DETERMINING THE EFFICIENCY OF CLEANING VEHICLE EXHAUST GASES WITH AN ULTRASONIC MUFFLER DEPENDING ON THE ENGINE OPERATING MODE AND ULTRASOUND POWER

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Resume

The dependence has been obtained that links the degree of coagulation of soot particles, the parameters of the ultrasonic equipment, the geometric dimensions of the ultrasonic muffler, the frequency characteristics of ultrasound, and the parameters of the engine operating mode. In the paper is presented solving of a problem of determining the number of particles in 1 cm3 of exhaust gas depending on the smoke index. An example of calculating the required ultrasound power for a full-size ultrasonic vehicle muffler bench has been given.

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1 Introduction

Present-day environmental safety standards for vehicles make it necessary to develop effective methods for reducing the toxicity of internal combustion engine exhaust gases. One of the most dangerous components of exhaust gases are the soot particles, especially fractions smaller than 10 microns (PM10). They easily penetrate the human respiratory system and cause diseases of the respiratory system and cardiovascular system. Long-term exposure to such particles can contribute to the development of chronic pathologies and negatively affect the environment, settling in the soil and water bodies [1-7]

Study in the field of developing the exhaust gas cleaning systems represents an urgent task aimed at reducing the content of soot particles and the other harmful substances in the exhaust gases of internal combustion engines. One of the promising areas for reducing the harmful emissions is the use of ultrasonic technologies in the exhaust gas neutralization system [8-14].

Works [8-9, 14] present the results of studies of the ultrasonic muffler operation that is a device in the form of a pipe with a built-in emitter of ultrasonic waves. In this case, the high-frequency acoustic vibrations contribute to the intensification of the processes of coagulation and sedimentation of solid particles. The set of parameters of the muffler mode and design determine the specific modes of its operation. The hypothesis of the study is an assumption of the existence of an optimal cleaning mode for specific designs of mufflers of different sizes and operating modes.

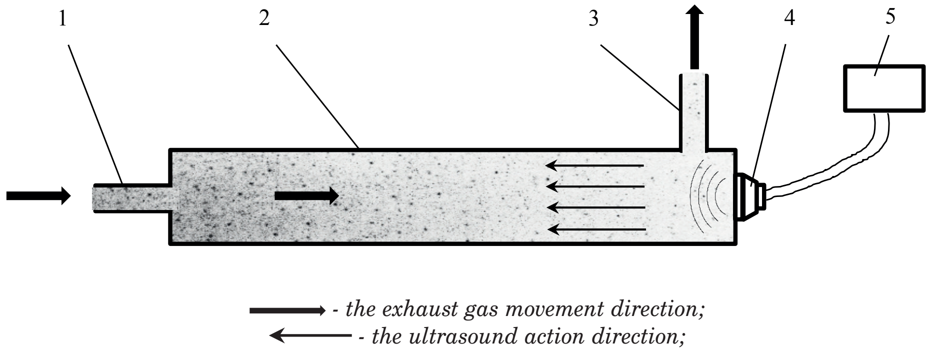
The aim of the study was to determine the optimal parameters of ultrasonic equipment for the most effective cleaning of exhaust gas during operation.

The scientific novelty of the study is establishing the dependence of the coagulation degree on the engine crankshaft speed, muffler characteristics and ultrasonic equipment.

The practical usefulness lies in the use of the established dependence in the design of exhaust gas cleaning systems to determine the characteristics of ultrasonic equipment and its operating mode.

Coagulation of particles in the exhaust gas of an internal combustion engine occurs almost constantly due to the chaotic movement of particles, their collisions and adhesion in the gas volume [15-17].

