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RESEARCH ARTICLE

Improving the performance of double-expansion chamber muffler using dielectric beads; optimization using factorial design

Niloofar Damyar[1,2] · Fariba Mansouri[3] · Ali Khavanin[3] · Ahmad Jonidi Jafari[4] · Hasan Asilian[3] · Ramazan Mirzaei[5]

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Abstract

Purpose Noise pollution is a common health hazard worldwide which is emitted along with chemical air pollutants, simultaneously from many sources. Some studies have been conducted to control these pollutants, simultaneously with promising results being achieved. Dielectric beads have been used in air pollution control technologies, successfully and probable effectiveness of them in noise reduction can be promising in dual use of them in the exhausts emitting noise and air pollution, simultaneously.
Methods In order to investigate the effectiveness of dielectric beads in noise reduction, two types of them; namely glass and ceramic beads, were placed separately inside the connecting tube of a double-expansion chamber muffler. Then the transmission loss (TL) of muffler was examined using impedance tube. A factorial design was used to evaluate and optimize the effect of noise related parameters on TL of such a system.
Results Results show that the presence of dielectric beads has significant effect on TL of muffler. The maximum TL was obtained as 74.76 dB for muffler with ceramic beads, under the optimal condition of 5250 Hz and 120 dB. Measurement of TL and sound absorption coefficient (SAC) of glass and ceramic beads showed that the noise reduction in muffler with ceramic and glass beads is probably due to SAC in ceramic beads and noise reflections in glass beads, respectively.
Conclusion These results promise the dual use of dielectric beads in the exhausts emitting noise and air pollution simultaneously.

Keywords Noise · Muffler · Dielectric beads · Factorial design

Introduction

Noise pollution is a common health hazard which, to some extent, exists in almost all workplaces and even in the environment of human life, which can cause auditory and non-auditory effects on peoples [1–3]. This pollution is emitted along with chemical air pollutants, simultaneously from many stationary and mobile sources in both industries and environment. Each of noise and air pollution has adverse effects on both human health and environment.

Health problems caused by noise in high-income European countries account for a loss of 1–1.6 million disability adjusted life years (DALYs). Excessive noise is not only a major environmental problem in the modern society, but also an occupational health hazard with many adverse effects, not only on the workers involved with noisy operations, but also on those around them. Exposure to high levels of noise at work can also lead to accidents due to misunderstanding of

✉ Ali Khavanin
khavanin@modares.ac.ir

1 Department of Occupational Health Engineering, Faculty of Health, Semnan University of Medical Sciences, Semnan, Iran

2 Tarbiat Modares University, Tehran, Iran

3 Department of Occupational Health Engineering, Faculty of Medical Sciences, Tarbiat Modares University, Tehran, Iran

4 Department of Environmental Health Engineering, School of Public Health, Iran University of Medical Sciences, Tehran, Iran

5 Department of Occupational Health Engineering, School of Public Health, Mashhad University of Medical Sciences, Mashhad, Iran

oral instructions, limited speech communication and masking the sounds of approaching danger or warnings.

On the other hand, exposure to air pollutants is associated with a range of adverse health effects including cardiovascular disorders, respiratory disease, and also genetic abnormalities which have been reported in animal exposure studies [4–9].

Since noise and air pollution are emitted simultaneously from many sources, some studies have been conducted to control these two pollutants using an integrated system [10–13]. These systems have different configuration: some of them consist of an exhaust resonator having one or more catalytic converter elements in combination therewith in a single device [11], some other comprising two chambers within the housing, a catalyst convertor within the first chamber, noise muffling means within the second chamber [14]. The noise reduction component in such systems often consists of a muffler or silencer, which can be easily connected to the exhaust.

In this study, in order to achieve an integrated noise and air pollution control system, the performance of the double-expansion chamber muffler is evaluated in the presence of dielectric granules in connecting tube. Theses granules have been used in air pollution control technologies such as packed-bed non-thermal plasma (NTP) reactors (as packing materials), thermal catalysis process (as catalyst's neutralized bed support), and in plasma-catalysis (IPC) hybrid systems, with promising results being achieved [15–19]. Probable effectiveness of them in noise reduction can be promising in dual use of them in the exhausts emitting noise and air pollution, simultaneously. The present study aims to investigate the effectiveness of two kinds of dielectric beads; namely glass and ceramic beads on noise reduction by placing them in the connecting tube of a double-expansion chamber muffler and measuring the transmission loss (TL) of resultant system using impedance tube.

To the best of our knowledge, the present research is the first report on investigation the TL of double-expansion chamber muffler in presence of dielectric beads in connecting tube, and optimization of TL of such a system using factorial design.

