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Leszek GIL[*], **Daniel PIENIAK**[**], **Edward KOZŁOWSKI**[***], **Jarosław SELECH**[****]

IMPACT OF SELECTED BIOFUELS AND DIESEL AS LUBRICANTS ON THE STATISTICAL DISTRIBUTION AND COURSE OF SLIDING FRICTION COEFFICIENTS FOR THE KINEMATIC PAIR 100Cr6-100Cr6

WPŁYW WYBRANYCH BIOPALIW I OLEJU NAPĘDOWEGO JAKO MEDIÓW SMARUJĄCYCH NA STATYSTYCZNY ROZKŁAD I PRZEBIEG WSPÓŁCZYNNIKÓW TARCIA ŚLIZGOWEGO DLA PARY KINEMATYCZNEJ 100Cr6-100Cr6

Key words: renewable motor fuels (biofuels), mixed friction, ball-disc method.

Abstract One of the functions of engine fuels is the lubrication of engine injection equipment components. The elements of the injection system are lubricated only with the fuel used to power the engine; therefore, the lubricity and its impact on the elements of the engine injection system are an important issue. The share of biofuels to power internal combustion engines is constantly increasing, because EU Member States are required to use fuel with the addition of biocomponents to power vehicle engines. These fuels are more ecological compared to petroleum fuels. Therefore, it is also necessary to identify the lubricating properties of these fuels, which can significantly affect wear processes.

In order to identify wear indicators, laboratory tests were carried out to determine the lubricating properties of biofuels based on vegetable oils in relation to diesel fuel. Tribological tests were carried out for the ball-disc friction node of 100Cr6 material, which is most often used in the construction of precision pairs of injection equipment. Comparative tests were carried out for samples immersed in a fuel bath on a CSM tribometer. The friction coefficient waveforms as a function of friction distance and sample load were determined. The measured force values indicate a significant impact of the fuel used on the operating conditions and consumption in the kinematic pair being the subject of the work.

Słowa kluczowe: paliwa silnikowe odnawialne (biopaliwa), tarcie mieszane, metoda kula–tarcza.

Streszczenie Jedną z funkcji paliw silnikowych jest smarowanie elementów aparatury wtryskowej silnika. Elementy układu wtryskowego są smarowane jedynie paliwem służącym do zasilania silnika, dlatego ważną kwestią jest smarność paliwa i jej wpływ na elementy układu wtryskowego silnika. Udział biopaliw do zasilania silników spalinowych ciągle wzrasta, ponieważ państwa członkowskie Unii Europejskiej mają obowiązek stosowania do zasilania silników samochodowych paliwa z dodatkiem biokomponentów. Paliwa te są bardziej ekologiczne w porównaniu z paliwami ropopochodnymi. Wobec tego też istnieje konieczność identyfikacji właściwości smarnych tych paliw, które istotnie mogą wpłynąć na procesy zużycia.

W celu identyfikacji wskaźników zużycia wykonano własne badania laboratoryjne, których celem było określenie właściwości smarnych biopaliwa na bazie olejów roślinnych w odniesieniu do oleju napędowego. Wykonano testy tribologiczne dla skojarzenia węzła tarcia kula–tarcza materiału 100Cr6, który najczęściej wykorzystywany jest w konstrukcji elementów par precyzyjnych aparatury wtryskowej. Badania porównawcze przeprowadzono dla próbek zanurzonych w kąpieli paliw na tribometrze CSM. Określono przebiegi współczynnika tarcia w funkcji drogi tarcia i obciążenia próbek. Zmierzone wielkości siły wskazują na istotny wpływ stosowanego paliwa na warunki pracy i zużycie w parze kinematycznej będącej przedmiotem pracy.

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[*] ORCID: 0000-0001-8978-7388. University of Economics and Innovations in Lublin, Faculty of Transport and Computer Science, 4 Projektowa St, 20-209 Lublin, Poland, e-mail: leszek.gil@wsei.lublin.pl.

