COMPARATIVE ASSESSMENT OF ACOUSTIC EFFICIENCY OF MUFFLERS WITH DIFFERENT POROUS METALS

Aleksandr A. Igolkin, Artur I. Safin, Dmitry M. Stadnik, Prokhor P. Almurzin

Samara National Research University, Moskovskoe shosse 34, Samara 443086, Russian Federation
email: igolkin97@gmail.com

The noise of the air jet exhaust contributes the major part of the general noise level in a working place where pneumatic systems are operated. To reduce the noise level exhaust mufflers are used. One of the main parts of the muffler is porous material. The aim of this paper is to compare the acoustic efficiency of mufflers with different porous metals. Three types of porous materials have been investigated: 1) aluminium foam, 2) porous fibrous material, 3) "Metal–rubber" (MR). In addition to noise measurement, the pressure in the tank (air receiver) was monitored. A mathematical model for calculating the pressure drop in pneumatic systems with the MR muffler has been developed. The model includes the influence of mufflers installation on the systems dynamics. The model describes the impact of the noise muffler on the pneumatic system fast operation. The results of the transition processes simulation in the pneumatic system are presented in this paper taking into consideration the installation of the noise muffler. The calculated data on the pressure drop in the pneumatic tank are compared with the experimental data. The muffler with porous fibrous material demonstrated a maximum efficiency of 36,3 dBA.
Keywords: noise muffler, porous metal, noise.

1. Introduction

The exhaust noise is caused by the high gas velocity [1]. The simplest noise muffler is a porous permeable valve [2]. It is installed onto the exhaust port and reduces the noise level by reducing the gas velocity due to the increased discharge area. The noise muffler has to provide a pressure relief over specific time according to the Russian State Standard GOST 25144-82 and resist destruction by the action of a gas jet. However, these requirements contradict each other because in order to ensure a quick drop of pressure it is necessary to have a thin porous wall which can collapse.

A great number of research papers suggest the following main ways to reduce vibrations and noise in pneumatic systems [1,2,3,4,5,6,7]:

- reduction of vibro-acoustic activity of the source;
- application of special compensation devices and noise mufflers;
- sound insulation of the source of vibrations and noise.

The most effective way to reduce vibro-acoustic loads is to eliminate their primary causes in sources of oscillations. The main sources of noise in pneumatic systems are compressed air exhaust pipes, compressors, pipelines and control valves.

Review of related publications showed the existence of two methods for reducing aerodynamic noise of pneumatic systems: stepwise throttling and flow separation (breaking into smaller streams).

When implementing the stepwise throttling method, a set of perforated (throttling) washers is used as a noise muffler. Porous materials can be used to expand the frequency range of the acoustic efficiency of noise mufflers together with throttling washers. Due to high loads and possible presence of oil impurities in the air, traditional building porous materials are not suitable for use in noise suppressors. Therefore, it is reasonable to use porous metals in the noise muffler [1, 3, 4, 8]. Depending on the type of raw materials and their method of production, porous materials are obtained with a porosity of up to 0.98 and a pore size from fractions of a micrometer to several millimeters. Installation of porous material in the exhaust pipe increases its impedance which requires developing a mathematical model for calculating the bleeding time. In [3] a mathematical model for calculation of the bleed time is described where sintered bronze was used as the porous material. However,, there is no mathematical description of the process of bleeding pressure through the MR material, porous-fiber metallic materials (PFMs) and porous aluminium. Sintered bronze as a sound-absorbing element in a pneumatic muffler was described in detail in [3,9], and does not require further investigation.

Nomeclature

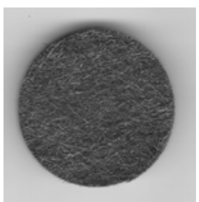
V	volume	p	pressure	ν	kinematic viscosity
d	diameter	φ	porosity	μ	dynamic viscosity
G	mass flow rate	R	specific gas constant	ρ	density
k	adiabatic exponent	S	area	Re	Reynolds number
l	length	T	temperature	α	normal sound absorption coefficients

Subscripts:
1, 2, p, out relating to volumes, pipe and orifice as shown in Fig. 1.

