Harmonizing Muffler Design: The Virtuoso Performance based on Inlet Diameter, Outlet Diameter and Material in Orchestrating Transmission Loss

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Abstract: This research paper delves into the intricate relationship between muffler design & acoustic performance, uncovering a symphony of variables that influence transmission loss (TL dB) in muffler systems. This comprehensive analysis explores the impact of inlet diameter, outlet diameter, muffler length, and material choice on noise reduction, presenting a nuanced understanding of their roles in achieving optimal acoustic outcomes. The data reveals that increasing the inlet diameter generally enhances noise reduction, akin to a conductor orchestrating a crescendo of frequencies. This effect is particularly pronounced during the transition from an inlet diameter of 15 to 19, resembling a musical composition reaching a breathtaking climax. Conversely, enlarging the outlet diameter plays a consistent baseline, driving frequencies to higher octaves with unwavering precision.

Muffler length emerges as a significant factor, the longer mufflers consistently exhibit higher TL values, although exceptions exist. Like a subtle harmony in a musical composition, the length of the muffler occasionally introduces its own unique influence. Material choice, akin to soloists in an orchestra, presents its own set of unique characteristics.

In the intricate realm of refrigeration systems, where science and engineering converge, refrigerants take centre stage as the virtuoso performers of the heat transfer ballet. With an artful choreography that rivals any stage production, elegant transition of these refrigerants takes place from gas to liquid and back to gas, all the while embracing and relinquishing heat with finesse. It's a performance that keeps our environments comfortable and our perishables preserved. In this captivating spectacle of thermodynamics, a diverse cast of refrigerants takes the limelight. Hydro-fluorocarbons (HFCs) like R-134a and R-410A perform their roles with precision, offering a symphony of cooling capabilities. Hydro-chlorofluorocarbons (HCFCs), once stalwarts of the industry, exemplified by R-22, now take a humble exit, prompted by environmental concerns, as the show must evolve.

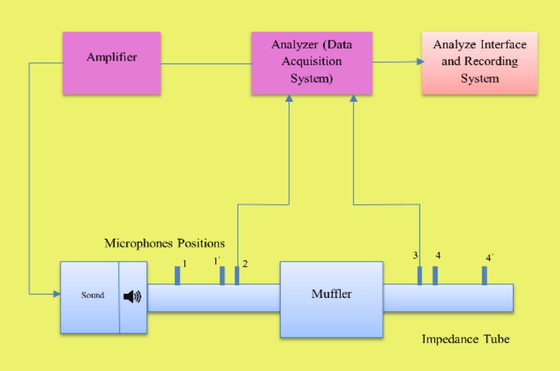

Fig 1: Graphical Abstract

Keywords: Suction Muffler, Optimization, Impedance tube, Transmission loss, reciprocating compressors, sound absorption coefficient.

1. Introduction

Suction mufflers, commonly employed in various industrial applications, play a pivotal role in noise control and system efficiency within fluid handling systems. These mufflers are specifically designed to attenuate the noise generated during the suction phase of fluid movement, ensuring quieter and more efficient operation of machinery such as compressors, vacuum pumps, and hydraulic systems [Allam-2019].

The optimization of suction mufflers has garnered significant attention from researchers and engineers due to their critical importance in noise reduction and system performance enhancement. As industrial operations continue to grow and diversify, the need for effective noise control solutions has become increasingly essential to meet regulatory standards and ensure worker safety [Decula-2020]. This research aims to explore the innovative approaches and emerging trends in the design and optimization of suction mufflers. By examining the complex interplay between various design parameters, such as geometrical configurations, material choices, and flow dynamics, it has been sought to provide valuable insights into the development of quieter and more efficient suction mufflers. Furthermore, this investigation delves into the potential applications of advanced computational techniques and simulation tools to refine the optimization process, allowing for more precise and tailored solutions [Ocorner-2018, van-2017]. In this pursuit, it has been built on the foundation laid by prior research in acoustics, fluid dynamics, and mechanical engineering. The following sections will review key studies, methodologies, and recent developments in the field, shedding light on the evolving landscape of suction muffler design and optimization. In this study, the authors endeavour to present an integrated design approach for a suction muffler within a fluid machine, addressing all three primary functions inherent to its operation. To achieve this, the research employs a topology optimization technique tailored to acoustic and fluid systems, with the aim of facilitating an integrated design process. Nevertheless, it is noteworthy that the conventional application of topology optimization did not account for the intricate interplay between fluid dynamics and acoustics [Oh-2016].

In this investigation, pulsations originating in the compressor discharge chamber are examined as they are transmitted to the refrigerator's cabinet through the connected condenser at the system's rear. Notably, the discharge muffler emerges as a significant contributor to the overall noise generated by the refrigerator. To mitigate this noise, the research explores the application of metallic porous material within the expansion chamber of the muffler. An essential aspect of this study involves the experimental characterization of key macro-acoustic parameters associated with the porous medium, including airflow resistivity, porosity, tortuosity, viscous and thermal length. These empirical measurements serve to validate the findings derived from numerical simulations and analytical assessments [Barbosa-2018].

This review aims to provide a comprehensive analysis of existing research on suction mufflers and highlight potential areas for improvement. The review discusses various design aspects, including acoustic performance, flow characteristics, and structural considerations. Furthermore, it explores recent advancements in material selection, computational modelling, and optimization techniques. By synthesizing the knowledge from different studies, this review offers valuable insights and recommendations for enhancing the performance and efficiency of suction mufflers in reciprocating compressors [K Santosh Kumar-2023].

2. Methodology

In the realm of acoustic materials and treatments, the conventional approaches for gauging sound absorption coefficients and sound transmission loss have long been synonymous with both time and cost-intensive endeavours. These traditional methods have often posed significant challenges, hindering the swift development and evaluation of acoustic solutions. However, in a relentless pursuit of efficiency and accuracy, a groundbreaking technique has emerged – one that revolutionizes the measurement of sound absorption and transmission loss, all the while sidestepping the drawbacks of the past. Enter the realm of "Normal Incidence Sound Absorption and Transmission Loss Measurement," a technique ingeniously devised is used to surmount the conventional limitations.

