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Muffler Design for a Refrigerator Compressor

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ABSTRACT

During its operation, a refrigerator compressor produces pulsating noise, primarily driven by the suction and discharge processes. Sound attenuating mufflers need to be designed without any additional pressure drop on both suction and discharge side. Higher pressure drop at the suction and discharge side will lead to lower charging and discharging of the compressor and hence reduces cooling capacity. Since a one dimensional formulation with plane wave assumption to calculate transmission loss is not applicable for small mufflers (ratio of length to diameter is less than 1), a numerical methodology was established and validated using an impedance tube transmission loss measurement. Detailed three dimensional Computational Fluid Dynamics (CFD) simulations were used to further study the pressure drop across the mufflers for a given flow and compressor operating frequency. In the proposed methodology, acoustic pressure distribution inside the chamber is observed as a function of frequency and an optimal position of inlet and outlet pipes is decided to improve transmission loss. Different muffler design options were evaluated and also discussed possible acoustic performance and pressure drop improvements. Mufflers designed with this approach showed better acoustic performance on the suction and discharge side of refrigerator compressor. The effect of different working fluids on acoustic frequencies is also studied, which would additionally help in tuning the muffler to improve its effectiveness.

Keywords: compressor, muffler, pressure drop, noise, transmission loss

1. INTRODUCTION

Domestic refrigerator compressor manufactures are interested to develop quieter and efficient compressor designs. Compressors have different types of noise sources, excited by structural vibrations and flow disturbances. Quieter compressor design might be possible by proper understanding of noise sources and transmission paths. Generally, major noise sources in the compressor are associated with working mechanism, pressure pulsations, valve operations, discharge tube vibrations, suspension system, lubrication, and shell design. Noise generated due to pressure pulsations on suction and discharge side have been reduced using mufflers [1]. Muffler designers have to consider acoustic performance, pressure drop, envelope and optimum weight. Very often acoustical performance and pressure drop requirements are contradictory. So, good predictive models have to be considered for compressor muffler designs.
An extensive literature is available on compressor muffler analysis and design [2-4]. Most of the literature about one-dimensional transfer matrix approach to calculate muffler transmission loss (TL) is based on plane-wave assumption. Munjal [5] discussed about muffler analysis and design methods. The muffler acoustic performance can

be expressed in terms of insertion loss (IL) or transmission loss (TL). There are different prediction methods available to calculate muffler TL and these methods are broadly classified as plane-wave based transfer matrix methods [5], mode summation methods [6], Green's function based three-dimensional transfer matrix method [7,8] and numerical modes based on Finite Element Method (FEM) and Boundary Element Method (BEM) [9,10].

A systematic procedure to design efficient mufflers for hermetic compressors is discussed in this paper. The need for three dimensional modeling of acoustic waves and CFD simulation is explained. The procedure followed for numerical simulation is validated by experimental results obtained from impedance tube test. Simple expansion chamber muffler (SEC), extended-inlet/outlet-muffler (EIEO), face-inlet/side-outlet muffler (FISO), concentric tube resonators (CTR) have been considered for current study. Design improvements of extended inlet/outlet (EIEO) chamber mufflers with high transmission loss and low pressure drop are presented. For a case with small gap between the extended inlet and outlet pipe, a criteria is proposed so that the flow jet doesn't expand in the chamber thus maintain low pressure drop. A perforated bridge is suggested to minimize the pressure drop for a muffler with large gap between the inlet and outlet pipes. For a muffler designed with side outlet configuration, a tuning procedure considering the pressure distribution of critical acoustic modes is presented.

2. THEORY AND ANALYSIS

2.1 Analysis of Small Mufflers

Mufflers used in suction and discharge side of domestic compressors are reactive type and are small in size. To estimate transmission loss, plane wave assumption is not valid for these small mufflers. Short chamber effects are significant when the length to diameter ratio is low ($l/d \leq 1$). Hence, 1-D transfer matrix will not provide accurate results and it requires three dimensional analysis. Figure 1 shows the schematic diagram of extended inlet/extended outlet muffler. A comparison of transmission loss obtained for an EIEO muffler with analytical calculations based on transfer matrix approach and that with numerical simulations are presented in Figure 2. At frequencies beyond 1500Hz, 1-D transfer matrix method incorrectly predicts higher transmission loss compared to numerical simulations. Three dimensional modeling of acoustic waves performed using FEM acoustic module of commercial software which takes into account the spatial variation of acoustic field over the 3-D domain and hence provide results close to the realistic situation.

