ABSTRACT

of the dissertation for the degree of Doctor of Philosophy (PhD)
in the research area 8D071 – "Engineering",
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DEVELOPMENT OF A METHODOLOGY FOR CALCULATING THE DESIGN AND OPERATING MODE OF THE EXHAUST GAS CLEANING SYSTEM FOR INTERNAL COMBUSTION ENGINES

Relevance. The dissertation was completed in accordance with the State program of infrastructural development of the Republic of Kazakhstan «Nurly Zhol» for 2020-2025.

Vehicles powered by internal combustion engines (ICE), despite compliance with the established Euro standards, continue to emit significant amounts of harmful emissions such as nitrogen oxides (NO_x), hydrocarbons (HC) and carbon dioxide (CO_2). On average, 40-75% pollutants entering the atmosphere come from motor vehicles. These emissions lead to additional environmental pollution, which leads to the formation of smog, acid rain and greenhouse gases. Such changes, in turn, affect climate change, lead to the destruction of the atmospheric layer and contribute to global warming. They also negatively affect human health, leading to the development of severe and chronic diseases of the cardiovascular, pulmonary and other systems.

The problem of air pollution by exhaust gases remains relevant not only worldwide, but also in Kazakhstan, which ranks 40th in the IQAir world ranking. The average annual concentration of particulate matter in the air exceeds the norm by 3-5 times, especially in cities such as Astana, Aktobe, Ust-Kamenogorsk, Karaganda, Balkhash and Zhezkazgan. Karaganda ranks 23rd among the cities of the world and 1st among the cities of Kazakhstan in terms of air pollution, exceeding the norm by more than 10 times.

Electric vehicles and hydrogen engines are used to reduce atmospheric pollution. Catalytic converters are placed in the mufflers of cars. The efficiency of cleaning with catalysts is high, but they are expensive and have a short service life. It is also promising to create mufflers based on the physical principles of the effect of ultrasound and electric pulse on the exhaust gas in the muffler of the car.

Currently, in order to reduce the level of harmful emissions and in order to improve the environmental parameters of the car, the direction of improving the efficiency and modernization of the exhaust gas purification system of ICE is actively developing through the use of electric pulse and ultrasonic cleaning methods in the muffler of the car. Despite the different ways of influencing the gas, these methods have an equivalent effect on smaller gas particles (due to the intensification of ionization and coagulation processes) and are able to increase

their degree of purification. In addition, the equipment of cleaning systems with electric pulse and ultrasonic mufflers does not require significant financial costs, does not increase the size of the system and does not create a large load on the engine. These mufflers can be successfully used both in the production of new cars and in the modernization of the existing fleet. The prospects and effectiveness of these methods are confirmed in a number of theoretical and experimental studies.

However, the issue of optimizing the operating mode of the proposed mufflers and choosing the main parameters of its design has not been resolved. In this regard, studies aimed at establishing of the optimal mode methods and design features are **relevant**.

The hypothesis of the study is the assumption that it is possible to achieve optimal operation of electric pulse and ultrasonic mufflers by regulating the main parameters that affect the degree of gas purification.

The purpose of the study was to obtain experimental and theoretical dependencies that allow developing a design calculation methodology and determine the optimal operating mode of the exhaust gas purification system of internal combustion engines.

The following **tasks** have been solved to achieve the purpose:

1. the designs of automobile mufflers and exhaust gas purification systems were analyzed;
2. the physical essence of electric pulse and ultrasonic effects on exhaust gas was considered;
3. the criterion of optimality of operation of electric pulse and ultrasonic mufflers was substantiated;
4. 4 the parameters describing the mode and design of electric pulse and ultrasonic mufflers were established by the methods of similarity theory;
5. the stands for experiments conducting were developed, the methodology and procedure of the study were described;
6. the optimal ranges of parameter changes (engine speed, ultrasound frequency, distance between electrodes, etc.) were established as a result of a joint analysis of theoretical dependencies and experimental data;
7. the fields of application of electric pulse and ultrasonic mufflers were established;
8. the terms of reference, calculation methodology and recommendations for the design, application and adjustment of the operating mode of electric pulse and ultrasonic mufflers were developed.

Thus, despite the fact that the dissertation examines different methods of ICE exhaust gas cleaning, its topic is united by a common structure of studies aimed at developing designs and determining the optimal operating modes of electric pulse and ultrasonic mufflers.

Methodically, the study is combined by one object of the study and the used methods.

