Acoustic and Energy Efficiency Analysis of Alternative Geometries of Plastic Suction Muffler

Merve Baykal and Nuri Onur Çatak

Abstract The suction muffler in a reciprocating compressor is used to attenuate sound pressure generated by vibrational noise, piston/valve movements and flowing noise. While the suction muffler directs the gas flow to the valve for compression, it also takes a critical role in damping the sound waves caused by the movement of the valve. The suction muffler in a reciprocating compressor is a reactive type silencer, therefore it absorbs the sound wave by reflecting it with geometries such as expansion chambers. However, the suction muffler adversely affects the compressor performance since it creates additional pressure drop to the system. Due to strong interdependency of components and parameters, Coefficient of Performance (COP) and noise trade-off are difficult to perform especially considering the geometric design constraints. For this reason, the most critical design objectives for hermetic reciprocating compressors are high energy efficiency and quiet operating conditions. In this study, the tesla valve, which prevents the reflow of the refrigerant gas into the suction muffler from the suction valve, is modified for the reciprocating compressor muffler to improve COP. The new designs will be optimized by considering computational fluid dynamics analysis and acoustic transmission loss analysis. The numerical results will be experimentally validated in semi-anechoic room and calorimetry test is performed with the most optimal cases. Additionally, it is expected that the tesla valve design provides energy efficiency with acoustic gain especially in 630–800 Hz band.

Keywords Muffler · Transmission loss · Hermetic reciprocating compressors · Tesla valve · Suction muffler · Compressor performance

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1 Introduction

A hermetic reciprocating compressor is a type of compression system that is commonly used in refrigeration and air conditioning applications. The compressor operates by using a piston to compress refrigerant gas and pump it through the system. The compressed gas then flows to the condenser where it releases heat and condenses into a high-pressure, high-temperature liquid that is then returned to the compressor to start the cycle over again. This process of compression and expansion is what moves heat and provides cooling in the system.

Hermetic reciprocating compressors can generate noise from several sources during operation. Some of the common sources of noise in hermetic reciprocating compressors are; piston and cylinder movement, the movement of the piston inside the cylinder generates mechanical noise as it compresses and expands the refrigerant. Valve operation, the opening and closing of the suction and discharge valves can also create noise as the refrigerant gas is admitted into and expelled from the cylinder. Refrigerant flow, the flow of refrigerant through the compressor and the discharge line can create noise as it passes through any restriction or changes in direction. Motor operation, the electric motor driving the compressor can also produce noise as it rotates the crankshaft and connecting rods. Vibration, all of the components in the compressor are subject to vibration. Reducing the noise generated by a hermetic reciprocating compressor can be achieved through proper maintenance, installation, and design techniques and isolating the compressor from the surrounding environment [1].

A compressor muffler is a type of muffler that uses a compressor to reduce the noise produced by a compressor exhaust system. The term "aeroacoustics" refers to the study of the generation, propagation, and perception of sound in air and other gaseous media. In the one of the aspects of a compressor muffler, aeroacoustics refers to the study of the noise produced by the compressor exhaust system and how it can be reduced by the compressor muffler.

Mufflers are utilized in various systems to control noise, such as in internal combustion engines, ventilation ducts, and turbo machinery. They can be active or passive, with absorptive silencers being a type of passive silencer that converts acoustic energy into heat energy through sound-absorbing materials. These silencers offer adjustable damping frequencies but may have limitations in low-frequency regions. In the context of hermetic reciprocating compressors, intake silencers fall into the category of reflective/reactive silencers, which rely on sound wave reflection and damping within specific structures [2]. The suction muffler in reciprocating compressors plays a crucial role in two key areas: ensuring efficient transfer of cold gas from the evaporator tube to the intake valve and minimizing noise generated by valve movement. It achieves these objectives through the integration of Helmholtz resonators, which effectively dampen sound waves and promote a quieter operating environment [3]. Additionally, the design of the silencer entrance and the optimization of the intake pipe geometry enhance refrigerant flow, improving flow rates and the compressor's coefficient of performance (COP). The inclusion of strategically placed

