DOI 10.52209/2706-977X_2024_4_58 **IRSTI 55.42.01** **UDC 621.43**

Modeling of Purification Process of Vehicle Exhaust Gases under the Influence of Ultrasound

Suyunbaev Sh.*
Tashkent State Transport University, Tashkent, Uzbekistan
*corresponding author

Abstract. Research is related to ultrasonic purification of exhaust gases of internal combustion engines of vehicles. The hypothesis of using ultrasonic radiation for purification of exhaust gases from harmful impurities and solid particles is proposed. The scheme of the ultrasonic muffler developed by the authors is presented. A mathematical model of the coagulation of exhaust gas particles in an ultrasonic muffler has been developed. Theoretical dependencies of coagulation coefficient are obtained. An experimental stand has been developed that models an ultrasonic muffler. The results of experimental studies proving possibility and efficiency of using the process of ultrasonic purification from harmful impurities and solid particles are presented. The dependencies of the content of harmful impurities in the exhaust gases were obtained, without exposure and under the influence of ultrasound at different engine revolutions. Experimental relationships of changes in toxic impurities and solid particles (exhaust carbon) are used in the calculation and design method when creating the design of an ultrasonic muffler.

Keywords: automobile, coagulation, exhaust gases, internal combustion engine, ultrasonic muffler.

Introduction

One of the main causes of air pollution is the operation of internal combustion engines of cars. The exhaust gas contains about 160 hydrocarbon derivatives, exhaust carbon and other harmful substances, which, together with salts of heavy metals, poison the atmosphere. An increase in the concentration of exhaust gases by harmful substances leads to an increase in diseases of the cardiovascular system and lungs. In this regard, the reduction of harmful emissions of exhaust gases is an important task in solving the environmental problem of pollution of the environment and modern cities [1-8].

At present time, revolutionary directions of green transport are being developed actively: electric vehicles, hydrogen fuel, etc. However, it will take a long time to completely replace internal combustion engines. Therefore, it is proposed the modernization of purification systems to reduce the harm of exhaust gases, based on ultrasonic exposure in an automobile muffler [9-19].

The exhaust gases of internal combustion engines are an aerodispersed system that is very sensitive to acoustic and electromagnetic effects. As early as the second half of the 19th century, a German physicist A. Kundt discovered that intense acoustic waves affect fine particles in gases. A visual illustration of this effect is the famous "Kundt tube" [20-22].

In 1938 the first experiments of ultrasonic purification of industrial gases were conducted by the scientist Giz, who used ultrasonic whistles and magnetostrictive emitters. At the end of the fifties of the last century "Ultrasonic Corporation" (USA) created gas purification installations with powerful ultrasonic sirens. Since this time, scientific research has been carried out on the coagulation of industrial dust in a number of countries, such as the USSR, France, Japan, Poland, etc. [23-28].

The reduction of toxic emissions of cars is carried out by installing in their mufflers various purification systems (devices), which are called neutralizers. The most common liquid, catalytic and thermal converters. These devices operate respectively on absorption, thermocatalytic and thermal afterburning methods.

Although these methods successfully perform their functions of purifying exhaust gases from nitrogen oxides, sulfur oxide, exhaust carbon and other harmful substances, they suffer from a number of disadvantages. The main disadvantages are: the high cost of chemical reagents; complexity in servicing the device; insensitivity to neutralization of carbon monoxide; difficulties at negative ambient temperatures; additional fuel consumption, etc. [29-30].

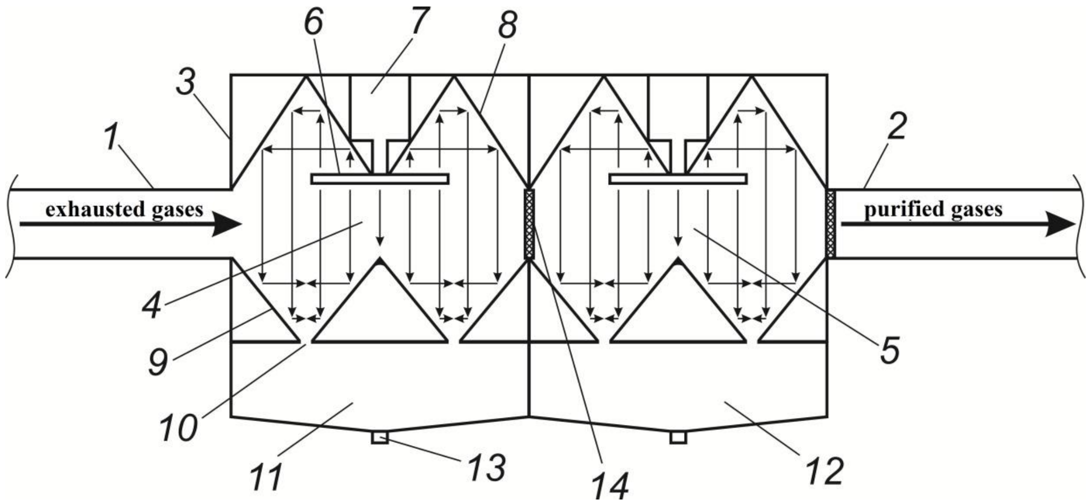
The ultrasonic method of purification is based on the ability of ultrasonic waves, a certain frequency and intensity, to accelerate the processes of coagulation and sedimentation of finely-dispersed particles. Coagulation is the physical- chemical process of adhering small particles of disperse systems to larger ones under the influence of coupling forces to form coagulation structures. There are orthokinetic and hydrodynamic coagulation of particles under the influence of ultrasound. Orthokinetic coagulation occurs as a result of the mutual collision of randomly moving particles. Hydrodynamic coagulation occurs as a result of mutual attraction of particles pulsating in the ultrasonic field, due to the Bjerknes force between them [31-33].

Ultrasonic purification may complement or replace the conventional methods described above. Ultrasound is widely used in geophysics, medicine, paint production, sonication, cleaning hard surfaces from paints and rust of pipes, baths, etc. Research was carried out and results were obtained on the speed of motion of ultrasonic waves in various media, the operation of standing waves and the process of reflection of waves. The works on purification air from suspension from fine particles are of particular interest due to their coagulation under the influence of ultrasound. The principle of operation of the ultrasonic purification device is based on the ability of ultrasonic waves to intensify coagulation processes of fine solid particles of exhaust gas. Solid particles of exhaust gases enlarged as a result of coagulation processes settle at the place of intended collection and after a certain time interval are extracted and disposed.

The advantage of the ultrasonic method is that chemicals, additional equipment are not needed, as well as the ability to deposit solid exhaust gas particles at a certain place, which can then be extracted and used as recyclables. This makes it possible to use the ultrasonic method in special exhaust gas utilization systems. The disadvantage of the ultrasonic method of purification is its harmful effect on a person and the need to use special ultrasonic insulation.

A patent is known for purification exhaust gases when ultrasonic waves occur in a quarter wave resonator, but without generating waves. The disadvantage of the design is chaotic waves, with an uncontrolled frequency and amplitude [34-37].

A device for ultrasonic purification of exhaust gases is proposed, in which an emitter or several ultrasound emitters are mounted inside the muffler (Fig. 1) [36].



1 – inlet nozzle; 2 – outlet pipe; 3 – case; 4 – first coagulation cell; 5 – second coagulation cell; 6 – ultrasonic oscillation emitters; 7 – ultrasonic converters; 8 – upper reflectors; 9 - lower reflectors; 10 – holes; 11 – first storage tank; 12 – second storage vessel; 13 – holes with plug; 14 – filtration nets.

