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Experimental Verification of the Effect of Fuel Additives on the Wear of Common Rail Pumps

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The article addresses the issue of failures of high-pressure fuel pumps in Common Rail systems and evaluates the influence of fuel additives on their wear. The first part discusses the operating principle of the Common Rail system, the design of high-pressure fuel pumps, and the most common failure modes occurring during their operation. The experimental section focuses on the disassembly and visual analysis of a damaged pump, as well as on the experimental verification of the effects of summer and winter fuel additives in various ratios with diesel fuel. Tribological properties were evaluated using laboratory measurements, supplemented by non-destructive spectral material analysis and hardness testing. The results indicate a significant effect of fuel additives on reducing friction and wear of selected pump components, which may contribute to increased service life and operational reliability.

Keywords: Fuel, Wear, Injection, Tribology, Pump

1 Introduction

The Common Rail high-pressure fuel injection system is currently one of the most widely used solutions in diesel internal combustion engines for both passenger and commercial vehicles. Its widespread adoption is primarily associated with requirements to reduce fuel consumption, increase engine performance, and comply with increasingly stringent emission limits. The high-pressure fuel pump represents a key component of this system, as it ensures the delivery of fuel to the injectors at very high pressures, which in modern systems exceed 3,000 bar. However, such high pressures, tight manufacturing tolerances, and demanding operating conditions make these pumps particularly susceptible to wear and failures [1,2].

In practice, damage to Common Rail high-pressure fuel pumps is one of the frequent causes of fuel system failure. The most significant failure mechanisms include excessive tribological wear of functional surfaces, seizure of plungers and cam mechanisms, generation of metallic particles in the fuel, as well as corrosion damage caused by the presence of water or poor-quality fuel. These failures may lead not only to reduced engine performance and impaired engine operation, but also to secondary damage to other fuel system components, especially injectors and the high-pressure fuel rail. In extreme cases, complete pump failure may occur, requiring replacement or costly repair [3,4].

The quality of diesel fuel has a significant impact on the service life of high-pressure fuel pumps. Modern environmentally friendly low-sulfur fuels contribute to emission reduction; however, they often exhibit poorer lubricating properties compared to older fuel types. Insufficient fuel lubricity increases friction between the moving components of the pump, thereby accelerating wear processes and increasing the risk of failures. For this reason, various fuel additives are increasingly used in practice, aiming to improve the tribological properties of the fuel, protect metallic surfaces against wear, and extend the service life of the fuel system [5,6].

Nevertheless, the use of diesel fuel additives is frequently a subject of debate among both professionals and the general public. While additive manufacturers declare positive effects on fuel lubricity, friction reduction, and corrosion protection, their effectiveness under real operating conditions is often assessed only subjectively. Therefore, it is essential to verify the functionality and benefits of fuel additives using objective experimental methods that allow quantification of their impact on the wear of materials used in high-pressure fuel pumps.

Verification of fuel additive performance is typically carried out through tribological tests that simulate real friction conditions within the fuel system. Such tests enable comparison of the behavior of pure fuel and fuel blended with additives at various mixing ratios. The results of tribological measurements provide important information on the extent of wear, changes in surface roughness, and the formation of damage on the tested samples. When combined with non-destructive methods such

as material hardness measurement and confocal microscopy, a comprehensive assessment of the influence of additives on the protection of functional surfaces of high-pressure fuel pumps can be achieved [7].

The aim of this article is therefore to highlight the most common forms of damage affecting high-pressure Common Rail fuel pumps and to analyze the influence of selected fuel additives on the degree of their wear. Attention is devoted not only to the theoretical description of failure mechanisms but also to the experimental verification of additive effectiveness through tribological testing. The obtained results may contribute to a better understanding of the role of fuel additives and to their rational application in practice, with the objective of increasing the reliability and service life of high-pressure fuel pumps.

2 Materials

The main object of the research was a high-pressure fuel pump of a Common Rail system used in a passenger vehicle. The pump is designed for a diesel engine, operates at very high working pressures, and is structurally engineered to ensure precise and reliable fuel delivery to the injection system. The selection of this particular pump was based on the presence of real operational damage and its availability for a detailed analysis of failure mechanisms.