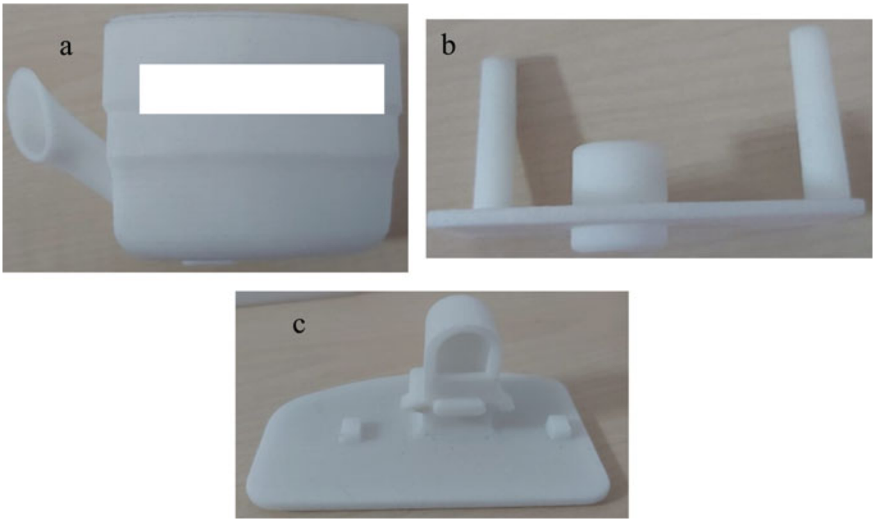

Fig. 1 Example of an plastic suction muffler; volume (**a**), tube (**b**) and connection part with valve (**c**)

oil drain holes prevents lubricating oil from contaminating the silencer, ensuring the compressor's integrity (Fig. 1).

Aeroacoustics plays a critical role in the design and optimization of compressor mufflers. By understanding the underlying physics of the noise generation and propagation in the compressor exhaust system, engineers can design mufflers that are effective at reducing noise while still allowing for maximum flow and system performance. This includes optimizing the design of the compressor to achieve the desired sound transmission loss and compressor performance. Overall, the field of aeroacoustics plays a crucial role in the design and optimization of compressor mufflers and other noise control systems.

Moreover, sound transmission loss is a measure of the reduction in sound energy that occurs when sound travels through the system. It is defined as the ratio of the sound pressure level on one side of the material or system to the sound pressure level on the other side, expressed in decibels (dB). Sound transmission loss is an important characteristic in a variety of applications, including building acoustics, automotive mufflers, and industrial noise control. In mufflers, the sound transmission loss is a measure of the effectiveness of the muffler in reducing the noise produced by the compressor exhaust system. The higher the sound transmission loss, the more effective the muffler is at reducing noise. Sound transmission loss is determined by a combination of factors, including the thickness, density, and mechanical properties of the material, the frequency of the sound, and the geometry and design of the system [4]. In general, reactive mufflers which is used in reciprocating compressor, are known to have good transmission loss compared to other types of mufflers. This is because they use reactive elements, such as Helmholtz resonators, piping, chambers to absorb and cancel out specific frequencies of noise in the exhaust system. The combination of these reactive elements and the muffler's geometry and materials can result in high transmission loss and effectively reduce the noise produced by the compressor exhaust. Overall, the transmission loss of a reactive muffler depends on the specific design as well as the operating conditions of the compressor. High-quality reactive mufflers are capable of achieving high transmission loss, reducing exhaust noise and improving the overall performance of the compressor exhaust system.

The Tesla valve, invented by Nicola Tesla in 1920, is a valve with no moving parts. Because of its geometry, the valve only allows one direction of flow. The Tesla valve is based on the Coanda effect, which describes the movement of air by following the slopes of a surface and returning to it if another surface is nearby. When reverse flow is applied to the Tesla valve, high pressure drops occur [5]. There have been studies published in the literature on optimizing the performance of the Tesla valve with structural parameters such as hydraulic diameter and valve angle when subjected to reverse flow. High inlet velocities, low hydraulic diameter and internal radius values, and large valve angles all contribute to high pressure drops. However, at low inlet velocities, changes in the discussed parameters have little effect on the pressure difference. When the valve angle is less than 60°, the pressure difference increases linearly, but when the valve angle is greater than 60°, the pressure difference decreases [6].

2 Methodology

2.1 Design Parameters

As previously stated, tesla valve design parameters such as diameters and degrees of tubes are limited due to muffler geometry. All tubes (main and side) in the first two design models have a diameter of 7 mm, with different degrees for side channels. The slope of the side tubes is the first design parameter. After that, symmetric and asymmetric side tubes are investigated (Table 1).

