DEVELOPING AND STUDYING THE METHOD OF ULTRASONIC PURIFICATION AND UTILIZATION OF INTERNAL COMBUSTION ENGINE EXHAUST GASES

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Resume

A method of purification and utilization of internal combustion engine exhaust gases, due to the ultrasound impact on gases in a special storage tank, has been proposed. Large soot particles of gases due to coagulation are deposited on the bottom of the device and disposed of. The hypothesis of analogy of the gas concentration law and the ratio of soot particles during coagulation has been proven. The soot coagulation coefficient has been determined theoretically and experimentally. An experimental bench has been developed. The technique of assessing coagulation processes by the degree of gas transparency before and after exposure to ultrasound has been developed and used, as well as the technique of calculating equipment and options for designing the devices for ultrasonic purification of exhaust gases.

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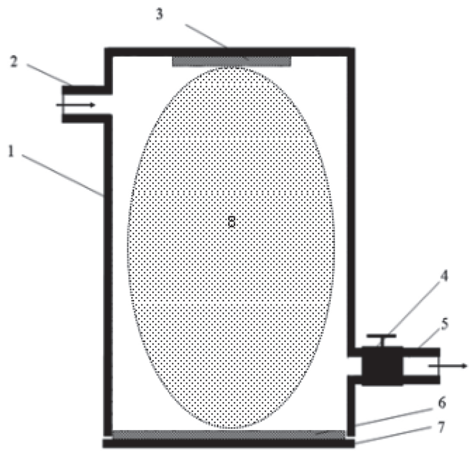
1 Introduction

Extreme gas contamination of the air basin, especially in large cities, is one of the urgent environmental problems. Motor transport is one of the main sources of contamination. Exhaust gases are emitted into the atmosphere and pollute it with carbon monoxide, nitrogen oxides, hydrocarbons, sulfur oxides, soot, carcinogens and other toxic components. Traffic blocks, associated with repair operations on the roads, contribute to the increased emission of harmful exhaust gases of internal combustion engines of transport equipment. This leads to increasing the incidence of cardiovascular and pulmonary diseases in the population [1-3].

Among the main methods of cleaning gases from technical pollution existing in industry, the absorption method, thermal afterburning and the thermo-catalytic method that is characterized by high costs, are the most widely used. These methods are effective against harmful components in the gaseous state, but they are ineffective against soot emissions from engine exhaust gases [4-5].

The method is known of cleaning gases of industrial enterprises by coagulation due to ultrasonic impact on the environment aimed at reducing the content of fine soot particles in gases and allowing it to be disposed of. In [6], based on the studies of Dong, Lipkens and Cameron, it was concluded that orthokinetic collisions prevail at low frequencies for intermediate size ratios, while the acoustic trace effect is more significant at higher frequencies for all the particles. Ran et al. [7] developed the ultrasonic scrubber, a device which combines an ultrasonic standing wave field and a water spray to eliminate particles from a gas flow. This device, which is essentially a wet scrubber enhanced by ultrasound, was shown to significantly improve the scavenging of micron-scale particles compared to the use of a water spray alone. The works [8-9] present the results of studies aimed at improving the



1 - storage tank;
2 - inlet pipe;
3 - ultrasonic emitter;
4 - bypass valve;
5 - outlet pipe;
6 - reflector of sound waves;
7 - tray
8 - zone of standing waves

Figure 1 *The device for ultrasound purification and utilization of ICE exhaust gases*

efficiency of gas cleaning equipment based on Venturi pipes using the high-intensity ultrasound. It has been experimentally established that ultrasonic exposure provides an increase in the efficiency of the scrubber for ash particle diameters in the range of 2-90 microns over 96%, especially in the area of diameters less than 5 microns. The efficiency of capturing ash particles in a scrubber with a size of 2 microns, at a sound pressure level of 150 dB, is about 99%. This significantly exceeds the degree of gas purification without the use of ultrasonic coagulation (no more than 75 %). In study [10], a modified model for acoustic agglomeration of aerosol particles has been studied.

The hypothesis of the presented study is the assumption of intensifying coagulation of soot particles in the storage tank under the action of ultrasound for their subsequent disposal.

The aim of the study is to establish theoretical and experimental dependences that describe the process of purification and utilization of exhaust gases from an internal combustion engine.

To achieve the aim, the following tasks have been solved:

- a mathematical model of the process of internal combustion engine exhaust gases utilization has been developed and studied;
- an experimental equipment has been developed and it confirmed the results obtained analytically;
- a design has been proposed as well as the method of calculating the system for utilization of internal combustion engine exhaust gases.

The scientific novelty of the study consists in the following:

- the possibility of using ultrasonic mufflers with a capacitive chamber for the disposal of exhaust gases from internal combustion engines of city buses has been confirmed;
- the dependences were been obtained of changing the light transmission and light absorbing ability of the exhaust gas on the time of solid particles settling under the action of ultrasound and without it, as well as the coagulation coefficient dependence on the time of solid particles settling in the storage tank of the device for ultrasonic purification and utilization of internal combustion engines of city buses exhaust gases;
- for the first time, the dependence is obtained of the rate of changing the coagulation coefficient of solid particles on the time of their settling in the storage tank of the device for ultrasonic purification and utilization of internal combustion engine exhaust gases.

Practical usefulness consists in developing a method of calculating a storage device for ultrasonic purification and utilization of exhaust gases.

2 Materials and methods

Using the increased coagulation of soot particles of the exhaust gases due to the action of ultrasound on them, especially in the zone of the formed ultrasonic standing waves has been proposed. At this, the orthokinetic coagulation is supplemented by hydrodynamic coagulation, which leads to acceleration of the collision and adhesion of gas particles [11-12].

The solid particles, enlarged in the course of the coagulation process, mainly soot, settle at the bottom of the device at the intended collection point with its subsequent extraction and disposal.

The following device is proposed for ultrasonic cleaning and disposal of exhaust gases (Figure 1) [3].