The examined pump originated from a vehicle that had been operated for a long period under standard road conditions. During operation, the vehicle exhibited typical symptoms of a high-pressure fuel system failure, such as irregular engine running, reduced power output, starting difficulties, and an illuminated check control indicator. Eventually, the vehicle became non-startable. In order to start the engine, the pump must reach a pressure of 250 bar; however, during diagnostics, the maximum pressure achieved was only 220 bar. Based on these diagnostic results, the pump was removed from the vehicle and subjected to a detailed analysis [3,8].

Following disassembly of the pump, a visual inspection of its internal components was performed, revealing significant signs of mechanical and tribological damage. The most pronounced damage was observed on the pump camshaft, the tappet roller, and the functional surfaces of the high-pressure plunger, as shown in Fig. 1 and Fig. 2.

In these areas, scoring, local seizure, and changes in surface structure were observed, indicating the long-term effect of increased friction.

A significant finding was the presence of metallic particles within the pump housing after removal of the fuel metering valve (Fig. 3), which were generated as a result of progressive wear of the contact surfaces. These metallic particles subsequently entered the fuel system, potentially causing secondary damage to other components, particularly the injectors and the high-pressure fuel rail. In practice, this phenomenon is considered one of the most serious consequences of failure of a Common Rail high-pressure fuel pump. Figure 4 documents the contact between the plunger roller and the pump camshaft.

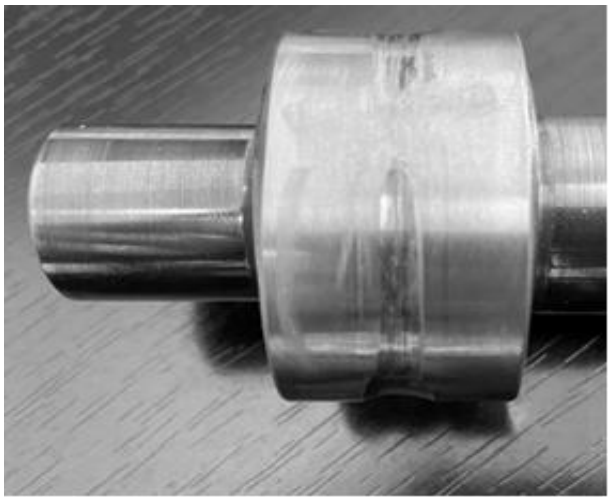


Fig. 1 *Pump camshaft*



Fig. 2 *Plunger roller*



Fig. 3 *Metallic particles*



Fig. 4 *Contact between the camshaft and the roller*

The nature of the damage observed on the examined pump indicated insufficient lubrication of the friction pairs by the fuel, which may have been caused by low diesel fuel lubricity, the presence of contaminants, or long-term operation without the use of suitable fuel additives. The surface damage exhibited characteristics of abrasive and adhesive wear, with locally observed onset of seizure. These manifestations are typical of components operating under high contact pressure and with an insufficient lubricating film [9].

Based on the extent and nature of the damage, the pump was assessed as unsuitable for further operation without replacement or repair. At the same time, it provided suitable material for experimental evaluation of the influence of fuel additives, as its damage could be directly compared with the results of tribological tests performed under laboratory conditions. The examined pump thus served as a representative example of a real failure state of a high-pressure fuel system in a modern diesel engine. Figure 5 shows significant wear of the plunger roller observed using a confocal microscope. Samples for further research were prepared from the damaged pump camshaft.

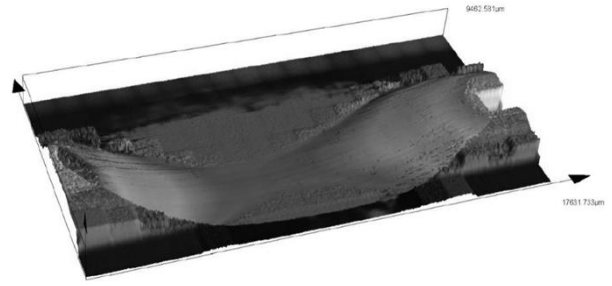


Fig. 5 *Surface morphology of the worn plunger roller*

To achieve the objectives of the article and to objectively assess the influence of fuel additives on the wear of high-pressure Common Rail pumps, several analytical and experimental methods were employed. The methodology was designed to combine practical analysis of a real damaged pump with laboratory verification of the tribological properties of diesel fuel and fuel blended with additives.

