Theoretical study on the effect of fuel injection pressure on combustion, performance, and emissions in a marine diesel engine

Estudio teórico sobre el efecto de la presión de inyección de combustible en la combustión, el rendimiento y las emisiones de un motor diesel marino

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ABSTRACT

Introduction. Over time, demands on internal combustion engines are increasing, with a focus on fuel efficiency, emissions reduction, improved reliability, and cost-effective production and operation. Studying diesel engines like the 2CH10.5/13 is relevant due to their significant potential in the modern world. The purpose of this study is to investigate the theoretical effect of the initial fuel injection pressure on the combustion process, engine braking performance, and efficiency. **Materials and Methods**. The paper describes the methods of choosing injectors for diesel engines with a high-pressure fuel system. **Results and Discussion**. Using mathematical calculations and modeling is an effective means to prevent engine operation issues. Developing a dedicated calculation method is necessary to understand the impact of diesel fuel ignition volume on engine performance parameters. The results of experimental studies, which included non-motorized, motorized, and operational tests of diesel nozzles, are also presented. Studies have shown that after 4,000 cumulative hours of operation, the residual life of the injector nozzles is insignificant since the dynamic performance of the diesel engine decreases to the limit value (7%). **Conclusions**. This may indicate the need for regular maintenance and replacement of nozzles in accordance with the manufacturer's recommendations.

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INTRODUCTION

The injector plays a key role in the process of mixing in diesel engine cylinders and is considered the most vulnerable element of fuel equipment. Despite this, the problem of complex changes in the operational and design parameters of nozzles and their impact on the functional characteristics of diesel engines is currently insufficiently investigated. The study of the effect of injection start pressure on combustion performance is an urgent topic for many researchers in the field of marine diesel engines.

The fact that changing the injection start time can have a significant impact on the combustion efficiency of fuel and exhaust gases conditions this. When the injection pressure increases, the fuel is ignited earlier, which leads to an increase in the maximum pressure in the cylinder and an increase in fuel combustion efficiency. However, if the injection is started too early, an increase in the combustion temperature may occur, which can lead to the formation of nitrogen oxides, which are harmful substances to the environment. Thus, the choice of the optimal fuel injection start time depends on many factors, including the engine design, the type of fuel used, and exhaust gas requirements.

The study of the effect of pressure at the beginning of fuel injection on the performance and efficiency of engine braking is a significant task in the field of engine development. A change in the pressure at the beginning of fuel injection can affect the combustion process in the cylinders, which affects the performance of the engine. In addition, engine braking performance also depends on the correct choice of fuel injection start pressure. Conducting research in this area allows us to determine the optimal parameters to achieve maximum efficiency in the engine. Modern requirements for the ship's diesel engine include high fuel economy, compliance with environmental standards, increased reliability in operation, compactness, reduction of mass and volume of materials, noise level, and simplification of manufacturing and operation.

According to K. Sanaliyev and A. Yusif-Zade (1), the creation of engines that are easily manufactured and used is an important requirement in modern industry. The use of new technologies, materials, and processes simplifies the process of manufacturing and operating diesel engines and increases their efficiency. According to G. Asadov et al. (2), compliance with environmental standards is an important aspect in the development and production of engines, as it helps reduce the harmful impact on the environment. In order to meet the requirements for the level of emissions into the atmosphere, modern engines use various technologies, including catalytic exhaust gas purification systems and exhaust gas recirculation systems. Y. Dzhabiev (3) determined that reducing the mass and volume of materials is an important factor in the design and manufacture of diesel engines. The lighter the engine, the less fuel it needs to operate, which reduces fuel consumption and improves the economy of the ship or other device in which it is used.

Mamedov et al. (4) note that the compactness of the ship's diesel engine is an important requirement in various areas where space is limited and it is necessary to fit the maximum number of components. This applies not only to marine ships and spacecraft but also to other vehicles, stationary installations, and industrial mechanisms. Based on the definition by S. Takhirov (5), high fuel economy is an important requirement for modern diesel engines, as it allows for reducing fuel costs and the negative impact on the environment. Various technologies are used to achieve high fuel economy, such as electronic engine control systems, improved fuel injection systems, nozzle geometry optimization, and other methods. S. Abdullaev (6) reports that increased reliability in operation is an important requirement for modern ships' diesel engines, especially in cases where the diesel engine is a key component in some device or system. A high level of reliability is achieved through the use of modern technologies and materials, as well as by improving the design of the engine and the production process.

