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Investigation of baffle configuration effect on the performance of exhaust mufflers

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A B S T R A C T

Using baffles in exhaust mufflers is known to improve their transmission loss. The baffle cut ratio should affect the muffler performance analogous to a shell-and-tube heat exchanger. To the authors' knowledge, there is no previous assessment reported in literature of the effects that the baffle cut ratio configuration has on acoustic response and back pressure. This investigation presents a parametric study on the effect of baffle configuration on transmission loss and pressure drop predicted. The effect of (i) the baffle cut ratio and baffle spacing, (ii) the number of baffle holes, and (iii) the hole distribution for their effect on transmission loss was investigated. Results show that decreasing the baffle cut ratio tends to increase the transmission loss at intermediate frequencies by up to 45%. Decreasing the spacing between muffler plates was shown to enhance the muffler transmission loss by 40%. To assess the baffle effect on flow, the OpenFoam CFD libraries were utilized using the thermal baffle approach model. Baffles were found to cause sudden drop in fluid temperature in axial flow direction. The outlet exhaust gases temperature was found to decrease by 15% as the baffle cut ratio changed from 75% to 25%.

1. Introduction

Transmission loss (TL) is usually measured using the three point (decomposition method) or four pole methods; the four pole method is carried out by a two-source method and two-load method [1]. Several numerical approaches are utilized to model transmission loss in exhaust mufflers using finite element softwares Actran [2] and Comsol Multiphysics [3], Boundary element methods (BEM) using COUSTYX [4], and transfer matrix approach using Ricardo wave [5,6]. In the current analysis both Ricardo wave and Comsol multiphysics were utilized for predicting transmission loss.

Reactive mufflers depend on reducing the exhaust noise through a volume depending on reflection of sound noises [7,8]. Utilization of baffles in exhaust mufflers have been reported to have an improvement effect on the transmission loss of muffler by more than 50% [9–11]. Roy investigated the effect of internal baffles complete circular baffles with single centred holes on the transmission loss using harmonic BEM using LMS's Virtual Lab Acoustics module with and without extensions on baffles. The TL in the lower frequency spectrum is reduced while the mid to high frequency spectrum is greatly increased using baffles [11]. The effect of tapered connected expansion chambers has been also reported by Horoub [12] investigating the effect of connecting different sizes of expansion chambers. CFD studies for the several connected expansion chambers showed that extension on baffles helps reducing

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the pressure drop in muffler compared to single expansion chamber with same size due to the reduction in secondary flow losses and separations [13]. Recent studies investigated the effect of baffle spacing on the Sound pressure level (SPL) [14] where less spacing between baffle reduces the SPL. The effect of holes' arrangement in perforated tubes on transmission loss has been investigated by [15].

There is no investigation on the effect of baffle configuration on both transmission loss and back pressure in exhaust mufflers. This investigation highlights the effect of geometrical baffle configurations associated with four main parameters; baffle cut ratio, number of holes, holes distribution and baffle spacing.

Ricardo-Wave is a one-dimensional gas dynamics code based on finite volume method for simulating engine cycle performance. It is widely used by automotive and exhaust manufacturers such as Eberspächer [16,17] and Jugar Land-Rover [18]. Also, COMSOL Multiphysics Modelling Software is known to the capability to model transmission loss of different mufflers such as reactive, absorptive and hydride mufflers. Therefore, Ricardo-wave and COMSOL Multiphysics have been proposed for the prediction of transmission.

2. Numerical solvers and models setup

Wave has acoustics tools that enables exhaust muffler designer to calculate the insertion loss as well as radiated shell noise, tailpipe noise of exhaust system, where information about the engine as an acoustic source is needed in such cases. Model geometries are established in wave build 3D software. In the pre-processing stage, Ricardo-wave 3D build discretised the CAD model into small element standard connection such as T-element or y-element to represent one dimensional acoustic network Based on transfer matrix method (correlates the wave sound pressure and acoustic velocity at inlet and outlet of muffler), in the acoustic analysis acoustic source at inlet and anechoic termination at outlet (material that absorbing reflected sound waves such as fibre). Four microphones are placed at a ratio of 0.4 and 0.8 of the upstream and downstream pipe lengths connected to the muffler based on Ricardo wave default settings. The muffler was discretized to 20 mm in spatial co-ordinates.

