Exhaust System Muffler Volume Optimization of Light Commercial Vehicle Using CFD Simulation

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Introduction

- Functions of automotive exhaust system:
  - Carries hot exhaust gases from engine to atmosphere.
  - Attenuates engine noise through muffler efficiently.
- Exhaust gases originate in pulses, creating low-pressure areas.
- Back pressure from exhaust system decreases engine efficiency.
- Maximum engine output achieved with minimum back pressure.
- Muffler design aims for optimal back pressure without subsystem disruption.
- Increased back pressure may increase torque, but not directly related.
- Muffler diameter and profile optimized to control back pressure.
- Main objective of muffler: noise level optimization.

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- Types of mufflers:
  - Reflective or reactive: Wave cancellation method for low frequencies.
  - Absorptive or dissipative: Converts energy into heat for high frequencies.
  - Hybrid: Combines reflective and absorptive properties, suitable for all frequencies.
- Existing system utilizes reflective type muffler.

Methodology

The cross section of a 3-cylinder muffler is explained in **Fig. 1.**

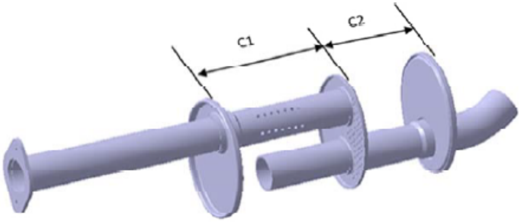

Fig.1. Internal construction of chambers

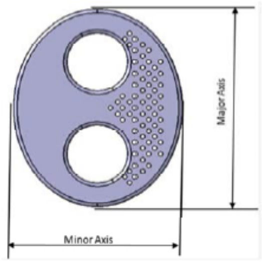

Fig.2. Major and minor axis of muffler.

- Muffler downsizing considered along length or width or both, with challenges in downsizing along minor axis due to pipe construction and tooling costs.
- Vehicle layout constraints favor downsizing along length.
- Two chambers inside muffler affect back pressure; volume changes in chambers 1 and 2 impact back pressure.

- Back pressure adjustments balanced by varying number of holes in inlet pipe.
- CFD analysis used to vary and analyze chambers C1 and C2, resulting in downsized muffler.
- Details tabulated in **Table 2**, with respective notations illustrated in **Fig. 3.**

Table 2.Comparison between 3 Cylinder existing muffler and downsized Muffler

Notation	Represents	Existing Muffler	Downsized Muffler
A	Inlet pipe dia (mm)	50.8	50.8
B	Outlet pipe dia (mm)	50.8	50.8
C	Number of holes in inlet pipe	49	70
D	Distance between baffles (mm)	200	170
E	Distance between baffles (mm)	110	50
F	Overall length (mm)	310	220

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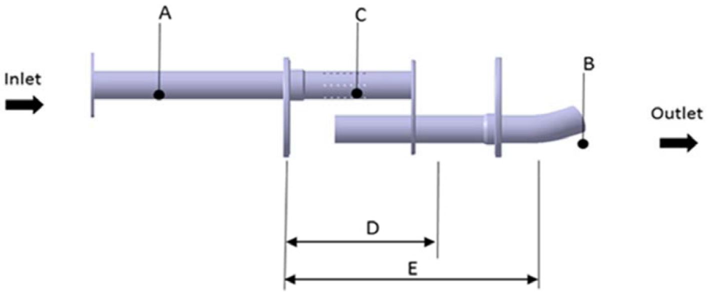

Fig.3. Internal construction of muffler

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- Muffler optimization historically relied on physical trials.
- Variables included pipe diameter, hole perforations, baffle placement, and damping volume.
- Modern simulation tools mitigate these challenges.
- Simulation aids in balancing conflicting factors like back pressure and noise.