At its core, this novel approach harnesses the power of an impedance tube, bringing forth a streamlined and precise methodology. Gone are the days of elaborate and protracted measurement processes; this technique offers a more immediate and cost-effective solution for acousticians, researchers, and engineers alike.

The impedance tube, a centrepiece of this innovation, plays a pivotal role in capturing data under normal incidence conditions. It empowers experts to explore the sound-absorbing capabilities and transmission loss characteristics of acoustic materials with unprecedented ease. By adopting this cutting-edge approach, acoustic professionals are poised to expedite their research and development endeavours, ultimately paving the way for more efficient and effective acoustic solutions.

Sound absorption, a fundamental concept in acoustics, elucidates the intriguing interaction between acoustic waves and materials. This phenomenon is characterized by the dissipation of acoustic energy within a material as sound waves traverse through it, undergoing a captivating transformation.

At the heart of sound absorption lies the sound absorption coefficient, symbolized as α. This dimensionless numerical entity is a treasure trove of information, encapsulating the essence of a material's interaction with sound across a spectrum of frequencies. It is a value that resides gracefully within the realm of numbers, bounded by the elegant constraints of zero and one.

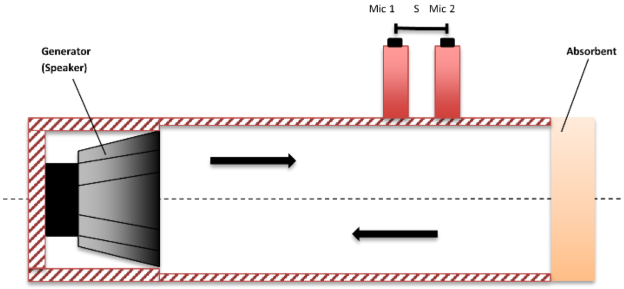

Fig 2: Impedance Tube

The incident wave impacts the face of the material, reflecting some of its energy and sending the rest into the material. The energy sent into the material is either transmitted through the material or absorbed within the porous structure of the material.

Experimentation on the frequency response of suction mufflers is a crucial aspect of understanding their performance and efficiency in various engineering applications, particularly in the field of fluid dynamics and acoustics.

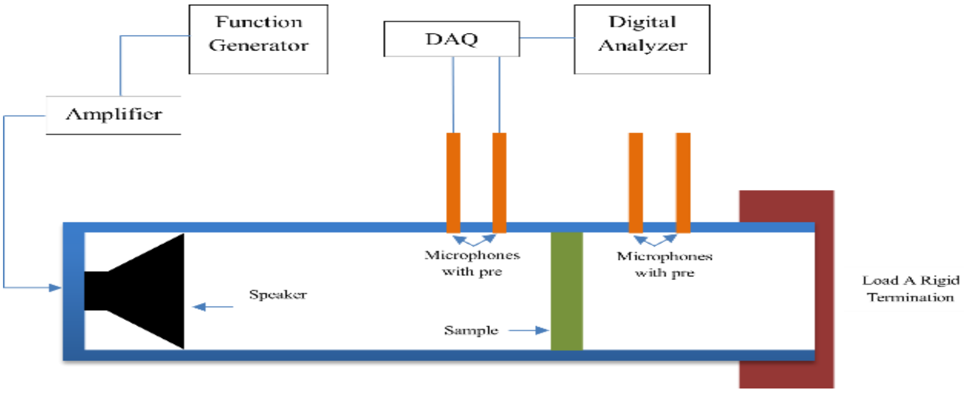

Fig 3: Impedance Tube Test Set-up for Transmission Loss

The Fast Fourier Transform (FFT) technique is a powerful tool employed to analyze and interpret the frequency response of suction mufflers. In this brief context, it has been delved into the significance and methodology of using FFT for such experimentation.

Fig 4: DAQ connected to PC and muffler

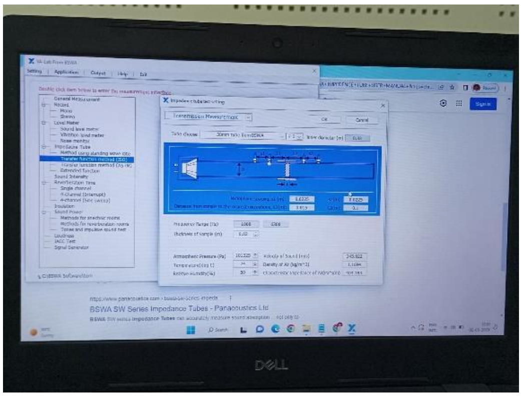

Fig 5: BSWA interface with muffler model

To assemble the experimental setup with precision and ensure seamless functionality, it has been embarked on a meticulous process. Diverse segments of tubes were meticulously tailored to their desired lengths, each piece representing a crucial element in the apparatus. These tube sections were expertly joined together with the utmost care, secured in place with the aid of sturdy flanges. The choice of PVC sealant emerged as the trusted ally in establishing airtight connections, guaranteeing the integrity of the apparatus.

Fig 6: Experimental Setup

Fig 7: Impedance tube connected to DAQ equipped sensors

For a comprehensive view of the meticulously crafted apparatus, both in schematic form and in actuality, Fig 6 and Fig 7. can be viewed. This visual documentation showcases the fruits of labour, offering a glimpse into the craftsmanship and precision that underpin the scientific endeavours. Through these schematics and actual photographs, the elegance of our assembly process is vividly illustrated, providing a clear window into the research apparatus's construction.

3. Design Considerations

a) **Frequency Range:** Muffler designs consider the specific frequency range of the noise they need to attenuate. Different designs are more effective at reducing certain frequency ranges.

b) **Flow Resistance:** Mufflers must balance noise reduction with maintaining acceptable fluid flow rates. Too much resistance can impact the system's efficiency.

c) **Pressure Drop:** Mufflers can create pressure drops in the fluid flow, affecting system performance. Engineers aim to minimize these pressure drops while maximizing noise reduction.

d) **Material Selection:** The choice of materials, including the type of sound-absorbing material used, is crucial for effective noise control and muffler durability.