The scientific novelty of this study lies in its comprehensive analysis of the effects of fuel injection pressure on combustion performance and emissions in marine diesel engines, an area that has not been thoroughly explored before. By integrating advanced theoretical modeling with experimental data, this research provides novel insights into the relationship between injection pressure and engine efficiency, breaking new ground in understanding the environmental implications and practical applications for marine engine technology. This approach marks a significant advancement in the field, offering both theoretical and practical contributions to the optimization and environmental sustainability of marine diesel engines. The study is aimed at improving the operation of engines, increasing their efficiency, and reducing emissions of harmful substances into the environment.

MATERIALS AND METHODS

As part of the experimental study, tests of non-motorized bench motors and operational tests of nozzles were carried out using adjustment stands, a control D-240 diesel engine, and type 2CH10.5/13 diesel engines. The experiments were divided into several stages: a test stage with the use of adjustment stands, a test stage with a control diesel engine, and a working stage including the use of 2CH10.5/13 type engines. The test stage with the use of adjustment stands and the test stage with a control diesel engine allowed checking the indicators of the control pump and nozzles before use at the working stage. At the working stage, type 2CH10.5/13 diesel engines were used to test the operation of nozzles in real operating conditions. The experimental stages included the use of various methods and tools to test and evaluate the performance of nozzles in various conditions, which provided a more complete picture of their characteristics and capabilities.

During the experiments, 480 cumulative hours of testing were carried out, and the test stages were completed after running at least 4,000 cumulative hours. In total, 8 test stages were carried out, before each of which a control pump equipped with a set of injectors and high-pressure fuel pipes were checked. The purpose of the test stages was to determine the injection pressure, identify coked nozzles, disassemble them, and remove carbon deposits, as well as perform a visual inspection to detect damage. In addition, the injector nozzles were adjusted to an injection pressure of 17.8 MPa (178 kg/cm2), and the quality of fuel atomization and the mobility of the nozzle needle were determined. Thus, this technique is an important tool for determining the condition of nozzles and identifying problems in their operation. Experimental studies of nozzles using various methods and means were carried out in order to obtain a more complete understanding of their characteristics and capabilities. The data obtained will help optimize the production of nozzles, improve the quality of diesel engines, and prevent and eliminate possible problems with their operation in the future.

As part of the experiments, a technique was used based on determining the characteristics of the nozzles in various conditions. This technique allows identifying problems with the operation of nozzles, such as coking, low injection start pressure, and inhomogeneous fuel atomization. The test stages were carried out in accordance with the regulations and provided additional data on the characteristics and performance of the nozzles. High-tech equipment was used for testing, including pressure sensors, high-precision pressure gauges, fuel analyzers, and smoke meters. According to the test results, detailed reports were generated, which contained data on the injection pressure, the quality of fuel spraying, the degree of spraying, and other characteristics of the nozzles. In general, the use of this technique and the implementation of test stages provided more complete information about the operation of atomizers, which can be used to optimize their operation and improve the quality of fuel supply in diesel engines. The research carried out is of great importance for the development of modern technologies and improving the efficiency of equipment operations.

RESULTS

Parameter determination and non-motor testing of nozzles are important steps in the process of their design and testing. The results of these tests can be used to optimize the design of the nozzle and its performance. The parameters of the nozzles include characteristics such as diameter, pressure in the fluid supply system, fluid flow rate, and spray angle. The determination of these parameters allows for optimizing the operation of the nozzle, improving the quality of the sprayed liquid, and reducing the cost of its use. Non-motorized tests of nozzles are carried out without connection to the electrical network or pressure water. During such tests, measurements are made of the diameter of the droplets, the distribution of their sizes, speed, and flight distance.

This data helps determine the performance of the nozzle and the necessary adjustments to improve its performance. These data allow manufacturers to improve the quality of their products and increase their efficiency, which has a positive effect on the final consumer (7). A deaf injection in three nozzles signaled the beginning of the stage.

Most nozzles had changes in the type of injection, from deaf to ringing and vice versa. However, the injection type remained unchanged for the three nozzles. **Tables 1-3** contain the values of the parameters of the used nozzles and high-pressure fuel pipes.

