THEORETICAL AND EXPERIMENTAL STUDY OF DIESEL ENGINE EXHAUST GAS PURIFICATION IN A VERTICAL ULTRASONIC MUFFLER STAND

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Resume

In this article is presented a new method of ultrasonic cleaning of exhaust gases of diesel engines by coagulation of soot particles and their subsequent sedimentation. The analytical modelling of the particle motion in a vertical muffler stand was carried out, taking into account the ultrasonic effect and gravitational forces. Experimental studies of the developed stand confirmed that ultrasound promotes agglomeration and sedimentation of soot, reduces the CO_2 content and increases the O_2 concentration in the exhaust gases. The maximum cleaning efficiency is achieved with the simultaneous use of all the ultrasonic emitters. The results of the work can be used in designing modern exhaust gas cleaning systems.

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1 Introduction

The Diesel engine emissions contain a wide range of harmful substances, including gaseous components and solid particles [1]. One of the most significant factors that affect the environmental safety of diesel engines is the mass concentration of soot in the exhaust gases [2]. Soot that is formed as a result of incomplete combustion of fuel, is a collection of carbon nanoparticles that can penetrate deep into the human respiratory tract and cause serious respiratory and cardiovascular diseases [3]. In addition to the negative impact on health, the soot emissions contribute to formation of smog and increasing the greenhouse effect [4-5].

The soot content in the exhaust gases varies depending on many factors: the engine operating mode, the fuel quality, the fuel system health, and air-fuel mixture characteristics [6-7]. At idle and under a high load, the soot concentration increases significantly, which leads to increasing the smoke index [8]. In particular, lack of oxygen, a low cetane number of fuel and incorrect operation of injectors contribute to the formation of particles whose sizes range from several nanometers to tens of micrometers.

Reducing the mass concentration of soot in the exhaust gases of diesel engines is achieved through various methods and technologies [9]. Among them, there is optimization of fuel combustion, including the use of fuel with a high cetane number, precise control of fuel supply using Common Rail systems, improved mixture formation with turbocharging and increased injection pressure, as well as exhaust gas recirculation (EGR) [10]. However, those technologies are sensitive to the fuel quality and require complex maintenance and precise calibration of systems.

Exhaust gas filtration is also carried out using diesel particulate filters (DPF) and nitrogen oxide filters (LNT) that effectively trap solid soot particles [11]. However, these systems are expensive, they require regular regeneration and are sensitive to fuel contamination. Catalytic technologies, such as selective catalytic reduction (SCR) systems with a urea solution and oxidation catalytic converters (DOC), reduce soot emissions, as well [12]. However, they have a number of disadvantages, such as a high cost, complexity of operation and the need for regular regeneration. In addition, filters are sensitive to the fuel quality, and the accumulation of soot in their structure reduces the engine efficiency [13]. In this regard, an urgent task is to develop alternative methods of reducing the soot concentration in exhaust gases.

Currently, studies are being conducted aimed at cleaning vehicle exhaust gases with the use of ultrasonic technologies. One such study is the work of scientists from Karaganda Technical University, who proposed using the ultrasonic coagulation method to reduce the content of harmful components in exhaust gases directly in the car mufflers [14-15].

Ultrasonic coagulation is based on the effect of high-frequency sound waves on exhaust gas particles. Under the effect of ultrasound, small particles begin to vibrate, to collide and to stick together, forming larger agglomerates [16]. Enlarged particles settle more easily and are better captured, which helps to reduce the content of solid pollutants in the exhaust [17-18].

Special experimental stands of horizontal ultrasonic mufflers were developed for the research. Ultrasonic equipment was installed on these stands, including a generator and emitters-reflectors of ultrasonic waves [19]. Experimental studies conducted on the stands made it possible to study the process of particle coagulation under the effect of ultrasound and to confirm the effectiveness of the proposed method in cleaning exhaust gases. To assess the effectiveness, changes in the oxygen concentration, the gas composition and the smoke level before and after the exposure to ultrasound were analyzed [20].

Despite some positive results obtained, current studies of ultrasonic coagulation for cleaning exhaust gases do not allow solving design issues. In particular, it is necessary to improve the design of the experimental muffler stand to ensure uniform distribution of the ultrasonic field and optimal placement of the emitters. In this regard, the authors proposed the development of a vertical ultrasonic muffler stand.

Unlike the previous horizontal designs [14-20], the proposed vertical configuration provides gravitationally assisted sedimentation, enabling multi-stage acoustic exposure and improved uniformity of ultrasonic field distribution.

The transition to a vertical design of the ultrasonic muffler is caused by the desire to improve the efficiency of settling the coagulated soot particles. In the vertical configuration, soot particles combined under the effect of ultrasound, settle down more easily under the force of gravity, which contributes to their more efficient collection at the bottom of the device. In addition, the vertical arrangement allows for the mounting of several ultrasonic emitters at different heights, providing step-by-step processing of the exhaust gas. This is especially important for removing fine particles that require longer or multiple exposures for effective coagulation.

The hypothesis of this study is that the vertical movement of the exhaust gas and the step-by-step processing of the gas flow with ultrasound contribute to increasing the efficiency of soot particle coagulation, which will lead to their enlargement and subsequent sedimentation. The optimal location and power of the ultrasonic emitters also make it possible to achieve a significant reduction in the mass concentration of soot in the exhaust gases of diesel engines.

