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ULTRASONIC UNIT FOR REDUCING THE TOXICITY OF DIESEL VEHICLE EXHAUST GASES

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Resume

The article presents materials on use of ultrasonic waves to reduce the smoke and toxicity of diesel engine exhaust gases. The results of the experiments are presented. The hypothesis on the reduction of smoke and toxicity of the exhaust gas due to the acceleration of the coagulation of its particles under the action of ultrasound has been confirmed.

The dependences of the degree of turbidity of a diesel car on the number of revolutions of the engine crankshaft per minute and the dependence of the content of harmful impurities in the exhaust gases, without exposure and under the influence of ultrasound, at various revolutions of the engine crankshaft per minute, have been obtained. In addition, graphs of the amount of settled soot in an ultrasonic device on the number of engine revolutions per minute were obtained experimentally without and under the influence of ultrasound.

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1 Introduction

Diesel fuel does not have a cost-effective alternative to this day, despite the tightening of environmental standards, it remains in demand in the road transport. Comparison of the energy characteristics of different fuels shows that the operational efficiency of freight transport on existing alternative fuels will require a significant increase in the mass and overall dimensions of a vehicle. When using alternative fuels, the truck would have to carry the additional weight of fuel instead of the cargo being transported. Currently, a car using diesel fuel drives about 2000 km. without refueling. Under the same conditions, the discounts of a car on electric batteries - this distance is reduced by about 80 times [1].

Diesel-fueled car exhaust contains substances that are very harmful to human health - nitrogen oxides, which cause smog and cause respiratory problems and ultrafine soot particles, which increase the risk of cardiovascular diseases and lung cancer [2]. To combat the emission of soot on diesel vehicles, additional catalytic converters are installed, which have a relatively short service life, require additional investment capital and have a high price characteristics. After the failure

of this filter, car owners often simply remove it, harming the environment.

Today, there is a number of methods for cleaning exhaust gases from harmful impurities. The most common ones are dry, wet, electric, catalytic and ultrasonic methods of gas cleaning. The dry cleaning method works with filter pipes of different diameters and lengths. The wet method of gas cleaning is carried out due to the interaction of the exhaust gas with water and the subsequent deposition of harmful impurities in the filter elements. This method is most widely used for capturing and further recovering finely dispersed components. Electric gas cleaning uses electrostatic precipitators, the work of which is based on the ionization of molecules. The catalytic gas cleaning method is based on deep cleaning of process gases. The essence of the method is to react with a catalyst. Ultrasonic works by accelerating the process of coagulation of soot particles.

The disadvantages of these methods include: high abrasive wear of the internal parts of the apparatus with a dry cleaning method; dust with low electrical conductivity is not filtered, it is necessary to clean the collecting and corona electrodes, the complexity and high cost of devices with an electric cleaning method;

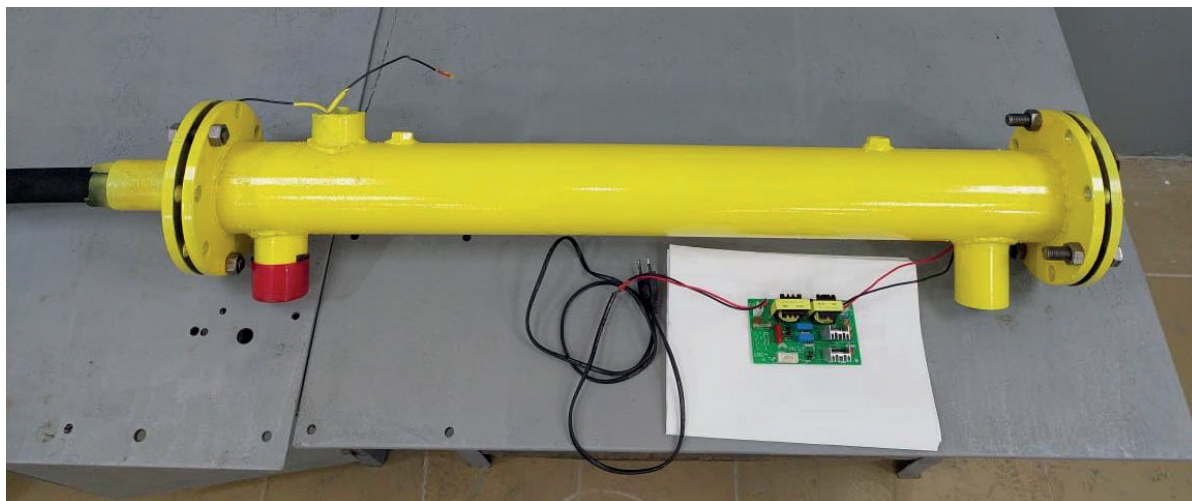


Figure 1 Experimental ultrasound unit (front view)

high consumption of electrical and thermal energy in the catalytic cleaning method.