In COMSOL Multiphysics, finite element approach is used solving HelmHoltz equation where volume mesh is generated and error weighting functions are solved to certain convergence tolerance.

The baffle cut ratio should affect the muffler performance analogous to a shell-and-tube heat exchanger. Fig. 1 summarizes the

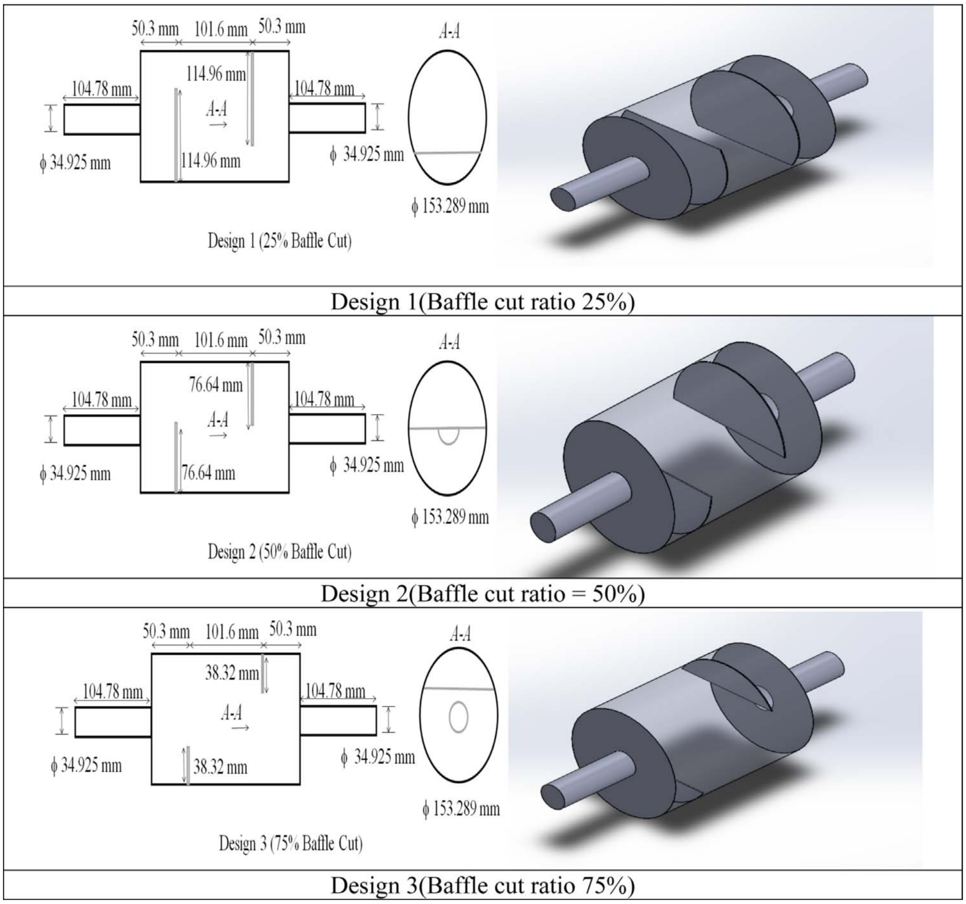

Fig. 1. Baffle cut configurations.

tested configurations regarding the effect of baffle cut ratio. The muffler chamber length is 202.2 mm with diameter of 153.289 mm, the inlet and outlet pipes of the muffler has 104.78 mm similar to dimension of muffler utilized in experimental validation section. A fixed baffles spacing of 101.6 mm is used during the investigation of the effect of the baffle cut ratio, the small baffle spacing was investigated with half of this distance placing the 50% cut ratio baffle at 50.8 mm spacing.