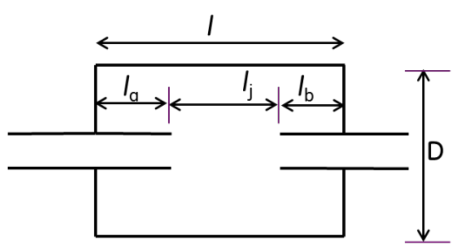


Figure 1: Schematic of extended inlet and extended outlet muffler (EIEO)

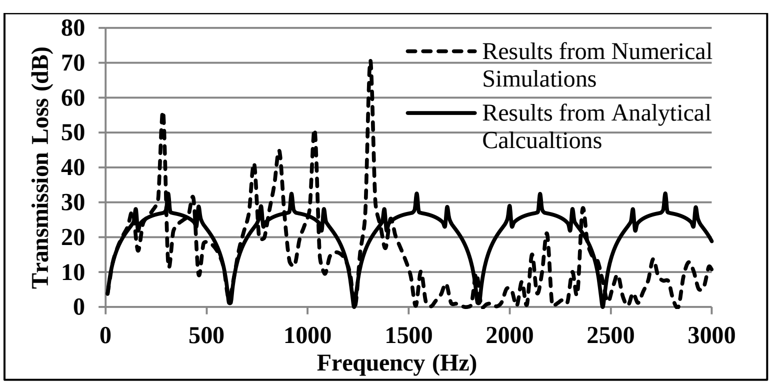


Figure 2: Comparison of analytical results with numerical simulation of an EIEO muffler

2.2 Validation of Numerical Simulation of Small Mufflers

Numerical simulations performed using commercial software is validated using an experimental setup. An impedance tube is used to measure transmission loss of a muffler consisting of two expansion chambers connected with a straight pipe. A schematic of muffler being tested is given in Figure 3. The results presented in the Figure 4 show a good match in frequency of peaks (maxima) and troughs (minima) between the numerical and experimental results. The troughs of transmission loss curve for numerical simulations reach zero value, but due to experimental limitations, the transmission of test results doesn't reach zero. As the peak values of transmission loss and frequencies of troughs of numerical simulations are close to that of experiments, it validates the procedure followed while performing 3D simulation in commercial software.

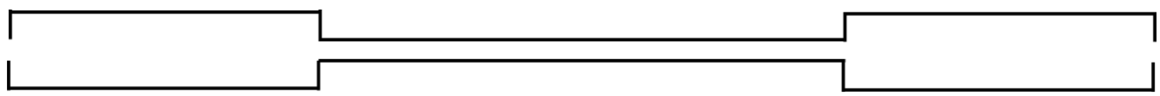


Figure 3: Schematic of two expansion chamber muffler used for numerical analysis validation

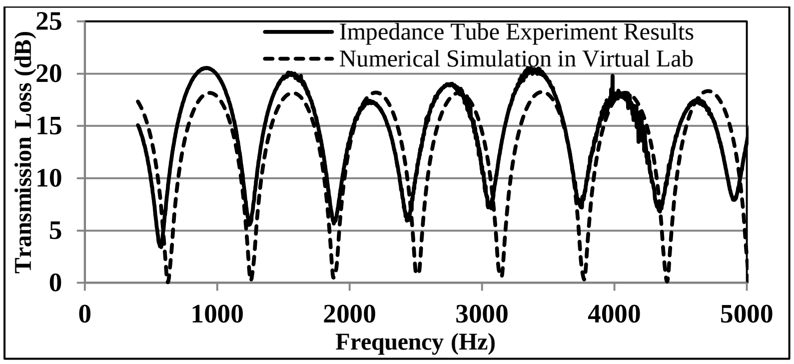


Figure 4: Comparison of numerical and experimental transmission loss curves

2.3 Extended–Inlet/ Extended-Outlet (EIEO) Muffler

Reactive type muffler works on the principle of impedance mismatch. The impedance mismatch along the length of the muffler can be obtained by several ways namely by changing the cross section of chamber, adding baffles, designing multiple chambers, introducing extended inlet/outlet pipe, creating multiple passes inside the muffler etc. Majority of these geometrical changes introduce additional back pressure. It is a contradictory design requirement. Extended inlet/outlet (EIEO) chamber muffler (Figure 1) can be designed for broader noise reduction compared to simple expansion chamber, but it needs few design modification to mitigate the additional pressure loss it introduces in the flow path [11]. The following sections give a methodology to analyze and design mufflers which satisfy acoustic and flow requirements of compressors.