The device works as follows. Exhaust gas enters the storage tank through the inlet pipe. From the ultrasonic transducer, located at the top, a direct wave arises that is reflected from the reflector of sound waves located on the container tray. During reflection, the direct and reflected waves move towards each other and, under the certain conditions, a standing wave is formed. When a standing wave occurs, the efficiency of the coagulation process increases due to increasing the amplitude of the resulting wave oscillations [11, 13].

The exhaust gases are made up of different size particles. Depending on their size and oscillation frequency, the particles are dragged by the sound vibrations to varying degrees, which leads to increasing the frequency of their collisions and intensifying the coagulation processes.

The degree of the particle participation in sound vibrations, in the case of a standing sound wave, is described by the ratio [13]:

$$\frac{U_p}{U_g} = \frac{1}{\left[(4\pi\rho r^2 f/9\eta)^2 + 1\right]^{1/2}}, \quad (1)$$

where U_p, U_g are respectively the amplitudes of the particle and gas oscillations, m;
ρ is the particle density, kg/m^3;
r is the particle radius, m;
f is the gas oscillations frequency under the action of ultrasound, Hz;
η is the dynamic viscosity, Pa·s.

The analysis of Equation (1) has shown that basically the degree of participation of particles in sound vibrations and consequently coagulation, is determined by the value:

$$Z = \frac{\rho r^2 f}{\eta}, \quad (2)$$

where Z is the gas particle drag coefficient [13].

The coagulation process is quantitatively described by the coagulation coefficient k [13]. In work [14], an attempt was made to determine its value and patterns of change by integrating the equation of motion of gas particles. The resulting dependence is very difficult to apply and gives significant discrepancies with practice.

In this work an assumption has been made about the qualitative similarity of the gas concentration model and the coagulation process, that is, by analogy with the kinetic equation [15]:

$$n = n_0 e^{-bt}, \quad (3)$$

where n and n_0 are the number concentrations of the airborne particles, current and at the initial moment, respectively, pcs/m^3; b is the concentration coefficient; t is the time, s, it will be fair that:

$$m = m_0 e^{-kt}, \quad (4)$$

where m and m_0 are respectively the current and the initial gas mass;
k is the coagulation coefficient;
t is the time, s.

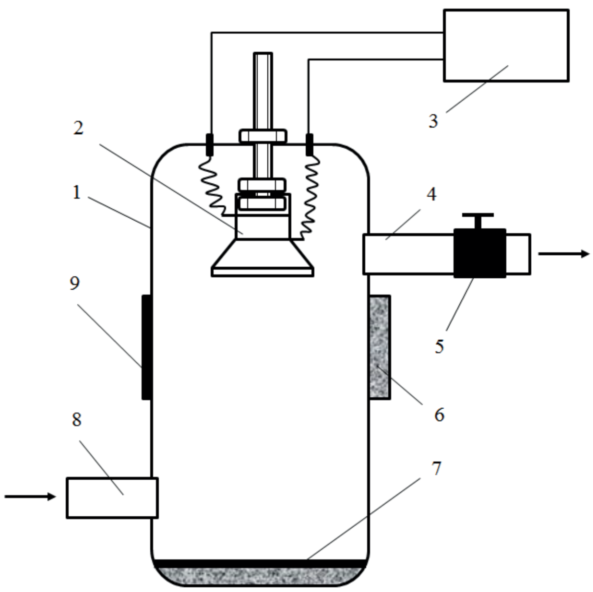
The value of the coagulation coefficient is to be experimentally determined.

It is proposed to determine the coagulation coefficient by the degree of gas transparency $\propto_i$ before and after exposure to ultrasound [16].

$$\propto_i = \frac{E_i}{E_{init}}, \quad (5)$$

where E_i is the illumination at present and after the ultrasound impact, lx;
E_{init} is the initial illumination, lx.

To carry out experiments according to the scheme (Figure 2), an experimental setup for ultrasonic cleaning of exhaust gases was developed (Figure 3) [3].



1 - body; 2 - emitter of ultrasonic waves; 3 - generator of ultrasonic vibrations; 4 - outlet pipe; 5 - valve; 6 - light source; 7 - reflector of ultrasonic waves; 8 - inlet pipe; 9 - luxmeter

***Figure 2** A scheme of the experimental setup for ultrasound purification and utilization of exhaust gases*

***Figure 3** Experimental setup for ultrasound purification and utilization of ICE exhaust gases*

Figure 4 *Experimental setup connection*

The material of the case is polyethylene terephthalate. It has good strength characteristics and transparency. A valve is installed on the outlet pipe, which is closed after the setup is filled with exhaust gas. Under the action of ultrasonic waves, generated by the ultrasonic emitter, the processes of coagulation of soot particles are intensified in the exhaust gas, as a result of which the soot particles become larger in size and mass and settle on the surface of the ultrasonic wave reflector.

The purified exhaust gas exits to the atmosphere through the exhaust pipe after opening the valve. To measure the illumination indicators, a light source and a device for measuring illumination have been fixed on the side surfaces opposite to each other.

At the preparatory stage, the assembled device, equipped with an ultrasonic emitter with the radiation frequency of 28 kHz and the power of 60 W, has been connected to the diesel engine of the experimental bench for studying the exhaust gas isolation. The bench has been assembled in the laboratory of the Transport Engineering and Logistics Systems Department of Karaganda Technical University (Figure 4).

A device for measuring illumination and a light source have been fixed on the opposite sides. The entire structure has been placed in a light-tight box to eliminate the effect of changing the ambient light on the results.

Having made the assumption that the average concentration of gas and soot particles is directly proportional to their masses, from Equation (4) was obtained:

$$m_c = m_0 - m_0 e^{-kt} = m_0(1 - e^{-kt}), \tag{6}$$

where m_c is the soot mass, kg;
m_0 is the gas initial mass, kg.

Based on the gas transparency coefficient from Equation (5), the light flux absorption coefficient β_i is equal:

$$\beta_i = 1 - \alpha_i, \tag{7}$$

where α_i is the gas transparency coefficient in the i-th interval of time.