The goal of this study was the theoretical and experimental confirmation of the proposed method of ultrasonic cleaning, which allows for reducing the content of harmful emissions in exhaust gases. To achieve this goal, several problems were solved, including the development of a mathematical model of the soot particle motion in a vertical muffler, numerical calculations of particle dynamics under the effect of ultrasound, development of an experimental stand, testing with various combinations of ultrasonic emitters, and comparison of analytical modelling results to experimental data.

The scientific novelty of the study represents the fact that a model of soot particle coagulation in a vertical ultrasonic muffler has been proposed and substantiated for the first time. A differential equation of particle motion has been developed that takes into account the effects of gravity, hydrodynamic resistance, ultrasonic wave pressure and the coagulation process. Comprehensive studies have been conducted, including both analytical modelling and experimental testing on a specially designed stand. The results have shown that ultrasound promotes agglomeration and sedimentation of soot particles, reduces the CO_2 content and increases the O_2 concentration in the exhaust gases. The maximum effect is achieved with the simultaneous use of all the emitters, which confirms the importance of selecting the optimal location and power of ultrasonic action.

The practical significance of the study lies in the fact that the developed method can be used in modern diesel engine emission reduction systems, providing an alternative to expensive and difficult to maintain particulate filters. Ultrasonic cleaning of mufflers can be used in transport and agricultural diesel engines, reducing their environmental impact and increasing the operating efficiency. The results and recommendations obtained can be useful for further modernization of exhaust gas cleaning systems and development of innovative solutions in the field of transport ecology.

2 Materials and methods

Mathematical modelling of the complex process of gas particle coagulation in a muffler under the effect of ultrasound does not allow obtaining strictly deterministic dependences that fully describe the mechanism of soot particle deposition. This is caused by a lot of factors that affect the process, including the gas flow characteristics, acoustic parameters of ultrasonic waves, particle interaction dynamics, and gas movement conditions inside the muffler.

In this regard, the results of the mathematical model study should be presented and supplemented by experimental results. It is necessary to analytically and then experimentally determine the nature of changing the mass of the deposited soot particles, to establish the coagulation coefficient K and the optimal operating modes of the ultrasonic emitters.

A mathematical model is known that describes the movement of a gas particle in an experimental stand of a horizontal muffler:

$$m \cdot a = F_D + F_a - F_G, \tag{1}$$

where:
F_D is the pressure force;
F_a is the ultrasonic pressure force;
F_G is the hydrodynamic resistance force.

The differential equation of motion of a gas particle in a horizontal stand of an ultrasonic muffler is:

$$m \cdot \ddot{x} = \frac{\pi \cdot r^2 \cdot d^2 P}{D^2} - \pi \cdot r^2 \cdot \rho \cdot A \cdot c \cdot \cdot \omega \cdot \cos\omega \cdot \left(t - \frac{n}{c}\right) - 6 \cdot \pi \cdot \mu \cdot r \cdot \frac{dx}{dt}. \tag{2}$$

However, this model cannot be used to describe the mechanism of the soot particle motion, since it considers only the horizontal movement of particles without taking into account the gravitational effect, which leads to insufficient accuracy in describing the coagulation processes in a vertical stand. After all, in the vertical direction, the particle is affected by the gravity force *mg*, which must be included in the equation of motion, since it has a significant effect on the dynamics of particle sedimentation.

Based on the above, the following equation was compiled to describe the motion of a soot particle in a vertical type of experimental muffler:

$$m \cdot a = F_{en} + F_{us} - F_{res} - m \cdot g, \tag{3}$$

where:
m is the mass of a soot particle, kg;
a is the acceleration that a body receives under the action of a force, m/s²;
F_{en} is the pressure force from the engine, N;
F_{us} is the force of ultrasonic effect from emitters, N;
F_{res} is the hydrodynamic resistance force (Stocks), N;
g is acceleration of gravity, m/s².

The pressure force from the engine is:

$$F_{en} = \frac{\pi \cdot r^2 \cdot d^2 \cdot P}{D^2}, \tag{4}$$

where:
F_{en} is the pressure force from the engine, N;
d is the inlet pipe diameter, m;
D is the muffler diameter, m;
r is the particle radius, m;
P is the muffler inlet pressure, Pa.

The ultrasound force is:

$$F_{us}(x) = A \cdot \sin(kx), \tag{5}$$

where:
F_{us} is the ultrasound force, N;
A is the ultrasound amplitude, m;
$k = \frac{2 \cdot \pi}{\lambda}$ is the wave number.

If there are several emitters N and they are installed at the distance d, then the resulting ultrasound power has the following dependence:

$$F_{us}(x) = \sum_{i=1}^{N} A_i \cdot \sin(k \cdot (x - x_i) + \varphi_i), \tag{6}$$

where:
F_{us} is the ultrasound power, N;
x_i is the location of the i-th emitter;
φ_i is the phase shift, m.

The resistance force is:

$$F_{res} = -b \cdot \vartheta_p = -6 \cdot \pi \cdot \mu \cdot r \cdot \vartheta_p, \tag{7}$$

where:
F_{res} is the resistance force, N;
b is the resistance coefficient;
μ is the viscosity, Pa·s;
ϑ_p is the particle velocity, m/s.

Changes in the engine crankshaft speed have a proportional effect on the gas flow velocity $\vartheta_g(n)$. However, the medium resistance depends on the relative velocity of the particle with respect to the gas flow, and not on its absolute velocity. If the particle moves with the gas, the relative velocity is zero and there is no resistance. If the particle moves against the gas flow, it experiences the greatest resistance. Therefore, the equation determining the resistance force is as follows:

$$F_{rf} = -b \cdot (\vartheta_p - \vartheta_g(n)), \tag{8}$$

where:
F_{rf} is the resistance force, N;
$\vartheta_n(n)$ is the gas flow velocity, m/s;
n is the number of the engine revolutions, rpm;
k_n is the coefficient of the gas velocity dependence on the engine revolutions.

