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Original Article

Character of Changes in Quantitative and Qualitative Parameters of the Lubrication System During Diesel Engine Operation

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Abstract - *The study examines the correlation between quantitative and qualitative parameters of the diesel engine lubrication system and the characteristics of their variations during engine operation. A calculation-analytical and experimental study of a wide range of problematic aspects stated in the topic was employed as a methodological basis. The study results demonstrate that the nature of current changes in the physical and chemical composition of engine oil in the diesel engine lubrication system determines the general nature of changes in the quantitative and qualitative indicators of the lubrication system. The progression of the oil ageing process inside the lubrication system directly influences the dynamics of alterations in its essential components, especially the order of its polymerization. The service of engine oil in diesel engine lubrication systems is significantly reduced, which necessitates its replacement. The nature of the changes in the technical condition of the diesel engine lubrication system makes it theoretically possible for oil fractions to enter the fuel system (in the event of lubrication system malfunctions), which leads to improper engine operating standards and increases the risk of premature engine wear and failure. Thus, the nature of changes in the quantitative and qualitative indicators of the lubrication system during the operation of a diesel engine is a function of many variables and can be represented in general by a graphical dependence that shows all key components that have a direct impact on engine performance over a set period.*

Keywords - *Motor transport equipment, Unit design, Wear, Oil consumption per carbon, Fuel consumption control, Power plants.*

1. Introduction

The reliable functioning of the lubrication system is essential for the performance and durability of diesel engines, as it ensures effective friction control and component protection in a variety of often harsh operating conditions. During engine operation, the lubrication system undergoes constant quantitative and qualitative changes, such as oil quality deterioration, contamination, oil pressure and viscosity fluctuations, which can significantly affect engine performance and accelerate engine wear. These changes are influenced by complex physical and chemical processes, such as oil degradation and interactions with fuel and combustion byproducts, which make it difficult to maintain optimal engine performance over time. While monitoring these parameters is crucial, current research often isolates individual elements without addressing the complex dynamic and interrelated aspects of lubricant system degradation under real-world operating conditions. This gap limits the ability to accurately assess engine conditions and predict maintenance needs, emphasizing the need to develop a holistic strategy that combines experimental analysis with mathematical modelling to improve the understanding and management of the dynamic state of diesel engine lubrication systems. Diesel engine malfunctions caused by the spontaneous flow of diesel oil into the lubrication system cause deterioration of engine performance (both quantitative and qualitative), significantly reduce the service life of oil in the lubrication system, and also negatively affect the safety of engine operation as a whole [1, 2].

At the same time, favourable changes in the lubrication system operation can be caused by the timely boosting of diesel engines. In this case, there is an increase in the volume of the engine crankcase and, consequently, the volume of oil consumed. There is a significant increase in the operating oil pressure in the engine, as well as a significant change in the adjustment parameters of the diesel engine. The examination of the effects of alterations in lubrication system parameters on diesel engine performance is highly pertinent to the technological advancement of the Republic of Kazakhstan, considering the extensive utilization of such engines across multiple sectors of the national economy, particularly in agriculture, the automotive industry, and rail transport. The specified range of questions was addressed by Aulin et al. [3], Hunicz et al. [4] and Zare et al. [5].

George et al. [6], McClellan et al. [7], and Ünver et al. [8] looked into several challenging issues related to figuring out what diagnostic parameters are needed for the engine oil used in diesel engines. The authors state that the most important diagnostic parameters determining the nature of quantitative and qualitative changes in the lubrication of the diesel engine are oil alkalinity and oil level in the engine crankcase.

Their changes determine the nature of engine functioning and the operation of the lubrication system. Kravtsov & Karnaukh [9], in a study of general principles of improving the efficiency of operation of formed automotive diesel engines by controlling the volume of oil in the fuel system, state that one of the most important tasks of the economy of the Republic of Kazakhstan is to improve the overall reliability of the functioning of automotive diesel engines.

