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NUMERICAL EVALUATION OF THE PERFORMANCE OF ABSORPTIVE LINER MATERIALS ON NOISE TRANSMISSION LOSS FOR PASSENGER TRICYCLE MUFFLERS

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Abstract

The prevalence of environmental noise pollution on local thoroughfares has increased significantly due to a notable increase in the popularity of passenger tricycles. Thus, the purpose of the current research intends to assess the effectiveness of absorptive liner materials in terms of noise transmission loss in passenger tricycle mufflers. For modeling, simulation, and analytical evaluation, ANSYS and COMSOL Multiphysics were the software packages utilized. The fluid was characterized as an ideal gas, with a fixed inlet flow velocity set at 10 m/s, while the gas temperature was varied between 20 and 200°C. The study reveals that the muffler incorporating absorptive liner materials, subjected to varying temperature treatments (ranging from 60 to 200°C), demonstrated superior performance compared to the muffler devoid of a liner, achieving improvements of 85.1% (Balsa LR), 80.8% (Ceramic), 87.5% (Rockwool), and 92.3% (Polyester), respectively. According to the study, when the muffler with the absorptive liner materials was exposed to different temperature treatments (60 to 200°C), it performed better than muffler without a liner. The results also show that there was an inverse relationship between the transmission loss and the flow resistivity and average fiber diameter metrics related to the absorptive liner materials. The numerical findings validate that the use of absorbent liner materials specifically, polyester into muffler systems improves efficiency by reducing the excessive noise produced during transmission. As a result, this study recommends using polyester, which was found to be the best absorbent material, as a liner in mufflers to effectively reduce noise in tricycles.

Keywords: Absorption Rate, Acoustics, COMSOL Multiphysics, Liner Materials, Mufflers.

I. INTRODUCTION

In order to efficiently transport people from one place to another, passenger tricycles are widely used in many developing countries, in Africa, and in other parts of the world [1]. These tricycles are quite efficient when running, the engine makes lot of noise when running. The noise from the exhaust system is around ten times louder than the noise from the structure [2]. Human hearing is negatively impacted by the noise pollution that the engines emit during combustion. Mufflers are typically used to reduce the noise produced by a combustion engine to a level that is more tolerable, which ensures passenger and driver comfort while simultaneously decreasing noise pollution in the environment. Muffler design is explicitly targeted at reducing unwelcome aspects of raw exhaust noise, especially low-frequency sounds [3]. The ratio of the acoustic power from the incoming (progressive) pressure wave at the muffler's inlet to the acoustic power from the departing pressure wave at the muffler's outlet is the quantitative expression

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for noise transmission loss. Figure 1 shows a tricycle muffler that is affixed to the engine and transmission systems to mitigate the auditory disturbances generated by the engine.

Fig 1: Tricycle muffler

Many geometric parameters have been incorporated into muffler design frameworks to achieve the best possible attributes for noise transmission loss, as research undertaken over the years indicated. The use of absorbent lining filters, resonator chamber perforation, input and output tube elongation, and resonator chamber expansion are some of the geometric factors that are included. The sound waves coming from the exhaust system can be effectively attenuated using these absorbent lining materials. Several academics have done in-depth examinations to demonstrate that materials like resonant cotton and balsa wood are known to be effective acoustic treatments and are even produced commercially. Textile-like materials are effective acoustic absorbers when used in acoustic treatments, but when it comes to vibration control, they are usually integrated into stiff frames or layered composites [4].

The passengers on the tricycle experience a great deal of inconvenience due to the noise that the motor of the vehicle produces. Long-term exposure to the noise produced by the current architecture could have a negative impact on tenants' health. In order to find the best material for noise reduction in passenger tricycle mufflers, the current study attempts to evaluate the effectiveness of several absorptive liner materials. The noise transmission loss characteristics of the model for various absorptive liner materials are numerically analyzed at temperatures ranging from 20 to 200°C. The results were compared to the efficiency of the muffler without any absorptive liner material, taking into account variables like temperature, pressure, and velocity.