Based on Equation (3) and its components, a differential equation was compiled that describes the motion of a soot particle in a vertical muffler:

$$\frac{m \cdot d^2 \cdot x}{dt^2} = \frac{\pi \cdot r^2 \cdot d^2 \cdot P}{D^2 dt^2} + \sum_{i=1}^{N} A_i \cdot \cdot \sin(k(x - x_i) + \varphi_i) - b \cdot (\vartheta_p - \vartheta(n)) - m \cdot g. \tag{9}$$

When the process of coagulation between particles is being taken into account, the mass of an individual particle m is a function of time $m(t)$, since when interacting, the particles can combine, increasing their size and mass. However, coagulation does not occur at every collision of particles, since its probability depends on a lot of factors, such as the particle velocity, the particle size, the concentration in the gas flow, the temperature of the medium and the intensity of the ultrasonic equipment.

To take this phenomenon into account, the concept of coagulation probability v was introduced. It determines the probability with which the colliding particles will actually combine. Consequently, changing the mass of a particle over time is described by an equation of the following type:

$$\frac{dm}{dt} = v \cdot K \cdot n_c, \tag{10}$$

$$m(t) = m_0 + v \cdot K \cdot \int_0^t n_c dt, \tag{11}$$

$$\left(m_0 + v \cdot K\int_0^t n_c dt\right)\frac{d^2x}{dt^2} = \frac{\pi \cdot r^2 \cdot d^2 \cdot P}{D^2 dt^2} + \\ + \sum_{i=1}^{N} A_1 \cdot \sin(k(x - x_i) + \varphi_i) - \\ - b \cdot (\vartheta_p - \vartheta_g(n)) - m \cdot g. \tag{12}$$

The resulting equation is a second-order differential equation. The Runge-Kutta method was used to solve it, which allows for transforming a second-order equation into a system of first-order equations. This method has higher accuracy compared to the Euler method, since it uses intermediate calculations at each step to refine the values. In addition, the Runge-Kutta method is well suited for solving nonlinear equations containing integral terms, variable mass, and nonlinear resistance of the medium, which makes it an effective way to solve the problem.

According to the Runge-Kutta method, variables for performing the intermediate calculations were introduced: x - the particle coordinate; $\vartheta = \frac{dx}{dt}$ - the particle velocity; $m(t) = m_0 + vK\int_0^t n_c dt$ - the particle mass taking into account coagulation.

Then, the system of the first-order equations was compiled as:

$$\begin{cases} \dfrac{dx}{dt} = \vartheta \\ \dfrac{d\vartheta}{dt} = \dfrac{1}{m(t)}\left[\begin{array}{l} \dfrac{\pi \cdot r^2 \cdot d^2 \cdot P}{D^2 dt^2} + \sum_{i=1}^{N} A_i \cdot \\ \cdot \sin(k(x - x_i) + \varphi_i) - \\ - b(\vartheta_p - \vartheta_g(n)) - m \cdot g \end{array}\right] \\ \dfrac{dm}{dt} = v \cdot K \cdot n_c. \end{cases} \tag{13}$$

The mathematical model, describing the motion and coagulation of soot particles in the vertical ultrasonic muffler is based on a set of physical assumptions and parameters supported by experimental measurements and literature sources. The model assumes that soot particles are spherical, which allows the use of Stokes' drag law, applicable to micron-sized particles at Reynolds numbers Re < 1. The gas flow inside the muffler is considered as steady and directed along its axis, while the turbulent fluctuations and temperature gradients are neglected due to their negligible influence on particle dynamics compared to acoustic and aerodynamic forces. Ultrasonic waves are assumed to propagate predominantly in the axial direction, without accounting for complex interference patterns, and the acoustic force is modeled as a sinusoidal function of the spatial coordinate, which is typical for standing or quasi-standing waves in narrow cylindrical channels. Coagulation is treated as a probabilistic process, and therefore, a sticking probability v is introduced into the governing equations, based on the exponential collision model. The model parameters were also selected based on experimental measurements and literature data: the ultrasonic frequency of 40 kHz corresponds to the operating range of the transducers used; the vibration amplitude on the order of 10^{-5} m was determined using a laser vibrometer; the particle radius $r = 10^{-6}$ m represents agglomerated soot clusters of micron size; the coagulation coefficient $K_c = 10^{-5}$ and sticking probability $v = 0.6321$ correspond to typical values for micron-sized particles in a low-velocity flow; the dependence of gas velocity on engine speed is defined by the experimentally determined coefficient $k_n = 0.01$; the drag coefficient $b = 6\varpi\mu r$ is calculated using the viscosity of hot exhaust gas $\mu \approx 1.7\times10^{-5}$ Pa·s; the particle concentration $n_c = 10^6$ m^{-3} reflects the typical range observed in diesel exhaust; and the wave number k is calculated from the wavelength of 0.017 m, corresponding to a sound speed of approximately 425 m/s in heated exhaust gas. The combination of these assumptions and parameters ensures an accurate representation of the key processes of particle coagulation and sedimentation.

Then, the initial conditions and the basic data were introduced. They are presented in Table 1.

