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Experimental study of the ultrasonic muffler efficiency for improving the exhaust gas cleaning system of internal combustion engines of automobiles

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Abstract. In this paper, an extensive study has been carried out on the use of ultrasound for the purpose of cleaning automotive exhaust gases. The main focus is on the use of ultrasonic emitter in automotive muffler design. The paper presents a detailed analysis of the theories associated with the ultrasonic coagulation process and an in-depth description of the physical aspects of the ultrasonic muffler. Methods for evaluating gas cleaning efficiency are also discussed and the importance of using energy consumption as a criterion for evaluating the efficiency of an ultrasonic silencer is emphasised. The paper presents a computational methodology for evaluating the efficiency of a new muffler design based on consideration of the power consumed by the engine to pass gases through the muffler. For experimental verification of the ultrasonic silencer efficiency, a special bench was created to measure the smokiness of gases at changing engine speeds. Experimental results confirmed the effectiveness of the ultrasonic silencer, showing a reduction in the smokiness of gases at a certain combination of speed and frequency of ultrasonic waves, which led to the best cleaning of exhaust gases.

Keywords: ultrasonic gas cleaning, car muffler design, muffler operation mode, exhaust gas cleaning system, internal combustion engine.

1. Introduction

In modern times, in an era of onrush of vehicle technologies, the problem of exhaust gas purification is making it as one of the most critical and important objectives facing mankind. Exhaust gas emissions containing harmful chemical compounds, hydrocarbons and heavy metals have increased with expansion of global traffic far more [1]. This problem has serious impacts on the environment, human health and climate change [2]. Studies show that these contaminants in the air are linked to a number of diseases and conditions, including respiratory diseases, allergies, lung cancer, cardiovascular disease and even neurological disorders. [3,4]

There are several methods of treating vehicle exhaust gases to reduce harmful emissions into the environment. These include catalytic converters (catalysts), exhaust gas recirculation (EGR) systems, diesel particulate filters (DPF), selective catalytic reduction (SCR), and particulate matter (PM) cleaning systems [5,6]. There are also industrial purification systems (absorption, sorption, oxidation, etc.), electric chambers and electric filters [7,8]. However, these cleaning methods have a shared disadvantage: they increase the energy and fuel costs of the engine, increase their operating costs and have a negative impact on the overall effectiveness of vehicles, causing reduced gas purification performance.

Moreover, not all the methods shown are capable to neutralize gases from their harmful fine particles. For example, catalysts, EGR and SCR are mainly focused on reducing nitrogen oxide (NOx) emissions [9,10]. As to gas purification systems each method specializes in cleaning a specific type of gas particles. For example, sorption is effective in capturing only aerosols and volatile organic compounds, oxidation methods - gaseous pollutants (hydrogen sulfide or nitrogen oxides), absorption - gases and their particles in liquids, and electrolysis is not used at all to capture fine particles in gases [11,12]. Therefore, the methods placed are potentially limited in the capture of all types of pollutants, including fine gas particles, requiring the search for new alternative purification methods.

This led to the idea of ultrasonic blast cleaning of vehicle exhaust. The advantage of ultrasound in exhaust gas purification is the ability to remove fine particles of gas, including soot, which contributes to an increased cleaning rate of up to 95%. Besides, the ultrasonic method does not require to use chemical reagents, thus avoiding to add second substances in the cleaning process [13,14]. Also unlike some traditional cleaning methods, this one does not require high energy costs. Design solutions are available for the installation of ultrasonic cameras between the engine collector and the muffler [15,16]. However, this approach can significantly complicate vehicle design and limit the possibilities of its modernization in the future.

So, we offer a more practical solution: installing an ultrasonic pulse in the body of the vehicle muffler. A muffler fitted with ultrasonic equipment (ultrasonic muffler) can reduce the toxicity of gas emissions without providing a significant pressure on the engine itself. This solution has a number of advantages, as the ultrasonic muffler does not take up a lot of power in the process, and its development and installation do not require significant financial costs. This approach combines efficiency with convenience and economy, making it a profitable option to increase the environmental compatibility of vehicles.

The hypothesis of the study was to confirm the potential ability to clean ultrasonic car exhaust emissions through the use of ultrasonic equipment in a muffler. The main objective of the study was to develop a methodology describing the efficiency of the ultrasonic muffler. This objective was achieved by solving several key problems: analysing existing theories related to acoustic coagulation; developing a research methodology that evaluates the efficiency of an ultrasonic silencer by measuring the engine power consumption of gas particles; developing a full-size ultrasonic muffler test rig to conduct the relevant experimental studies; conducting experiments to confirm the initial hypothesis and obtaining specific numerical values that confirm the products of the ultrasonic muffler.