II. THEORETICAL ANALYSIS OF MODEL

Absorptive mufflers operate based on the principle of sound energy absorption. The propagation of sound waves is diminished as the energy is transformed into thermal energy by the liners composed of absorptive materials. The proposed muffler model consists of two hollow pipes connected to an elliptical casing at either end, functioning as the input and output terminals for wave propagation. The casing houses the material liner, which absorbs sound pressure pulses during transmission. In most acoustic scenarios, fluid flow losses and viscous effects are typically disregarded, which facilitates the application of a linearized equation of state. Under this assumption, the acoustic field, characterized by pressure, is described by wave formulation Eq. (1) as;

$$\frac{1}{\rho_o c^2}\frac{\partial^2 p}{\partial t^2}+\nabla.\left[-\frac{1}{\rho_o}(\nabla p-q)\right]=Q \tag{1}$$

Where ρ_o is the density of the fluid in (kg/m^3), t is the time in seconds, q and Q are the expected acoustic sources (N/m^3). The model equation can further be simplified into a modified version of the Helmholtz equation for the acoustic pressure p in the muffler as Eq. (2),

$$\nabla.\left(-\frac{\nabla p}{\rho}\right)-\frac{\omega^2 p}{c^2\rho}=0 \tag{2}$$

Where, ρ is the density, c is the speed of sound and ω is the angular frequency. The mechanical characteristics of porous absorptive material liners with a rigid skeleton-like including flow resistivity and frequency, are estimated using a well-known model. With a homogenous porous absorptive material liner, the Delany-Bazley model provides a quick and easy way to estimate the parameters of the acoustic isotropic layer [5]. The acoustic parameters such as characteristic impedance (Zc), the propagation constant k_c and surface acoustic impedance (Z) can be computed as in Eq. (3);

$$\begin{aligned} k_c &= k_a\left(1+0.098\cdot\left(\frac{\rho_a f}{R_f}\right)^{-0.7}-i\cdot0.189\cdot\left(\frac{\rho_a f}{R_f}\right)^{-0.595}\right) \\ z_c &= z_a\left(1+0.057\cdot\left(\frac{\rho_a f}{R_f}\right)^{0.734}-i\cdot0.087\cdot\left(\frac{\rho_a f}{R_f}\right)^{-0.732}\right) \end{aligned} \tag{3}$$

Where, R_f is the flow resistivity, $k_a=\omega/c_a$ and $z_a=\rho_a/c_a$ are the free space wavenumber and impedance of air respectively. The flow resistivity for glass wool-like materials was determined based on the Bies and Henson formulation, Eq. (4) as follow;

$$R_f=\frac{3.18\cdot10^{-19}\cdot\rho^{1.53}}{{d_{av}}^2} \tag{4}$$

Where, d_{av} is the mean fiber diameter of the absorptive material liners; an important parameter of an absorptive muffler is the transmission loss or attenuation. The transmission loss characteristic of the absorptive muffler is the ratio of incoming acoustic energy to outgoing acoustic energy as Eq. (5);

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$$TL = 10\log\left(\frac{\omega_{in}}{\omega_{out}}\right) \tag{5}$$

Where, TL is the transmission loss characteristics, ω_{in} is the incoming acoustic energy and ω_{out} is the outgoing acoustic energy. The incoming acoustic energy (ω_{in}) and outgoing acoustic energy (ω_{out}) can be calculated by Eq. (6) as;

$$\omega_{in} = \int_{\partial\Omega} \frac{|p|^2}{2\rho c} dA; \omega_{out} = \int_{\partial\Omega} \frac{p_o^{\ 2}}{2\rho c} dA \tag{6}$$

The finite element analysis was performed in the acoustic module of Comsol Multiphysics software. Since the absorptive liner materials are porous, Delany and Bazley's equations were used to determine the complex wavenumber k_c and complex impedance z_c of the liners which estimates the acoustic parameters as a function of frequency and airflow resistivity.

III. SIMULATION OF MODEL

A. Geometry Modeling and Materials

In this study, ANSYS-Fluent software was used to model and simulate a circular absorptive muffler (Fig. 2), with Table 1 providing the associated parameters. Table 2 explains the material qualities of the four different absorptive liner materials used in this study: rockwool, polyester, balsa LR, and ceramic fiber.

Table 1: Modelling Parameters

Parameter	Value (mm)
Length of muffler	1300
Height of muffler	200
Width of muffler	400
Diameter of resonator chamber	40
Length of absorptive liner	200
Inlet and outlet diameter of liner	50
Absorptive liner thickness	15~20

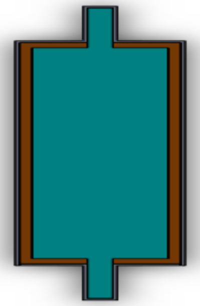

Fig 2: Geometrical model of muffler

Table 2: Material properties of absorptive materials

Material	Flow Resistivity ($N/s\ m^{-4}$)	Poisson Ratio (v)	Young Modulus (MPa)	Density kg/m^3	Mean Fiber Diameter (m)
Polyester	5356	-0.75	920	44.00	0.032
Rockwool	11817.5	0.21	72	62.20	0.050
Balsa LR	9.93e10	0.26	22	192	20
Ceramic fibre	6060	0.37	288	68.00	0.055

B. Finite Element Analysis

The model was subjected to an analytical evaluation using the COMSOL Multiphysics program. The models' features related to pressure drop and fluid dynamics were methodically simulated. The fluid was modelled as an ideal gas in the CFD model analysis, with a temperature variation of 20 to 200°C and a flow inlet velocity of 10 m/s. Tables 3 and 4 provide a detailed input-dependent acoustic medium and fluid parameters used in the simulation, respectively.