Then, for each time step h, the intermediate indicators of the coefficients k_1, k_2, k_3, k_4 for the coordinate, velocity and mass of the particle are calculated taking into account coagulation using the following formulas:

Coefficient k_1:

$$k_1^x = h \cdot v_n, \\ k_1^\vartheta = h \cdot \frac{1}{m_n}\left[\begin{array}{l} \dfrac{\pi r^2 d^2 P}{D^2 dt^2} + \sum_{i=1}^{N} A_i \cdot \\ \cdot \sin(k(x_n - x_i) + \varphi_i) - \\ - b \cdot (\vartheta_p - \vartheta_g(n)) - m \cdot g \end{array}\right], \\ k_1^m = h \cdot v \cdot K \cdot n_c. \tag{14}$$

Coefficient k_2:

$$k_2^x = h \cdot \left(v_n + \frac{k_1^\vartheta}{2}\right),$$

Table 1 Initial conditions and basic data

No.	Initial conditions and basic data	Indicators	Units
1	Initial position	$x_0 = 0$	m
2	Initial velocity	$v_0 = 0$	m/s
3	Initial particle mass	$m_0 = 1 \cdot 10^{-6}$	kg
4	Integration step	h = 0.00001	s
5	Maximum simulation time:	t_{max} = 0.00004	s
6	Manifold pressure parameters	P_{amp} = 500	Pa
7	Coagulation coefficient	$K_c = 1 \cdot 10^{-5}$ (for particle of the10^{-6} size)	
8	Concentration of soot particles in gas	$n_c = 1 \cdot 10^6$ 1/m^3 (for diesel exhaust from 10^5-10^9 part/m^3)	
9	Coagulation probability	v = 0.6321 (according to the exponential law 1-e^{-Kt})	
10	Amplitude of ultrasonic vibrations	$A = 1 \cdot 10^{-5}$	m
11	Wave number	$k = \frac{2\pi}{0.017}$ (wave length 0.017)	m
12	Gas drag coefficient	$b = 1 \cdot 10^{-6}$	
13	Gas flow velocity coefficient	k_n = 0.01	
14	Soot particle radius	$r = 1 \cdot 10^{-6}$	m
15	Inlet pipe diameter	d = 0.04	m
16	Muffler diameter	D = 0.09	m
17	Gravity acceleration	g = 9.81	m/s^2

$$k_2^{\vartheta} = h \cdot \frac{1}{m_n + \frac{k_1^m}{2}} \begin{bmatrix} \frac{\pi \cdot r^2 \cdot d^2 \cdot P}{D^2 dt^2} + \sum_{i=1}^{N} A_i \cdot \sin \\ \left(k\left(x_n + \frac{k_1^x}{2} - x_i\right) + \varphi_i\right) - \\ - b \cdot \left(\vartheta_n + \frac{k_1^v}{2} - \vartheta_g(n)\right) - \\ - g \cdot \left(m_n + \frac{k_1^m}{2}\right) \end{bmatrix}, \quad (15)$$

$$k_2^m = h \cdot v \cdot K \cdot n_{c.}$$

Coefficient k_3:

$$k_3^x = h \cdot \left(v_n + \frac{k_1^{\vartheta}}{2}\right),$$

$$k_3^{\vartheta} = h \cdot \frac{1}{m_n + \frac{k_1^m}{2}} \begin{bmatrix} \frac{\pi \cdot r^2 \cdot d^2 \cdot P}{D^2 dt^2} + \sum_{i=1}^{N} A_i \cdot \sin \\ \left(k\left(x_n + \frac{k_1^x}{2} - x_i\right) + \varphi_i\right) - \\ - b \cdot \left(\vartheta_n + \frac{k_2^v}{2} - \vartheta_r(n)\right) - \\ - g \cdot \left(m_n + \frac{k_2^m}{2}\right) \end{bmatrix}, \quad (16)$$

$$k_3^m = h \cdot v \cdot K \cdot n_{c.}$$

Coefficient k_4:

$$k_4^x = h \cdot (v_n + k_3^{\vartheta}),$$

$$k_4^{\vartheta} = h \cdot \frac{1}{m_n + k_3^m} \begin{bmatrix} \frac{\pi \cdot r^2 \cdot d^2 \cdot P}{D^2 dt^2} + \sum_{i=1}^{N} A_i \cdot \sin \\ \left(k\left(x_n + \frac{k_2^x}{2} - x_i\right) + \varphi_i\right) - \\ - b \cdot \left(\vartheta_n + \frac{k_2^v}{2} - \vartheta_r(n)\right) - \\ - g \cdot \left(m_n + \frac{k_2^m}{2}\right) \end{bmatrix}, \quad (17)$$

$$k_3^m = h \cdot v \cdot K \cdot n_{c.}$$

After calculating the coefficients, the coordinates, velocity, and mass of the particle were determined, taking into account coagulation using the following formulas:

$$\begin{aligned} x_{n+1} &= x_n + \frac{1}{6}(k_1^x + 2 \cdot k_2^x + 2 \cdot k_3^x + k_4^x), \\ \vartheta_{n+1} &= \vartheta_n + \frac{1}{6}(k_1^{\vartheta} + 2 \cdot k_2^{\vartheta} + 2 \cdot k_3^{\vartheta} + k_4^{\vartheta}), \\ m_{n+1} &= m_n + \frac{1}{6}(k_1^m + 2 \cdot k_2^m + 2 \cdot k_3^m + k_4^m). \end{aligned} \quad (18)$$

The coupled ODE system was solved for position, velocity and mass growth due to coagulation in a vertical muffler using the classical 4th-order Runge-Kutta method with fixed step h (Table 1). At each step, engine pressure, acoustic radiation force, hydrodynamic drag and gravity are evaluated; the mass rate follows a probabilistic coagulation term (Figure 1).