Assuming that n and n_0 the number concentrations of gas particles, respectively current and at the initial moment, are proportional to the degree of absorption of the light flux β, the coagulation coefficient is equal:

$$k_i = -\frac{\ln\frac{\beta_i}{\beta_{i-1}}}{t}, \tag{8}$$

where i = 1…10;
t is the time interval between taking the readings, s. t = 60 s.

From Equation (4) the coagulation coefficient is determined as:

$$k = -\frac{\ln\left(1 - \frac{m_c}{m_0}\right)}{t}. \tag{9}$$

Based on the hypothesis of a close correlation between coagulation and the degree of gas transparency, Equations (8) and (9) have been equated and the dependences obtained that are needed to justify the experimental method [11]:

$$-\frac{\ln\left(1-\frac{m_c}{m_0}\right)}{t}=-\frac{\ln\frac{\beta_i}{\beta_{i-1}}}{t}. \quad (10)$$

From here it follows that:

$$m_c=m_0\left(1-\frac{\beta_i}{\beta_{i-1}}\right). \quad (11)$$

Or:

$$m_c=m_0\left(1-\frac{1-\alpha_i}{1-\alpha_{i-1}}\right)=m_0\left(1-\frac{1-\frac{E_i}{E_{init}}}{1-\frac{E_{i-1}}{E_{init}}}\right). \quad (12)$$

Thus, knowing the value of m_0 that can be determined from the volume of the container and the density of the gas, determine the value of m_c, it is necessary to establish experimentally the ratio $\frac{\beta_i}{\beta_{i-1}}$ through the corresponding indicators of illumination. An experimental study has been carried out to confirm the relationship between the degree of transparency and the coagulation coefficient.

3 Results

At the first stage of the experiment, the device was filled with exhaust gas in the engine start mode until the measured illumination decreased from 140 to 60 lx. Then, without turning on the ultrasonic equipment, the illumination was measured with the frequency of 1 minute in the interval of ± 5 seconds from the control point within 10 minutes. At the second stage of the experiment, the device was also filled with exhaust gas until the measured illumination decreased to 60 lx, the ultrasonic equipment was turned on and the illumination was measured at the frequency of 1 minute in the interval of ± 5 seconds, from the control point, within 10 minutes.

Figure 5 shows the reflector of ultrasonic waves after the operation of the experimental setup for ultrasonic purification of exhaust gases.

The results of the two stages of the experiment are presented in Tables 1 and 2.

Comparison of the obtained experimental illumination data to the theoretical ones shows that the nature of changing the theoretical and experimental illumination dependences on time without exposure to ultrasound and with exposure to ultrasound have sufficient convergence of the obtained experimental data with the theoretical ones. Figure 6 shows the theoretical and experimental graphs of the illumination E dependence on time t without the ultrasound action and under the ultrasound action.

At this, the error in the average values of the experimental data in comparison to the theoretical ones makes 16.9% without exposure to ultrasound and 14.23% under the ultrasound action.

The experimental data obtained made it possible to use them for determining the indicators of changes in illumination, the degree of transparency, the degree of absorption, the coagulation coefficient and to draw a conclusion about the effectiveness of the ultrasonic coagulation processes.

Table 3 presents the results of calculations of the coagulation coefficient.

As a result of ultrasonic intensification of coagulation

Figure 5 *Ultrasonic wave reflector after operation of the experimental setup*

***Table 1** Illumination values E, lx, without the ultrasound action*

No.	Sampling time, s									
	60	120	180	240	300	360	420	480	540	600
1	62	69	74	77	77	81	81	85	87	83
2	60	73	70	75	80	79	81	84	83	84
3	65	73	75	77	76	78	76	81	84	85
4	68	69	70	77	79	78	81	80	80	84
5	70	72	71	76	73	80	84	82	79	85
6	66	76	75	75	79	78	78	82	88	88
7	64	69	74	74	75	81	77	81	83	85
8	69	67	72	75	75	79	82	82	82	87
9	68	68	74	73	74	78	79	81	88	84
10	64	70	73	74	80	78	79	82	81	82
11	66	69	71	79	75	78	80	86	85	83
$\overline{E}$	65.64	70.45	72.64	75.64	76.64	78.91	79.82	82.36	83.64	84.55

***Table 2** Illumination values E, lx, s under the ultrasound action*

No.	Sampling time, s									
	60	120	180	240	300	360	420	480	540	600
1	81	86	94	100	107	111	115	115	116	119
2	83	93	95	101	104	108	112	115	115	119
3	75	89	99	100	106	106	110	114	117	119
4	79	89	95	103	104	110	112	117	117	118
5	76	92	92	100	103	109	110	116	118	117
6	79	92	92	101	105	106	113	116	120	121
7	78	95	96	98	106	108	113	114	119	117
8	83	84	97	100	108	107	111	113	120	121
9	79	90	96	99	103	107	113	117	118	123
10	81	91	96	102	106	113	113	116	121	124
11	86	88	94	104	105	113	116	118	117	118
$\overline{E}$	80.00	89.91	95.09	100.73	105.18	108.91	112.55	115.55	118.00	119.64

