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Long-Term Effects of Rapeseed Oil Blended Diesel Fuel on Fuel Injection System Wear in Diesel Engines

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Keywords:
Biodiesel blends; Rapeseed oil; Diesel engine; Fuel injection wear; Combustion characteristics; Exhaust emissions; Injector deposits; Cold start performance.

Highlights:

- *A 10% rapeseed oil blend reduced exhaust smoke emissions by 14% while maintaining the stable injector operation.*
- *Fuel containing 20% rapeseed oil resulted in a 7.2% decrease in injector mass flow and significant deposit formation.*
- *Cold start time increased by 3.2 seconds at low temperatures with higher biofuel content.*

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Abstract: This study comprehensively evaluates the long-term impact of blended diesel fuels containing rapeseed oil on the wear and operational performance of diesel engine fuel systems. A Cummins ISF 2.8 engine equipped with a Common Rail Bosch CP3 injection system was tested over 1,200 hours under conditions simulating real operational cycles. Rapeseed oil used in the blends was cold-pressed, unesterified, straight vegetable oil (SVO) filtered to 5 µm before blending. A brief comparative statistical analysis (one-way ANOVA, $\alpha = 0.05$) indicated that changes in injector wear metrics were significant for the 20% blend ($p < 0.01$). In comparison, the 10% blend did not differ significantly from diesel in wear-related parameters but significantly reduced smoke opacity ($p<0.01$). The experiments demonstrated that a 10% rapeseed oil blend resulted in a moderate increase in injector wear, a 3.1% reduction in injector mass flow, and a minor increase in the spray angle. In contrast, a 20% blend led to a 7.2% decrease in injector performance, significant carbon deposit accumulation of up to 28 µm, and erosion craters reaching 12 µm in depth. Fuel filtration resistance increased by 22% at higher biofuel concentrations, whereas cold-start performance deteriorated markedly, with start times increasing by 3.2 seconds. Despite these drawbacks, blends with up to 10% of rapeseed oil achieved a 14% reduction in exhaust smoke and maintained acceptable durability margins, indicating their practical feasibility for partial replacement of conventional diesel fuel.