When exposed to ultrasound, the coagulation process is intensified, not only due to increasing orthokinetic



1 - inlet pipe; 2 - muffler body; 3 - outlet pipe; 4 - ultrasonic wave emitter; 5 - ultrasonic pulse generator

Figure 1 *Ultrasonic muffler schematics*

coagulation, but due to the occurrence of hydrodynamic coagulation of solid particles in the ultrasonic field, as well, which contributes to the greatest efficiency of the coagulation-sedimentation process. Hydrodynamic coagulation occurs in the ultrasonic field, in which the large particles begin to converge under the action of hydrodynamic forces in the sense of Bjerknes and coagulate due to friction. The coagulation process is described by the Bjerknes equations [8, 17-18].

In works [8-9, 14] experiments were conducted using the ultrasound of different frequencies, power characteristics, different directions of ultrasonic radiation, with different crankshaft rotation speeds. Based on the obtained research results, one of the conclusions is that the greatest cleaning efficiency is achieved by transmitting the ultrasonic waves in the horizontal direction against the direction of movement of exhaust gases [8-9]. The scheme of the ultrasonic muffler is shown in Figure 1.

An assumption was made about the existence of the cleaning efficiency of an ultrasonic device dependence on a number of factors, including the rotation speed of the ICE crankshaft and the intensity of ultrasonic radiation [8-9, 14].

Thus, the experiments carried out on ultrasonic mufflers [8-9, 14] indicate the need for further research in the field of determining the cleaning efficiency dependence on the parameters of ultrasonic equipment, which is required for the design of ultrasonic devices for cleaning exhaust gases of ICEs.

2 Materials and research methods

Several dependences of the coagulation process have been analyzed, such as the Smoluchowski coagulation kinetics, the Einstein diffusion coefficient [19], and the Kidoo dependence [19], of which the last has attracted the greatest interest. The dependence proposed in 1951 by scientist Kidoo Gordon based on the calculations of Vivian and Stokes [17, 20] between the degree of coagulation E, the number of particles G in 1 cm^3 and the time of irradiation t with ultrasound of intensity j allows for identifying the relationship between the degree of coagulation, the time of ultrasonic exposure, which depends on the rotation frequency of the internal combustion engine crankshaft, and the intensity of ultrasonic radiation:

$$\lg(100 - E) = \frac{k}{G \cdot t \cdot \sqrt{J}}, \quad (1)$$

where:
E is the coagulation degree, %;
k is a constant value for the studied design of the ultrasonic muffler depending on the frequency of ultrasound, the nature of the particles and the equipment used;
G is the number of particles in 1 *cm*^{3}*, particles/cm*^{3}. It is determined based on the initial smoke index of the exhaust gas D_0;
t is the time of ultrasound action, s;
j is the ultrasound intensity, W/cm^2. It is determined according to the formula:

$$j = \frac{W}{S},\ W/cm^2, \quad (2)$$

where:
W is the ultrasound power, W;
S is the cross section of the ultrasound muffler, cm^2.

From Equation (1), the constant value k is determined as follows:

$$k = \lg(100 - E) \cdot G \cdot t \cdot \sqrt{j}. \quad (3)$$

The degree of coagulation E is the ratio of changing the smoke content of the exhaust gas to the initial smoke index and is determined as follows:

$$E = \frac{D_0 - D_i}{D_0} \cdot 100,\ \%, \quad (4)$$

where:
D_0 is the initial smoke index of the exhaust gas without

the ultrasound action, m^{-1};

D_i is the smoke index of the exhaust gas after the ultrasonic cleaning, m^{-1}.

The most important task not solved in works [8-9, 14], is determining the number of soot particles in 1 cm^3. To determine the number of particles G in 1 cm^3, the smoke index of the exhaust gas is used that corresponds to a certain mass concentration of soot M, g/m^3, determined according to the table "Ratios of units of measurement of smoke and mass concentration of soot" of the Operating Manual for the exhaust gas smoke meter [21]. If the data in the table do not cover the measured range of values D, then the value of M is determined by the empirical dependence on the absorption coefficient D, m^{-1}, determined based on the data in the table:

$$M = 0.00334D^3 - 0.01208D^2 + \\ + 0.18064D - 0.01032, \mathrm{g/m^3}. \quad (5)$$

Knowing the mass concentration of soot and the mass of one soot particle, the number of particles in 1 cm^3 is determined using the formula:

$$G = \frac{M}{m_{s.p.}} \cdot 10^{-6} \text{ particles/cm}^3, \quad (6)$$

where:

M is the mass soot concentration, g/m^3;

$m_{s.p}$ is the soot particle mass, g.

