ANNOTATION
of the dissertation for the degree of Doctor of Philosophy (PhD)
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Design development and research of the modular ultrasonic muffler of a diesel engine

Relevance of the dissertation research. The dissertation research was carried out within the framework of the implementation of the State policy of the Republic of Kazakhstan in the field of climate change and sustainable development, as outlined in the Strategy for Achieving Carbon Neutrality of the Republic of Kazakhstan by 2060 (approved by the Decree of the President of the Republic of Kazakhstan No. 121 dated February 2, 2023 "On approval of the Strategy for Achieving Carbon Neutrality of the Republic of Kazakhstan by 2060"). The dissertation research was also carried out within the framework of the grant project "Development of methods for calculating operation modes, device designs, and materials for exhaust gas cleaning using ultrasonic and laser emission" (This research has been/was/is funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP26197113), Contract No. 309/25-27 dated September 29, 2025).

The operation of diesel engines used in road construction, mining, and municipal equipment is accompanied by significant emissions of harmful substances, including particulate matter (PM), nitrogen oxides (NO_x), carbon monoxide (CO), and hydrocarbons (HC). Despite the introduction of modern fuel systems and catalytic converters, the problem of air pollution remains relevant, especially for specialized machinery operating under harsh conditions, at low and variable loads, and outside well-developed urban infrastructure.

According to national and international climate reviews, the transport sector of the Republic of Kazakhstan accounts for approximately 8-11% of total greenhouse gas emissions, with the dominant share attributed to road transport powered by internal combustion engines. In 2023, CO_2 emissions from the transport sector amounted to about 24 million tons of CO_2 equivalent, indicating a significant contribution from diesel-powered equipment, including freight, road construction, and municipal transport. In large cities and industrial agglomerations, the share of mobile sources of pollution exceeds 50%, and during periods of high traffic load, it reaches 70-80%.

Traditional diesel exhaust gas aftertreatment systems - diesel particulate filters (DPF), selective catalytic reduction (SCR), and exhaust gas recirculation (EGR) - are characterized by high cost, sensitivity to fuel quality, maintenance complexity, and reduced efficiency at low exhaust temperatures, which limits their application

in road construction and municipal machinery. In this regard, physical methods of exhaust gas purification are of particular scientific and practical interest.

The analysis has shown that among physical methods, ultrasonic and laser technologies have the greatest potential, as they are distinguished by the absence of reagents and filtering elements, compactness, and the possibility of flexible adjustment of operating parameters. However, the application of laser systems in the exhaust environment is associated with significant engineering and operational limitations, including high energy consumption, degradation of optical elements, and the complexity of ensuring safety and reliability. As a result, at this stage, the ultrasonic method of exhaust gas purification is the most rational, combining efficiency, structural simplicity, and operational reliability, whereas the idea of the combined use of ultrasound and laser is promising and requires further research.

Existing studies and developments in the field of ultrasonic воздействие on exhaust gases show that ultrasonic systems are predominantly implemented in horizontal muffler configurations, which limits the efficiency of coagulated particle deposition, leads to non-uniform acoustic fields, and increases the risk of clogging in the flow path. An analysis of the operating conditions of tractors, road construction, and specialized machinery shows that vertically oriented exhaust systems are more preferable for this class of equipment. The alignment of the exhaust flow direction with gravity ensures more efficient deposition of enlarged particles, while the uniform distribution of ultrasonic emitters along the height of the корпус enables multi-stage acoustic воздействие and increases the capture efficiency of $PM_{2.5}$ and PM_{10} fractions.

Despite the obvious advantages of vertical ultrasonic mufflers, there are currently no studies devoted to the development of their design, the substantiation of the effects of ultrasonic воздействия, and the experimental evaluation of exhaust gas purification efficiency. In this regard, the development of the design and the investigation of the operation of a vertical modular ultrasonic muffler is a relevant scientific and technical task aimed at reducing harmful emissions from transport and special-purpose machinery.

Research hypothesis. The hypothesis of the study is the assumption that the efficiency of diesel engine exhaust gas purification can be improved through the use of a vertically oriented modular ultrasonic muffler with a rational selection of power and spatial arrangement of ultrasonic emitters.

The aim of the dissertation research is to develop the design of a vertical modular ultrasonic muffler and to substantiate its operation in order to improve the efficiency of smoke reduction and the deposition of fine particulate matter in the exhaust gases of diesel engines used in road construction and specialized machinery.