[**] ORCID: 0000-0001-7807-3515. University of Economics and Innovations in Lublin, Faculty of Transport and Computer Science, 4 Projektowa St., 20-209 Lublin, Poland, e-mail: danielp60@o2.pl.

[***] ORCID: 0000-0002-7147-4903. Lublin University of Technology, Department of Quantitative Methods in Management, 38 Nadbystrzycka St., 20-618 Lublin, Poland, e-mail: e.kozlovski@pollub.pl.

[****] ORCID: 0000-0002-2656-3800. University of Technology, Faculty of Transport Engineering, 3 Piotrowo St., 60-965 Poznań, Poland, e-mail: jaroslaw.selech@put.poznan.pl.

INTRODUCTION

European Union countries are required to use liquid biofuels to power traction engines in road transport. The main purpose of this action is to reduce oil consumption and reduce greenhouse gas emissions. In Europe and Poland, for the climatic and agrotechnical reasons, rapeseed oil methyl esters and their mixtures with diesel fuel are most often used as liquid biofuels.

The use of vegetable fuels causes controversial opinions on the impact of their use on the technical condition of engines. The biggest differences concern the change in viscosity and behaviour of the fuel at low temperatures, especially negative. A particularly important parameter is kinematic viscosity, which determines the process of atomizing fuel and sealing and lubrication of precision vapours. Tribological processes are one of the most important causes of operational damage to the injection apparatus of compression-ignition engines. In compression-ignition engines (ZS), fuel is not only an energy medium, but also a lubricant for the cooperating elements of the injection system. Fuel, which is a lubricant, should have adequate viscosity and lubricity. The viscosity of the fuel cannot be too high because it hinders the process of atomizing the fuel during injection, but it should also not be too low due to the conditions of creating a lubricating oil film affecting the wear of mating elements.

Diagnosis and assessment of precision steam – piston – cylinder consumption is a difficult undertaking, requiring good knowledge of the construction and operation of fuel apparatus and extensive experience in the technological processing of cooperating parts. Tests of the wear of precisely made kinematic pairs of injection pump associated with the need to disassemble it. Each disassembly interferes with the cooperation of matched pairs and limits the possibility of accurate prospective wear of the pressing sections. Precision pairs stand out from other fuel apparatus components with very precise workmanship and small gaps, they are individually fitted elements.

In technology, the main directions of activities aimed at minimizing friction wear are the following:

- The modification of cooperating surfaces, usually by hardening the surface layer; and,
- The use of lubricants to replace dry friction with liquid friction.

The hard surface of the element is subjected to slower abrasion, and the lubricated surfaces are subjected to less wear if a lubricating film is formed between them or friction occurs between the surfaces covered with a lubricant boundary layer.

The boundary layer strongly bound to the substrate is formed by adhesion forces due to the molecular interaction of atoms on the steel surface with lubricant particles. The polar structure of lubricating particles promotes the formation of the boundary layer. In diesel engines, fuel is the only source of lubrication for precisely matched injection system components. Therefore, lubricity of the fuel is important here, which determines its ability to produce boundary layer strongly bound with the lubricated surface **[L. 9]**.

Chemically, the boundary layer consists of hydrocarbon chains „attached" to the steel surface with a polar carboxyl group. This group is characteristic for carboxylic acids; therefore, the acidification of fuel improves its ability to produce a boundary layer. The boundary layer protects the mating surfaces against wear in the absence of a lubricating film. The use of new fuels such as biofuels requires conducting preliminary tests on the elements of the injection apparatus and engine tests. During the operation of an internal combustion engine, the elements of the fuel system are subject to comprehensive mechanical, chemical, and thermal loads resulting in functional changes of individual components of this system. In the case of injection pumps, the working surfaces of the cylinder and piston of the pressure section are particularly intensively worn, as well as the surfaces of the stop cone of the pump pressure valve **[L. 1, 2]**. In addition, impurities in the fuel, which get through the filter system, have a negative impact on wear. The abrasive action of pollutants in the fuel and active chemical compounds intensify the wear process **[L. 7]**. Most of the available research has a beneficial tribological effect on biodiesel, but some studies have shown some negative effects. The impact of the fuels used should be subject to subsequent analysis **[L. 10]**.