3.1 Finite Element Analysis for designing and Analysis of acoustic muffler

FEA acoustic muffler design and analysis software is a specialized type of FEA software that is used to design and optimize mufflers and other noise reduction devices. Acoustic mufflers are designed to reduce noise levels by attenuating sound waves, and FEA software can help designers simulate the behaviour of the muffler and optimize its design for maximum noise reduction. Below is a complete description of FEA acoustic muffler design and analysis software.

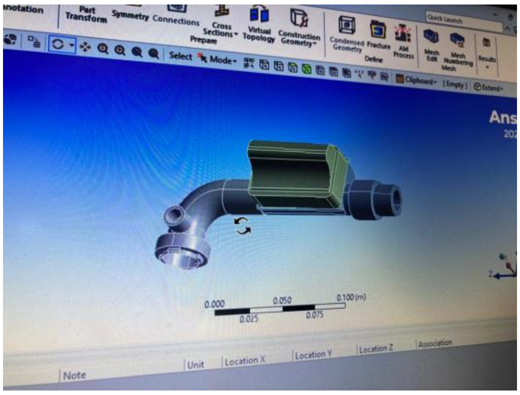

Fig 8: 3D Assembly of designed muffler

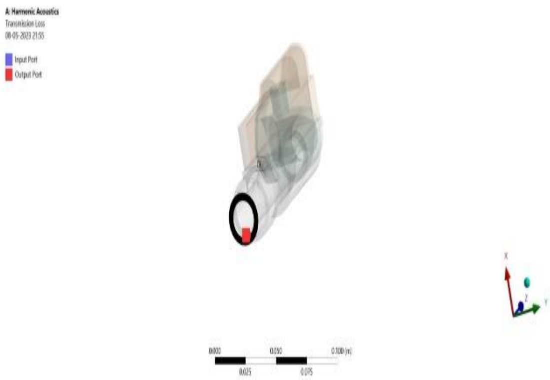

Fig 9: Harmonic acoustics in ANSYS loading

3.2 Harmonic Acoustics Analysis

FEA acoustic muffler Design and analysis using harmonic acoustics in ANSYS involves the simulation of sound waves generated by the flow of gas or air through an acoustic muffler. This approach involves solving the governing equations of sound propagation that take into account sound wave frequencies and the way they interact with the muffler's geometry and materials.

3.3 Analytical Investigation

1. Import the muffler's CAD model into ANSYS, either directly from CAD software or by drawing it in ANSYS using geometry tools.
2. Generate a mesh to discretize the geometry into elements, choosing a mesh generation algorithm based on accuracy requirements.
3. Create a harmonic acoustics analysis setup, specifying flow conditions, acoustic material properties, and the frequency range of interest.
4. Solve the harmonic acoustics equations using ANSYS's solver to visualize the muffler's acoustic behaviour for specified frequencies.
5. Analyze simulation results using ANSYS's post-processing tools, such as visualization and plotting to assess muffler effectiveness in reducing noise.
6. To optimize the muffler design, iterate through multiple simulation runs by modifying the model and repeating the analysis process until achieving the optimal design.

