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Investigation of transmission loss in muffler by varying absorption material

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Abstract—Due to the increase in the number of vehicles, the amount of noise and pollution is also increasing .So it is necessary to make an environment free from noise pollution. Noise control is the most important criteria as it will lead to friendly environment. It can be achieved by various techniques, out of which absorbing the sound coming out of the exhaust system of vehicles by using muffler is the most important technique. Porous and fibrous materials are widely used as sound absorbing materials. In this paper the amount of transmission loss occurring because of application of different sound absorbing materials are compared. Air flow resistivity which is one of the physical properties of absorption material is taken for the transmission loss calculation in muffler. Here the different mufflers are modeled and analyzed in 'Comsol' Multiphysics where the transmission loss is determined at various frequencies. This paper also reveals one of the effective designs of muffler that could be fitted in automobile industry.

Index Terms—Air flow resistivity; Absorption materials; Comsol Multiphysics; Design; Ceramic acoustic absorber with SiC fibers; Packed Muffler; Polyester; Transmission Loss(TL).

1. INTRODUCTION

Day by day noise and pollution is increasing at alarming rates. The amount of noise produce by the exhaust is almost ten times more than the structural noise [1]. Muffler plays an important role in reducing the intake and exhaust system noise. It is a device for reducing the amount of noise emitted by the exhaust of an internal combustion engine. M L Munjal (1987) [2] in his book described the different aspects of muffler. According to him transmission loss is one of the main acoustic performance parameter of muffler. Transmission loss is the ratio of the sound power of the incident (progressive) pressure wave at the inlet of the muffler to the sound power of the transmitted pressure wave at the outlet of the muffler [1]. Selamet and Munjal (1998) [3] together performed some work on this parameter. Different geometric features such as sudden expansion chamber, extended tubes, resonator and perforated tubes are used. These are some of the acoustic filters that are fitted in a muffler. Absorption material is one such filter. These filters absorb the sound waves propagating from the exhaust system of vehicles. These absorption materials play an important role in the performance of the muffler because of its properties. Air flow resistivity is one such property of material which reduces the sound coming out from the exhaust of vehicles.

FEM is one of the methods that are used for determining the transmission loss. With the evolution of different simulation software, the use of FEM is becoming easier. Virtual. Lab, ABACUS, MSc Actran and ANSYS are some of the 3D simulation software and in recent year's three dimensional acoustic simulation modules is also incorporated in thissoftware.

In this study one of such test is performed by using our 3D linear pressure acoustic module of 'COMSOL", simulation software. Following this introduction and reviews, section 2 gives us some of the approaches or equations to evaluate the TL of muffler. Section 3 briefly describes the FEM approach. Section 4 gives us the methodology for solving it in "Comsol Multiphysics" and Section 5 discusses the results evaluated from this software. Finally Section 6 concludes the work.

2. LITERATURE REVIEW

According to Conrad (1983), when sound waves enters the material, the amplitude is decreased by the friction as this waves try to move through convoluted passages[15]. By these the acoustic energy is converted into the heat energy (Conrad, 1983). This friction quantity that could be described by the resistance of the material to airflow is called airflow resistance and is defined as

$$\sigma = \frac{\nabla p}{\Delta T u} \text{MKS.Rayls/m} \qquad (1)$$

Where σ = specific flow resistance, MKS. Rayls/m,

u = particle velocity through sample, m/s

∇p = difference in sound pressure across the thickness of the sample

ΔT = incremental thickness, m

The muffler with absorption lining is packed or dissipative muffler. Mehdizadeh Et Al (2005) [4] performed his work in this packed muffler. Tyler de la Roy (2011) [1] performed work in this respect.