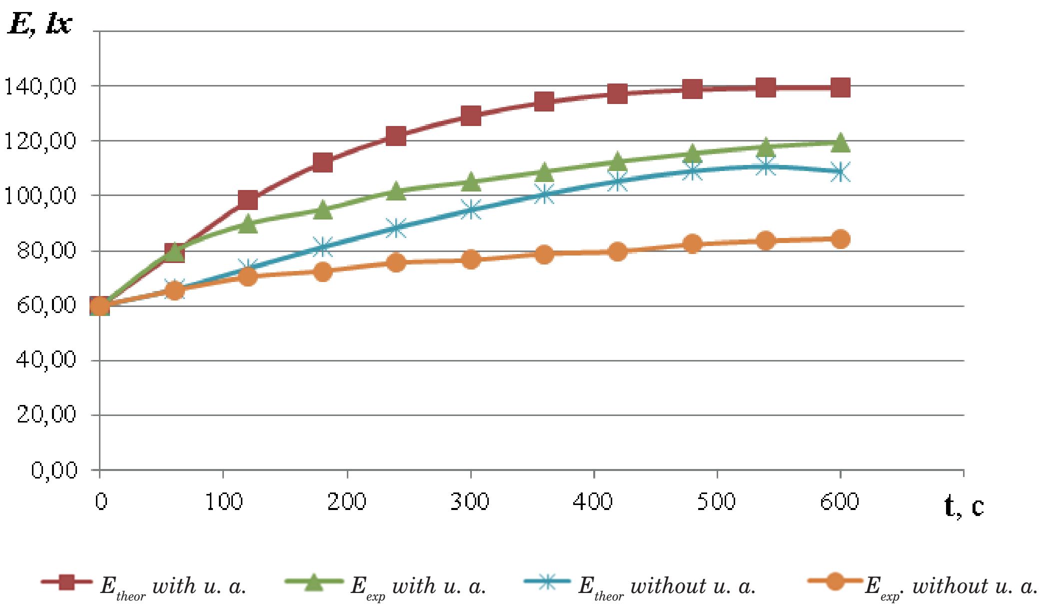


***Figure 6** Theoretical and experimental dependences of illumination E on time t without and with the ultrasound action*

***Table 3** The results of calculating the coagulation coefficient*

Seconds	Illumination indicator, E, lx		Transparence degree, ∝∝		Light flux absorption degree, β		Coagulation coefficient, k	
	Without ultrasound	With ultrasound	Without ultrasound	With ultrasound	Without ultrasound	With ultrasound	Without ultrasound	With ultrasound
0	60.00	60.00	0.429	0.429	0.571	0.571		
60	65.64	80.00	0.469	0.571	0.531	0.429	0.0012	0.0048
120	70.45	89.91	0.503	0.642	0.497	0.358	0.0011	0.0030
180	72.64	95.09	0.519	0.679	0.481	0.321	0.0005	0.0018
240	75.64	100.73	0.540	0.719	0.460	0.281	0.0008	0.0022
300	76.64	105.18	0.547	0.751	0.453	0.249	0.0003	0.0020
360	78.91	108.91	0.564	0.778	0.436	0.222	0.0006	0.0019
420	79.82	112.55	0.570	0.804	0.430	0.196	0.0002	0.0021
480	82.36	115.55	0.588	0.825	0.412	0.175	0.0007	0.0019
540	83.64	118.00	0.597	0.843	0.403	0.157	0.0004	0.0018
600	84.55	119.64	0.604	0.855	0.396	0.145	0.0003	0.0013

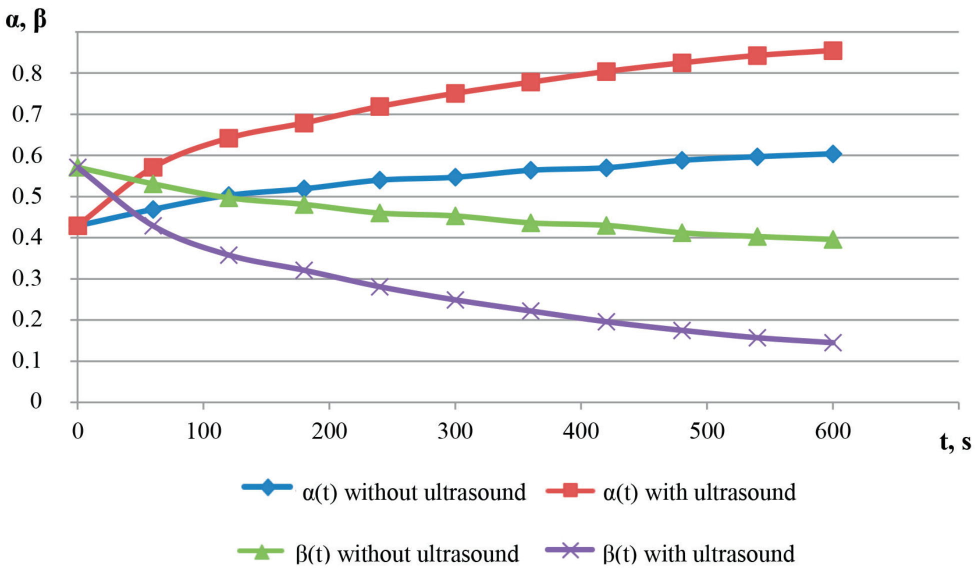


***Figure 7** The transparency degree α and absorption degree β dependence on settling time t*

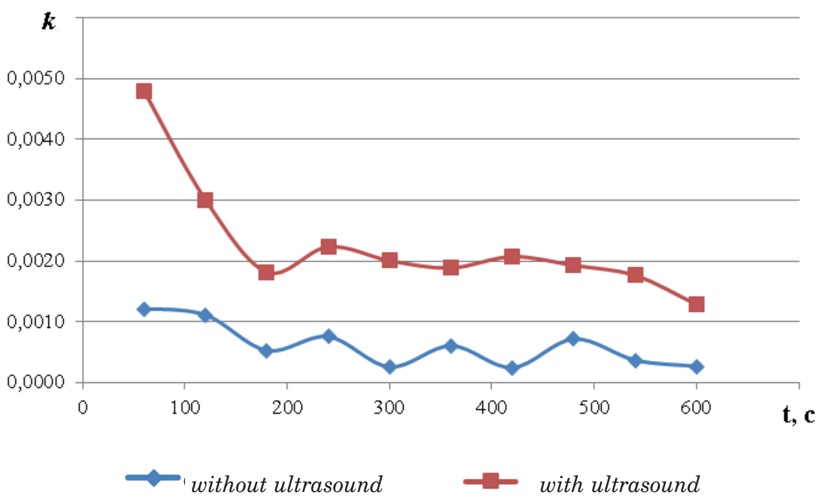


***Figure 8** The coagulation coefficient k dependence on settling time t*

processes, the initial values of the rate of changing the degree of transparency, coagulation coefficient with the ultrasonic exposure are 3 times higher than those without the ultrasonic exposure.

Based on the calculation results, graphs of the degree of transparency and the degree of absorption (Figure 7), the coagulation coefficient (Figure 8) dependence on the settling time have been plotted.