Methods of the study. The dissertation uses the methods of similarity theory and dimensional analysis, methods of mathematical statistics, planning and processing of the experiment.

The scientific novelty of the study is as follows:

– it was confirmed that it is possible to achieve optimal operation of electric pulse and ultrasonic mufflers by regulating the main parameters that affect the degree of gas purification, in particular, changing the parameters of the distance between the electrodes and the frequency of the electric pulse for an electric pulse muffler and the parameters of the ultrasound frequency for an ultrasonic muffler;

– for the first time, the hypothesis of the existence of a close relationship between the indicators of gas smokiness and the parameters of the light-absorbing ability, transparency and illumination of gas was confirmed;

– regression dependences describing the change in the ratio of gas smokiness (which are the criterion for the optimal operation of an electric pulse muffler) from the ratio of the parameters of the frequency of the electric pulse f to the distance between the electrodes Δ and the angular rotation velocity of the crankshaft of the engine ω were experimentally obtained;

– regression dependences describing the change in the ratio of the smokiness content of gas (which are the criterion for the optimal operation of an electric pulse muffler) from the ratio of the parameters of the frequency of the electric pulse f to the angular rotation velocity of the crankshaft of the engine ω were experimentally obtained;

– similarity criteria evaluating the efficiency of operation and flow modes of the gas flow in electric pulse and ultrasonic mufflers were obtained;

– optimal parameter values describing the design and regulating modes of operation of electric pulse and ultrasonic mufflers were obtained.

Scientific provisions submitted for defense:

– the criterion for the optimality of gas purification processes for the studied mufflers is the ratio of gas smokiness before and after exposure to ultrasound or electric pulse;

– the proposed system of similarity criteria describes the mode and design of mufflers;

– the dependences between the smokiness of the exhaust gas and its transparency were established;

– the dependencies that determine the optimal range of changes in the engine speed and the distance between the electrodes for an electric pulse muffler and the optimal ranges of changes in the parameters of the engine speed and ultrasound frequency for an ultrasonic muffler.

The author defends:

1. Methods of cleaning the exhaust gases of ICE with ultrasound and an electric pulse in a car muffler;

2. Methodology for calculating similarity criteria describing the operation of electric pulse and ultrasonic mufflers;

3. The methodology for calculating the indicators of gas smokiness according to the relationship with the parameter of gas light-absorbing ability and according to experimental indicators of gas illumination;

4. The results obtained in the course of experimental studies;

5. Developed examples of methods for calculating the design and determining the optimal mode of operation of electric pulse and ultrasonic mufflers;

6. Terms of reference and recommendations for the design of a prototype of electric pulse and ultrasonic mufflers for the exhaust gas purification system of car engines.

7. The obtained optimal values of the parameters of the distance between the electrodes (Δ) and the electric pulse frequency (f) depending on the change in the angular velocity of rotation of the engine crankshaft (ω): at 79.5 rad/s (750 rpm): Δ =0.008 m, f =23.04 Hz; at ω = 130.9 rad/s (1280 rpm) Δ=0.004 m, f =20.43 Hz; at ω=471 rad/s (4500 rpm): Δ=0.0026 m, f =46.57 Hz;

8. The obtained optimal values of the ultrasound frequency (f) depending on the change in the angular velocity of rotation of the engine crankshaft: at 79.5 rad/s (750 rpm): f = 13 kHz; at ω=272.63 rad/s (2600 rpm) f =46 kHz; at ω=471 rad/s (4500 rpm): f =79 kHz;

9. Certain geometric parameters (diameter and length) of electric pulse and ultrasonic mufflers: d=0.27 m and L=0.32-0.4 m.

The object of the study was the exhaust gas purification system of the car engine (electric pulse and ultrasonic muffler designed for exhaust gas purification).

The subject of the study was the process of increasing the degree of exhaust gas purification by regulating parameters that affect the efficiency of electric pulse and ultrasonic mufflers.

The practical significance lies in the development of technical specifications for prototypes of electric pulse and ultrasonic mufflers for the exhaust gas purification system of an internal combustion engine. In particular:

– compilation of methods examples for calculating the design and determining the operating mode of electric pulse and ultrasonic mufflers;

– offer of sketches and recommendations for the design and adjustment of the operating mode of electric pulse and ultrasonic mufflers.

The results of the study were transferred to the GRADIENT PROJECT INSTITUTE LLP and introduced into the educational process of the discipline «Classification and device of transport equipment» for bachelor students of the 1st year of the educational program 6B07106 – Transport, transport equipment and technologies.