A method of ultrasonic cleaning is proposed. Authors have developed an ultrasonic unit for reducing the toxicity of diesel vehicle exhaust gases from solid particles, in which an ultrasonic emitter is mounted inside the body. Research is needed to obtain concrete results. In this regard, it is important to conduct an experimental study using modern diagnostic equipment from the manufacturer "BOSCH".

Research has been carried out and results have been obtained on the speed of the ultrasonic wave in different media, the work of standing waves, the process of wave reflection, as well as on the purification of the exhaust gas of a gasoline car [3-10].

The aim of the research was the experimental confirmation of the fact of reducing the smoke and toxicity of the exhaust gas of an internal combustion engine under the influence of ultrasonic waves on it.

Research objectives: analysis of the physics of the process; development of an experimental stand; conducting and analyzing the results of the experiment.

2 Materials and methods

Coagulation (from Latin *coagulatio* - coagulation, thickening), also flocculation (from Latin *flocculi* - shreds, flakes) is a physicochemical process of adhesion of small particles of dispersed systems into larger ones under the influence of cohesion forces with formation of coagulation structures. [11-14]

The physics of the exhaust gas cleaning process of a car with ultrasound occurs due to the coagulation process. Coagulation of exhaust gases in a car muffler occurs constantly (orthokinetic coagulation), it is accelerated when exposed to ultrasound, which has a dispersing effect on emulsions and liquid sols and has a coagulating effect on aerosols (smoke, fog, dust) (hydrodynamic coagulation). This is due

to the fact that only the longitudinal waves causing compression are possible in gases. In a longitudinal wave, the particles of the medium oscillate about their mean position in the direction parallel to the wave propagation and lead to the appearance of hydrodynamic coagulation [15-16].

The Polish scientist M. Smoluchowski in 1906 proposed the theory of coagulation, which was developed based on the fact that coagulation occurs as a result of the fact that particles of the dispersed phase, performing Brownian motion at a certain moment, approach each other at a distance equal to the radius of the sphere of influence of the particles, equal to the sum of particle radii. In this case, the forces of interaction between the particles create an opportunity for their adhesion (aggregation). Due to the fact that the probability of collision of several particles at once is very small, coagulation occurs, as a rule, between two particles. A binary particle can interact with a single, double, triple, etc. particles, as a result of which large aggregates of particles are formed, which, upon reaching a certain critical mass, lose the ability to perform Brownian motion and settle under the action of gravity [17-19].

The occurring processes are theoretically described by equations of the kinetics of gases [20]

$$n = n_0 \cdot e^{-kt}, \quad (1)$$

where:

n and n_0 - current and initial particle concentration,

k - concentration factor,

t - time coordinate.

It was shown in [17] that, by analogy, it is true:

$$m = m_0 \cdot e^{-kt} \quad (2)$$

where:

m and m_0 - respectively, the current and initial mass of coagulated particles,

k - coagulation coefficient;

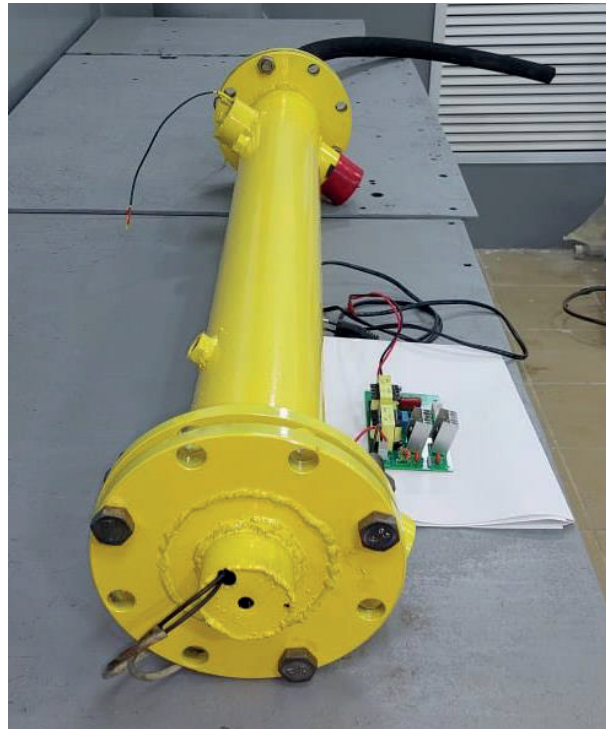
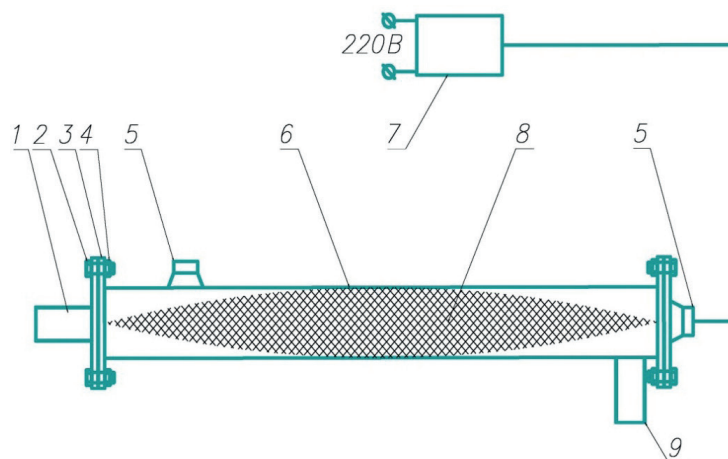