The presented graphic dependencies clearly show a high efficiency of ultrasonic coagulation of exhaust gas particles.

In the work, an approximation was made of the coagulation coefficient values in time t, according to the results of which it has been proposed to use the following cubic regression equation for the coagulation process using ultrasound:

$$k = (-0.0000012t^3 + 0.0012994t^2 - -0.4562322t + 69.30) \cdot 10^{-4}. \quad (13)$$

Figure 9 shows the dependencies k(t) built based on the experimental data and the data calculated using the cubic regression Equation (13).

Since the obtained dependence in Equation (13) has a significant coefficient of determination, differentiation of the function is possible. Then, the rate of changing the coagulation coefficient for processes with ultrasonic action would obey the following dependence:

$$k' = (-0.0000036t^2 + 0.0025988t - -0.4562322) \cdot 10^{-4}. \quad (14)$$

Figure 10 shows the dependence of the coagulation coefficient changing rate on time.

Decreasing the coagulation rate is explained by decreasing the concentration of soot particles in the gas, that is, its purification to a some extent.

The work proposes several constructive options for using the effect of ultrasonic purification and utilization

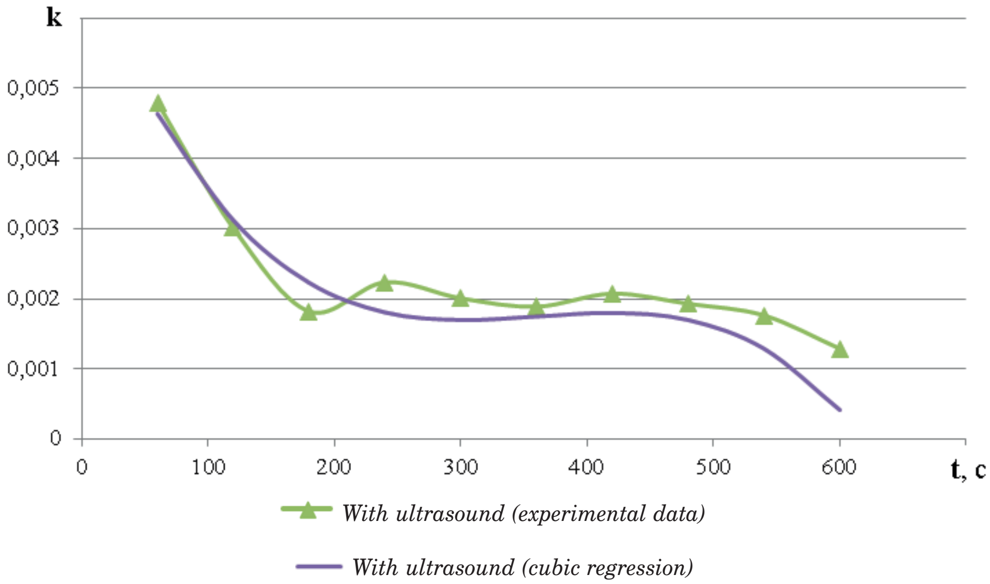


Figure 9 *Changing the coagulation coefficient k with the time t under ultrasound action*

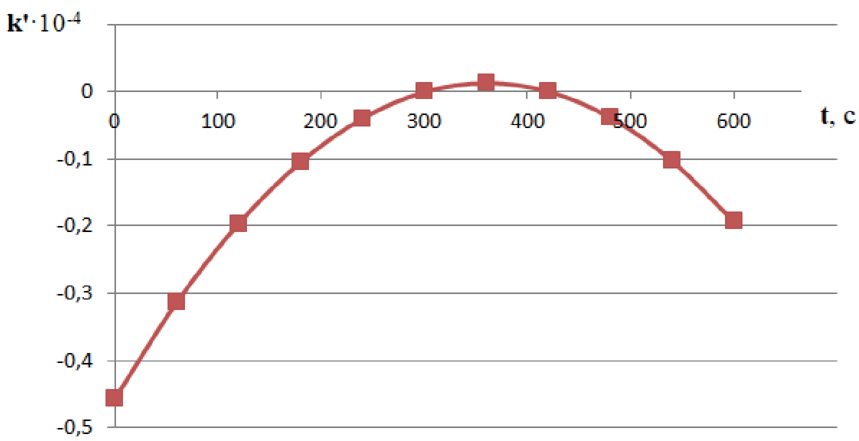


Figure 10 *The coagulation coefficient changing rate k′ dependence on time t*

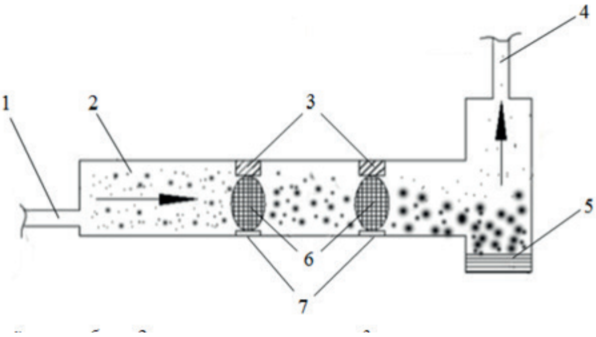
of internal combustion engine exhaust gases.

Figure 11 shows the scheme of operation of the ultrasonic device for cleaning the exhaust gases of a flow type with the transverse action of ultrasound.

Figure 12 shows the schemes of operation of an ultrasonic device for cleaning the exhaust gases of a flow type with the longitudinal action of ultrasound in two versions: with generation of ultrasonic waves in the direction of the gas flow and against the direction of its movement.