To achieve the stated goal, the following tasks were accomplished in the dissertation:

- an analysis of diesel engine designs and exhaust systems of motor vehicles and road construction machinery was carried out;
- an analysis of physical methods for exhaust gas purification was conducted;
- the physics of ultrasonic воздействия on a gas medium was studied;

- the main parameters of ultrasonic воздействие influencing the efficiency of particle coagulation were determined;

- a mathematical model of particle motion and agglomeration in a vertical ultrasonic muffler was developed;

- using the methods of similarity theory and dimensional analysis, similarity criteria describing the design and enabling the determination of effective operating conditions of the modular ultrasonic muffler were obtained;

- an experimental modular ultrasonic test bench with staged activation of emitters was constructed;

- experimental studies were conducted to determine the influence of the number, power, and combination of ultrasonic emitters on smoke opacity, exhaust gas composition, and the mass of deposited particles;

- experimental data were processed and the obtained results were analyzed;

- a feasibility study for the implementation of an ultrasonic muffler in road construction machinery was carried out.

Object of research. The object of the study is the exhaust gas purification system of a diesel engine used in specialized machinery.

Subject of research. The subject of the study is the processes of coagulation and deposition of solid particles in exhaust gases under the influence of ultrasonic vibrations in a modular muffler.

Research methods. The dissertation employs methods of theoretical analysis, mathematical modeling, experimental design and data processing, as well as methods of similarity theory and dimensional analysis.

The scientific novelty of the dissertation is as follows:

- the possibility of increasing the efficiency of diesel engine exhaust gas purification through the use of a vertically oriented modular ultrasonic muffler with a rational selection of power and spatial arrangement of ultrasonic emitters has been confirmed;

- within the framework of mathematical modeling, a system of equations was developed linking particle mass growth with their motion dynamics in a vertical ultrasonic field;

- similarity criteria describing the design and operation of the modular ultrasonic muffler were established;

- the effectiveness of modular activation of ultrasonic emitters for intensifying coagulation processes was confirmed;

- a regression relationship was experimentally obtained describing the variation of gas smoke opacity as a function of engine speed, ultrasonic emitter power, and the distance between emitters.

Scientific provisions submitted for defense

- the vertical configuration of a modular ultrasonic muffler is structurally and physically justified, as it provides more favorable conditions for particle agglomeration and gravitational settling compared to horizontal designs;

- the efficiency of ultrasonic воздействие on exhaust gas is determined by a set of ultrasonic parameters, including the power and spatial distribution of the acoustic

field, as well as the number and combination of simultaneously operating ultrasonic emitters;

- the developed mathematical model of particle motion and coagulation in a vertical ultrasonic muffler adequately describes the growth of particle mass in relation to their motion dynamics in a vertical ultrasonic field, which is also experimentally confirmed by an increase in the mass of deposited particles;

- the developed system of similarity criteria makes it possible to determine the design and operating parameters of a modular ultrasonic muffler;

- the modular-combined activation of ultrasonic emitters allows comparison and optimization of the ultrasonic воздействие process on exhaust gas, ensuring improved coagulation efficiency;

- the application of a vertical modular ultrasonic muffler in road construction machinery provides not only environmental but also economic benefits, expressed in reduced fees for pollutant emissions and the prevention of socio-economic damage caused by air pollution.

The author defends:

- the design of a vertical-type modular ultrasonic muffler for a diesel engine, intended for exhaust gas purification through coagulation and deposition of solid particles;

- a mathematical model of particle motion and agglomeration in a vertical ultrasonic muffler;

- a methodology for calculating similarity criteria, describing the design and operation of a modular ultrasonic muffler;

- the results of experimental studies confirming the influence of the number, power, and combinations of ultrasonic emitters on smoke opacity, exhaust gas composition, and the mass of deposited particles;

- the results of a techno-economic justification for implementing the ultrasonic muffler in diesel road-construction machinery, confirming the feasibility of its practical application.

The practical significance lies in the possibility of applying the research results in the design of emission purification systems, the preparation of technical documentation for them, as well as in substantiating measures aimed at reducing harmful emissions from vehicles and special-purpose machinery. The proposed solutions make it possible to extend the system’s maintenance interval and reduce operating costs.

The reliability of the conclusions obtained in the dissertation is confirmed by the clear formulation of the research tasks, the use of well-founded and adequate research methods, as well as the consistency of the experimental results with the analytical calculations.

The key provisions of the dissertation are reflected in published scientific articles and conference materials. A certificate of state registration of copyright on the objects of intellectual property has also been obtained.

The structure of the dissertation is logically organized, with sections interconnected and presenting the research in a single methodological line. All tasks set by the author have been fully accomplished, and the research objective has been

achieved. The scientific novelty and practical significance of the work fully correspond to the topic, aim, and objectives of the dissertation.

The personal contribution of the dissertation author is as follows. The author independently designed and fabricated an experimental ultrasonic muffler test bench, providing the capability to conduct experimental studies. The researcher developed a methodology for carrying out experimental investigations, conducted a series of experiments under various combinations of ultrasonic emitter operation, and ensured the measurement and recording of key parameters characterizing the degree of exhaust gas purification.