2. Methods

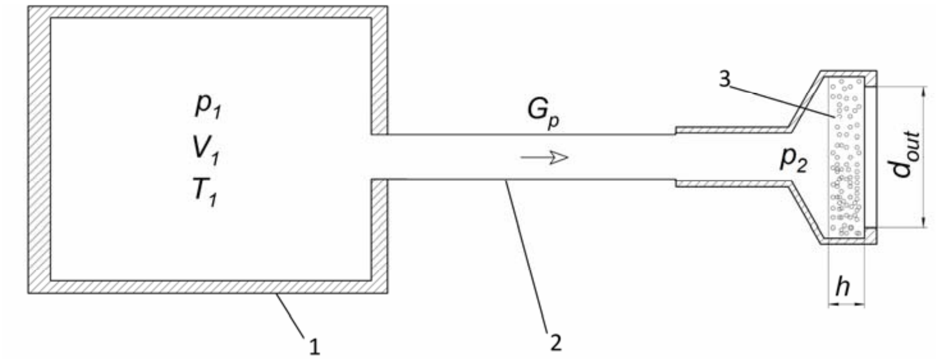
The method of the investigation involves experimental study of acoustic efficiency of noise mufflers with porous metals which characteristics are presented in Table 1 [8, 10, 11].

Table 1 – Characteristics of porous metals

Characteristics	MR	PFMs	Porous aluminium
Porosity	0,13…0,95	0,7…0,9	0,5…0,65
Specific weight	390-6786 kg/m^3	780-2340 kg/m^3	950-1356 kg/m^3
Advanced characteristics	High α over a wide range of frequencies	A fairly uniform absorption spectrum at frequencies above 1.6 kHz	Possibility of material processing, no size limitations
Temperature range	As high as 1700 °C	As high as 750 °C	As high as 400 °C
Disadvantages	Low produceability	Vulnerable to vibration	Presence of closed pores and a rigid one-piece structure
Appearance			

According to [2], the noise of the exhaust jet has a wide band-like character, and to estimate the efficiency of using porous metals in the noise muffler, the normal sound absorption coefficient was measured by the method described in [8, 13, 14].

To investigate the effect of the porous element properties on the dynamic characteristics of the pneumatic system, an installation was developed with its scheme shown in Figure 1. The muffler with the porous element 3 inside is mounted on the end of the pipeline 2, which in turn is connected to the receiver 1. The air is forced into the receiver from the compressor (not shown in the diagram). After opening the outlet, the pressure from the receiver is discharged along the pipeline through the porous element. To calculate the time of pressure drop in the receiver, a mathematical model was developed.



1 – receiver, 2 – pipeline, 3 – porous part

$V_1 = 200l$, $l_p = 6m$, $d_p = 12mm$, $d_{out} = 30mm$

Fig. 1 – Computational scheme

When compiling a mathematical model, the following assumptions were made: the working body is a perfect gas; there is no heat exchange with the environment, the process of gas outflow is isothermal. Assuming that the state of the gas in the receiver 1 varies according to the isothermal law, we can write [15]:

$$\frac{V_1}{nRT_1} \cdot \frac{dp_1}{dt} = -G_p RT_1 . \quad (1)$$

The equation of the gas flow in the pipeline 2, taking into account hydraulic losses, is:

$$p_1 - p_2 - Z_p = \frac{l_p}{S_p} \cdot \frac{dG_p}{dt} . \quad (2)$$

Pressure losses along the length of the pipeline Z_p are determined according to the following expressions:

$$Z_p = \frac{RT_1}{p_1} \cdot \frac{32 \cdot \nu \cdot l_p}{S_p \cdot d_p^2} \cdot G_p \text{ for laminar flow,} \quad (3)$$

or $Z_p = f \cdot \frac{RT_1}{p_1} \cdot \frac{l_p}{d_p} \cdot \frac{G_p^2}{2 \cdot S_p^2}$ for turbulent flow, (4)

where f – the friction factor which is defined by Haaland function:

$$f = \left(-1.8 \log_{10} \left(\frac{6.9}{\mathrm{Re}} + \left(\frac{e}{3.7 d_p} \right)^{1.11} \right) \right)^{-2} . \quad (5)$$

where $\boldsymbol{e}$ – is the surface roughness for the pipe material.