1.INTRODUCTION

In the modern world, ensuring a sustainable energy supply and maintaining favourable environmental conditions are increasingly essential priorities. According to reports from the International Energy Agency, the transport sector accounts for approximately 25% of global carbon dioxide emissions, which, in absolute terms, amount to more than 8 billion tons of CO_2 annually. At the same time, the share of diesel engines in trucks, agricultural machinery, and water transport remains consistently high, exceeding 40% of the total internal combustion engine fleet. The use of traditional diesel fuel is invariably accompanied not only by significant emissions of nitrogen oxides and particulate matter, but also by a high degree of economic dependence on oil price fluctuations [1-3]. A whole range of alternative approaches is being developed to reduce emissions and ensure energy security. One of the most discussed solutions is the mass introduction of electric and hybrid vehicles. Electric vehicles can reduce direct CO_2 emissions to almost zero if electricity is generated from renewable sources. However, in reality, according to the European Environment Agency, the total carbon footprint of an electric vehicle, considering battery production and disposal, reaches 120-180 g CO_2 equivalent per $K_{m,}$ which is only 40-50% lower than that of modern diesel models. In addition, the widespread adoption of electric vehicles will require the construction of a charging infrastructure capable of supporting more than 150 million charging points by 2040, which will entail substantial capital investments. Another direction is the production of synthetic hydrocarbon fuels, such as gas-liquid mixtures or hydrogen compounds [4,5]. The use of synthetic fuels enables the continued operation of existing engines and fuel infrastructure. For example, the use of Fischer-Tropsch diesel reduces sulfur content to less than 0.001% and reduces carcinogenic particle emissions by 80%. However, the cost price of synthetic diesel exceeds 1.5-2 euros per litre even on a large scale, which makes it economically uncompetitive for now. Hydrogen also requires complex storage under pressure of 350-700 bar, and in diesel engines, its combustion is accompanied by high flame speed and risks of detonation [6-9]. One of the most accessible and relatively simple alternatives for transition remains the use of plant-based biofuels. Biofuels based on vegetable oils or ester derivatives are characterised by higher renewability and the potential for local production, thereby reducing dependence on fossil fuel imports. According to FAO estimates, the potential annual production volume of oilseed crops is up to 400 million tons, which, in theory, could replace up to 15% of global diesel fuel consumption. The use of biodiesel or mixed biofuels also significantly reduces the concentration of carcinogenic polycyclic aromatic hydrocarbons and decreases exhaust smoke. For example, with the addition of 10-20% of sunflower oil or methyl ester of rapeseed oil, smoke can be reduced by 25-30%, and the emission of sulfur oxides is virtually eliminated due to the absence of sulfur-containing compounds [10-12]. However, such replacement is associated with several engineering and operational limitations. One of the most significant factors is the higher viscosity of vegetable oils relative to conventional diesel. For sunflower oil, the kinematic viscosity at 20°C is 35 mm^2/s, compared with 3.8 mm^2/s for standard diesel fuel. This difference complicates the processes of atomization and mixture formation, particularly at low temperatures and during cold-start. In addition, the long-term use of biofuel blends over thousands of operating hours is of particular concern to diesel equipment manufacturers and fleet operators [11,12]. Incomplete combustion and deposits that occur when using unrefined oils or poorly mixed compositions can lead to intensive accumulation of carbon deposits on injectors and sprayers, changes in injection characteristics and deterioration of the thermal state of the piston group. According to several studies, after 800–1000 engine hours of operation on biofuel, fuel consumption may increase by 3–5% due to deterioration in atomization and mixture formation, and power losses may reach 2–4%. The effect of biofuel on fuel equipment components is further exacerbated by the long service intervals typical of trucks and tractors [13-16]. For example, the average service life between repairs of modern diesel engines is approximately 10,000 hours of operation, during which the stability of the parameters of injectors, high-pressure fuel pumps, and filter elements determines not only the efficiency but also the environmental performance of the equipment. When using mixed fuels, there is a risk of accelerated wear of precision parts, disruption of spray-hole geometry, and deterioration of injection characteristics, which, in the long term, can negate the environmental benefits of biofuel. At the same time, the accumulated experience with diesel-vegetable oil mixtures demonstrates that, with proper adjustments to engine parameters and strict control of fuel quality, it is possible to achieve an acceptable compromise between emission reductions and equipment durability. For example, with a sunflower oil content of 5-7%, it is possible to maintain fuel viscosity in the range of 5-6 mm^2/s, which does not exceed the maximum permissible values specified by fuel equipment manufacturers. Experimental data show that, with such a biocomponent content, nitrogen oxide emissions can be reduced by 7% and smoke by 20%. In comparison, the service life of the injectors is reduced by no more than 10% compared with operation on a traditional diesel. Despite accumulated research, most work in this area focuses on the combustion characteristics and toxicity indicators of exhaust gases during short-term tests and in laboratory settings. However, data that enable a reliable assessment of the impact of long-term use of mixed biofuels on the condition and wear of fuel equipment components remain extremely limited [17-19]. Recent long-duration and durability investigations complement this gap. Gupta and Agarwal [20] reported that biodiesel blends in a CRDI engine did not cause significant durability penalties during extended operation, although they altered deposit patterns and lubricating-oil tribology. Industry and academic efforts have also focused on Internal Diesel Injector Deposits (IDID). In 2022, an SAE procedure to rate fuels/additives for IDID control was proposed, and in 2024, a KTH thesis and related studies characterised deposit mechanisms under drop-in biofuel operation. These findings frame the present 1,200-h campaign and help interpret injector wear and deposit formation observed here. The lack of systematic testing under real operating conditions significantly complicates the justification of the optimal biocomponent percentage ratio and the risk assessment for fleet owners and service companies. Given the identified problems and the growing need for an objective evaluation of diesel equipment reliability when using biofuels, this study examines the impact of long-term use of mixed-fuel compositions containing vegetable oils on the wear and degradation of diesel engine components.