The candidate processed experimental data, which revealed the effectiveness of ultrasonic treatment on smoke, gas composition, and the mass of settled particles. He also developed a mathematical model describing the movement of gas particles in a vertical ultrasonic muffler.

Furthermore, the author performed a techno-economic analysis of the proposed solution, substantiated the practical feasibility of its implementation, and formulated recommendations regarding the design and operating conditions of the device.

Publication and validation of the work. The main provisions of the dissertation have been published in two articles included in the Scopus and Web of Science databases, in two articles recommended by the Committee for Quality Assurance in Science and Higher Education of the Ministry of Science and Higher Education of the Republic of Kazakhstan, in two certificates of state registration of copyright rights, and in three abstracts of international scientific and practical conferences.

In the article “Optimization of Vertical Ultrasonic Attenuator Parameters for Reducing Exhaust Gas Smoke of Compression - Ignition Engines: Efficient Selection of Emitter Power, Number, and Spacing,” published in the journal Soft Acoustic Metamaterials: Advances in Geometry, Mechanism, and Responsiveness, https://doi.org/10.3390/app15147870, the author’s contribution included: Conceptualization of the research, methodology development, software implementation, validation, formal analysis, conducting experiments, resource provision, data curation, writing the original draft of the manuscript, reviewing and editing the text, visualization of results, project administration, as well as securing funding..

In the article “Theoretical and Experimental Study of Diesel Engine Exhaust Gas Purification in a Vertical Ultrasonic Muffler Stand,” published in the journal Komunikacie communications, Scientific Letters of the University of Žilina (https://doi.org/10.26552/com.C.2026.009), the author’s contribution included the development of the mathematical model, conducting experimental studies, data processing, preparation of the article text, editorial refinement of the material, and visualization of the obtained results.

In the article “Comparison of the Efficiency of Cleaning the Exhaust Gas of Internal Combustion Engines of Cars with Ultrasonic Emitters,” published in Trudy Universiteta, No. 3 (92), 2023, section “Construction. Transport,” DOI: 10.52209/1609-1825_2023_3_284, the author’s contribution included participation in the development of the methodology and experimental plan, preparation of the experimental setup, selection of operating modes for the ultrasonic emitters, as well

as conducting and analyzing the results of experimental studies aimed at evaluating the efficiency of exhaust gas purification of internal combustion engines.

The article “Development and Study of the Operation of a Modular Ultrasonic Muffler for Diesel Engines,” published in the journal Trudy Universiteta No. 4 (101), 2025, section “Construction. Transport,” DOI: 10.52209/2706-977X_2025_2_102.

The author’s contribution consists of the design and study of the operating principle of a modular ultrasonic muffler intended to reduce the content of harmful impurities in the exhaust gases of diesel engines. During the experiments, measurements were taken of changes in oxygen content and gas smoke indicators, which showed that ultrasonic exposure contributes to an increase in oxygen concentration and a decrease in smoke density. The obtained results allowed for a substantiated conclusion about the effectiveness of modular ultrasonic mufflers in reducing harmful emissions from diesel engines.

Structure and volume of the dissertation. The dissertation is presented in 171 pages of typed text, consisting of a list of abbreviations, an introduction, four sections, and a conclusion. It includes 45 figures, 28 tables, a reference list of 110 sources, and five appendices.

Summary of the dissertation.

All sections of the dissertation are presented in a methodological sequence and are logically interconnected. All tasks set by the doctoral candidate have been accomplished, and the research objective has been achieved. The practical significance and scientific novelty correspond to the stated aim, objectives, and title of the dissertation.

Summary

The first chapter substantiates the influence of the design, operating mode, and technical condition of a diesel engine on fuel combustion processes and the formation of harmful emissions. It has been established that diesel engine exhaust gases represent a complex toxic mixture, requiring effective purification methods to ensure environmental safety and compliance with modern regulatory requirements. Existing emission reduction systems have been analyzed, revealing their high cost and maintenance complexity, which justifies the feasibility of using physical methods of purification.

Physical methods of affecting exhaust gases are considered, among which ultrasonic and laser cleaning methods are of greatest interest. It has been determined that laser radiation has high potential due to photothermal and photochemical effects on the gas-aerosol medium; however, its application in exhaust systems is limited by high energy consumption, degradation of optical elements, and difficulties in ensuring reliability and safety.

As a result, the promise of the ultrasonic method has been demonstrated, characterized by high efficiency, simple design, and low operating costs. The use of vertical mufflers with integrated ultrasonic emitters is justified as the most effective solution for tractors and specialized machinery. Based on the conducted analysis, the aim and objectives of the research have been formulated.