To investigate the effect of holes' number, the number was changed from 1 hole up to 5 holes keeping one hole centred in the muffler baffles for all configurations as presented in Section 6. The hole diameter utilized was 34.925 mm positioned at centre of the baffles. For arrangements with more than a single hole, the holes were arranged on a circle radius of 47.9 mm with keeping one hole at the centre of the baffle. Regarding the effect of baffle distribution, two configurations were investigated. The first configuration with three inline holes each of 34.925 mm diameter and one of the holes fixed in the centre. The second configuration had three holes with a diameter of 34.925 mm which were distributed on a radius of 47.9 mm without any holes in baffles centre.

CFD simulations were performed using OpenFoam 2.3.x to assess the effect of the baffles on the flow. OpenFoam is an open source CFD solver based on control volume discretization. Compressible steady state solver rhoSimplecFoam was used. Inlet velocity of 45 m/s and outlet pressure of 1.1 bar was used. The baffle thermal conductivity used 16 W/m. K and specific heat of 490 J/kg. K and density of 8000 kg/m^3. To ensure robust convergence of the solver and accurate results, a relative tolerance of 10^{-8} was used. A relaxation factor of 0.3 was used for all variables except pressure and density, where a value of 0.9 was used for this evaluation.

During the pre-processing, the geometry files includes the inlet, external walls, outlet surface of the muffler. Internal parts of muffler were included in baffle1D.stl file. MeshDict file script was used to control the meshing process using Cfmesh with mesh enhancement level 3 at baffle1D surface. After the initial mesh generated for domain excluding the internal baffles, the baffle was incorporated using createBaffles -overwrite.

3. Model setup

To study the effect of the baffle cut-off ratio three configurations were investigated; these are shown within Fig. 1. The Reynolds-averaged Navier-Stokes equation (RANS) approach has been used in the current analysis. The flow was assumed as compressible steady state ideal gas, the gravity effects and source terms were neglected and the forced convection was dominant. Viscosity was calculated based on Sutherland model; velocity inlet and pressure outlet were utilized. Here the turbulent model used within RANS is the k-epsilon realizable. It exhibits superior performance for flows involving rotation, boundary layers under strong adverse pressure gradients, separation, and recirculation. In virtually every measure of comparison, Realizable k-ε demonstrates a superior ability to capture the mean flow of the complex structures [19]. The mesh was adjusted so that y+ values were above 25–30 (below 75). The Compressible Continuity Eq. (1):

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0 \tag{1}$$

Momentum Eq. (2):

$$\frac{\partial}{\partial x}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] - \frac{\partial}{\partial x_j}(\rho\overline{u_i^{/}u_j^{/}}) \tag{2}$$

Transport Eqs. (3) and (4) for the turbulence energy generation and dissipation rates [20]:

$$\frac{\partial(\rho k u_j)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon - Y_M + S_K \tag{3}$$

$$\frac{\partial}{\partial x_j}(\rho\varepsilon u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right] + \rho C_1 S\varepsilon - \rho C_2\frac{\varepsilon^2}{k + \sqrt{\nu\varepsilon}} + C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b + S_\varepsilon \tag{4}$$

G_k represents the rate generation of turbulent kinetic energy (TKE) the arises due to mean velocity gradients, G_b is the rate generation of turbulent kinetic energy the arises due to buoyancy, and Y_M represents the fluctuating dilation in compressible turbulence that contributes to the overall dissipation rate. S_ε and S_k are source terms defined by the user.