The pressure drop across the porous element depends on its airflow resistivity and thickness, as well as on the air flow through it:

$$p_2 - p_a = \frac{r \cdot h \cdot G_p}{\rho_3 \cdot S_{out}}, \quad (6)$$

In this case, airflow resistivity for MR and PFM is determined according to the following expression obtained by empirical studies:

$$r = \frac{K_1}{d_H^{K_2}}, \quad (7)$$

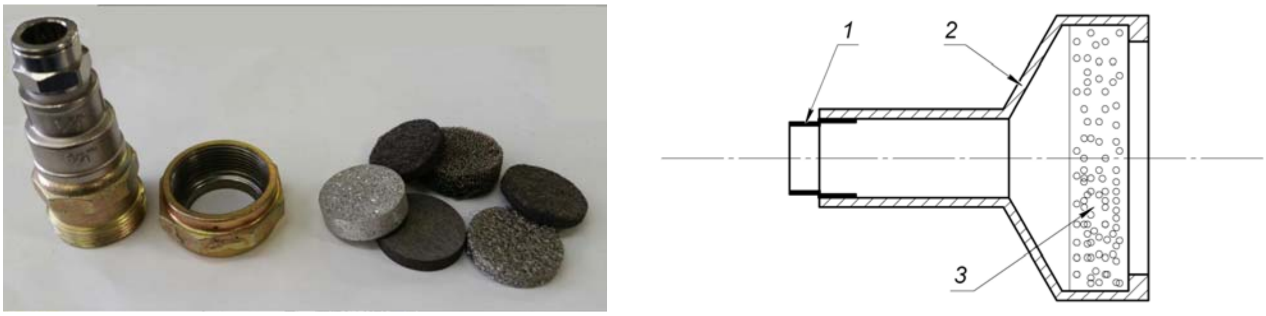
where $d_H = \frac{\varphi \cdot d_w}{(1-\varphi)}$ – is hydraulic diameter; d_w – fibre or wire diameter.

The airflow resistivity for porous aluminum can be determined by the following empirical relationship:

$$r = \frac{\mu}{K_3(\varphi)}. \quad (8)$$

Coefficients K_1, K_2 and $K_3(\varphi)$ were obtained as a result of fitting theoretical and experimental curves. Theoretical curve was received by solving the system of equations (1) - (8) in MatLab / Simulink.

To determine the efficiency of mufflers, the authors have carried out a series of experiments. Figure 2 shows the appearance of the muffler with various porous elements and its design diagram. Investigations of the effect of various porous metals and changes in their parameters on the efficiency of noise suppression have been conducted. Among such parameters, one can distinguish the porosity and height of the porous material. Our experimental study of the acoustic efficiency of a noise muffler have been carried out in a small echo-free room of the Samara University, which have made it possible to reduce the influence of external sources of noise and vibration on the system to a minimum, and also to avoid reflected waves inside the chamber.



a) muffler appearance; б) muffler design diagram
1 – air supply fitting; 2 – muffler casing; 3 – porous part
Figure 2 – Muffler

The experimental test bench also included a pressure gauge which recorded the time of a pressure drop. According to Russian State Standard GOST 25144-82, the time of the pressure drop in the system from 0.5 MPa to 0.2 MPa has to correspond to the inequality:

$$t_1 \leq 1.4t$$

where t is the pressure drop time in the system with the muffler made of porous metal, sec; t_1 is the time of a pressure drop in the system without a muffler, sec.