Experimental design technique was used to investigate all possible conditions in an experiment where a certain response is influenced by multiple factors. Factorial design, as a kind of experimental design technique, has various applications including characterizing how known factors interact and individually affect the process. Multilevel Categorical (general factorial) Design is a type of factorial design which allows the investigation of categorical factors with different numbers of levels. It can create an experiment that includes all possible combinations of categorical factor levels and optimizes desired response. The main objective of this study is to optimize the TL of double-expansion chamber muffler in presence of dielectric beads in connecting tube, using factorial designs (Multilevel Categorical Design).

Material and methods

Design and construction of double-expansion chamber muffler

A double-expansion chamber muffler has been designed and constructed to achieve the TL of 18 dB. This TL has been selected according to the result of noise measurement study on the unsilenced motor exhaust and comparing the results with noise exposure standards [20]. According to the results of such studies, sound pressure level is above 100 dB over a wide range of frequency. In this study, muffler design has been carried out for noise reduction focusing on a frequency of 4000 Hz, to which human ear is most sensitive.

In the design phase, the length of chambers and tubes (inlet, connecting and outlet) and the cross-section ratio of chambers to tubes are determinants of TL at designated frequency [21]. Numerous studies have been conducted on optimization of double-expansion chamber mufflers with different sizes, and contradictory results have been achieved [22, 23]. According to the results of some studies [22, 23], for the purpose of maximum TL, the length of expansion chambers and connecting tubes has been set to be equal in the present study. Moreover, the diameters of chambers have been considered to be equal; the same was set in case with the diameter of tubes as well. The cross-section ratio of chambers to tubes has been selected in a way that the TL achieved was 18 dB theoretically (in frequency range of 2000–4000 Hz).

According to the calculations, diameter ratio of chambers to tubes has been selected to be 3 and the length of chambers and tubes has been set as 15 cm (Fig. 1).

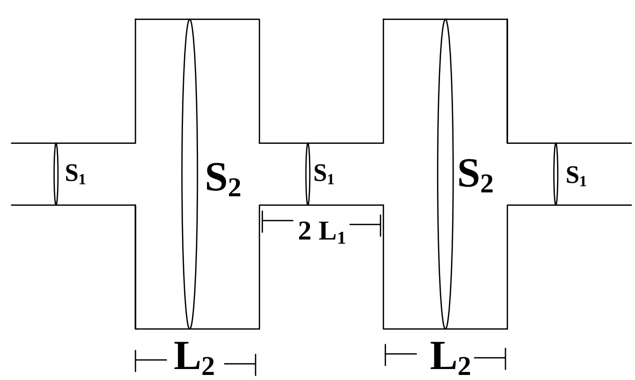

Fig. 1 Geometrical information of double-exoansion chamber muffler

In Fig. 1, the quantity L_1 is the half-length of the connecting tube (total length, $2L_1$), L_2 is the length of one expansion chamber, and $m = S_2/S_1$ = cross-sectional area ratio for chamber and inlet tube (have the same diameter as the connecting tube). (inlet tube length = outlet tube length = $L_2 = 2L_1 = 15$ cm, $S_2 = 50.24$ cm^2, $S_1 = 7.065$ cm^2, and $m = S_2/S_1 = 7.11$).

Then, the designed muffler was constructed and its performance was evaluated for noise reduction in the acoustic chamber by means of impedance tube. The TL of the designed muffler has been measured in three different conditions; empty muffler (E), muffler with its connecting tube being filled with glass beads (G), or ceramic beads (C) in the next status. Also the TL and SAC of glass and ceramic beads have been measured.

Fig. 2 Experimental setup for muffler TL measurement by use of impedance tube

Experimental analysis

Impedance tube In this study, the impedance tube model of SW (SW 477 and SW 422) made in China (according to standard of ISO10534-2:1998(E)) has been used for experiments. It can measure both TL and SAC of materials in a wide range of frequencies (63–6300 Hz) and different intensities. The components of this type of impedance tube include a 30-mm tube (model: SW477) for frequency range of 1000 to 6300 Hz, a 100-mm tube (model: SW422) for frequency range of 63 to 500 and 250 to 1600 Hz (63–1600 Hz), four microphones ($\frac{1}{4}''$), a frequency analysis system model of MC3242, data acquisition system, sound source, amplifier and diffuser.

Impedance tube software has been developed based on BSWA digital acquisition hardware. This software has been developed by BSWA to measure the TL and absorption coefficient through the accurate separation of input waves and reflected waves. Measurement of the TL and absorption coefficient in the impedance tube is based on the transfer function method. Before each series of tests, the microphones must be calibrated using a specific calibrator.