In the initial phase of the research, disassembly and visual inspection of the high-pressure fuel pump exhibiting operational failures were performed. The aim of this method was to identify the main areas of damage and wear on the functional surfaces of the pump, particularly the cam mechanism, lifting elements, and contact surfaces of the plungers. Visual diagnostics enabled localization of metallic particles, scoring, seizure, and other manifestations of tribological wear, which are typical of insufficient fuel lubrication. A more detailed surface analysis was subsequently carried out using an OLYMPUS LEXT OLS 5100 confocal laser scanning microscope. The method was employed for the qualitative evaluation of surface morphology and wear characteristics of the damaged pump components and the wear tracks generated during the tribological tests. Three-dimensional surface topography images were acquired to identify characteristic features of abrasive and adhesive wear, such as grooves, local material transfer, and surface irregularities. Since the confocal microscopy observations served only as a complementary qualitative technique and no quantitative surface texture parameters were evaluated, no specific testing standard was applied.

Subsequently, tribological tests were performed using a BRUKER UMT TriboLab tribometer to experimentally verify the effect of fuel additives on friction and wear reduction. The measurements were carried out using the pin-on-disk method in accordance with ASTM G99 – Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus, while the testing conditions were adjusted to simulate the real friction conditions of metallic surfaces occurring in Common Rail fuel systems. The tribological measurements were conducted under a normal load of 50 N, at a rotational speed of 300 rpm, with a total test duration of 7200 s. A G40 bearing steel ball with a diameter of 4.76 mm was used as the counterbody during the experiments. The test media included pure diesel fuel without additives and diesel fuel blended with summer and winter additives at various mixing ratios. During the measurements, particular attention was paid to the evolution of the coefficient of friction, wear mechanisms, and the width of the generated wear tracks [10].

To compare the effectiveness of individual fuel mixtures, the results of the tribological tests were processed graphically and evaluated in terms of wear intensity. This approach enabled an objective comparison between pure diesel fuel and fuels

containing additives and allowed assessment of their ability to improve fuel lubricity and protect friction surfaces against excessive wear.

Another applied method was material hardness measurement using a QATM QNESS 250 CS evo hardness tester. The measurements were performed using the Vickers hardness method in accordance with ISO 6507-1 (Metallic materials – Vickers hardness test under a test load of 10 kg (HV10). To increase the accuracy and representativeness of the results, ten individual hardness measurements were performed at different locations on the surface of the examined material. The measured values were automatically recorded by the hardness tester and subsequently exported for further evaluation. Hardness testing was used to evaluate the mechanical properties of the examined material and to determine whether material degradation had occurred as a result of operational loading or insufficient lubrication. The measured hardness values were compared with typical values reported for high-pressure fuel pump components, enabling a better interpretation of the observed damage.

By combining visual diagnostics, tribological testing, and non-destructive material analyses, it was possible to comprehensively assess the damage mechanisms of the high-pressure fuel pump while simultaneously verifying the effectiveness of fuel additives in terms of friction and wear reduction. The selected methodology provides a relevant basis for the objective evaluation of the influence of fuel additives on the service life of Common Rail system components and their practical application under operating conditions.

3 Results

This chapter presents the results of the experimental investigation focused on the wear of a high-pressure Common Rail fuel pump and on the verification of the effectiveness of fuel additives. The results are based on visual analysis of the damaged pump, tribological measurements, evaluation of worn surfaces, and material analyses.

Following the visual inspection of the pump, the main cause of damage was identified. As a result of operation and gradual deterioration of the pump condition, seizure of the plunger roller occurred, leading to a rotation of the plunger relative to the camshaft by 90°. Consequently, the rolling motion of the roller along the camshaft was no longer present; instead, point contact loading occurred between the camshaft and the plunger roller contact surfaces. This resulted in excessive wear of these components, as shown in Fig. 1, Fig. 2, and Fig. 5.