3. RESULTS

The measured normal sound absorption coefficients of the investigated porous metals are shown in Figure 3.

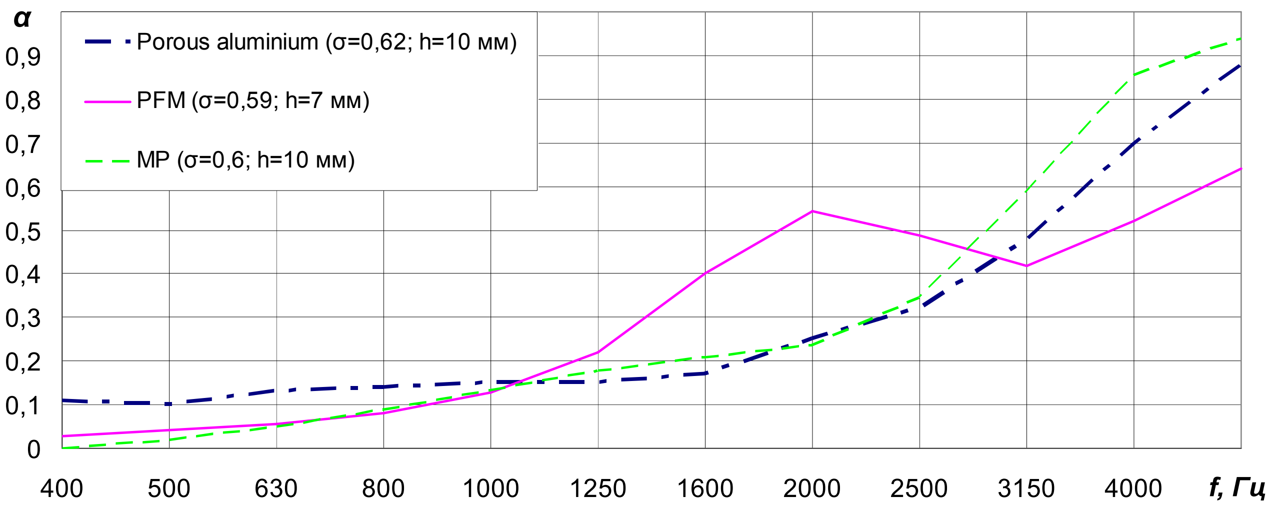


Figure 3 - Normal coefficient of sound absorption of the investigated porous metals

Figure 3 shows that porous metals have a rather low coefficient of sound absorption at frequencies as high as 1600-2500 Hz, at higher frequencies the sound absorption coefficient is more than 0.3, which indicates the high efficiency of using these materials in the noise muffler.

As a result of a series of experiments for different configurations of the muffler, the pressure drop in the receiver was determined.

Table 2 - Pressure drop time in the receiver

Sound absorber of the muffler	L_A, dBA	t, sec.	t/t_1
Without a muffler	121	15,4	1
Porous aluminium (σ=0,62; 10 mm)	89,2	25,2	1,64
Porous aluminium (σ=0,51; 15 мм)	94,5	42,4	2,75
PFM (σ =0,76; h=5 mm)	93,2	16,6	1,08
PFM (σ =0,59; h=7 mm)	93,1	27,1	1,76
PFM (σ =0,85; h=6 mm)	93,7	16,4	1,06
PFM (σ =0,85; h=6,5 mm)	94	18	1,17
PFM (σ =0,85; h=12,5 mm)	84,7	20,3	1,32
MR (σ =0,9; h=10 mm)	109,8	15,6	1,01
MR (σ =0,6; h=6,5 mm)	107,3	17,5	1,14
MR (σ =0,7; h=10 mm)	97,8	19,1	1,24

According to the experimental data shown in Table 2, the noise muffler made of porous aluminum and based on PFM (P = 0.59, h = 7 mm) does not correspond to Russian State Standard GOST 25144-82. Therefore, they are not considered in the further analysis of the experimental data.