According to scientists, such improvement is possible only with proper control of the condition of engine lubrication systems during their operation in motor transport enterprises of the country. Studies by Aulin et al. [3], Madey [10], and Niknafs et al. [11] addressed the causes of changes in the power parameters of a diesel car engine operating in non-stationary conditions, along with changes in the quantitative and qualitative indicators of the fuel system. Scientists note that the operation of automotive diesel engines in nonstandard conditions is one of the most difficult tasks of the transport system of any country. The authors claim that controlling the changes in the amount and quality of the lubrication system in such an engine helps solve problems related to effectively managing engine operation.

Utaev considered the issue of changes in the physicochemical and operational characteristics of internal combustion engine oils [12]. The author observes that the oil within the fuel system of a diesel engine experiences several quantitative and qualitative alterations throughout the operation. Quantitative alterations are attributed to oil depletion in the cylinder-piston assembly of the diesel engine, whereas qualitative transformations, commonly referred to as "oil ageing," encompass a comprehensive array of physical and chemical processes occurring within the engine's lubrication system. Consequently, alterations in oil quality result in quantitative changes specifically increased oil consumption during diesel engine operation.

At the same time, McClellan et al. [7] addressed the general principles of changes in diesel technology related to the need for pre-cleaning of oil in the lubrication system and the assessment of carcinogenic hazards of diesel engines. The authors observe that diesel engines are a distinct category of internal combustion engines that operate based on utilizing compression heat instead of an electrical ignition spark. The efficiency of engines and their efficiency factor depends on the nature of changes in the quantitative and qualitative parameters of the lubrication system, and the nature of cleaning of fuel and oil mixtures before their use should also be accounted for.

Although extensive research has examined the quantitative and qualitative aspects of diesel engine lubrication systems and their effects on engine performance, a notable research gap persists concerning a thorough analysis of the dynamic variations in these parameters under actual operating conditions, taking into account oil ageing, regeneration processes, and interactions with the fuel system.

Current research predominantly emphasizes discrete factors like viscosity, alkalinity, or oil pressure, neglecting the comprehensive interrelations between quantitative and qualitative lubrication indicators and their impact on the durability and reliability of diesel engines under extended use and varying operational conditions. This study fills the gap by creating a comprehensive mathematical model that integrates the key factors affecting lubricant property variations and experimental validation of the relationships between lubrication system parameters and engine wear, thus improving the precision of diagnostics and prognostics regarding engine condition.

The study examines the alterations in the key performance indicators of the lubrication system in a diesel internal combustion engine.

2. Literature Review

The lubricating system of a diesel engine is crucial for maintaining its reliable and efficient functioning. Prior research has thoroughly examined the relationship between quantitative and qualitative aspects of lubrication systems and engine performance. Kravtsov and Karnaukh [9] established that alterations in the physical and chemical composition of engine oil during operation directly impact the critical parameters of the lubrication system, hence affecting engine durability. Monitoring oil ageing processes, including oxidation, polymerization, and contamination, was emphasized as essential for assessing oil service life and maintenance schedules.

Aulin et al. [3] and Hunicz et al. [4] similarly highlighted the dynamic characteristics of lubrication system parameters under non-stationary operating conditions, observing that fluctuations in oil pressure and fuel system attributes significantly affect diesel engine power output and operational stability. These investigations highlight the intricacy of sustaining ideal lubrication conditions throughout engine operation, characterized by varying loads and external influences.

George et al. [6] and Ünver et al. [8] have examined the importance of diagnostic measures, including oil alkalinity and oil level in the crankcase, correlating these signs with engine wear and failure risk. They proposed that prompt monitoring of these factors can reduce premature engine deterioration. Moreover, Madey [10] and Niknafs et al. [11] introduced expert systems that include fuzzy logic for real-time monitoring of soil conditions, hence enabling proactive maintenance and fault detection.

The type and quality of fuel significantly influence the performance of the lubricating system. Zare et al. [5] indicated that oxygenated fuels and biofuels impact combustion characteristics and oil consumption rates, influencing lubrication system parameters and engine emissions. George et al. [6] have identified engine oil contamination with diesel soot and other particulates as a significant factor in engine wear, highlighting the necessity for efficient oil purification techniques.

These works offer an extensive overview of the elements influencing diesel engine lubrication system performance, including oil chemistry, diagnostics, fuel interactions, and environmental effects. Nonetheless, deficiencies persist in comprehensively delineating the interaction among these variables across various operational situations and assimilating this understanding into predictive models for engine maintenance and efficiency improvement.