Fig. 1. – Device for ultrasonic purification of exhaust gases

The device (Fig. 1) is installed in the vehicle by mounting into a muffler or elsewhere in the exhaust system. During operation of the engine, exhaust gases enter the exhaust system, where they pass through the inlet 1 through the first 4 and second 5 coagulation cells. In upper parts of coagulation cells emitters of ultrasonic oscillations are installed 6, which are mechanically and acoustically connected to ultrasonic converters 7. Upper 8 and lower reflectors 9 of ultrasonic oscillations are also installed in coagulation cells, which make it possible to create ultrasonic fields in cells with resonance propagation of ultrasonic oscillations.

Purification of exhaust gases from solid particles is carried out due to created ultrasonic fields in coagulation cells. Oscillations in ultrasonic fields affect solid particles, which begin to move actively, collide and stick together (ultrasonic coagulation occurs). To contain coagulated particles, filtration nets 14 are installed at the outlets of the cells, which are also purified using ultrasonic fields. Removal of coagulated particles is carried out through holes 10 in lower reflectors. The particles settle in the collecting vessels 11 and 12, where some of the gases condense and merge through the holes with the plug 13. The purified gases are discharged from the nozzle 2.

Thus, the ultrasonic muffler apparatus of the present invention improves the environmental safety of vehicles when operating internal combustion engines. In addition, it has a significant advantage: it can be equipped with both new and used cars, as well as other vehicles. Patent has been obtained for the device [36].

The solutions proposed in patents have not been theoretically analyzed and have not been experimentally confirmed. Analysis of studies on the effects of ultrasound on various media gives a rich material, but cannot be applied without clarification to describe the process of operation of the ultrasonic muffler.

The importance of the environmental problem of air purification, insufficient results of theoretical and experimental studies on ultrasonic effects on gas media, a limited level of technical solutions and patents make it possible to consider the task of creating ultrasonic mufflers relevant.

The research was carried out in the laboratory of the Department of Transport Technology and Logistics Systems at the Karaganda Technical University (Karaganda, Kazakhstan) from 11/05/2020 to 30/04/2024.

2. Materials and Methods

A hypothesis was put forward about the possibility of reducing the toxicity of exhaust gases in an ultrasonic muffler and increasing the deposition of coagulated particles (soot) to the bottom of the muffler due to the influence of ultrasonic waves [38].

The exhaust gases in the muffler are coagulated continuously. Coagulation is accelerated by exposure to ultrasound, which has a dispersing effect on emulsions and liquid sols, and on aerosols (smoke, mist, dust) has a coagulating effect. This is due to the fact that in gases only longitudinal waves causing compression are possible. Transverse waves cause deformation shifts. In the longitudinal wave, the medium particles oscillate relative to their average position in the direction parallel to the wave propagation.

The efficiency of the coagulation process increases when a standing wave occurs. Standing waves are a special case of interference. They occur when the reflector (the boundary of two media) is hit and two identical waves propagate in opposite directions, since the medium and the reflector have different acoustic resistances. In this case, a standing wave zone is formed, in which coagulation occurs intensively. The gas particles, including those enlarged in size, are shifted towards the exhaust pipe at a certain speed. Coagulating particles are deposited at the bottom of the muffler, most likely closer to the exhaust hole [39-42].

The standing sound wave force $\vec{F}_a$ is determined by the following relationship:

$$F_a = b\cos\omega\left(t - \frac{n}{c}\right), \tag{1}$$

where $b = \pi r^2 A\rho c\omega$;

r - particle radius;

A - amplitude of ultrasonic oscillations;

ρ - gas particle density;

c –is the speed of sound in the gas medium;

t – time;

n – is the phase rate;

f – oscillation frequency.

For gas particles of different sizes, a certain oscillation frequency occurs. Initially, the particles follow the movement of gas between the beams and nodes, while sticking together and increasing in size. After that, the particles increase due to chaotic fluctuations. Exhaust gas consists of particles of different sizes. Depending on their magnitude and frequency of oscillation, particles can follow sound oscillations and coagulate.

This process occurs at low oscillation frequencies. With an increase in oscillation frequency, there is an optimal frequency segment at which particles of different sizes have a different amplitude, collide with each other and coagulate. This kind of coagulation is called orthokinetic. When the frequency increases above 15000 Hz, coagulation becomes hydrodynamic and it is carried out due to friction. This process is described by hydrodynamic friction force that is the Bjerknes force $\vec{F}_G$:

$$F_G = 6\pi\eta\, r\frac{dx}{dt}, \tag{2}$$

where η – dynamic viscosity of the gas particles;

r – the average radius of the particle;

dx/dt – derivative of the difference in the speed of movement of particles during a collision.

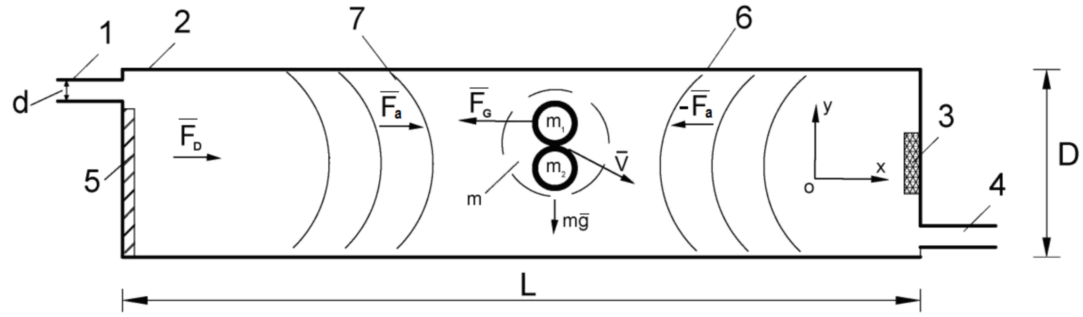
The aim of the study was to obtain theoretical and experimental dependencies describing the process of coagulation and purification from harmful impurities in a developed ultrasonic muffler. To achieve the goal, the following objectives were achieved:

- the speeds of movement of the coagulated particle are theoretically determined when moving in a muffler;
- theoretically established the mass of precipitated exhaust carbon particles and coagulation coefficient in the muffler;
- an experimental stand has been developed and tests have been carried out to reduce toxicity and establish the mass of precipitated particles;
- comparisons of theoretical and experimental results were made.

Thus, our research methods were both theoretical and experimental. The solution of the first problem consisted in modeling the movement of a gas particle m_1 under the influence of forces acting on it during its coagulation with another particle m_2 and the formation of a larger particle under the influence of ultrasound (Fig.

2). This problem is based on solving the differential equation of motion of a gas particle in a muffler under the action of forces acting on this particle. In the first approximation, a one-dimensional problem was considered. To simplify the model, one longitudinal ultrasonic emitter 3 was used (Fig. 2).

Two coagulated particles m_1 and m_2 are subjected to mass and pressure force from the engine exhaust collector $\vec{F}_D$, which is considered constant, the Bjerknes force $\vec{F}_G$, reflected alternating force of standing sound wave $\vec{F}_a$ and gravity (Fig. 2). As a result of friction, a particle mass *m* is formed, moving under the pressure of the mentioned forces.



1 - exhaust gas inlet pipe; 2 - muffler case; 3 - ultrasonic emitter; 4 - outlet pipe; 5 - wave reflector; 6 and 7 - straight wave and reflected wave respectively; L and D - length and height of the muffler; d - diameter of the inlet and outlet branch pipe.