Design of Muffler 3D Modeling

- Predict muffler system performance using CFD tool pre-release.
- Modify design inputs based on flow results.
- Utilize CATIA V5 for parametric CAD modeling.
- Achieve 3D associativity for easy updates.
- Identify problematic areas and adjust input parameters.
- Parameters include muffler length, diameters, hole count, and baffle position.
- Drastically reduce muffler design time.

Mesh preparation

- CAD data exported as STEP file from CATIA V5, then imported into CFD.
- Fluid domain extracted and converted into closed volume for CFD analysis.
- Tetrahedral mesh used with mesh quality of 0.2 for meshing the fluid domain.
- See **Fig. 4** and **Fig. 5** for meshed geometry of the muffler.

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Fig.4. Meshed geometry of muffler (transparent view)

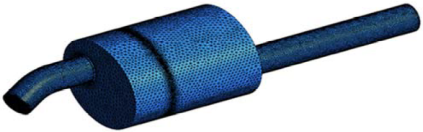

Fig.5. Meshed geometry of muffler

Boundary conditions

- Turbulence model: k epsilon
- Working fluid: Exhaust gas (density: $0.5508\,\mathrm{kg/m^3}$, viscosity: $3.814 \times 10^{-5}\,\mathrm{Pa.s}$)
- Mass flow rate: 180 kg/hr
- Inlet conditions: 400°C temperature
- Muffler outlet pressure: 1 atm
- Solver settings:

Results and Discussion

- CFD analysis conducted using ANSYS CFX for existing and newly designed mufflers.
- Results compared between existing muffler and final design concept.
- Final design features increased number of holes and termed as down-sized muffler.
- **Fig. 6** and **Fig. 7** depict 3D geometry and cross-sectional view of existing muffler, respectively.

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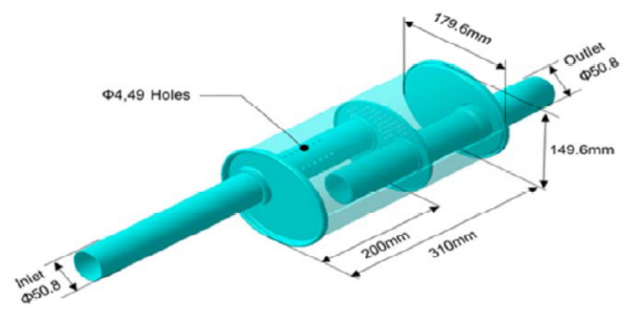

Fig.6. Three dimensional view of existing muffler

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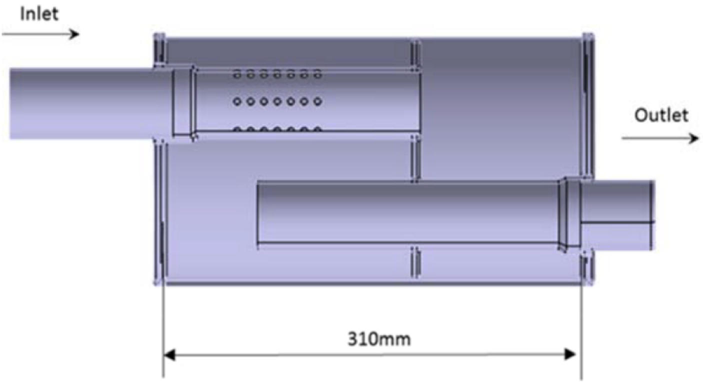

Fig.7. Geometry existing design

- **Fig. 8** and **Fig. 9** depict the 3D geometry and cross-sectional view of the downsized muffler, respectively.