The reliability of the dissertation results is determined by the applied research methods: similarity theory and dimensional analysis, experiment planning, conducting full-size bench tests, the use of modern equipment. At the initial stage of the study, an optimality criterion was established, similarity criteria were calculated, which made it possible to evaluate the efficiency of the electric pulse and ultrasonic mufflers and determine the main parameters of the design and operating mode of the muffler. Experimental studies were also carried out,

according to the results of which it was established a relationship between the indicators of the optimality criterion and the adjustable parameters, including a change in the angular velocity of the engine crankshaft rotation. The reliability of the dissertation conclusions is ensured by the correct formulation of tasks, the use of adequate methods and the coordination of experimental results with analytical data. The main provisions of the dissertation were published in scientific articles and abstracts. A patent for a utility model and a certificate of state registration of copyright rights were also obtained.

All sections of the dissertation are carried out in a methodical sequence and are logically interconnected. All the tasks set by the dissertation have been solved, and the purpose of the research has been achieved. The practical significance and scientific novelty correspond to the set goal, objectives and title of the dissertation.

Brief summary.

The first chapter of the dissertation contains an analysis of existing technologies and designs for the engine cleaning system, alternative types of cars and gas purification methods used to reduce harmful exhaust emissions of cars. The physical essence of the exhaust gas purification process using electricity was considered, the efficiency of using corona discharge was also justified; the physical aspects of exhaust gas purification by ultrasound were analyzed, as well as the main types and theories of coagulation. In the same part of the dissertation, a justification was given for the need to develop a design and determine the operating mode of electric pulse and ultrasonic mufflers, the goals and objectives of the study were set.

In the second chapter of the dissertation, the process of gas purification using an electric pulse muffler was described, and key parameters affecting the efficiency of the corona discharge were determined. A new design of spiral electrodes has been proposed to improve the effect on the gas flow. The optimality criterion was chosen – the ratio of gas smokiness before and after the electric pulse. Dimensionless criteria describing the effectiveness of the muffler and also the method of experiments on laboratory and full-size stands were developed. The results of the experiment were analysed. The level of gas purification on the laboratory bench reached 40%. The values of control parameters (distance between electrodes and frequency of electric impulse) providing optimal operation of the laboratory bench were determined: $\Delta \approx 0.027$ and $f \approx 19$. On the full-size bench the smoke index decreased to 29%, and the gas cleaning efficiency was about 30%. They were established the optimal values of the frequency parameters and the distance between the electrodes ($\Delta \approx 0{,}006$ and $f \approx 14$), preventing the transition to a spark discharge and gas smoking reducing in a full-size stand of an electric pulse muffler.

The third chapter of the dissertation describes the process of gas purification in an ultrasonic muffler and highlights the key factors affecting the movement of gas particles and the efficiency of coagulation. In the same chapter, the optimal parameters and design characteristics of the ultrasonic muffler were determined

and experimental methods were developed. Gas smokiness decrease and purification increase with a change in the frequency of ultrasound were confirmed. The total degree of gas purification by ultrasound in the muffler stand was 20-25%. The optimal ratio of the ultrasound frequency and the angular velocity of the engine rotation (f/ω =402.01) was determined. The optimal values of the ultrasound frequency (at the maximum values of the angular velocity) were established, allowing to reduce gas smokiness to 35%. The optimal length of the ultrasonic muffler (L=0.4 m) was determined experimentally, ensuring effective deposition of gas particles.

The fourth chapter of the dissertation contains the results of experimental studies, as well as justifications and arguments regarding the expediency and applicability of electric pulse and ultrasonic mufflers on gasoline and diesel engines. Studies have shown that electric pulse mufflers are more effective for reducing the smokiness of diesel engine exhausts, while ultrasonic mufflers are promising for cleaning gases from solid particles in the exhaust of gasoline engines. Methods have been developed for calculating and determining the optimal operating mode of electric pulse and ultrasonic mufflers based on dimensionless criteria and experimental data. An assessment of the economic effect of the introduction of these mufflers was carried out to reduce the environmental damage to cars. Technical specifications were created for industrial samples of mufflers, including requirements for their design. Recommendations were developed on the design and adjustment of the operating mode of electric pulse and ultrasonic mufflers.