Sound pressure p, was calculated with HelmHoltz equation using Comsol by Eq. (5) [3]:

$$\nabla\left(\frac{1}{\rho_0}\nabla p\right) + \frac{k^2 p}{\rho_0} = 0 \tag{5}$$

$k = 2\pi f/c_0$ is the wave length, ρ_0 is the density of the air, and C_0 is the speed of sound. The Transmission loss is usually referred as a muffler characteristic property, not dependent on the internal flow conditions. Transmission loss (Eq. (6)) is defined as the incident sound (Eq. (7)) over transmitted sound powers (Eq. (8)) calculated using:

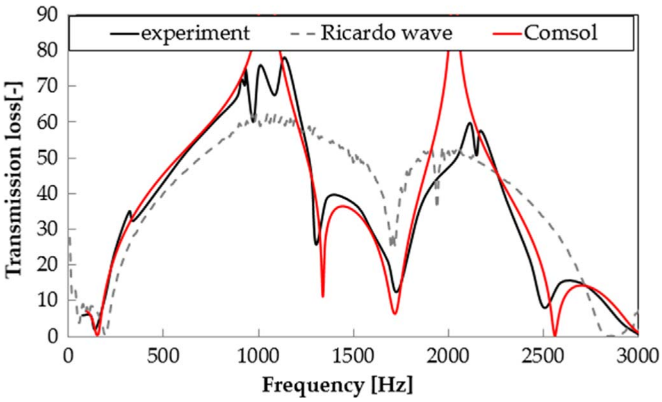

Fig. 2. validation of double chamber.

$$TL = 10\log\left(\frac{P_{in}}{P_{tr}}\right) \tag{6}$$

$$P_{in} = \int \frac{p_i^2}{2\rho c_0} dA \tag{7}$$

$$P_{tr} = \int \frac{p_{tr}^2}{2\rho c_0} dA \tag{8}$$

4. Validation of baffle modelling in Ricardo wave and Comsol

Double chamber exhaust chamber with the dimension reported in reference [4] was used for validation, the diameter of pipes utilized were 34.925 mm, and 153.289 mm. The model has been built up in Ricardo wave with mesh 20 mm element sizes. The software predicts the experimental transmission loss with good agreement for most frequency ranges – Fig. 2. It could be observed that both finite element using Comsol Multiphysics and Ricado Wave predict the transmission loss of experimental data accurately overwide range of operating frequencies.

5. Effect of baffle cut-off ratio

Figs. 3–5 represent the effect of baffle configuration on the transmission loss using Ricardo wave and Comsol Multiphysics, it could be observed from the model that reducing the baffle size shifts the peak transmission loss to higher frequency. Additionally, mufflers with large baffle sizes are more effective in the intermediate frequency region design 1 (25% baffle cut ratio) compared to design 2 (50% baffle cut ratio) and design3 (75% baffle cut ratio) (60% improvement at frequency 1200). This may be attributed to the increased possibility of wave reflections in each muffler chamber leading to a reduction in the source noise and enhancement in the transmission loss. This technique is more effective at low traveling speed sound waves (low and intermediate frequencies). As the baffle size becomes smaller, increasing the wave frequency could help in enhancing the transmission loss by increasing the wave reflections as the wave travel faster for the same chamber length.

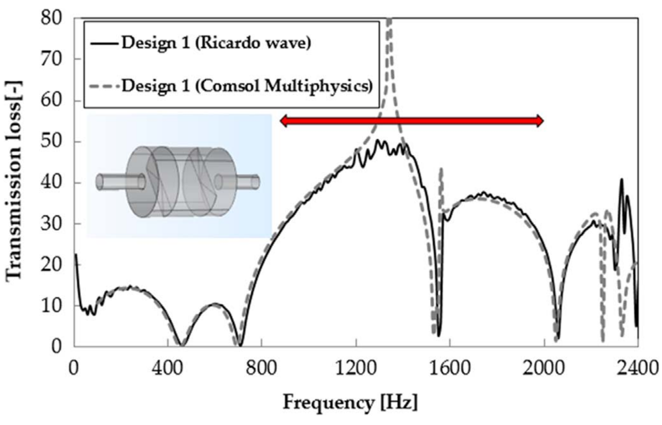

Fig. 3. Transmission loss design 1.