The calculation results are presented in Table 2.

According to the calculations, the particle mass increases over time, which indicates a coagulation process in which the particle absorbs the other particles colliding with them in the gas flow. This leads to a gradual increase of its size and mass, which in turn affects its dynamics. As the mass increases, the particle begins to settle faster, since the gravitational forces acting on it become more significant, and the resistance of the environment does not compensate for the increase in mass. This leads to accelerated sedimentation, which is confirmed by decreasing the x coordinate indicating downward movement. At the same time, the particle velocity rapidly increases, which indicates intense downward acceleration. Such a rapid increase in velocity is caused not only by gravitational attraction, but by changing the mass, as well, since the larger particles experience less aerodynamic resistance relative to their mass and therefore, settle faster under the action of external forces.

The obtained analytical dependences require confirmation by experimental studies. In this regard,

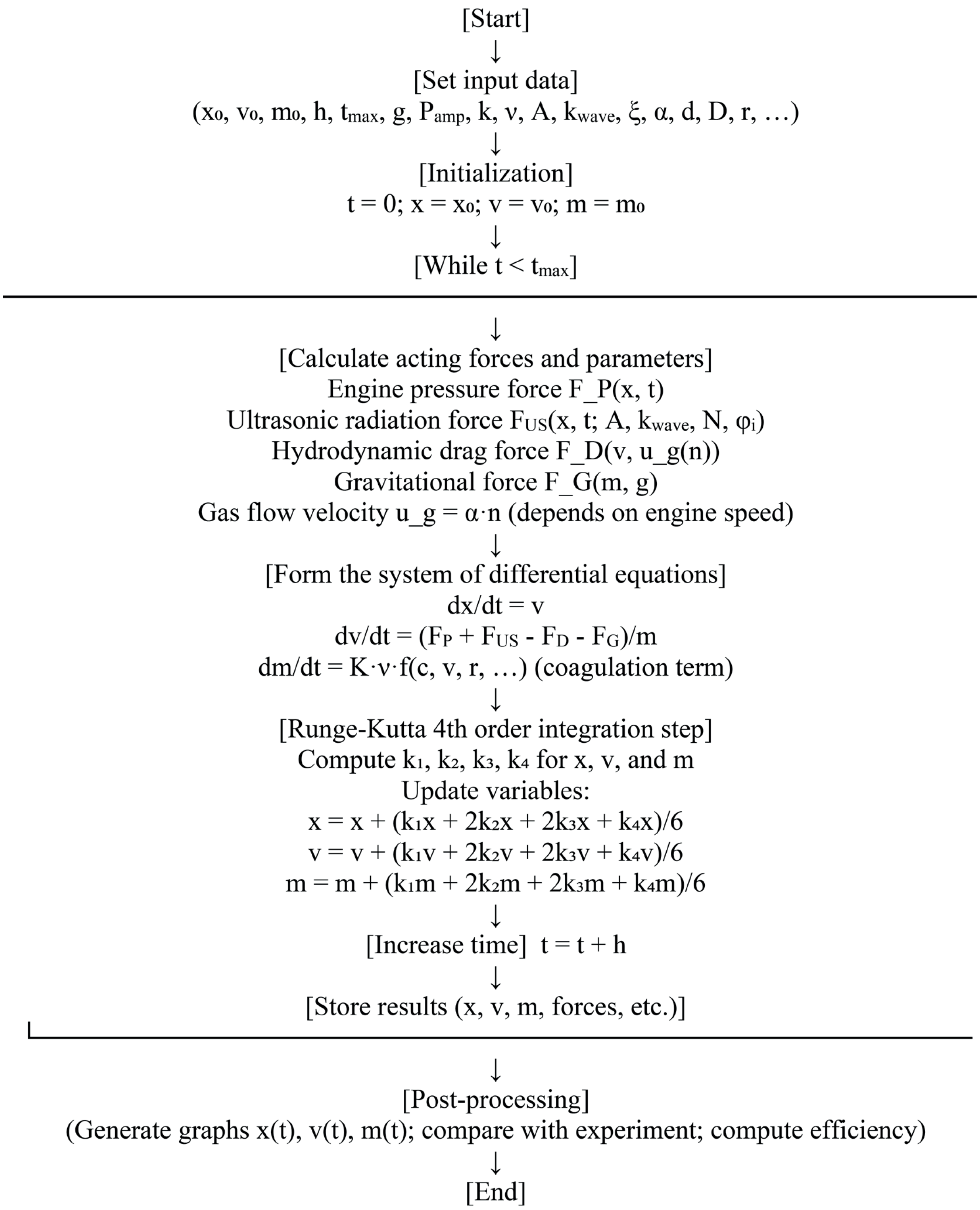

Figure 1 *Flowchart of the modelling algorithm using the 4th-order Runge-Kutta method for particle motion and coagulation in the vertical ultrasonic muffler*

Table 2 *The calculation results*

Time (s)	Coordinate x (m)	Velocity v (m/s)	Mass m (kg)
0	0	0	0
0.00001	-0.000002	-0.608884	0.000064
0.00002	-0.000016	-2.435372	0.0001270
0.00003	-0.000055	-5.479444	0.000191
0.00004	-0.000130	-9.741067	0.000254

Figure 2 *Experimental stand of the ultrasonic muffler of a Diesel engine*

Figure 3 *The process of preparing and weighing paper sheets*

a vertical ultrasonic muffler stand was developed (Figure 2).

