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Review of Previous Studies: From Classical Coagulation Theory to Practical Ultrasonic Purification of Exhaust Gases

Kadyrov A.S.[1], Sakhapov R.L.[2], Kukesheva A.B.[1*]
[1]Abylkas Saginov Karaganda Technical University, Karaganda, Kazakhstan
[2]Kazan (Volga region) Federal University, Kazan, Russia
* corresponding author

Abstract. The purpose of this study is to critically review and generalize theoretical and experimental research on ultrasonic coagulation of aerosol and soot particles as a promising approach to reducing the smoke opacity and toxicity of exhaust gases from internal combustion engines. The scope of the work encompasses both classical diffusion-based coagulation theories and contemporary studies of acoustic agglomeration in stationary aerosols, flow channels, and automotive mufflers. The research methodology is based on a systematic analysis and comparison of existing models and experimental results, with an emphasis on their relevance to real exhaust-system operating conditions.
The analysis demonstrates that most diffusion and acoustic coagulation models are formulated under idealized assumptions, such as stationary and isothermal media and negligible turbulence. These assumptions significantly restrict their applicability to real exhaust flows, which are characterized by high temperatures, turbulent and pulsating motion, variable composition, and limited particle residence time. A synthesis of experimental data shows that ultrasonic exposure enhances soot particle growth and promotes their subsequent sedimentation in flowing gases. The effectiveness of ultrasonic purification is determined by several interrelated factors, including turbulence intensity, pressure pulsations, residence time of particles in the active zone, acoustic field configuration, muffler geometry, and the polydisperse structure of soot.
The study also identifies the main shortcomings of existing theoretical and experimental approaches, such as the widespread use of batch-type accumulation chambers, simplified test-bench designs, and the lack of reliable experimental data under high-temperature exhaust conditions. Based on the obtained results, the main conclusions highlight the necessity of optimizing ultrasonic muffler geometry, developing adaptive and multi-frequency acoustic fields, and implementing control algorithms for ultrasonic emitters. The revealed regularities form a scientific basis for the rational design of ultrasonic mufflers and confirm their potential to improve analytical modeling accuracy, reduce experimental workload, and enhance exhaust gas purification efficiency.

Keywords. ultrasonic coagulation, acoustic particle agglomeration, soot (aerosol) particles, flow-through ultrasonic muffler, turbulent pulsating flow

Introduction

Exhaust emissions from motor vehicles are one of the major factors contributing to the development of chronic diseases and the deterioration of urban environmental quality. Prolonged exposure to fine particulate matter, nitrogen oxides, carbon monoxide, and polycyclic hydrocarbons leads to an increased incidence of chronic obstructive pulmonary disease, bronchial asthma, allergic airway reactions, and chronic bronchitis [1]. In addition to respiratory disorders, polluted air elevates the risk of cardiovascular diseases, including arterial hypertension, ischemic heart disease, and cardiac arrhythmias, and also contributes to a higher likelihood of strokes [2, 3].

Particular attention is given to PM2.5 particles and benzopyrene, which are associated with an increased risk of oncological diseases, primarily lung cancer. In recent years, the negative impact of vehicle emissions on cognitive functions has also been demonstrated: long-term exposure to polluted air can lead to reduced attention and impaired memory. Taken together, these factors underscore the urgent need to develop and implement effective solutions aimed at reducing the toxicity of exhaust gases and improving environmental conditions in urban areas.

Along with infrastructural measures, the use of ultrasound is an important and promising area [4]. Ultrasonic exposure leads to coagulation and possible subsequent cavitation of aerosol and soot particles. [5, 6]. This method is considered an effective tool for enhancing the environmental safety of motor vehicles by significantly reducing the concentration of solid particles in exhaust gases [7]

Fundamental concepts of coagulation mechanisms were established in the early 20th century in the works of Albert Einstein and Marian Smoluchowski [8]. However, the classical Einstein–Smoluchowski theory was originally formulated for idealized conditions: stationary, homogeneous, predominantly isothermal systems with Brownian or shear-induced mixing and without any consideration of an organized gas flow.

The gaseous medium in an automotive exhaust system differs fundamentally from the idealized conditions assumed in classical coagulation theory. Exhaust gases have high temperatures, variable composition (a mixture of gaseous components and solid soot particles), and are subject to strong fluctuations in pressure and velocity caused by engine cycles. The flow in the muffler is typically turbulent. Soot particles move within a directed, high-velocity stream, simultaneously experiencing gas-dynamic forces, viscous drag, gravity, and when ultrasound is applied – acoustic pressure and Bjerknes forces. Under such conditions, classical diffusion-coagulation equations are clearly insufficient: they do not account for the influence of turbulence on effective mixing, the contribution of the acoustic field to the relative motion of particles of different sizes, or the features of flow-through reaction volumes.

To describe the behavior of exhaust gases in an automotive muffler, as well as the processes of particle growth and deposition under the influence of ultrasound, it is necessary to draw upon a broader range of studies. It is essential to consider works that:

- analyze the influence of acoustic forces on particles and the formation of concentration zones;
- investigate coagulation in flow channels and chambers with directed gas streams;
- develop mathematical models of particle motion in mufflers and reaction chambers that incorporate the superposition of gravitational, gas-dynamic, and acoustic forces.

For this reason, the present study finds it appropriate to conduct a targeted review of previous research: from classical models of Brownian and diffusion-induced coagulation to contemporary theoretical and experimental studies on ultrasonic gas cleaning in flow systems and automotive mufflers. Such a review makes it possible, on the one hand, to demonstrate the evolution of understanding of coagulation mechanisms, and, on the other hand, to identify the limitations of existing approaches when applied to exhaust gases of internal combustion engines, thus substantiating the need to account for acoustic, turbulent, and gas-dynamic factors.

The purpose of this study is to conduct a comprehensive analysis of theoretical and experimental research in the field of ultrasonic coagulation of aerosol and soot particles, in order to develop an integrated understanding of particle interaction mechanisms within a flow-through ultrasonic automotive muffler and to identify the key patterns that determine the efficiency of ultrasonic exhaust-gas purification.

To achieve this goal, the following objectives were set:

- to analyze the fundamental coagulation models developed by Einstein and Smoluchowski and to determine the limits of their applicability in real gas-flow conditions;
- to examine modern studies on acoustic coagulation, including the influence of Bjerknes forces, acoustic pressure, standing waves, and orthokinetic mechanisms on particle interactions;
- to analyze research on coagulation in flow systems, including chambers with directed gas streams and mufflers operating under turbulent-flow conditions;
- to identify the main problems and limitations of existing approaches that hinder their direct application in automotive exhaust systems;
- to determine directions for further research aimed at improving the efficiency of ultrasonic coagulation and adapting it to real operating conditions of motor vehicles.