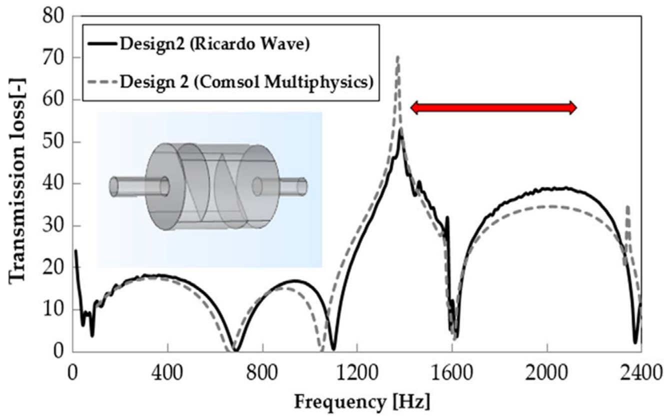

Fig. 4. Transmission loss design 2.

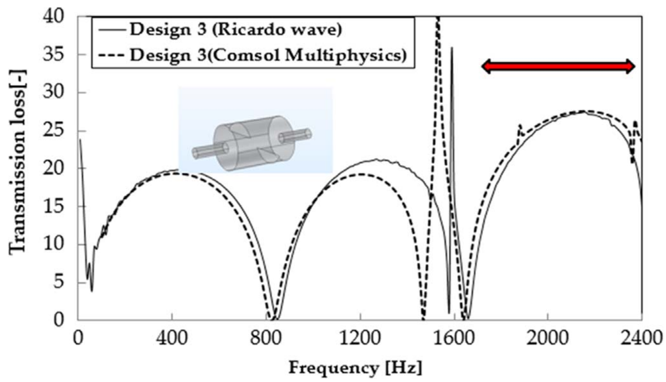

Fig. 5. Transmission loss design 3.

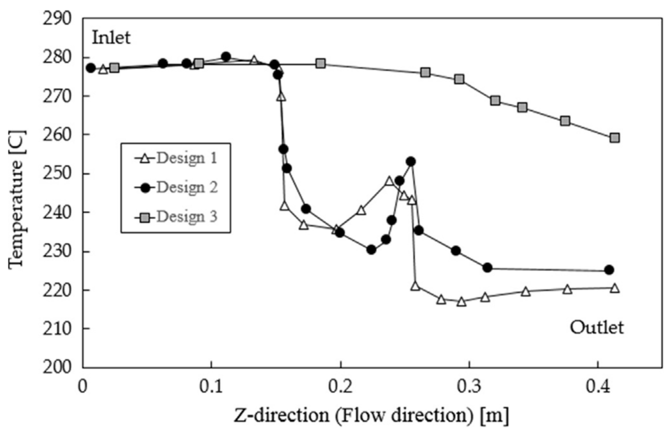

Fig. 6. Temperature change in flow direction.

In Fig. 6, the effect of the baffle cut ratio is apparent in dropping gas temperature due the axial conduction in the baffle, the larger the baffle size the lower outlet gas temperature. In design 1 and 2, the temperature rise close to baffle is due to the conversion of dynamic head and reduction of velocity due to the existence of baffle in fluid domain. This lead to an increase in static pressure leading to temperature increase. After the baffle, there is a temperature drop due to both the heat transfer to the baffle and the drop in the static pressure behind the baffle. In design 3 the baffle height was small and without changing the direction of the core fluid at the centre of the muffler, the flow path length is considered less than other geometries leading to a higher outlet temperature compared to other configurations.

In Fig. 7, the flow with large baffle sizes exposed to large changes in direction compared to other configurations leading to larger pressure drops and lower outlet temperatures from the muffler as confirmed by Figs. 8 and 9. Using a half baffle cut could have improved performance from both an acoustic and pressure drop combination.