Experimental setup for TL and SAC measurement The TL of designated muffler has been measured in three different conditions as mentioned above. For this end, the muffler was built in such a way that its connecting tube could be separable to put glass or ceramic beads inside. In this study, 140 gr of glass beads and 50 gr of ceramic beads were used with a size of 3–5 mm. Then the TL and SAC of dielectric granules have been measured, separately. Experimental setup for muffler TL measurements is presented in Fig. 2.

Design of experiments, data analysis and optimization

Optimization of the study variables was carried out through following the factorial design of experiment. The effect of noise frequency of 80–6300 Hz (totally in 27 level) and intensity (totally in 5 level) have been investigated in three different conditions of muffler. Using Multilevel Categorical Design technique, the overall number of experiments would be 405 runs. All the investigated factors are presented in Table 1 together with their variation levels. The experimental data was analyzed using a statistical package of Experimental Design software, version 11.

Result

A double-expansion chamber muffler has been designed and constructed to achieve TL of 18 dB in high frequencies (2000-4000 Hz). This TL has been selected according to the results of noise measurement studies on the unsilenced motor exhaust and comparing the results with noise exposure standards [20]. In this study, the lengths of chambers and tubes have been selected to be equal and the diameter ratio of chambers to tubes has been set to be approximately 3. For designated muffler with above specifications, the theoretical value of TL would be 18 dB.

Muffler TL measurement

The effects of the study variables (frequency in 27 levels and intensity in 5 levels) on TL of double-expansion chamber muffler in three different conditions (E, G, and C) were evaluated by means of impedance tube, through 405 runs by factorial design of experiments.

Statistical analysis

The data obtained from 405 runs of muffler TL measurement was statistically analyzed to recognize the significant terms. The analysis of variance (ANOVA) results is presented in

Table 1 The experimental levels of the independent variables

Variable	Levels
A: Noise intensity (dB)	80-90-100-110-120
B: Noise frequency (Hz)	80-126-250-500-750-1000-1250-1500-1750-2000-2250-2500-2750-3000-3250-3500-3750-4000-4250-4500-4750-5000-5250-5500-5750-6000-6300
C: Packing condition	*E, **G, and ***C

*E: Empty muffler, **G: muffler with its connecting tube being filled with glass beads, ***C: muffler with its connecting tube being filled with ceramic beads

Table 2 ANOVA results for the response of TL

Source	Sum of squares	df	Mean square	*F*-value	*P*-value
A-Noise intensity	92.02	4	23.00	8.59	< 0.0001
B-Noise frequency	81,743.65	26	3143.99	1173.36	< 0.0001
C-Packing condition	293.53	2	146.77	54.77	< 0.0001
AB	1614.76	104	15.53	5.79	< 0.0001
AC	74.73	8	9.34	3.49	0.0008
BC	4573.89	52	87.96	32.83	< 0.0001

Table 2. The second column of this table shows the sum of squares for each term, the third column presents the degree of freedom, the fourth column indicates the mean squares (sum of squares divided by the degree of freedom), the fifth column shows variance ratio (*F*-value) which is the ratio of variance derived from the effect of factor to the variance from the error term, and sixth column represents *P*-value which should be smaller than 0.05 for significant terms at confidence level of 0.95.

The *P*-value of terms indicates that all three different categorical variables are highly significant. Also, the interactions between noise intensity and noise frequency (AB), noise intensity and packing condition (AC), and noise frequency and packing condition (BC) were significant, as shown by the low *P*-value.

Figure 3 shows the interaction of frequency and packing condition (BC) as the most important interaction. Evaluation of this type of interaction shows that in all the studied noise intensities (for example intensity of 100 dB (Fig. 3)) the muffler with its connecting tube being filled with glass beads (G) has higher TL in low and very high frequencies, empty muffler (E) has higher TL in middle range of frequency, and the muffler with its connecting tube being filled with ceramic beads (C) has higher TL in high frequencies. To investigate the above event, additional tests were performed by means of impedance tube in order to measure the SAC and TL in glass and ceramic beads. The results are presented in Figs. 4 and 5.

As can be seen in Fig. 4, the SAC of ceramic beads is more than that of glass beads may be due to its porous surface in full range of frequency especially upper than 1000 Hz. While, the glass beads have some SAC in low frequencies. Also, the TL of glass beads is more than that of ceramic beads in almost all range of frequency (Fig. 5). These results can be due to the reflective surface of glass beads without any porosity in comparison with ceramic beads with porous surface.