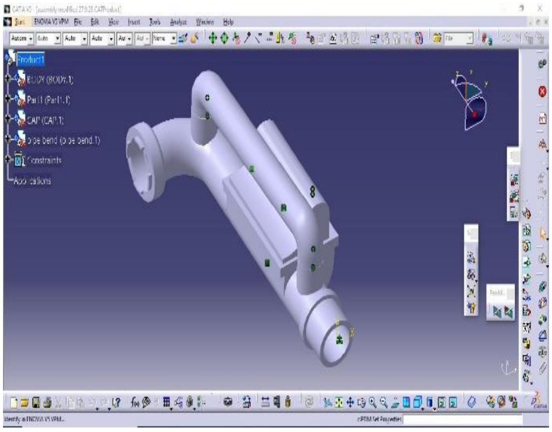

Fig 10: 3D Cad Model designed using CATIA

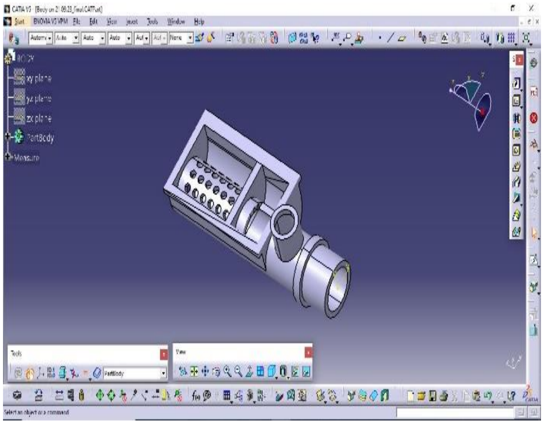

Fig 11: Second component of Muffler

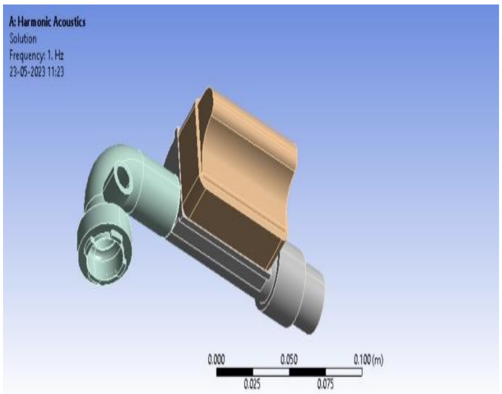

Fig 12: CAD model imported to ANSYS

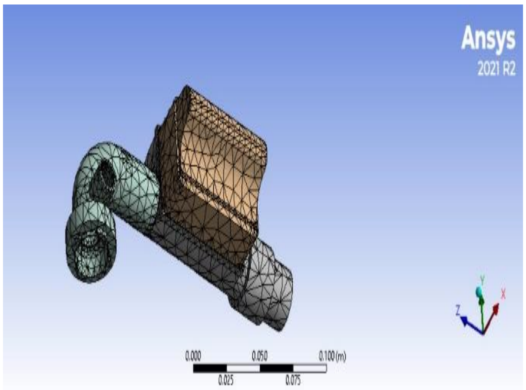

Fig 13: Meshed model

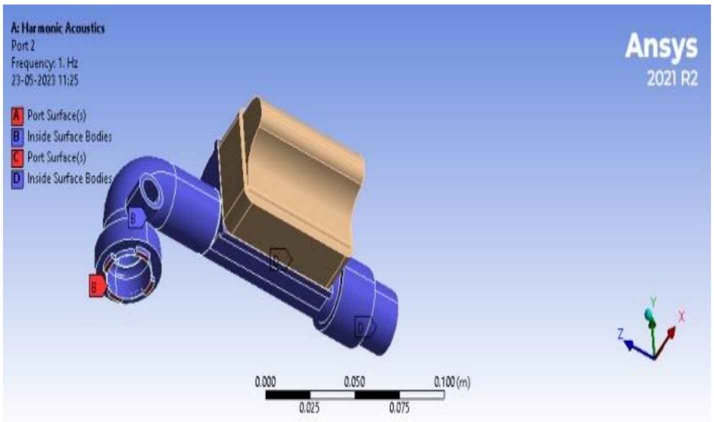

Fig 14: Selection of faces in HA

Acoustic mufflers are designed and used to reduce the noise generated by engines and other machinery. The optimization of acoustic mufflers involves the use of different techniques to design mufflers that are more efficient in attenuating noise.

3.4 Optimization Methodology

After an exhaustive brainstorming, a carefully curate set of parameters emerged as pivotal influencers in determining the unique characteristics of attenuation and pressure drop within the muffler. These selected parameters, chosen with utmost deliberation, serve as the compass guiding our journey into the intricate realm of acoustic muffler design and performance optimization.

a) Diameter of inlet and outlet tubes.

b) Insertion length of the inlet tube.

c) Number of holes on the outlet tube.

d) Outlet tube hole diameter.

This research meticulously structured an orthogonal array encompassing the pertinent parameters, a visual representation of which can be found in table 1. With precision and diligence, each individual trial was meticulously scrutinized, yielding a comprehensive Transmission Loss (TL) curve for analysis.

These TL curves were subject to thorough examination, scrutinizing them against the specific criteria established for the study. The discerning eye was immediately drawn to the remarkable performance exhibited by Trial 8, as vividly depicted in table 1. Its TL curve stood out as the most promising among the contenders.

To delve deeper into the intricacies of Trial 8's combination, an ANOVA table, was generated shedding light on its statistical significance and effectiveness.

4. Results & Discussions

The transmission losses (TL) associated with harmonic acoustic waves is propagating through a suction muffler. TL represents the reduction in sound level as sound waves pass through a medium, and harmonic acoustics specifically deals with harmonic frequencies (i.e., sinusoidal vibrations) in the analysis.

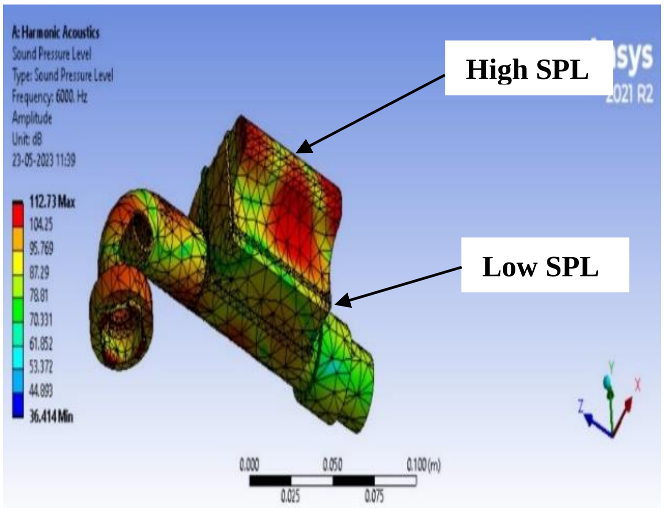

Fig 15: Sound Pressure loss air as medium

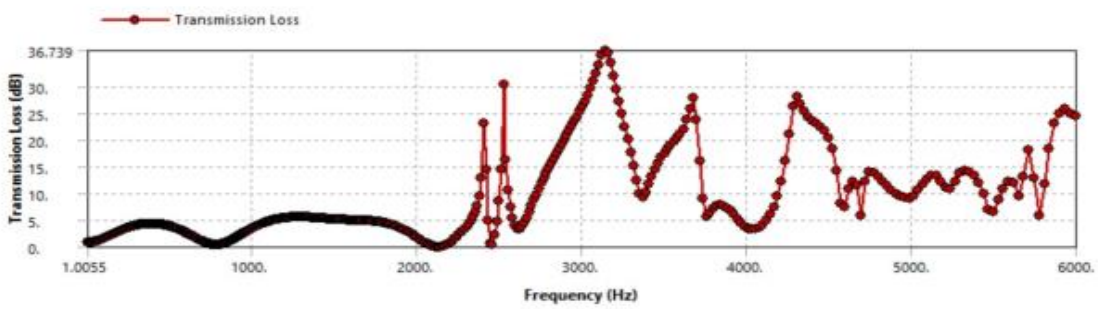

Fig 16: Transmission Loss vs. Frequency Air as medium

Transmission loss (TL) for a muffler is a crucial parameter used to evaluate its acoustic performance. TL measures the reduction in sound level as sound waves pass through the muffler, indicating how effective the muffler is at attenuating noise. TL is typically calculated by comparing the sound pressure level (SPL) at the inlet (before the muffler) to the SPL at the outlet (after the muffler) across a range of frequencies.