The mass of one soot particle is determined based on the average size of the radius of soot particles r = 15.25 nm, density ρ = 1.9 g/cm^3 [22]:

$$m_{s.p.} = V_{s.p.} \cdot \rho, g, \quad (7)$$

where:

$V_{s.p.}$ is the average volume of the soot particle, cm^3;

ρ is the soot particle density, g/cm^3.

Assuming that the soot particle has the shape of a sphere [15-16], the volume of the soot particle is determined by the formula:

$$V_{s.p.} = \frac{4}{3}\pi r^3, \mathrm{cm^3}; \\ V_{s.p.} = 1.48483 \cdot 10^{-17} \mathrm{cm^3}; \quad (8) \\ m_{s.p.} = 2.82118 \cdot 10^{-17} \mathrm{g}.$$

The time of ultrasonic action t, depending on the speed of the exhaust gas movement depends on the rotation frequency of the crankshaft and the volume of the engine cylinders according to the formula [23]:

$$t = \frac{L \cdot \pi \cdot R^2}{2\omega \cdot Q}, s, \quad (9)$$

where:

ω is the crankshaft rotation frequency, rps;

Q is the engine cylinder volume, cm^3.

Thus, the constant value k is determined as:

$$k = \lg\left(100 - \frac{D_0 - D_i}{D_0}100\right) \cdot G\frac{L \cdot \pi \cdot R^2}{\omega \cdot Q}\sqrt{j}. \quad (10)$$

From Equation (1), the coagulation degree E is determined as:

$$E = 100 - 10^{\frac{k}{Gt\sqrt{j}}}, \%. \quad (11)$$

This formula is applicable to determining the degree of soot particle coagulation in a flow-through muffler equipped with an ultrasonic emitter. The constant k calculated using Equation (10) adapts Equation (11) to a specific muffler design with given geometric dimensions and a set ultrasonic frequency under various engine operating conditions and ultrasonic equipment power levels.

Substituting Equations (6), (9) and (10) into the formula for determining the degree of coagulation E, in Equation (11) and changing the values of ω and j, the dependences of the degree of coagulation that characterize the cleaning efficiency on the rotation frequency of the ICE crankshaft and the intensity of ultrasonic radiation are determined.

The calculation is now performed of a full-size ultrasonic automobile muffler bench (Figure 2) developed in the laboratory of the Transport Equipment and Logistics Systems Department of the Abylkas Saginov Karaganda Technical University (Karaganda, Kazakhstan), where experiments were carried out to determine the efficiency of ultrasonic exposure [9].

The ultrasonic equipment provided the ultrasound radiation with frequency of 25 kHz and power of 50 W, horizontally against the direction of the exhaust gases in the muffler. The inlet pipe of the bench was connected to the muffler of a vehicle equipped with a diesel engine with the volume of 2700 cm^3. The smoke content of the exhaust gas was measured with a smoke meter on the outlet pipe of the ultrasonic vehicle muffler bench.

Figure 2 *Full-size ultrasonic vehicle muffler bench*

The results of the experiments are shown in Table 1.

The average value of the absorption coefficient for five measurements without ultrasound exposure was D_0 = 1.19 m^{-1} with a standard deviation of 0.012, with ultrasound exposure - D_i = 0.86 m^{-1} with a standard deviation of 0.014 [9].