This work focuses on the use of absorption material in the muffler for reducing the exhaust noise. Mehdizadeh Et Al (2005) used polyester lining in his work. The exhaust noise problem could be worked out by application of 3D Finite Element Method. Transmission Loss (TL) for muffler is evaluated by this method. Hazel et al (2006) [5] used the finite element approach for predicting the 4 pole parameter for different combination of the muffler to receive the transmission loss characteristics. In their work Rockwool is used as absorption material. This method was further utilized by Zheng et al (2011) [6] in a coupled hybrid muffler. The FEM is performed either by the Galerkian or Variational method. Farhat et al (2004) [7] used the Galerkian method for solution of the Helmholtz problem i.e. Helmholtz equation. Denia et al (2007) [8] worked on the muffler dimensions, extended inlet/outlet duties, absorbent resistivity and applied the two dimensional axisymmetric approach to match the acoustic pressure and velocity across the muffler. Its work reveal that quarter wave resonances provide improved acoustical performance at low and mid frequencies and absorption materials attenuate sound at high frequency and reveals that increase in radius and chamber length heads to higher transmission loss. According to a work performed by Jorge P Arenas, Malcohn J Crocker (2010) [9] several porous or fibrous absorption materials can be used for the reduction of the noise of the exhaust system. According to them all materials absorb incident sound but the term "acoustical material" is used to only those materials which absorb most of the sound waves transmitting only a little. They said that the materials have absorption properties depending upon frequency, composition, thickness, surface finish and the method of mounting. According to them metal foam or ceramic foams could be the most helpful sound absorption material in near future. One such ceramic form is SiC which has high heat resisting capability. Oishi et al (2006) [10] patented ceramic acoustic absorber with SiC fiber as a light weight sound absorption material. It has high sound absorption properties. It can resist heat to a temperature of about 1800 ^{o}C to 2300 ^{o}C. It can also act as a perforated body as it has a void ratio of 80-92% .Its mean diameter is 50-450 μm near the front surface and 500-3400 μm near the rear surface. The material is having air flow resistivity of 4 to 60[CGS Rayls/cm].

.In a study Bilawchak and Fyfe (2003) [11] calculated the TL in different silencer by using the numerical methods. They concluded that FEM and three-Point method in a packed muffler. They used perforated plates and air and absorption materials acoustic media. To validate its results different test cases were analyzed and compared with experimental results.

3. EVALUATION OF TRANSMISSION LOSS

The transmission loss in muffler can be evaluated by mathematical or analytical method. Mathematically, TL can be determined by [1]

$$\mathrm{TL} = 10\,Log_{10}\left(\frac{\text{incident energy}}{\text{transmitted energy}}\right) \tag{2}$$

$$\text{i.e. } \mathrm{TL} = 20Log_{10}\left(\left|\frac{p_{inc.}}{p_{trans.}}\right|\right) + 10\,Log_{10}\left(\frac{S_o}{S_i}\right) \tag{3}$$

Where S_i and S_o are the inlet and outlet area.

$p_{inc.}$ = incident pressure at the inlet of muffler, $p_{trans.}$ = transmitted pressure at the outlet of muffler

For an empty chamber the TL can be determined by

$$\mathrm{TL} = 10\,Log_{10}\left[1 + \frac{1}{4}\left(M - \frac{1}{M}\right)^2 \sin^2 kL\right] \tag{4}$$

Where M = ratio of area of expansion chamber to the area of inlet tube

k = wave number represents the normalized frequency spectrum over the speed of sound.

L = length of empty chamber

Numerically the TL is determined by using Transfer Matrix Method where the 4 pole parameter is used.

$$\mathrm{TL} = 20Log_{10}\left(\left|\frac{1}{2}\left[A + \frac{B}{\rho_o c} + (\rho_o c)C + D\right]\right|\right) + 10Log_{10}\left(\frac{S_o}{S_i}\right) \tag{5}$$

Here A, B, C and D are the 4-pole parameters.

ρ_0= Density of fluid, c = speed of sound

$S_i$andS_o are the inlet and outlet area.

4. FINITE ELEMENT APPROACH

The finite element method [4] is one of the advanced numerical techniques that can be used for the analysis of muffler. This Method is considered in the linear frequency domain approach which is based on the fundamental 3-D wave equations. It can be performed by using the Galerkian method [2] or by the variational formulation method [5]. The acoustic waves in the chambers are complex so this technique is used. The finite element method was originally developed for the structural analysis but it was later extended to the acoustic analysis by Gladwell Et Al. and Craggs. The finite element analysis procedure consists in discretizing the chamber into number of finite elements of equivalent length. A field function is selected for the exact and approximate field analysis within the element. The element matrices are evaluated by the variational principle or residual methods. The algebraic equation for the finite element system is formulated and the various unknown pressures and velocities at the nodes are calculated. Finally after computing the acoustical performance parameters in the form of four pole parameters, the transmission loss is determined. The linear wave equation for a perfect gas with no damping is given

$$\frac{\partial^2 P}{\partial t^2} = c^2 \nabla^2 P \qquad (6)$$

Where P is the sound pressure and c is the speed of sound such that

$$c^2 = \left[\frac{\partial P}{\partial \rho}\right]_{isentropic} \qquad (7)$$

For time-harmonic solution the assumed sound pressure is

$$P = pe^{i\omega t} \qquad (8)$$

Where $\boldsymbol{\omega}$ is angular frequencyand t is time period.