PHYSICO-CHEMICAL CHARACTERISTICS OF THE ANALYSED FUELS

Four types of fuel were used in the presented research. The first one was generally commercially available pure diesel fuel meeting the requirements of PN-EN 590: 2009 standard „Fuels for motor vehicles. Diesel oils. Requirements and test methods". The reason for choosing diesel was the fact that it is the most commonly used fuel. The second fuel used was rapeseed oil esters that are also available at service stations. The third fuel was linseed oil methyl esters, whose measured parameters were compared with the requirements of ASTM D 6751-06b and PN-EN 14214: 2009 „Automotive fuels. Fatty acid methyl esters (FAME) for compression ignition engines (Diesel). Requirements and test methods". Sunflower oil esters were the fourth fuel tested. Pure methyl esters produced in the esterification process were used in the research. Selected properties of fuels used for the tests are presented in **Table 1**.

Table 1. Selected properties of diesel fuel and methyl esters of vegetable oils [L. 4, 6]
Tabela 1. Wybrane własności oleju napędowego i estrów metylowych olejów roślinnych **[L. 4, 6]**

Oil	Density at 20°C [Kg/dm³]	Energy value [MJ/kg]	Kinematic viscosity at 40°C [mm²/s]	Cetane number	Freezing temperature about [°C]	Ignition temperature [°C]
ON (without FAME)	0.84	42.7	2.0–4.5	50	Below –20	80
Linseed oil methyl esters	0.88	37.5	5.18	52	–16	–
Rapeseed oil methyl esters	0.88	38	5.20	45 –59	–5	ca. 170
Sunflower oil methyl esters	0.88	–	–	–	–6	ca. 170

RESEARCH METHODOLOGY

Friction tests

The wear test was conducted using the „ball-on-disc" method, which measured the coefficient of friction and wear. Devices of this type, similarly to the HFRR system, used mainly for testing fuels, are used primarily for testing the properties of lubricants and materials in conditions of repeated sliding movement. The tribometer used enabled the registration of friction resistance expressed by a friction coefficient with high sampling frequency and measurement accuracy, which is not possible at the HFRR stand. Statistical correlation between friction resistance and wear were sought in this study. A tribometer (CSM Instruments) was used for the tests, and the tests were carried out with a load of 2 N, the slip speed was set at 0.05 m/s, and the counter-sample friction path (ball 6 mm in diameter made of 100Cr6 steel) and the tested sample (disc 30 mm in diameter and thickness 6 mm made of 100Cr6 steel) was 1500 m. The samples were tested immersed in fuel, which was heated to 60°C during the tests **(Fig. 1)**. Four types of fuel for diesel engines were used: ON – diesel, LME (EL) – linseed oil methyl esters, SME (ES) – sunflower oil methyl esters and RME (RZE) – rapeseed oil methyl esters. The friction coefficient (COF) and the friction force (F_T) and linear wear (Pd) were recorded.