Figure 2 Experimental ultrasonic unit (side view)



1- exhaust gas inlet branch pipe, 2- bolt, 3- flange, 4- nut, 5- ultrasonic emitter, 6- steel pipe, 7- ultrasonic generator, 8- ultrasonic impact area, 9- exhaust gas outlet branch pipe.

Figure 3 Scheme of an ultrasonic unit for reducing the toxicity of exhaust gases of a diesel car

Equation (2) implies:

$$k = \ln \frac{m}{m_0} / t. \quad (3)$$

In work [17], dependences on the change in the transparency of exhaust gases are given.

To carry out the study, a full-size ultrasound unit was manufactured (Figure 1 and Figure 2)

The purpose of the experiment was to determine the opacity of the gas after exposure to an ultrasonic wave, the change in concentration, the ratio of various gases in the exhaust gas and the value of the mass of coagulated particles.

The scheme of an ultrasonic installation for reducing the toxicity of exhaust gases of a diesel vehicle is shown in Figure 3.

An ultrasonic installation for reducing the toxicity of exhaust gases of a diesel vehicle was manufactured according to the scheme in Figure 3 from the following elements:

- steel pipe with a diameter of 110 mm, a length of 1000 mm, a wall thickness of 1.8 mm;
- flat flanges with an outer diameter of 205 mm, an inner diameter of 110 mm and a thickness of 15 mm;
- ultrasonic emitters with a frequency of 40 kHz, a static capacity of ~ 4400 - 4610 pF, a radiating

surface of 45 mm, insulation resistance of 10,000 mΩ and a power of 50 W;

- ultrasonic generator with a frequency of 40 kHz and a power of 100 W.

The body of the installation was made and the two ultrasonic transducers of the longitudinal and transverse directions were mounted, as shown in Figure 3.

To determine the qualitative and quantitative composition of the exhaust gas mixture, the diagnostic complex "BOSCH FSA 740" was used.

The experiment with the ultrasonic installation was carried out as follows:

- to the car Mercedes Benz ML 2.7 CDI, engine capacity 2700 cc.see the production year 2001, fuel grade - diesel, an ultrasonic installation was connected;
- the composition of the exhaust gas was measured by a gas analyzer and the smoke of the exhaust gases was measured without the influence of ultrasound and with the action of a longitudinal ultrasonic wave after 1 minute, depending on the range of rotation of the engine crankshaft (750, 1000 and

1400 (1600) rpm).

The ultrasonic unit was connected to the car using a rubber hose to the inlet pipe 1 for supplying exhaust gases to the unit. In an ultrasonic installation, with the ultrasonic generator turned on, longitudinal ultrasonic waves were applied to the exhaust gas.

In the installation, ultrasonic intensification of coagulation processes and cleaning of exhaust gases took place due to the sedimentation of enlarged particles of exhaust gas at the bottom of the installation. The cleaned exhaust gas was discharged through the outlet pipe 9.