The scientific novelty of the research lies in the systematization of existing studies and the identification of key patterns governing ultrasonic coagulation processes in internal combustion engine exhaust systems. The established dependencies form a scientific basis for the subsequent development of ultrasonic mufflers, enabling a reduction in the volume of experimental work and an increase in the accuracy of analytical models and engineering methodologies.

The practical significance of the study is that the obtained results create prerequisites for the design of an ultrasonic muffler and the justification of optimal operating modes. This will ensure a reduction in smoke opacity and exhaust-gas toxicity, thereby improving the environmental performance of motor vehicles.

1. Materials and Methods

The history of research on ultrasonic coagulation of gas-phase particles originates from the fundamental studies of the 20th century (Figure 1).

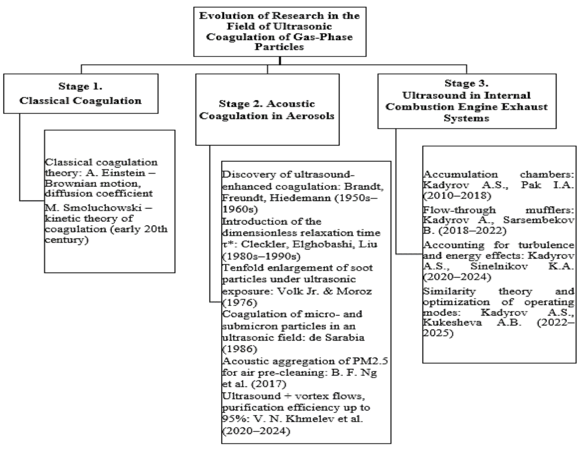


Fig. 1 – Timeline of Research on Ultrasonic Coagulation of Gas-Phase Particles

Figure 2 also presents the geographical distribution of key studies in the field of ultrasonic coagulation of gas-phase particles, which clearly illustrates the evolution of this research area from fundamental physical theories to applied engineering solutions.

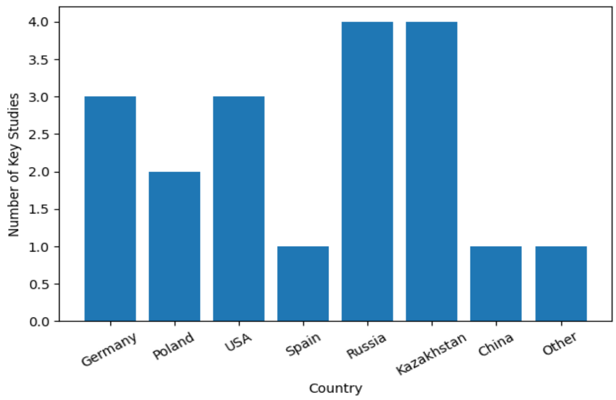


Fig. 2 – Distribution of Ultrasonic Coagulation Research by Countr

Figure 2 was compiled based on publications indexed in the Scopus and Web of Science databases. The literature selection covered the period from 1905 to 2025 and included studies specifically addressing Brownian coagulation, acoustic agglomeration, ultrasonic particle coagulation, aerosol purification, and ultrasonic exhaust gas treatment. Only peer-reviewed journal articles and conference papers directly related to particle coagulation mechanisms were considered.

According to Figure 2 while early theoretical foundations were established in Germany and Poland, recent advances demonstrate a shift toward applied and engineering-oriented research. A significant contribution is provided by Kazakhstan, where ultrasonic coagulation has been adapted to flow-through automotive mufflers with consideration of turbulence, similarity criteria, and real engine operating conditions.

The first concepts of coagulation were formulated by Einstein and Smoluchowski, who examined particle merging in a closed medium without a directed gas flow. Their models were based on Brownian motion and shear fields, which made it possible to describe the probability of particle collisions and aggregate formation.

In the early 20th century, Einstein laid the foundation for describing the Brownian motion of particles by deriving the equation for the diffusion coefficient [9]. The diffusion coefficient characterizes the rate at which particles disperse in a gaseous medium due to their thermal motion: the higher its value, the more intensively the particles move, and the greater the probability of their collision and subsequent interaction [10].

$$D = \frac{k_B T}{6\pi\mu r}, \tag{1}$$

where k_B – Boltzmann constant;

T – absolute temperature;

μ – dynamic viscosity of the gas;

r – particle radius.

Building on Einstein's work, the Polish scientist Marian Smoluchowski developed a quantitative theory of coagulation – the process by which particles collide and merge into larger structures [11]. While Einstein focused on describing the motion of an individual particle, Smoluchowski examined their collective behavior and interactions [12].

For Brownian coagulation, the equation takes the following form:

$$\frac{dN}{dt} = -KN^2, \tag{2}$$

where N is the particle concentration, and the quadratic dependence shows that doubling N increases the coagulation rate by a factor of four;

K is the coagulation constant associated with diffusion, and for spherical particles it is equal to K=8πDr.

Substituting Einstein's expression for D, was obtained [13] :

$$\frac{dN}{dt} = -8\pi \frac{k_B T}{6\pi\mu r} rN^2 = \frac{4}{3}\frac{k_B T}{\mu} N^2, \tag{3}$$

Based on the studies described above, the key principles of coagulation theory were formulated. First, coagulation leads to a reduction in the number of fine particles due to their merging into larger aggregates, which are more easily deposited under external forces. The efficiency of this process decreases with low impurity concentration, small particle radius, increased medium viscosity, and rising temperature, all of which limit collision frequency and the likelihood of adhesion.

Building on the fundamental works of Albert Einstein and Marian Smoluchowski, Brandt, Freundt, and Hiedemann were the first to note that acoustic forces can significantly enhance particle collisions and growth [14]. In their experiments, including studies on the coagulation of tobacco smoke, it was shown that ultrasonic exposure increases the probability of particle interaction severalfold, and the process itself becomes a distinct mechanism of intensified deposition [15]. These studies laid the foundation for the so-called "BFH model," which mathematically described the oscillatory motion of a particle in an acoustic field [16]:

$$m\frac{d^2x}{dt^2} = F_{\text{acous}} + F_{stokes} + F_{\text{grav}}, \quad (4)$$

where F_{acous} – the acoustic radiation force acting on the particle,

F_{stokes} =−6πμrdtdx – stokes drag force, which depends on the viscosity μ and particle radius r,

F_{grav}=mg – the gravitational force.

