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Transmission Loss of Absorptive Mufflers Lined with Expanded Clay Granulates

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Abstract The article presents the results of tests on sound attenuation by two types of cylindrical absorptive mufflers with the same length and different diameters of chambers filled with expanded clay granulates. Using a laboratory stand for testing acoustic mufflers with an impedance tube, the transmission loss parameter was determined. To compare the effectiveness of sound attenuation, the transmission loss of mufflers without sound absorbing material was also determined. The results of these tests were compared to the results obtained with the use of a known calculation model for reflective mufflers. Using an impedance tube, the normal incidence sound absorption coefficients of the expanded clay granulates with thicknesses of material samples from 10 to 100 mm were determined. The dependence between the sample thickness and the first resonance frequency of the sound absorption coefficient was determined, which was then used in the proposed calculation model of the effectiveness of the cylindrical absorptive mufflers with expanded clay granulates. Using the proposed theoretical model, the results of transmission loss calculations, satisfactory for engineering applications, were obtained.

Keywords: absorptive mufflers, transmission loss, expanded clay granulates.

1. Introduction

Acoustic mufflers are used to reduce the noise level associated with the flow of air or gas along the axis of ducts. The use of mufflers includes various types of technical devices, including ventilation, air conditioning, blowers, suction and discharge systems for compressors, acoustic enclosures and others [1,2].

The basic division of mufflers includes two groups: reflective (reactive) and absorptive ones, containing sound-absorbing material [3]. The first group is most effective at low and mid frequencies and is used in conditions with high flow velocities and high temperatures. On the other hand, the second group of mufflers, the most effective in the range of mid and high frequencies, is most often used in ventilation ducts. Reflective mufflers operate on the basis of such phenomena as reflection, interference and compensation of acoustic waves, while absorptive mufflers prevent the transfer of acoustic wave energy along the duct by absorbing a significant part of it. The energy of the acoustic wave is absorbed by the sound-absorbing material that the walls of the duct are lined with, where, due to friction processes in the pores of this material, acoustic energy is converted into heat.

The following calculation methods are used to calculate the effectiveness of mufflers: the Transfer Matrix Method (TMM) [4,6], Finite Element Method (FEM) [4], and the Boundary Element Method (BEM) [5-7]. Issues related to the design of mufflers can be found in the literature [8-10]. Problems related to mufflers and the acoustic field of ducts are the subject of the research described in [11,12].

The sound-absorbing materials used in absorptive mufflers are usually materials with a porous and fibrous structure. In addition to typical materials such as mineral wool or glass wool, materials like basalt wool, polyester, needle fibre and cell foam [13] as well as natural fibre, like coconut fibre and paddy straw [14], can also be used.

In design solutions for noise protection, apart from sound-absorbing materials with porous and fibrous structures, materials with a granular structure are also used. The research described in [15] showed that, due to good sound-absorbing properties, materials such as lead shot, plastic materials, materials from built aggregates and quartz sand can also be used in the construction of this type of protection. Examples of the practical application of baffles with granular materials are lathe and press enclosures [15,16].

The article presents an attempt to use granular materials as a sound-absorbing layer used in two cylindrical absorptive mufflers with different chamber diameters. The subject of the research was expanded clay granulates, with one of the properties being resistance to high temperatures. The tests were carried out on a laboratory stand consisting of an impedance tube designed to test muffles for conditions without air flow. The measurement stand made it possible to determine the effectiveness of the mufflers using the Transmission Loss (TL) parameter. Another parameter that can be used to assess the effectiveness of acoustic mufflers, not determined in the tests described in the article, is Insertion Loss (IL) [10, 14].

For comparative purposes, tests were also carried out on two reflective mufflers (without sound-absorbing material) with dimensions corresponding to absorptive ones. For both reflective and absorptive mufflers, known theoretical models were used to calculate their effectiveness. In the case of the tested sound-absorbing material with characteristics different than typical porous and fibrous materials, due to the divergent results of calculations and experimental tests, a modification of the TL formula for absorptive mufflers was proposed.