Fig. 2. – Scheme of forces acting on the coagulated gas particles

The equation of motion of the particle m along the axis Ox has the form:

$$m\ddot{x} = F_D \pm F_a - F_G. \tag{3}$$

Taking into account expressions (1), (2) and conversions:

$$m\ddot{x} - 6\pi\eta\, r\dot{x} = F_D \pm b\cos\omega\left(t - \frac{n}{c}\right). \tag{4}$$

The initial conditions will be as follows:

$$x_0 = 0, \quad \dot{x}_0 = v_0, \tag{5}$$

where $x_0 = 0, \quad \dot{x}_0 = v_0$ – the initial position and initial speed of the particle at the entrance to the muffler. The solution of equation (4) with initial conditions (5) is given in the section "Results and discussion". These solutions allow you to determine the speed of movement of gas particles, which are necessary for the theoretical determination of the coagulation coefficient.

It is important to establish the value of the coagulation coefficient and the regularity of its change. The coagulation coefficient *K* is meant as a change in the mass of precipitated particles per unit time. The coagulation coefficient in its physical essence determines the magnitude of the speed of this process and has a the dimension c^{-1}.

It is assumed that the law of exhaust carbon mass change is similar to the law of particle concentration in gas:

$$n = n_0 \exp(-Kt), \tag{6}$$

where n and n_0 – counting concentrations of gas particles in the current and initial phase, respectively. Then it turns out:

$$m = m_0 \exp(Kt), \tag{7}$$

where m and m_0 – the mass of exhaust carbon obtained when exposed to ultrasound and the mass of exhaust carbon without ultrasound effect, respectively.

It is necessary to determine the parameters on which the coagulation coefficient depends. For these purposes, experimental studies were carried out. The purpose of the experiment is to obtain dependencies determining coagulation parameters: the mass of precipitated exhaust carbon, the coagulation coefficient and its speed. As well as testing the hypothesis of purification exhaust gases from harmful impurities such as CO and CH [9-12].

A full-size experimental stand was made for the full-scale experiment (Figures 3–5). The scheme of the experimental ultrasonic stand (muffler) is shown in Figure 4.

The experimental ultrasonic muffler (Figures 3–5) consists of a polypropylene pipe with a diameter *D*=110 mm and a length *L*=3000 mm. The following equipment is installed in the muffler case: ultrasonic generator 9; two ultrasonic emitters 4; ultrasonic wave reflector 15; digital USB-microscope MIKMED 3 with an increase coefficient from 20 to 200 with the possibility of photo and video fixation at a resolution 1920 × 1080 pixels; temperature sensor 5 and hygrometer 6 transmitting information to thermometer-hygrometer 13; electronic pressure gauge 7.

To determine the qualitative and quantitative composition of the exhaust gas mixture, "Meta Avtotest 01.03" gas analyzer (Russia) was used. An ultrasonic generator was used by the manufacturer "TOCOOL" (China). Input voltage of AC current 220V, with power of emitters – 50W, frequency of ultrasonic waves generation – 40 kHz. To study the internal processes of the ultrasonic muffler, a USB-microscope "MIKMED 2.0" was installed into the case, designed to check the quality and testing of industrial facilities.

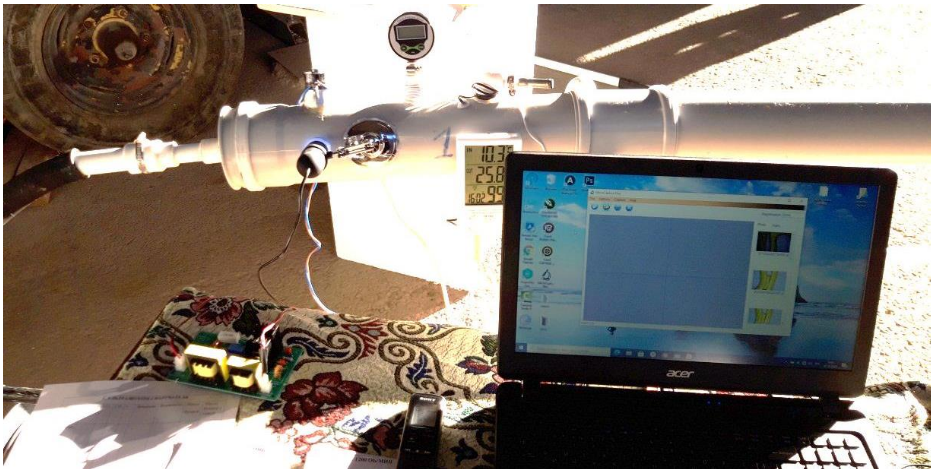
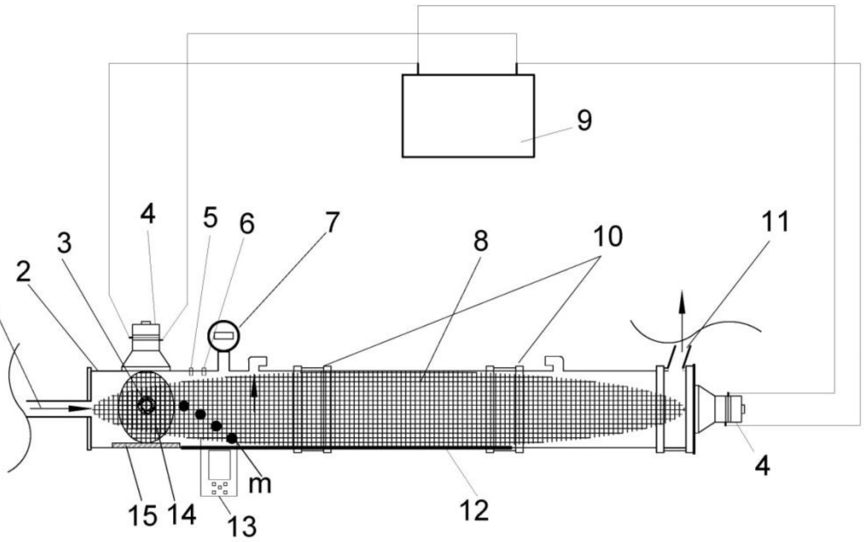


Fig. 3. – Experimental ultrasonic stand



1 – inlet nozzle; 2 – muffler case; 3 – electronic microscope MIKMED 2.0; 4 – ultrasonic emitter; 5 – temperature sensor; 6 – moisture meter; 7 – electronic pressure gauge; 8 – area of impact of longitudinal ultrasonic waves; 9 – ultrasonic generator; 10 – pipe connection coupling; 11 – outlet pipe; 12 – place of soot collection; 13 – thermometer-hygrometer; 14 – the area of impact of transverse ultrasonic waves; 15 – reflector.

Fig. 4. – Scheme of experimental ultrasonic stand

1– ultrasonic muffler case, 2 – ultrasonic radiator, 3 – digital USB microscope, 4 – reflector.

Fig. 5. – Internal design of ultrasonic muffler

During the experiment, at the first stage, the degree of purification of the exhaust gas from CO and CH was determined. At the second stage, graphs of the mass of the sediment exhaust carbon versus the length of the muffler L were established.

The experimental study was conducted as follows:

– tests were carried out without switching on and with switching on the ultrasonic equipment for 5 minutes each;

– the study was carried out at the engine crankshaft speed at idle (1000 rpm) and at 1250 rpm.

Volkswagen Passat B3 of 1991 release was used, engine capacity 1800 cc. see, fuel injection - mono engine, engine power 90 kW, fuel grade - gasoline AI-92.