These conclusions were later confirmed by more advanced theoretical and computational studies. In the works of Jay Cleckler, Said Elghobashi, and Feng Liu, it was shown that particle motion is governed primarily by the Stokes force. The dimensionless relaxation time parameter they introduced, $\tau^*= \omega\tau$ (where τ is the particle relaxation time and ω is the angular oscillation frequency), made it possible to refine the ranges in which acoustic forces become dominant and lead to substantial aggregation [17].

Experimental confirmation of the effectiveness of acoustic aggregation was obtained in 1976 by Volk Jr. and Moroz [18]. They demonstrated that even under relatively moderate conditions, sound pressure levels of 100–120 dB and a frequency of about 3 kHz, it is possible to achieve nearly a tenfold increase in the diameter of soot particles in an aerosol. This served as important evidence of the practical applicability of acoustic coagulation for gas purification.

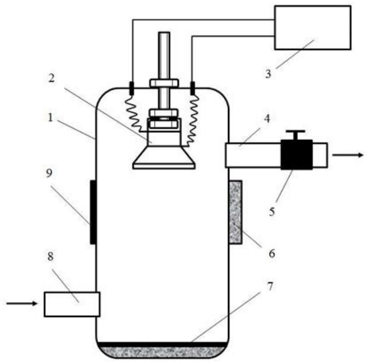
In 1986, the studies by de Sarabia advanced this research further by focusing on the dynamic growth of micron- and submicron-sized particles [19]. Their experiments confirmed that an ultrasonic field not only accelerates particle collisions but also consistently increases the average particle radius, which can be quantitatively described using the Smoluchowski equation (2).

The development of practical applications of these ideas was reflected in the work of B. F. Ng and colleagues, who employed acoustic aggregation as a method of pre-treating air to improve the filtration efficiency of fine particulate matter (PM2.5) [20]. Their experiments showed that within just 1–5 seconds of ultrasonic exposure, particle radii increased multiple times, thereby facilitating their subsequent capture by filters.

The most recent and advanced studies belong to V. N. Khmelev and co-authors (2020–2024). The researchers demonstrated that using not only ultrasound but also specially generated vortex flows significantly enhances the agglomeration process. In 2020, they showed that the combination of ultrasound with a swirling flow increases gas-cleaning efficiency from 46% to 85%, while the average particle size (d32) increases by a factor of 4.5 (compared with only 1.6 in a straight flow) [21]. In subsequent experiments (2024), it was proven that in a non-uniform ultrasonic field, agglomeration efficiencies of up to 95% for PM2.5, 92% for PM1.5, and 85% for PM 0.5 can be achieved at a sound pressure of 165 dB and a concentration of 2×10^{-2} g/m 32×10^{-2} g/m^3 [22]. These results provided important confirmation that optimizing the frequency, amplitude, and structure of the acoustic field makes it possible to achieve nearly complete removal of solid impurities from gases.

However, classical models based on these principles did not account for additional factors that arise under real operating conditions. In particular, they overlooked nonlinear effects associated with ultrasonic vibrations, as well as turbulence and gas-flow pulsations that inevitably accompany the operation of an internal combustion engine. For this reason, such approaches proved insufficient for fully describing the processes occurring in ultrasonic mufflers, where particle interactions are governed not only by Brownian or shear-induced coagulation, but also by the combined action of acoustic pressure, Bjerknes forces, gas-dynamic oscillations, and gravitational settling.

In our previous studies [23,24], the coagulation process was investigated using an accumulation-type ultrasonic purification device. The schematic of the accumulation device is shown in Figure 3.



1 – housing; 2 – ultrasonic wave emitter; 3 – ultrasonic vibration generator; 4 – outlet pipe; 5 – valve; 6 – light source; 7 – ultrasonic wave reflector; 8 – inlet pipe; 9 – luxmeter

Fig. 3. – Diagram of the experimental setup for ultrasonic cleaning and treatment of exhaust gases

As part of this study, a mathematical model was developed to describe the coagulation process of soot particles under the influence of ultrasonic waves. This process is governed by two key physical mechanisms:

- orthokinetic coagulation, which arises due to differences in oscillation amplitudes of particles of varying sizes. In an alternating acoustic field, small particles are almost fully entrained by the surrounding gas, while larger and more inertial particles "lag behind." This difference in motion velocities leads to frequent collisions and subsequent merging.
- hydrodynamic coagulation, which becomes significant at high ultrasonic frequencies. This mechanism is determined by a combination of phenomena, including viscous drag forces, Bjerknes forces (interactions between oscillating bodies in a gaseous medium), and acoustic pressure gradients.

The developed mathematical model is based on the principles of kinetic gas theory and describes the dependence of soot mass on its initial quantity, the coagulation coefficient, and the duration of ultrasonic treatment.

The central element of the model is the description of the degree to which a particle is entrained in the acoustic oscillations of the gas medium. This relationship is derived from Newton's second law with consideration of the Stokes drag force and is expressed by the following formula:

$$\frac{U_d}{U_f} = \frac{1}{\left[(\frac{4\pi r^2 f}{9\eta})^2+1\right]^{1/2}}, \quad (5)$$

where U_d – amplitude of particle oscillations, m;

U_f – amplitude of gas-medium oscillations, m;

ρ – density of the particle material (soot), kg/m³;

r – particle radius, m;

f – frequency of ultrasonic oscillations, Hz;

η – dynamic viscosity of the gas medium, Pa·s..

From the equation, it follows that the amplitude ratio U_d/U_f approaches 1 for very small particles (small radius r) and approaches 0 for large particles (large radius r) or at high frequencies *f*. This dependence creates the conditions for orthokinetic coagulation: small particles move together with the gas, while larger particles remain almost stationary, which leads to their intensive collisions.

The coagulation process results in a change in the mass distribution of particles within a closed volume. The total mass of the system m remains constant and consists of the mass of the gas m_g and the mass of the suspended soot particles m_c:

$$m=m_g+m_c=\rho V, \quad (6)$$

where ρ is the average density of the mixture and V is the volume.

The decrease in the concentration of fine particles and, consequently, the increase in the mass of soot deposited from the gas phase are described by a first-order kinetic equation:

$$m_c(t)=mc_0(1-e^{-kt}) , \quad (7)$$

where m_{c0} – initial mass of suspended soot particles, kg;

$m_c(t)$ – mass of coagulated (settled) particles at time t, kg;

k – effective coagulation coefficient, s^{-1};

The effective coagulation coefficient closely correlates with the concept of light absorption. The more particles present in a volume, the less light passes through it. For this reason, the following parameters were introduced to quantitatively evaluate the efficiency of coagulation:

- relative illumination ($\alpha i = E/Ei$): the ratio of the light intensity transmitted through the particle-containing medium (E) to the light intensity transmitted through the clean medium (E_i):
- light absorption coefficient ($\beta i = 1 - \alpha_i$): the fraction of light absorbed by the particles.