Table 1. Description of the characteristics of the parameters of highly reliable nozzles and high-pressure fuel supply systems

Parameter name	Nozzles		Fuel pipes	
	Approximate	Spare	Approximate	Spare
Nozzles and high-pressure fuel pipes	No. 4	No. 14	No. 14	No. 3
Effective area of the passage, expressed in square millimetres (mm^2)	0.193	0.192	0.84	0.84
Tightness in the area of the locking cone	sealed	sealed	-	-
Hydraulic density, s	21.4	12.3	-	-
Efficiency of the spraying process	good	good	-	-
Needle mobility	mobile	mobile	-	-

Source: compiled by the author.

Hydraulic density provides a measure of the level of nozzle clogging by contaminants in the fuel. Lower density values indicate less clogging/restriction. Spray efficiency describes the quality of the fuel atomization process as the fuel exits the nozzle.

Finally, needle mobility refers to the movement capability of the needle valve component in opening/closing the nozzle outlet. These parameters were measured and tracked across testing stages to monitor nozzle condition and performance over time.

Issues like reduced cross-sectional area, leakage, diminished mobility, and poor spray patterns would indicate loss of nozzle quality from factors like component wear, contaminant build-up, and injector coking. The accompanying fuel pipes were also analysed by measuring their effective flow areas which, like the nozzles, impact flow rates and injection system performance.

Table 2. Description of the characteristics of the parameters of the kit for monitoring high-pressure fuel drives

For testing with and without an engine		Pump section number
No. of high-pressure fuel pipe	**μ f, mm2**	
8	0.82	1
10	0.82	2
19	0.82	3
5	0.83	4

Source: compiled by the author.

13 nozzles at the second stage showed a deaf injection, but in subsequent stages the number of such nozzles decreased: at the third, fourth, and 5th stages there were 10 units, and at the 6th – 7 out of 17, at the 8h and final stages – 15 out of 20, which is 75%. At the same time, at the second stage, after 1.000 cumulative hours of operation, a decrease in the quality of spraying was detected in nine nozzles, but later this quality was restored. The fuel pipes channel high pressure fuel from the pumps to the nozzles and thus their inner diameter and resulting flow area are critical parameters. Over time contaminants, component wear, or pipe inner surface degradation can restrict this area. By tracking the flow areas and linking each pipe to specific pump sections, the performance of different injection system components can be analysed over the testing stages. A reduction in flow area would point to a pipe restriction requiring maintenance. Comparing pipes between pump sections helps localize any developing problems.

Table 3. Description of the characteristics of a set of nozzles for control

No. of nozzle	No. of pump section	Effective cross-section, mm2	Degree of tightness in the area of the l ocking cone	Water resistance, s	Degree of uniformity of spraying
1	1	0.219	hermetically sealed	11	Good
16	2	0.224	hermetically sealed	8.6	Good
11	3	0.217	hermetically sealed	8	Good
9	4	0.216	hermetically sealed	14.9	Good

Source: compiled by the author.

By measuring and comparing these parameters at different test stages, performance changes in the control nozzles can be tracked to detect factors like wear, contaminant build-up, and loss of sealing effectiveness over time. Nozzle issues would then require maintenance or replacement. The first stage was characterised by a breach of tightness in two nozzles, and in the second stage – in seven. There was also a deterioration in the uniformity of distribution at these stages. At the 6th stage (operating time in the range from 2.800 to 3.000 cumulative hours), a leak-tightness was detected in two nozzles, at the 7th and 8th stages (operation in the range from 3.500 to 4.000 cumulative hours) in eleven atomisers. The wear of the locking cones of the needle and the nozzle body caused a deterioration in tightness. The assessment of the hydraulic density showed that there was an increase in this indicator from 10.5 to 13.9 after comparing the first and second stages. In the last three stages, a constant decrease in hydraulic density was noted. The initial stage was characterised by a water density that did not exceed 5 s, which is in the range of acceptable values. During the 5th and 6h stages, 25% and 60% of the nozzles, respectively, had a hydraulic density exceeding the permissible values, and at the 7th and 8th stages – 65% of the nozzles.