***Table 1** Experimental results*

Measurement number	D_0	D_i
1	1.2	0.86
2	1.17	0.84
3	1.19	0.88
4	1.21	0.85
5	1.18	0.88

***Table 2** The k value calculation*

Indicator	Value
Ultrasound frequency *f*, Hz	25
Ultrasound power *W*, W	50
Absorption coefficient value D_0 without ultrasound exposure, m^{-1}	1.19
Absorption coefficient value D_i with ultrasound exposure, m^{-1}	0.86
Degree of coagulation *E*, %	11.84
Mass concentration of soot *M*, g/m^3	0.122
Number of soot particles in 1 cm^3 *G*, particles/cm^3	4324424448
Engine crankshaft rotation frequency ω, rpm	750
Engine crankshaft rotation frequency ω, rps	12.5
Engine capacity V_{cyl}, m^3	0.0027
Ultrasonic muffler length *L*, m	1
Ultrasonic muffler radius *R*, m	0.055
Ultrasonic muffler cross-sectional area *S*, m^2	0.009499
Ultrasound intensity *j*, W/cm^2	5263.989
Ultrasonic exposure time t, s	0.141
Constant value *k*	82073908106

***Table 3** Calculation of the coagulation degree E in the course of ultrasonic during cleaning with frequency of 25 kHz and power of 50 W and various crankshaft speeds of a diesel engine of a volume of 2700 cm^3*

f, Hz	k	ω, rpm	ω, rpm	V_{cyl}, m^3	L, m	R, m	t, s	J, W/m^2	E, %
25	82073908106	750	12.50	0.0027	1	0.055	0.141	5263.99	27.731
25	82073908106	800	13.33	0.0027	1	0.055	0.132	5263.99	3.865
25	82073908106	850	14.17	0.0027	1	0.055	0.124	5263.99	-27.883
25	82073908106	900	15.00	0.0027	1	0.055	0.117	5263.99	-70.115
25	82073908106	950	15.83	0.0027	1	0.055	0.111	5263.99	-126.293
25	82073908106	1000	16.67	0.0027	1	0.055	0.106	5263.99	-201.025
25	82073908106	1050	17.50	0.0027	1	0.055	0.101	5263.99	-300.435
25	82073908106	1100	18.33	0.0027	1	0.055	0.096	5263.99	-432.675
25	82073908106	1150	19.17	0.0027	1	0.055	0.092	5263.99	-608.586
25	82073908106	1200	20.00	0.0027	1	0.055	0.088	5263.99	-842.589
25	82073908106	1250	20.83	0.0027	1	0.055	0.084	5263.99	-1153.870
25	82073908106	1300	21.67	0.0027	1	0.055	0.081	5263.99	-1567.948
25	82073908106	1350	22.50	0.0027	1	0.055	0.078	5263.99	-2118.772
25	82073908106	1400	23.33	0.0027	1	0.055	0.075	5263.99	-2851.500
25	82073908106	1450	24.17	0.0027	1	0.055	0.073	5263.99	-3826.204

3 Results

Based on the results of the experiment on an ultrasonic muffler with the following parameters: length - 1000 mm, diameter - 110 mm, ultrasonic emitter frequency 25 kHz, power - 50 W, the value of k was calculated. The initial data and calculation results are given in Table 2.

The found value k = 82073908106 is a constant for the studied design of the ultrasonic muffler and is used to determine the dependences of the coagulation degree on the engine crankshaft speed and ultrasound power. Based on the calculated value k, changes in the coagulation degree were determined using Equation (11), when cleaning with frequency of 25 kHz and power of 50 W and various crankshaft speeds of a diesel ICE with the volume of 2700 cm^3. The calculation results are presented in Table 3. The graph of changing the coagulation degree, when cleaning with frequency of 25 kHz and power of 50 W and various crankshaft speeds of a diesel ICE with the volume of 2700 cm^3, is shown in Figure 3.