Further, we will consider noise mufflers based on PFM and MR which satisfy the requirement $t_1 \leq 1.4t$.

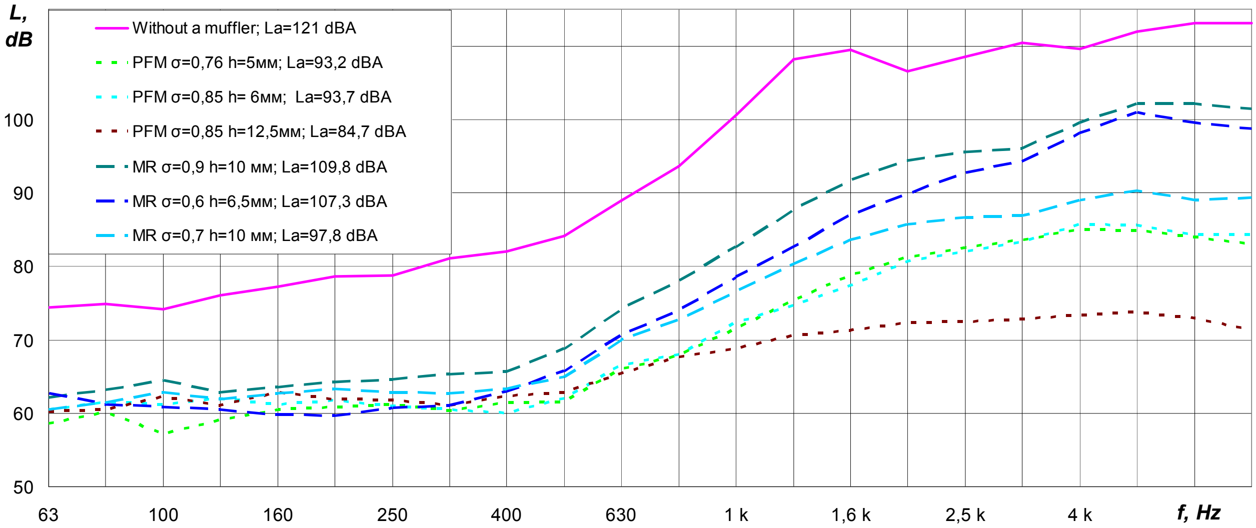
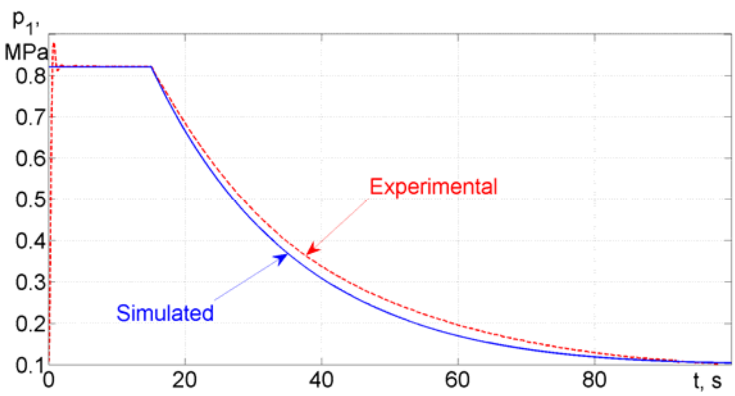


Figure 5 - Comparison of the sound pressure levels without a muffler and a muffler made of porous metals

When conducting these measurements, the background noise level (not shown in the graph) appeared to be lower by more than 10 dB than noise level with a silencer.