To collect the settled soot, the lower part of the device was lined with five numbered sheets of paper measured 100 × 100 mm, with a total length of 500 mm, the mass of which was determined before testing by high-precision jewelry scales "MN-500" (Russia).

Exhaust gas from the vehicle was supplied to the ultrasonic muffler (see Fig. 4) through the inlet pipe 1 under the pressure depending on the speed of rotation of the crankshaft of the vehicle. In the muffler, when ultrasonic equipment was turned on, the exhaust gas was exposed to ultrasonic waves in the transverse and longitudinal direction. In the muffler, ultrasonic intensification of coagulation processes and purification of exhaust gases occurred due to sedimentation of enlarged exhaust gas particles at the exhaust carbon collection point 12. The purified exhaust gas was discharged through outlet 11.

During the operation of the ultrasound muffler, the readings of the gas analyzer, monometer, thermometer-hygrometer were taken. Photo and video recording were performed inside the ultrasonic muffler using a digital microscope 3. Photos are not presented due to a fuzzy image during transfer.

After each test, the numbered paper with settled soot particles was carefully removed and weighed again. Based on the difference in mass readings before and after the test, the mass of settled soot particles was determined. The sediment distance of the soot particles was determined by the location of the paper sheets (Tables 2 and 3).

Preliminary 5 repeated experiments were carried out. The coefficient of variation W is determined:

$$W = \frac{\sigma}{\overline{X}} = 0.07 , \quad (8)$$

where σ – the standard deviation, $\overline{X}$ – the arithmetic mean of the results of five measurements (experiments).

The minimum allowable value of repeated experiments with a confidence probability of 90% and a maximum relative error of the experiment of 9% was determined. The number of repeated experiments was determined from the expression:

$$n = \left(\frac{t_s W}{\varepsilon}\right)^2 = \left(\frac{2.13 \times 0.07}{0.09}\right)^2 = 2.66 \approx 3, \quad (9)$$

where t_s – the Student coefficient, ε – the ultimate relative error of the experiment. The number of repeated experiments equal to 3 was obtained.

3. Results and discussion

The analytical solution of equation (4) with initial conditions (5), for the positive direction of the standing sound wave force $\vec{F}_a$, made it possible to determine the following dependencies of the particle speed V_x in the projections on the Ox axis of the muffler length:

$$V_x = \frac{F_D}{a} - \left[\frac{F_D}{a} - v_0 + \frac{ba}{a^2 + m^2\omega^2} \left(\cos\frac{\omega n}{c} - \frac{m\omega}{a} \sin\frac{\omega n}{c} \right) \right] e^{-\frac{a}{m}t} + \\ + \frac{b}{a^2 + m^2\omega^2} \left[a\cos\omega\left(t - \frac{n}{c} \right) + m\omega\sin\left(t - \frac{n}{c} \right) \right], \tag{10}$$

where $a = 6\pi\eta\, r$ is denoted and $b = \pi r^2 A\rho c\omega$ is determined from expression (1).

By logarithmizing expression (7) and performing the conversions, the dependence of the gas coagulation coefficient K on the initial concentration and time was obtained:

$$K = \ln\frac{m}{m_0} / t, \tag{11}$$

where t – the travel time of the gas particle through the muffler.

Since the average travel time of the particle through the muffler:

$$t = \frac{V_x}{L}, \tag{12}$$

then, for a specific muffler, an analytical expression was determined to determine the coagulation coefficient K:

$$K = \frac{L}{V_x} \ln\frac{m}{m_0}, \tag{13}$$

where V_x is determined by expression (10).

At the first stage of the experiment, the validity of the hypothesis about the possibility of purification exhaust gases with ultrasound in an automobile muffler was proved. Table 1 and Figures 6 and 7 show CH and CO concentrations in the muffler.

Table 1. CH and CO concentration at 1000/1250 rpm

Ultrasonic muffler operation	CH (ppm/min)	CO (%)
Without ultrasound	50/27	1.2/0.62
With ultrasound (1 transverse emitter)	31/14	1.2/0.76
With ultrasound (2 emitters)	29/12	1.6/0.9
With ultrasound (1 longitudinal emitter)	27/-	1.2/-