This study enhances existing knowledge by empirically examining the kinetics of quantitative and qualitative alterations in lubricating system parameters during diesel engine operation, underpinned by mathematical modelling and experimental validation.

3. Materials and Methods

The methodological approach in this study was based on a combination of calculation and analytical and experimental methods. At the same time, the appropriate material and technical base were prepared and used to implement the stated methods, including a full range of technological capabilities for conducting experimental and analytical studies. As samples of internal combustion diesel engines for the experimental study, the models YAMZ-236 and Mercedes 611 were chosen. Nominal operation and idling conditions were investigated.

The study was conducted based on the AUTOSILA repair and transport enterprise in Kostanay. Expressions were derived to estimate the variations in the characteristics of engine oil during its operation within the lubrication system of a diesel engine, together with a figure illustrating the kinetics of changes in the quality indicators of engine oil throughout its use. The established relationships show how factors like the time the engine runs without needing more oil, the rate at which oil quality changes and the amount of new oil added each time are connected.

A computational mathematical model was developed to assess engine oil properties (ageing) changes during diesel engine operation. This model is represented by formulas (1, 2):

$$\lim_n \to \infty\left(P_0 - P_p\right)_p = \alpha \times \Delta t, \tag{1}$$

$$\lim_n \to \infty \sum_1^n k^n = \alpha \times \Delta t \times \frac{k}{1-k}, \tag{2}$$

Where: α – slope angle of the straight line kinetics of oil quality index change in the engine lubrication system; Δt – time of continuous engine operation between consecutive oil additions to the lubrication system; n – number of fluid circulation cycles in the engine; k – a selected unit of fresh oil volume in the engine lubrication system in the process of orderly addition of new oil; P represents the analysis of the lubrication system's oil characteristics, where fresh, unused oil is denoted as P_0.

As the oil ages, without considering the effects of renewal processes, its changes exhibit a linear progression relative to the operational time parameter, culminating in the final value of π in the subsequent operating cycle. Using a mathematical model for processing experimental data, graphical dependences of the oil pressure in the lubrication system on the mileage of a diesel engine were obtained. In this case, expression (3) is used to estimate the total engine wear during operation:

$$S = S_0 e^b \tag{3}$$

At the same time, the wear rate parameter also increases exponentially (4):

$$A = A_0 e^b \tag{4}$$

Where A_0 and S_0, respectively, are indicators of wear intensity and actual wear at the stage of final running-in of parts, noted now of the beginning of operational use of the diesel engine; b – parameter of change of wear intensity of parts per unit of their wear. By analyzing expressions (1) and (2), a formula was derived to ascertain the relationship between oil pressure in the lubrication system and diesel engine output [5]:

$$P = \frac{a}{S_0^m} = P_0 e^{-BPL}, \tag{5}$$

Where: $P_0 = \frac{a}{S_0^m}$ – The pressure at the final running-in stage of the engine components, given the beginning of its operational use.

To study the informativeness of the operating parameters of oil in the lubrication system, formula (6) was derived:

$$\Delta S = \frac{S_0 - S_k}{S_0} \times 100\%, \quad (6)$$

Where: S_0 – the initial; and S_k – the final value of the design parameter.

4. Results

The lubricating system characteristics alter the functioning of a diesel engine. In general, they can be divided into qualitative and quantitative. The qualitative indicators of the lubrication system include oil ageing and dilution with fuel and diesel fuel. Quantitative metrics of the lubrication system are oil pump performance, losses due to oil leakage and carbon black, as well as wear and clearances in engine crankshaft bearings [13, 14]. The nature of the change in the quantitative and qualitative indicators of the lubrication system during the operation of a diesel engine affects its performance. It determines the overall service life of the unit, considering the peculiarities of its operation and maintenance.

The process of engine oil operation during diesel engine operation involves partial regeneration of properties, which takes place when topping up the oil in the volume recommended for this type of lubrication system, as well as when filtering the oil in a diesel engine [15-17]. Thus, when analyzing changes in the quantitative and qualitative indicators of the lubrication system during diesel engine operation, the full complex of physical and chemical processes in oil ageing and oil renewal, through the infusion of fresh oil to the required volume, must be considered.