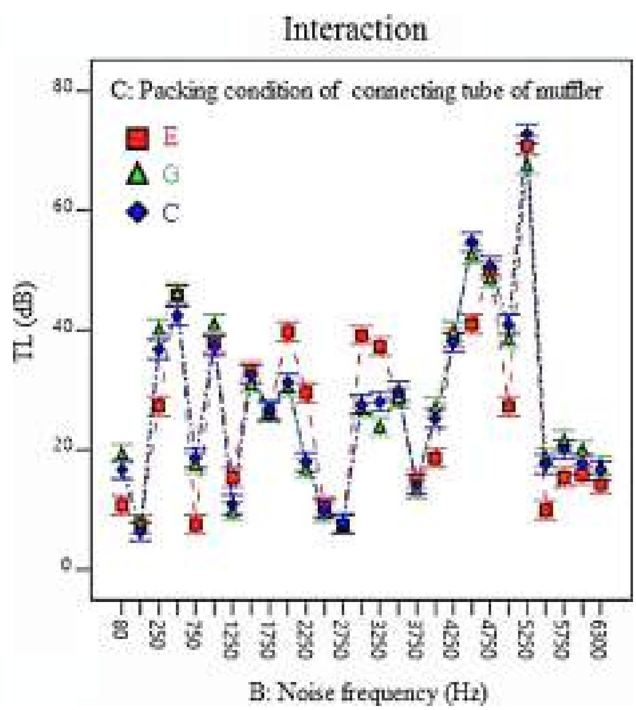

Fig. 3 Interaction of frequency and muffler packing condition in the intensity of 100 dB

In study conducted by Pispola, the TL of three porous consolidated granular media (recycled rubber, consolidated flint, and recycled foam) were measured and results showed

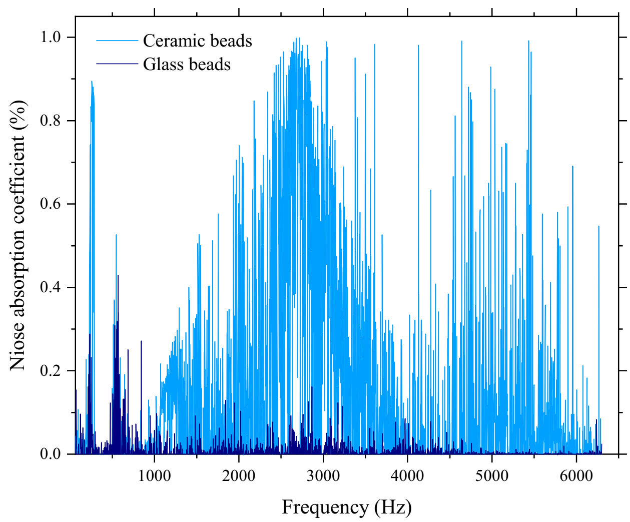

Fig. 4 SAC of glass and ceramic beads in the intensity of 100 dB

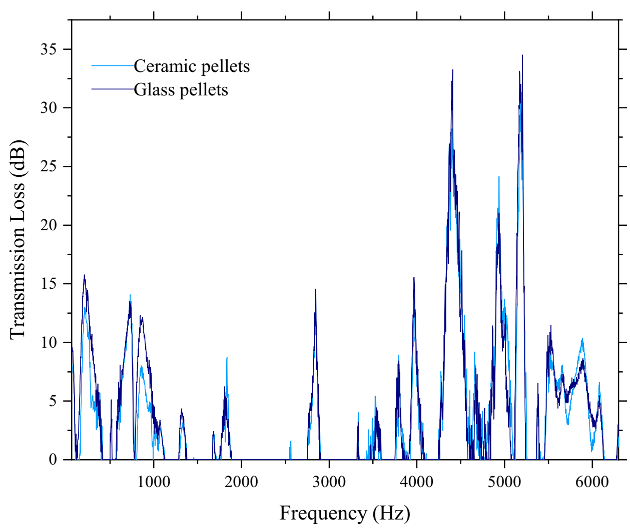

Fig. 5 TL of glass and ceramic beads in the intensity of 100 dB

that the TL of recycled rubber varied from lower than 5 dB (in frequencies lower than 600 Hz) to maximum 8 dB (in frequency of 16,000 Hz) with a very low fluctuation, the TL of recycled foam varied from approximately 15 dB (in frequencies lower than 500 Hz) to 18 dB (in frequency of 16,000 Hz), and in this range at a frequency of about 600 Hz the TL of recycled foam decreased to 12.5 dB. Considering the consolidated flint, the TL varied from 6 to 8 dB (in low frequencies towards high frequencies) also with a very low fluctuation [24]. All of these samples are probably good sound absorbers that their SAC's were not measured. The results of TL measurement in glass and ceramic beads in the current study are comparable with the results of mentioned study. The TL of glass and ceramic beads varied from 15 dB (in low frequencies) to 35 dB (in high frequencies) with a lot of fluctuations that approximately in many of frequencies in the middle range, the TL was zero.