Then the linear wave equation is written in terms of Helmholtz's equation [5] which is the governing equation for muffler analysis.

$$\nabla^2 p + k^2 p = 0 \qquad (9)$$

Here $p$is in the frequency domain which results in complex value [4] and k is the wave number.

For the mufflers with air and porous material the governing equation becomes

$$\nabla^2 p_a + k^2 p_a = 0 \text{ in } \Omega_a \qquad (10)$$

$$\nabla^2 p_b + k^2 p_b = 0 \text{ in } \Omega_b \qquad (11)$$

Here Ω_a and Ω_b are the domains for air and bulk porous material respectively. The boundary conditions for the muffler are

for fixed walls of chamber $\frac{\partial p}{\partial n} = 0$

For the inlet and outlet of tube p =1

$$\partial p / \partial n = ikp \qquad (12)$$

The variational formulation for this case of muffler is

$$\int_{\Omega_a} (\nabla_v \nabla p_a - k_a^{\,2} v p_a) d\Omega + \int_{\Omega_b} \frac{\rho_a}{\rho_b} (\nabla v \nabla p_b - k_b^{\,2} - v p_b) d\Omega + \int_{s_{pl}} i \frac{k_a}{z_t} v (p_{p1} - p_{p2}) ds + \int_{s_{p2}} i \frac{k_a}{z_t} v (p_{p2} - p_{p1}) ds - \int_{s_o} i k_a v p_0 ds = 0 \qquad (13)$$

Here the first two terms i.e. volume integrals are for the air and absorption material and the next two terms are used for the pressure jump when a perforated plate is used in the muffler and the last term is the Robin boundary condition for the anechoic termination at the outlet of the tube. $s_0$is output pipe cross-sectional area. The Galerkian Finite element method is used as the computational method. For modeling the curved surface iso-parametric quadratic elements are used.

Now applying global basis function to any function,v

$$v(X) \approx v_h(X) = \sum_{m=1}^{N} v_m \phi_m(X) \text{ where } v_m = v(X_m) \qquad (14)$$

This equation is used for expanding equation

The linear algebraic equation is obtained from discretizing equation

$$Ap = f \qquad (15)$$

Where A is coefficient matrix and its components are obtained by

$$A_{mn} = \int_{\Omega_a} \left(\nabla\phi_m . \nabla\phi_n - k_a^{\,2} \nabla\phi_m \nabla\phi_n\right) d\Omega + \int_{\Omega_B} \frac{\rho_a}{\rho_B} \left(\nabla\phi_m . \nabla\phi_n - k_B^{\,2} \nabla\phi_m \nabla\phi_n\right) d\Omega + \int_{S_{p1}} i \frac{k_a}{Z_t} \phi_m (\phi_n - \phi_n) dS + \int_{S_{p2}} i \frac{k_a}{Z_t} \phi_m (\phi_n - \phi_n) dS - \int_{S_o} i k_a \phi_m \phi_n dS, 1 \le m,n \le N \qquad (16)$$

5. ANALYSIS IN COMSOL

Methodology to be applied in this study is FEM approach. These FEM approach is performed through 'Comsol' simulation softwarewhich is a finite element analysis simulation software package for different physical and engineering applications. This software allows for using coupled systems of partial differential equation and different modules are present for analyzing various systems. In this the analysis are performed in the acoustic module. For the highly porous material, Delany and Bazley's equation are used for determining the complex wave number, k_c and complex impedance, Z_c of the absorption material which estimates the acoustic parameters as the function of frequency and air flow resistance [12].

In this system we will first choose the 3D pressure acoustic time harmonic analysis module. The model is then created with the different tools available. The model created in Comsol is shown in figure 1.