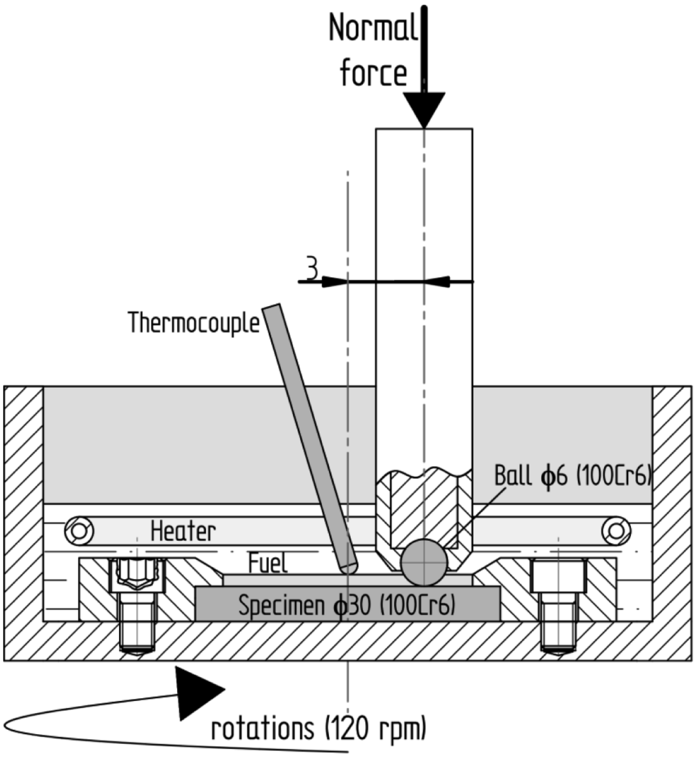

Fig. 1. Schematic illustration of the friction node
Rys. 1. Schematyczna ilustracja węzła tarcia

Study of the significance of fuel friction differences

The verification of the significance of differences in fuel friction coefficients was carried out using the Kolmogorov-Smirnov test and the Kruskal-Wallis rank test. Let them $\left\{c_t^j\right\}_{t\in N}$ be sequences of fuel friction coefficient values ($j \in \{1, 2, 3, 4\}$, 1 – „LME”, 2 – „SME”, 3 – „RME”, 4 – „ON”) obtained on the basis of studies. An empirical cumulative distribution function has been designated for each of the fuels. For fuel j–, we designate the fuel distributor using the formula

$$F_j(t) = \begin{cases} 0, & \mathrm{t} < c_{(1)}^{j}, \\ \frac{\mathrm{k}}{\mathrm{p}}, & c_{(k)}^{j} \leq \mathrm{t} < c_{(k+1)}^{j}, \\ 1, & c_{(p)}^{j} \leq \mathrm{t}, \end{cases} \tag{1}$$

where $p \in N$ is the sample size taken into account.

The Kolmogorov-Smirnov test was used to compare empirical distributions of friction coefficient values for different fuels. At the level of significance $\alpha \in (0, 1)$, we create a working hypothesis:

H_0: fraction coefficients for fuels and are identical and the alternative hypothesis:

H_1: coefficients of friction coefficients differ significantly.

The test statistics are given by the following formula (5):

$$D_{ij} = max_{t \geq 0}\left|F_i(t) - F_j(t)\right| \tag{2}$$

for $i, j \in \{1, 2, 3, 4\}$.

Statistics D mean the biggest difference between fuel and fuel distributors i and j. The statistics D has a distribution of Kolmogorov, where $F_i(t)$ and $F_j(t)$ denote cumulative distributions (fuels) for fuels i and j respectively. From the tables for the significance level α, we determine the critical value for statistics. If $\sqrt{\frac{p+q}{pq}}D_{ij} > K_\alpha$ (values p and q denote sample numbers for fuels i and j respectively), we reject the null hypothesis H_0 in favour of the alternative hypothesis H_1.

To compare the friction coefficient distributions for different fuels, the Kruskal-Wallis test was also performed. (In general, the Kruskal-Wallis test can be used to compare distributions for many populations; however, the above test was used to make comparisons between groups.) For each fuel group $i, j \in \{1, 2, 3, 4\}$, $i \neq j$ at the level of significance α ∈ (0, 1), we create a working hypothesis:

H_0: fraction coefficients for fuels and are identical and the alternative hypothesis:

H_1: coefficients of friction coefficients differ significantly.

To determine the test statistics of the Kruskal-Wallis test, we first determine the sum of the ranks R_i and R_j for groups i and j. The test statistics is given by the following formula (6):

$$T_{ij} = \frac{12}{(p+q)(p+q+1)}\left(\frac{R_i^2}{p} + \frac{R_j^2}{q}\right) - 3(p+q+1) \tag{3}$$

where p is the number of this sample i, q – number of this sample j. If $p, q \to \infty$, the statistics T_{ij} have an asymmetrical distribution x^2.