Table 1 Design parameters

Parameters	Model 1	Model 2	Model 3
Side tube diameter (mm)	7	5	5
Main tube diameter (mm)	7	7	7
Side tube symmetry	Asym	Asym	Sym
Side tube angle (°)	60	45	45

Table 2 Properties and boundary conditions for CFD analysis

Model	SST-kw	
Properties	Cooler gas	R600
	Density	Ideal gas
	Heat conduction coefficient W/m K	0.02249
	Cp (J/kgK)	1911
	Viscosity	8.72 e − 6
	Mesh size (m)	0.0001
	Element number (million)	9
	Skewness	< 0.5
	Molecular weight (kg/kg mol)	58.12
Boundary conditions	Mass flow rate (kg/s)	0.0006

2.2 Numerical Analysis of the Muffler

2.2.1 CFD Analysis of Muffler

The Ansys Fluent module was used for computational fluid dynamics analysis. To begin, a 0.0001-m quadratic mesh was created using 9 million elements. Fluent analysis was performed after a suitable mesh was created using the K-w turbulence model [7]. The results are shown below. Analysis temperatures set as 50 and 70 °C for inlet and outlet of the valve. Other assumptions can be seen in the Table 2.

2.2.2 Transmission Loss Analysis of the Muffler

The acoustical simulation model is developed model by PLM Simcenter 3D based finite element method (FEM). The geometry of the models was constructed in three dimensions in the CAD application environment using NX Nastran and then muffler cavity and meshing into small element as illustrated in Fig. 2a, b. In this simulation, the gas is assumed at 55 °C so the sound speed is 222 m/s and the mass density is 1.31 kg/m^{-3}. The acoustic mesh creation is done as minimum six elements per wavelength. Since the analysis is solved up to 10 kHz, the mesh size is set as 5.67 mm. Two boundary conditions are applied at the inlet and outlet of the muffler. The noise source was modelled as the acoustic pressure with 1 Pa at the inlet of the muffler as shown in Fig. 2c. The anechoic termination condition at the outlet tube of model can be achieved by acoustic match layer which prevents reflection. The microphone is placed at the inlet and outlet of the muffler. The sound pressure levels at the inlet and outlet of the model were measured at specific microphone points in order to calculate the transmission loss (TL) (Fig. 3).

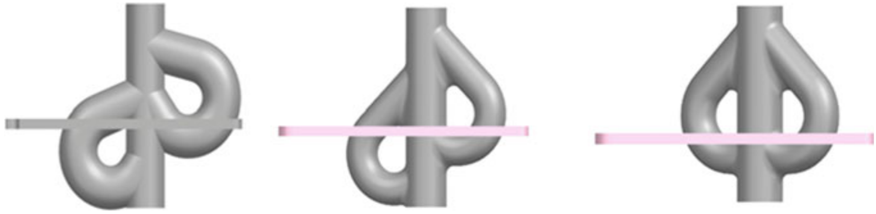

Fig. 2 Suction muffler design

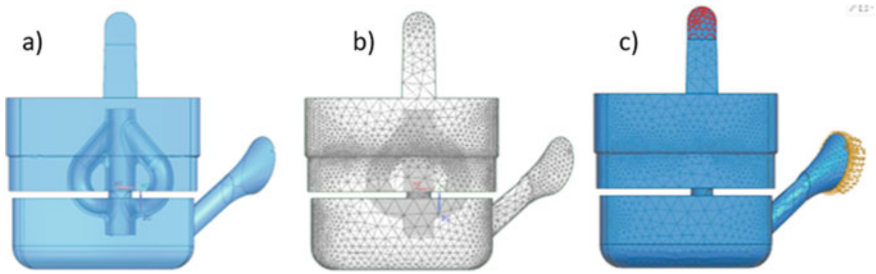

Fig. 3 Muffler cavity (**a**), acoustic mesh (**b**), boundary conditions (**c**)