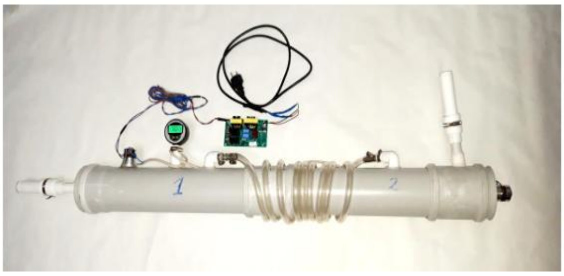
Assuming that the absorption coefficient β_i is directly proportional to the particle concentration n, the concentration ratio n_0/n was expressed through measurable optical parameters. This made it possible to calculate the coagulation coefficient k_i directly from the experimental data:

$$k_i = \frac{\ln(\frac{n_0}{n})}{t} \approx \frac{1}{t}\left(\frac{1}{1-\beta_i}\right). \tag{8}$$

To verify the obtained results, experimental studies were conducted using the accumulation device (Figure 3). The results demonstrate that under the influence of ultrasound, the coagulation rate increases by a factor of 3–5, and the gas transparency at the end of the experiment increases almost 2.5 times compared with natural coagulation. Thus, ultrasound not only intensifies the processes of particle growth and deposition but also reduces soot concentration and increases exhaust transparency, confirming the potential of ultrasonic technologies for exhaust-gas purification systems [24].

The authors also proposed several structural variants of the chambers, including vertical and multi-section designs, which provided longer gas residence time and facilitated the formation of standing acoustic waves. However, a limitation of these studies was that the process was considered in a "batch mode." According to this experimental approach, the gas was introduced into a closed volume and treated there for a certain time without continuous flow. In other words, the treatment was performed in a static chamber, and coagulation occurred over a fixed time interval. In this configuration, engine-induced pressure, gas-flow turbulence, and other dynamic factors were not taken into account; therefore, the obtained results have limited applicability to real operating conditions of an ultrasonic muffler.

In our subsequent studies [25], the research was extended to full-scale flow-through ultrasonic mufflers. The authors developed several bench designs, including two-section and all-metal configurations (Figure 4).



(a) Two-section ultrasonic muffler

(b) Polypropylene ultrasonic muffler

(c) Metal ultrasonic muffler

Fig. 4 – Experimental ultrasonic mufflers: (a) two-section design; (b) polypropylene design; (c) metal design

The authors also developed a mathematical model describing the motion of a gas particle along the experimental muffler test benches.

In this model, each soot particle is subjected to a superposition of four main forces:

- gravitational force (F_g) directed vertically downward and determined by the particle’s mass.

$$F_g=mg, \tag{9}$$

- acoustic radiation force (F_a) – a rises from the pressure gradients in the ultrasonic field (Bjerknes force). This force tends to move particles toward the nodes or antinodes of a standing sound wave, promoting their concentration and deposition.

$$F_a = \pi r^2 pAc\omega cos\omega(t - \frac{n}{c}), \tag{10}$$

where A – amplitude of the acoustic pressure,
ρ – gas density,
c – speed of sound.

- flow drag force (F_D), caused by the pressure of the exhaust gases, which carries the particle along the axis of the muffler:

$$F_D = P\frac{d^2}{4D^2}, \tag{11}$$

where P – exhaust-gas pressure,
d – particle diameter,
D – muffler diameter.

- hydrodynamic drag force (F_c) – the viscous friction force described by Stokes’ law, which opposes the motion of the particle relative to the gas:

$$F_c = 6\pi\mu r\frac{dx}{dt}. \tag{12}$$

where μ – dynamic viscosity of the gas,
r – particle radius.

The total equation of motion of a particle, according to Newton’s second law, has the form:

$$\frac{md^2x}{dt^2} = \overrightarrow{F_g} + \overrightarrow{F_a} + \overrightarrow{F_D} - \overrightarrow{F_c}\,, \tag{13}$$

For trajectory analysis, the general equation was decomposed into components along the x-axis (flow direction) and the y-axis (vertical direction, corresponding to particle settling):

- motion along the x-axis:

$$\frac{md^2x}{dt^2} + 6\pi\mu r\frac{dx}{dt} = F_D, \tag{14}$$

- motion along the y-axis::

$$\frac{md^2y}{dt^2} + 6\pi\mu r\frac{dy}{dt} = mg + F_a, \tag{15}$$

These are linear second-order differential equations. Introducing the damping parameter θ=6πμr/m, which characterizes the effect of viscous drag, their analytical solutions were obtained:

$$x(t) = \frac{F_D}{m\theta}t + (x_0 - \frac{F_D}{m\theta^2})e^{-\theta t}, \tag{16}$$

$$y(t) = \frac{mg+F_a}{m\theta}t + (y_0 - \frac{mg+F_a}{m\theta^2})e^{-\theta t}. \tag{17}$$

For soot particles in exhaust gases, the damping parameter θ is small (on the order of 0.02 s^{-1}). This means that the transient process described by the exponential term $e^{-\theta t}$ decays very rapidly. Within fractions of a second, particle motion becomes almost steady. Therefore, the analysis was transitioned to steady-state velocities.

Under steady-state motion, the particle velocities along the x and y axes become constant:

- longitudinal velocity (carryover velocity):

$$\vartheta_x \approx \frac{F_D}{6\pi\mu r} = \frac{Pdr}{6\mu D}, \tag{18}$$

- vertical settling velocity produced by the combined action of gravity and acoustic radiation forces:

$$\vartheta_y = \frac{mg}{6\pi\mu r} = \frac{Pdr}{6\mu D}, \tag{19}$$

Effective particle deposition onto the muffler wall occurs only if the time required for it to traverse the vertical distance (t_y=D/V_y) is less than the particle's residence time in the muffler (t_x=L/V_x).This leads to the key criterion for deposition efficiency:

$$V_x/V_y > L/D. \tag{20}$$

where L – the length of the muffler,

D – its diameter.

This criterion indicates that, for effective particle capture, the velocity of their transverse displacement (under the action of gravity and acoustic forces) must be sufficiently high compared to the longitudinal flow velocity.

For a macroscopic assessment of the process, a coagulation (deposition) coefficient K was introduced, defined as the ratio of the mass of deposited soot m_c to the total mass of gas m that passed through the engine during time t:

$$K = m_c/m, \tag{21}$$

The mass of gas was expressed through the engine parameters:

$$m = Q\rho\omega t, \tag{22}$$

where Q – the combustion chamber volume,

ρ – the gas density,

ω – the crankshaft rotation frequency.