The maximum smoke index of a diesel engine is usually observed in the range of 1200-1800 rpm [24]. The dependence of the coagulation degree E using Equation (11) during the cleaning with ultrasound at frequency of 25 kHz and the maximum rotation frequency of the crankshaft of a diesel internal combustion engine in the

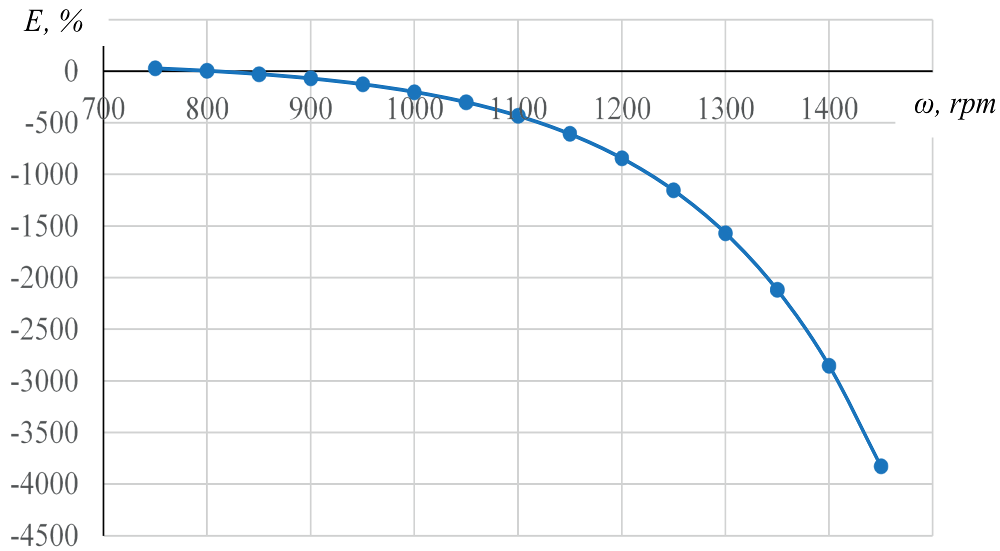


Figure 3 *Graph of changing the degree of coagulation E in the course of ultrasonic cleaning with frequency of 25 kHz and power of 50 W and different crankshaft speeds of a diesel engine of a volume of 2700 cm³*

Table 4 *Calculation of the coagulation degree E dependence during the cleaning with ultrasound at frequency of 25 kHz and the crankshaft speed of 1800 rpm of a diesel engine of a volume of 2700 cm³ on the power of ultrasonic radiation W*

f, Hz	k	ω, rpm	ω, rps	V_{cyl}, m^3	L, m	R, m	t, s	W, W	E, %
25	82073908106	1800	30	0.0027	1	0.055	0.059	50	-28839.004
25	82073908106	1800	30	0.0027	1	0.055	0.059	125	-563.269
25	82073908106	1800	30	0.0027	1	0.055	0.059	200	-70.115
25	82073908106	1800	30	0.0027	1	0.055	0.059	275	20.130
25	82073908106	1800	30	0.0027	1	0.055	0.059	350	51.440
25	82073908106	1800	30	0.0027	1	0.055	0.059	425	66.094
25	82073908106	1800	30	0.0027	1	0.055	0.059	500	74.246
25	82073908106	1800	30	0.0027	1	0.055	0.059	575	79.317
25	82073908106	1800	30	0.0027	1	0.055	0.059	650	82.726
25	82073908106	1800	30	0.0027	1	0.055	0.059	725	85.153
25	82073908106	1800	30	0.0027	1	0.055	0.059	800	86.957
25	82073908106	1800	30	0.0027	1	0.055	0.059	875	88.345
25	82073908106	1800	30	0.0027	1	0.055	0.059	950	89.443
25	82073908106	1800	30	0.0027	1	0.055	0.059	1025	90.331
25	82073908106	1800	30	0.0027	1	0.055	0.059	1100	91.063