$$Sound\ Pressure\ Level,\ L_p = 10 * \log \frac{p^2}{p_0^2}\ \mathrm{dB}$$

2.2.3 Test Methodology

The initial model proposed in this study was manufactured using the Selective Laser Sintering (SLS) method through 3D printing technology. Subsequently, an assembled compressor incorporating this prototype was subjected to rigorous testing. Prior to testing within the semi-reflective sound chamber, the compressor underwent operational conditions conforming to the guidelines set by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). These conditions included maintaining a condensation temperature of 54.4 °C and an evaporation temperature of − 23.3 °C, while the compressor operated at an inlet pressure of 0.624 bar and an outlet pressure of 7.61 bar until it reached thermal equilibrium. The sound produced by the compressor was then recorded within the test environment using ten strategically positioned microphones in accordance with the ISO 3745 standard. The collected sound data was analyzed using the B&K Pulse Analyzer, generating frequency-A-weighted sound power level (dBA) graphs and total sound power level outputs in the 1/3 octave band, which varied depending on the compressor's operating cycles. Furthermore, Calorimeter tests were conducted

(a) *Semi-Anechoic Room* (b) *Calorimeter Test Setup*

Fig. 4 **a** Semi-anechoic room, **b** calorimeter test setup

to assess the hermetic reciprocating compressor's cooling capacity, power consumption, and engine performance under varied operating conditions. These tests provided valuable insights into the compressor's characteristics and performance.

3 Results

3.1 CFD Results

The results obtained from the Fluent analysis indicate that the flow through the side tubes is not as prominent as through the main tube in the primary flow direction for all the models. However, a clear relationship is observed between the turbulence intensity and the slope of the side tubes. The findings demonstrate that reducing the slope of the side tubes can effectively decrease turbulence inside the tube openings (Fig. 4). Additionally, the upper opening of the side tube has an impact on the COP gain and should be wider and inclined (Fig. 5).

3.2 Transmission Loss Analysis Results

Figure 4 illustrates the transmission loss analysis, which reveals that all Tesla valve models exhibit superior transmission loss compared to the original model. Furthermore, different geometries of the Tesla valve provide better transmission loss performance in various frequency ranges. For instance, Model 3, an asymmetric design, demonstrates the best transmission loss performance between 4000 and 5000 Hz, whereas Model 1 exhibits optimal attenuation performance at low-frequency bands.

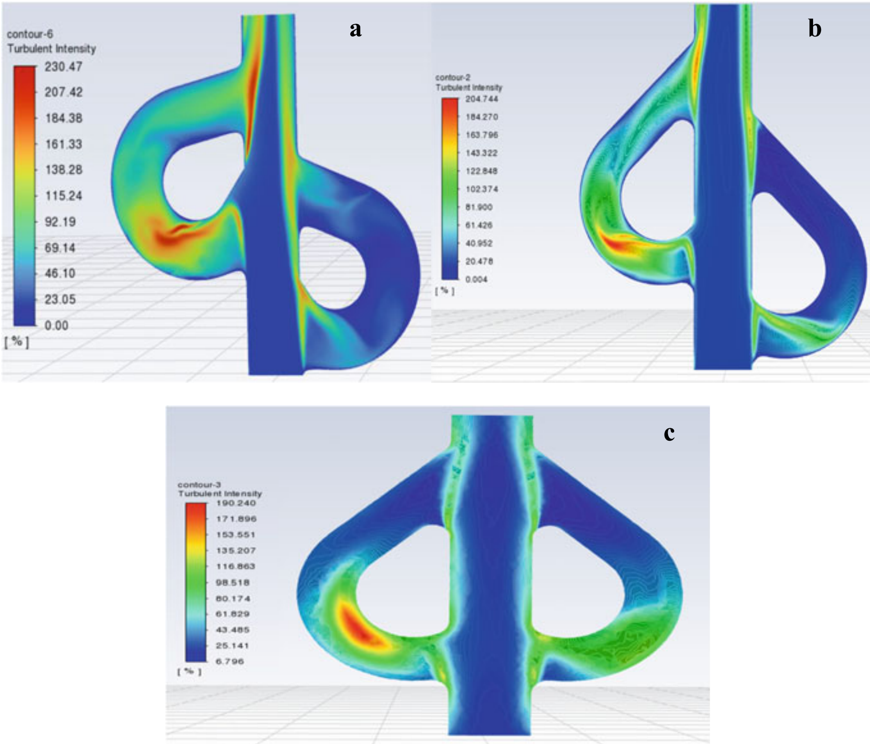

Fig. 5 CFD results **a** model 1, **b** model 2, **c** model 3

In summary, in terms of acoustic performance, all proposed models surpass the original model, and each model can be tailored to excel in specific frequency bands. When comparing the transmission losses calculated using Simcenter 3D for the original model and Model V3, it is evident that the damping value has nearly doubled, particularly between 1000 and 3000 Hz, and the damping frequency range has expanded. The study found that in this frequency range, the compressor's damping has increased both within the range of human hearing and its intense operational range (Figs. 6, 7 and 8).