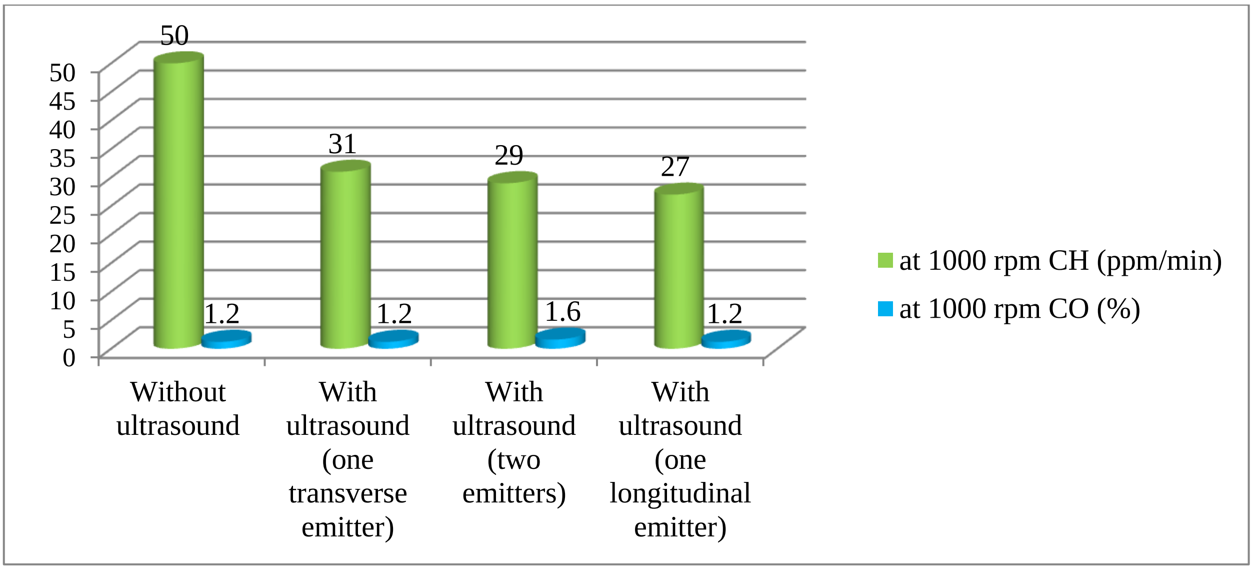


Fig. 6. – Diagram of CH and CO content in exhaust gas at 1000 rpm

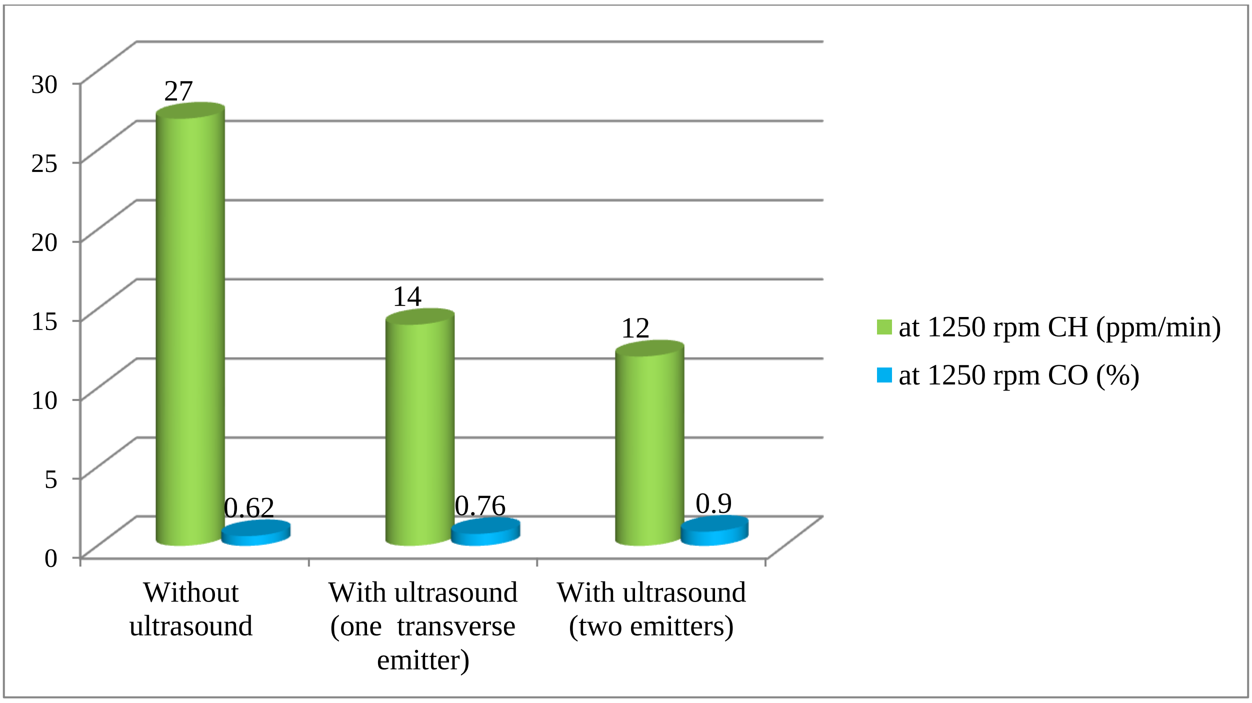


Fig. 7. – Diagram of CH and CO content in exhaust gas at 1250 rpm

The hypothesis about the possibility of reducing the toxicity of exhaust gases in an ultrasonic muffler has been confirmed. Moreover, purification is most effective when installing a muffler in the longitudinal direction of gas movement, since the friction force of particles against each other (hydrodynamic coagulation) is supplemented by gravity (Figures 6 and 7). The decrease in CH concentration shows the effectiveness of the ultrasound in purification the exhaust gas. The change in CO indicates an increase in concentration due to the effect of ultrasonic waves. At the same time, the length L on which CO molecules were to be deposited is not enough. The volatility of CO is higher than CH.

Table 2. Mass of settled exhaust carbon at 1000/1250 rpm without ultrasound

Time		Thermometer readings at 1000/1250 rpm	Determination of exhaust carbon mass at 1000/1250 rpm			
Total time (min)	Minute	t (ºC)	Distance (mm)	Mass of paper (g)	Mass of paper with exhaust carbon (g)	Net mass of settled exhaust carbon (g)
5	1	10.5/23.9	100	0.75/0.8	1.00/1.5	0.25/0.70
	2	11.7/26.0	200	0.84/0.79	1.00/1.18	0.16/0.39
	3	12.3/29.2	300	0.84/0.76	0.95/0.88	0.11/0.12
	4	18.5/31.7	400	0.87/0.73	0.92/1.35	0.05/0.62
	5	20.3/33.0	500	0.84/0.74	0.94/1.05	0.10/0.31
					Totally:	0.67/2.14

Table 3. Mass of settled exhaust carbon at 1000/1250 rpm with ultrasound with two emitters

Time		Thermometer readings at 1000/1250 rpm	Determination of carbon black mass at 1000/1250 rpm			
Total time (min)	Minute	t (ºC)	Distance (mm)	Mass of paper (g)	Mass of paper with exhaust carbon (g)	Net mass of settled exhaust carbon (g)
5	1	16.1/26.4	100	0.74/0.85	1.08/1.92	0.34/1.07
	2	18.8/28.8	200	0.77/0.77	0.98/1.86	0.21/1.09
	3	23.0/31.5	300	0.74/0.76	0.88/1.51	0.14/0.75
	4	26.3/33.3	400	0.75/0.78	1.20/1.62	0.45/0.84
	5	29.2/35.4	500	0.72/0.79	1.10/1.49	0.38/0.70
					Totally:	1.52/4.45

At the second stage of the experiment, the dependencies of the mass of settled exhaust carbon on the length of the settling (muffler) *L* were determined. Tables 2 and 3 provide the examples of the registration of experimental results.

Tables 2 and 3 show the mass of settled exhaust carbon without ultrasound and ultrasound (with two emitters) at 1000/1250 engine crankshaft rpm. The net mass of exhaust carbon was determined by subtracting the mass of paper from that of exhaust carbon.

From the tables it follows that the efficiency of solid particle sedimentation with two emitters is more than 2 times higher compared to the tests without exposure to ultrasound. Thus, gas coagulation is most effective in the longitudinal radiator, since the exposure to ultrasound extends over a longer length. Figures 8 and 9 show experimental graphs of the mass of settled soot versus the length L of the muffler. It was also established that the mass of coagulation increases significantly (2-2.5 times) with an increase in the number of engine speeds (Fig. 9). Figure 10 shows the resulting exhaust carbon from hydrodynamic coagulation.

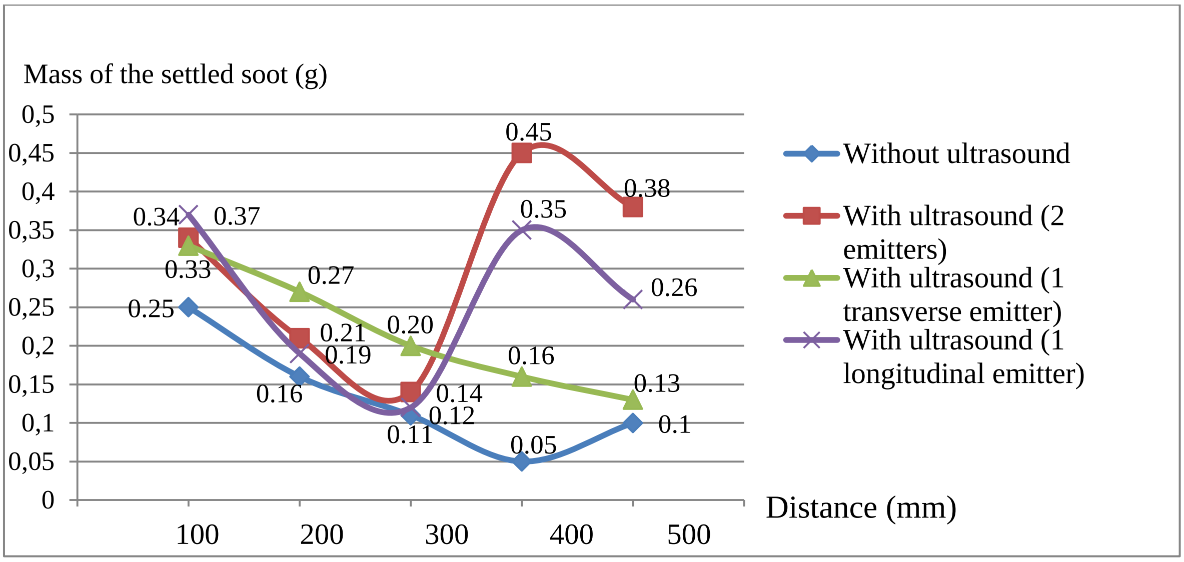


Fig. 8. – Graph of the mass of settled exhaust carbon dependence on the settling distance at 1000 rotations of the crankshaft per minute