For the experimental tests, samples were prepared from the damaged camshaft. Tribological measurements were performed using the pin-on-disk method. The normal load during each measurement was 50 N, the rotational speed was 300 rpm, and the test duration was 120 minutes.

The first tribological measurement focused on evaluating the influence of pure diesel fuel without any additives on the coefficient of friction. The measurement was carried out after applying the fuel into a measuring adapter designed for tribological testing. The aim of this test was to establish a reference friction coefficient curve for subsequent comparison with fuels containing additives.

The measured results indicate that the coefficient of friction did not change significantly during the test. After an initial stabilization phase, the coefficient remained at approximately the same level, with minor fluctuations and local variations. At the beginning of the measurement, a higher coefficient of friction was recorded; however, after several tens of seconds, rapid stabilization occurred. Subsequently, the friction coefficient oscillated around an average value of approximately 0.115.

Throughout the entire measurement duration of 7,200 s, only minor fluctuations in the coefficient of friction were observed, without any pronounced trend of rapid increase or decrease. At the end of the test, the coefficient of friction remained at a level comparable to that observed during the middle phase of the measurement, confirming stable tribological behavior of pure diesel fuel under the given test conditions.

The time dependence of the coefficient of friction for pure diesel fuel is illustrated in Fig. 6, which presents the coefficient of friction values as a function of measurement time. The values plotted in the graph were recorded at regular time intervals and serve as reference data for evaluating the influence of fuel additives on changes in the tribological properties of the fuel in subsequent measurements.

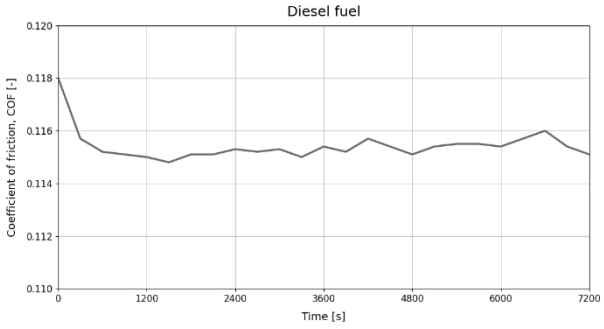


Fig. 7 *Time dependence of the friction coefficient of diesel fuel with a summer additive at a ratio of 1:1000*

The third tribological measurement investigated the influence of a winter fuel additive added to conventional pure diesel fuel at a ratio of 1:1000. The measured results indicate that the time evolution

of the coefficient of friction was less pronounced compared to the previous measurements, with the values fluctuating within a relatively narrow range of approximately 0.002. At the beginning of the test, a higher initial coefficient of friction was recorded; however, during the first few hundred seconds, a rapid decrease occurred, followed by stabilization.

After the initial stabilization phase, the coefficient of friction remained predominantly within the range of approximately 0.095–0.096, with slight, irregular fluctuations. No significant step increase or decrease in the friction coefficient values was observed during the measurement, indicating stable but weakly dynamic tribological behavior of the system. Toward the end of the test, minor oscillations without a clear trend of improvement or deterioration were observed.

In comparison with the measurement performed using the summer additive at the same mixing ratio, the average values of the coefficient of friction did not differ significantly. Similarly to the summer additive measurement, the assumption of a substantial reduction in the coefficient of friction relative to pure diesel fuel was not confirmed. Instead, the friction coefficient values remained at a comparable level, with only minimal differences between the individual measurements.

The course of the third tribological measurement is shown in Fig. 8, which presents the dependence of the coefficient of friction on time. The values were recorded at the same time intervals as in the previous measurements, enabling direct comparison of the results and an objective evaluation of the influence of the winter additive at a mixing ratio of 1:1000.