Given the fact that in real conditions of engine operation, not only does the quality undergo significant changes over time due to the development of regeneration processes but also under the influence of physical and chemical processes occurring throughout the entire volume of diesel engine oil, an objectively relevant representation of the kinetics of changes should be considered as exponential curves.

Simultaneously, it should be regarded as a specific approximation of average characteristics, the benefit of which lies in its capacity to provide a relatively precise depiction of the overarching trend in the quality indicators of engine oil during the operation of a diesel engine. The absolute difference between the parameters of new engine oil and that of the oil after a certain duration of operational use enables the evaluation of changes in its properties due to ageing during use compared to fresh samples. The sequence of changes of this kind is presented in the form of formulas:

$$\lim_n \to \infty (P_0 - P_i)_p = \alpha \times \Delta t = 0.33 \times 122 = 40.26,$$

$$\lim_n \to \infty \sum_1^n k^n = \alpha \times \Delta t * \frac{k}{1} - k = 0.33 \times 122 \times \frac{0.35}{1-0.35} = 21.68,$$

The mathematical model described using the presented expressions can be used to conclude that the process of engine oil ageing during diesel engine operation does not have a direct dependence on the time parameter. Thus, the index of kinematic viscosity of motor oils functioning at the working temperature of 100°C in any operating conditions can be used to draw preliminary forecasts of engine oil behaviour at any stage of diesel engine operation. Meanwhile, it is essential to consider that acquiring a comprehensive understanding of the current alterations in engine oil necessitates correlating the kinematic viscosity parameter with dynamic viscosity parameters, in addition to evaluating the oil's oxidation and acidity levels.

All these criteria can significantly affect the reliability of the diesel engine at any operational stage, underscoring the necessity for continual monitoring of the engine oil's ageing process. In addition, the nature of the operation of the diesel engine in specific weather conditions, as well as features of its starting, warming up, idling, and stopping, is important [18]. Consequently, the nature of changes in the quantitative and qualitative indicators of the lubrication system during the operation of a diesel engine does not always correspond to the real changes that occur in the engine during its operation in average statistical conditions, as well as at average working loads. The wear rate of diesel engine crankshaft bearings is crucial in understanding the overall dynamics of quantitative and qualitative changes in the lubrication system [19-21]. During the operation of a diesel engine, the total wear rate increases exponentially:

$$S = S_0 e^b = 3.23 \times 0.56 = 1.8088.$$

At the same time, the wear intensity parameter also increases in exponential dependence:

$$A = A_0 e^b = 1.55 \times 0.56 = 0.868,$$

An expression for ascertaining the relationship between oil pressure in the lubrication system and diesel engine output can be derived from the above equations:

$$P = \frac{0.33}{3.23} = 0.102,$$

Figures 1 and 2 illustrate the correlation between the oil pressure parameter in the lubrication system and the diesel engine output over time, derived from the mathematical analysis of this statement. The experiment was carried out using YAMZ-236 and Mercedes 611 engines.