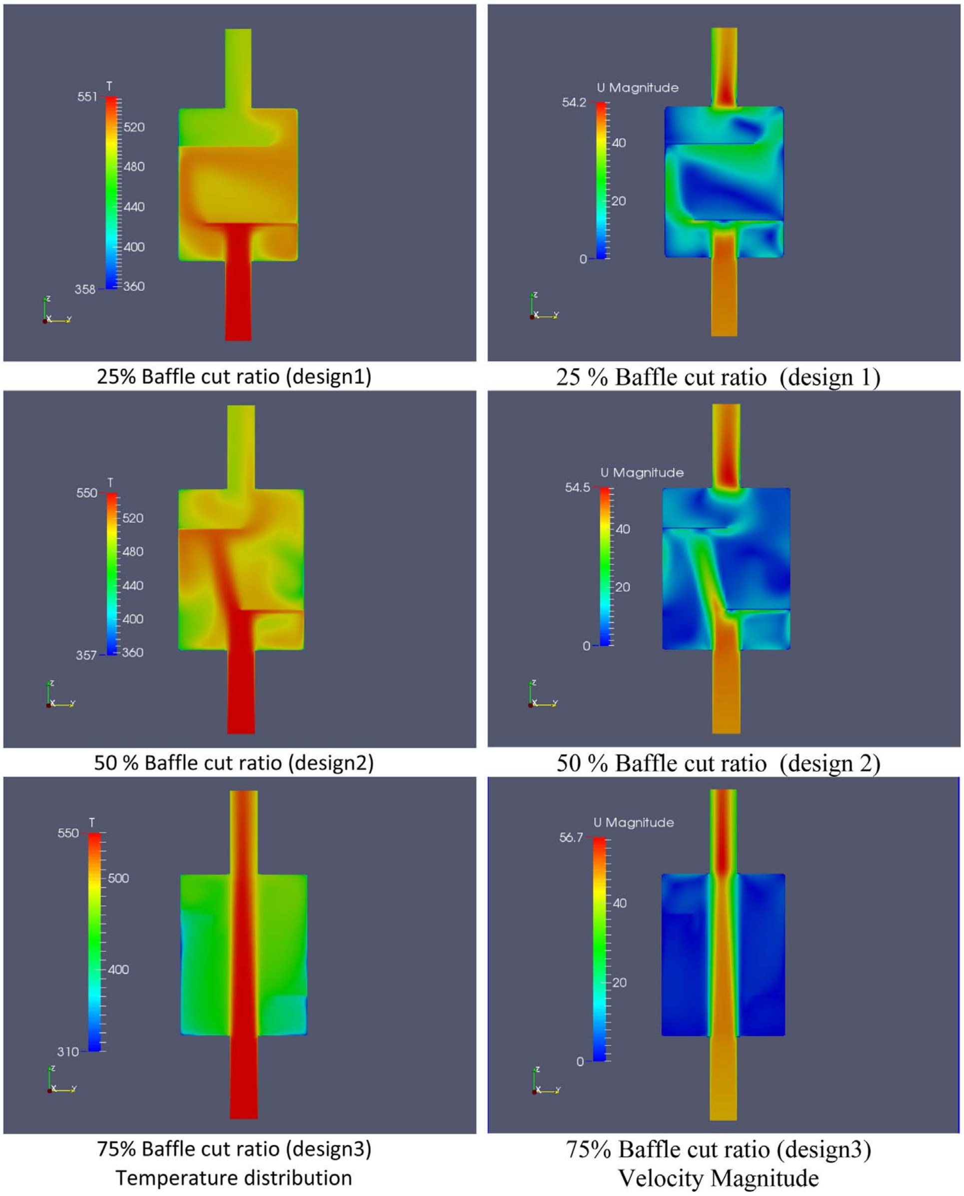

Fig. 7. Temperature and velocities through different designs.

6. Effect of number of holes

Each baffle has the same number of holes changing them from one hole up to 5 holes per baffle. The performance of a single hole regarding transmission loss was found to be better for single hole than higher number of holes as shown in Fig. 10. The throttling of fluid through single hole helps to damp the noise through increased number of reflections in each chamber volume as there is only single connection between different chamber volumes, where the damping of noise is apparent at intermediate sound wave speed resulting in increased number of wave reflections and noise cancellation. However, using two or three holes is recommended to reduce the back pressure without much deterioration in transmission loss. Throttling the flow through single hole could lead to excessive pressure loss and deterioration of engine performance; passing the flow through multi-holes introduces the flow through parallel paths that help to reduce the back pressure with some loss in acoustic performance as the transmission loss decreases with increasing the number of holes.