Table 3: Input parameters of acoustic medium

Parameters	Value
Fluid	Air (ideal gas)
Speed of sound	343 m/s
Atmospheric pressure (P_O)	1.0133e5 Pa
Inlet pressure (P_{in})	1 Pa
Temperature	20-200(°C)

Table 4: Input parameters of fluid

Parameters	Value
Fluid	Air (ideal gas)
Speed of sound, c	343 m/s
Density, ρ	1,2041 kg/m^3
Inlet velocity, u	10 m/s

IV. RESULTS AND DISCUSSION

To validate the model, numerical findings for noise transmission loss characteristics at 20°C obtained from the absorptive materials without a liner were analyzed. The temperature, pressure, and velocity of several types of liner materials are described for analysis in the temperature range between 20 to 200°C, which is relevant to computational fluid dynamics.

A. Validation of Model

To validate the model, a baseline muffler was developed, and the transmission loss characteristics were ascertained without the integration of an absorptive material liner. An absorptive muffler without a liner material was simulated at the temperature threshold of 20°C in order to verify the effectiveness of the various absorptive liner materials. The findings depicted in Figure 3 show variations in transmission loss in the region of medium to high frequencies. The muffler without an absorptive material lining records a 13 dB transmission

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loss in the low-frequency range (0–1000 Hz), but it performs exceptionally well in the high-frequency ranges. The model measures transmission loss maxima at 18 dB, 28 dB, and 44 dB in the high-frequency range of 1000 to 3000 Hz, respectively. This implies that the muffler without a material lining is effective at attenuating high frequencies, which is consistent with studies in the literature [6] on the use of Helmholtz resonators to reduce low frequencies.

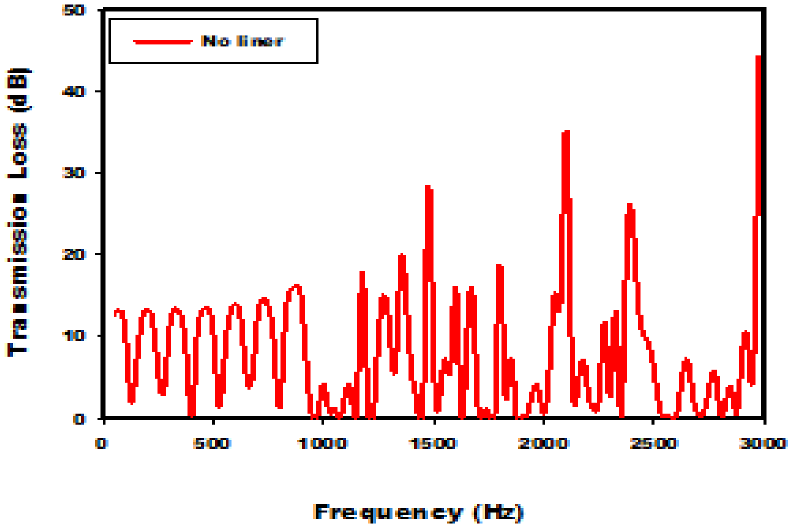

Fig 3: Noise transmission loss for absorptive material without liner at 20°C

B. Noise Transmission Loss at Different Temperature Levels

The transmission loss results of the muffler with a ceramic absorptive material liner are shown in Figure 4(a). Sustained transmission loss peaks are seen in this model from low to high frequencies. The recorded peaks of effective transmission loss are 30 dB, 40 dB, and 69 dB, in that order. When comparing performance with and without an absorptive material liner, the results suggest that the liner's integration improves the transmission loss characteristics. This pattern is also seen in the use of liners made of different absorbent materials, such as polyester, rockwool, and balsa LR, in that order. When polyester is added to the model, as shown in Fig. 4(b), the transmission loss characteristic increases to 40 dB, 50 dB, and 70 dB, respectively.

As illustrated in Fig. 4(c), the muffler with a rockwool material liner exhibits a transmission loss characteristic of 20 dB, 40 dB, and 96 dB, correspondingly. The transmission loss characteristic of the muffler with a balsa LR material liner, as shown in Fig. 4(d), is 10 dB, 45 dB, and 72 dB, respectively. Overall, the results show that adding different absorptive liner materials to the model muffler design improves the transmission loss characteristics at 20 °C.