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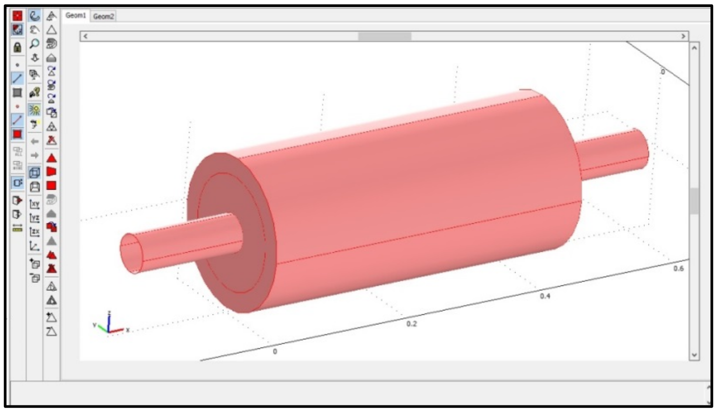

Figure 1 : Model created in Comsol showing the absorption lining

As the model is created we would now apply the different boundary conditions applicable to it. Here boundary conditions are:

a) The outer wall i.e. the solid boundaries of the chamber and tubes, sound hard (wall) boundary condition is applied and here normal velocity applied is zero.
b) At the inlet boundary, incoming and outgoing plane waves exist so inlet pressure is taken as 1 Pa.
c) At the outlet boundary, radiation condition is applied for outgoing plane waves.

The absorption material properties are put in the subdomain condition. The model is then meshed and placed for solution under a certain frequency range. As the boundary conditions are set, next we are required to fit the proper ties for absorption material. It is set in subdomain settings by selecting the layer of absorption. The flow resistivity, fluid density and speed of sound for the material is set in this case. The model is then meshed and set for solution under certain frequency range. This solution gives us the acoustic pressure variation and sound pressure level (SPL) production inside the muffler at respective frequency. We also receive the attenuation to frequency curve for the muffler from the software.

6. RESULTS AND DISCUSSIONS

The dimension of the muffler used in this study is as follows:

Design 1: The length of the chamber is 45.72 cm (18 in) and the diameter of the chamber is 20.32 cm (8 in). The inlet and outlet tube are of length 15 cm and diameter 5.08 cm (2 in) respectively. The thickness of the absorptive lining is 2.54 cm (1 in).Design 1 is shown in figure 2(a).

Design 2: Here the length of the chamber is 50 cm and the diameter of the chamber is 20 cm. The inlet and outlet tube are of length 9.6 cm and diameter 5.1 cm respectively. Design 2 is shown in figure 2(b).

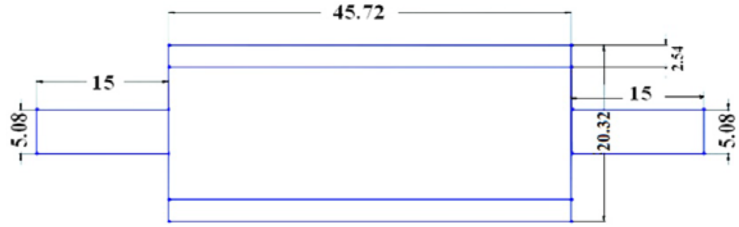

Figure 2(a) Design 1

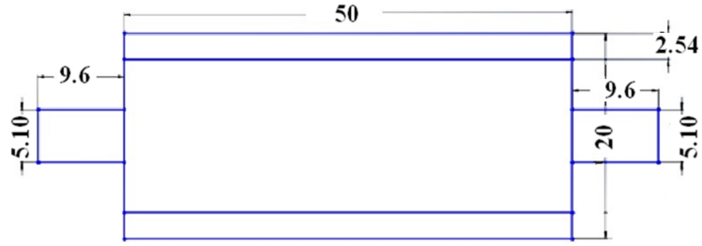

Figure 2(b) Design 2

The thickness of the absorptive lining is 2.54 cm. The materials that are taken for study in this work are ceramic acoustic absorber, polyester and Rockwool. The analyses are performed in Comsol for frequency range of 100 to 3000 Hz. These analyses would give us a complete overview of the amount of sound absorbed in the muffler on application of absorbing material.From these analysis we could justify that ceramic acoustic absorber could also be used in the mufflers of automobiles.

Validation of the method: Wu Et Al, in 1996had performed this work experimentally [13] and Mehdizadeh Et Al. in 2005 had performed this work by mathematical modeling [4],to calculate transmission loss .The work performed by them is shown in figure 3(a) and their work performed in Comsol Multiphysics in this paper is shown in figure 3(b) and it is found that the result performed is almost equal. Thus the method followed for determining TL is accurate and could be used for TL evaluation. In this work their study is compared with the results obtained by using different sound absorption materials.