To perform the high-precision measurements of smoke and toxicity in the course of the experiment, the diagnostic complex "BOSCH FSA 740" was used. The BOSCH diagnostic complex includes: KTS 560 diagnostic scanner; gas analyzer "BEA 050"; optical opacimeter "BEA 070". With help of the "KTS 560" scanner, the vehicle engine speed was monitored to record data at a certain moment of the engine crankshaft speed. The gas analyzer "BEA 050" was used to determine the composition of the exhaust gases, namely the

Table 1 Indications of an autonomous mobile opacimeter for diesel engines "BEA 070"

Ultrasonic muffler operation	Rotation frequency crankshaft (rpm)	Working time (sec)	Gas turbidity degree (%)
without ultrasound	750	60	30.6
with ultrasound	750		25.5
without ultrasound	1000		27.4
with ultrasound	1000		21.6
without ultrasound	1600		31.6
with ultrasound	1600		30.1

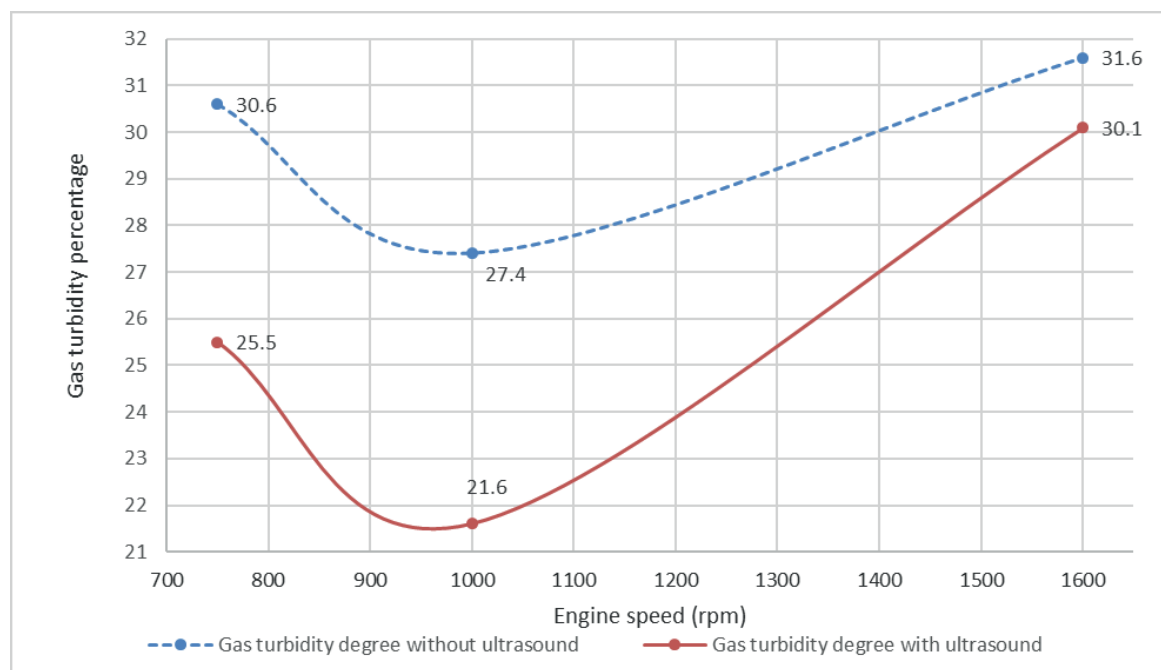


Figure 4 Graph of the degree of turbidity of diesel exhaust gas at 750, 1000 and 1600 engine rpm

Table 2 Experimental data on the degree of turbidity without ultrasonic exposure

Engine speed (rpm)	Degree of turbidity without ultrasonic exposure (%)	Degree of turbidity without ultrasound exposure, by cubic regression (%)
750	30.6	30.0
800	30	29.6
850	29.3	29.2
900	28.7	28.9
950	28	28.6
1000	27.4	28.5
1050	27.8	28.4
1100	28.1	28.4
1150	28.5	28.4
1200	28.8	28.5
1250	29.2	28.7
1300	29.5	29.0
1350	29.9	29.4
1400	30.2	29.8
1450	30.6	30.3
1500	30.9	30.9
1550	31.3	31.5
1600	31.6	32.3

Table 3 Experimental data on the degree of turbidity under the influence of ultrasound

Engine speed (rpm)	Degree of turbidity with ultrasonic exposure (%)	Degree of turbidity with ultrasound exposure, by cubic regression (%)
750	25.5	24.6
800	24.7	24.1
850	23.9	23.7
900	23.2	23.4
950	22.4	23.2
1000	21.6	23.2
1050	22.3	23.2
1100	23	23.4
1150	23.7	23.6
1200	24.4	24.0
1250	25.1	24.5
1300	25.9	25.1
1350	26.6	25.8
1400	27.3	26.7
1450	28	27.6
1500	28.7	28.7
1550	29.4	29.8
1600	30.1	31.1