Taking into account that the gas residence time in the muffler is t=L/V_x, the final formula for the coefficient K was obtained:

$$K = \frac{m_c\vartheta_x}{LQ\rho\omega}. \tag{23}$$

Analysis of the obtained equations allows the following conclusions to be drawn. The longitudinal velocity V_x increases with higher exhaust pressure P and larger particle radius r, which accelerates their passage through the muffler. The deposition efficiency decreases with increasing gas viscosity μ and muffler diameter D, as both factors reduce the velocities V_x and V_y.

The acoustic force F_a directly increases the vertical velocity V_y, which is a key factor in improving deposition efficiency according to the criterion $V_y/V_x > D/L$.

The coagulation coefficient K is directly related to the mass of captured soot m_c and the flow velocity V_x. It is inversely proportional to the engine displacement and the rotation frequency, which is logical, since as the gas flow rate increases, capturing the same percentage of particles becomes more challenging.

Thus, the proposed model makes it possible to link microscopic particle-motion parameters (size, density) with macroscopic system characteristics (engine pressure, muffler geometry, ultrasound parameters). It enables prediction and optimization of the performance of ultrasonic exhaust-gas cleaning systems.

According to the above, three types of ultrasonic mufflers were investigated (a two-section design, a polypropylene design, and a metal design), all connected to the exhaust system of a VW Passat B3 vehicle. The experiments were conducted in two modes: without ultrasound and with the activation of ultrasonic emitters (longitudinal, transverse, or their combination). The following performance indicators were measured: the mass of deposited soot (collected on paper sheets) and the concentrations of harmful substances (CO, CH) using gas analyzers.

The experimental studies confirmed the hypothesis that ultrasonic coagulation significantly intensifies the deposition of soot particles in exhaust gases. The greatest effect was observed when using the longitudinal emitter and the combination of emitters. The cleaning efficiency in terms of deposited soot mass increased by more than a factor of two, while the concentration of hydrocarbons (CH) in the exhaust was reduced by nearly half. However, the effect on CO concentration was less pronounced, indicating the need for further investigation.

Overall, the ultrasonic mufflers demonstrated strong potential as an effective method for reducing the toxicity of exhaust gases.

In our later investigations [26], a comprehensive force-balance model was developed, which focused on the balance of forces acting on a particle inside the muffler. A significant innovation was the separation of laminar and turbulent drag components and the introduction of correction factors that allow accurate description of the turbulent regime.

In a turbulent flow, the drag force acting on a particle greatly exceeds the classical Stokes drag force (F_c). To account for this effect, two key corrections are introduced:

- turbulent viscosity (μ_T) – an effective viscosity reflecting the intense momentum exchange in a turbulent flow. It is significantly higher than the molecular viscosity μ;

Composite particle velocity (V_a) – the motion of a particle is determined by the superposition of two velocities: the velocity of the main flow (V) and the particle's oscillation velocity in the ultrasonic field (U_1). Therefore:

$$V_a=V+U_1, \quad (24)$$

Considering these factors, the drag force in a turbulent flow (F_{sT}) can be expressed in terms of the original Stokes drag using correction coefficients:

$$F_{sT},T=F_c(K_1+K_2), \quad (25)$$

where two dimensionless criteria are introduced:

1. Turbulence criterion (K_1)::

$$K_1=\mu_T/\mu, \quad (26)$$

This criterion indicates how many times the effective resistance of the flow exceeds the laminar resistance due to turbulent fluctuations.

Ultrasound intensity criterion (K_2):

$$K_2=U/V, \quad (27)$$

This criterion (an analogue of the Strouhal number) reflects the relative "agitation" of particles by the acoustic field compared to their advection by the main flow. The higher the particle oscillation velocity U relative to the flow velocity V, the more intensive the orthokinetic coagulation becomes.

In addition to the force-based analysis, an energy-based approach was proposed. The total power required for particle transport consists of the power supplied by the engine flow (N_{eng}) and the power introduced by the ultrasonic emitter (N_{US}). To evaluate the relative contribution of the acoustic system, a third dimensionless criterion (the energy criterion) K_3 was introduced:

$$K= N_{US}/ N_{eng}. \quad (28)$$

This parameter can be interpreted as a measure of the energetic "loading" of the purification process. It indicates what fraction of energy is added to the system by ultrasound compared with the energy of the gas flow itself, and indirectly characterizes the intensity of purification.

Thus, the behavior of the complex system was described using three dimensionless criteria (K_1,K_2,K_3), which reflect the degree of turbulence, the relative intensity of the acoustic field, and the energetic contribution of the ultrasonic system.

The proposed dimensionless criteria (K_1,K_2,K_3) make it possible to analyze and compare different operating modes. The model predicts that coagulation efficiency will be maximal under conditions with a high value of criterion K_2 (when U/V is large), which is achieved either by increasing ultrasonic power or by reducing flow velocity.

The authors emphasize that due to the complex nature of wave processes (reflection, interference) and the stochastic character of turbulence, the model does not claim to provide a strictly deterministic description. It formulates general dependencies that require verification through experimental studies.

For the experimental investigations, a flow-through ultrasonic muffler test bench was constructed. It consisted of a steel pipe with a diameter of approximately D≈110 mm and a length of L=1000 mm. Two ultrasonic emitters with a frequency of 40 kHz and a nominal power of 50 W each were integrated into the section and connected to a common 100 W generator. The emitters were oriented to create a longitudinal standing wave inside the section. The scheme of exhaust gas flow in bench was shown in Figure 5.

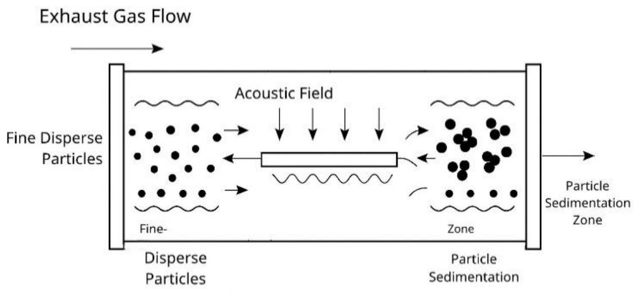


Fig. 5 – Flow ultrasonic muffler stand

Experimental studies were carried out on a Mercedes-Benz ML 2.7 CDI diesel vehicle. All measurements were performed using a certified BOSCH FSA 740 diagnostic system, which includes the BEA 050 gas analyzer for determining O_2, CO_2, HC, and CO concentrations, and the BEA 070 opacity meter for measuring the optical opacity (smoke level) of exhaust gases. The investigations were conducted at three characteristic engine operating modes: idle (750 rpm), low speed (1000 rpm), and medium speed (1400 rpm). For each mode, two measurements were taken: a control measurement (without ultrasound) and a measurement with ultrasonic exposure (with the ultrasonic system activated). The duration of each measurement, including exposure, was 60 seconds.