In the initial period, at the first and second stages, there was a decrease in the effective cross-sectional area by 0.003 and 0.005 mm^2, respectively, compared with the indicator at the initial stage. However, in the future there was an increase in this parameter. As an example, at the 8th stage, the effective cross-sectional area was 0.255 mm^2, which is 0.031 mm^2 more than at the initial stage and 0.036 mm^2 more than at the second stage. The movement of the nozzle needle was assessed. It follows from the conducted studies that, on average, the stroke of the nozzle needle increased by 0.06 mm. The analysis of the cyclic feed showed that this parameter practically does not change at most stages, with the exception of the second, where there was a decrease in the average cyclic feed by 2.2 mm^3/cycle in comparison with other stages. The decrease in productivity is associated with a decrease in the effective flow section.

During the motor tests, it was revealed that the power was systematically reduced throughout all stages. When the diesel engine is operating at the upper power limit in the nominal mode equal to 55.1 kW, the power for the generalised cylinder is 13.8 kW. However, for the initial stage, the power was 13.9 kW, which indicates a decrease in power. As a result of the research, the mean square deviation was calculated, which is 0.1-0.05 kW. An increase in specific fuel consumption was observed by 31 g/·kWh (11.2%). It was found that the actual output power of the tested diesel decreased as the operating time increased, with the greatest decrease occurring in the 4th and 5th sets of injectors. At the final 8th stage, the power decreased by 3.6 kW (the mark of 51.5 kW of power was reached), which is very close to the lower limit of 51.24 kW. At the 4th stage, a decrease in hourly fuel consumption to 14 kg/h was recorded, which is 0.6 kg/h (or 4.1%) less than at the initial stage. Later, at the final stage, the hourly consumption increased and reached 15.5 kg/h. With a decrease in power, the specific fuel consumption increased, reaching the mark of 37 g/kWh, which is an increase of 14% compared to the previous value. Analysis of the result in overload mode showed a decrease in the maximum effective torque by 26 Nm (9.8%) and an increase in specific fuel consumption by 22 g/kWh (8.1%).

After analyzing various methods of mixing fuel and air in the combustion chamber, it was found that all of them lead to inhomogeneity of the mixture inside the chamber, which then affects the fuel combustion process. However, it is possible to significantly improve the uniformity of the mixture by adding additional air under excessive pressure, bypassing the main suction path. This method is not ideal, but it makes it possible to investigate the processes occurring inside the engine chamber. To improve the power, efficiency, and reduce the toxicity of the engine at high temperatures and high mountains (environment-friendly ships), new methods of mixing fuel and air have been developed, which have been tested theoretically and mathematically. These methods include a correction of the operational coefficient and the determination of optimal conditions for achieving the best economic performance with minimal exhaust gas toxicity (8).

The characteristics of heat release have a major impact on the accuracy of calculations made using models, from the simplest to the most complex. They are directly related to the process of phase-by-phase combustion in the engine. Combustion is a complex of multi-stage physicochemical processes that occur in all its stages. Chemical reactions between the fuel and the oxidizer (atmospheric oxygen) are the basis of this complex. The results of combustion, as an exothermic equilibrium chemical reaction, can be determined using thermochemical oxidation equations. They theoretically determine the volumes of components, the composition of combustion products, and the required amount of air for the combustion of a given amount of fuel (9). In engines with forced ignition of the mixture from an electric spark, after the appearance of activation centers (invisible burning phase), the mixture passes into the phase of effective combustion (visible burning) by a moving flame front, the speed of which depends on many factors, including the composition of the mixture, its temperature and pressure, and ignition conditions. Combustion of the fuel-air mixture in the engine cylinders with forced ignition occurs under conditions of increased charge turbulence (10).

The speed of propagation of the flame front in the burning mixture depends on the temperature of the mixture and is inversely proportional to the pressure, the reaction time of the oxidation of the fuel, and its composition. The turbulent propagation velocity of the flame front, on the other hand, increases with increasing pressure. For a more accurate description of the combustion process and the mechanism of heat and mass transfer in the combustion chamber of the engine, a complex mathematical model is needed that includes many factors, such as the heterogeneity of the temperature field, turbulence, pressure, composition, and propagation velocity of the flame front (11). The model must consider the conditions of diffusion and chemical reactions at each point. For simplicity of modeling, it is possible to use the heat release curve obtained experimentally or approximated by the function (12).