The study acquires practical significance due to the possibility of applying the obtained functional relations and dependencies to the design and calculation of ultrasonic mufflers. This, in turn, can contribute to improving the efficiency of the process of purification of car exhaust gases.

2. Methods and Experiments

The ultrasound study showed its ability to intensify the process of "coagulation", leading to the sticking or joining of gas particles during collisions with each other. Therefore, ultrasound can effectively increase the size and mass of the finest particles in the gaseous environment, making them more suitable for capture and disposal.

The fundamental approach to get the formation of coarse particles from fine ones is given by Smoluhovsky's Theory. The basic principles of Smoluhovsky's Theory of coagulation include the following:

1) Diffusion process: Smoluhovsky suggested that coagulation is a result of random collisions of particles. These impacts may result in larger aggregates if the collision energy exceeds the separation barrier energy;

2) Diffusion barrier: Particles can move as a result of thermal motion. However, for them to coagulate, it is necessary to overcome the diffusion barrier requiring auxiliary energy. This barrier becomes higher as the particle size decreases and the charge increases;

3) Electrostatic interactions: An important aspect of Smoluhovsky's Theory is the cost of electrostatic interactions between particles. Particle charges can cause repulsion or attraction between them, which affects the probability and nature of coagulation;

4) Coagulation kinetics: Smoluhovsky's Theory describes coagulation kinetics using an equation known as the Smoluhovsky equation:

$$-\frac{dn}{d\tau} = Kn^2, \tag{1}$$

where K – thermal coagulation constant, m/s. It characterizes the probability of particle convergence.

This equation entertains the possibility of molecular collision and the dependence of coagulation rate on particle concentration and temperature. A more complete picture of coagulation kinetics is provided by Smoluhovsky's equation including the Einstein's diffusion equation. Einstein's equation describes the diffusion of particles in gas and can be integrated into Smolukhovsky's equation to account for diffusion contributions to the coagulation process. So, Smoluhovsky's modified equation with Einstein's equation for diffusion will be as follows [17, 18]:

$$\frac{dn}{dt} = 2\pi DSn^2 \tag{2}$$

$$D = \frac{RT}{6\pi\eta rN} \tag{3}$$

$$\frac{dn}{dt} = \frac{1}{3}\frac{RTSn^2}{\eta rN} \tag{4}$$

However, insight of ultrasonic coagulation in the muffler is difficult and requires additional cost factors that are not included in the classical Smoluhovsky Theory. For example, hydrodynamic movement also arises in the muffler, apart from the Brownian particle movement, which can lead to turbulence in the gas flow. Moreover, the particle may fluctuate under radiation pressure under a calm environment [19,20].

However, there is a gas movement at a certain speed within the muffler changing the nature of these particle oscillations. Hence, to get such a complex process requires more in-depth research and even the development of individual models and experiments to further assess the gas purification and ultrasonic muffler effectiveness.

The evaluation of gas purification degree and the effectiveness of the vehicle ultrasonic muffler can be done using various methods and parameters. There are the following main ways to evaluate gas purification:

- Measurement of the content of gas emissions. The most direct way is to measure the concentration of the exhaust gas before and after exposure to ultrasound. This method involves the measurement of carbon dioxide (CO_2), oxygen (O_2) hydrocarbon (HC), carbon oxides (CO), fine particles and other pollutants. By comparing these values, it is possible to assess how effectively the ultrasonic muffler reduces emissions.

- Use of standards and regulations. Comparison of measurement results with environmental standards and regulations set by regulators to determine the conformity of exhaust gases with established norms. According to GOST *"P 51250-99. Internal combustion engines piston-type. Smoke of exhaust gases. Standards and test methods"* [20] where D gas opacity is the normative parameter for determining gas toxicity. This indicator not only evaluates the fume cleaning performance, but also fully reflects the performance of the muffler and the exhaust system. Providing the assessment of ultrasonic muffler operation and cleaning degree, it is necessary to take the ratio of gas smoke after and before the exposure to ultrasound D_2/D_1.

- Testing unit: Laboratory tests and tests on specially designed testing units can be performed to better evaluate gas purification. Under these conditions, you can control the parameters and repeat the experiments.
- Fuel consumption monitoring: Changes in fuel consumption may indicate the efficiency of the cleaning system. If the system does not operate optimally, it may affect fuel consumption.
- Exhaust temperature measurement: Increased exhaust temperature may indicate cleaning problems as some systems may require certain temperatures for efficient operation.