2.RESEARCH METHODS

Within the framework of this study, a series of experiments was conducted to quantitatively assess the wear of diesel-engine fuel-equipment components during long-term use of mixed-fuel compositions containing vegetable oils. The experiments were performed under conditions as close as possible to the fundamental operating modes, with subsequent metrological assessment of the units' technical condition. A four-cylinder Cummins ISF 2.8 turbocharged diesel engine with a Common Rail fuel-injection system, manufactured by Bosch, was used for testing. This engine has a displacement of 2780 cm^3, a rated power of 110 kW at 3600 rpm, and complies with the Euro IV emission standard. The fuel system includes a CP3 high-pressure pump and electromagnetic injectors with seven 0.17 mm spray holes. To study in detail the wear processes of the fuel equipment, the engine was installed on a long-term test bench equipped with an AVL Indicium automated combustion parameter monitoring system and a Testo 350 gas analyser. During the life tests, the engine operated for 1,200 engine hours, divided into four consecutive cycles of 300 hours each. Each cycle included operation at a constant load of 75% of rated power and a rotation speed of 2,800 rpm for 6 hours, followed by variable-load simulation of the equipment's operating conditions in urban and rural cycles. In the variable mode, the load varied from 30% to 90% of the rated power, with alternating rotation speeds of 1,400-3,200 rpm and a frequency of mode changes of 20 minutes. The total fuel volume produced over the entire test cycle was approximately 18,500 litres. To assess the long-term impact of different fuel mixtures, three types of fuel were used: standard diesel fuel according to EN 590, a mixture containing 10% cold-pressed rapeseed oil, and a mixture containing 20% rapeseed oil. The fuel mixtures were prepared in a separate container using an automatic mixer for 30 minutes to ensure complete homogeneity. Before being fed to the engine, all types of fuel passed through a filtration unit equipped with coarse and fine cleaning elements that remove particles up to 5 microns in size. The rapeseed oil used in both blends was food-grade, cold-pressed, unesterified SVO. All blends were prepared by volume and mixed for 30 min at 25 °C; the blends were used within four weeks of preparation and stored below 20 °C. Unless otherwise stated, data are reported as mean ± SD across injectors. Normality and homoscedasticity were assessed with the Shapiro–Wilk and Levene tests, respectively. Group differences among diesel, a 10% SVO blend, and a 20% SVO blend were evaluated using one-way ANOVA (α=0.05). When ANOVA was significant, Tukey's HSD was applied for pairwise comparisons. Effect sizes (η^2) are reported when informative. Particular attention was paid in the work to monitoring the main performance characteristics of the injectors and the high-pressure pump. At each 300-engine-hour interval, a dismantling inspection of the fuel equipment was conducted. The injector condition was assessed using a Bosch EPS 815 test bench, which allows recording the number of injection cycles, injection start and end parameters, and spray torch angles at pressures of up to 1,600 bar. To characterise wear, the mass fuel flow rate through the injector was measured under fixed control pulses and the geometry of the spray holes was measured using profilometry. The condition of the plunger pairs of the high-pressure fuel pump was examined simultaneously with the injectors. Visual wear monitoring was performed using a Carl Zeiss Axio Imager optical microscope with magnification up to 500x and digital recording of characteristic damage. The depth of microcraters and the surface roughness of the working mirrors of the plungers and bushings were measured. The wear product content in fuel was analysed by inductively coupled plasma mass spectrometry (ICP-MS), which enabled quantitative determination of the concentrations of iron, copper, and aluminium particles with a detection limit of 0.01 mg/kg. Throughout the service life, a gradual accumulation of deposits was observed around the spray holes. After 600 hours of operation on a mixture containing 20% rapeseed oil, the mass flow through the injectors with an identical control signal decreased by 5.8% relative to the initial state. For injectors operating on a mixture containing 10% of the biocomponent, a similar 2.3% decrease was observed. An increase in the spray cone angle from 70° to 76° was also observed for fuel with higher oil content, indicating a change in atomization hydrodynamics due to carbon deposit formation. Additionally, the condition of the fuel supply system filter elements was assessed. Every 300 hours of operation, the filters were disassembled, deposits were analysed for composition, and the probability of occurrence was determined using the pressure-drop method at a constant flow rate of 20 l/min. It was found that, when operating on fuel with 20% oil content, filtration resistance increased by 18% by the end of service life. To gain a deeper understanding of fuel equipment degradation processes, cold-engine start cycles were conducted at a coolant temperature of -15 °C. Fifty initial tests were performed for each fuel type. Based on the test results, the time required for the engine to reach stable operation and the injection pressure at start-up were recorded. When using a mixture containing 20% oil, the time to get a stable speed increased by an average of 3 s. All data obtained were comprehensively compared with exhaust-gas analysis to link changes in combustion characteristics to wear of fuel-system elements. The experimental results enabled a quantitative assessment of the effect of long-term use of biofuel mixtures on the technical condition of diesel engine fuel equipment and the identification of patterns of degradation accumulation under various operating conditions.