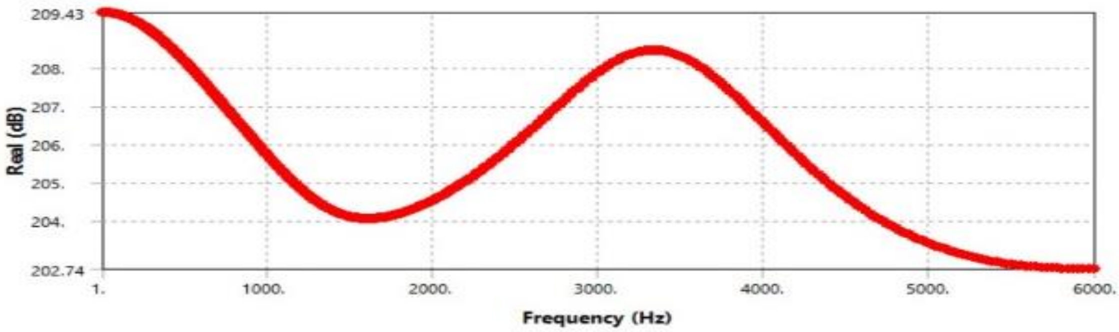

Fig 17: SPL vs. Frequency Refrigerant as medium

High value of TL results in lower SPL, it means muffler effectively reduces the noise generated by exhaust. For Effective performance of muffler, High value of TL and Low value of pressure drop are important parameters to be considering while designing the muffler.

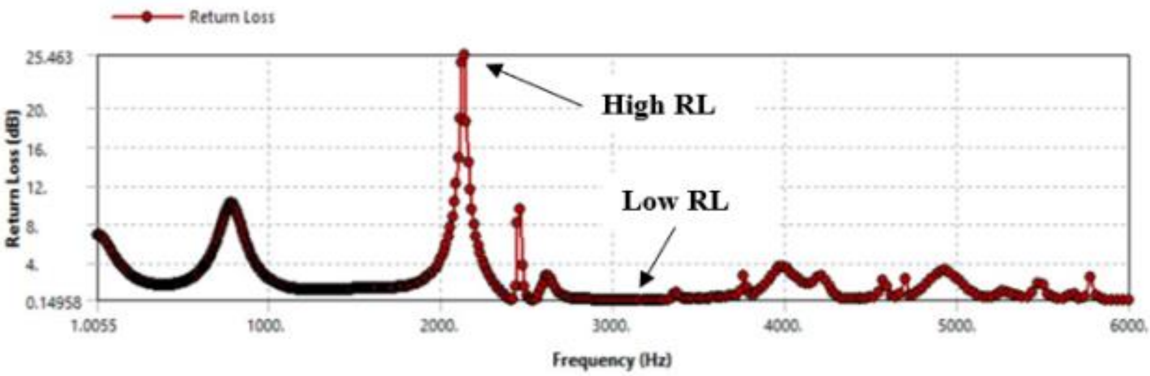

Fig 18: Return loss air as medium

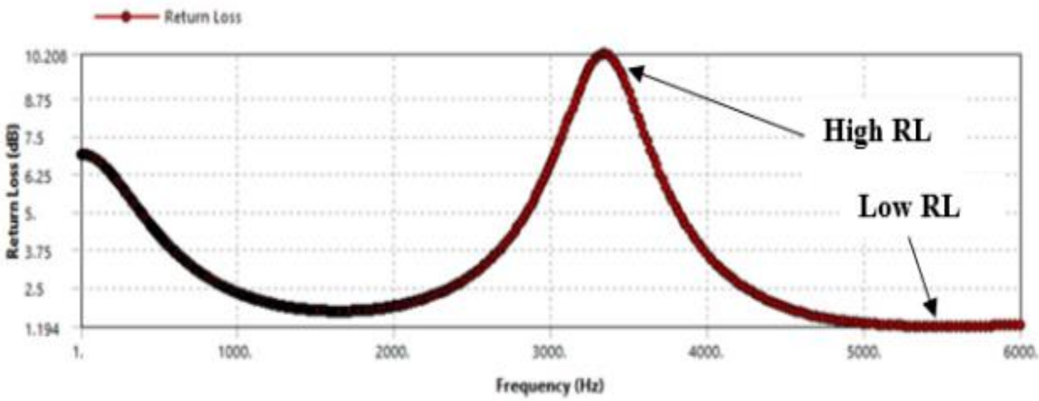

Fig 19: Return loss refrigerant as medium

Return Loss (RL) and Transmission Loss (TL) are both important metrics in muffler design and acoustic analysis, but they focus on different aspects. RL deals with reflections and sound energy not effectively transmitted, while TL evaluates the overall noise reduction achieved by the muffler. Both metrics are valuable for understanding and optimizing the acoustic performance of mufflers.

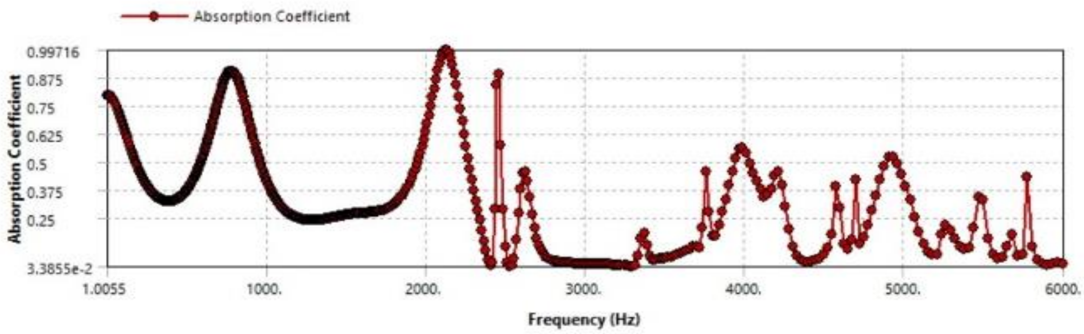

Fig 20: Absorption coefficient air as medium

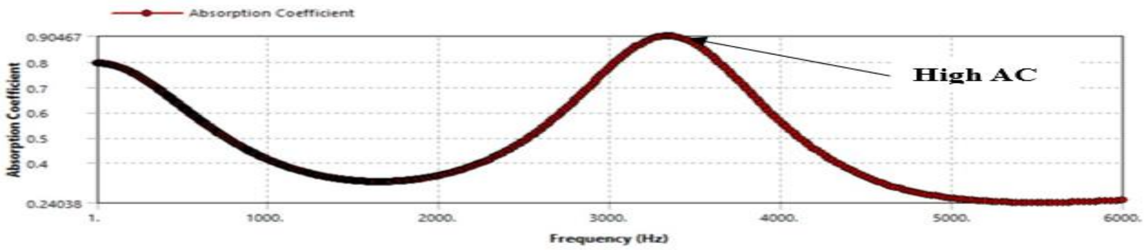

Fig 21: Absorption coefficient refrigerant as medium

The absorption coefficient relates to a material's ability to absorb sound energy, while TL evaluates the overall reduction in sound levels achieved by a muffler or acoustic device. While absorption can contribute to TL within a muffler, they are not directly interchangeable as TL considers multiple aspects of sound transmission and reflection.