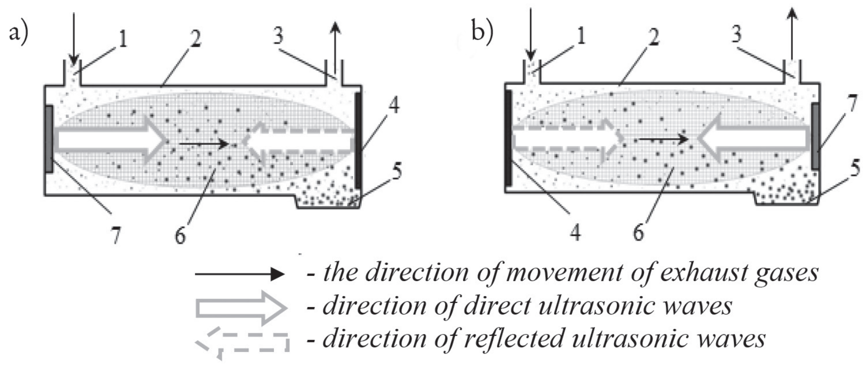
Figure 13 shows a device for ultrasonic cleaning of exhaust gases with exposure to ultrasound at different angles.

One more device for cleaning exhaust gases of a



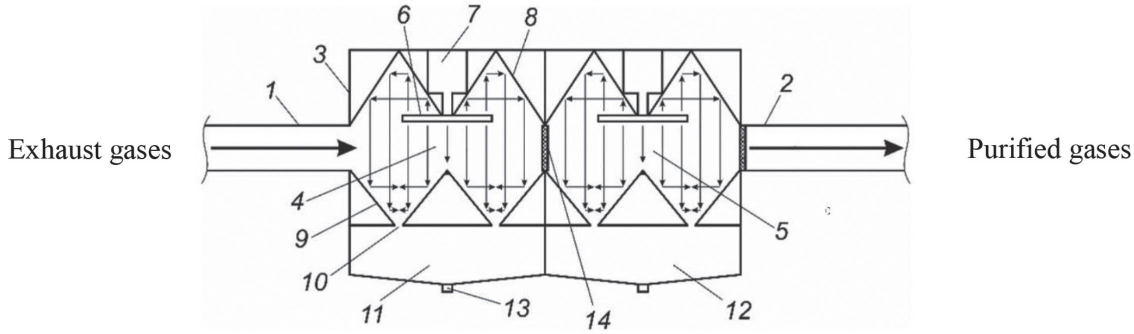
1 - inlet pipe; 2 - muffler body; 3 - emitter of ultrasonic waves; 4 - outlet pipe; 5 - place of collecting and extracting soot particles; 6 - zone of standing waves; 7 - reflector of ultrasonic waves

Figure 11 *The scheme of operation of the ultrasonic muffler the transverse action of ultrasound*



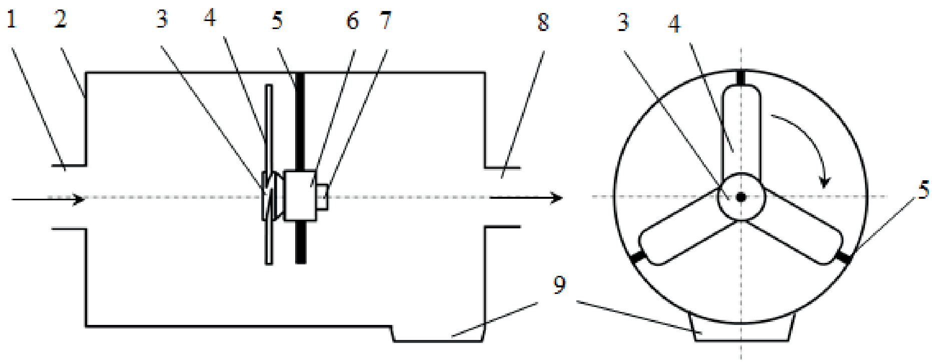
1 - inlet pipe; 2 - muffler body; 3 - outlet pipe; 4 - reflector of ultrasonic waves; 5 - place of collecting and extracting soot particles; 6 - zone of standing waves; 7 - emitter of ultrasonic waves

Figure 12 *Schemes of operation of the ultrasonic muffler with the longitudinal action of ultrasound: a) in the direction of the gas flow; b) against the direction of the gas movement*



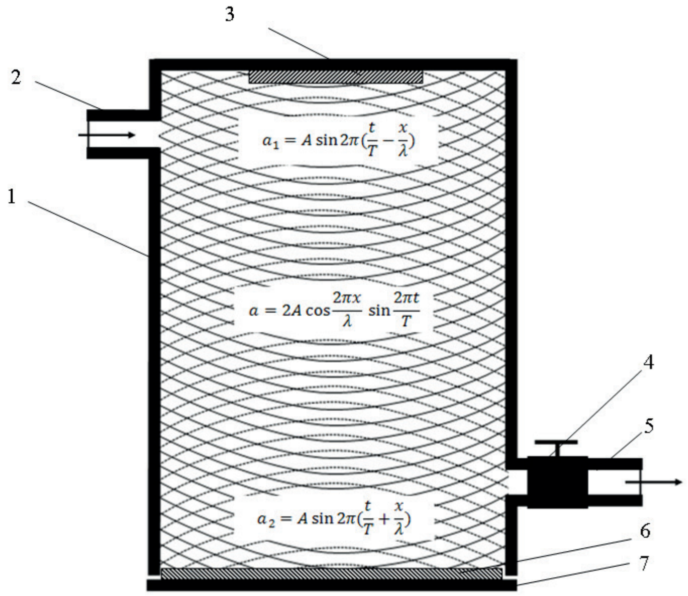
1 - inlet pipe; 2 - outlet pipe; 3 - body; 4 - coagulation chamber; 5 - coagulation chamber; 6 - emitter of ultrasonic vibrations; 7 - transducer of ultrasonic vibrations; 8 - upper reflectors; 9 - lower reflectors; 10 - holes for removal of particles; 11, 12 - storage tanks for collecting particles; 13 - holes with a plug; 14 - filtration grids