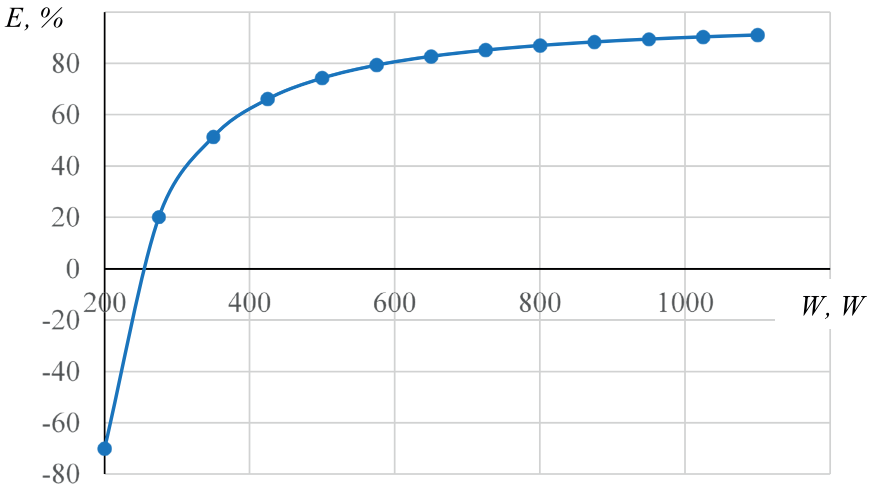


Figure 4 *Graph of the coagulation degree E dependence in the course of cleaning with frequency of 25 kHz and the crankshaft speed of 1800 rpm of a diesel engine of a volume of 2700 cm³ on the power of ultrasonic radiation W*

Table 5 *Calculation of the coagulation degree E during cleaning with ultrasound with frequency of 25 kHz and power of 600 W and various crankshaft rotation frequencies of a diesel ICE of a volume of 2700 cm³*

f, Hz	k	ω, rpm	ω, rps	V_{cyl}, m³	L, m	R, m	t, s	J, W	E, %
25	82073908106	750	12.50	0.0027	1	0.055	0.141	63167.869	96.559
25	82073908106	950	15.83	0.0027	1	0.055	0.111	63167.869	95.217
25	82073908106	1150	19.17	0.0027	1	0.055	0.092	63167.869	93.350
25	82073908106	1350	22.50	0.0027	1	0.055	0.078	63167.869	90.754
25	82073908106	1550	25.83	0.0027	1	0.055	0.068	63167.869	87.146
25	82073908106	1750	29.17	0.0027	1	0.055	0.060	63167.869	82.129
25	82073908106	1950	32.50	0.0027	1	0.055	0.054	63167.869	75.155
25	82073908106	2150	35.83	0.0027	1	0.055	0.049	63167.869	65.458
25	82073908106	2350	39.17	0.0027	1	0.055	0.045	63167.869	51.977
25	82073908106	2550	42.50	0.0027	1	0.055	0.041	63167.869	33.234
25	82073908106	2750	45.83	0.0027	1	0.055	0.038	63167.869	7.177
25	82073908106	2950	49.17	0.0027	1	0.055	0.036	63167.869	-29.050
25	82073908106	3150	52.50	0.0027	1	0.055	0.034	63167.869	-79.415
25	82073908106	3350	55.83	0.0027	1	0.055	0.032	63167.869	-149.437
25	82073908106	3550	59.17	0.0027	1	0.055	0.030	63167.869	-246.787