Measurements of optical opacity showed a significant reduction in smoke level when ultrasound was applied. The maximum effect (a 21.1% reduction in smoke opacity) was observed at medium and low engine speeds. This can be explained by the fact that at lower flow velocities, the particle residence time within the active zone (L = 1 m) is sufficient for effective coagulation (through hydrodynamic and orthokinetic mechanisms) and subsequent gravitational sedimentation onto the bottom of the section. At higher engine speeds, the residence time decreases, resulting in a reduction in deposition efficiency.

A slight but consistent increase in the relative oxygen fraction was also observed in all modes (from 17.34% to 17.36% at 750 rpm). This is attributed to the removal of some of the solid phase (soot) and unburned hydrocarbons from the flow, which shifts the composition of the gas mixture toward a higher relative concentration of O_2. The CO_2 concentration remained practically unchanged.

The influence of ultrasound on hydrocarbons (HC) and carbon monoxide (CO) was found to be strongly dependent on the engine operating mode. A reduction in their concentrations was recorded at idle.

Overall, the experimental investigation confirmed the hypothesis regarding the effectiveness of ultrasonic coagulation for purifying diesel exhaust gases.

First, ultrasonic exposure significantly reduces exhaust smoke opacity (up to 21%), especially at low and medium engine speeds. Second, purification efficiency for toxic gas components (HC and CO) is highest at low speeds, where the particle residence time in the treatment zone is sufficient for their coagulation and sedimentation.

Third, at high engine speeds, the efficiency of the method is limited by the geometry of the experimental section (length L = 1 m), which results in insufficient time for deposition of enlarged particles.

The results are in good agreement with the previously obtained theoretical findings. To further improve the efficiency of the technology, it is necessary to optimize the geometry and length of the reaction chamber, as well as the parameters of the ultrasonic field (power, frequency), taking into account the turbulent nature of the flow.

However, the process of gas purification by ultrasound in a muffler depends on a large number of factors. In our recent study [27], similarity theory was applied to describe the multifactor coagulation process. According to this method, the following key physical parameters governing the process were identified:

- engine operating parameters: engine speed (n), combustion chamber volume (Q);
- ultrasonic parameters: ultrasound frequency (*f*);
- geometric parameters: muffler diameter and length (d, L);
- physical properties of the medium: gas density (ρ), gas viscosity (μ), gas and soot masses (m_g, m_s);
- performance indicators: smoke opacity before (D_1) and after (D_2) ultrasonic treatment.

Based on these parameters, a functional equation was formulated linking the output variable (smoke opacity D_2) with the other parameters. Application of the Buckingham π-theorem made it possible to reduce the large set of variables to four main dimensionless similarity criteria:

- structural-operational criterion (k_1):

$$k_1 = \frac{\pi f L d^2}{30\omega Q}, \tag{29}$$

This composite parameter links the geometry of the muffler (L, d) with the operating parameters of the system: ultrasonic frequency (*f*), angular engine speed (ω=πn/30), and engine displacement (Q). It characterizes the conditions under which the gas is treated inside the muffler chamber.

- hydrodynamic criterion (k_2):

$$k_2 = Re = \frac{d\vartheta\rho}{\mu}, \tag{30}$$

The Reynolds number – a classical criterion describing the flow regime (laminar or turbulent) and determining the nature of viscous friction forces.

- coagulation criterion (k_3):

$$k_3 = \frac{m_c}{m_g}, \tag{31}$$

which represents the ratio of the mass of deposited soot to the mass of the gas that has passed through the system, directly characterizing the efficiency of particle deposition.

- optimality criterion (k_4):

$$k_4 = \frac{D_2}{D_1}. \tag{32}$$

The ratio of smoke opacity after and before ultrasonic treatment serves as the optimality criterion of the ultrasonic muffler: the lower the value of k_4, the higher the purification efficiency.

This composite parameter links the geometry of the muffler (L, d) with the operating parameters of the system: ultrasonic frequency (*f*), angular engine speed (ω=πn/30), and engine displacement (Q). It characterizes the conditions under which the gas is treated inside the muffler chamber.

The obtained criteria make it possible to determine that maximum process efficiency (minimum k_4) is achieved at a certain optimal ratio between the parameters included in the criteria, in particular, when the ultrasonic frequency *f* is matched to the angular engine speed *ω*.

To verify the results, experimental studies were carried out on a full-scale ultrasonic muffler test bench (Figure 3). The muffler was equipped with a set of ultrasonic emitters operating at frequencies of 25, 28, and 40 kHz. Exhaust-gas smoke opacity and the mass of deposited particles were measured at engine speeds of 750, 950, and 1250 rpm.

The experiments demonstrated that activation of the ultrasonic field consistently reduced smoke opacity by 15–20% compared with control measurements. Under optimal conditions, the maximum reduction reached 35%. In addition, it was found that the frequency of 40 kHz was the most effective for coagulating soot particles. At this frequency, the minimum value of the optimality criterion was achieved, $k_4=D_2/D_1\approx0.8–0.85$.

The theoretical hypothesis regarding the presence of an optimal ratio between ultrasonic frequency and shaft rotational speed was also experimentally confirmed. Minimum smoke opacity was observed at *f*/ω≈402.01. This indicates that each engine speed corresponds to its own optimal ultrasonic frequency. Additionally, gravimetric analysis showed that the mass of deposited soot nearly doubled when ultrasound was applied, directly indicating intensification of coagulation and sedimentation processes. It was also determined that the optimal deposition zone length is 0.4 m.

Thus, the practical validity of the proposed approach has been fully confirmed, opening promising prospects for further development and implementation of ultrasonic exhaust-gas purification systems.

2. Results and discussion

Despite significant progress in coagulation theory and the development of ultrasonic technologies, existing models and experimental methods have several limitations that significantly hinder their direct application to automotive exhaust systems (Figure 6).