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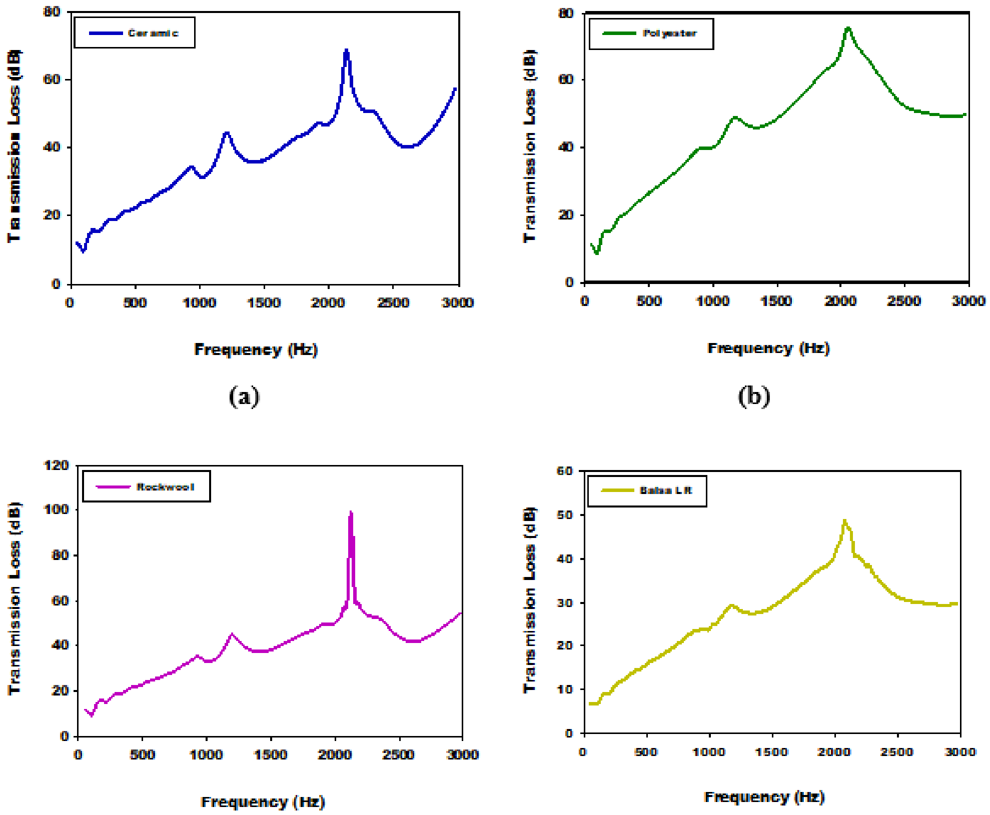

(a) (b)

(c) (d)

Fig 4: Noise Transmission Loss at 20oC (a) Ceramic fibre liner (b) Polyester liner (c) Rockwool liner (d) Balsa LR liner

The simulation results for the model parameters at a temperature of 60°C are depicted in Fig. 5. Temperature variations influence the transmission loss properties, yet the parameters of the absorptive materials used in the initial model optimization remain unchanged. At 60oC, mufflers with absorbent liner materials exhibited enhanced transmission loss characteristics, whereas mufflers lacking absorbent material liners showed no notable change. This behavior can be attributed to the inherent mechanical properties associated with the materials of the absorbent liners. The simulation findings, which are shown in Fig. 5, show that Balsa LR and Rockwool performed less well in the low-frequency band, producing transmission loss characteristics of 10.12 dB and 16.93 dB, respectively. However, there was a noticeable improvement in the high-frequency region, with Rockwool and Polyester registering noise transmission losses of 120.21 and 158.29 dB, respectively. In contrast to the data recorded at a temperature of 20°C, the noise transmission loss characteristics for Ceramic and Polyester in the low-frequency region increased to 21 dB and 20 dB, respectively, suggesting better performance at a temperature of 60°C. Additionally, the results validate that muffler with liners made of absorbent material functioned better than those without, supporting earlier research by [7, 8]. At a temperature of 100°C, the noise transmission loss characteristics of different