Figure 13 *A device for ultrasonic purification of exhaust gases*



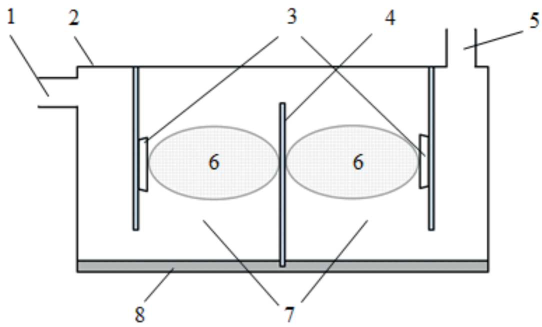
1 - inlet pipe; 2 - body; 3 - ultrasonic emitter; 4 - bladed propeller; 5 - rack; 6 - rotation mechanism; 7 - rotating contact device; 8 - outlet pipe; 9 - place for collecting and extracting soot particles

Figure 14 *A device for purification of exhaust gases with a dynamic system of ultrasonic action*



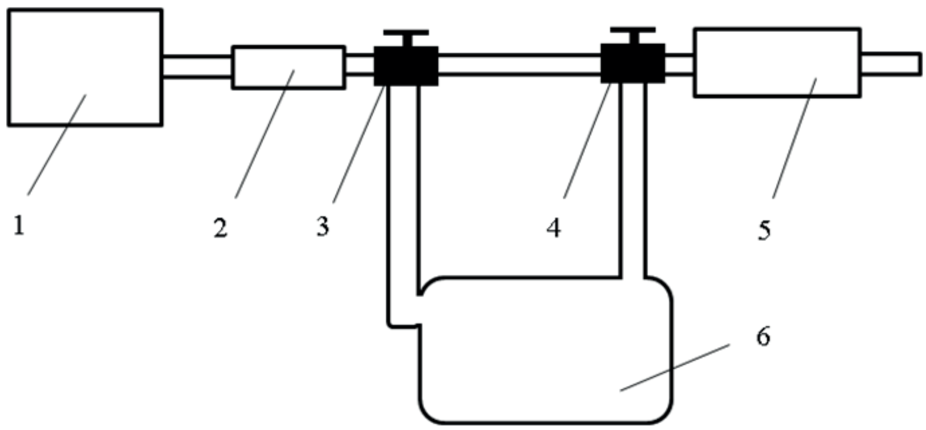
1 - storage tank; 2 - inlet pipe; 3 - ultrasonic generator; 4 - bypass valve; 5 - outlet pipe; 6 - reflector of sound waves; 7 - tray

Figure 15 *The accumulative ultrasonic device for cleaning exhaust gases with the vertical arrangement of ultrasonic equipment*



1 - inlet pipe; 2 - body; 3 - ultrasonic emitter;
4 - sound-reflecting partition; 5 - outlet pipe; 6 - zone of standing waves;
7 - coagulation chambers; 8 - tray

Figure 16 *The combined type device for purification of exhaust gases with the horizontal arrangement of ultrasonic equipment*



1 - engine; 2 - resonator; 3 - inlet valve; 4 - exhaust valve; 5 - silencer; 6 - ultrasonic cleaning device

Figure 17 *The recommended scheme of mounting the equipment for ultrasonic purification and utilization of exhaust gases*

flow type, with a dynamic system of ultrasonic action, is shown in Figure 14. Here, a bladed propeller serves as an emitter of ultrasonic waves.

The accumulative ultrasonic device for cleaning the exhaust gases, with the vertical arrangement of ultrasonic equipment, is shown in Figure 15.

The device shown in Figure 16, with the horizontal arrangement of ultrasonic equipment, can be used in both flow and storage modes, i.e. it is combined.

All of the above devices make it possible not only to clean exhaust gases but also to utilize the soot particles enlarged and settled as a result of ultrasonic exposure.

Figure 17 shows the recommended scheme of mounting the equipment for ultrasonic purification and utilization of vehicle exhaust gases [3].

4 Example of the calculation technique

The method of calculating the ultrasonic equipment includes:

1) determining the distance between the emitter and the ultrasound reflector for the formation of standing waves, at which the coagulation process occurs most efficiently;
2) checking the compliance with coagulation conditions;
3) calculating the required time of exposure to exhaust gases, for a given degree of purification, to determine the required volume of the storage tank.

1. For formation of the standing waves, it is necessary that the distance between the emitter and the reflector of ultrasonic waves be a multiple of half the wavelength. The ultrasonic wave length is determined by the formula:

$$\lambda = \frac{v}{f}, \tag{15}$$

where v is the sound propagation velocity, v = 300 m/s; f is the oscillation frequency, Hz.

For ultrasonic equipment with the ultrasonic waves radiation frequency of 28 kHz:

$$\lambda = \frac{300}{28000} = 10.7\,mm\,. \tag{16}$$

Thus, the distance between the emitter and the reflector is to be determined by the formula:

$$L = \frac{\lambda}{2} \cdot i\,, \tag{17}$$

where i = 1, 2, 3…

2. For ρ = 1900 kg/m^3; f = 28000 Hz; η = 0.00017 from Equation (2) the drag coefficient Z can be determined, which should have values from 0.54 to 3.51 [13], the range of the particle radii that are most efficiently affected by the ultrasonic equipment:

$$r = \sqrt{\frac{Z\eta}{\rho f}}\,, \tag{18}$$

$$r_0 = \sqrt{\frac{0.54 \cdot 0.00017}{1900 \cdot 28000}} = 1.31 \cdot 10^{-6} m = 1.31 \mu m\,; \tag{19}$$

$$r_0 = \sqrt{\frac{3.51 \cdot 0.00017}{1900 \cdot 28000}} = 3.34 \cdot 10^{-6} m = 3{,}34 \mu m. \tag{20}$$

In this case, the degree of participation of particles with the size of 1.31 μm and 3.34 μm in the sound vibrations of a standing ultrasonic wave $\frac{U_p}{U_g}$ will be equal to 0.8 and 0.2, respectively.

The results of the calculation indicate that the conditions for occurrence of the ultrasonic coagulation are met and indicate the highly efficient coagulation processes of fine particles of exhaust gases with the radius of 1.31 to 3.34 μm.

3. To determine the volume of the storage tank that is required for the most efficient operation of ultrasonic cleaning and disposal equipment, it is necessary to determine the rational time of ultrasonic exposure to the exhaust gas. The volume of the storage tank is determined by the calculation method described in literature [17].