As a result of the tests, the acoustic efficiency of various porous metals in a noise silencer was evaluated. PFM, MR within the whole frequency range showed high efficiency within the whole investigated frequency range. The highest efficiency in the samples made of PFM was shown by a specimen with porosity of 0.85 and height of 12.5mm (Fig. 5a). The time of pressure drop from 0.5 MPa to 0.2 MPa was 27 sec. The efficiency of the muffler with this PFM was 36.3 dBA. In the MR, the most effective specimen had porosity of 0.7 and height of 10mm. The time of pressure drop from 0.5 MPa to 0.2 MPa was 24 sec (Fig. 5c). The efficiency of the muffler with this MR sample was 23.2 dBA.



a

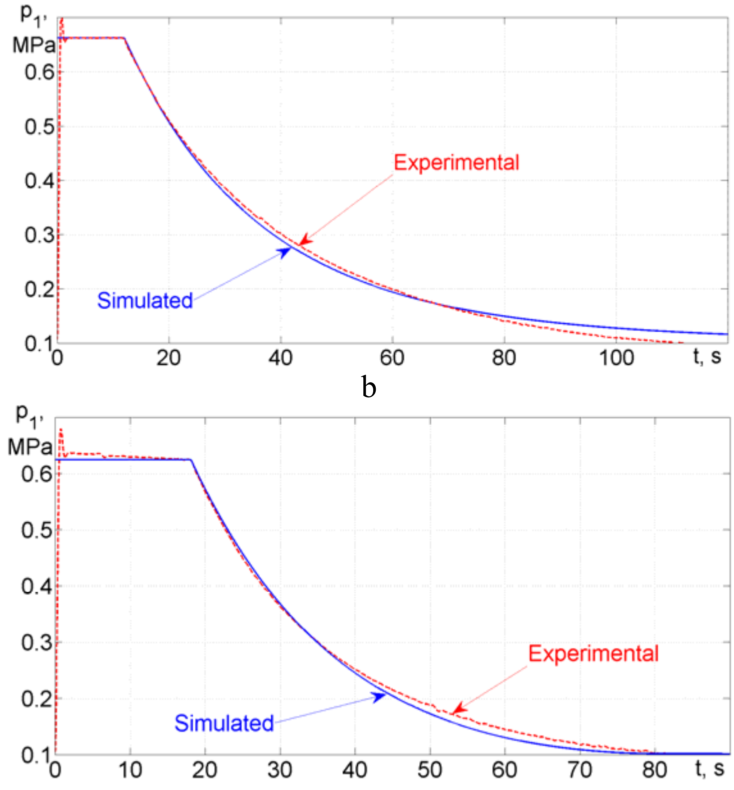


Fig. 5. Transient processes of pressure change in the receiver when installing a muffler with PFM (a) ($\varphi = 0.85$, $h = 12.5 mm$), porous aluminium (b) ($\varphi = 0.62$, $h = 10 mm$) and MR (c) ($\varphi = 0.7$, $h = 10 mm$)

These figures demonstrate agreement between simulated and experimental data.

We have found that coefficients for PFM were determined $K_1 = 0.1$ and $K_2 = 1.83$; for MR $K_1 = 0.002$ and $K_2 = 2$; for porous aluminium ($\varphi = 0.62$, $h = 10 mm$) $K_3 = 9.5 \cdot 10^{-12}$.

4. Conclusions

As a result of this research, a noise muffler based on porous metals has been developed. The test bench has been upgraded to test various noise-based mufflers based on porous metals to assess the acoustic efficiency. The software for data processing in LabVIEW has been developed. We have also developed a measurement system based on National Instruments equipment which allows recording real-time noise and pressure values.

A large number of tests were carried out at the upgraded test bench for evaluating acoustic efficiency of a muffler based on porous metals. In particular, the acoustic efficiency of the following porous metals was estimated: MR, PFM, porous aluminum. As a result of a number of tests, acoustic efficiency of 36.3 dBA was achieved, a noise muffler based on PFM which meets all GOST 25144-82 requirements. One of the disadvantages of PFM material is that such material is vulnerable to vibrations due to the fact that it is sintered, while MR has no such disadvantage. MR let us achieved acoustic efficiency of 23.2 dBA.