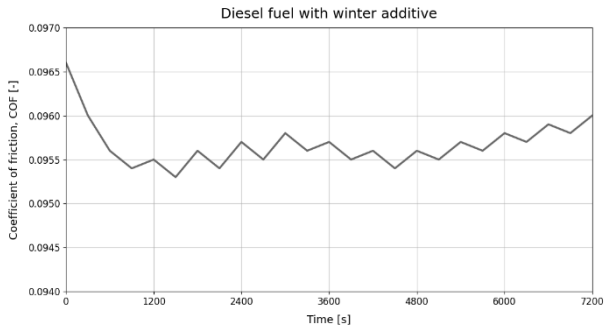


Fig. 8 *Time dependence of the friction coefficient of diesel fuel with a winter additive at a ratio of 1:1000*

The fourth tribological measurement was performed using a summer fuel additive added to conventional pure diesel fuel at a ratio of 1:100, i.e., with a higher additive concentration compared to the previous measurement, where a ratio of 1:1000 was used. The aim of this test was to verify whether an increased additive content would lead to a more pronounced change in the coefficient of friction.

The initial value of the coefficient of friction in this measurement reached approximately 0.094; however, a significant increase in the friction coefficient was observed within the first several tens of seconds. After the initial stabilization phase, the coefficient of friction values were predominantly within the range of approximately 0.096–0.097, with slight fluctuations throughout the measurement.

The measured curve indicates that after the initial increase in the coefficient of friction, a slight decrease occurred in the middle part of the test; however, toward the end of the measurement, an increase in the coefficient of friction was again recorded, with the final measured value reaching approximately 0.097. Overall, the measurement did not exhibit a clear trend of sustained friction coefficient reduction.

In comparison with the measurement conducted at a mixing ratio of 1:1000, no significant improvement in tribological properties was observed. On the contrary, the increased concentration of the summer additive did not result in the expected reduction of the coefficient of friction compared to the measurement with pure diesel fuel. The differences between the individual measurements were relatively small, suggesting that from the perspective of practical application and economic efficiency, a higher additive concentration does not provide a substantial benefit.

The time dependence of the coefficient of friction for the summer additive at a mixing ratio of 1:100 is shown in Fig. 9. The values were recorded at the same time intervals as in the previous measurements, enabling direct comparison of the results.

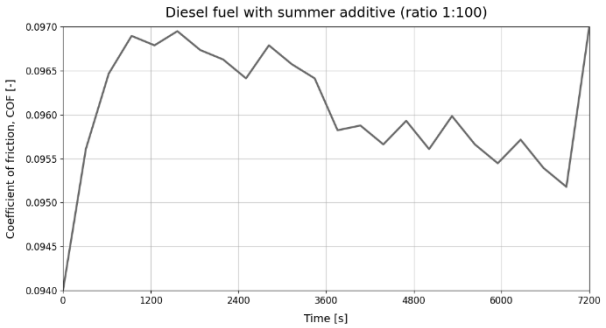


Fig. 9 *Time dependence of the friction coefficient of diesel fuel with a summer additive at a ratio of 1:100*

The final tribological measurement was performed using a winter fuel additive added to conventional pure diesel fuel at a ratio of 1:100, i.e., at an increased additive concentration, analogously to the previous measurement with the summer additive.

The initial value of the coefficient of friction in this measurement reached approximately 0.092; however, a pronounced increase in the friction coefficient was observed within the first few hundred seconds. Up to a time interval of approximately 400 s, the coefficient of friction increased to a value of around 0.095, representing the most significant change during the initial phase of the measurement.

Following this initial increase, a gradual decrease in the coefficient of friction occurred, reaching a minimum approximately in the middle of the measurement, where the values ranged around 0.093–0.094. In the subsequent phase of the test, a smooth and nearly monotonic increase in the coefficient of friction was observed, continuing until approximately 5,000–6,000 s, at which point maximum values approaching 0.095 were recorded.

Toward the end of the measurement, a slight decrease in the coefficient of friction was observed, with the final measured value reaching approximately 0.0945. Overall, the measurement exhibited a gradual, wave-like behavior without abrupt step changes or a clear trend of sustained improvement in tribological properties.

In comparison with measurements performed at lower additive concentrations and with pure diesel fuel, no significant reduction in the coefficient of friction was achieved. Thus, the increased concentration of the winter additive at a ratio of 1:100 did not provide the expected improvement in tribological properties, either from the perspective of practical application or economic efficiency. Consequently, the original hypothesis was not confirmed in this case.