2. Experimental set-up

The tests of mufflers were carried out in the laboratory of acoustic properties tests of materials and structures, at the Department of Mechanics and Vibroacoustics of AGH. To determine the transmission loss of the mufflers, the same apparatus was used as for the sound transmission loss tests of soft materials [17], with the difference that the tested muffler was installed in place of the sample container.
Each of the mufflers consisted of five parts constituting an integral whole, such as: inlet and outlet tube connectors, a pipe constituting the muffler chamber and two side walls. Additionally, the absorptive mufflers were equipped with a perforated tube 1 mm thick and with a 34.9 mm internal diameter, mounted along the axis of the muffler chamber. The perforated tube, with the degree of perforation σ=61%, was covered with a textile material to form a sheath. The inlet and outlet tube connectors were screwed to the tube stubs by 12 bolts. The test stand is shown in Fig. 1.

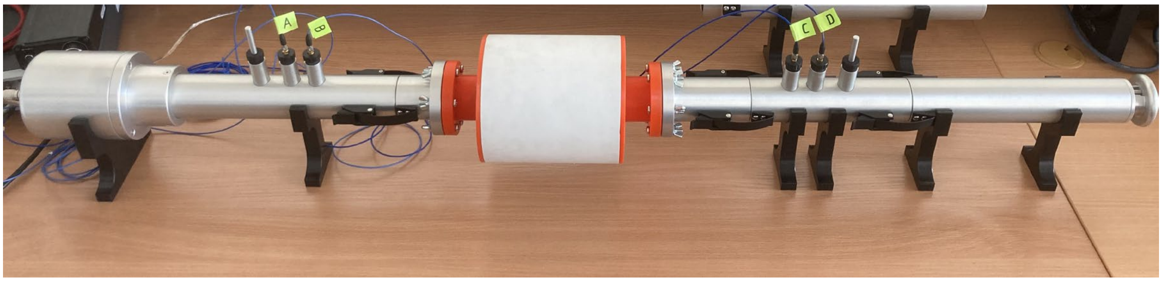

Figure 1. Measurement stand for testing acoustic mufflers.

The kit included a Mecanum Inc. impedance tube with a loudspeaker, an SMSL SA-36A Pro amplifier, type 378A14 PCB measuring microphones, a Siemens LMS SCADAS Mobile analyzer and a computer with Simcenter Testlab software. The internal diameter of the tube was 34.9 mm, which enabled measurements in two frequency ranges: 50 Hz - 2400 Hz and 119 – 5700 Hz, while maintaining the distance between the microphone holders, which was 65 and 29 mm, respectively. The tests were carried out in accordance with the ASTM E2611-19 standard [18].

Two types of mufflers were tested: reflective, without absorbing material, and absorptive, shown schematically in Fig. 2a and Fig. 2b, respectively. Expanded clay granulates with a density of 281 kg/m^3 and a grain fraction of 0-4 mm were used as the absorbing material in the absorptive muffler.

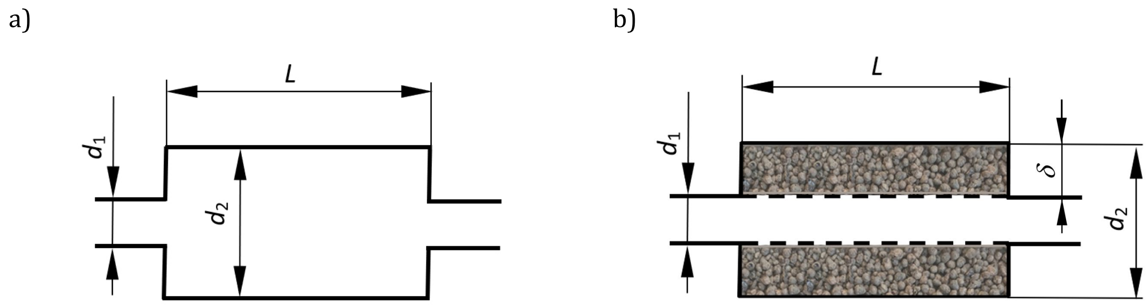

Figure 2. Schemes with parameters of the reflective (a) and absorptive (b) mufflers.