One of the methods of reducing pressure drop of EIEO muffler is to connect the extended inlet and extended outlet by a perforated bridge which has higher porosity. For EIEO muffler with large gap between the extended inlet and extended outlet pipes, a perforated bridge as shown in Figure 5 will also reduce the pressure drop across the muffler. Another advantage of having this perforated bridge is increase in mechanical strength and durability of muffler. Numerical simulations were performed to evaluate the impact of perforated bridge in EIEO muffler.

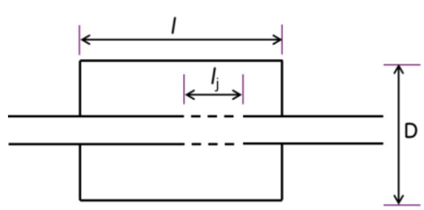


Figure 5: Schematic diagram of extended inlet and extended outlet muffler connected with perforated bridge

Numerical acoustic simulations are performed to estimate the transmission loss of EIEO muffler. Results presented in Figure 6 show troughs with low transmission loss for muffler without incorporating perforated bridge at frequencies 1500Hz and 3000Hz.

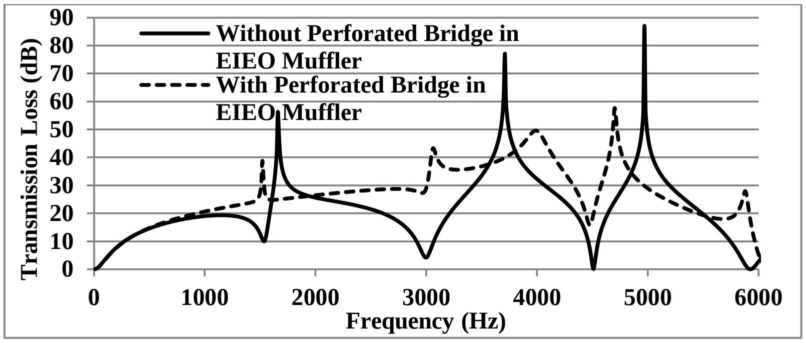
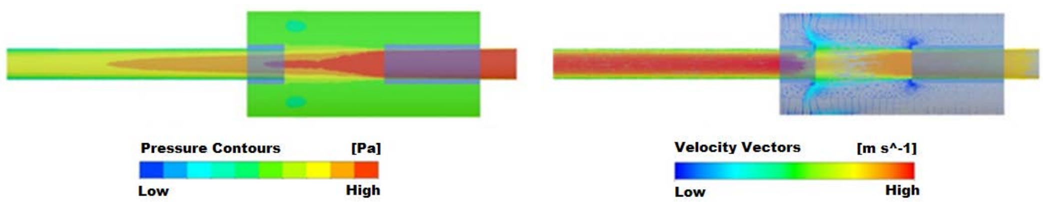


Figure 6: Transmission loss improvement of perforated bridge EIEO muffler

A three dimensional CFD simulations using CFX software is performed on EIEO muffler to study the effect of perforated bridge on the pressure drop across the muffler. Results from steady state 3D CFD simulations are presented in Figures 7 and 8. A pressure drop of 28 Pa is observed in the design with perforated bridge as compared to the 48 Pa in the one without perforated bridge. Hence, muffler with perforated bridge causes lesser pressure drop in the suction line as compared to muffler without perforated bridge.



Figures 7: Pressure and velocity contours for EIEO muffler without perforated bridge

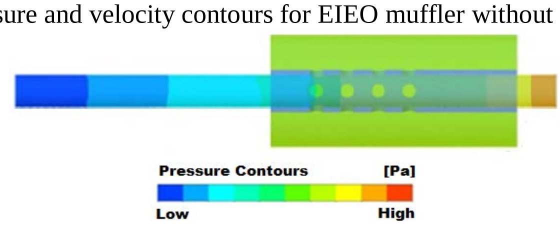


Figure 8: Pressure contours for EIEO muffler with perforated bridge

An observation from the CFD simulations presented in the Figure 7 is that the flow passes through inlet pipe to outlet pipe without expanding into the chamber. The velocity vector contours of a small EIEO muffler presented in Figure 7 show high velocity between the inlet and outlet pipes. A conclusion is drawn for small size EIEO mufflers, that the location of extended outlet can be adjusted to have less flow circulation. The dimensions l_j shown in Figure 9 should be less than the jet expansion length of the flow to maintain low pressure drop across the muffler. The pressure drop of the muffler designed to satisfy this criterion has pressure loss only due to pipe friction and not due to flow expansion inside the muffler. J. M. Middleberg *et al*. (2004) also observed that the mufflers with extended pipes has the lowest pressure drop due to the flow remaining attached to the pipes as it travels through the expansion sections.