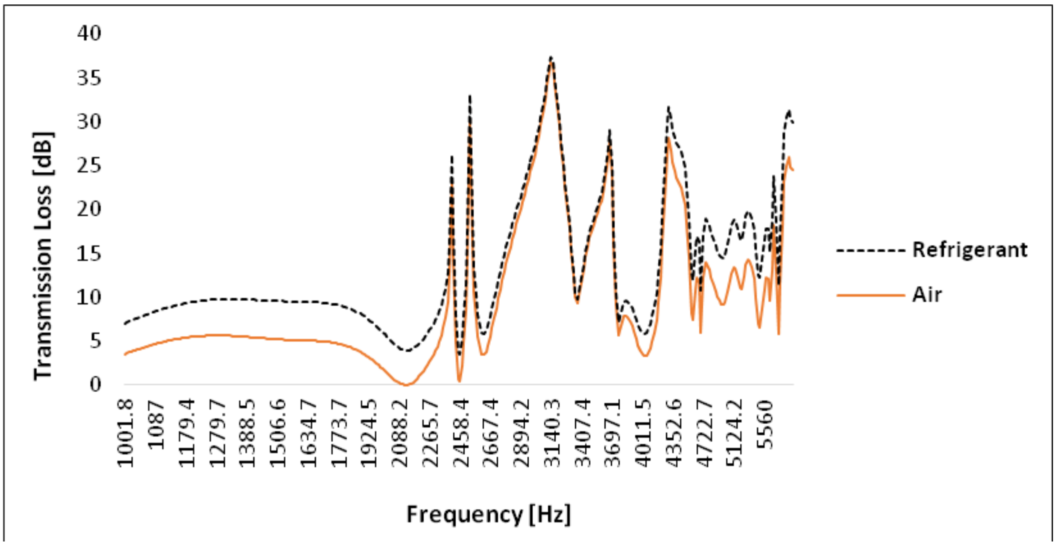

Fig 22: Comparison between refrigerant and air

Air having less TL compared to refrigerant is due to the effect of air density. Air's lower density can result in a lower TL at certain frequencies. This can impact the muffler's performance in attenuating sound. Speed of sound of air can affect wavelength of sound waves at different frequencies, while designing muffler at different wavelength characteristics which can be considered. High refrigerant density compared to air results in high TL.

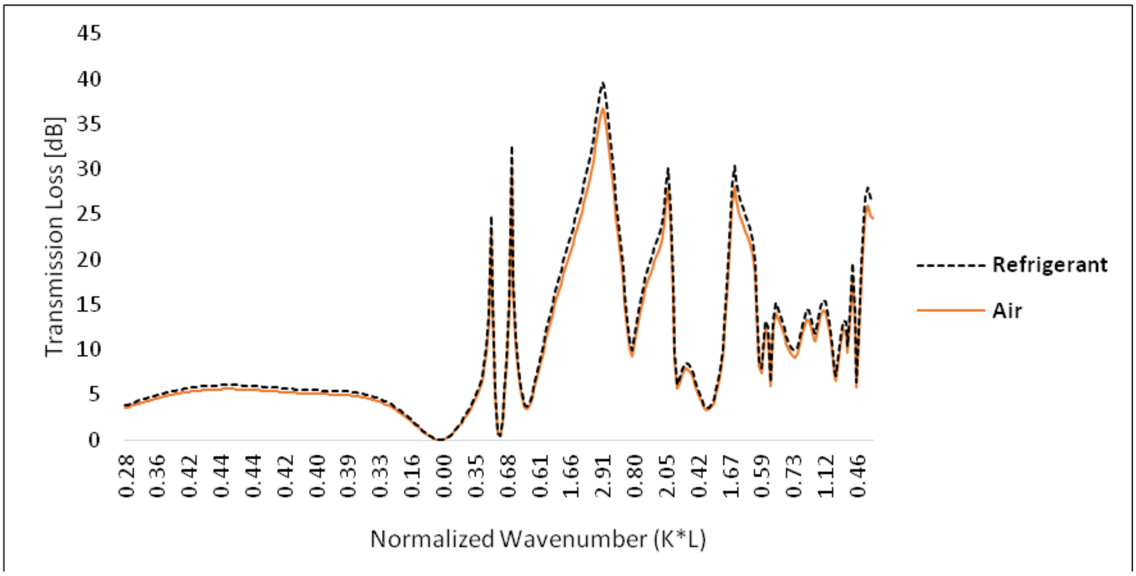

Fig 23: Normalized wave number (k*L)

Normalized wave number is one of the important aspects of muffler analysis and optimization for desired acoustics performance. It helps assess how different frequencies of sound waves interact with the muffler's dimensions and is valuable for muffler design and optimization.

Table 1: Optimized Results of the Experimental work

Inlet dia. (mm)	**Outlet dia.(mm)**	**Length of muffler (mm)**	**Material**	**TL dB (Transmission losses)**	**Frequency (HZ)**
19	25	73	ABS	34	2845
19	27	75	PPE	34.4	2856
19	28	76	PLA	35.3	2890
21	25	75	PLA	36.8	2915
21	27	76	ABS	37.2	2942
21	28	73	PPE	38.3	2958
22	25	76	PPE	39.4	2982
22	27	73	PLA	39.8	3100
22	28	75	ABS	41.2	3150

The optimization results for the given muffler configurations demonstrate the variation in transmission losses (TL) under different design parameters. The TL values also vary with frequency, as shown in the table. It's important to note that frequency is a crucial factor in muffler performance, and optimizing for specific frequency ranges may be necessary in practical applications.

In summary, the optimization results highlight the interplay between inlet and outlet diameter, muffler length, and material choice in achieving desired transmission losses for noise reduction.