The experimental technique consisted of determining the parameters of carbon dioxide, oxygen and the mass of settled soot before and after the exposure to ultrasound depending on changing the combination of ultrasonic emitters, and taking into account the change in the number of revolutions of the engine crankshaft. The experiments were carried out in two stages: Stage 1 - before the gas exposure to ultrasound, Stage 2 - after the gas exposure to ultrasound. The gas was exposed to ultrasound by installing ultrasonic emitters in the muffler housing and with their random connection in various combinations. The frequency and power of the ultrasonic emitters were fixed at the frequency of 25 kHz and the total power of 100 W. The experiments were carried out on an MTZ-80 tractor, the fuel grade was diesel.

The procedure for the conducting experimental studies was as follows:

- experiments to obtain parameters of carbon dioxide, oxygen and the mass of settled soot were carried out without turning on and with turning on the ultrasonic equipment for 5 minutes each;
- the lower part of the device was lined in a semicircle with five numbered sheets of paper measuring 10×10 cm, with the total length of 50 cm, the mass of which was determined before the testing, using high-precision jewelry scales “MH-500” (Figure 3);
- experimental studies were carried out with the engine crankshaft speeds of 1000, 1500, 2000 rpm;
- the exhaust gas was fed into the test stand body through the inlet pipe under pressure depending on the engine speed. In the muffler, with the ultrasonic equipment turned on, the exhaust gas was exposed to ultrasonic waves in the longitudinal direction. In the sections, ultrasonic intensification of coagulation processes and purification of exhaust gases occurred due to sedimentation of coarse particles of exhaust gas at the soot collection point. Purified exhaust gas was discharged through the outlet pipe;
- after each test, numbered paper with settled soot particles was carefully removed and weighed again. The mass of settled soot particles was determined by the difference in mass readings before and after the test.

Then, the process of comparing and processing the obtained results without ultrasound and under the influence of ultrasound took place.

3 Results

The results of experimental studies for obtaining indicators of carbon dioxide (CO_2) and oxygen (O_2) are presented in Table 3, where u/e stands for the ultrasonic emitter.

Table 3 *Results of experimental studies for obtaining indicators of carbon dioxide and oxygen*

Indicators	without u/e	with u/e 1	with u/e 3	with u/e 6	with u/e 1-3	withu/e 1-6	with u/e 3-6	with u/e 1-3-6	all u/e
1000 rpm									
$CO_{2,}$ %	1.98	1.94	1.84	1.82	1.8	1.77	1.79	1.8	1.73
$O_{2,}$ %	17.9	17.98	17.14	18.19	18.22	18.29	18.33	18.26	18.23
1500 rpm									
$CO_{2,}$ %	2.22	2.18	2.06	2.03	2	1.98	1.96	2.01	1.9
$O_{2,}$ %	17.92	17.96	18.2	18.3	18.31	18.32	18.4	18.38	18.48
2000 rpm									
$CO_{2,}$ %	2.36	2.3	2.2	2.18	2.15	2.12	2.1	2.14	2.5
$O_{2,}$ %	17.95	17.98	18.4	18.45	18.46	18.48	18.46	18.349	18.53

Note: u/e - ultrasonic emitter

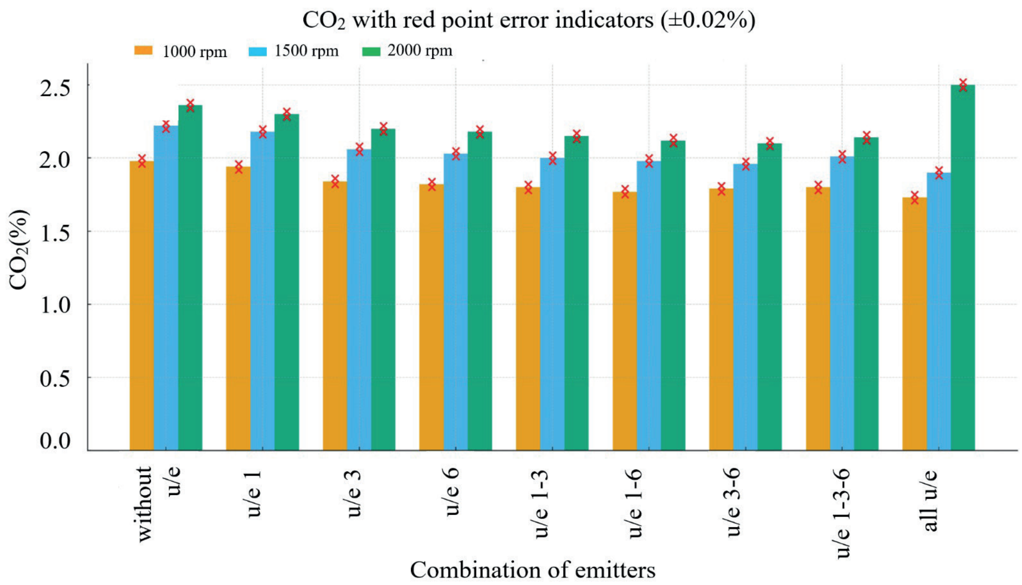

Figure 4 *Changing of the carbon dioxide levels depending on the combination of emitters*