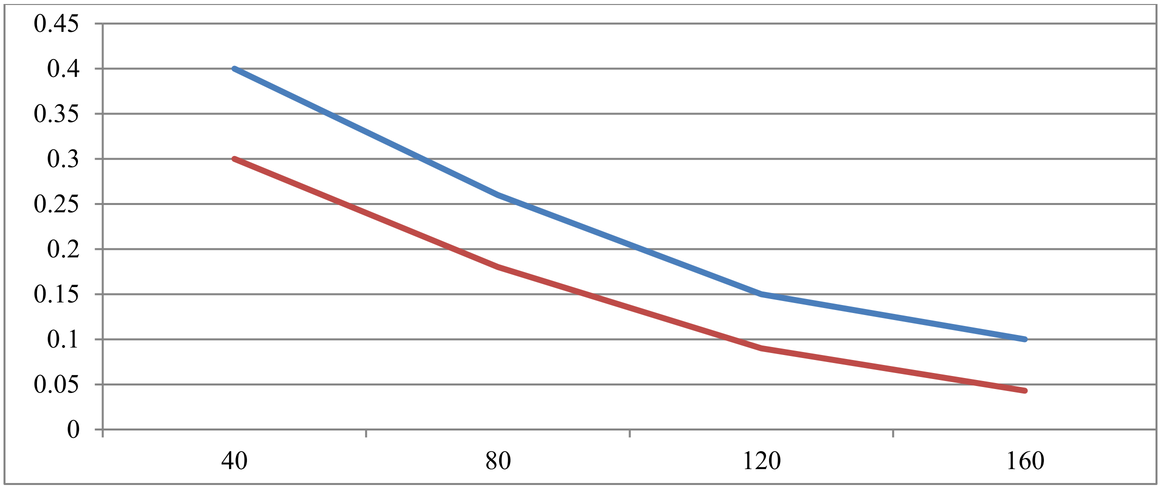

Fig. 1 Correlation between the pressure parameter in the lubricating system and the mileage of the YAMZ-236 engine
Source: compiled by the authors.

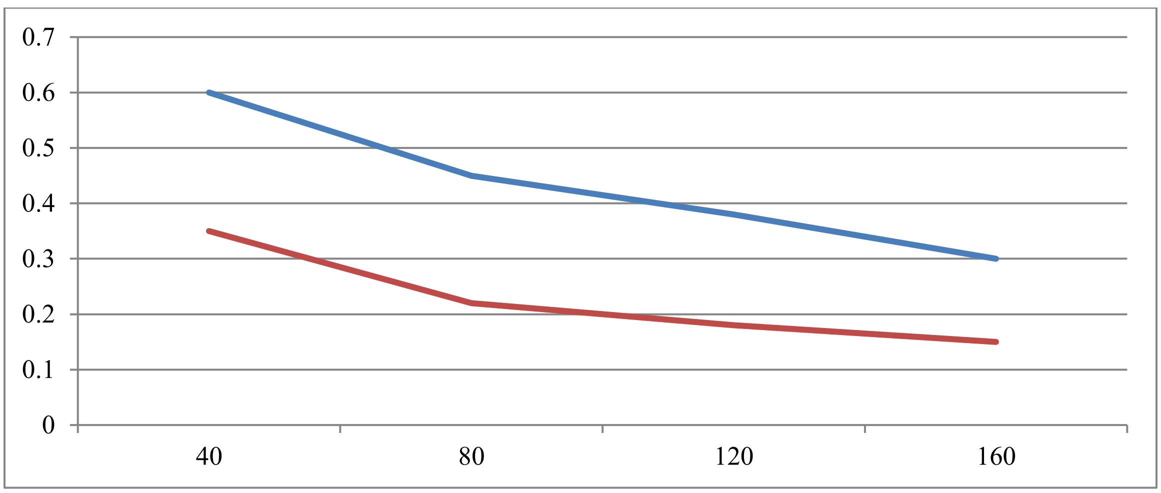

Fig. 2 Correlation of the pressure parameter in the lubricating system with the mileage of the Mercedes 611 engine
Source: compiled by the authors.

Figures 1 and 2 show the dependencies at nominal engine operation mode in blue and idle speed in red. When the oil pressure in the engine's lubrication system drops, there is a clear effect on the friction force affecting the engine crankshaft bearings, which shows up in the wear indicators. The experiment demonstrates a significant reduction in oil pressure within the lubricating system as engine mileage increases. As engine mileage increases beyond 120,000 km, the oil pressure in the fuel system decreases less intensively than it does at lower mileage. It is natural that, in this case, there is much less wear on the rubbing parts, particularly the bearings of the engine crankshaft. There is a direct correlation between the uniformity of oil pressure drop in the engine crankcase and the duration of its service life and wear in general. It is important to closely examine how certain engine oil characteristics, like alkaline number C, oil viscosity index ʍ, flash point t, and density p, change as the engine is used over time. Formula (6) was used to calculate these parameters [22]. The nature of the change in these parameters of diesel engines YAMZ-236 and Mercedes 611 at 5000 kilometres was investigated during the experiment. Tables 1 and 2, respectively, display the findings.

