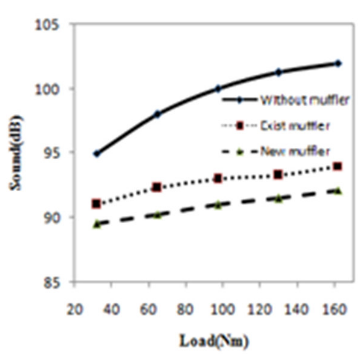

Fig. 5 (a) Sound pressure level Vs. load at 1000rpm

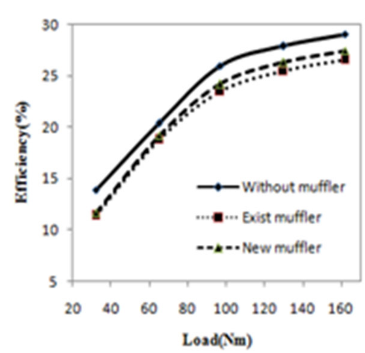

Fig. 5 (b) Brake thermal efficiency Vs. load at 1000rpm

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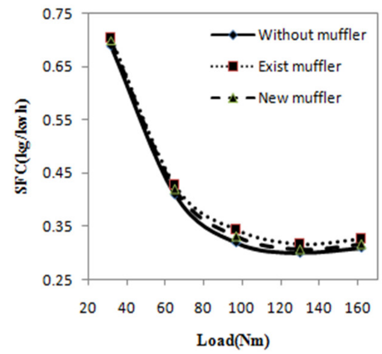

Fig. 5 (c) Specific fuel consumption Vs. load at 1000rpm

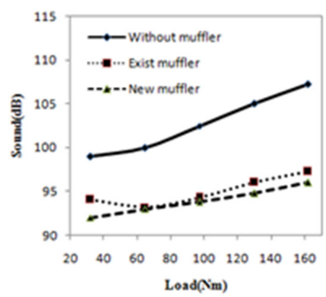

Fig. 6 (a) Sound pressure level Vs. load at 1400rpm

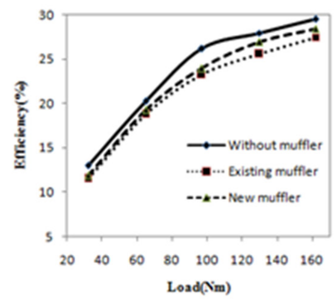

Fig. 6 (b) Brake thermal efficiency Vs. load at 1400rpm

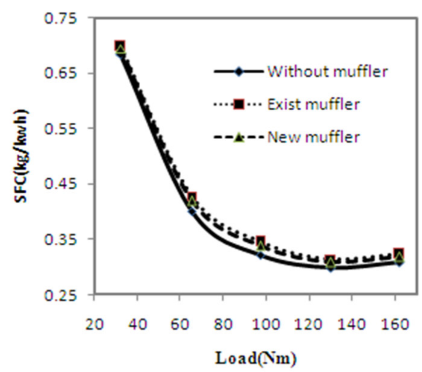

Fig. 6 (c) Specific fuel consumption Vs. load at 1400rpm

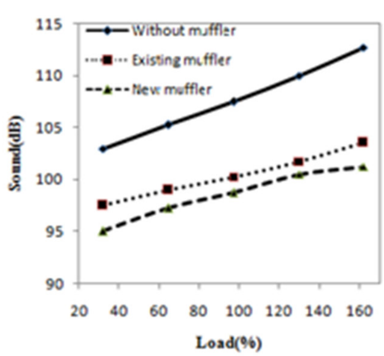

Fig. 7 (a) Sound pressure level Vs. load at 1800rpm

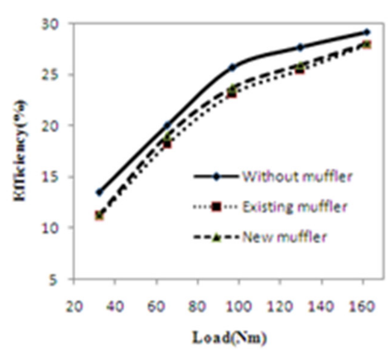

Fig. 7 (b) Brake thermal efficiency Vs. load at 1800rpm

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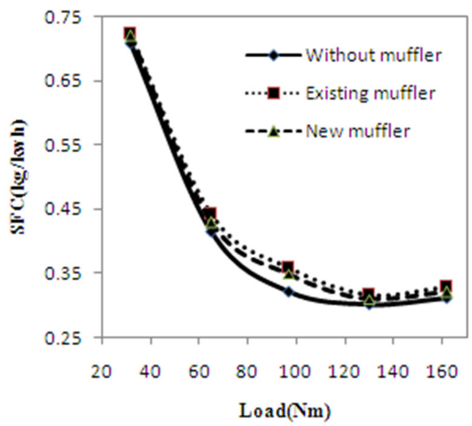

Fig. 7 (c) Specific fuel consumption Vs. load at 1800rpm

X. Result and Discussion

Figure 5 to 7 represent the graphs of sound pressure level, brake thermal efficiency and brake specific fuel consumption versus load at 1000, 1400 and 1800 rpm respectively. The graphs demonstrate that the sound pressure level decreases under all engine conditions tested. This is due to the configuration having a resonative and perforated reactive structure. The observations show that at no load, there is an increase in back pressure and hence an expected rise in fuel consumption with respect to the existing muffler. But as soon as the engine is loaded, the back pressure decreases (compared with the existing muffler) and hence the fuel consumption decreases, break thermal efficiency improves and break specific fuel consumption falls. The plots of SPL versus load at constant rpm show an increase in noise reduction with increases in load. This is very favorable feature, since an engine tends to generate more noise at higher load than at lower loads. The rate of in exhaust noise is less steep and hence the progressive increase in load affects the exhaust noise to a lesser extent than with the introduction of the new muffler.

The newly developed muffler, being of elliptical cross section can be fabricated so as to be easily opened on one of the larger faces for maintenance and repair. Thus ease of maintenance is a note worthy feature of the muffler compared with the existing straight through resonator.

XI. Conclusions

1. The sound pressure level of the Ashok Leyland HINO (HIN-ED-W06D) six cylinder diesel engine recorded with the developed muffler is lower than that with the existing muffler. The maximum noise reduction recorded with the developed and existing muffler was 9.25 dB (A) and 11.5 dB (A) respectively.
2. The engine break thermal efficiency is improved up to 2.4 percentages by using the developed muffler instead of existing muffler.

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