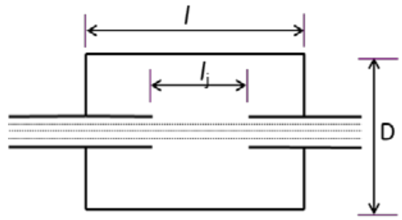


Figure 9: Schematic of EIEO muffler with flow jet passing without expansion

An EIEO muffler showed improved acoustic attenuation with addition of perforated bridge, the troughs at 1500Hz and 3000Hz are eliminated, thereby increasing the frequency range of muffler considerably (refer figure 6).

2.5 Design of Side Inlet Side Outlet (SISO) Mufflers Equivalent to EIEO

A Side–Inlet/Side-Outlet (SISO) muffler with acoustic performance similar to an EIEO can be designed by maintaining the component dimensions as given in Figures 10 and 11. It is an alternate to EIEO muffler and easy to manufacture. The overall length of cylindrical muffler is to be maintained same and length of extended inlet (l_a) is to be matched with the location of side inlet. Similarly the extended outlet (l_b) is to be matched with the location of side outlet as shown in Figure 10 and Figure 11. Munjal (1997) discussed the acoustic equivalence of these two models based on plane wave analysis [13]. So, these results are not reproduced here. Tuning of the side outlet position for higher transmission loss is presented in the next section.

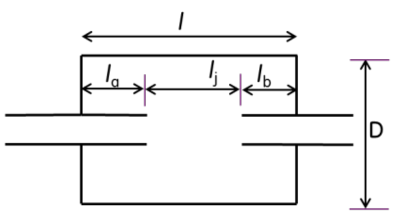


Figure 10: Schematic diagram of EIEO muffler

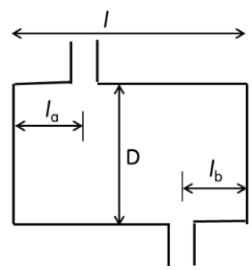


Figure 11: Schematic diagram of SISO muffler

2.6 Methodology of Tuning Side Outlet Muffler

In order that the sound transmitted by a side outlet muffler is minimum, the outlet position can be selected based on acoustic pressure distribution of acoustic modes. Placing outlet pipe at acoustic pressure node location of a particular acoustic mode improves transmission loss at that mode frequency. By choosing the outlet pipe location close to maximum number of pressure nodal locations improves the transmission loss significantly. Figure 12 shows the pressure distribution of first four acoustic modes of a side outlet muffler, the outlet pipe can be moved close to lines of low pressure amplitude to reduce the pulsations coming out of the muffler. Figure 13 shows the improvement in transmission loss after tuning the outlet position of side outlet muffler. After tuning the muffler, the frequency bandwidth of muffler has increased from 2000Hz to 4500 Hz. Selamet *et al*. (1998) applied a similar approach to design a circular expansion chamber with offset inlet/outlet for improved acoustic attenuation of mufflers.

2.7 Effect of fluid Properties on Transmission Loss of Muffler

Generally, transmission loss calculations are performed using air as medium. When comparing the transmission loss of muffler calculated with air and any other refrigerant, the peak/trough frequencies needs to be scaled appropriately. Acoustic modal frequencies are proportional to speed of sound (C) of the refrigerant. Refrigerant properties shift trough and peak frequencies (f) in the ratio of C_{refr}/C_{air}. Numerical simulations were performed on an EIEO configuration of muffler and are presented in Figure 14. The shift in trough and peak frequencies can be observed from the plots and trend is similar. A good match between the TL curves of air and refrigerant can be observed by plotting (Figure 15) them as a function of normalized wave number (k*L, where k is 2πf/C).

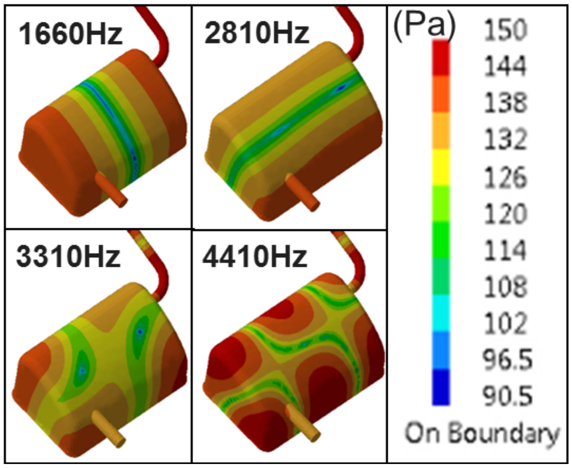


Figure 12: Pressure distribution of expansion chamber at first four acoustic modes of muffler