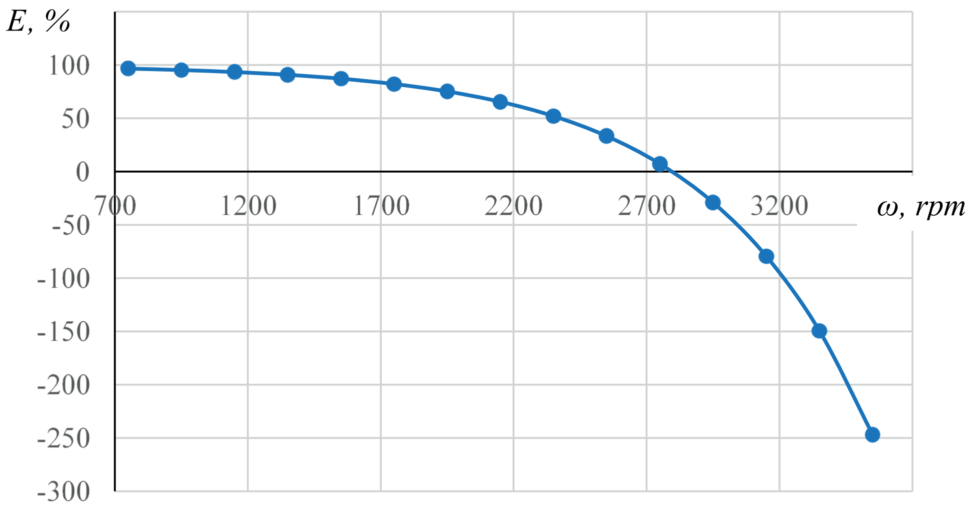


Figure 5 *Graph of changing the degree of coagulation E in the course of ultrasonic cleaning with frequency of 25 kHz and power of 600 W and different crankshaft speeds of a diesel engine of a volume of 2700 cm³*

range at which the maximum smoke is usually observed, i.e., 1800 rpm, on the power of ultrasonic radiation was calculated (Table 4).

Figure 4 shows the graph of the coagulation degree *E* dependence in the course of cleaning with frequency of 25 kHz and the crankshaft speed of 1800 rpm of a diesel engine of a volume of 2700 cm3 on the power of ultrasonic radiation W.

The performance characteristics of the ultrasonic muffler of a calculated parameters of the ultrasonic equipment were determined. The calculation of the coagulation degree *E* during the cleaning with ultrasound with frequency of 25 kHz and power of 600 W and various crankshaft rotation frequencies of a diesel ICE of a volume of 2700 cm^3 using Equation (11), is presented in Table 5.

Figure 5 shows the graph of changing the degree of coagulation *E* in the course of ultrasonic cleaning with frequency of 25 kHz and power of 600 W and different crankshaft speeds of a diesel engine of a volume of 2700 cm^3.

characteristics of ultrasound.

According to the graph of the coagulation degree E dependence in the course of ultrasonic cleaning with frequency of 25 kHz and the crankshaft speed of 1800 rpm of a diesel ICE of a volume of 2700 cm^3 on the ultrasonic radiation power W (Figure 2), the required ultrasonic radiation power was determined. In this case, its value was 600 W.

With ultrasound power of 600 W at idle speed, the purification degree was 96.6% (Figure 3). With increasing the engine crankshaft speed, the coagulation degree decreases. With the crankshaft speed of over 2800 rpm, ultrasonic coagulation does not occur due to insufficient ultrasound power and short time of ultrasonic action on the exhaust gas.

The given calculation method allows for determining the optimal parameters of ultrasonic mufflers for the most effective cleaning of exhaust gases and is suitable for use in designing the exhaust gas purification systems to determine the characteristics of ultrasonic equipment and its operating mode.

4 Discussion and conclusions

According to the graph of changing the coagulation degree *E* in the course of ultrasonic cleaning with different crankshaft speeds of a diesel ICE of a volume of 2700 cm^3 (Figure 1), it was concluded that the ultrasonic cleaning with frequency of 25 kHz and power of 50 W will still occur at idle crankshaft speeds of the engine of 750 rpm and will amount to 27.73%. With such a cleaning efficiency, the use of an ultrasonic muffler is impractical. To increase the cleaning degree to 80% and higher, it is necessary to increase the power

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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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