Each of the mufflers, shown in Fig. 2, had two variants (A and B), which differed in the dimensions of the inner diameter of the muffler chamber d_2, as shown in Table 1.

Table 1. Geometrical parameters of tested mufflers.

Muffler Id.	Muffler type	Chamber length	Diameter of the inlet and the outlet tube	Diameter of the chamber	Thickness of absorptive layer
		L	d_1	d_2	δ
		m	m	m	m
A1	reflective	0.15	0.0349	0.105	-
A2	absorptive	0.15	0.0349	0.105	0.034
B1	reflective	0.15	0.0349	0.15	-
B2	absorptive	0.15	0.0349	0.15	0.057

In order to determine the sound-absorbing properties of expanded clay granulates, tests of the normal incidence sound absorption coefficient were also carried out using an impedance tube. The research was carried out in accordance with the ISO 10534-2 standard [19]. The measurement procedure with the apparatus was identical to that used for this purpose in the previous tests described in [17]. The sound absorption coefficient was determined for expanded clay granulates placed in material specimen containers, of 34.9 mm in diameter and 0.01, 0.02, 0.03, 0.04, 0.05, 0.08 and 0.1 m thick. The sleeves constituting the granulate containers were secured on both sides with a textile material.

3. Calculation models of transmission loss of reflective and absorptive mufflers

The effectiveness of the damper can be determined using the Transmission Loss (TL) parameter, which is defined as:

$$\mathrm{TL} = 10\log_{10}\frac{W_i}{W_t}, \tag{1}$$

where W_i is the incident sound power at the inlet of the muffler and W_t is the transmitted sound power at the outlet of the muffler.

In the case of a cylindrical reflective (chamber) muffler, TL is determined by the known theoretical model [1]:

$$\mathrm{TL} = 10\log_{10}\left[1 + 0.25\left(m - \frac{1}{m}\right)^2 \sin^2(kL)\right], \tag{2}$$

where k is the wavenumber, L is the chamber length, and m is the area ratio given by $m=S_2/S_1$, where S_2 is the area of the chamber cross section and S_1 that of the inlet or outlet tubes. The effectiveness of mufflers lined with sound-absorbing material is determined by the formula [2,20]:

$$\mathrm{TL} = 1.1\frac{f(\alpha)\cdot P\cdot L}{F} \tag{3}$$

where $f(\alpha)$ is a function depending on the reverberation sound absorption coefficient of the damping lining, P is the perimeter of the free cross-section of the muffler and F is the free surface area of the muffler.

In the case of cylindrical absorptive mufflers, which are the subject of the research, with a duct diameter d_1 (Fig. 1b), formula (3) is transformed into the form [18]:

$$\mathrm{TL} = 4.4\frac{f(\alpha)\cdot L}{d_1}. \tag{4}$$

The function $f(\alpha)$, given in [2], can be approximated by the dependence in the form of a polynomial (R^2=0.9633), according to the formula:

$$f(\alpha) = 0.6803\alpha^2 + 0.4353\alpha - 0.029. \tag{5}$$

The reverberant sound absorption α can be calculated on the basis of the normal incidence sound absorption coefficient, using the nomogram given in [21].

4. Experimental test results

4.1. Transmission loss of mufflers

Figures 3 and 4 show the spectral characteristics of the TL of mufflers A and B, respectively. These figures present the TL curves for a reflective muffler (including one with a perforated sheath), obtained from experimental tests and calculations using formula (2), as well as for an absorptive muffler, obtained from measurements. As can be seen in Figures 3 and 4, the effect of the perforated sheath, necessary for testing granulated materials, is small, but more visible at frequencies above 2.8 kHz, especially for the muffler A, with a smaller chamber diameter (d_2 = 0.105 m).