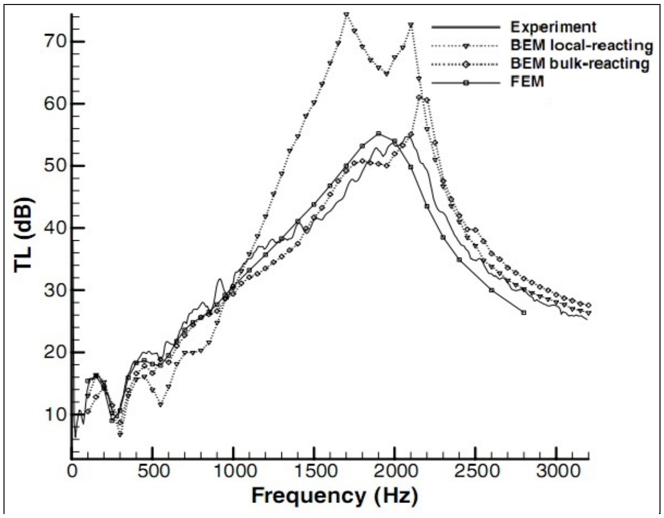

Figure 3(a) Work performed by Mehdizadeh Et aland Wu Et al,

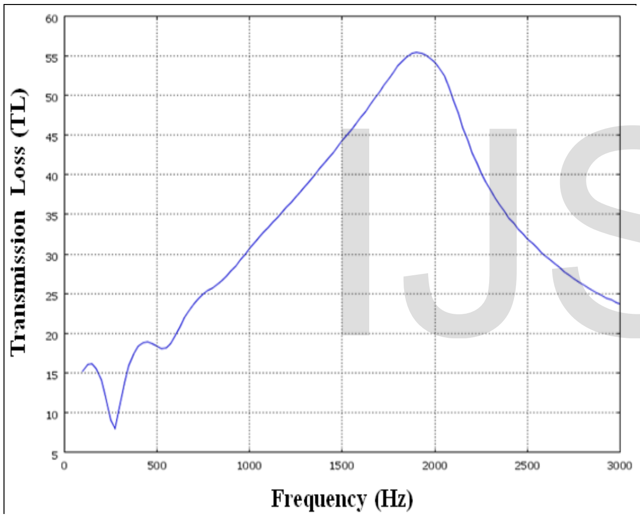

Figure 3(b) Results obtained from Comsol

6.1 Effect of Air flow resistivity

Here the resistivity values are: Polyester: 16000 [Rayls/m], Ceramic Acoustic Absorber (SiC): 60.6[CGS Rayls/cm] and Rockwool: 13813[Rayls/m]

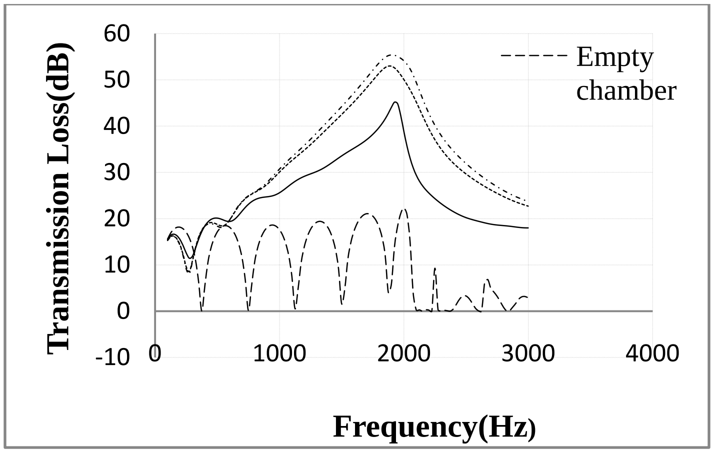

Figure 4 : Transmission loss in muffler w.r.t. the resistivity of each material for design 1

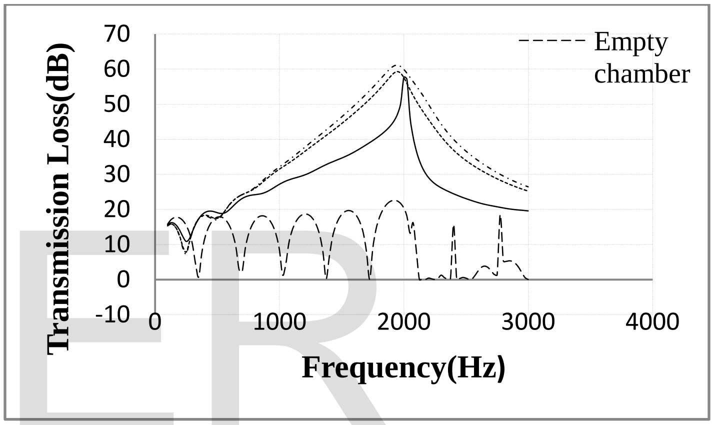

Figure 5 : Transmission loss in muffler w.r.t. the resistivity of each material for design 2