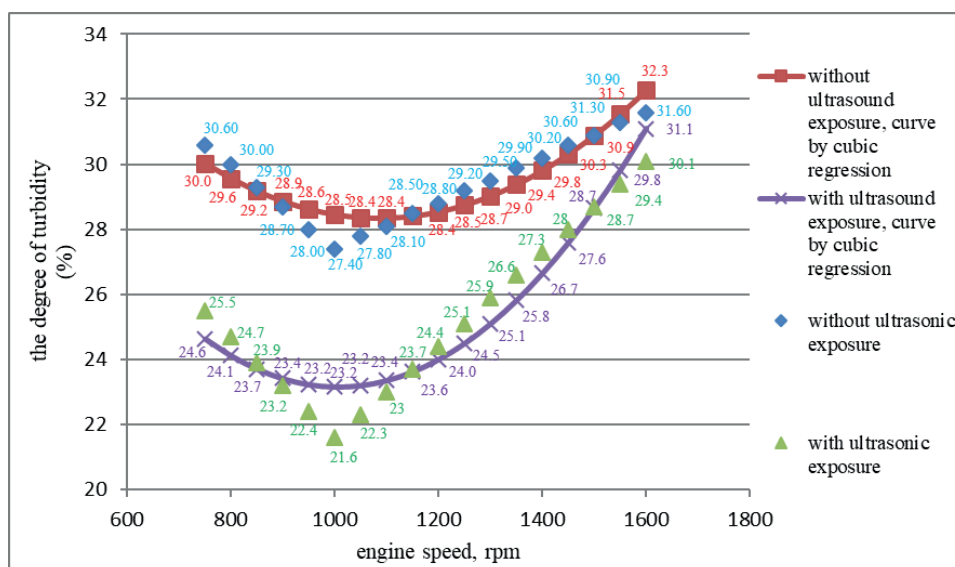


Figure 5 Experimental turbidity curves

Table 4 Readings of the gas analyzer “BEA 050” without ultrasound

No.	Engine speed (rpm)	O ₂ (% vol)	CO ₂ (% vol)	HC (ppm vol)	CO (% vol)	Measurement time (sec.)
1	750	17.34	2.25	16	0.027	60
2	1000	17.44	2.24	17	0.034	
3	1400	17.46	2.18	19	0.053	

Table 5 Readings of the gas analyzer “BEA 050” under the influence of ultrasound on the exhaust gases

No.	Engine speed (rpm)	O ₂ (% vol)	CO ₂ (% vol)	HC (ppm vol)	CO (% vol)	Measurement time (sec.)
1	750	17.36	2.26	14	0.022	60
2	1000	17.46	2.23	18	0.036	
3	1400	17.50	2.18	19	0.054	

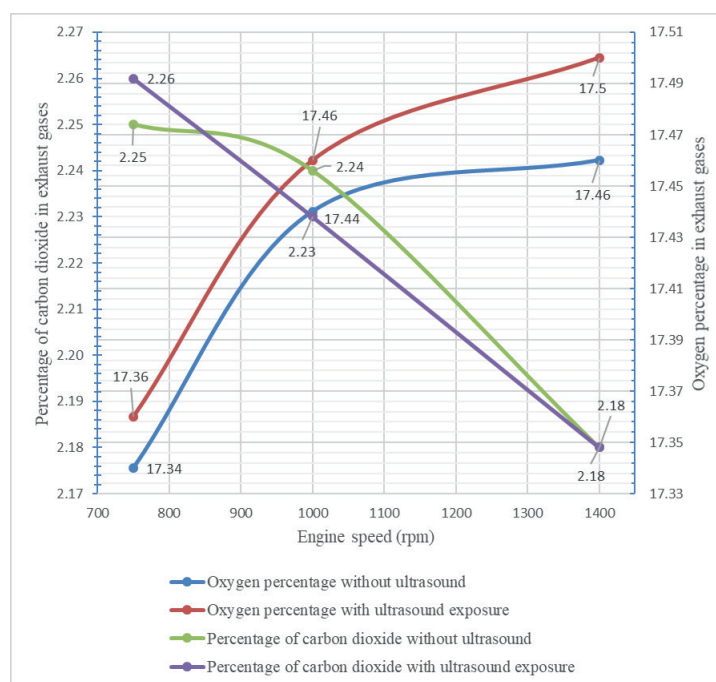


Figure 6 Graph of the oxygen and carbon dioxide content in the exhaust gases, without exposure and under the influence of ultrasound at 750, 1000 and 1400 engine rpm

oxygen content in the exhaust gases, carbon dioxide, hydrocarbon and carbon monoxide. The data from the optical opacimeter “BEA 070” was used to determine the percentage of turbidity of the diesel engine exhaust gases.