Considering the relatively high TL in glass beads in all range of frequency and some SAC in low frequencies, and also high SAC in ceramic beads in all range of frequency especially in high frequencies, and according to the results, the TL of muffler with glass beads is more than that of muffler with ceramic beads in low frequencies and TL of muffler with ceramic beads is more than that of muffler with glass beads in high frequencies. Finally, the TL of muffler in three different conditions mentioned above, is presented in Fig. 6.

As can be seen in Fig. 6, in the frequency of 4000 Hz which is the muffler design frequency, the TL of empty muffler is about 20 dB which is near to the theoretical TL of muffler (18 dB), and in muffler with glass or ceramic beads is about 25–30 dB. Also, the maximum TL of muffler is about 75 dB (in the frequency range of 5200–5300 Hz in each condition of E, G and C) and then 55–60 dB (in the frequency of about 4500 Hz in both condition of G and C).

Optimization

The optimum conditions obtained by software for maximizing the TL, estimated to be a frequency of 5250 Hz and intensity of 120 dB. The maximum TL obtained at this optimum condition was 74.76 dB which was achieved by muffler with ceramic beads in connecting tube. The TL values obtained for empty muffler and muffler with glass beads in connecting tube, at this optimum condition were 69.06 and 71.00 dB, respectively. An additional experimental test has been done at optimum condition determined by design of experiment software as validation experiments. The values corresponding to optimized

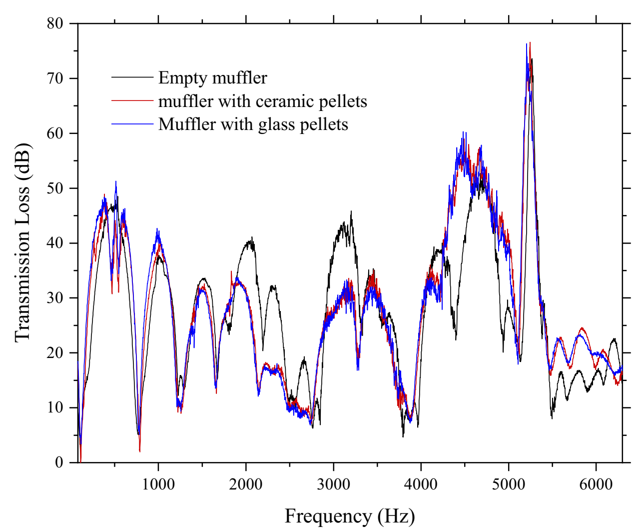

Fig. 6 Transmission Loss of muffler in three different conditions at 100 dB

Table 3 Optimized condition with predicted and experimental values of TL

Response	Target	Optimum condition			Desirability	Confirmation experiment	C.I (95%)	
		Noise intensity	Noise frequency	Packing condition			Low	High
TL	Maximization	120	5250	C*	0.96	73.48	72.51	77.01

C*: Muffler with ceramic beads in connecting tube

parameter, as obtained from the experimental design software and validation experiments, are presented in Table 3.

Conclusion

A Multilevel Categorical Factorial Design was employed to optimize the TL of double-expansion chamber muffler in presence of dielectric beads in connecting tube. The ANOVA results shows that the noise frequency and intensity and the presence of dielectric beads in muffler connecting tube have significant effects on TL of muffler. The results of TL measurements showed that the muffler with glass beads (G) has higher TL in low and very high frequencies, empty muffler (E) has higher TL in middle range of frequency, and the muffler with ceramic beads (C) has higher TL in high frequencies. In optimization, the maximum values of TL were 74.76 dB, which was achieved by muffler with its connecting tube being filled with ceramic beads, in the frequency of 5250 Hz and intensity of 120 Hz. Measurement of SAC and TL of ceramic and glass beads showed that the noise reduction in muffler with ceramic and glass beads is probably due to noise reflections in glass beads and SAC in ceramic beads with porous surface, respectively.

Given that the studied dielectric beads, which have been used in air pollution control process successfully, have significant effect on noise reduction, it can be concluded that they can be used in the integrated systems to control noise and air pollution in exhausts emitting these pollutants, simultaneously.

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Declarations

Conflict of interest The authors have no conflicts of interest to declare.

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