According to the theoretical model defined by formula (2), TL is a periodic function of the parameter kL and the greatest values of TL, related to the diameter of the muffler chamber d_2, are 13 and 19 dB for the reflective mufflers A1 and B1, respectively. However, comparing the TL of the reflective mufflers A1 and B1 (Figs. 3 and 4), calculated and obtained from the measurements, it can be concluded that with the length of the muffler chamber A1 and B1 amounting to L=0.15 m, the simplified theoretical model works only in the low frequency range, up to f <1144 Hz.

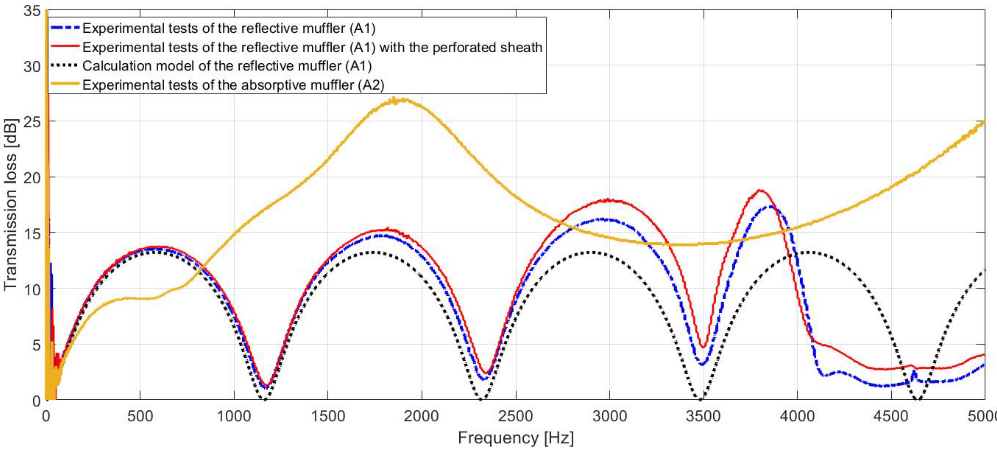

Figure 3. Transmission loss of muffler A: reflective (A1, with and without the perforated sheath) and absorptive, with expanded clay granulates (A2), obtained from measurements, and reflective (A1), obtained from the calculation model.

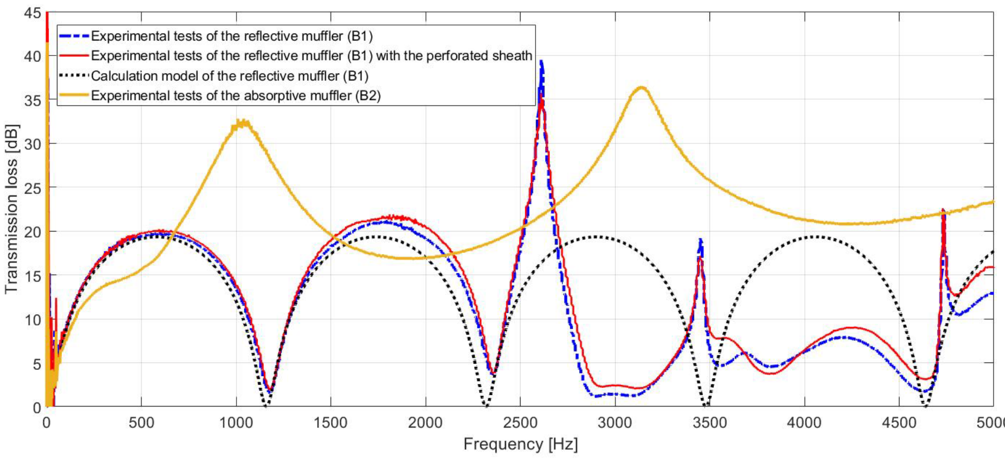

Figure 4. Transmission loss of muffler B: reflective (B1, with and without the perforated sheath) and absorptive, with expanded clay granulates (B2), obtained from measurements, and reflective (B1), obtained from the calculation model.