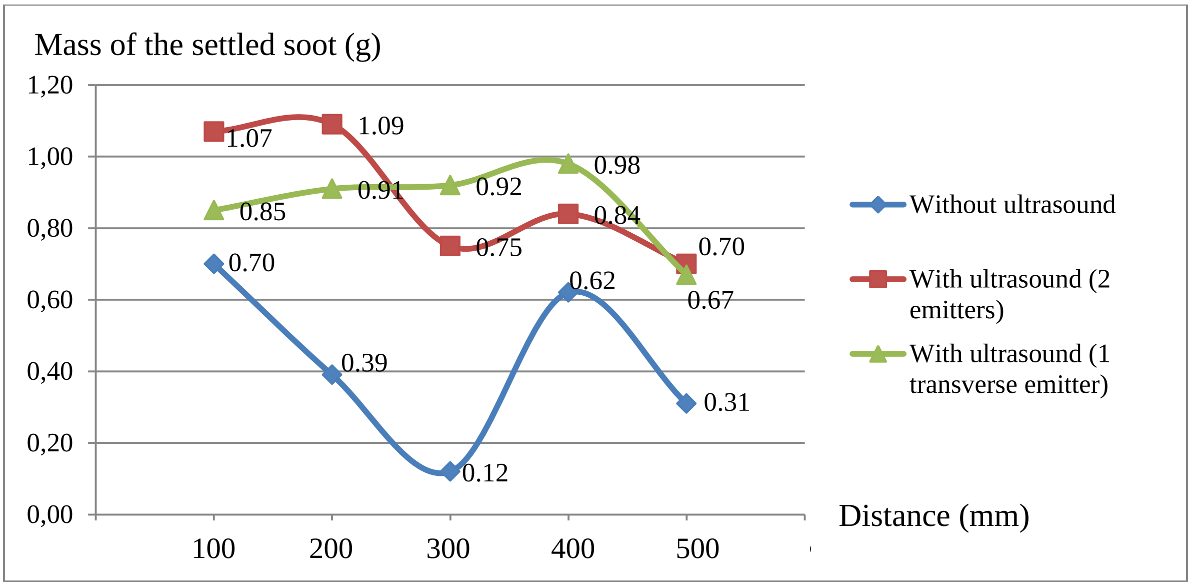


Fig. 9. – Graph of the mass of settled exhaust carbon dependence on the settling distance at 1250 rotations of the crankshaft per minute

Having determined the difference in the exhaust carbon mass under the action of ultrasound and without it, the value of the exhaust carbon mass from hydrodynamic coagulation was found (Table 4).

Table 4. Exhaust carbon mass from hydrodynamic coagulation at 1000/1250 rpm when exposed to 2 ultrasonic emitters

Determination of exhaust carbon mass			
Distance (mm)	Mass of settled exhaust carbon when exposed to ultrasound (g)	Mass of settled exhaust carbon without ultrasound (g) (effect of orthokinetic coagulation)	Mass of settled exhaust carbon when exposed to hydrodynamic coagulation (g)
100	0.34/1.07	0.25/0.70	0.9/0.37
200	0.21/1.09	0.16/0.39	0.05/0.7
300	0.14/0.75	0.11/0.12	0.03/0.63
400	0.45/0.84	0.05/0.62	0.4/0.22
500	0.38/0.70	0.10/0.31	0.28/0.39

Table 4 shows the dimension data of orthokinetic and hydrodynamic coagulation. The obtained data made it possible to quantify the mass of hydrodynamic coagulation (Fig. 10).

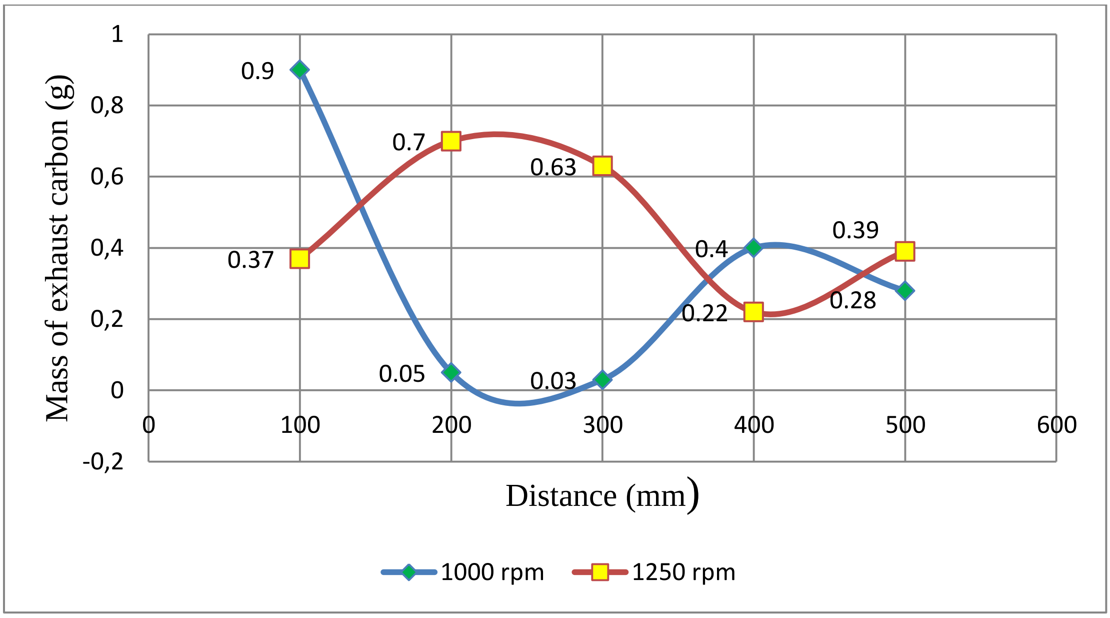


Fig. 10. – Graph of exhaust carbon mass dependence at hydrodynamic coagulation on the sedimentation distance at 1000/1250 crankshaft rotations per minute for the variant with two ultrasonic emitters

As it can be seen from the graphs, there is a local maximum of exhaust carbon deposition at the distance of 400mm from the exhaust pipe. It is true quantifiably for the stand, but the qualitative dependence will be true for polypropylene mufflers as well.

According to the formula (11), the coagulation speed coefficient *K* was determined for the version of operation with two ultrasound emitters in the muffler. The travel time of the gas particles through the muffler is equal to the operation time of the ultrasonic muffler t=300 seconds, the coagulation coefficient is obtained.

Since 5 sheets of paper measuring 100×100 mm were lined in the muffler, the total mass of the resulting exhaust carbon was calculated for all sheets of paper. According to Table 2, the sum of the obtained exhaust carbon without ultrasound at 1000/1250 rpm was 0.67/2.14 grams.

According to Table 3, the sum of the obtained exhaust carbon with ultrasound (2 emitters), at 1000/1250 rpm = 1.52/4.45 grams. Then, substituting these values into the formula, the coagulation speed coefficient *K* was obtained (Table 5).