Table 1. Changes in the oil parameters in the lubrication system of the YAMZ-236 engine at 5000 kilometres

Parameter	**S_0**	**S_k**	**ΔS%**
The volume of oil in the system l	35	19	45.7
Alkaline number	18	14	22.2
Oil density, kg/m^3	875	868	0.8
Oil viscosity, mm^2/s	10.5	8.1	22.8
Flashpoint, °C	225	210	6.6

Source: compiled by the authors.

Table 2. Nature of changes in oil parameters in the lubrication system of the Mercedes 611 engine at 5000 kilometres of mileage

Parameter	S_0	S_k	ΔS%
Oil volume in the system, litres	42	20	52.3
Alkaline number	17	11	35.2
Oil density, kg/m^3	886	880	0.6
Oil viscosity, mm^2/s	10.6	8.2	22.6
Flashpoint, °C	234	215	8.1

Source: compiled by the authors.

The data in Tables 1 and 2 indicate that oil characteristics, including oil volume in the system, alkaline number, viscosity, and flash point, exhibit substantial changes across the 5000 kilometres of mileage analyzed in the experimental investigation. The oil density does not undergo similar significant changes. This condition applies to both types of engines used in the experimental study. At the pre-determined values of the parameter selected for the study at the beginning of oil use, the actual dynamics of change of the parameter of the operating oil at any stage of the engine operation determines the boundary of engine faults [23]. It also determines the final value of the investigated indicator at the established nature of scientific research.

The results from the experiments show that the oil indicators after a certain distance drive help identify how faults develop in the diesel engine. Changes in the oil level indicator in the diesel engine's crankcase (increase in this parameter) may indicate the presence of faults in the operation of the fuel system. During the conducted experimental study, the values of 35 litres of oil for the YaMZ-236 engine and 42 litres of oil for the Mercedes 611 engine were obtained, with a decrease in these parameters to the level of 19 and 20 litres, respectively. In addition, fuel atomization disturbances in the fuel system can lead to the ingress of some fuel into the engine crankcase, which increases the oil volume and negatively affects the functioning of the engine lubrication system as a whole [24].

The alkaline number is the second most important indicator of oil performance in the diesel engine lubrication system [25, 26]. During the experiment, the indicators of alkaline number reduction went from 18 for the YaMZ-236 engine and 17 for the Mercedes 611 engine, respectively, to 14 and 11. In case of a more intensive reduction of the parameter in question, the engine may overheat, which will cause premature failures. Oil viscosity is also an important indicator in terms of assessing the overall performance of the oil in the lubrication system [27-29]. During the conducted experiment, a decrease of this index from the values of 10.5 mm²/s for the YaMZ-236 engine and 10.6 mm²/s for the Mercedes 611 engine, respectively, to the values of 8.1 mm²/s and 8.2 mm²/s was observed. A more intensive decrease in this parameter may be an indicator of a violation of the integrity of the oil inlet path in the system. At the same time, an increase in this parameter indicates a high degree of contamination of the lubrication system filters. The flash point of oil is an indicator that can be used to judge the degree of serviceability of fuel equipment [30, 31]. During the experimental study, a significant decrease in this indicator was noted from 225°C for the YAMZ-236 engine and 234°C for the Mercedes 611 engine, respectively, to 210°C and 215°C. In both cases, such a decrease indicates malfunctions of the fuel system that require timely elimination. The oil density index did not undergo significant changes during the experiment and should not be considered when assessing the dynamics of change in the main indicators of the lubrication system.

The way the main measurements of the lubrication system change while the diesel engine is running shows how well the engine is working and can indicate issues that affect its performance. The dynamics of alterations to these parameters can be used to assess the engine's overall condition and the functionality of its systems, which is crucial for ensuring the uninterrupted operation of the diesel engine and conducting scheduled maintenance when necessary.

5. Discussion

The study results reveal a significant correlation between the alterations in the qualitative and quantitative metrics of the diesel engine's lubrication and the chemical and physical composition of the utilized oil. The critical significance of prompt monitoring of the lubrication system's technical state, regarding its influence on engine performance, was validated.

In the context of the topic stated in this research paper, it is necessary to assess the possible risks arising from the operation of a diesel engine. A wide range of problematic aspects of risk reduction in the maintenance of two-stroke diesel engines were addressed by Ünver et al. [8]. The scientists state that timely maintenance of diesel engines is necessary for their safe subsequent use. The authors say that how long a diesel engine can run without stopping depends on how well its lubrication system works and how closely its oil quality and quantity are monitored. The author's views are substantiated by the findings of this study, highlighting the correlation between the parameters of the engine lubrication system and the engine's reliable performance.