Increasing the inlet diameter results in higher TL values, indicating better noise reduction. Conversely, increasing the outlet diameter tends to reduce TL values. Longer mufflers tend to exhibit an higher TL value, which is expected as they provide more space for sound attenuation. However, this trend is not always consistent, as some shorter mufflers also demonstrate good noise reduction. The choice of material influences

TL to some extent, but it is not the primary determinant of muffler performance. Other factors like dimensions and design play a more significant role.

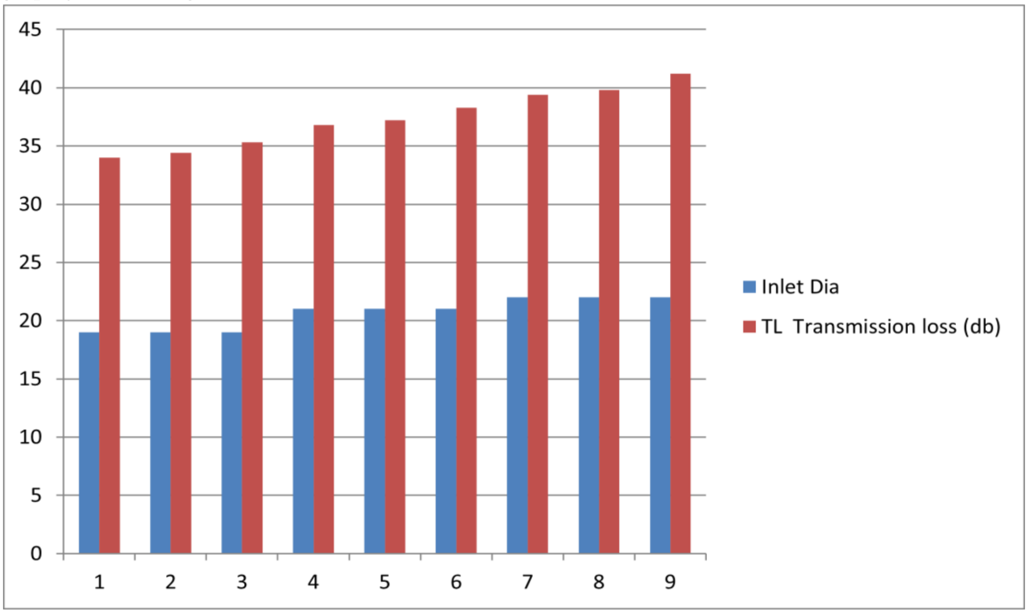

Fig 24: Inlet dia. Vs Transmission Loss

At this frequency of 2845 Hz, the muffler exhibits a TL of 34 dB. This value represents the reduction in sound transmission due to the muffler's design and specifications. As the frequency increases to 2856 Hz, the TL slightly improves to 34.4 dB. This suggests that the muffler becomes more effective at attenuating noise in this higher-frequency range.

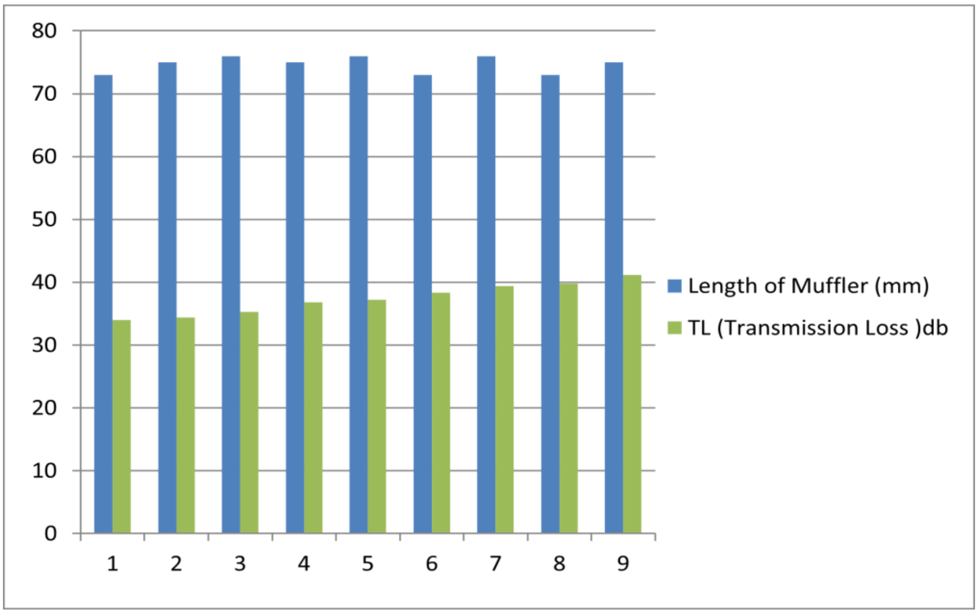

Fig 25: Length of muffler Vs Transmission Loss

The muffler's TL at 2958 Hz is 38.3 dB, showing further improvement in noise reduction as the frequency increases. With a frequency of 2982 Hz, the muffler achieves a TL of 39.4 dB, Its excellent performance is seen at the frequency 3150 Hz, as per the table 1, attenuating noise in this range. At 3100 Hz, the TL remains high at 39.8 dB, showcasing the muffler's consistent noise reduction capabilities. The highest associated with a TL of 41.2 dB.