The first phase describes the ignition and preparation of the flame front. In this phase, invisible burning occurs, also known as charge activation. The rate of fuel combustion depends on many physicochemical factors, including the composition of the mixture, the normal rate of preparation of the flame front, and the intensity of small-scale turbulence. The impact of large-scale turbulence at this stage is impossible since the surface of the flame front is not yet curved. The rate of flame front formation at the beginning of the first phase is approximately equal to the rate of the laminar flame front. However, as the size of the combustion focus increases, the speed of the flame front increases due to turbulent pulsations of small scales. Therefore, the combustion process in this phase is determined by fine-scale turbulent combustion patterns, which depend on the normal velocity of the flame front and the molecular and turbulent diffusion coefficients.

In the second phase, an active increase in the flame source occurs due to strong turbulence and the mixing of a large-scale charge. The main factor determining the rate of combustion is large-scale turbulent processes that ensure maximum combustion efficiency of the mixture at maximum temperatures and pressures. A shift in the combustion phase can change the combustion rate, which depends on the level of turbulence. Different characteristics of cylinders and mixtures can lead to the development of combustion velocity gradients inside the cylinder, especially at the boundaries of the mixture jets. At the beginning of the compression process, turbulence is reduced to a minimum, and at the end of compression, its intensity increases with an increase in the speed of rotation of the crankshaft and the opening of the throttle valve, causing large turbulence in the mixture. In the second phase, the values of turbulent pulsations are less variable, which indicates that the combustion process occurs under conditions of almost stationary turbulent charge movement, almost the same throughout the entire volume of the combustion chamber. In the 3rd phase, small volumes of charge are burned out deep within the combustion zone when the piston has almost reached the bottom dead center. The normal propagation velocity of the flame front in this case primarily determines the combustion rate of the mixture. As in the initial phase, combustion in the third phase follows the laws of fine-scale turbulent combustion, where the rate of combustion depends on the physical and chemical properties of the combustible mixture. This also affects the rate of burning out of individual volumes of the mixture behind the front of the main turbulent flame, which determines the amount of toxic exhaust gas emissions (13).

After analyzing various methods of mixing fuel and air in the combustion chamber, it was found that all of them lead to inhomogeneity of the mixture inside the chamber, which then affects the fuel combustion process. However, it is possible to significantly improve the uniformity of the mixture by adding additional air under excessive pressure, bypassing the main suction path. This method is not ideal, but it allows for investigating the processes occurring inside the engine chamber (14). To improve the power and efficiency and reduce the toxicity of the engine at high temperatures and in high mountains, new methods of mixing fuel and air have been developed and have been tested theoretically and mathematically. These methods include the correction of the operating coefficient and the determination of optimal conditions for achieving the best economic performance with minimal exhaust gas toxicity.

DISCUSSION

The study of the effect of fuel injection start pressure on the characteristics of the combustion process and on the performance and efficiency of engine braking is an important task in the development of modern diesel engines. The fuel injection start pressure is a key parameter in the injection system that affects the injection start time, duration, and amount of fuel. A change in the injection start pressure can lead to a change in the combustion process of the fuel in the combustion chamber and, accordingly, to a change in the characteristics of the engine, such as power, torque, fuel consumption, and emissions. When the fuel injection starts, pressure changes, and the combustion parameters of the fuel in the combustion chamber change. Changing this parameter can lead to a more complete combustion of fuel and an increase in engine power and torque, provided that the change occurs within certain parameters. However, if the fuel injection start pressure is outside the optimal range, this can lead to deterioration in engine performance and an increase in emissions of harmful substances. Therefore, the study of the effect of the pressure at the beginning of fuel injection on these parameters is important to improve the efficiency of the engines (15; 16).

To understand how changes in fuel injection pressure affect the combustion process in marine diesel engines, it's important to examine several key aspects: combustion rate, temperature, combustion formation, and emissions. Each of these factors plays a critical role in the overall efficiency and environmental impact of the engine. The combustion rate in a diesel engine is significantly influenced by the fuel injection pressure. Higher injection pressures lead to finer atomization of the fuel, which in turn allows for a more homogeneous mixture of fuel and air. This homogeneity facilitates a faster and more complete combustion process. Conversely, lower injection pressures result in larger fuel droplets, which burn slower and less efficiently. Therefore, increasing the fuel injection pressure can enhance the combustion rate, leading to a more efficient conversion of fuel to energy. The temperature within the combustion chamber is also impacted by changes in injection pressure. Higher pressures typically increase the temperature due to a more thorough and rapid combustion process. This elevated temperature can improve the thermal efficiency of the engine. However, it's important to note that excessively high combustion temperatures can lead to issues like engine knocking and can increase the formation of nitrogen oxides (NOx), which are harmful pollutants.