The time dependence of the coefficient of friction for the winter additive at a mixing ratio of 1:100 is shown in Fig. 10.

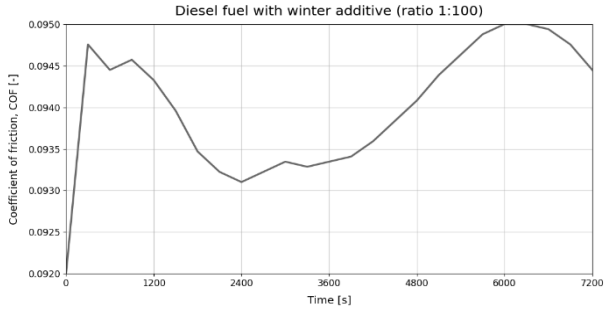


Fig. 10 *Time dependence of the friction coefficient of diesel fuel with a winter additive at a ratio of 1:100*

As part of the experimental investigations, a material hardness test was also performed, the objective of which was to determine the hardness of the material used in the analyzed pump. Hardness measurements were carried out using a QATM Qness 250 CS evo hardness tester employing the Vickers hardness testing method.

The applied load was set to 10 kg, corresponding to the HV10 designation. To increase the accuracy and representativeness of the results, ten individual hardness measurements were performed at different locations on the surface of the examined material. The measured values were automatically recorded by the measuring device and subsequently exported in tabular form.

Based on the measured values, the average material hardness was calculated, reaching a value of 675.1 HV10. Figure 11 shows the location of the hardness measurement on the material surface.

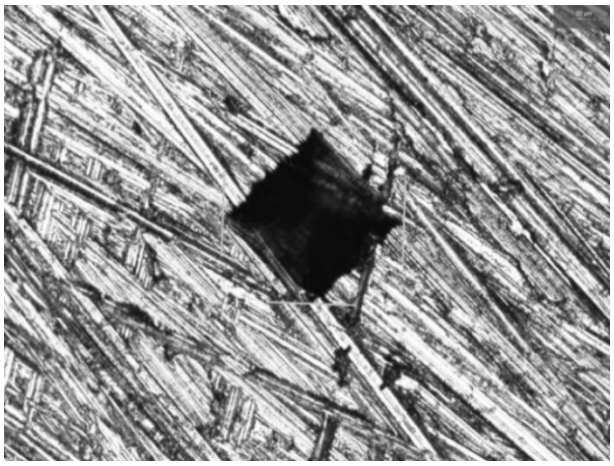


Fig. 11 *Material hardness measurement location*

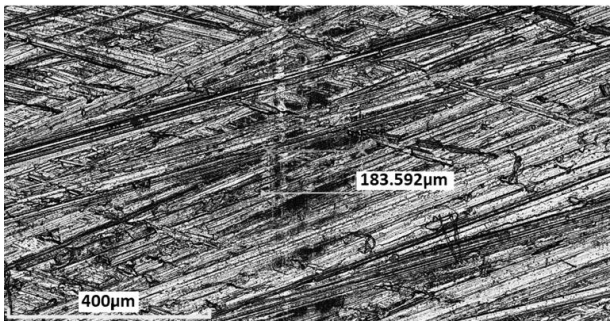


Fig. 12 *Wear track*

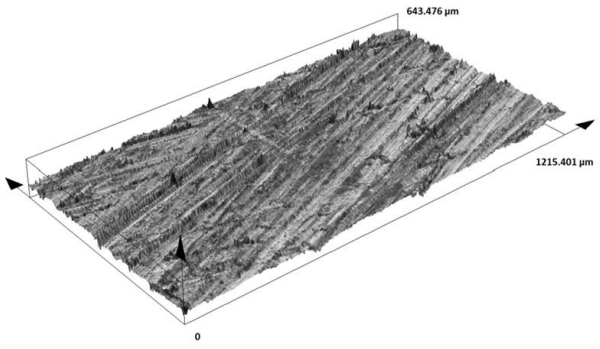


Fig. 13 *Surface topography of the wear track*

As part of the experiment, a visual surface analysis using a confocal microscope was also performed as a complementary method to the tribological measurements. The objective of this analysis was to assess the character and extent of wear on the examined surface after the conducted tests.