However, the methods placed are not able to fully assess the performance of the ultrasonic muffler, as they do not include the efficiency of energy consumption, as in do not describe how much energy the muffler consumes to operate in optimal modes and to ensure the necessary level of reduction of harmful particles in the environment. Thus, the efficiency of the ultrasonic muffler is offered to be evaluated by the gas tolerance. Gas flow estimation in the exhaust system of vehicle based on the gas capacity is an important aspect of engineering calculations and optimization. Key aspects to estimate the effectiveness of the ultrasonic muffler of gas power costs are as follows:

- system efficiency. Estimation of the gas power consumption allows to determine the efficiency of the exhaust system. The lower the power required to move gases through the system, the more efficient the system is;
- resistance minimization: The power cost estimate allows to identify possible resistance to gas movement in the exhaust system. Minimizing this resistance can reduce engine load and improve operation efficiency;
- reducing toxic emissions: Reducing the gas capacity can also help reduce emissions to the atmosphere. Less efficient systems can cause increased pollutant emissions, which negatively affects the environment;
- design and upgrade: The estimation of gas capacity is important when designing new exhaust systems or upgrading existing ones. This helps engineers to choose optimal components and configurations for maximum efficiency;
- economic efficiency: Gas capacity cost analysis also has an economic aspect. Lower costs can reduce operating costs and improve the competitiveness of vehicles or production processes.

In general, the estimation of gas flow based on power input plays an important role in engineering calculations and optimization of exhaust systems. This helps not only to reduce the negative impact on the environment, but also to improve the optimum and efficient operation of vehicles.

In order to estimate the power input for the movement of gas particles inside the muffler, the following calculation method was developed, which considers the equation of gas energy change in the purification system. Gas energy change equation ΔE is shown as a change in the kinetic energy of the gas on exit from the engine collector and at the input to the muffler (without the influence of ultrasound), as well as the operation performed by external forces (under the condition of ultrasonic action) from the ultrasonic emitter:

Without ultrasound:

$$\Delta E = E_{\text{exit}}^{\text{collector}} - E_{\text{input}}^{\text{muffler}}, \quad (5)$$

With exposure to ultrasound:

$$\Delta E = E_{\text{exit}}^{\text{collector}} - E_{\text{input}}^{\text{ultrasonic muffler}} + A_{\text{ultrasound}}. \quad (6)$$

where $E_{\text{exit}}^{\text{collector}}$ – exhaust gas energy from engine collector, J;

$E_{\text{input}}^{\text{muffler}}$ – input gas energy in engine muffler, J;

$E_{\text{input}}^{\text{ultrasound muffler}}$– input gas energy in ultrasonic engine muffler, J;

$A_{\text{ultrasound}}$ – operation performed by ultrasonic gas, J.

Then equation (5) was converted as follows:

Without ultrasound:

$$\Delta E = \frac{m\vartheta_{\text{exit}}^2}{2} - \frac{m\vartheta_{\text{input}}^2}{2}, \quad (7)$$

With exposure to ultrasound:

$$\Delta E = \frac{m\vartheta_{\text{exit}}^2}{2} - \frac{m\vartheta_{\text{ultrasound input}}^2}{2} + \mathrm{A}_{\text{ultrasound}}, \quad (8)$$

where m – gas mass, kg;

ϑ_{exit} – engine collector exhaust gas speed, m/s;

ϑ_{input} – speed of input gas to engine muffler, m/s;

$\vartheta_{\text{ultrasound input}}$ – speed of input gas to engine ultrasonic muffler, m/s.

The operation performed by the ultrasonic action on gas in turn has been converted as kinetic energy of the gas particles oscillating from the ultrasound side:

$$A_{\text{ultrasound}} = \frac{mU^2_{\text{ultrasound}}}{2}, \quad (9)$$

where $U_{\text{ultrasound}}$ – ultrasonic oscillation speed of gas particles.

Hence the following equation for changing the energy of gas ΔE was obtained under the condition of ultrasound:

$$\Delta E = \frac{m\vartheta^2_{\text{exit}}}{2} - \frac{m\vartheta^2_{\text{input}}}{2} + \frac{mU^2_{\text{ultrasound}}}{2} \quad (10)$$

By dividing equation (4) for the operation time t, the equation for the change of power consumption for the movement of gas particles ΔN was obtained:

Without ultrasound:

$$\frac{\Delta E}{t} = \frac{m\vartheta^2_{\text{exit}}}{2t} - \frac{m\vartheta^2_{\text{input}}}{2t}, \quad (11)$$

$$\Delta N = N_{\text{collector}} - N_{\text{muffler}}. \quad (12)$$

With exposure to ultrasound:

$$\frac{\Delta E}{t} = \frac{m\vartheta^2_{\text{exit}}}{2t} - \frac{m\vartheta^2_{\text{input}}}{2t} + \frac{mU^2_{\text{ultrasound}}}{2t}. \quad (13)$$

$$\Delta N = N_{\text{collector}} - N_{\text{muffler}} + N_{\text{ultrasound}}. \quad (14)$$