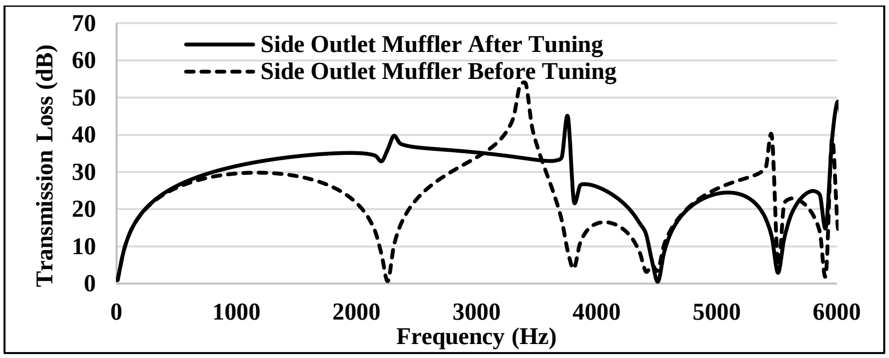


Figure 13: Transmission loss improvement of a tuned side outlet muffler

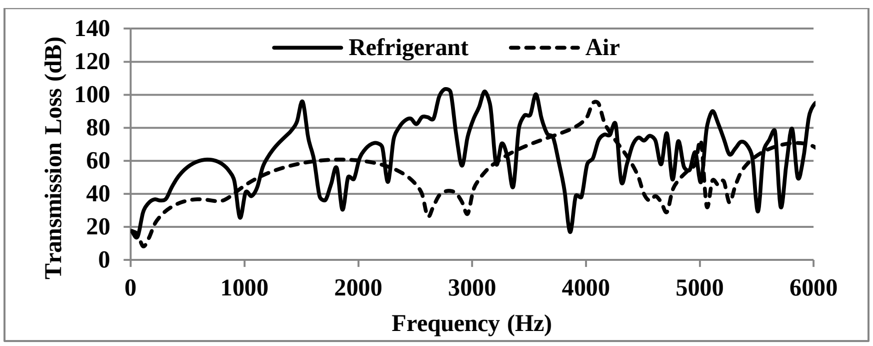


Figure 14: Transmission loss with refrigerant and air as medium

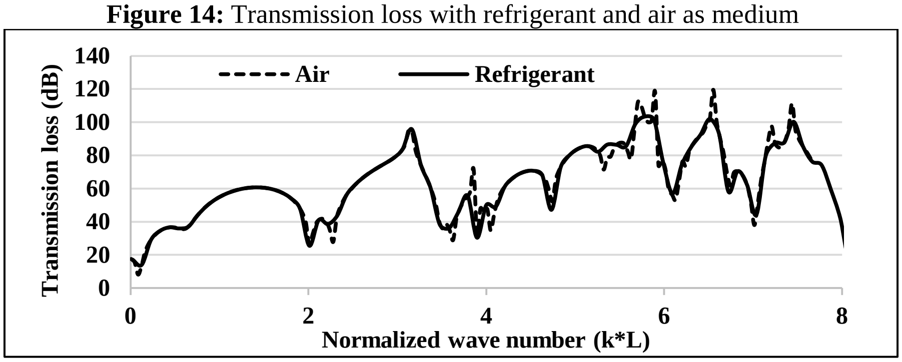


Figure 15: Transmission loss with refrigerant and air as medium plotted as function of normalized wave number

3. CONCLUSION

Requirement of three-dimensional numerical analysis for mufflers with short chamber effect is presented and the procedure is validated with impedance tube experiments. Design of acoustically equivalent SISO muffler from EIEO muffler and also a procedure to tune the positions of inlet and outlet to improve the TL of mufflers have been discussed. The tuned muffler showed increase in acoustic attenuating frequency range from 2000Hz to 4500Hz. The location of outlet pipe of muffler is chosen based on the pressure distribution of acoustic modes. Another variation to EIEO which includes perforated bridge is presented; it increased the frequency range of high TL from 1500Hz to 3000Hz. Detailed three dimensional Computational Fluid Dynamics (CFD) simulations were performed to further study the pressure drop across the mufflers. Inclusion of perforated bridge showed slightly lower pressure drop and increased structural strength. For large EIEO mufflers, use of perforated bridge is proposed and for small EIEO mufflers it is recommended to maintain the gap between the pipes less than jet expansion length. Integrated acoustic and fluid dynamic models have to be considered for an optimum muffler design to meet the acoustical performance and pressure drop requirements. The effect of various refrigerants on acoustic frequencies is also studied, which would help in tuning the muffler to improve its effectiveness.

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