Figure 4 and figure 5 shows the parametric frequency study for two designs of muffler without the application of absorption material .The amount of attenuation obtained by implementing an absorption lining of polyester, Rockwool and ceramic acoustic absorber along the inside diameter of the chamber is also shown in these figures. The analysis showed that TL increases with the increase in air flow resistivity. For low frequency the damping is not linear but with the increase in frequency damping works well and maximum TL is achieved at high frequency.

6.2 Comparison of the mufflers wrt air flow resistivity value

Here the Transmission Loss produced by design 1 and design 2 on application of absorption material are compared.

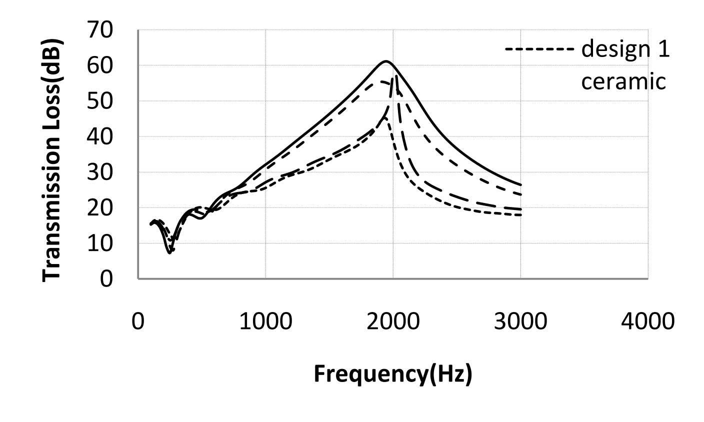

Figure 6 : Comparison of TL in mufflers when ceramic acoustic absorber (sic fibers) and polyester absorption material is used

Table 1 : Transmission Loss obtained after analyses of the muffler

Design	Absorption Material	Maximum transmission loss (dB)
Design 1	Empty Chamber	22
	Polyester	55
	Rockwool	53
	Ceramic Acoustic Absorber (SiC fibers)	46
Design 2	Empty Chamber	23
	Polyester	61
	Rockwool	59
	Ceramic Acoustic Absorber(SiC fibers)	58

These analyses are performed to determine the most effective muffler. Figure 6 and the values of transmission loss shown in table 1, depicts that the maximum TL produced in design 2 is more than that produced in Design 1, for empty chamber as well as for the case with absorption material. Therefore, design 2 would be the most effective muffler for operation. It is also found that there is not much difference in the maximum transmission loss value for design 2 when different absorption material is used.

7. CONCLUSION

From the different analysis we found that the amount of transmission loss in an empty muffler is very low i.e. it occurs in the range of about 15 to 30 dB for respective frequency. As we apply an absorptive lining inside the muffler the amount of transmission loss increases by 30 dB to 40 dB which is very efficient for the vehicles. It is found that for low frequency range (i.e. below 500 Hz) the transmission loss(TL)with polyester lining, Rockwool lining and ceramic acoustic absorber (with SiC fibers lining)is almost same in both the designs, but for high frequency range (i.e. 1800 Hz to 2200 Hz) the variation in transmission loss (TL) is below 10 dB (in Design) 1 and below 5 dB (in design 2) by using ceramic acoustic absorber (with SiC fibers lining) as compared with polyester lining or Rockwool lining. So, it can be concluded that the ceramic acoustic absorber could be used as an absorption material in muffler.

Further, it is found that polyester can resist heat to a temperature of about 250 °C and Rockwool to a temperature of 1000 °C, whereas light weight ceramic acoustic absorber can resist temperature around 1800 °C to 2300 °C. Thus the muffler with polyester, Rockwool lining could be replaced by ceramic acoustic absorber lining as this material have high heat absorbing capacity and could be directly exposed to heat for long time.

.It is also appraised that TL increases with the increase in air flow resistivity. Further the analysis depicts design 2 produces maximum TLthan design . Thus it can be concluded that design 2 will be the most favorable muffler for application in automobile industry.

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