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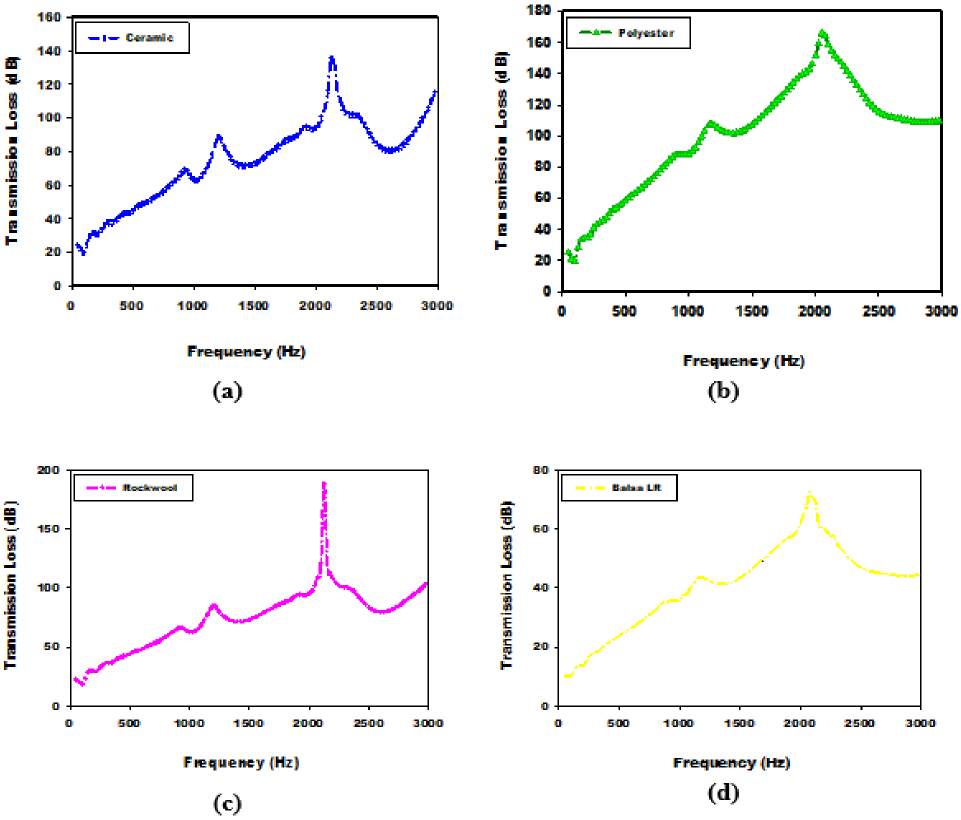
absorptive liner materials were simulated and compared with the muffler without any absorptive liner material (Fig. 6). Among the absorptive liner materials, the trend shows a noticeable rise to notable peaks at different frequencies; the only exceptions are Balsa LR and the non-lined design, where several peaks were seen along the transmission channel. It was also demonstrated that a rise in transmission loss is accompanied by a corresponding decrease in the number of transmission peaks.



(a)

(b)

(c)

(d)

Fig 5: Noise Transmission Loss at 60°C (a) Ceramic fibre liner (b) Polyester liner (c) Rockwool liner (d) Balsa LR liner

A higher output and a lower input-to-output ratio are correlated with an elevated flow resistivity value, which lowers the transmission loss. The existence of overlaps and crosses makes qualitative analysis of the data difficult. However, as Figure 6 illustrates, there was a noticeable increase in the noise transmission loss characteristics at 100°C compared to the noise transmission loss characteristics at 20°C and 60°C.

The noise transmission loss performance characteristics of different absorptive liner materials, with and without a liner at 200°C, are compared in Figure 7. It is clear that the muffler's noise transmission loss characteristics were greatly improved by the addition of absorptive material liners. This is further supported by the transmission loss for polyester increasing from 48.22 dB (low frequency range) to 224 dB (high frequency range), which is consistent with the findings for 20°C, 60°C, and 100°C. The results also show that the integration of absorptive liner materials lowers the threshold of resonances within sharp peaks, signifying a broad peak reduction in transmission losses at the relevant frequencies. As a result of the applied absorptive liner materials, the study's findings demonstrate a strong correlation in the transmission loss characteristics. An average person's ear can withstand 85 dB of noise per day, according to reference; sustained exposure to noise levels higher than tolerable thresholds can cause hearing impairments. It is decided that the absorptive liner materials are appropriate for use as an alternative to tricycle mufflers because their transmission loss characteristics are higher than the acceptable limits for human exposure. Based on a computational fluid dynamics simulation of the suggested muffler model, the most efficient absorptive materials are shown in Figures 8–10. The contour plots' color gradations illustrate different pressure levels, from low to high, as determined by the computational fluid dynamics analysis. Green represents locations of moderate pressure, yellow represents conditions of medium pressure, red represents places of high pressure, and blue represents areas of low-pressure concentration. The results of the model run at 20°C show that the lowest recorded velocity was 0.05 m/s, and the highest recorded velocity was 12.67 m/s (Fig. 8). The temperature changed between 293.2 K and 293.1 K, while the pressure varied between 87.8 Pa and -0.517 Pa, supporting results from earlier research by [9, 10].