The resulting equation (12) was then converted as follows:

$$N_{\text{collector}} = P_{\text{collector}} S_{\text{collector}} \vartheta_{\text{exit}} \quad (15)$$

$$N_{\text{muffler}} = P_{\text{muffler}} S_{\text{muffler}} \vartheta_{\text{input}} \quad (16)$$

$$N_{\text{ultrasonic muffler}} = P_{\text{ultrasonic muffler}} S_{\text{ultrasonic muffler}} \vartheta_{\text{ultrasonic input}} \quad (17)$$

Without ultrasound:

$$\Delta N = P_{\text{collector}} S_{\text{collector}} \vartheta_{\text{exit}} - P_{\text{muffler}} S_{\text{muffler}} \vartheta_{\text{ input}} \quad (18)$$

With exposure to ultrasound:

$$\Delta N = P_{\text{collector}} S_{\text{collector}} \vartheta_{\text{exit}} - P_{\text{ultrasound muffler}} S_{\text{ultrasonic muffler}} \vartheta_{\text{ultrasonic input}} + N_{\text{ultrasound}}. \quad (19)$$

where $P_{\text{collector}}$ – Engine exhaust collector pressure, Pa;

P_{muffler}– Engine pressure in muffler, Pa;

$P_{\text{ultrasound muffler}}$– Pressure in ultrasonic engine muffler, Pa.

Exhaust gas losses at collector exit (ϑ_{exit}) and at muffler input (ϑ_{input}) were calculated using the mass retention equation for gas flow and the Bernoulli equation.

Mass conservation equation for gas flow:

For the collector:

$$S_{\text{exit}} \rho_{\text{exit}} \vartheta_{\text{exit}} = S_{\text{collector}} \rho_{\text{collector}} \vartheta_{\text{collector}}, \quad (20)$$

where S_{exit} – gas flow exit area from the collector, m^2;

ρ_{exit} – reservoir exit gas density, kg/m^3;

$S_{\text{collector}}$ – collector flow area, m^2;

$\rho_{\text{collector}}$ – gas density in collector, kg/m^3;

$\vartheta_{\text{collector}}$ – gas velocity in collector, m/s.

For no impact and ultrasonic muffler:

$$S_{\text{input}}\rho_{\text{input}}\vartheta_{\text{input}} = S_{\text{muffler}}\rho_{\text{muffler}}\vartheta_{\text{muffler}}, \tag{21}$$

$$S_{\text{input}}\rho_{\text{input}}\vartheta_{\text{input}} = S_{\text{ultrasonic muffler}}\rho_{\text{ultrasonic muffler}}\vartheta_{\text{ultrasonic muffler}}. \tag{22}$$

where S_{input} – gas input flow area in the muffler, m^2;

ρ_{input} – input gas density to the muffler, kg/m^3;

S_{muffler} – muffler flow area, m^2;

ρ_{muffler} – gas density in muffler, kg/m^3;

$\vartheta_{\text{muffler}}$ – gas velocity in muffler, m/s.

Bernoulli equation (with minor changes in height and possible pressure):

For the collector:

$$\frac{1}{2}\rho_{\text{exit}}\vartheta_{\text{exit}}^2 = \frac{1}{2}\rho_{\text{collector}}\vartheta_{\text{collector}}^2, \tag{23}$$

For no impact and ultrasonic muffler:

$$\frac{1}{2}\rho_{\text{input}}\vartheta_{\text{input}}^2 = \frac{1}{2}\rho_{\text{muffler}}\vartheta_{\text{muffler}}^2, \tag{24}$$

$$\frac{1}{2}\rho_{\text{input}}\vartheta_{\text{input}}^2 = \frac{1}{2}\rho_{\text{ultrasonic muffler}}\vartheta_{\text{ultrasonic muffler}}^2. \tag{25}$$

Given the collector/muffler areas and their sections $S = const$ and that the gas is not compressed or expanded substantially $\rho = const$ remain, so the equation of mass conservation for the gas flow and the Bernoulli equation follows:

For the collector:

$$\vartheta_{\text{exit}} = \vartheta_{\text{collector}}, \tag{26}$$

For no impact and ultrasonic muffler:

$$\vartheta_{\text{input}} = \vartheta_{\text{muffler}}, \tag{27}$$

$$\vartheta_{\text{input}} = \vartheta_{\text{ultrasonic muffler}}. \tag{28}$$

This means that the exhaust gas velocity at the collector exit is equal to the gas velocity in the collector and the exhaust gas velocity at the exhaust input to the muffler is equal to the gas velocity in the muffler. Therefore, equation (7) has been converted as follows:

Without ultrasound:

$$\Delta N = P_{\text{collector}}S_{\text{collector}}\vartheta_{\text{collector}} - P_{\text{muffler}}S_{\text{muffler}}\vartheta_{\text{muffler}} \tag{29}$$

With exposure to ultrasound:

$$\begin{aligned}\Delta N = P_{\text{collector}}S_{\text{collector}}\vartheta_{\text{collector}} \\ -P_{\text{ultrasonic muffler}}S_{\text{ultrasonic muffler}}\vartheta_{\text{ultrasonic muffler}} + N_{\text{ultrasound}}.\end{aligned} \tag{30}$$

Collector and muffler pressure is defined as follows:

$$P_{\text{collector}} = P_{atmosphere} + \frac{1}{2}\rho\vartheta_{\text{collector}}^2, \tag{31}$$

Without ultrasound:

$$P_{\text{muffler}} = P_{\text{collector}} + \frac{1}{2}\rho\vartheta_{\text{collector}}^2 - \frac{1}{2}\rho\vartheta_{\text{muffler}}^2 \tag{32}$$

With exposure to ultrasound:

$$P_{\text{ultrasonic muffler}} = P_{\text{collector}} + \frac{1}{2}\rho\vartheta_{\text{collector}}^2 - \frac{1}{2}\rho\vartheta_{\text{ultrasonic muffler}}^2, \tag{33}$$

The gas velocity in collector, in muffler and in the ultrasonic muffler is determined as follows:

$$v_{\text{collector}} = \frac{Q\omega}{\pi r_{\text{collector}}^2}, \quad (34)$$

$$v_{\text{muffler}} = \frac{Q\omega}{\pi r_{\text{muffler}}^2} \quad (35)$$

$$v_{\text{ultrasonic muffler}} = \frac{Q\omega}{\pi r_{\text{ultrasonic muffler}}^2{}^2} \quad (36)$$

where Q – engine volume, m^3;

ω – engine rotational speed, rad/s;

r – radius of exhaust collector and mufflers.

Then experimental studies should be carried out to assess the degree of gas purification and the efficiency of the ultrasonic vehicle muffler. An experimental Ultrasonic Muffler Stand developed in the scientific laboratory of the Transport Engineering and Logistic Systems Department was used for experimental studies (Figure 1).

Fig. 1. – A full-sized Ultrasonic Vehicle Muffler Stand

A full-sized Ultrasonic Vehicle Muffler Stand (Figure 2) includes a 110 mm metal pipe and ultrasonic equipment. The experimental Ultrasonic Muffler Stand consists of the following structural components: 1 – Input pipe; 2 – Ultrasonic muffler body; 3 – ultrasonic emitter which propagates the ultrasonic wave through the inner casing of the muffler; 5 – Exit pipe.

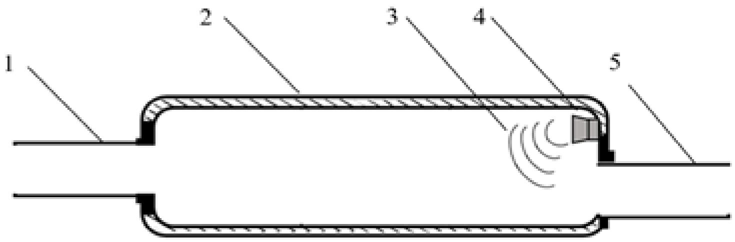

Fig. 2. – Schematic diagram of a full-sized Ultrasonic Vehicle Muffler Stand

Ultrasonic equipment consists of an ultrasonic generator and ultrasonic emitter (Figure 3). The power of ultrasonic equipment is 100 W.

Fig. 3. – Ultrasonic generator with ultrasonic wave emitters

To analyze the qualitative and quantitative composition of emissions from the exhaust system, the vehicle-type 4-component gas analyzer "Infracar M-1.01" was used.

The pilot studies were conducted in two phases. The first phase was to determine gas composition and the second one was to measure the opacity of the gases, including the effects and without ultrasound.

The pilot studies were as follows. The experimental tests were carried out in two modes: with and without ultrasonic equipment, where the ultrasonic exposure time was one minute, and the frequency of ultrasound exposure was 40 kHz.

These studies were performed on the laboratory diesel engine "D245" with a volume of 4750 cm^3 and a capacity of 245 horsepower. Engine ran at different crankshaft speeds: 1000, 1200 and 1400 rpm.