The alterations in the quantitative and qualitative metrics of the lubrication system during diesel engine operation are dictated by the extent of oil purification within the system. Hunicz et al. [4] found that how the lubrication system's measurements change when a diesel engine runs depends on the type of oil used in that system. In particular, the high speed of exhaust gas circulation in the combustion process affects the parameter of supercharging pressure, which, in turn, affects the volume of emissions, and the nature of changes in these volumes directly depends on the oil purification indicator in the lubrication system. The researchers' conclusions must be validated, as boost pressure indirectly influences the alterations in the engine lubricating system characteristics.

Consideration of types of oils used in the lubrication system when operating a diesel engine is noteworthy. The issues of application of different types of oils in diesel engine operation at cold and hot starts on oxygen-containing fuels were considered by Zare et al. [5]. Scientists note that today, most diesel engines are equipped with turbocharging, which allows them to significantly save fuel and reduce oil consumption in the lubrication system. At the same time, changes in the quantitative and qualitative indicators of the lubrication system during the operation of a diesel engine are also related to the type of fuel used; biofuels with a high concentration of oxygen improve combustion at turbocharger delay. The opinion of the researchers is supported by the results obtained since the type of fuel directly affects the change in the parameters of the engine lubrication system.

The quality of oil cleaning is a critical factor in evaluating the quantitative and qualitative alterations in the lubrication system parameters during diesel engine running. George et al. [6] considered how oil contamination in the lubrication system influences the wear parameters of a diesel engine. The authors note that contamination of oil in the lubrication system with diesel soot is one of the causes of engine wear and premature failure. In this context, the study of factors influencing the change of soot surface and its modification, as well as entailing changes in the operation of the diesel engine, leading to a decrease in engine life and premature failure, is of particular importance. The nature of wear of a diesel engine is directly related to the contamination of its lubrication system, which indicates that the scientists' results are consistent with the results of this scientific study.

The influence of oil emissions into the environment on the nature of changes in quantitative and qualitative parameters of the lubrication system is noteworthy. Pardo-García [27] and Ajuka et al. [32] looked at how important emission features and oil flow in the lubrication system affect the properties of a double-diesel double-acting internal combustion engine that runs on diesel fuel and hydrogen. Researchers note that, as a rule, the effect of hydrogen on the change of oil characteristics in the lubrication system is completely ignored, even though it is one of the main types of gaseous fuels. The change in the physicochemical characteristics of the fuel mixture has an impact both on the environment and on the nature of the diesel engine operation, which must be accounted for in technical calculations of key parameters. In the context of the study results, this opinion is controversial since the nature of the impact of changes in the physicochemical characteristics of the fuel mixture on the environment has not been fully studied.

A secondary issue arising from alterations in the quantitative and qualitative metrics of a diesel engine's lubrication system is the occurrence of ignition misses in the cylinders. This issue was addressed by Syno et al. [33], noting that the vibration of a diesel engine is one of the key indicators of its normal functioning. Disturbances of the lubrication system manifested in ignition problems and malfunctions, as well as increased engine vibration, are a consequence of the violation of the optimal combination of quantitative and qualitative parameters of the lubrication system, which leads to its premature wear and failure. The results corroborate this opinion, as the alterations in both quantitative and qualitative characteristics of a diesel engine's lubrication system directly influence its wear and operational lifespan.

A study by Mikulski et al. [34] is of relevance in the context of the relationship between the oil consumption processes in the lubrication system of diesel engines and the processes of fuel combustion and exhaust gas emission into the environment. According to the authors, many studies from different countries were devoted to the influence of different types of oils on the functionality of the lubrication system. The diversity of studies leads to many contradictory results, which causes uncertainty in assessing the degree of influence of quantitative and qualitative indicators of the engine lubrication system on the course of fuel combustion and exhaust gas emissions in the environment. Scientists have different views on the study results because a specially designed mathematical model can realistically show how the wear of a diesel engine and its lifespan depends on changes in the amount and quality of its lubrication system.