The formation of the combustion process, including the initiation and propagation of the flame front, is closely tied to injection pressure. Higher pressures tend to produce a more uniform and controlled spread of the flame, which is beneficial for efficient fuel burning. This control over the combustion process can lead to reduced fuel consumption and improved engine performance. However, it's crucial to optimize the injection pressure to avoid incomplete combustion, which can occur if the pressure is too low, leading to higher emissions and reduced engine performance. One of the most significant impacts of fuel injection pressure is on engine emissions. Higher injection pressures can reduce emissions of particulate matter (PM) and unburned hydrocarbons (HC), as the finer atomization of the fuel leads to more complete combustion. However, as mentioned earlier, higher pressures can also increase NOx emissions due to higher combustion temperatures. This creates a trade-off scenario where engine designers must balance the injection pressure to optimize for both efficiency and emission standards. Changes in fuel injection pressure have a profound impact on the combustion process in marine diesel engines, affecting the combustion rate, temperature, and formation, as well as the emission of pollutants. Understanding these relationships is key to optimizing engine performance and reducing environmental impact. This area of research is critical, as it offers pathways for advancements in marine engine technology that are both efficient and environmentally responsible.

In the course of the study, experiments are carried out, including changes in the injection start pressure and analysis of the characteristics of the combustion process, braking efficiency, and other parameters. The experimental data determine the optimal injection start pressure for each type of diesel engine, which contributes to its efficiency. In addition, it is also possible to determine the effect of changes in the injection pressure on emissions of harmful substances and the environmental performance of the engine. The results obtained can be used to develop more efficient fuel systems and optimize the operation of engines in order to reduce the negative impact on the environment. Propulsion machines in the power transmission system must maintain the stability of their parameters in various operating conditions. Internal combustion engines are often used in the marine industry for their excellent performance, but their performance depends on marine operating conditions, including weather conditions and fuel properties (17-19). With the increasing importance of environmental protection, the requirements for exhaust emissions are becoming more stringent. In Europe, starting in 2017, all passenger vehicles (ships) must pass emissions tests in real sea trial conditions, and in the future, marine engines will also be subject to similar requirements. This underlines the need to ensure the stability of engine performance in a wide range of conditions.

Moreover, the study of the effect of the pressure at the beginning of fuel injection can help in the development of more accurate models and software for controlling the injection system, which will improve the performance of the engine and reduce harmful emissions into the atmosphere (20; 21). The findings can be used to improve models that predict the process of fuel combustion in the combustion chamber and to optimize the operation of the fuel injection control system. This, in turn, can lead to more accurate control of engine operation parameters, an improvement in its characteristics, and a reduction of harmful emissions into the atmosphere.

According to the results of the study by O. Ogunkunle and N.A. Ahmed (22), in order to ensure uniform distribution of fuel throughout the entire volume of the combustion chamber, it is necessary to ensure its maximum crushing. This is achieved due to the fuel supply equipment, which regulates the volume and moment of fuel injection into the cylinder. In vortex-chamber engines, in addition to fuel-feeding equipment, additional fuel crushing is carried out due to vortex air flows that are formed in the combustion chamber. The quality of fuel atomization directly depends on its physicochemical properties, such as viscosity, density, temperature, pressure, and other parameters. Therefore, the quality of the fuel also affects the efficiency of the diesel working process. Thus, in order to ensure optimal efficiency of the diesel working process, it is necessary to ensure maximum crushing and uniform distribution of fuel in the combustion chamber. This can be achieved due to the correct operation of the fuel supply equipment and the creation of vortex air flows in the combustion chamber. In addition, it is necessary to use high-quality fuel that has the necessary physical and chemical properties.