3 Results

The experiment was divided into three stages. At the first stage of the experiment, the data on influence of ultrasonic waves on the content of the degree of turbidity of the exhaust gases of a diesel car was recorded. Three measurements of exhaust gas opacity without ultrasonic waves and three measurements under the influence of ultrasound were carried out at different ranges of engine operation 750, 1000, 1600 rpm. Recorded readings of the degree of turbidity of exhaust gases are given in Table 1. According to the readings from Table 1, a graph was constructed (Figure 4), demonstrating the significant effect of ultrasound on the degree of turbidity of diesel exhaust gas [15-20].

The significant effect of the ultrasonic wave on the degree of turbidity of the exhaust gas shown in the graph in Figure 4 occurs due to the coagulation of soot particles

and their deposition in the ultrasonic installation.

At the first stage of the experiment, the influence of ultrasonic waves on the degree of turbidity of the exhaust gases of a diesel engine was proved in accordance with the graph shown in Figure 4. When ultrasound was applied to the exhaust gas of a car, a decrease in the degree of turbidity was revealed. In particular, at an engine speed of 750 rpm, a decrease in the degree of turbidity by 16.6% was detected, at 1000 rpm, a decrease of 21.1% was noted and at an engine speed of 1600 rpm, it decreased by 4.7%.

As a result of the conducted full-scale experiment, the decrease in the degree of turbidity of the exhaust gas was more than 21%. The physical process is explained by an increase in the hydrodynamic coagulation of the gaseous medium during the operation of an ultrasonic installation, which has been proven experimentally.

The obtained experimental data were interpolated. A regression analysis of the degree of turbidity was performed and the regression equation was established. From the analysis of the calculations for the largest values of the correlation coefficients, determination and the smallest values of the average approximation error for the process of changing the degree of turbidity of the exhaust gas without ultrasound and under the influence