The impact of the friction factor on the efficacy of the lubrication system is crucial for assessing diesel engine performance [35-37]. Dubey et al. [38], Graboski et al. [39], and Guan et al. [40] examined how friction modifiers affect the condition of engine oil in passenger cars equipped with diesel engines. Scientists have found that tests on how well organic and inorganic friction modifiers work show changes in the friction coefficient, wear on contact surfaces, and how the lubricating film forms, which are all important signs of how well the lubrication system works. This opinion aligns with the findings of this study, as a direct correlation between the friction force and the kind of diesel engine wear during operation has been demonstrated.

The issues with using different types of diesel fuel in engines and how the fuel system works in each case are very important for understanding how the lubrication system's performance changes. In relation to how different types of diesel fuel affect the lubrication system, Claxton's study is important because it gathers information on how the harmful effects of diesel fuel relate to the lubrication system [41]. According to the researcher, modern fuel and oil additives have greatly expanded the possibilities of using different fuels and oils, which improves lubrication system operation and diesel engine operation for a long time. Confirmation of the researcher's findings is necessary, as the effects of fuel and oil additives on the lubrication system and diesel engine remain largely unexplored.

When assessing the nature of changes in the quantitative and qualitative performance of the lubrication system for diesel engines, the factor of using special types of fuel, in particular biodiesel, is of particular importance. Kataria et al. [42] and Hasannuddin et al. [43] addressed various aspects of this problem and noted that the use of biodiesel significantly reduces the friction index in the lubrication system, which positively affects the duration of the lubrication system and the service life of the diesel engine. The results of a scientific study support this opinion, as it has been shown that reducing the friction force in the lubrication system of the diesel engine has an impact on the actual service life of the engine.

The results of this study, in comparison to existing methodologies, stem from a holistic methodology that combines experimental research with an innovative mathematical model. In contrast to previous studies focusing on individual lubricant parameters, the present methodology encompasses the dynamic interaction of quantitative and qualitative parameters under real-world engine conditions. Taking into account the kinetics of oil ageing and regeneration processes is important to improve the results, as they reflect the constant physicochemical changes during engine operation and, therefore, improve the accuracy of predicting oil life and maintenance requirements.

An experimental study of several engine models and operating conditions validated the model and revealed significant trends often overlooked in previous studies. In addition, a precise study of oil contamination by soot and gasoline dilution contributed to a clearer understanding of the impact of lubricant degradation on engine wear.

The analysis includes modern elements such as turbocharging and biofuels, making the conclusions relevant to current engine technology and environmental regulations. The established analytical correlations between oil pressure, engine wear, and engine power provide a solid foundation for improved diagnostics beyond empirical associations. Integrating multivariate analysis, extensive experiments, and sophisticated modelling contributes to a more accurate assessment of the lubrication system and its impact on diesel engine performance and durability.

6. Conclusion

The study concluded that engine oil and physical attributes determine changes in lubrication quality indicators during diesel engine operation. The development of the engine oil's ageing process determines the sequence of oxidation of its key components and their polymerization and neutralization. This limits the permissible service life of engine oil, which implies the need to change it more frequently than the regulations for operating the diesel engine. In addition, ongoing malfunctions of the lubrication system can lead to the ingress of unburned diesel fuel fractions into the engine oil, which causes significant qualitative changes in the oil's structure. Similar processes also occur when coolant gets into the engine oil due to a diesel engine cooling system malfunction. In such cases, it is necessary to repair the engine on time to avoid issues and subsequent engine failure.

A decrease in the oil viscosity in the lubrication system causes an increase in the likelihood of failure in the normal hydrodynamic friction mode in the mating components and mechanisms. The oil level in the crankcase of a diesel engine should be considered one of the key indicators of the normal functioning of the lubrication system. Nevertheless, even if this parameter remains stable, the quality parameters of the system may vary significantly. The creation and implementation of diesel engine diagnostic systems should address this fact. The study's limitations arise from specific technical elements of diesel engine lubrication systems that influence engine performance parameters across various modes. The need to identify appropriate solutions for the functioning of engine lubrication systems dictates the potential for further research in this paper.

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