In the second chapter, it is established that ultrasonic exposure to exhaust gases exerts a combined mechanical and physical effect, enhancing the coagulation of solid particles and reducing the toxicity of the gas medium. It is shown that the efficiency of ultrasonic purification is determined by a set of interrelated parameters of ultrasonic exposure and the conditions of the gas flow, allowing the process to be considered controllable. A hierarchy of key parameters is formed, and a scheme of their mutual influence is proposed, providing a basis for adaptive control of the operating modes of ultrasonic purification systems. A vertical mathematical model of particle motion in exhaust gases is developed, providing a more accurate description of coagulation and sedimentation processes. In addition, a methodology for calculating similarity criteria is developed, describing the design and conditions for the effective operation of the proposed modular ultrasonic muffler.

In the third chapter, the effectiveness of ultrasonic vibrations for cleaning diesel engine exhaust gases is experimentally confirmed. It is established that the vertical design of the ultrasonic muffler with a multi-level arrangement of emitters enhances the coagulation and sedimentation of soot particles, resulting in a 30–35% reduction in exhaust smoke density and stabilization of the gas composition. Rational modes of ultrasonic exposure are determined, under which the maximum cleaning effect is achieved. The developed regression model, with a high coefficient of determination, reliably describes the influence of the main parameters of ultrasonic exposure on smoke density and allows the determination of optimal values for given engine operating modes. The obtained results confirm the practical applicability and prospects of ultrasonic technologies for the ecological modernization of diesel engines.

In the fourth chapter, the efficiency of the ultrasonic muffler is evaluated, and a techno-economic justification for its implementation in the fleet of road-construction machinery in Kazakhstan is provided. Using the Cat 12M3 motor grader with a Caterpillar C9.3 ACERT engine as an example, it is shown that the use of the ultrasonic muffler reduces the mass of pollutant emissions, lowers smoke density and fuel consumption, and decreases environmental fees. Calculations confirmed a positive economic effect for the enterprise and a high socio-economic benefit for society, characterized by an efficiency coefficient of over 2 and a payback period of less than one year. The costs of manufacturing the ultrasonic muffler are analyzed, showing that its price is significantly lower than that of traditional particulate filters and DPF modules while providing comparable environmental performance. Technical requirements for the ultrasonic muffler for the Caterpillar C9.3 ACERT engine are formulated, ensuring reliable, safe, and energy-efficient operation under the operating conditions of specialized machinery. The structural features of the vertical ultrasonic muffler, as well as issues of installation, maintenance, and repair, are considered, confirming its practical applicability and potential for industrial implementation.

The dissertation presents new, scientifically substantiated results aimed at solving an important applied problem: the development of a vertical modular ultrasonic muffler and the justification of its operation, ensuring increased efficiency in reducing smoke and enhancing the deposition of fine particulate matter in the

exhaust gases of diesel engines used in road construction and specialized machinery. Based on the results of the research, the following conclusions were drawn:

- an analysis of diesel engine designs and operating modes was conducted, revealing that traditional exhaust gas purification systems used in road construction and mining equipment have significant operational limitations, such as high cost, dependence on temperature conditions, sensitivity to fuel and reagent quality, and the need for regeneration;

- an analysis of physical methods for exhaust gas purification showed that ultrasonic and laser methods have the greatest potential, as they do not require reagents or filtering elements. It was determined that the practical implementation of laser systems in the exhaust environment of diesel engines is associated with significant engineering and operational constraints, making the ultrasonic method the chosen baseline. The combined use of both methods is considered a promising direction for further research;

- a hypothesis was proposed and confirmed that the vertical configuration of a modular ultrasonic muffler creates the most favorable conditions for particle coagulation and deposition mechanisms compared to horizontal designs;

- the physics of ultrasonic interaction with the gas medium was investigated, establishing a hierarchy of process parameters, their interrelationships, and the possibility of controlling them under ultrasonic exposure;

- as a result of mathematical modeling, a system of equations was developed linking particle mass growth with their motion dynamics in a vertical ultrasonic field, which quantitatively describes coagulation and particle deposition processes;

- based on the application of similarity theory and dimensional analysis, a system of similarity criteria was obtained, characterizing the design and operating modes of the vertical modular ultrasonic muffler, and a methodology was developed for calculating its structural and operational parameters;

- an experimental vertical modular ultrasonic test bench was developed with adjustable numbers and configurations of emitters;

- it was experimentally demonstrated that the efficiency of ultrasonic impact on exhaust gas depends on the ultrasonic power and emitter combination;

- regression relationships were obtained between engine speed, ultrasonic emitter power, emitter spacing, and exhaust gas smoke opacity, allowing prediction of the ultrasonic treatment process under various engine operating conditions;

- techno-economic analysis showed that implementing the ultrasonic muffler reduces environmental fees and operating costs, providing both economic and social benefits;

- the combination of theoretical, modeling, experimental, and economic results confirms the scientific validity of the developed vertical modular ultrasonic muffler and its suitability for practical application in transport machinery.