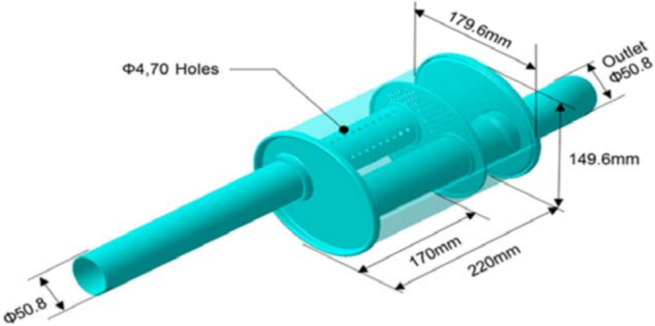

Fig.8. Three dimensional view of downsized muffler

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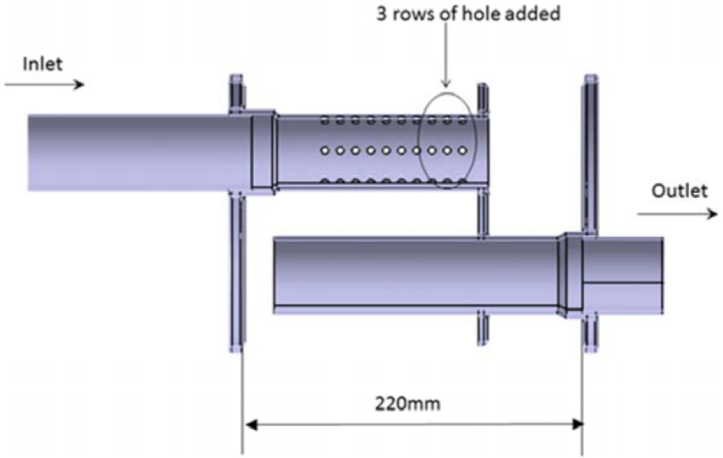

Fig. 9. Geometry-downsized design

Exhaust Gases Path Lines

- Existing muffler flow analysis results depicted in **Fig. 10.**
- CFD analysis conducted for downsized muffler, maintaining identical boundary conditions as the existing muffler CFD analysis.
- Results plotted and illustrated in **Fig. 11.**

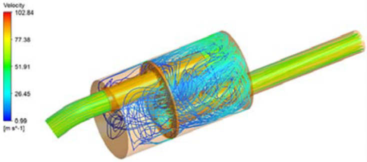

Fig.10. Air flow field - Existing design (Base model)

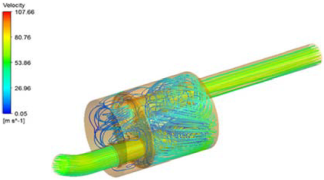

Fig.11. Air flow field - downsized design with same number of holes

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- Exhaust flow denser in C1 & C2 chambers, increasing back pressure from **2.655 kPa to 2.949 kPa.**
- Number of holes in inlet pipe increased from 49 to 70 to reduce back pressure.
- Contour plot for muffler with **70 holes (Fig. 12)** shows reduced pressure drop from **2.655 kPa to 2.472 kPa.**
- Optimized pressure drop comparable and better than existing muffler, improving exhaust flow restriction by 6.89%.

Fig.12. Air flow field - downsized design with increased number of holes

Pressure and Velocity Plot

- Noise quality determined by pressure and velocity plots.
- Exhaust gases in pulse lead to discontinuous gas flow, creating varied noise.
- High velocity escaping gases can result in whistling noise.
- Analysis of pressure and velocity plots for existing and downsized mufflers conducted.
- Result: Total pressure and flow velocity remain unchanged.
- Concludes existing design maintains sound quality.
- **Fig. 13** and **Fig. 14** show the velocity plots of exhaust gases in the outlet at existing and down sized muffler.

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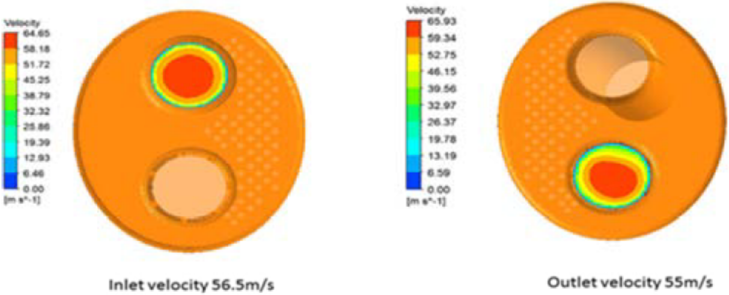