The exhaust gas from the vehicle was fed into the full-sized Ultrasonic Muffler Stand via an input pipe. Inside the stand, ultrasonic waves in the longitudinal direction were applied at 40 kHz ultrasonic frequency. The effects of ultrasound on gas flow have improved coagulation and cleaning by increasing particle size and soot deposition. The cleaned exhaust gas is then discharged through the exit pipe of the full-sized Ultrasonic Muffler Stand.

3. Results and discussion

The results of the pilot studies are shown in Table 1.

Table 1. Results of the pilot studies

Engine crankshaft speed (rev/min)	1000 rev/min		1200 rev/min		1400 rev/min	
	Without ultrasound	Ultrasonically *f*= 40 kHz	Without ultrasound	Ultrasonically *f*= 40 kHz	Without ultrasound	Ultrasonically *f*= 40 kHz
CH, ppm	0,00	0,00	0,00	0,00	0,02	0,02
CO, %	0,02	0,01	0,02	0,02	0,01	0,01
CO_2, %	1,38	1,36	1,39	1,36	1,40	1,39
O_2, %	18,66	18,7	18,97	18,98	18,56	18,56

Based on the results of the experiments, including the analysis of the emission composition, diagrams have been constructed (Figures 4 and 5) illustrating how oxygen (O_2) and carbon dioxide (CO_2) are changing depending on engine crankshaft speed, with or without the use of ultrasound with a constant impact frequency of 40 kHz.

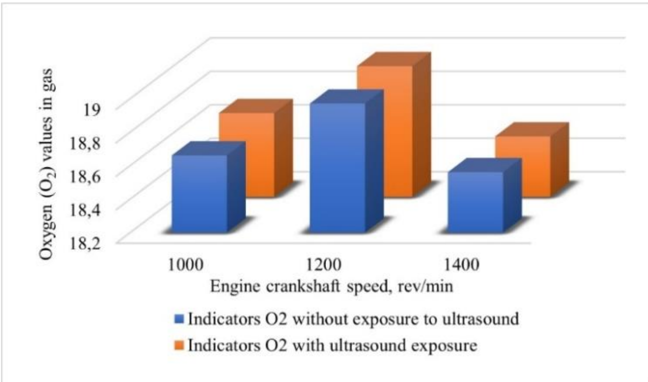

Fig. 4. – Changes in oxygen values (O_2) without exposure and with ultrasound

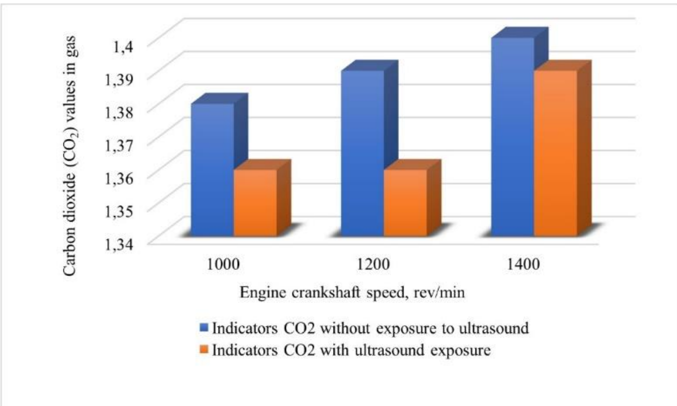

Fig.5. – Carbon dioxide CO_2 change without exposure and with ultrasound

The diagrams in Figures 4 and 5 confirm that ultrasound is indeed effective in influencing the composition and purification of emissions. Based on results obtained, it was found that when the engine crankshaft speed increases and under ultrasound, the percentage oxygen content increases and the carbon dioxide concentration in the exhaust gas decreases.

Then a diagram (Figure 6) was constructed based on results of the fumes experiments, showing how the smoke levels of the gases change depending on the presence or absence of ultrasound at a constant exposure frequency of 40 kHz.