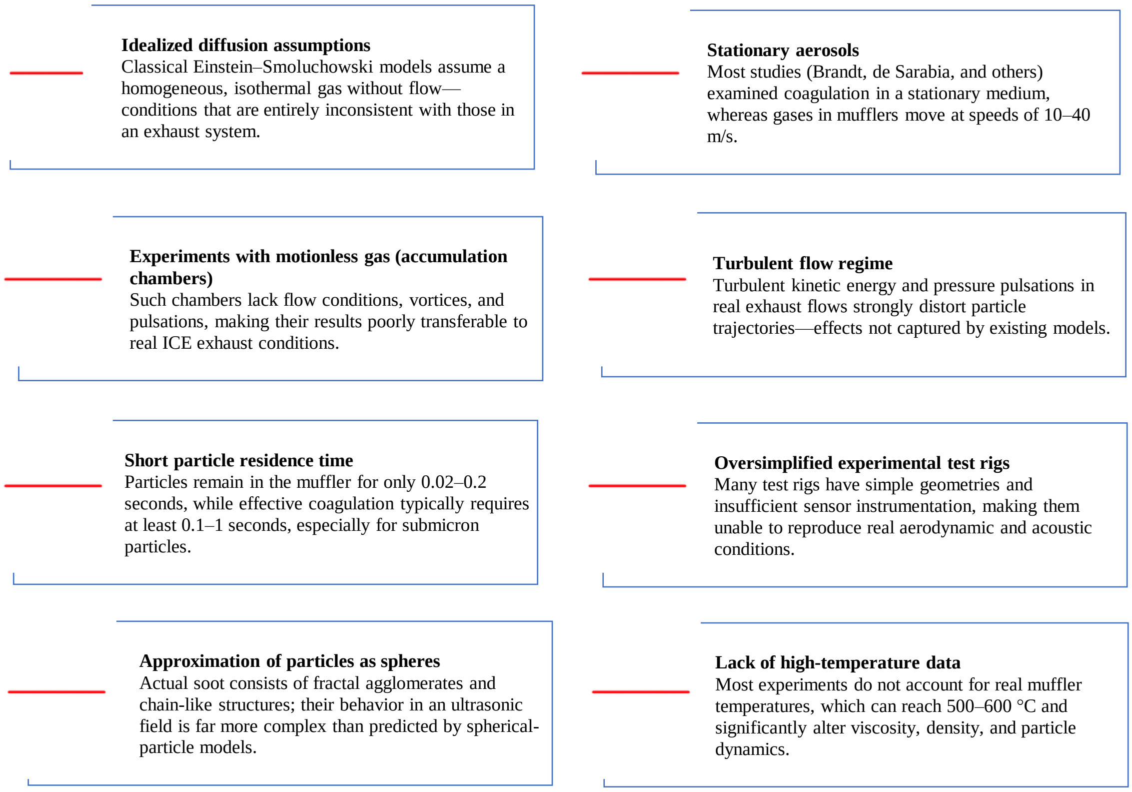


Fig. 6 – Limitations of existing research

First of all, the classical Einstein–Smoluchowski models were developed for idealized conditions: a stationary, isothermal, homogeneous medium without directed gas flow or pressure pulsations. In a real muffler, the temperature ranges from 80 to 600 °C, the flow is high-velocity, pulsating, and turbulent, and the composition of the gas mixture is continuously changing. Under such conditions, classical diffusion coagulation does not reflect the actual mechanisms of particle motion and collision.

Existing acoustic coagulation models also have significant limitations. Numerous studies by Brandt–Freundt–Hiedemann, de Sarabia, Volk Jr. & Moroz were carried out in stationary aerosols and did not account for particle velocity, turbulent diffusion, velocity gradients, or the intermittency of acoustic fields characteristic of automotive mufflers. As a result, it becomes impossible to accurately describe the combined effects of ultrasound, flow velocity, and pressure pulsations.

Another limitation is the "batch-mode" experiments using accumulation chambers, common in early research. In such setups, the gas fills a closed volume and is exposed to ultrasound for a fixed period. However, the absence of flow conditions, vortex structures, and dynamic loads means that the results of these experiments cannot be scaled to real exhaust systems.

A major limitation remains the insufficient treatment of turbulent flow regimes. Diesel and gasoline engines generate complex vortex structures, multiple pulsations, and high turbulent kinetic energy, while most models assume laminar or weakly turbulent flow. Even refined models incorporating turbulent viscosity provide only qualitative descriptions and require adaptation for different vehicle types and engine operating modes.

Additional difficulties arise from the formation of a stable acoustic zone in a flow-through muffler. Sound interference, variable flow velocity, and reflections from walls, perforated inserts, and baffles lead to instability of standing waves, complicating the creation of stable node and antinode zones necessary for effective acoustic aggregation.

A significant limitation is the short residence time of particles in the muffler. At real exhaust-gas velocities, particles pass through the reaction zone in 0.02–0.2 s, whereas ultrasonic coagulation requires 0.1–1.0 s for the formation of stable agglomerates. At high engine speeds, this time decreases even further, reducing the method's effectiveness.

The lack of data on particle behavior at high temperatures also constrains technological development. Most experiments have been conducted under ambient conditions, whereas real exhaust temperatures reach 500–600 °C, causing drastic changes in viscosity, gas density, and particle properties—including their fractal structure and reactivity.

Experimental test rigs used in modern research often do not reproduce the structural complexity of real exhaust systems. Limited length, simplified geometry, and insufficient sensor instrumentation hinder accurate assessment of processes under real operating conditions.

Finally, most mathematical models treat soot particles as spherical objects of uniform diameter, whereas real soot consists of polydisperse fractal agglomerates. This leads to substantial discrepancies between modeled and actual mechanisms of coagulation and sedimentation.

To enhance the efficiency of ultrasonic coagulation in real exhaust systems and to develop practical prototypes of ultrasonic mufflers, a comprehensive set of scientific and engineering directions must be pursued.

An important direction involves optimizing the geometry of the ultrasonic muffler. It is necessary to design flow-slowing zones, expanded reaction chambers, internal baffles, and recirculation sections that increase particle residence time and create conditions for the formation of stable acoustic structures (Figure 7).

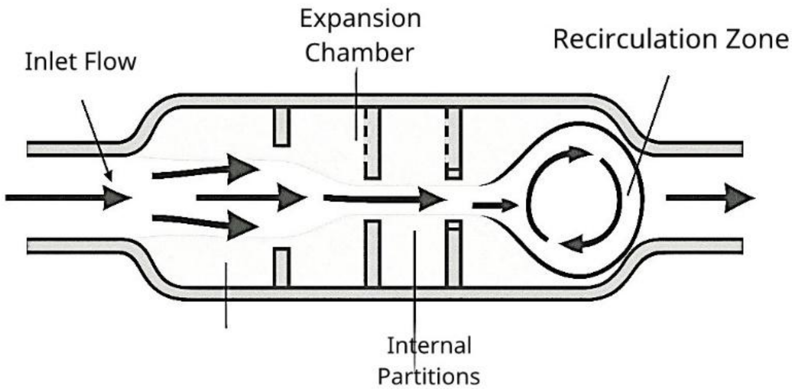


Fig. 7 – Optimization of Ultrasonic Muffler Geometry

Engineering control of the acoustic field is of particular importance. Research is required on the formation of standing waves in turbulent flow, the development of non-uniform (vortical and focused) ultrasonic fields, as well as the creation of resonant chambers and adaptive systems that automatically adjust the ultrasonic frequency to engine speed. Especially promising is the identified pattern of the optimal f/ωf/\omegaf/ω ratio, which enables synchronization of acoustic exposure with the operating mode of the internal combustion engine.