Here is the entire volume of soot present in the tank, both in suspension and settled on the bottom of the device as a result of coagulation, accepted as a unit and then it is determined what part of the solid particles is settled, using Equation (3) of the calculated concentrations of suspended solid particles of the gas dependence [15]:

$$n = n_0 \exp(-kt) \tag{21}$$

and obtained Equation (14) of the coagulation coefficient changing:

$$k = (-0.0000012t^3 + 0.0012994t^2 - \\ -0.4562322t + 69.3) \cdot 10^{-4} \tag{22}$$

The s value characterizes the share of settled solid particles and will determine the degree of the exhaust gas purification:

$$s = 1 - n \tag{23}$$

$$s = 1 - n_0 \exp(-kt) \tag{24}$$

It is assumed that at the initial time t = 0 all the soot particles are in suspension, i.e. if n = 1, then s = 0.

Table 4 *Calculating the degree of the exhaust gases purification s depending on the time of the ultrasound action*

t	k	n_0	n	s
0	0.00693	1.00	1	0
60	0.004634	1.00	0.76	0.24
120	0.003119	0.76	0.52	0.48
180	0.002228	0.52	0.35	0.65
240	0.001806	0.35	0.23	0.77
300	0.001698	0.23	0.14	0.86
360	0.001747	0.14	0.07	0.93
420	0.001799	0.07	0.03	0.97
480	0.001698	0.03	0.02	0.98
540	0.001288	0.02	0.01	0.99
600	0.000414	0.01	0.01	0.99

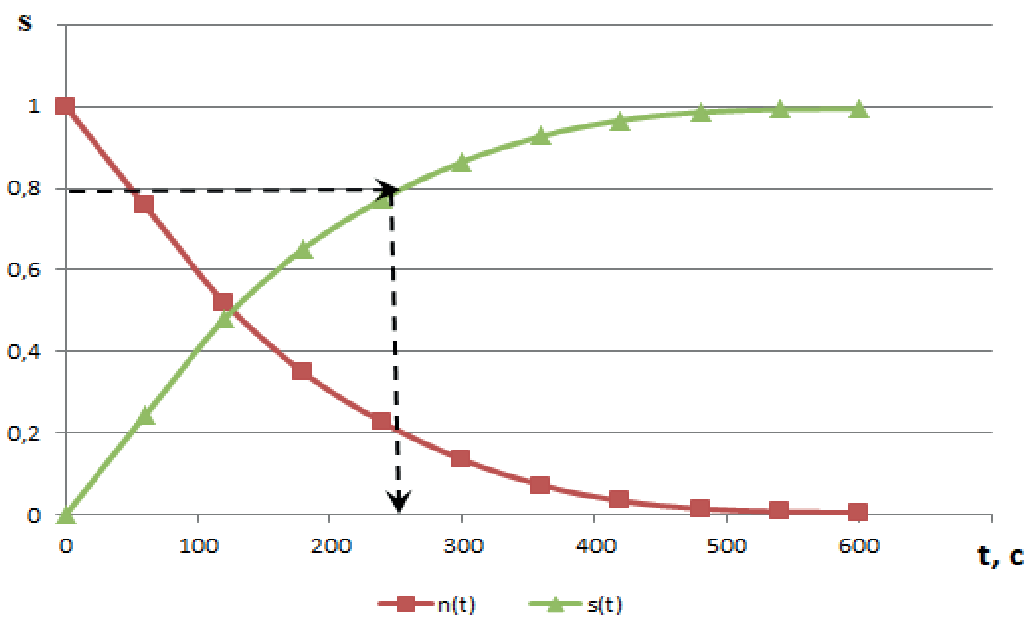


Figure 18 *The graphs of the n(t) and s(t) dependences*

The calculation of the degree of the exhaust gases purification depending on the time of ultrasonic exposure is presented in Table 4.

The graphs of the $n(t)$ and $s(t)$ dependencies are presented in Figure 18.

According to the graph of the exhaust gases degree of purification dependence on time, it is possible to determine the required time of exposure to ultrasound for a given degree of purification. For example, for the 80% degree of purification, the required time of ultrasonic exposure will be t = 260 s.

5 Conclusions

In the course of studying the operation of devices for ultrasonic purification and utilization of exhaust gases, there has been made the following work and draw the following conclusions:

- analyzing the cleaning methods and composition of the exhaust gases of internal combustion engines substantiates the need for their disposal due to the ultrasonic action;
- the physical essence of the process of exhaust gases coagulation under the action of ultrasound is described, the understanding of which is needed for development of a mathematical model of the process of exhaust gases utilization. A mathematical model of the process of exhaust gases of internal combustion engine utilization, based on the formula of the molecular-kinetic theory of gases, has been developed and studied. The obtained dependence that takes into account the number concentrations of gas and soot particles, which vary depending on the time and the coagulation coefficient, makes it possible to determine the amount of soot settled and to determine the efficiency of cleaning exhaust gases with an ultrasonic device;
- based on the proposed hypothesis of a close relationship between the content of soot particles in suspension and the light transmission capacity of a certain volume of gas, the concept of illumination has been introduced as a parameter for assessing the content of soot particles in suspension;
- an experimental ultrasonic accumulative device has been developed that allows measuring the light transmission of the volume of gas in the device, according to the illumination parameter E and based on the data obtained, determining the change in the concentration of soot particles in suspension, the coagulation coefficient over time without exposure to ultrasound and with exposure to ultrasound;
- experiments have been carried out on the developed experimental equipment and the results obtained have been analytically confirmed. At this, the error in the average values of the experimental data in comparison with the theoretical ones has made 16.9% without exposure to ultrasound and 14.2% under the ultrasound action;
- alternate options of using the effect of ultrasonic cleaning of internal combustion engine exhaust gases of transport equipment have been proposed that determine the trends for the further scientific research;
- a method of calculating the capacitive equipment has been developed that makes it possible to determine the main design parameters of ultrasonic cleaning systems for exhaust gases of internal combustion engines and the terms of reference for designing an ultrasonic cleaning system for exhaust gases from internal combustion engines of city buses.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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