The different nature of TL curves as a function of frequency can be observed in Fig. 3 and Fig. 4 for mufflers equipped with absorbing material. For the A2 muffler with expanded clay granulate layer thickness of δ_{A2} =0.034 m the highest peak of the TL curve is 26.9 dB for f=1900 Hz. For the B2 muffler, for which

δ_{B2} =0.057 m, two peaks are visible in Fig. 4. The first peak is equal to 32.4 dB for f =1040 Hz, and the second one is 36.4 dB for f=3140 Hz.

4.2. Absorption properties of the expanded clay granulates

Figure 5 shows the spectral characteristics of the normal incidence sound absorption coefficient in the 1/3 octave frequency bands, obtained from the measurements for material specimens with thicknesses of 0.01, 0.02, 0.03, 0.04, 0.05, 0.08 and 0.1 m.

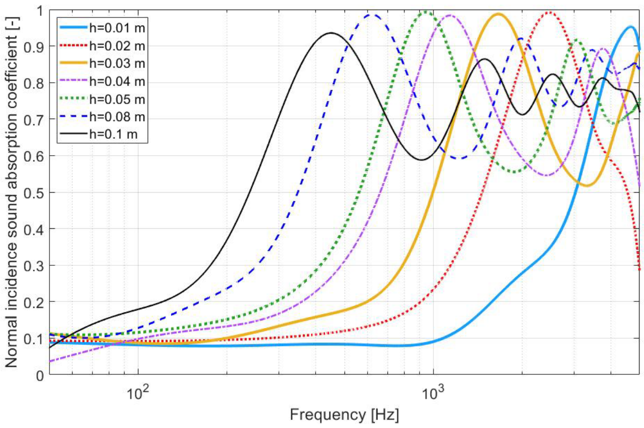

Figure 5. Spectral characteristics of the normal incidence sound absorption coefficient for expanded clay granulates with a sample thickness of 0.01-0.1 m.

Along with increasing sample thickness, the sound insulating properties of expanded clay granulates improve, widening the absorption band towards lower frequencies. The characteristic peaks corresponding to the first absorption resonance frequencies reach the values of normal incidence sound absorption coefficient in the range of 0.93-0.99.

5. A proposal for a TL calculation model for absorptive mufflers with granulate lining

The use of formula (4) to calculate the acoustic efficiency of circular absorptive mufflers with a granular material, instead of the porous or fibrous material that is typically used, resulted in considerable discrepancies in relation to the experimental tests. The calculation of TL spectral characteristics using formula (4) was preceded by the determination of normal incidence sound absorption coefficients for expanded clay granulates with absorbing layer thicknesses δ=0.034 and δ=0.057 m. Figure 6 shows an example comparison of TL spectral characteristics in 1/3 octave frequency bands obtained from experimental tests and calculations using the calculation model for absorptive mufflers (formula (4)).

a) b)

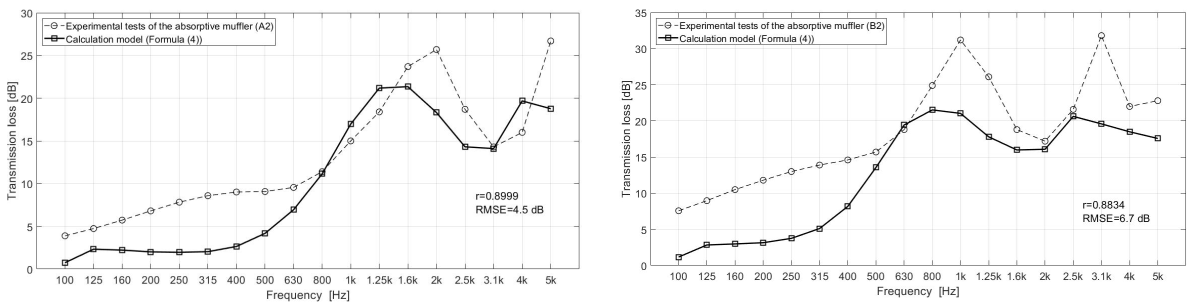

Figure 6. Spectral characteristics of TL in 1/3 octave frequency bands obtained from experimental tests and calculations using the calculation model for the absorptive mufflers: (a) A2 and (b) B2.