RESEARCH RESULTS AND DISCUSSION

Friction coefficient and linear wear depending on the number of friction cycles

The graph **(Fig. 2)** presents changes in the friction coefficient as a function of the number of friction cycles. The highest values of the coefficient of friction were observed for the case of using ES fuel (sunflower oil methyl esters) as a lubricating medium. The lowest values of the friction coefficient were observed for the friction case in ON fuel.

Fuels that have a higher coefficient of friction may cause greater wear on the engine injection apparatus than when using diesel as fuel **[L. 3]**. On the other hand, fuels with a lower coefficient of friction are friendlier to injection apparatus. All tested fuels based on vegetable oil esters showed a higher coefficient of friction than the coefficient of friction for diesel. **Table 2** presents linear wear values.

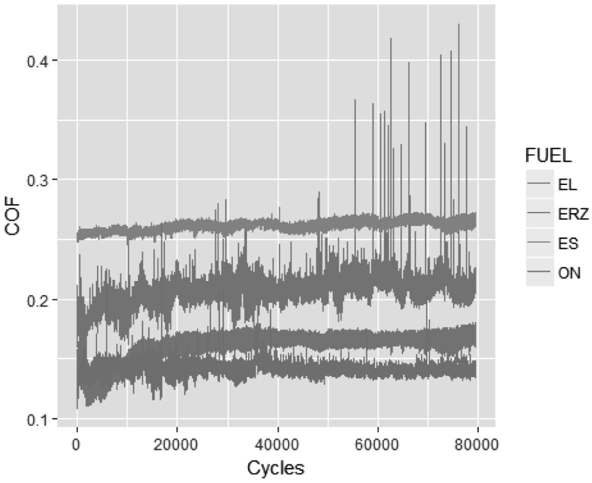

Fig. 2. Changes in the coefficient of friction (COF) as a function of friction cycles for the tested fuels

Rys. 2. Zmiany współczynnika tarcia (COF) w funkcji cykli tarcia dla badanych paliw

Table 2. Linear wear in kinematic pairs used in lubricity tests
Tabela 2. Zużycie liniowe w parach kinematycznych wykorzystanych w próbach smarności

Oil	ON (without FAME)	Linseed oil methyl esters	Rapeseed oil methyl esters	Sunflower oil methyl esters
Linear wear Δh [μm]	0.55	2.05	0.95	0.45

In diesel engines, fuel is the only source of lubrication for precisely matched injection system components. The coefficient of friction is affected by the ability to produce a bond boundary surface that is strongly bonded to the surface. In vegetable oil esters, in chemical terms, this layer consists of hydrocarbon chains „attached" to a clean metal surface with a polar carboxyl group. The created boundary layer protects the surface against wear in the absence of a lubricating film.

The selected course of linear wear is presented in **Fig. 3**. Linear wear was measured as the total wear of the sample and counter-sample, which is measured as the change in the tilt angle of the tribometer arm on which the counter-sample is mounted, and it is then converted from an angular to a linear measure. The measurement was carried out with an accuracy of 0.01 μm and the sampling frequency was 10 Hz. It can be seen that the linear wear of the cooperating kinematic pair is not proportionally dependent on the coefficient of friction for the associated elements of the tribological node. Based on the tests carried out, what is its dependence on the coefficient of friction cannot be clearly determined.

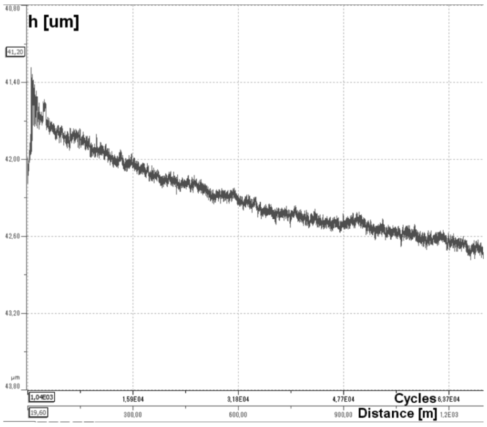

Fig. 3. The course of linear consumption of the kinematic pair 100Cr6-100Cr6 in the „LME (EL)" fuel bath
Rys. 3. Przebieg zużycia liniowego pary kinematycznej 100Cr6-100Cr6 w kąpieli paliwa „EL"

Friction coefficient statistics

Table 3 presents the parameters of the statistical distribution of the results of measurements of the friction coefficient. The table includes the smallest, largest, average, standard deviation, asymmetry and kurtosis coefficients, and quantiles. In addition, the ranges composed of 5% and 95% quantiles for fuels „LME (EL)" and „ON" and for fuels „SME (ES)" and „ON" are severable (it indicates quite **important** differences in COF for those fuels).