3.3 Calorimeter and Semi-anechoic Test Results

Initially, the original compressor model was assembled and tested, followed by the replacement of the suction muffler with Model 1. The suction muffler noise was reduced by approximately 50% at 3000 RPM and within the 60–800 Hz range. Due to limitations in the manufacturing method, the prototype did not achieve maximum

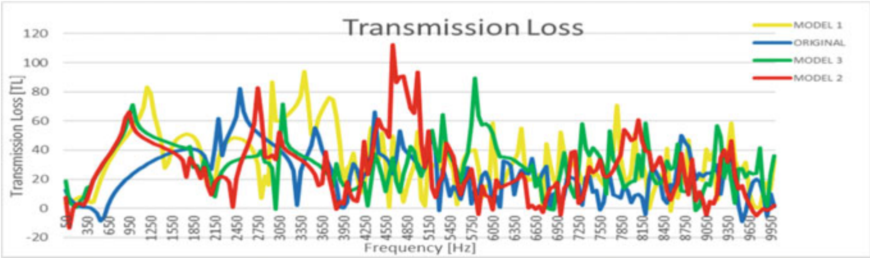

Fig. 6 Transmission loss results of the muffler designs

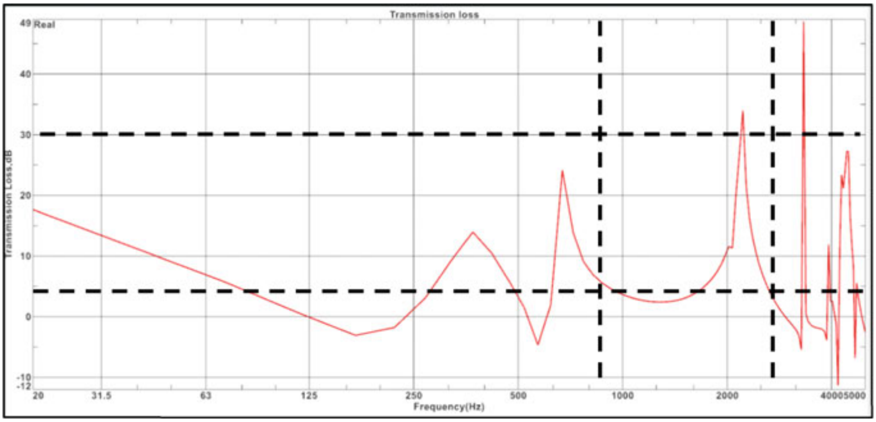

Fig. 7 Transmission loss results of the original muffler

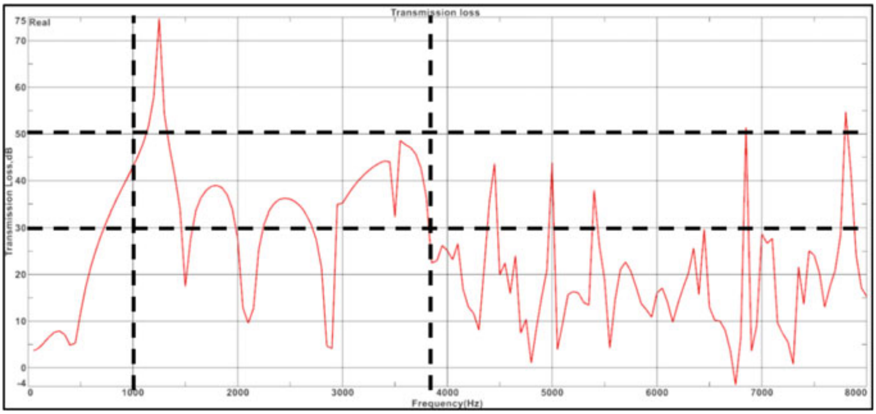

Fig. 8 Transmission loss results of the V3 muffler

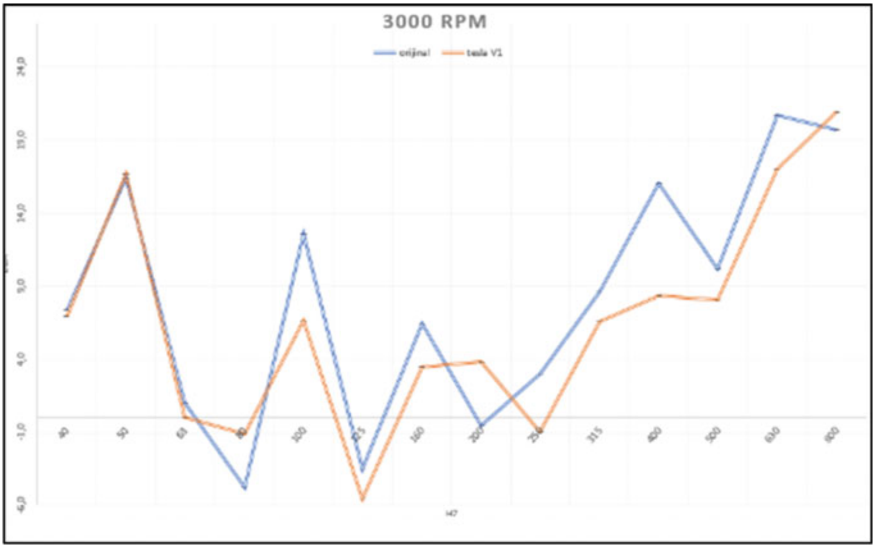

Fig. 9 Semi-anechoic room test results

Table 3 Test results of calorimeter setup

	Model	COP	Power [W]	Capacity
1300 RPM	Original	1.87	57.1	91.9
	The tesla valve	1.87	52	91,6
3000 RPM	Original	1.80	133	205.9
	The tesla valve	1.80	127.8	198.2
4000 RPM	Original	1.60	182.1	250.5
	The tesla valve	1.62	175	243.1

efficiency. The side tubes were not fully open and therefore could not function optimally. Despite this manufacturing issue, which stemmed from the capabilities of 3D printing and the size of the prototype, both the calorimeter setup and semi-anechoic test results showed improvement. The calorimeter setup tests indicated that the overall Coefficient of Performance (COP) values remained unchanged at any RPM, but power consumption decreased by approximately 9% at 1300 RPM while maintaining the same cooling capacity (Fig. 9; Table 3).

4 Conclusion

In this study, the adaptation of the Tesla valve to the reciprocating compressor muffler was investigated, considering computational fluid dynamics (CFD) results and transmission loss analysis. The CFD analysis revealed that the flow predominantly travels through the main tube rather than the side tubes, while the slope of the side tubes influences turbulence intensity. Reducing the slope of the side tubes was found to decrease turbulence within the tube