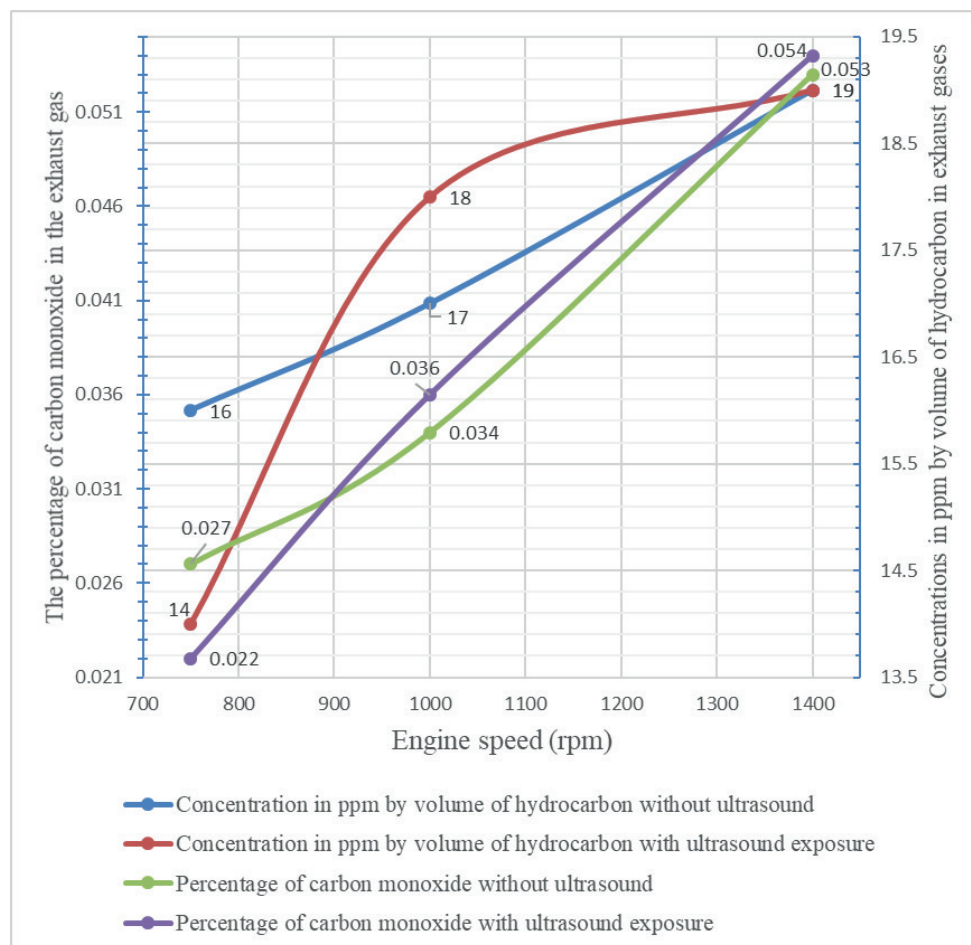
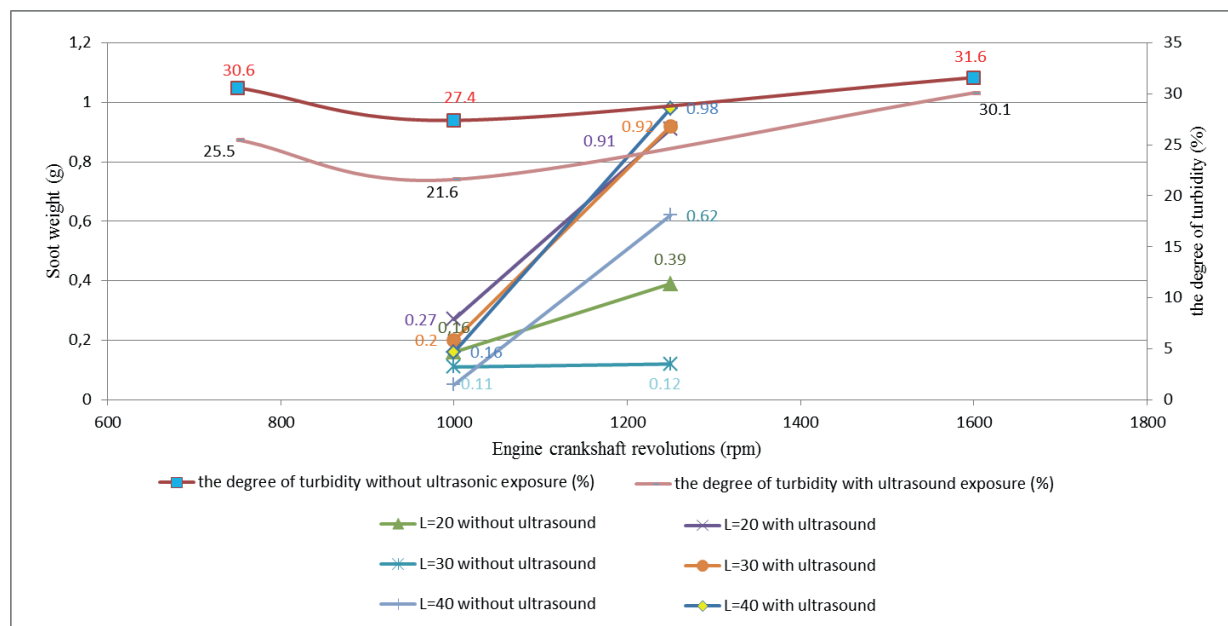


Figure 7 Graph of the content of hydrocarbon and carbon monoxide in exhaust gases, without exposure and under the influence of ultrasound at 750, 1000 and 1400 engine rpm

Table 6 Mass of settled soot at 1000/1250 rpm without ultrasound and under the influence of ultrasound

Distance (mm.)	At 1000 rpm		At 1250 rpm	
	without ultrasound (g.)	with ultrasound (g.)	without ultrasound (g.)	with ultrasound (g.)
100	0.25	0.33	0.70	0.85
200	0.16	0.27	0.39	0.91
300	0.11	0.2	0.12	0.92
400	0.05	0.16	0.62	0.98
500	0.1	0.13	0.31	0.67
Σ	0.67	1.09	2.14	4.33



where: $L = 200$, $L = 300$, $L = 400$ is the settling distance of soot particles (mm)

Figure 8 Dependence of the mass of settled soot and the degree of turbidity on the number of engine revolutions per minute without and under the influence of ultrasound

of ultrasound, cubic regression equations were used. The values obtained are shown in Tables 2 and 3 and in the graph in Figure 5.

The graphs show that values of the degree of turbidity do not vary much. This indicates the correctness of an experimental study on the purification of diesel vehicle exhaust gas from harmful impurities by ultrasound.

At the second stage of the experiment, six measurements were made to determine the composition of the vehicle's exhaust gases. Measurements were made without the influence of an ultrasonic wave at the engine operating ranges of 750, 1000, 1400 rpm. The data are shown in Table 4. Further, the experiment was carried out with the action of longitudinal ultrasonic waves at the same engine speeds. Measurements of the composition of exhaust gases were recorded, which are presented in Table 5. According to the tables, graphs were built without exposure and under the influence of ultrasound, shown in Figures 6 and 7, which show

the composition of the exhaust gases of a diesel engine depending on the crankshaft speed.