Personal contribution of the author of dissertation. The author personally carried out a study that includes the substantiation of the criterion of optimality of the operation of electric pulse and ultrasonic mufflers and the calculation of similarity criteria evaluating their work. The author participated in the development of experimental stands and, together with the members of the scientific group, conducted appropriate experimental studies on them. The author independently processed the results of experimental studies, performed a regression-correlation analysis of the change in the ratio of gas smokiness indicators depending on the ratio of parameters affecting the operating mode of electric pulse and ultrasonic mufflers. Together with the scientific supervisor, the author developed methods for calculating the design, determining gas smokiness and the optimal values of the parameters governing the operation of electric pulse and ultrasonic mufflers. Also, together with the scientific supervisor, the author developed a methodology for calculating the economic efficiency from the commissioning of electric pulse and ultrasonic mufflers, technical specifications, sketches and recommendations for their design.

Publication and approbation of the study results. The main provisions of the dissertation are set out in three articles published in the rating editions of the Scopus database, as well as in seven 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 one patent for a utility model

of the Republic of Kazakhstan, in one certificate of state registration of copyright rights and in three theses at international scientific and practical conferences.

The article «Establishing the parameters of the operation mode of the electric pulse automobile muffler» in the Journal «Applied Engineering Science», part of Scopus database, 3rd quartile, 47th percentile for Mechanical engineering (Available online: https://www.engineeringscience.rs/images/pdf/45196.pdf) contains the results of experimental studies and calculations of similarity criteria to assess the effectiveness of the proposed electric pulse muffler.

The article «Development of calculation methodology for optimizing the operating mode of an electric pulse unit for cleaning exhaust gases», published in the journal «KOMUNIKACIE», included in Scopus database, 3rd quartile, 38th percentile for Mechanical engineering, section «Mechanical engineering in Transport» (Available online: https://doi.org/10.26552/com.C.2024.011) describes the results of the experimental research and their analysis.

The article «Studying the process of the internal combustion engine exhaust gas purification by an electric pulse», published in the journal «KOMUNIKACIE», included in Scopus database, 3rd quartile, 38th percentile on Mechanical engineering, section «Mechanical Engineering in Transport» (Available online: https://doi.org/10.26552/com.C.2022.4.B275-B287) contains the results of experimental studies and their analysis, as well as a description of the development of a methodology for calculating parameters that optimize the operation of the stand and installations for electric pulse exhaust gas purification.

The author presented the results of preliminary studies on the developed stands of an electric pulse muffler for changing the concentration of oxygen in the gas composition in the article «Avtokoliktin paidalanylgan gazdaryn electrympulsti beitaraptandyr processin zertteuge arnalgan experimenttik kondyrgylardi azirleu», published in the journal «University Proceedings» of Abylkas Saginov Karaganda Technical University NP JSC, section «Construction. Transport». Also, together with the co-authors of the article, the author of the dissertation developed a patent for a utility model for a method of gas purification by electric pulse.

The article «Experimental determination on cleaning the exhaust gas of an automobile muffler by an electric pulse», published in the journal «Bulletin of the L. Gumilyov Eurasian National University», the series «Technical Sciences and Technologies», contains an analysis of existing gas purification methods and justification of the expediency of using an electric pulse cleaning method for car exhaust gases. In the presented article, the author also conducted a regression and correlation analysis of the change in gas transparency depending on the change in the distance between the electrodes and compared the empirical results with experimental data.

In the article «Establishment of Parameters of Electric Pulse Equipment Storage Device for Exhaust Gas Purification», published in the journal «University Proceedings» of Abylkas Saginov Karaganda Technical University NP JSC, section «Construction. Transport», the author described the physics of the process of electric pulse exhaust gas purification and developed a methodology for

experimental studies conducting. The author also participated in experimental studies conducting to obtain the dependences of the illumination of the purified gas on the time of exposure to the electric pulse, the frequency of the electric pulse and the distance between the electrodes, and analyzed the obtained results.

In the article «Study of the process of electric pulse cleaning of internal combustion engine exhaust gases», published in the scientific journal «Bulletin of KazATC», section «Transport, transport engineering», the author presented a methodology for experimental studies conducting on the developed stand of an electric pulse muffler, and also analyzed the results obtained.

The article «Development of a methodology for experimental studies to determine the optimal operating modes of an ultrasonic muffler», published in the the scientific journal «Bulletin of KazATC», section «Transport, transport engineering», contains the results of calculating the similarity criterion describing the operation of an ultrasonic muffler, as well as the development of a plan and methodology for experimental studies conducting.

In the article «Comparison of the Efficiency of Cleaning the Exhaust Gas of Internal Combustion Engines of Cars with Ultrasonic Emitters», published in the journal «University Proceedings» of Abylkas Saginov Karaganda Technical University NP JSC, section «Construction. Transport», the author described the physics of the gas purification process by ultrasound and compiled a methodology for conducting experimental studies on the developed ultrasonic muffler stand, as well as analyzed the obtained results.