Graphic measures of the variability of the statistical distribution of the results obtained in the friction test and their levels and statistical dispersion are shown in

Table 3. Descriptive statistics of the friction coefficient
Tabela 3. Statystyki opisowe współczynnika tarcia

Statistical measure	**Test fuels**			
	LME (EL)	**SME (ES)**	**RME (ERZ)**	**ON**
Measures of central tendency				
Mean	0.2070	0.2616	0.1619	0.1414
Median (quantile 50%)	0.2078	0.2620	0.1662	0.1408
Interval				
Min	0.1514	0.2456	0.1104	0.1083
Max	0.4302	0.2771	0.1802	0.2624
A measure of variation				
Standard deviation	0.0106	0.0038	0.0120	0.0047
Shape parameters of empirical distributions				
Skewness	–0.6806	–0.2532	–2.0223	0.9268
The graphs presented in the figure can also be considered in the context of the parameters „skewness" and „kurtosis". The values of which are presented in **Table 1**.	3.5772	–0.5455	3.1260	13.3743
Quantile				
Quantile 5%	0.1870	0.2549	0.1295	0.1351
Quantile 10%	0.1942	0.2560	0.1397	0.1364
Quantile 25%	0.2021	0.2588	0.1617	0.1383
Quantile 50%	0.2078	0.2620	0.1662	0.1408
Quantile 75%	0.2135	0.2643	0.1687	0.1444
Quantile 90%	0.2192	0.2664	0.1704	0.1475
Quantile 95%	0.2224	0.2675	0.1713	0.1491

a frame diagram **(Fig. 4)** **[L. 5, 12]**. The box-whiskers graph shows the coefficient of friction for different types of fuels: the largest and smallest values, outliers, 1/4 and 3/4 order quantiles and medians. The graph shows clear differences in the coefficients of friction for different types of fuels in comparisons of „SME (ES)" and „RME (RZE)". The highest statistical spread was observed for „LME (EL)", and the smallest for „SME (ES)".

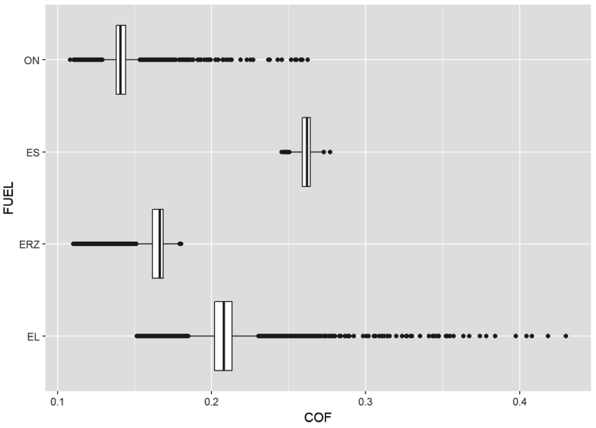

Fig. 4. Frame graph of friction coefficients depending on the fuel used

Rys. 4. Wykres ramkowy współczynników tarcia w zależności od użytego paliwa

Figure 5 presents empirical distributions of the coefficient of friction depending on the type of fuel tested. Charts have one-modal shape. The friction coefficient diagram for „LME (EL)" biofuel is clearly different. This shape of the „LME (EL)" chart indicates a higher uniqueness of the friction coefficient value. The graphs presented in the figure can also be considered in the context of the parameters „skewness" and „kurtosis", the values of which are presented in **Table 3**. The highest left-hand asymmetry in the COF distribution was found for „RME (ERZ)" fuel. Right-hand asymmetry of the COF distribution was shown for „ON" fuel. The COF results obtained for „RME (RZE)" and 'ON' are characterized by significant asymmetry. The „kurtosis" statistical parameter is a measure of the flattening of the statistical distribution. The higher the positive value of the „kurtosis" parameter, the more the coefficient of friction is concentrated in relation to the theoretical normal distribution. A negative „kurtosis" value indicates a lower concentration of the friction coefficient than in the theoretical normal distribution.