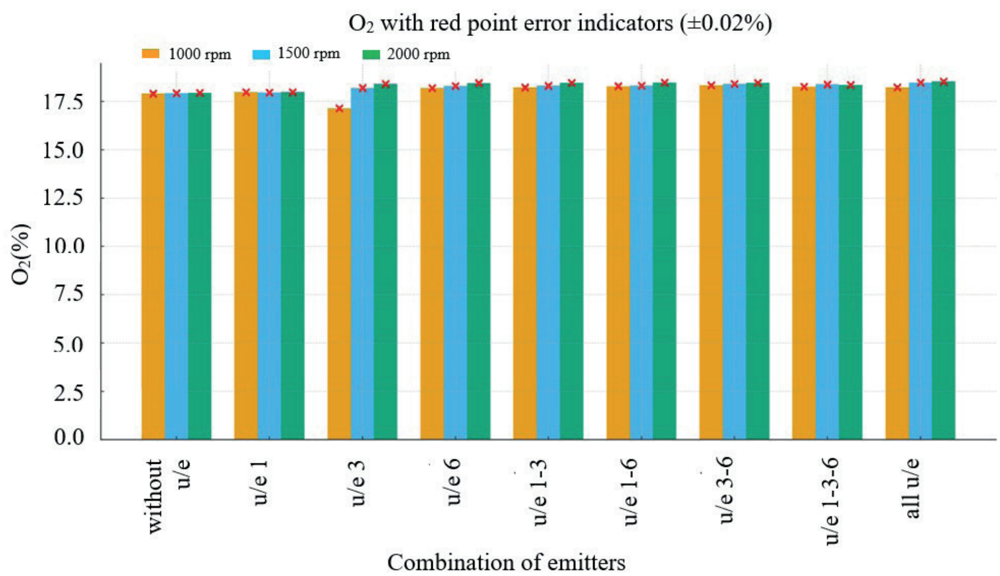

Figure 5 *Changing of the oxygen levels depending on the combination of emitters*

The measurement uncertainty of the gas analyzer was ± 0.02 % for CO_2 and O_2. Based on the obtained results of experimental studies, graphs were drawn of changes in carbon dioxide and oxygen depending on the inclusion and combination of ultrasonic emitters at engine crankshaft speeds of 1000, 1500 and 2000 rpm (Figures 4 and 5).

The observed increase in O_2 concentration indicates more complete oxidation of carbon monoxide and unburned hydrocarbons. Ultrasonic waves intensify gas mixing and promote secondary oxidation reactions due to the formation of localized high-temperature microzones in the acoustic field.

The results of experimental studies have shown that the use of ultrasonic emitters has a significant effect on the composition of exhaust gases. The graph of changes in CO_2 concentration shows a tendency for the level of carbon dioxide to decrease at each value of the engine speed when using different combinations of emitters. Without ultrasonic exposure, the concentration of CO_2 has maximum values, which indicates insufficient intensity of oxidation processes occurring in the exhaust gases. When the individual emitters and their combinations are turned on, such as emitters 1-6 and 1-3-6, the concentration of CO_2 begins decreasing but the maximum effect is achieved only when using all emitters simultaneously, which confirms the intensification of oxidation processes due to complex ultrasonic exposure.

A similar tendency is observed in the graph of changes in O_2 concentration, where the maximum oxygen content is recorded when using all emitters. Without ultrasonic exposure, the oxygen level remains lower than with its effect, which indicates a less intense chemical reaction in the gas environment. When the

Table 4 *The settled soot mass*

Rpm	without u/e	with u/e 1	with u/e 3	with u/e 6	withu/e 1-3	with u/e 1-6	withu/e 3-6	with u/e 1-3-6	all u/e
1000	0.64	0.642	0.645	0.65	0.66	0.662	0.667	0.67	0.68
1500	0.66	0.661	0.663	0.665	0.672	0.675	0.68	0.69	0.71
2000	0.69	0.7	0.672	0.675	0.7	0.713	0.72	0.73	0.75
N, (W)	0	100	100	100	200	200	200	300	600
L, (m)		0.27	0.61	1.12	0.34	0.85	0.51	0.95	1.12

Note: *N* - Power of the ultrasonic emitter, W;

L - distance from the muffler inlet to the ultrasonic emitter affected by the signal, m.

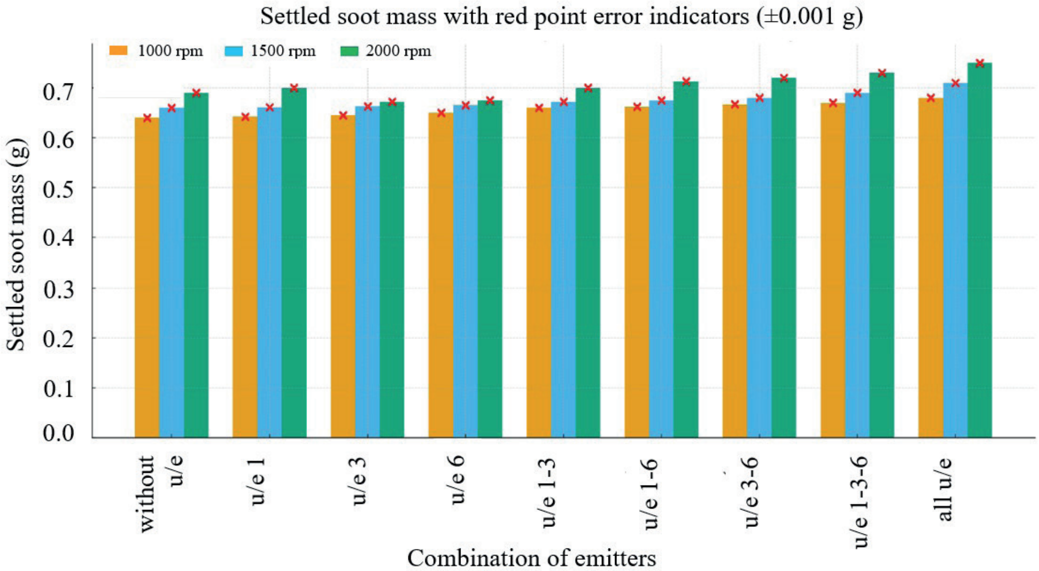

Figure 6 *Change in the mass of settled soot depending on the combination of ultrasonic emitters (at 1000, 1500, and 2000 rpm)*