The studies showed that the results of the calculations underestimated the results of the experimental tests and that the first resonance frequencies of the TL spectral characteristics calculated and obtained from the experimental tests are shifted in relation to each other. Despite the discrepancies, estimated using Root

Mean Square Error (RMSE), amounting to 4.5 and 6.7 dB (Fig. 6), Pearson's linear correlation coefficients *r* are quite high and amount to 0.8999 and 0.8834 for the A2 and B2 muffler, respectively. In order to better adapt the calculation model for absorptive mufflers with porous and fibrous materials to mufflers with granular materials, modification of formula (4) has been proposed.

Figure 7 shows the dependence of the first resonance frequencies of the normal incidence sound absorption coefficient, on the thickness of the expanded clay granulate sample. This relationship can be approximated using the power function (Fig. 7).

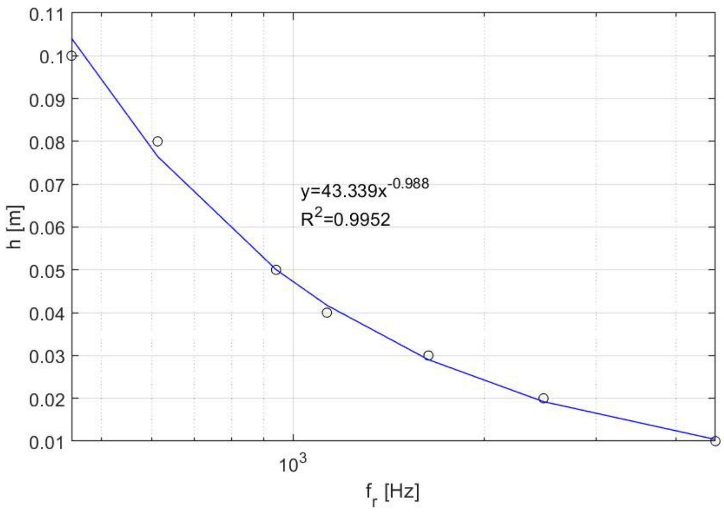

Figure 7. Dependence of the first resonance frequencies of the normal incidence sound absorption coefficient f_r on the thickness of the expanded clay granulates sample *h*.

From the obtained results of the tests, the values of the first resonance frequency TL (Figs. 3 and 4) for the expanded clay granulates layer with a thickness of δ_{A2}=34 mm and δ_{B2}=57 mm, respectively, using the power function (Fig. 7), the thickness of the samples h_{A2} (for the muffler A2) and h_{B2} (for the muffler B2), corresponding to their first resonant frequencies of the normal incidence absorption coefficient f_r, can be calculated. The calculated h_{A2} and h_{B2} values are 26 and 46 mm respectively. The values of the quotients h_{A2}/δ_{A2} and h_{B2}/δ_{B2} are, respectively, 0.76 and 0.81, which gives their mean value ≈0.79.

To determine the effectiveness of a cylindrical absorptive muffler with granulated material in the form of expanded clay granulates with a fraction of 0-4 mm, a modified formula (4) is proposed, determined by the relationship:

$$\mathrm{TL} = 4.4\,\frac{(0.6803(\propto^*)^2+0.4353\propto^*-0.029)\cdot L}{d_1}+4.5, \quad (6)$$

where $\propto^*$ is the reverberant sound absorption coefficient of a granular material with a sample thickness equal to 0.79 of the thickness of the absorbing material layer in the circular muffler δ.