Table 5. Coagulation Speed Coefficient

Engine (rpm)	Coagulation coefficient value, c^{-1}		
	With ultrasound (2 emitters)	With ultrasound (1 transverse emitter)	With ultrasound (1 longitudinal emitter)
1000/1250	$2.7\times10^{-3}/2.4\times10^{-3}$	$1.6\times10^{-3}/2.7\times10^{-3}$	2.9×10^{-3}/-

Having compared the obtained data of the coagulation speed coefficient, it can be concluded that the operation of the longitudinal emitter is maximally effective, since ultrasound had an effect on the entire path of the movement of exhaust carbon particles.

Conclusions

The assumption of reducing the toxicity of exhaust gases when exposed to ultrasound is experimentally confirmed. Moreover, in this case, the longitudinal emitter is more effective. The decrease in the concentration of CH and CO was from 40% to 50%.

The hypothesis of increasing the particles of coagulated particles (exhaust carbon) to the bottom of the muffler due to the effect of ultrasonic waves on them has been proved. The physical process is explained by the increase in hydrodynamic coagulation of the gas medium, as proved by the experiment. The mass of settled exhaust carbon with ultrasonic exposure is significantly (4-5 times) higher than its mass without exposure to ultrasound.

The efficiency of solid particles sedimentation at two (transverse and longitudinal) emitters is more than twice. Working with a longitudinal emitter is more efficient, since the ultrasonic wave moves towards the movement of the gas.

The nature of the dependence graphs of the exhaust carbon mass on the distance from the collector shows that there is a local maximum (for these parameters) that equals to 400 mm.

On the basis of hypothesis on analogy of laws of concentration of particles in gas and distribution of mass by exponent, dependencies of coagulation concentration on initial mass and time of influence on medium are obtained and experimentally confirmed.

For the first time, the obtained theoretical dependence of the coagulation coefficient (13) and experimental results, the practical significance of which is the possibility of calculating and designing mufflers.

References

[1] Shamim T. Effect of engine exhaust gas modulation on the cold start emissions. International Journal of Automotive Technology, Vol. 12, No. 4, 2011, pp. 475−487

[2] Dong, S., Lipkens, B., Cameron, T.V. The effects of orthokinetic collision, acoustic wake, and gravity on acoustic agglomeration of polydisperse aerosols. Journal of Aerosol Science, Volume 37, Issue 4, April 2006, pp. 540-553.

[3] Riera-Franco de Sarabia, Elvira-Segura, González-Gómez, Rodríguez-Maroto, Muñoz-Bueno, Dorronsoro-Areal. Investigation of the influence of humidity on the ultrasonic agglomeration of submicron particles in diesel exhausts, Ultrasonics, Volume 41, Issue 4, June 2003, Pages 277-281.

[4] Yessenbayeva A., Apsalikov B., Massabayeva M., Kazymov M., Shakhanova A., Mussazhanova Zh., Kadyrova I., Aukenov N., Shaimardanov N. Biomarkers of immunothrombosis and polymorphisms of IL2, IL6, and IL10 genes as predictors of the severity of COVID-19 in a Kazakh population. // PLoS ONE, Vol. 18, Issue 6, 2023. – p. 61-67. https://doi.org/10.1371%2Fjournal.pone.0288139

[5] Yegorov S., Kadyrova I., Korshukov I., Sultanbekova A., Kolesnikova Y., Barkhanskaya V., Bashirova T., Zhunusov Y., Li Y., Parakhina V., Kolesnichenko S., Baiken Y. Application of MALDI-TOF MS and machine learning for the detection of SARS-CoV-2 and non-SARS-CoV-2 respiratory infections // Microbiology Spectrum, Vol. 12, No. 5, 2024. https://doi.org/10.1128/spectrum.04068-23

[6] Turmukhambetova A., Yegorov S., Korshukov I., Barkhanskaya V., Kolesnichenko S., Klyuyev D., Zhumadilova Z., Pralieva A., Absaghit L., Belyaev R., Babenko D., Hortelano G. Miller, M., Vazenmiller D., Kadyrova I. The impact of Gam-COVID-Vac, an Adv5/ Adv26 COVID-19 vaccine, on the biomarkers of endothelial function, coagulation and platelet activation // PLoS ONE Vol. 18, No. 10, 2023. https://doi.org/10.1371/journal.pone.0293074

[7] Kadyrova I., Kolesnichenko S., Kolesnikova Ye., Korshukov I., Barkhanskaya V., Sultanbekova A., Babenko D. SARS-COV-2 detection in MALDI-TOF mass spectra by machine learning. // AIP Conf. Proc., Vol. 2872, Issue 1, 2023. – p. 1-13. doi: https://doi.org/10.1063/5.0164375

[8] Akhmaltdinova L., Korshukov I., Kolesnikova Ye., Kolesnichenko S., Babenko D., Kadyrova I., Kabildina N., Sirota V., Zhumaliyeva V., Taizhanova D., Vazenmiller D., Turmukhambetova A. Association of four genetic variants with colorectal cancer in Kazakhstan population. // Oncotarget, Vol.12, Issue 21, 2021. – p. 2215-2222. doi: https://doi.org/10.18632%2Foncotarget.28070

[9] Kadyrov A., Sarsembekov B., Ganyukov A., Zhunusbekova Z., Alikarimov K. Experimental research of the coagulation process of exhaust gases under the influence of ultrasound. Communications – Scientific Letters of the University of Zilina, 2021, 23(4), B288-B298. https://doi.org/10.26552/com.C.2021.4.B288-B298

[10] Kadyrov A., Sarsembekov B., Ganyukov A., Suyunbaev Sh., Sinelnikov K. Ultrasonic unit for reducing the toxicity of diesel vehicle exhaust gases. // Communications - Scientific Letters of the University of Zilina, Vol. 24, Issue 3, 2022. – p. 189-198, doi: https://doi.org/10.26552/com.

[11] Kadyrov A., Ganyukov A., Pak I., Suleyev B., Balabekova K. Theoretical and experimental study of operation of the tank equipment for ultrasonic purification of the internal combustion engine exhaust gases (2021) Communications - Scientific Letters of the University of Žilina, 23 (3), pp. B219 - B226

[12] Kadyrov A., Bembenek M., Sarsembekov B., Kukesheva A., Nurkusheva S. The Influence of the Frequency of Ultrasound on the Exhaust Gas Purification Process in a Diesel Car Muffler. // Appl. Sci. Vol.14, Issue 12, 2024, – p. 1-19. doi: https://doi.org/10.3390/app14125027

[13] Kadyrov A., Sarsembekov B., Kukesheva A., Sinelnikov K. Application of electric pulse and ultrasonic mufflers for increasing the degree of exhaust gas purification in car engines // International Journal of Innovative Research and Scientific Studies. - 2024, P.33-40. Online ISSN : 2617-6548. DOI: https://doi.org/10.53894/ijirss.v8i1.3570

[14] Kadyrov A., Kukesheva A., Kryuchkov Ye., Pak I., Kurmasheva B,. Kabikenov S. Development of Calculation Methodology for Optimizing the Operating Mode of an Electric Pulse Unit for Cleaning Exhaust Gases. // Communications - Scientific Letters of the University of Žilina, Vol. 26, Issue 1, 2024. – p. 41-53, doi: https://doi.org/10.26552/com.C.2024.011

[15] Pak I., Kadyrov A., Askarov B., Suleyev B., Karsakova A. Developing and studying the method of ultrasonic purification and utilization of internal combustion engine exhaust gases (2023) Communications - Scientific Letters of the University of Žilina, 25 (3), pp. B245 - B258 DOI: 10.26552/com.C.2023.060

[16] Kukesheva A., Kadyrov A., Kryuchkov Y. Establishing the parameters of the operation mode of the electric pulse automobile muffler. // Journal of Applied Engineering Science. Vol. 22, Issue 1, 2024. – p.89–99. doi: 10.5937/jaes0-45196

[17] Kadyrov, A., Kryuchkov, Y, Sinelnikov, K, Ganyukov, A., Sakhapov, R., Kukesheva, A. (2022). Studying the process of the internal combustion engine exhaust gas purification by an electric pulse. // Communications - Scientific Letters of the University of Zilina, Vol. 24, Issue 4, 2022. – p. 275-287, doi: https://doi.org/10.26552/com.C.2022.4.B275-B287\

[18] Ibatov M.K., Kadyrov A.S., Pak I.A., Kadyrova I.A., Askarov B.S. The results of experimental studies of the capacitive equipment of ultrasonic cleaning of exhaust gases of vehicles. Ugol, 2020, (2), pp. 73–78.