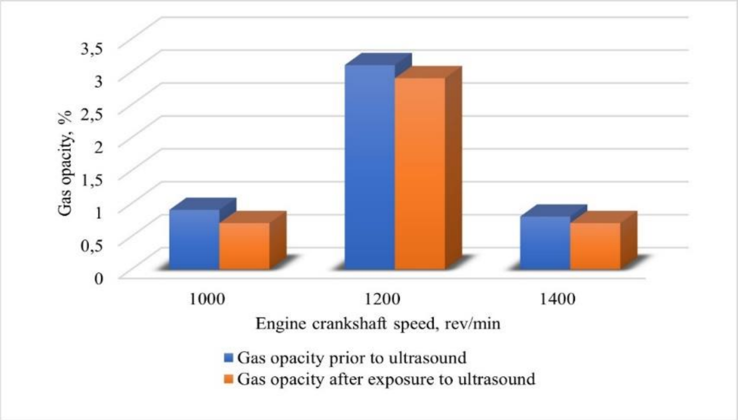

Fig.6. – Changes in gas opacity without exposure and with ultrasound

Studies have shown that the use of ultrasound has a positive effect on reducing smoke levels. This is confirmed by the fact that the numerical opacity of the gases after the application of ultrasound was lower than that of the non-ultrasonic gases. The use of ultrasound resulted in a reduction in smoke levels from 6 to 22 per cent.

It was also noted from the pilot studies that ultrasonic exposure does not cause significant changes in temperature and fuel consumption. This indicates that the ultrasonic equipment does not adversely affect the efficiency of the cleaning system and does not cause any deviation.

Using data on the smoke level of the gases, the ratio between the opacity of the ultrasonic gas exposed to ultrasound and not exposed to such exposure was calculated. This ratio is an important indicator of the ultrasonic muffler effectiveness, reflecting the degree of gas purification depending on the engine crankshaft rotation speed. The results of the D_2/D_1 calculations are shown in Table 2.

Table 2. D_2/D_1 ratio calculation results

Engine crankshaft speed (rev/min)	Engine crankshaft angular speed (rad/s)	Gas smoke ratio (D_2/D_1)
1000	104,7	0,77
1200	125,6	0,93
1400	146,6	0,875

Based on the calculations obtained, a diagram has been drawn up showing the relationship between the gas smoke ratio (D_2/D_1) and the engine crankshaft rotation rate (Figure 7).

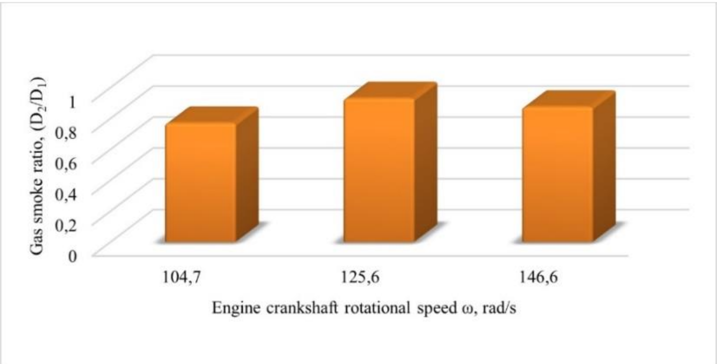

Fig.7. – Change in the ratio of gas smoke to engine crankshaft angular speed

The diagram in Figure 7 shows that when the engine crankshaft speed is increased, the gas smoke ratio is increased, for example at the angular speed of 125.6 rad/s the ratio (D_2/ D_1) has reached the maximum (0.93). This is because the increased angular velocity increases the velocity of the gas flow entering the inside of the muffler and, the coagulation process does not be in seconds at a faster gas flow. It takes time for the finest particles to come together and start settling. During this period, particles of different sizes should come into contact with each other and create major agglomerates. Therefore, it is possible to increase the gas opacity ratio with a sharp increase in angular velocity values, as the intensity of the coagulation process has not reached the required level. However, there is a decrease in the opacity (0.875) with a further increase in the angular velocity (146 rad/s), which indicates that the coagulation process has entered an intensive phase and the gas particles have gradually started to coagulate and settle, thereby increasing the transparency of the gas and reducing its smoke level. Thus, the coagulation process intensifies the gas purification efficiency and reduces the number of partially burned particles when exposed to the gas by ultrasound.

The efficiency of the ultrasonic muffler was then estimated by the power input per gas movement through the exhaust system. Typically, the exhaust system, as in, to conduct the exhaust gas through the system and to remove it to the atmophere is spent in the order of 1-5% of the power of the entire engine of the vehicle. It is supposed that the power consumption for gas movement will decrease using the ultrasonic muffler. This is because, compared to the current mufflers, the ultrasonic muffler has a simple design that does not allow for the free passage of gases and provides no resistance, thus keeping the engine power input. Moreover, ultrasonic equipment does not consume much power and does not impose other load on the engine. So, to confirm these assumptions, a calculation of the gas flow capacity cost was made through the muffler, including the impact and without the impact of ultrasound, according to the earlier calculation method provided.