The article «Establishment of the Reynolds Criterion for Ultrasonic Cleaning of Exhaust Gases of Internal Combustion Engines», published in the journal «University Proceedings» of Abylkas Saginov Karaganda Technical University NP JSC, section «Construction. Transport», demonstrates the author's calculations of the Reynolds criteria and other similarity criteria describing the operation of an ultrasonic muffler, and based on this, the development of a plan for experimental studies conducting.

The structure and scope of the dissertation. The dissertation is presented on 208 pages of typewritten text, consists of designations and abbreviations, an introduction, 4 sections and a conclusion, includes 93 figures, 54 tables, 185 sources and 9 appendices.

The dissertation presents new, scientifically based results aimed at solving an important applied problem – the development of a design calculation methodology and determining the optimal operating mode of electric pulse and ultrasonic automobile mufflers. These mufflers are designed to reduce the toxicity of exhaust gases from internal combustion engines in road transport. Conclusion based on the results of the study:

– the analysis of the design of automobile mufflers and exhaust gas purification systems, as well as existing studies on reducing the toxicity of gases using electric pulse and ultrasonic methods justified the purpose and objectives of the study;

– the physical essence of exhaust gas purification processes by electric discharge and ultrasound was described, and parameters affecting the efficiency of corona discharge and the process of ultrasonic coagulation were also established;

– the criterion of optimality of the operation of electric pulse and ultrasonic mufflers was justified, which is the ratio of gas smokiness, after and before exposure to electric pulse or ultrasound;

– using the methods of similarity theory and dimensional analysis, they were obtained the similarity criteria that describe the design and evaluate the operating mode of electric pulse and ultrasonic mufflers;

– experimental stands were developed and experimental studies were conducted;

– according to the results of experimental studies, the effectiveness of exhaust gas purification using electric pulse and ultrasonic mufflers has been confirmed. The analysis of experimental studies showed a decrease in the smoke content of the gas after exposure to ultrasound (up to 35%) and electric pulse (up to 29%);

– the results of experimental studies and analysis of theoretical dependencies have confirmed the hypothesis about the possibility of optimizing the exhaust gas purification process. This is achieved by adjusting parameters such as the distance between the electrodes and the frequency of the electric pulse for an electric pulse muffler, as well as the frequency of ultrasound and the angular velocity of rotation of the crankshaft of the engine for an ultrasonic muffler;

– according to a comparative analysis of the obtained experimental results, the fields of their application on gasoline and diesel engines of cars have been established on full-size stands of electric pulse and ultrasonic mufflers. Electric pulse mufflers are effective for reducing the smokiness of diesel engines, while ultrasonic mufflers are promising for cleaning the exhaust of gasoline engines from solid particles;

– the methods for calculating the optimal values of the parameters regulating the operation of electric pulse and ultrasonic mufflers and being the basis for their design were developed;

– the optimal values of the parameters of the distance between the electrodes (Δ) and the electric pulse frequency (f) were obtained depending on the change in the angular velocity of rotation of the engine crankshaft (ω) for an electric pulse muffler: at 79.5 rad/s (750 rpm): Δ=0.008 m, f =23.04 Hz; at ω =130.9 rad/s (1280 rpm) Δ=0.004 m, f =20.43 Hz; at ω=471 rad/s (4500 rpm): Δ=0.0026 m, f =46.57 Hz;

– the optimal values of the ultrasound frequency (f) were obtained depending on the change in the angular velocity of rotation of the engine crankshaft for the ultrasonic muffler: at 79.5 rad/s (750 rpm): f =13 kHz; at ω =272.63 rad/s (2600 rpm) f =46 kHz; at ω=471 rad/s (4500 rpm): f =79 kHz;

– the optimal geometric parameters of the design of the electric pulse and ultrasonic mufflers were determined: d=0.27 m and L=0.32 m for the electric pulse muffler; d=0.27 m and L=0.4 m for the ultrasonic muffler;

– the calculations of the economic efficiency of the introduction of electric pulse and ultrasonic mufflers were carried out. The economic effect of the introduction of electric pulse and ultrasonic mufflers for 151 000 cars is 290 billion tenge and 116 billion tenge, respectively;

– the technical specifications with drawings and design recommendations were developed to create experimental designs of electric pulse and ultrasonic car mufflers.