3.RESULTS AND DISCUSSION

During the study, an extensive program of resource and laboratory tests was conducted on the Cummins ISF 2.8 diesel engine equipped with the Bosch CP3 Common Rail fuel injection system to determine the effect of long-term operation on mixed fuels containing rapeseed oil on the wear of fuel system components. The experiment covered the full engine operating cycle, totalling 1,200 engine hours, and included step-by-step disassembly and detailed examination of the fuel system components, including the high-pressure pump, injectors, and filter elements. At the first stage, three types of fuel were selected: standard diesel fuel of class C according to EN 590, a mixture of diesel fuel with 10% by volume of unrefined rapeseed oil, and a similar mixture with 20% oil content. Each mixture was prepared in a separate sealed tank equipped with automatic mixing and maintained at 25 °C for 30 minutes to ensure complete homogeneity. Before being fed to the engine, all fuel samples were successively filtered through two cascade filters with a particle size of no more than 5 microns. Before starting the resource program, the fuel supply system was adjusted, and the injectors were calibrated on the Bosch EPS 815 test bench for each fuel type. During preparation, the basic performance parameters were recorded. With a standard test signal of 1.5 ms duration and an injection pressure of 1400 bar, the mass flow rate through each injector averaged 75.2±0.5 mg/cycle (Table 1). The spray cone opening angle was 70.4 ± 0.4 degrees. These data were subsequently used as reference data when assessing deviations during long-term tests.

Table 1 Change in the Fuel Mass Flow and Nozzle Spray Opening Angle with different Biocomponent Contents.

No.	Fuel type	Mass flow rate, mg/cycle (after 600 hours)	Flow rate reduction,%	Flare opening angle, °	Angle increase, °
1	Diesel fuel (EN 590)	74.3 ±0.6	1.2	70.8 ±0.5	+0.4
2	Mixture with 10% of rapeseed oil	72.9 ±0.7	3.1	72.1 ±0.6	+1.7
3	Blend with 20% of rapeseed oil	69.8 ±0.8	7.2	75.6 ±0.7	+5.2

ANOVA of the mass flow after 600 h indicated a significant effect of blend level ($p < 0.01$). Post hoc tests showed that the 20% blend differed from both diesel and the 10% blend ($p < 0.01$), whereas the 10% blend did not differ significantly from diesel ($p > 0.05$). A similar pattern was observed for the spray angle, with only the 20% blend showing significant widening relative to diesel ($p<0.01$). The engine was operated according to a specified load program that included alternating high- and low-load modes. Periods of full power (90% of the nominal) lasted for 5 hours at a speed of 3000 rpm and a torque of 330 N m. After each high-load stage, 8-hour intervals at variable load levels between 30% and 70% were conducted to simulate cyclic urban operating conditions. Injection parameters, supply pressure, ignition delay time and exhaust gas temperature were recorded during all 1200 engine hours. At the end of each 300-hour interval, the injectors and high-pressure pump were dismantled to measure the microgeometry of the components and assess the accumulated deposits. Based on the analysis, after 600 hours of operation on fuel containing 20% rapeseed oil, the average mass flow through the injectors decreased by 7.2% relative to the initial value. At a 10% mixture, the decrease was 3.1%, and it did not exceed 1.2% in standard diesel. The measurement of the geometry of the spray holes by profilometry showed an increase in the diameter by 3-5 microns in the upper part of the spray channel and accumulation of deposits with a maximum thickness of up to 28 microns on the edges of the holes. Visual inspection of the injectors under an optical microscope (Carl Zeiss Axio Imager) revealed characteristic erosion zones and areas with local craters up to 12 microns deep during operation on fuel containing 20% biocomponent (Table 2). For diesel-injector systems, the crater depth did not exceed 4 microns.