Fig.13. Velocity contours-existing design

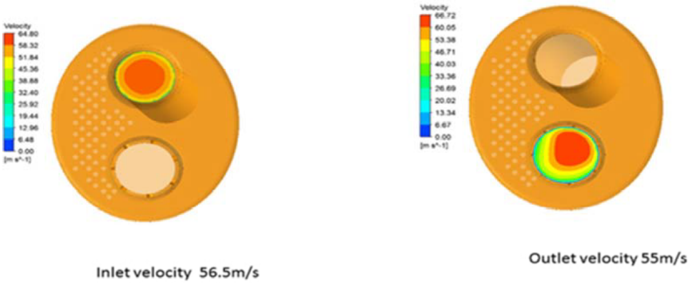

Fig.14. Velocity contours-downsized design

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- Pressure is crucial for optimizing muffler noise levels.
- Comparison of pressure contours between existing and downsized mufflers indicates no change in noise level.
- **Fig. 15** and **Fig. 16** display pressure distributions for existing and downsized mufflers, respectively.

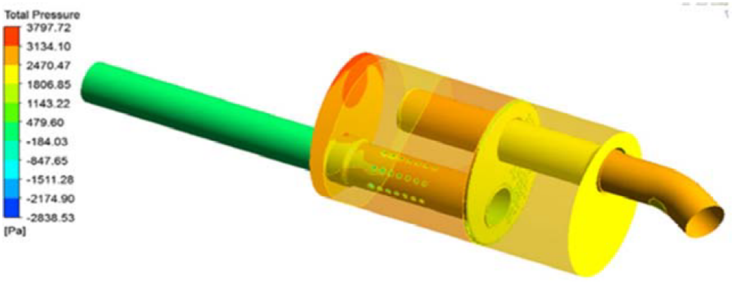

Fig.15. Total pressure- existing design

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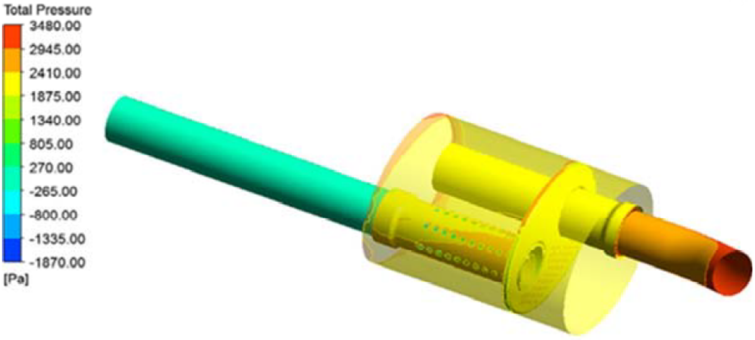

Fig.16. Total pressure- downsized design

Test Result

- CFD results for downsized muffler back pressure verified with vehicle-level test.
- Back pressure measured by inserting probe into pipe center; barometer connected for calculation.
- Quality of noise tested on vehicle with existing and downsized muffler, results tabulated in **Table 3.**

Table 3.Test results comparison between existing and downsized muffler

Parameter	Existing Muffler	Downsized Muffler
Backpressure in Exhaust system (kPa)	2.655 kPa	2.472 kPa
Quality of noise (Subjective)	Good	Good

Conclusions

- Muffler downsizing increased back pressure from 2.655 kPa to 2.949 kPa.
- Increasing inlet pipe holes to 70 and adjusting baffle position to 170 mm reduced back pressure to 2.472 kPa.
- Downsized muffler outperforms existing in pressure reduction.
- Pressure drop improved by 6.89% in downsized muffler.
- No deterioration in noise quality or vehicle noise.
- Overall muffler volume reduced by 15%, leading to 2% weight reduction, cost, and fuel economy benefits.

References

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Thank You

Thank You!