The 4.5 dB correction value in formula (6) was adopted on the basis of experimental research and calculations. With this correction value, the results of TL calculations for 1/3 octave frequency bands have the smallest discrepancies compared to the TL results obtained from experimental tests. The RMSE values were 2.7 and 3.0 dB for the A2 and B2 mufflers, respectively.

Figure 8 shows the results of calculations using the proposed formula (6) with the results of the TL experimental tests for the A2 and B2 mufflers. A satisfactory result of TL calculations was obtained for absorption mufflers filled with granulated material in the form of expanded clay. The discrepancies in the results are much smaller than when using formula (4) for typical absorbing materials (porous and fibrous). The values of Pearson's linear correlation coefficients (*r*=0.9548 and *r*=0.9307) have significantly improved, in relation to the results shown in Fig. 6, and the RMSE has decreased to the values of 2.5 and 3.3 dB for the A2 and B2 mufflers, respectively.

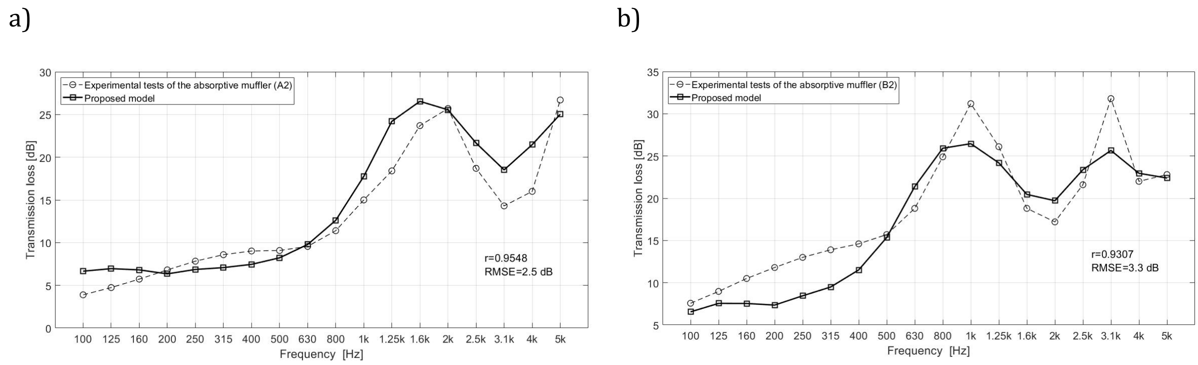

Figure 8. Spectral characteristics of TL in 1/3 octave frequency bands obtained from experimental tests and calculations using the proposed model for the absorptive mufflers: (a) A2 and (b) B2.

The effectiveness of sound attenuation in absorptive mufflers strongly depends on the thickness of the granulate layer. By increasing this thickness, better efficiency towards lower frequencies can be obtained. Depending on the assumed effectiveness of a muffler with granulated material, related to a specific frequency range, the TL parameter can be adjusted by selecting the appropriate layer thickness of this material.

6. Conclusions

The article shows the possibilities of using sound-absorbing materials in cylindrical acoustic mufflers, other than those with a porous and fibrous structure.

The proposed solution in the form of granulated materials has been validated on the example of expanded clay granulates with a fraction of 0-4 mm. Reflective mufflers are generally used for operating at high temperatures. However, as part of the preliminary research, it was shown that a material with an unusual structure - granular, resistant to high temperatures, can be used in absorption mufflers and can bring about a satisfactory noise reduction effect. The research showed that the characteristics of the parameter used to determine the effectiveness of mufflers, in the form of transmission loss, for cylindrical absorption mufflers with an expanded clay granulates sound-absorbing layer, can be obtained using the proposed modification of the known formula for absorption mufflers with porous and fibrous materials. The results of the transmission loss calculations for the muffler and the results of experimental tests were sufficiently convergent for engineering applications.

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Additional information

The authors declare: no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited and that appropriate permits are obtained.

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