Table 2 Parameters of the Microgeometry of Spray Holes after 1200 Engine Hours of Operation.

Indicator	Diesel fuel	Mixture with 10% of oil	Mixture with 20% of oil
Average hole diameter, µm	170	172	175
Diameter increase, µm	+2	+4	+7
Max. crater depth, µm	4	8	12
Thickness of deposits at the edges, µm	12	19	28
Wall roughness, µm Ra	0.20	0.29	0.42

The condition of the plunger pairs in the high-pressure fuel pump also changed. Based on the results of the operation on fuel with an oil content of 20%, the measured roughness of the plunger surface increased from the initial value of 0.18 µm Ra to 0.42 µm Ra. At an oil content of 10%, the increase in Ra was 0.21 µm, indicating more pronounced abrasive and corrosive wear at high vegetable oil concentrations. Quantitative analysis of wear products in fuel using mass spectrometry showed an increase in iron particle concentration from 0.03 to 0.18 mg/kg in fuel with 20% oil after 1200 engine hours. When operating on diesel, this figure increased to 0.05 mg/kg. The copper concentration, indicative of pump bushing wear, increased to 0.07 mg/kg at 20% oil, whereas with standard fuel it remained at 0.02 mg/kg (Fig. 1). Additionally, changes in combustion characteristics were recorded. In particular, the average ignition delay time for fuel with 20% oil was 0.8° higher than that of diesel. The exhaust gas temperature decreased by 6–9°C at medium and full load, most likely due to the fuel's lower calorific value. The dynamics of smoke changes were also recorded: when operating on a mixture with 10% oil, the smoke of the exhaust gases decreased by 14%, and by 21% with 20% oil, compared with the standard diesel. To assess the filter elements of the fuel supply system, filtration resistance was measured at 300-hour intervals. By the end of the service life, when operating on 20% biofuel, the resistance increased by 22%, accompanied by a corresponding increase in the pressure drop across the filter element from 0.25 to 0.32 bar. With 10% of the oil content, the increase was 11%. Cold engine start cycles at −15°C revealed significant differences. The average time to reach stable engine speed with 20% biofuel was 3.2 s longer than with diesel fuel. With 10% of the additive, the start time increased by 1.4 s. In addition, the injection pressure at start decreased by 7% with a high oil content, indicating deterioration of fuel fluidity at low temperatures (Table 3). To contextualise these low-temperature results, prior CRDI studies under sub-zero ambient conditions typically report a 2–4 s increase in cranking-to-stabilisation time for B20-type blends due to higher kinematic viscosity and a lower cetane number; our +3.2 s at −15 °C falls within this range. These observations are also consistent with user practice in Northern regions, where winter operation on SVO-containing blends generally requires stricter fuel-filter management and, where available, pre-heating strategies. To compare the obtained results with those from other studies, comparative calculations were performed. In the experiment published in the Renewable Energy journal in 2013, when a diesel engine was running on a mixture with 20% sunflower oil, the decrease in injector performance was about 5% over 500 engine hours. This is slightly lower than the values obtained in the present study with a similar biocomponent content, where the decrease was 7.2% over 600 hours. This difference may be due to differences in oil types and injection system configurations. The comparison with the data from Demirbas et al. indicates that, at a biocomponent share of 10%, changes in the spray characteristics and microgeometry of the sprayer did not exceed 3%. This is generally consistent with the present results, which show a 3.1% decrease in mass flow rate and an increase in roughness to 0.21