individual emitters are switched on, the changes are local in nature, but when several emitters are used simultaneously, the O_2 level increases steadily, which confirms the improvement of the oxidation processes of pollutants.

Thus, the conducted studies confirm that ultrasonic cleaning of exhaust gases has a positive effect on their composition. The use of individual emitters also helps to improve the characteristics of the gas environment, but the greatest effect is achieved with the complex inclusion of all the emitters. This confirms the feasibility of using ultrasonic technology in the processes of cleaning exhaust gases, ensuring a decrease in emissions of harmful substances and an increase in the efficiency of their oxidation.

The results of experimental studies of obtaining the mass of settled soot are presented in Table 4.

The weighing error of soot mass determination was ± 0.001 g. Based on the obtained results of the experimental studies, a graph was drawn of the change in the mass of settled soot, depending on the combination of emitters at engine crankshaft speeds of 1000, 1500 and 2000 rpm (Figure 6).

With increasing the engine crankshaft speed from 1000 to 2000 rpm, a general increase in the mass of deposited soot is observed in all the operating modes, which is associated with increasing the volume of exhaust gases passing through the muffler. Turning on the ultrasonic emitters leads to a significant increase in the deposited soot compared to the operating mode without the ultrasonic action, confirming the effectiveness of ultrasonic waves in the gas cleaning process. As the number of active emitters increases, the cleaning efficiency increases, which is especially noticeable when using two or three emitters simultaneously, and the maximum increase in the amount of soot is achieved when all the ultrasonic emitters are turned on simultaneously. The difference in the efficiency of various emitter combinations becomes more pronounced with an increase in the number of revolutions, which confirms the intensification of coagulation processes and the effectiveness of ultrasonic action with a more intense gas flow.

To quantify the efficiency of ultrasonic cleaning, the relative improvement of the exhaust parameters was calculated using the following expressions:

Table 5 *Relative improvement of exhaust gas parameters (%)*

Engine speed, rpm	ΔCO_2, %	ΔO_2, %	Δm, %
1000	-12.6	+1.8	+6.3
1500	-14.4	+3.1	+7.6
2000	-13.1	+3.2	+8.7

$$\Delta CO_2 = (CO_{20} - CO_{21})/CO_{20} \times 100\ \%,$$
$$\Delta O_2 = (O_{21} - O_{20})/O_{20} \times 100\ \%, \quad (19)$$
$$\Delta m = (m_1 - m_0)/m_0 \times 100\ \%,$$

where: the subscript “0” refers to the value before the ultrasound exposure, and “1” - after exposure. The calculation results are presented in Table 5.

Calculations are based on the averaged data from Tables 3 and 4. A negative sign for ΔCO_2 indicates a decrease in concentration, while a positive sign denotes an increase in the parameter.

Thus, the results of analytical modelling and experimental data turned out to be mutually consistent, which confirms the efficiency of the proposed method of cleaning the exhaust gases. Both approaches show that ultrasonic treatment promotes coagulation and accelerated sedimentation of soot particles, reducing their content in the gas environment. The analytical model predicted increasing the mass of particles due to their enlargement and subsequent accelerated sedimentation under the effect of gravity and ultrasound, and the experiments confirmed these conclusions by increasing the mass of settled soot when the ultrasonic emitters were turned on. The comparison between the analytical modelling and experimental data shows a high degree of agreement, with the correlation coefficient R^2 = 0.91. This confirms the adequacy of the developed mathematical model for predicting soot particle coagulation and sedimentation processes.

4 Conclusion

In this research was examined the possibility of using the ultrasound to clean diesel engine exhaust gases. The studies have shown that the efficiency of ultrasonic cleaning of exhaust gases is confirmed both theoretically and experimentally, since ultrasound promotes agglomeration of soot particles and their sedimentation, which reduces the level of air pollution. The mutual complementarity of analytical and experimental methods provides a comprehensive understanding of coagulation processes, where the mathematical modelling makes it possible to predict the dynamics of particles and to determine the optimal parameters of ultrasonic action, and experimental studies make it possible to evaluate the real efficiency of the technology and make adjustments to the model. The maximum effect is achieved when using all the emitters simultaneously, since the more active ultrasonic sources are involved, the higher the level of deposited soot. It is also noted that the concentration of carbon dioxide decreases, and the oxygen content increases, which indicates more complete oxidation of exhaust gases under the effect of ultrasound. In addition, the vertical arrangement of the emitters improves the efficiency of particle deposition, since compared to the horizontal design of the muffler, it promotes more uniform deposition of soot due to the combined action of gravity and ultrasonic waves. As a result, the use of six emitters at 25 kHz reduced CO_2 by ≈ 12 %, increased O_2 by ≈ 3 %, and doubled the mass of deposited soot compared to the baseline mode. The results obtained can be used to further improve the design of ultrasonic mufflers and to adapt them to real operating conditions.

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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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