[19] Sarsembekov B.K., Kadyrov A.S., Kunayev V.A., Issabayev M.S., Kukesheva A.B. Experimental Comparison of Methods for Cleaning Car Exhaust Gas by Exposure Using Ultrasound and Laser Radiation // Material and Mechanical Engineering Technology, №3, 2024. ISSN 2706977X DOI: https://doi.org/10.52209/2706-977X_2024_3_44

[20] Raj Baldev, Rajendran V., Palanichami P. Applications of ultrasound. – M.: Tekhnosfera, 2006. - 576 p.

[21] Bergman L. Ultrasound and its application in science and technology. - Moscow: Publishing house of foreign literature, 1957. - 726 p.

[22] Kadyrov A.S., Kunaev V.A., Georgiadi I.V. Prospects for Processing of Ferrous Metallurgical Waste Based on Arcelormittal Temirtau Experience. Metallurgist, 2018, 62(1-2), pp. 22–28.

[23] Kadyrov A., Zhunusbekova Z., Ganyukov A., Kadyrova I., Kukesheva A. General characteristics for loading the working elements of drilling and milling machines when moving in the clay solution. Communications – Scientific Letters of the University of Zilina, 2021, 23(2), B97–B105.
[24] Kadyrov A.S., Kunaev V.A., Georgiadi I.V. Ferrous metallurgy waste and waste technical fluids for obtaining the material of road bases. Ecology and Industry of Russia, 2017, 21(12), pp. 44–48.
[25] Sherov K.T., Mardonov B.T., Kurmangaliyev T.B., Elemes D.E., Tusupova S.O., Izotova A.S., Smakova N.S., R. Gabdysalik, Buzauova T.M. The research of micro-hardness of side surfaces of teeth cylindrical wheels processed by "shaver-rolling device". Journal of Theoretical and Applied Mechanics, Sofia, Vol. 50, No.1 (2020), PP.50-56.
[26] Kadyrov A., Balabekova K., Ganyukov A., Akhmediyev S. The constructive solution and calculation of elements of the unified module of the mobile bridge overcrossing. Transport Problems, 2017, 12(3), pp. 59–69.
[27] Nasad T.G., Sherov K.T., Absadykov B.N., Tusupova S.O., Sagitov A.A. Abdugaliyeva G.B., Okimbayeva, A.E. Formation management in parts processing regenerated by surfacing. News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences, 2019, 3(435), pp. 102–108.
[28] Aliev S.B., Suleev B.D. Study and calculation of the disk-milling tool (2018) Ugol, (11), pp. 32 - 34 DOI: 10.18796/0041-5790-2018-11-32-34
[29] Kadyrov A.A., Ganyukov A.A., Balabekova K.G., Zhunusbekova Z.Z., Suleev B.D. Scientific and engineering bases for development of mobile overpasses (2020) Material and Mechanical Engineering Technology, 2020 (2), pp. 7 – 13
[30] Kyzylbaeva E.Zh., Kukesheva A.B., Kunaev V.A. Mathematical model of plate movement in thixotropic mud. // Material and Mechanical Engineering Technology, Vol. 2, Issue 2, 2020. – p. 26-30.
[31] Kadyrov A., Sakhapov R., Ganyukov A., Sinelnikov K., Kurmasheva B., Suyunbaev Sh. Studying the process of transport equipment cooling system ultrasonic cleaning. // Communications - Scientific Letters of the University of Zilina, Vol. 24, Issue 4, 2022. – p. 288-300, doi: https://doi.org/10.26552/com
[32] Menon G., Pego R.L. Approach to self-similarity in Smoluchowski's coagulation equations. // Communications on pure and applied mathematics, Vol. 57, Issue 9, 2004. – p. 1197-1232, doi: https://doi.org/10.1002/cpa.3048
[33] Pak I., Baurova N., Kurmasheva B., Karsakova A., Kadyrova I. Technical and Economic Efficiency of Devices for Ultrasonic Cleaning of City Bus Exhaust Gases. // Bulletin of L.N. Gumilyov Eurasian National University Technical Science and Technology Series. Vol.139, Issue 2, 2022. – p.133–142. doi: https://doi.org/10.32523/2616-7263-2022-139-2-133-142
[34] Patent RU 2 373 409 C2. Device for cleaning automobile exhaust gases from particles / Savinykh Yuri Alexandrovich (RU), Logachev Viktor Grigorievich (RU), Logachev Sergey Viktorovich (RU), Vasilyeva Anastasia Yuryevna (RU); declared 10.06.2009; published 20.11.2009 Bulletin No. 32.
[35] Patent RU 2 364 736 C2. Method for cleaning automobile exhaust gases from particles / Savinykh Yuri Alexandrovich (RU), Logachev Viktor Grigorievich (RU), Logachev Sergey Viktorovich (RU), Vasilyeva Anastasia Yuryevna (RU); declared 20.12.2008; published 20.08.2009 Bulletin No. 23.
[36] Patent of the Republic of Kazakhstan No. 3194. Device for ultrasonic cleaning of exhaust gases / M.K. Ibatov, A.S. Kadyrov, O.T. Balabayev, B.S. Askarov, I.A. Pak; declared 20.12.2017; published 02.10.2018.
[37] Patent of the Republic of Kazakhstan No. 9263. Ultrasonic muffler for cleaning the exhaust gases of an internal combustion engine. Kadyrov, A.S., Sarsembekov, B.K., Kadyrova, I.A.
[38] Pak I. Experimental Study of the Ultrasonic Muffler Efficiency for Improving the Exhaust Gas Cleaning System of Internal Combustion Engines of Automobile / Material and Mechanical Engineering Technology, №2, 2024
[39] Isagulov A., Akberdin A., Sultangaziyev R., Kim A., Kulikov V., Isagulova D. Diagram of equilibrium phase composition of Fe – C – Si – B system // Metalurgija.- 2016. Vol. 55 №3. – P. 305-308
[40] Ilesaliev D.I. Design of Ultrasonic Technology to Improve the Efficiency of Car Exhaust Gas Cleaning System//Material and Mechanical Engineering Technology, №2, 2024
[41] Sakhapov R. L. Method of Cleaning Internal Combustion Engine Radiator Tubes with Ultrasound//Material and Mechanical Engineering Technology, №2, 2024
[42] Ganyukov, A.A., Sinelnikov, K.A., Kabikenov, S.Z., Karsakova, A.Z. Research and Calculation of the Deformed State of the Roadway Mobile Overpass//Material and Mechanical Engineering Technology, 3, 2024, pp.88–95.

Information of the authors

Suyunbaev Shinpolat Mansuralievich, d.t.s, professor, Tashkent State Transport University
e-mail: shinbolat_84@mail.ru