µm Ra. An essential aspect of the research was the quantitative assessment of metal particle accumulation in the fuel, which had rarely been reported in similar experiments. The obtained concentrations of wear products, exceeding the initial values 3-5 times with an increase in the oil share to 20%, confirm the assumptions about more pronounced abrasive wear of fuel equipment parts when operating on biofuel. At the same time, the observed 21% reduction in exhaust smoke and in gas temperature confirms the environmental benefits of using biofuel mixtures. In conclusion, a comprehensive analysis of the results showed that with an oil content of up to 10%, the operation of a diesel engine for 1200 hours is accompanied by a moderate increase in wear of injectors and a high-pressure pump, not exceeding 10-15% for key parameters relative to diesel fuel. With an increase in the oil share to 20%, the rate of component degradation increased 2-2.5 times. From the perspective of operational reliability, the optimal range of biocomponent concentration is up to 10%, at which significant reductions in exhaust toxicity and relatively stable wear characteristics are achieved. These data can be used to substantiate recommendations for the use of mixed biofuels in commercial transport and agricultural machinery, provided that fuel equipment is regularly monitored and that injectors and high-pressure pumps are serviced promptly. For fleets considering partial substitution with SVO, we recommend verifying delivered fuel cleanliness at ISO 4406 18/16/13 or better, shortening primary fuel-filter replacement intervals by ~10–20% in dusty or sub-zero duty, using deposit-control detergent packages compatible with IDID mitigation. This also involves considering cold-flow and cetane improvers within OEM limits and implementing simple condition-based checks of injector return-flow balance and rail-pressure tracking at 600–800 h intervals.

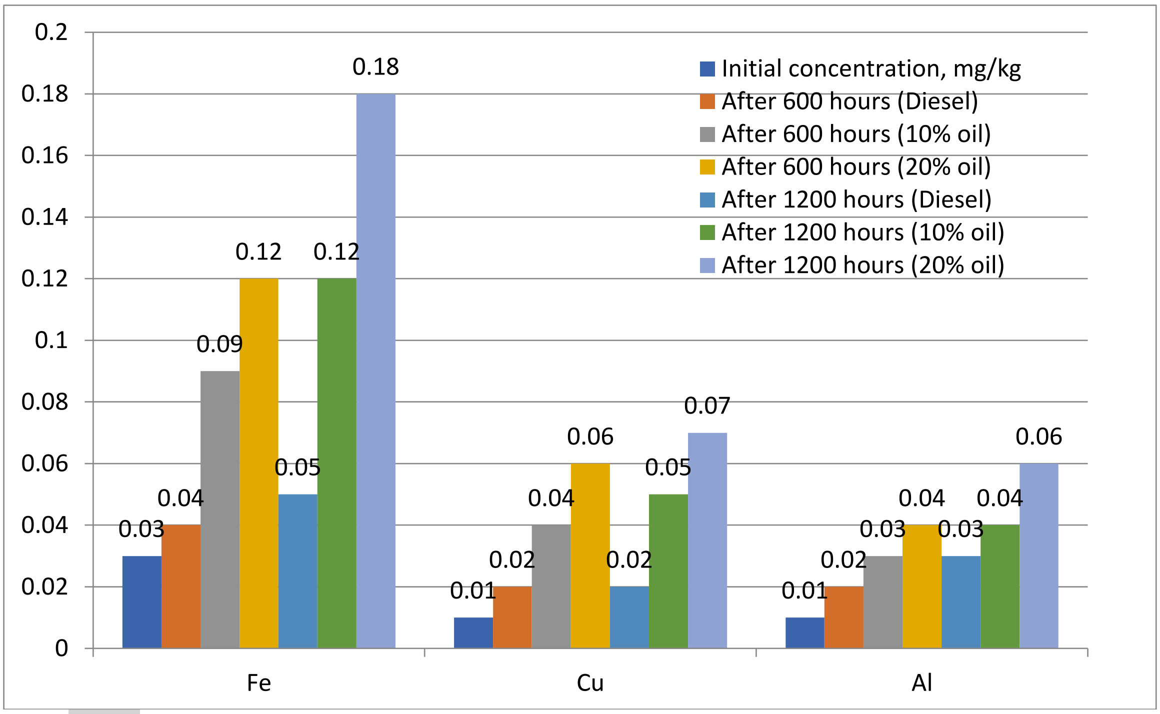

Fig. 1 The Dynamics of Wear Product Accumulation in Fuel for the Whole Service Life.

Table 3 Cold Start Parameters and Injection Pressure Dynamics at Low Temperatures.