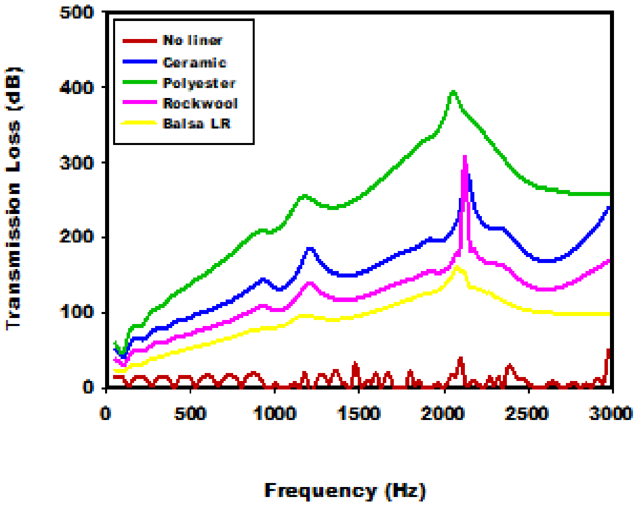


Fig 7: Comparison of noise transmission loss for different absorptive liners at 200°C

C. Characteristics Analysis of Absorptive Liner Materials

The contour at 60°C is shown in Figure 9, and the velocity range that results is between 0.058 and 12.2 m/s. Once more, the recorded temperature showed a maximum of 293.2 K and a minimum of 293.1 K, while the recorded pressure varied from -0.517 Pa to 87.8 Pa. This result is consistent with research by [9] which assesses sandwich panels' numerical vibroacoustic response. The recorded findings at 80°C, as shown in Figure 10, reveal that the temperature varied from 354 K to 353 K, the velocity varied between 12.2 m/s and 0.0583 m/s, and the pressure varied between 129.7 Pa and -22.14 Pa. These findings are in line with a study by

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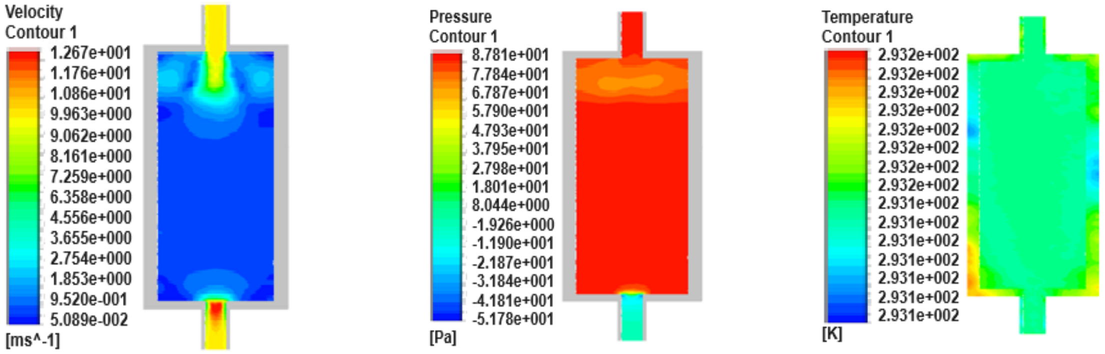
[11], which looks into the connection between temperature, pressure, and flowing air as descriptive factors.

The contour at 100°C is shown in Figure 11, the maximum velocity was recorded at 129.7 Pa, the lowest pressure at -22.14 Pa, and the temperature ranged from 373 K to 372 K. The outcomes are in line with the research by[12] which sought to reduce flow-induced vibrational noise in double-panel structural applications by using porous, sound-absorbing materials as internal linings. The recorded results at a high temperature of 150°C, as shown in Figure 12, were as follows: a maximum velocity of 12.2 m/s and a minimum of 0.058 m/s; the temperature varied between 423.3 K and 423.1 K; the pressure readings varied between 129.7 Pa and -22.14 Pa. This outcome is consistent with studies that looked into passive noise reduction techniques in mufflers and specifically examined how geometric layouts affect the best possible noise transmission loss performance [13].