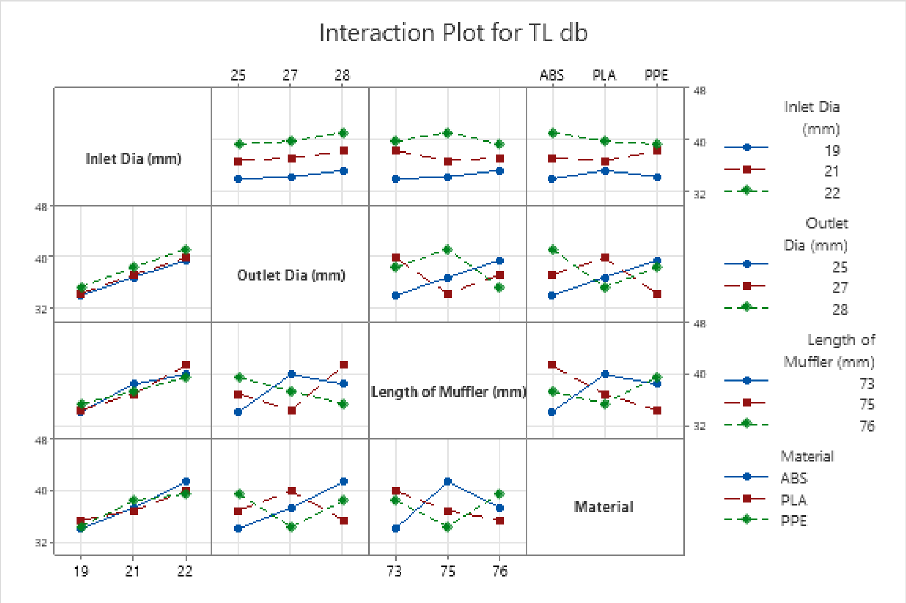

Fig 26: Interaction Plot for TL (dB)

As it is seen, there is a significant interaction effect between Inlet Diameter and Material. For Inlet Diameter 19, ABS results in the lowest TL dB, while PPE leads to the highest TL db. Conversely, for Inlet Diameter 22, PPE results in the lowest TL dB, while PLA leads to the highest TL db. Inlet Diameter 21 shows a mixed pattern; with ABS and PPE having similar TL dB values. There is a noticeable interaction effect between Outlet Diameter and Length of Muffler. For outlet diameter 25, the TL dB tends to decrease as the Length of Muffler increases.

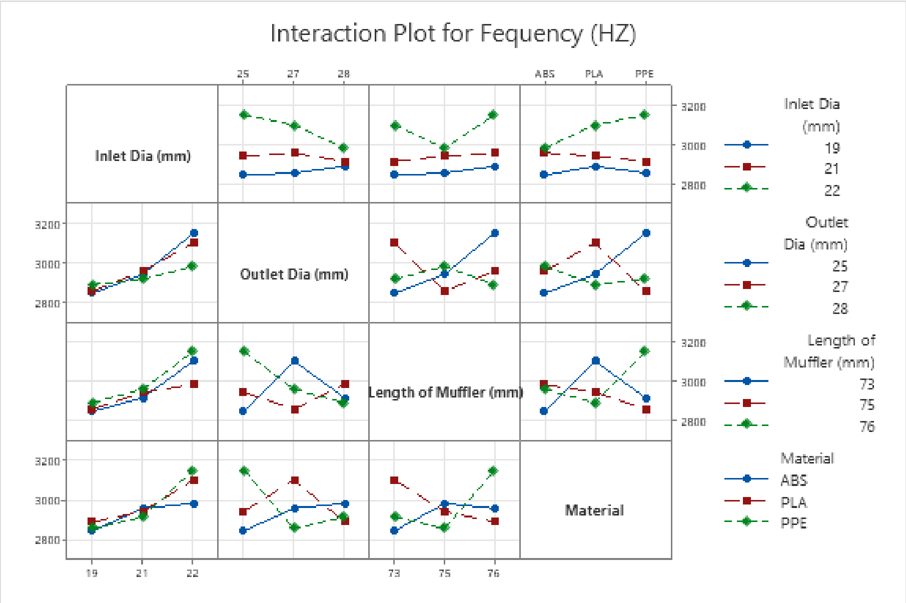

Fig 27: Interaction Plot for Frequency (Hz)

There appears to be a noticeable interaction effect between Inlet Diameter and Material on the frequency. For Inlet Diameter 19, ABS results in the lowest frequency, while PPE leads to the highest frequency. Conversely, for Inlet Diameter 22, PPE results in the lowest frequency, while PLA leads to the highest frequency. Inlet Diameter 21 shows a mixed pattern; with ABS and PPE having similar frequency values. There is a subtle interaction effect between Outlet Diameter and Length of Muffler.

In summary, this interaction plot demonstrates that the frequency (Hz) of the muffler system is influenced by both individual factors and their interactions. Understanding these interactions is essential for designing muffler systems that meet specific frequency requirements. The choice of Inlet Diameter should be considered alongside the Material selection to achieve the desired frequency response. Additionally, Outlet Diameter and Length of Muffler also play roles in shaping the system's frequency, with interactions that require careful consideration during the design process.

5. Conclusions

In conclusion, the data presented here highlights the complex relationship between muffler design and acoustic performance. Increasing the inlet diameter generally leads to better noise reduction, while increasing the outlet diameter tends to have the opposite effect. Muffler length plays a significant role, with longer mufflers generally exhibiting higher transmission loss (TL) values, though exceptions exist. Material choice has some influence, but dimensions and design remain pivotal factors.

The frequency of sound is a critical consideration, as TL values vary with frequency, indicating that mufflers perform differently across various frequency ranges. This information underscores the importance of selecting the right combination of parameters to achieve desired noise reduction outcomes. Engineers and researchers can use this data as a valuable reference, aiding them in making informed decisions for muffler design and acoustic engineering projects. Ultimately, understanding how mufflers perform at different frequencies is essential for creating effective noise reduction systems tailored to specific needs.

In conclusion, Transmission Loss (TL) is a fundamental and critical parameter in the design and evaluation of mufflers and other noise control devices. TL quantifies the reduction in sound level as sound waves pass through the muffler, and it serves as a key indicator of the muffler's acoustic performance. Here are some key points to summarize the significance of TL for mufflers:

1. **Noise Reduction Assessment**: From the observation of TL results, TL is high for refrigerant mainly due to the effect of acoustic property of the medium selected. From the literature survey for higher the value of TL gives higher the impact on the effective performance of muffler.
2. **Sound Pressure Levels vs. Transmission Loss** were affectively investigated, and observed that the TL values changing at different frequencies.
3. **Geometry and shape:** it is also investigated that geometry of the muffler influences the TL values, which increases the performance of considered muffler.
4. **Design Optimization:** Return Loss (RL) and Absorption Coefficient (AC) also influence the Higher TL values in terms of noise reduction and control.
5. Finally refrigerant gives better results compared to air.

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