However, based on the acquired images, it was not possible to perform a quantitative evaluation of material loss, as the observed changes in surface topography were very small and were close to the resolution limit of the applied method. The material

losses were negligible and did not exhibit sufficient distinctiveness to allow reliable measurement or comparison between individual samples. For this reason, the visual analysis was used only for qualitative surface assessment and was not included in the detailed quantitative evaluation of the results. For illustration purposes, representative images are provided in Fig. 12 and Fig. 13.

4 Discusion and conclusion

The obtained results indicate a complex influence of fuel additives on the tribological behavior of a high-pressure Common Rail fuel pump. Experimental measurements confirmed that diesel fuel without any additives exhibits a relatively stable evolution of the coefficient of friction over the entire measurement period. After an initial stabilization phase, the friction coefficient remained within a narrow range without significant fluctuations, indicating steady tribological conditions under the given load and simulated operating conditions. This behavior was therefore adopted as a reference state for subsequent comparison with fuels containing additives.

- The addition of a summer fuel additive at a ratio of 1:1000 resulted in a reduction of the average coefficient of friction compared to pure diesel fuel. The obtained results suggest that, at the manufacturer-recommended dosage, the summer additive has a positive effect on the lubricating properties of the fuel, manifested by a lower friction level and a stable measurement course. However, no pronounced trend of further friction reduction over time was observed, indicating that after the initial stabilization, the additive effect is mainly reflected in maintaining stable tribological conditions.
- In the case of the winter additive at the same mixing ratio of 1:1000, the coefficient of friction values were distributed within a very narrow interval with minimal dispersion. Although the measurement exhibited stable behavior, the average friction coefficient values did not differ significantly from those obtained with the summer additive. This indicates that, at the recommended mixing ratio, the winter additive does not provide a substantially greater benefit in terms of friction reduction. The results also show that differences between individual additive types are relatively small from a tribological perspective when applied at recommended dosages.
- Increasing the concentration of the summer additive to a ratio of 1:100 did not lead to the expected improvement in tribological properties. On the contrary, the measurement results showed that after an initial increase, the coefficient of friction oscillated at values comparable to those obtained at the lower additive concentration. The increased additive content therefore did not result in a significant reduction in friction, which may be related to saturation of the lubricating effect of the additive components or unfavorable interactions at higher concentrations. This finding demonstrates that higher additive dosages do not automatically result in improved tribological performance of the fuel.
- A similar trend was observed when using the winter additive at a mixing ratio of 1:100. Although a more pronounced increase in the coefficient of friction occurred during the initial phase of the measurement, the subsequent course exhibited a wave-like character without a clear trend of sustained improvement. The maximum friction coefficient values were comparable to those recorded in other measurements, and a slight decrease was observed toward the end of the test. Thus, the increased concentration of the winter additive proved to be ineffective in terms of friction reduction, confirming that excessive additive dosing does not necessarily improve tribological properties of the system.
- The results of the tribological tests correspond well with the visual surface analysis performed using a confocal microscope. Despite observable microstructural surface changes, no measurable material loss was detected, indicating a very low wear rate under the selected test conditions. Consequently, reliable quantitative evaluation of material loss was not possible, and the visual analysis served only as a supplementary qualitative method.

- Material hardness measurements confirmed a high hardness value of the examined material, verifying its suitability for use in high-pressure fuel pump components. At the same time, the results indicate that high material hardness alone is insufficient to compensate for unfavorable tribological conditions caused by inadequate fuel lubricity.
- Based on the obtained results, it can be concluded that the use of fuel additives at manufacturer-recommended dosages may have a moderate positive effect on reducing the coefficient of friction. However, increasing additive concentrations beyond the recommended levels does not provide further improvement in tribological properties and appears ineffective from both practical and economic perspectives. Therefore, the original hypothesis regarding a significant reduction of the coefficient of friction through the use of fuel additives was only partially confirmed.

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