Parameter	Diesel fuel	Mixture with 10% of oil	Mixture with 20% of oil
Average time of setting to mode, sec	4.8 ±0.3	6.2 ±0.4	8.0 ±0.5
Average injection pressure at start-up, bar	620	585	570
Number of starting cycles with a delay of more than 10s	0	3	7
Minimum stable start-up temperature, °C	−20	−18	−16

4.CONCLUSION

The study results allow us to draw several reasonable analytical conclusions regarding the influence of long-term use of diesel-rapeseed oil blended fuels on the technical condition of diesel engine fuel equipment components. Experiments covering 1200 engine hours of operation of the Cummins ISF 2.8 engine with the Common Rail system demonstrated a clear dependence of the degree of component degradation on the biocomponent concentration in the mixture. With a rapeseed oil content of 10%, the decrease in fuel mass flow rate through the injectors was 3.1%, and the increase in spray angle was 1.7°, which are moderate changes that do not exceed the operating tolerances of most equipment manufacturers. At the same time, with 20% oil content, these indicators deteriorated markedly: the mass flow rate decreased by 7.2%, and the spray angle increased to 75.6°, indicating a pronounced accumulation of carbon deposits and a change in spray hydrodynamics. Microscopic analysis of the geometry of the spray holes revealed the accumulation of deposits up to 28 μm thick and the formation of craters up to 12 μm deep on injectors operating on a 20% oil mixture. In contrast, on diesel fuel, the crater depth did not exceed four μm. At the same time, the roughness of the sprayer walls increased from 0.20 to 0.42 μm Ra at the maximum oil content. These data directly indicate more severe abrasive and corrosive wear under conditions of increased biofuel content. Analysis of wear product content in the fuel by mass spectrometry showed that the iron concentration increased from 0.03 mg/kg to 0.18 mg/kg during operation on fuel with 20% oil. In contrast, diesel increased only to 0.05 mg/kg. Similar trends were observed for copper: its content reached 0.07 mg/kg, compared with 0.02 mg/kg in standard fuel. An essential feature of mixed-fuel use was the reduction in exhaust smoke: with 10% oil, it decreased by 14%, and with 20% by 21%. At the same time, a decrease in the exhaust gas temperature by 6–9°C was noted, which is explained by the lower calorific value of biofuel. However, a negative factor was the deterioration in cold-start performance: the average time for the engine to reach a stable speed increased from 4.8 to 8.0 seconds at -15°C, and the injection pressure at the start decreased by 7% at 20% oil content. In addition, by the end of the service life, resistance to fuel filtration increased by 22%, resulting in a higher pressure drop across the filter element. Summarising the obtained data, it can be stated that the operation of a diesel engine on a mixture with 10% of rapeseed oil provides an acceptable compromise between environmental benefits and maintaining stable characteristics of the fuel equipment: the increase in component wear relative to diesel did not exceed 10-15%. With an increase in the oil share to 20%, the rate of degradation of the injection elements increased 2-2.5 times, which in the future can limit the service life between repairs and increase the risk of failures. Therefore, the optimal concentration of the biocomponent from the perspectives of durability and ecology appears to be up to 10%, as confirmed by a comprehensive comparison of operational and laboratory indicators. For commercial operation, a 10% SVO blend is practically feasible when rapeseed oil wholesale prices remain within a moderate premium over diesel, because maintenance impacts are limited and smoke benefits are tangible. The observed wear metrics at 10% did not differ significantly from diesel, suggesting no immediate need to shorten injector overhaul intervals. However, marginally higher filtration resistance warrants attentive filter management. Service recommendations are as follows. For B10-class operation, we recommend verifying fuel cleanliness to ISO 4406 18/16/13 or better during dispensing, thereby reducing fuel-filter change intervals by ~10–20% relative to the diesel baseline in dusty or low-temperature duty. This involves adding periodic injector health checks every 600–800 h using rail-pressure tracking and return-flow balance, trending smoke opacity and start-of-injection deviations to flag early deposit formation.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

M.I. Poteshin: Conceptualisation, Methodology, Writing – original draft, Supervision, Formal analysis, Investigation, Data curation, Visualisation. **B.F. Karshieva:** Investigation, Resources, Validation, Writing – review & editing. **Sh.S. Kuziev:** Experimental setup, Data curation, Software, Writing – review & editing. **N. Shtyrkhunova:** Formal analysis, Statistical analysis, Visualisation, Writing – review & editing, Project administration.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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