According to the data from the graph in Figure 6, an increase was revealed in the oxygen content under the influence of a longitudinal ultrasonic wave on the exhaust gas of a diesel car. When exposed to ultrasound, soot particles coagulate and further precipitate these particles in the ultrasonic installation, thereby increasing the oxygen concentration in the exhaust gases. In the engine operating range of 750 rpm, heavy particles settle to the bottom of the installation, due to which the concentration of carbon dioxide in the exhaust gases increases.

From the data of the graph in Figure 7 one can see the effect of ultrasound on hydrocarbon and carbon monoxide. With an increase in the engine speed, the coagulated hydrocarbon particles deposited by ultrasound are not retained on the walls of the ultrasonic installation. In this regard, the content of hydrocarbon

and carbon monoxide increases with increasing engine speed.

During the second stage of the experiment, according to the data from the graphs (Figures 6 and 7), it was revealed that ultrasonic waves affect the composition of the exhaust gases. During the combustion of diesel fuel in an ultrasonic device without ultrasound, excess carbon contributes to the formation of carbon monoxide (CO). According to the data in Table 4, an increase in hydrocarbon (HC) increases the percentage of carbon monoxide (CO). An increase in oxygen (O₂) oxidizes carbon monoxide and forms carbon dioxide (CO₂). There is a change in the ratio of the number of particles of various gases in the process of coagulation. In this regard, the most important factor is the value of the mass of gases at the outlet of the muffler. The experimental data confirm this.

When exposed to ultrasound at 750 rpm. (Table 2) due to the coagulation process, which is enhanced by ultrasound, the picture of the chemical reaction changes and shows a decrease in hydrocarbon (HC), since the inlet pressure of the exhaust gas into the device is small, soot particles have time to increase in size and settle to the bottom of the ultrasonic device.

An increase in engine speed has a less significant effect on the hydrodynamic coagulation process since the length of the device is 1000 mm and is insufficient for effective cleaning of the exhaust gas of a diesel vehicle. According to Table 5, starting from 1000 rpm insufficient radiation occurs in the ultrasonic device, since the inlet pressure of the exhaust gas increases and the soot particles fly out without having time to settle to the bottom.

At the third stage of the experiment, the mass and distance of the deposited soot particles were determined, without exposure and under the influence of ultrasound in an experimental ultrasonic device (Tables 6-7). Figure 8 shows experimental graphs of the dependence of the mass of settled soot and the degree of turbidity on the number of revolutions of the crankshaft per minute without and under the influence of ultrasound.

The graph (Figure 8) shows the dependence of the mass of settled soot and the degree of turbidity on the number of engine revolutions per minute without ultrasound and under the influence of ultrasound. The

obtained values of the soot mass generally confirm Equation (3). Thus, despite the sometimes paradoxical picture of the concentration of various gases in the exhaust gas, the mass of coagulated particles (soot) increases and the smokiness decreases.

4 Conclusions

In the course of the research experiment, the possibility of ultrasonic waves' impact on the degree of turbidity, the composition of the exhaust gases of a diesel car and the sedimentation mass of soot particles was determined.

It was found that when exposed to ultrasound, the degree of turbidity of the exhaust gas is significantly reduced by more than 21 %. In particular, at an engine speed of 750 rpm, a decrease in the degree of turbidity by 16.6 % was detected, at 1000 rpm, a decrease of 21.1 % was noted and at an engine speed of 1600 rpm, it decreased by 4.7 %.

When measured with a gas analyzer at 750 rpm of the internal combustion engine, due to the coagulation process, the concentration of hydrocarbon (HC) decreased by 12.5 %, the mass of deposited soot under the action of ultrasound increased more than 2 times. An increase in the speed of the internal combustion engine does not have a significant effect during the operation of the ultrasonic installation, since the length of the ultrasonic device is not sufficient and the soot particles do not have time to increase in size at the expense coagulation process. The recommended length of the ultrasonic device is at least 3 m [4]. Coagulation of molecules of different gases occurs at different rates, which explains the ratio of their changes in the total volume of exhaust gases.

The hypothesis of reduction of harmful impurities of diesel exhaust gas due to coagulated particles in the ultrasonic device under the action of longitudinal ultrasonic waves on them has been proven.

Experimental data have been obtained, the practical significance of which lies in the possibility of calculating and designing an ultrasonic installation for mufflers of diesel cars of a new type, which allows to qualitatively reduce the toxicity of road transport [3-4].

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