However, K_3 was determined for a particular material, whereas, in further research we intend to proceed with an investigation of acoustic efficiency of porous aluminium and we will determine K_3 for a material in general.

Acknowledgements

This work was supported by the Ministry of Education and Science of the Russian Federation and by the Russian Federation President's grant (project code MD-3082.2017.8).

REFERENCES

1 V.A. Budaev, E.A. Krainova, Mufflers of aerodynamic noise for machine tools, Interbranch Scientific and Technical Magazine «Vestnik Mashinostroeniya»/Russian Engineering Research. 2 (2001) 272-276.

2 A. Igolkin, Muffler of exhaust air, 21st International Congress on Sound and Vibration. (2014) 2027–2034

3 L. Jingxiang, Z. Shengdun, I.Kunihiko Study on acoustical properties of sintered bronze porous material for transient exhaust noise of pneumatic system, Journal of Sound and Vibration. 2 (2001) 332 (2013) 2721–2734

4 A.B. Finkel'stein, I.S. Kazantsev, V.G. Starkov Acoustic characteristics of porous cast aluminum, Life safety. 4 (2006) 21-23.

5 Igolkin, A., Afanasev, K., Shakhmatov, E. and Stadnik, D. The Study of Muffler Parameters Influence on Pressure Regulator Dynamics and Acoustic Characteristics, *Proceedings of the 23^d International Congress on Sound and Vibration*, Athens, Greece, 10-14 July (2016).

6 Kosenkov, P., Makaryants, G. Experimental investigation of semi-active pneumatic isolator, *Proceedings of the 23^d International Congress on Sound and Vibration*, Athens, Greece, 10-14 July (2016).

7 Ermilov, M.A., Kryuchkov, A.N., Balyaba, M.V., Shabanov, K.U. Development of a Pressure Pulsation Damper for Gas Pressure Regulators with Account of Operation Parameters, *Procedia Engineering.* Volume 106 (2015) 277-283.

8 Safin, A.I. , Igolkin, A.A., Degtyarev, M.V., Izzheurov, E.A., Shakhmatov, E.V. Some research aspects of acoustic characteristics of metal rubber produced with new technology, 21st International Congress on Sound and Vibration. (2014) 4297-4303

9 Fraltsov, A.S., Igolkin, A.A., Ilyukhin, V.N., Shakhmatov, E.V. Investigation of the characteristics of exhaust mufflerss for pneumatic systems, Proceedings of the 9th International Scientific and Technical Conference "Innovation, Ecology and Resource-Saving Technologies". (2010) 804-807.

10 Borisov, B.V., Serov, M.M. Forming porous fibrous materials by the pendant drop melt extraction, Russian Journal of Non-Ferrous Metals. Volume 54 (2013) 407-411

11 Nikitin, K.V., Finkel'shtein, A.B., Chikova, O.A., Timoshkin, I.Y. Influence of the structure of the AlSi20 foundry alloy on the microstructure and viscosity of the Al-6% Si model silumin in solid and liquid states, Russian Journal of Non-Ferrous Metals. Volume 54 (2013) 314-319

12 Igolkin, A., Kryuchkov, A., Safin, A., Soroka, I. Silencer optimization for the pressure reducing valve, 20st International Congress on Sound and Vibration. (2013) 1009–1016

13 Chung, J.Y., Blaser, D.A. Transfer function method of measuring in-duct acoustic properties. I. Theory, Journal of the Acoustical Society of America. Volume 68 (1980) 907-913.

14 Chung, J.Y., Blaser, D.A. Transfer function method of measuring in-duct acoustic properties. II. Experiment, Journal of the Acoustical Society of America. Volume 68 (1980) 914-921.

15 Gerc, E. V. Raschyot pnevmoprivodov: sprav. posobie / E. V. Gerc, G. V. Krejnin. – M.: Mashinostroenie, 1975. – 272 s. (In Russian)