To increase efficiency, multi-frequency ultrasonic systems should be investigated. The polydisperse structure of soot requires the use of multiple frequencies that promote coagulation of both large and submicron particles. Promising approaches include frequency-modulation modes and combinations of low and high frequencies, which enhance orthokinetic and hydrodynamic coagulation mechanisms.

Significant prospects are offered by the development of combined purification systems in which ultrasound operates together with infrared radiation, corona discharge, vortex structures, or catalytic neutralization (Table 1).

Such combined systems can significantly improve the purification of fine particulate matter and toxic components.

A promising direction is the development of control algorithms for ultrasonic emitters, including adaptive power regulation, frequency tuning, and automatic adjustment of operating modes depending on engine load, temperature, and exhaust density.

There is also a need to develop simplified engineering models, nomograms, and diagrams that will enable designers to quickly assess the influence of muffler geometry, ultrasonic frequency, engine speed, and pressure on deposition efficiency.

The final stage of research should involve the creation of an industrial prototype of an ultrasonic muffler, along with the development of design documentation, recommendations for integration into existing vehicles, and modular solutions suitable for different types of transport equipment.

Table 1. Combined Ultrasonic Exhaust-Gas Purification Systems

№	Combination	Primary Mechanism of Action	Key Effects	Expected Outcome
1	Ultrasound + Vortex Flows [28]	Flow swirling creates zones of recirculation and flow deceleration	• Increased particle residence time; • Enhanced orthokinetic coagulation; • Higher collision frequency.	Improved particle deposition efficiency
2	Ultrasound + Infrared Radiation [29]	Thermal activation and partial oxidation of particles	• Breakdown of organic compounds (HC); • Reduced fractality of agglomerates; • Improved settling of enlarged particles.	More complete purification of the mixed (gas + solid particles) phase [30]
3	Ultrasound + Corona Discharge [31]	Charging of soot particles and electrostatic aggregation	• Electrostatic attraction between agglomerates [32] • Combined coagulation and deposition • Reduction of PM concentration [33]	Accelerated agglomeration and effective deposition of submicron particles
4	Ultrasound + Catalytic Neutralization	Vibrational impact and pre-catalyst particle enlargement [34]	• Reduced catalyst clogging • Increased active surface area • Removal of carbon deposits	Improved catalyst performance and reduced CO, HC, and NO_x[35]

Conclusion

The analysis of theoretical and experimental studies in the field of ultrasonic coagulation of aerosol and soot particles has demonstrated that, over recent decades, a substantial scientific foundation has been established. This foundation encompasses both classical diffusion coagulation (Einstein–Smoluchowski) and acoustic aggregation in stationary aerosols and flow-through systems. It has also been shown that the direct application of these models to the exhaust systems of internal combustion engines is limited due to significant discrepancies between real operating conditions and the idealized assumptions of classical theories. High temperature, pulsating turbulent flow, variable chemical composition, and the restricted residence time of particles in the treatment zone necessitate the expansion and modification of existing approaches.

A synthesis of the findings from Brandt–Freundt–Hiedemann, de Sarabia, Volk Jr & Moroz, BF Ng, and others, as well as recent research by V.N. Khmelev and co-authors, has confirmed the fundamental effectiveness of ultrasound as a tool for intensifying particle coagulation and deposition. It has been demonstrated that, with optimal selection of frequency, amplitude, and acoustic field structure, it is possible to achieve a multiple increase in characteristic particle size and substantially enhance gas purification efficiency. However, most of these studies were conducted in stationary aerosols or simplified channels and chambers, which limits their applicability to real engine exhaust systems.

The works by Kadyrov A.S., Pak I.A., Sarsembekov B., Sinelnikov K.A., and Kukesheva A.B. demonstrated the transition from batch-type chambers to full-scale flow-through ultrasonic mufflers and made it possible to link microscopic mechanisms of particle motion and coagulation with macroscopic parameters of the exhaust system. Several dimensionless criteria were introduced and justified, accounting for the influence of muffler geometry, engine operating mode, gas medium properties, ultrasonic intensity, and flow turbulence. Experimental data showed a reduction in smoke opacity by 15–35%, an almost two-fold increase in the mass of deposited soot, and the highest efficiency at a frequency of 40 kHz with optimization of the f/ω ratio in accordance with engine speed. These results confirm the practical feasibility of implementing ultrasonic mufflers in exhaust gas purification systems.

At the same time, a number of key limitations were identified in existing models and experimental methodologies: idealized assumptions of diffusion coagulation, incomplete representation of turbulent flow and pressure pulsations, simplified geometry of experimental setups, insufficient residence time of particles in the treatment zone, and the simplified representation of soot particles as monodisperse spheres. These limitations define the boundaries of applicability for existing solutions and highlight areas that require further investigation.

Based on the conducted review, a comprehensive set of directions for future research was formulated: optimization of ultrasonic muffler geometry (flow deceleration zones, expanded chambers, recirculation regions), development of methods for controlling the acoustic field in turbulent flow, investigation of mult frequency regimes for polydisperse soot, creation of combined systems (ultrasound + vortical flow, infrared irradiation, corona discharge, catalytic neutralization), as well as the development of simplified engineering models and adaptive control algorithms for ultrasonic emitters. The implementation of these directions will enable the transition from laboratory prototypes to industrial-grade ultrasonic mufflers capable of ensuring stable reduction of smoke opacity and exhaust toxicity, thereby improving the environmental performance of motor vehicles.

Thus, the study forms a comprehensive scientific and methodological basis for the further development and refinement of ultrasonic exhaust gas purification systems and serves as a starting point for creating efficient, practically implementable designs of next-generation ultrasonic mufflers.

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Information of the authors

Kadyrov Adil, d.t.s., research professor, Abylkas Saginov Karaganda Technical University
e-mail: adil.suratovich@mail.ru

Sakhapov Rustem, d.t.s., professor, Kazan (Volga region) Federal University
e-mail: rustem@sakhapov.ru

Kukesheva Aliya, PhD, assistant professor, Abylkas Saginov Karaganda Technical University
e-mail: aliya.kukesheva@bk.ru