7. Arrangement of hole (distribution of holes from centre of baffle)

Two designs were investigated for the same number of holes and holes diameters. It was observed that holes placed at the centre

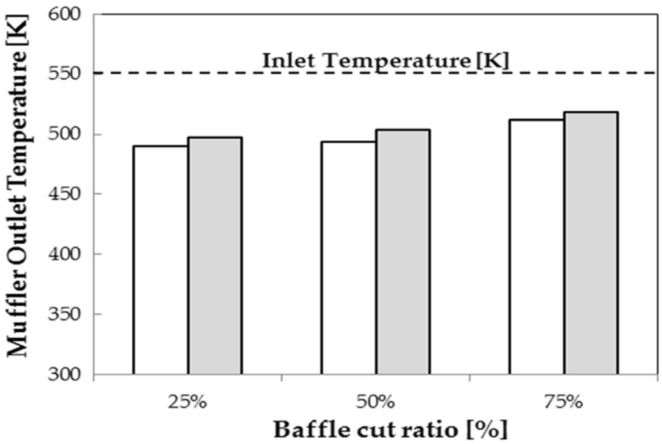

Fig. 8. Effect of baffle cut on back pressure.

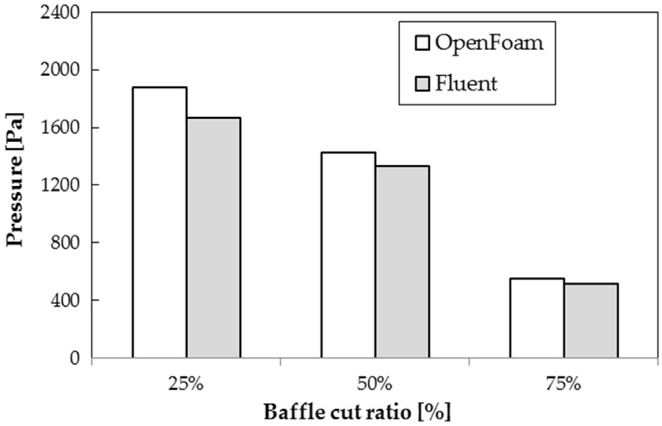

Fig. 9. Effect of baffle cut on outlet temp.

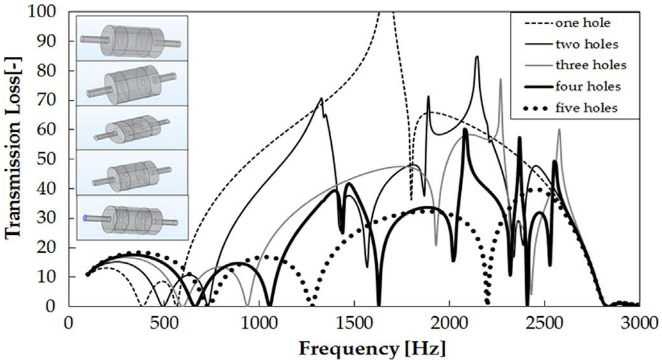

Fig. 10. effect of number of holes on transmission loss with centred hole.

of baffles enhance the transmission loss in the middle frequency range as shown in Fig. 11. It is desirable for a high performing muffler to achieve high transmission loss with less back pressure to avoid engine losses. The creation of centre holes could secure the return of reflected wave close to the inlet chamber and enhances the noise attention.

8. Baffle spacing

Closer baffle spacing enhances the transmission loss at intermediate and high frequencies ranges as shown in Fig. 12. This could be attributed to the smaller gap (SG) between the baffles throttling the fluid and dampens the noise through small cross sections [21,22]. The attenuation is apparent at intermediate and high frequencies as the sound wave travels with high speed in same small gaps increases the number of wave reflections with muffler wall and helps to reduce the noise in the incident waves.