As can be seen in Figure 13, at 200°C, the temperature was found to be between 473.6 and 473.0 K, while the maximum velocity was once again measured at 12.2 m/s and the lowest at 0.058 m/s. The pressure measurements ranged from 129.7 Pa to -22.14 Pa. The results align with a study [14] utilized factorial design techniques to evaluate and maximize the impact of noise-related parameters on the transmission loss of those kinds of systems. The contours show several directions of changes in the fluid velocity inside the absorbent muffler. The deviations in the velocity result values that have been noticed can be ascribed to the average fiber diameter of the absorbent materials that were used in the numerical analysis. Since the average fiber diameter is closely correlated with flow, an increase in fluid velocity instantly impacts the total algebraic sum of potential and kinetic energy, keeping flow pressure constant.



(a) (b) (c)

Fig 8: Simulation maps of muffler with different parameters (a) Velocity, (b) Pressure, c) Temperature for Polyester Liner at 20°C

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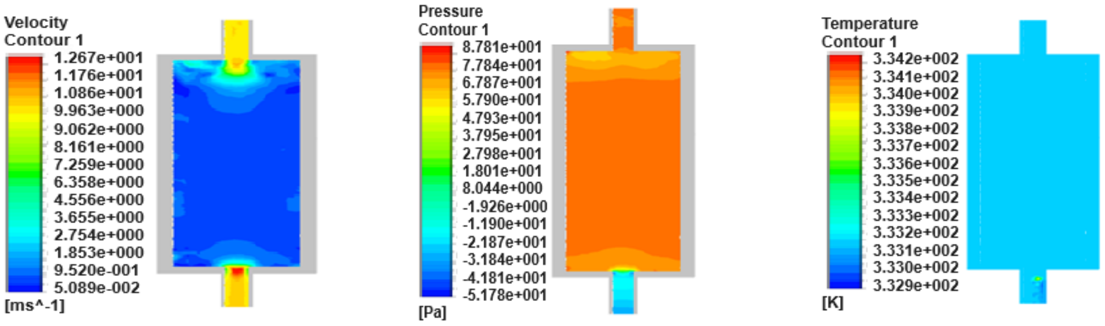
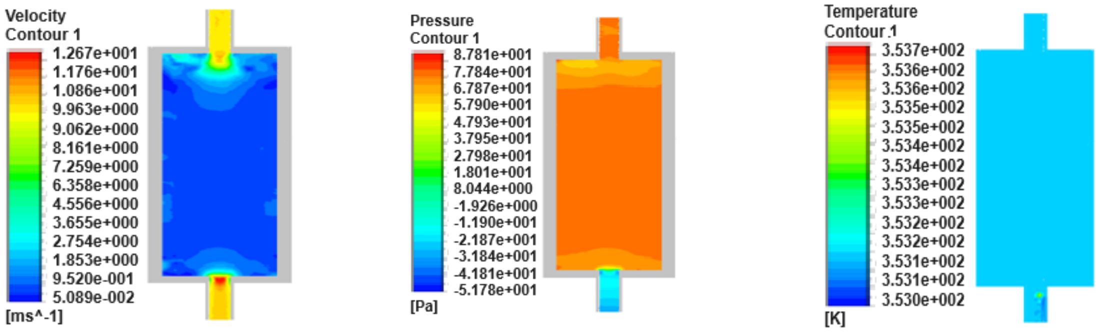


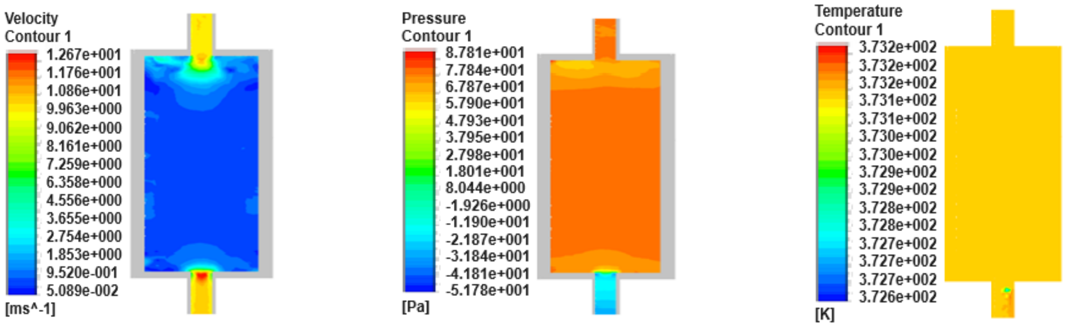
(a) (b) (c)

Figure 9: Contour of Muffler with different parameters, (a) Velocity, (b) Pressure, (c) Temperature for Polyester Liner at 60°C