Calculation of the capacity cost for gas movement in a muffler with and without the exposure to ultrasound:

Without ultrasound:

Collector gas velocity:

$$v_{\text{collector}} = \frac{0{,}00475 \cdot 104{,}7}{0{,}0052} = 95{,}63$$

Collector pressure:

The average atmospheric pressure is about $P_{atmosphere}$ = 101.3 kPa

The average exhaust gas density is ρ=0,8-1,4 kg/m³ for more accurate calculations is assumed ρ=1,225 kg/m³.

$$\mathrm{P}_{\text{collector}} = 101{,}3 \cdot 10^3 + 5601{,}37 = 106901{,}37$$

Gas velocity in muffler:

$$v_{\text{muffler}} = \frac{0{,}00475 \cdot 104{,}7}{0{,}002826} = 175{,}98$$

Muffler pressure:

$$\mathrm{P}_{\text{muffler}} = 106901{,}37 + 5601{,}37 - 18968{,}48 = 93534{,}26$$

Gas flow capacity costs:

$$\Delta N = 53159{,}48 - 46516{,}40 = 6643{,}085$$

With exposure to ultrasound:

Ultrasonic muffler area S_{muffler}:

$$S_{\text{ultrasonic muffler}} = 3{,}14 \cdot 0{,}055 = 0{,}0094985$$

Gas velocity in ultrasonic muffler:

$$v_{\text{ultrasonic muffler}} = \frac{0{,}00475 \cdot 104{,}7}{0{,}0094985} = 52{,}35$$

Pressure in ultrasonic muffler:

$$P_{\text{ultrasonic muffler}} = 106901{,}37 + 5601{,}37 - 1678{,}57 = 110824{,}17$$

Gas flow capacity costs:

$$\Delta N = 53159{,}48 - 50490{,}07 + 50 = 2719{,}4$$

Total engine power:
$N_d = 180197$ W
Percentage of muffler power consumption of total engine power:

Without ultrasound:

$$180197 - 100\%$$
$$6643{,}085 - x$$

$$x = \frac{6643{,}085 \cdot 100\%}{180197} = 3{,}68\%$$

Ultrasonically:

$$180197 - 100\%$$
$$2719{,}4 - x$$

$$x = \frac{2719{,}4 \cdot 100\%}{180197} = 1{,}5\%$$

Reduction of the power cost for gas movement if using the ultrasonic muffler:

$$3{,}68\% - 1{,}5 = 2{,}18\%$$

As it was noted earlier, engine power costs per exhaust system are about 1-5%. Therefore, if an ultrasonic muffler is used, the power consumption of the exhaust system will be reduced by 2.18%.

In this way, it is possible to achieve positive changes in gas composition, to get reduced gas opacity and to reduce power costs using an ultrasonic muffler that may be important for compliance with environmental standards, increase efficiency and reduce harmful gas emissions in the vehicle exhaust system.

Conclusion

The study described in the article represents a new method of exhaust gas purification of internal combustion engines from harmful particles by using ultrasonic emitters in vehicle mufflers. The authors emphasize that the use of ultrasound for exhaust gas purification is proved by its low energy consumption and rather low development and installation costs. This approach combines efficiency, accessibility and economic viability, making it the palatable option for improving the environmental sustainability of vehicles.

The article describes various ways to assess muffler effectiveness equipped with an ultrasonic emitter, including analysis of the emission composition, measurement of gas opacity, conducting testing units and monitoring the parameters of the temperature and fuel consumption. Also to assess the economic feasibility to use such a muffler, it is offered to assess using indicators of power costs for the gas flow through the exhaust system.

The article also describes a full-sized Ultrasonic Muffler Stand where pilot studies were conducted to determine the gas composition, gas opacity and temperature and fuel consumption fixation, including the effects and non-effects of ultrasound on gas.

The results of the experiments on the full-sized stand showed that the introduction of ultrasonic emitters reduces gas opacity, increases the oxygen content and reduces the level of carbon dioxide in emissions, and the change in temperature and fuel consumption were almost negligible, confirming the optimum operation of the ultrasonic muffler. Overall cleaning efficiency reached 6 to 22 per cent depending on the experimental conditions, as in, engine speed change.

Also, there is a change in the ratio of gas opacity when increasing the engine crankshaft angular speed. For example, a decrease in the gas opacity ratio was achieved and the overall cleaning rate was rather 12-23% at the maximum engine crankshaft angular velocity values selected in the pilot studies. As to the developed methodology for calculating the gas power consumption, it was determined that if we use an ultrasonic muffler, the engine power input for the exhaust system will be reduced by 2.8%. The obtained results prove that ultrasound has the potential as an effective method of exhaust gas purification and underlines the importance of realising further study in this area.

Studies obtained in the article makes an important contribution to the development of innovative methods of exhaust gas purification contributing to more efficient and eco-friendly vehicle operation.

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