Referring to the definition by K. Santosh et al.(23), with an increase in engine speed, other problems associated with an increase in engine load arise, such as an increase in temperature, wear of parts, and an increase in fuel consumption. It is also important to note that if the engine speeds are too high, it may be necessary to change the fuel injection parameters in order to achieve optimal atomization and combustion. Although increasing the engine speed may in some cases increase the efficiency of fuel atomization, this must be balanced with other factors, such as engine load and optimal fuel injection parameters. Therefore, the optimal engine speed to achieve maximum fuel atomization efficiency should be determined based on all these factors (24; 25).

Gopal et al. (26) determined that, in general, an increase in the engine speed leads to an increase in the flow rate of air and fuel in the combustion chamber, which can increase the pressure and temperature in the combustion chamber, improve fuel crushing, and, consequently, increase combustion efficiency. Increasing the engine speed may, in some cases, increase the efficiency of fuel atomization, but this should be balanced with other factors such as engine load and optimal fuel injection parameters. S. Uslu (27) has determined that the fineness and uniformity of spraying are determined by the quality of the nozzle as well as the properties of the fuel, such as viscosity, density, and surface tension. The thinner and more homogeneous the jet, the better the fuel mixes with the air in the combustion chamber, which ensures more complete combustion of the fuel. In general, the quality of fuel atomization is one of the key factors affecting the efficiency of the engine, and its optimization can lead to improved efficiency and performance (28; 29).

Sener et al. (30) showed that the average diameter of the droplet determines how thinly the fuel is sprayed, and the smaller this diameter, the better the fuel will mix with the air in the combustion chamber. Fuel atomization uniformity determines how evenly the fuel is distributed in the combustion chamber, which is important for achieving an optimum fuel/air ratio for combustion. If the diameters of the droplets in the jet are very different from each other, then larger droplets may not have time to evaporate before they get into the combustion zone, which will lead to incomplete combustion of fuel and a decrease in engine efficiency. To ensure optimal engine performance, it is necessary to ensure the fineness and uniformity of fuel atomization by controlling parameters such as the diameter of the droplet, the angle of the jet cone, and the relative distribution of fuel in the jet (31; 32). As noted by A. Apazhev et al. (33), an increase in injection pressure usually leads to a thinner atomization of fuel, which increases combustion efficiency and reduces emissions of harmful substances in exhaust gases. It should be borne in mind that an increase in injection pressure can also lead to an increase in the load on the injectors, which may affect their wear and require more frequent replacement. In addition, too high injection pressure can lead to inefficient use of fuel since part of it may remain unflushed and not burn at all. Thus, when choosing the optimal injection pressure, it is necessary to consider both the requirements for the efficiency and environmental friendliness of fuel combustion, the potential risks for injectors, and the economic aspects of fuel use (34; 35).

CONCLUSIONS

The pressure at the beginning of fuel injection has a significant impact on the combustion process and diesel engine performance. The pressure at the beginning of fuel injection affects the quality of the mixture in the combustion chamber, namely, the distribution of fuel by volume and the speed of its diffusion. The optimal injection starts time and pressure allow obtaining a better mixture of fuel and air, which contributes to a more complete combustion of fuel and an increase in engine efficiency. The pressure at the beginning of fuel injection affects the characteristics of the combustion process, such as the pressure in the cylinder, the temperature of the gases, and the speed of their movement. The optimal injection starts time and pressure facilitate a more uniform and stable combustion process, which helps reduce emissions of harmful substances and increase the efficiency of the engine. Ultimately, the fuel injection start pressure affects the engine's braking performance, such as power and torque. The optimal injection starts time and pressure allow you to achieve maximum power and torque with minimal fuel consumption, which increases the efficiency of the engine. After conducting motor tests on a control diesel using experimental nozzles, it was found that after 4,000 cumulative hours, their residual life turned out to be insignificant. This was manifested in the fact that the reduction in power and torque of the diesel engine approached the limit of the permissible value of 7%.

As a result of research, it was found that the use of charge stratification in diesel engine cylinders can improve traction and reduce the toxic performance of the ship since the combustion process of the mixture occurs at different speeds and temperatures. To achieve this effect, it is proposed to develop a mathematical model of the working cycle of a diesel internal combustion engine. It is proposed to conduct additional studies to determine the most optimal parameters of charge separation in the cylinders in order to achieve maximum improvement in traction and economy and reduce the toxic indicators of the ship. It is also necessary to conduct tests on other types of diesel engines and nozzles to confirm the effectiveness of this method and its applicability to a wide range of ships' engines.

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