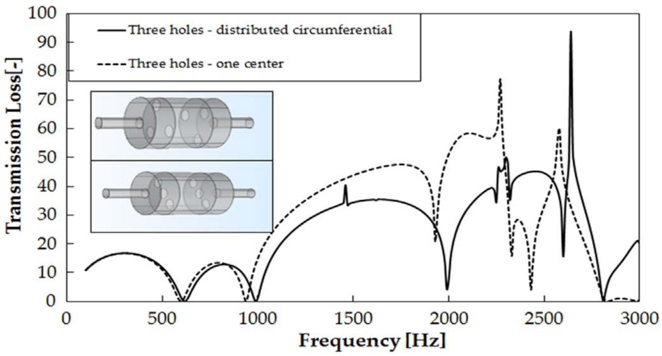

Fig. 11. Effect of three holes distribution on baffles.

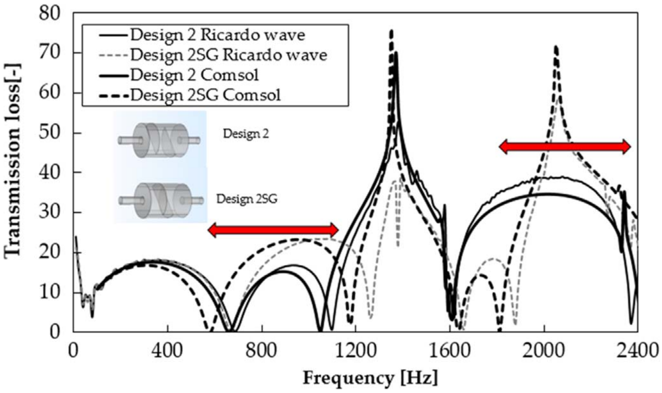

Fig. 12. Effect of Baffle spacing on transmission loss.

9. Conclusions

Several researchers investigated multiple expansion chambers including the number of chambers and tapering effects, and extension connections. The present work investigates the effect of baffle size on muffler transmission loss and back pressure. The paper highlights some design parameters on transmission loss that has not been covered in previous literature including baffle cut ratio, number of holes, holes distribution and baffle spacing. Increasing the Baffle size was found to increase the back pressure and shift the peak transmission loss to lower frequencies. Increasing the number of holes in baffles deteriorate the transmission loss compared to centred single hole. However, multiple holes are preferable to reduce the back pressure. Using centred holes was found to be more effective than distributing the holes on baffle surface. Reducing the baffle spacing was found to enhance the transmission loss at high and medium frequency regions. The transmission loss could be improved by more than 40% by adjusting the highlighted parameters.

C_0 sound velocity [m/s].
$C_{1\varepsilon}$, C_2, σ_k, σ_ε empirical turbulent model constants with values 1.44, 1.9, 1, and 1.2 [-].
dA cross sectional area [m^2].
G_k rate generation of TKE due to $_{mean}$ velocity gradients[kg/(m.s^3)].
G_b rate generation of TKE the arises due to buoyancy[kg/(m.s^3)].
ρ density [Kg/m^3].
p sound Pressure [Pa].
P sound power [W].
S_ε, S_k source terms [kg/(m.s^3)].
S rate of strain tensor [1/s].
T temperature [K].
TL transmission loss [-].
x, y, z, x_i, x_j cartesian coordinates [m].
$\rho\overline{u_i' u_j'}$ Reynolds stress [Pa].
Y_M fluctuating dilation due to the overall dissipation rate [kg/(m.s^3)].
u, v, w, u_i, u_j velocity components in Cartesian coordinates[m/s].
μ dynamic viscosity [Pa.s].

k mean turbulent kinetic energy [m^2/s^3].
ε Turbulence kinetic energy dissipation rate [m^2/s^3].

Subscript

in incident wave.
tr transmitted wave.
t turbulent.

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