openings, indicating an important design consideration. The transmission loss analysis demonstrated that all proposed Tesla valve models outperformed the original model in terms of acoustic performance. Different geometries of the Tesla valve showed superior transmission loss performance in specific frequency ranges, suggesting the potential for tailored designs optimized for various frequency bands. Calorimeter and semi-anechoic tests further validated the improvements achieved through the Tesla valve adaptation. The replacement of the suction muffler with Model 1 resulted in a significant reduction in noise, and the overall power consumption decreased while maintaining the same cooling capacity. However, it was noted that the manufacturing limitations of the prototype, attributed to 3D printing capabilities and size constraints, hindered its full efficiency.

Key findings highlighted the critical role of the side tube angle for achieving COP gain, with an optimal angle of 45°. Additionally, the wider and inclined upper openings of the side tubes were found to enhance performance. Model 2, an asymmetric and inclined design, showcased the best overall acoustic performance, while Model 1 excelled in attenuating lower frequency bands.

Future studies are recommended to explore variations in tube angle, symmetry, and valve rotations. Improvements in the opening of the side tubes should also be considered to further enhance COP results. Comprehensive testing in semi-anechoic rooms and calorimeter setups will provide additional insights into the acoustic and performance characteristics of the proposed Tesla valve designs.

Overall, this research contributes valuable insights into optimizing the acoustic performance of reciprocating compressor mufflers through the application of the Tesla valve. These findings offer potential for enhanced noise reduction and improved efficiency in compressor systems, paving the way for further advancements in the field.

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