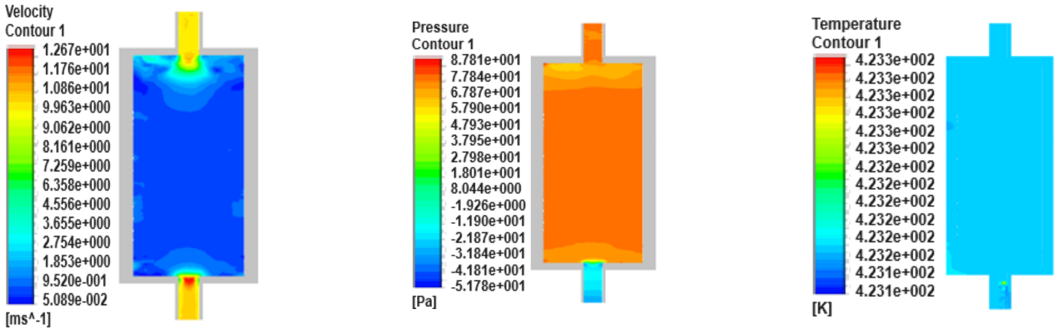
(a) (b) (c)

Figure 10: Contour of Muffler with different parameters, (a) Velocity, (b) Pressure, (c) Temperature for Polyester Liner at 80°C



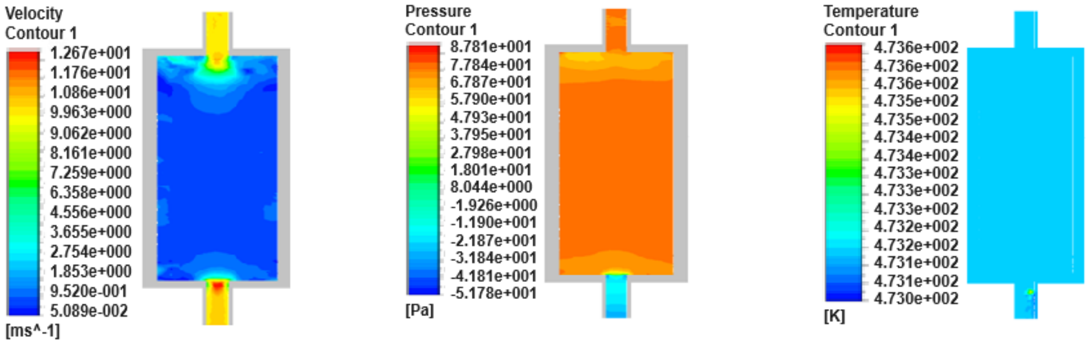
(a) (b) (c)

Figure 11: Contour of Muffler with different parameters, (a) Velocity, (b) Pressure, (c) Temperature for Polyester Liner at 100°C



(a) **(b)** **(c)**

Figure 12: Contour of Muffler with different parameters, (a) Velocity, (b) Pressure, (c) Temperature for Polyester Liner at 150°C



(a) **(b)** **(c)**

Figure 13: Contour of Muffler with different parameters, (a) Velocity, (b) Pressure, (c) Temperature for Polyester Liner at 200ºC

V. CONCLUSION

A pivotal performance metric referred to as transmission loss quantifies the degree to which the incident acoustic pressure is diminished within a controlled system. The present investigation elucidates that the absorptive material lining demonstrates advantageous damping properties that exhibit variability in accordance with the flow resistivity of the material. In the temperature spectrum of 20°C, 60°C, 100°C, and 200°C, the features of transmission loss demonstrated a consistent advancement. The outcomes of all calculations, in juxtaposition with a conventional muffler devoid of an absorptive lining material, indicate a direct relationship between the transmission loss characteristics and the presence of the liner. The incorporation of liners composed of absorbent material resulted in an enhancement of the transmission loss characteristics exceeding 70% in comparison to the standard muffler. The results of the study unequivocally indicate that the mean fiber diameter, temperature, and flow resistivity exhibit a strong correlation. Furthermore, the results have substantiated that liners composed of absorbent materials exert a significant influence on transmission loss within the medium to high frequency spectrum. The findings revealed that all four types of absorbent material liners:

Polyester, Ceramic fiber, Rockwool, and Balsa LR demonstrated exceptional performance and exhibited considerable peaks in maximum transmission loss. Nevertheless, polyester surpassed the other liners by achieving a temperature-dependent maximum transmission loss peak of up to 220 dB at a temperature of 200°C.

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Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors declare no financial interests/personal relationships which may be considered as potential competing interests.

Authors' contributions

Author 1' designed the study, performed the statistical analysis and wrote the protocol. Author '2' wrote the first draft of the manuscript. 'Authors 2 and 3' managed the analyses of the study. 'Author 1' managed the literature searches. All authors read and approved the final manuscript.

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Ethics approval and consent to participate

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Consent for publication

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List of abbreviations

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