In the light of the results of the Kolmogorov-Smirnov test **(Table 4)**, it turns out that at the significance level of even0.001 working hypothesis H_0 (empirical distributions of the wear coefficients for fuels are identical) should be rejected in favour of the alternative hypothesis; therefore, the empirical distributions of friction coefficients for each of the fuels significantly differ **[L. 11, 12]**.

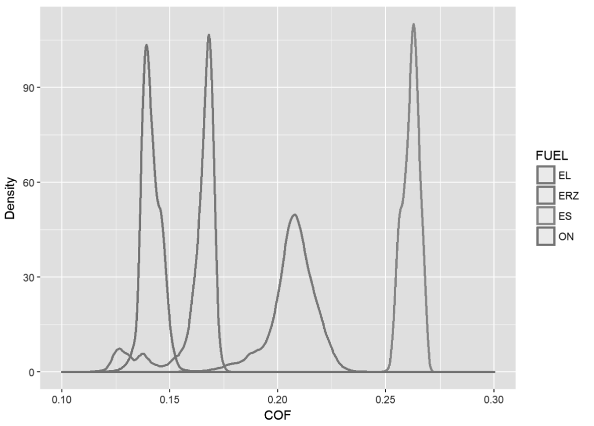

Fig. 5. Empirical distributions of friction coefficients depending on the fuel used

Rys. 5. Rozkłady empiryczne współczynników tarcia w zależności od użytego paliwa

Table 4. Values of Kolmogorov-Smirnov test statistics

Tabela 4. Wartości statystyk testu Kołmogorowa-Smirnowa

	LME (EL)	SME (ES)	RME (ERZ)	ON
LME (EL)	–	0.99974	0.98693	0.99732
SME (ES)	0.99974	–	1	0.99998
RME (ERZ)	0.98693	1	–	0.85408
ON	0.99732	0.99998	0.85408	–

Table 5 shows the statistics values $T_{i,j}$. Based on the results of the Kruskal-Wallis test, it was shown that, at the significance level of even *0.001,* working hypothesis H_0 (no differences between wear coefficients for fuels) should be rejected in favour of the alternative hypothesis. Because, for the level α = 0,001, the critical value of T^* statistics is *10,828*. Because $T_{i,j} \geq T^*$ for any pair of fuels i and j $(i \neq j)$, the H_0 hypothesis should be rejected in favour of H_1 for each pair of comparisons presented in **Table 3**.

Table 5. Statistics values of the Kruskal-Wallis test

Tabela 5. Wartości statystyk testu Kruskala-Wallisa

Oil type	LME (EL)	SME (ES)	RME (ERZ)	ON
LME (EL)		1494327.33	1477941.18	833982.47
SME (ES)	1494327.33		1495780.65	834332.36
RME (ERZ)	1477941.18	1495780.65		526443.45
ON	833982.47	834332.36	526443.45	

Biofuels used as fuel to power internal combustion engines can cause increased wear of engine injection equipment components. This is due to the higher coefficient of friction between the mating surfaces, which can translate into wear.

The use of biofuels as additives to diesel oil, on the other hand, reduces the consumption of cooperating elements, which may be the result of increased lubrication film durability **[L. 8]**. It seems appropriate to research not only the biofuels themselves, but also various mixtures of biofuels in combination with diesel fuel.

CONCLUSIONS

Based on the results of the research, the following conclusions were made:

- Esters of rapeseed oil, which are most often used in Poland as an alternative fuel for compression-ignition engines, showed the most similar lubricating properties among the tested vegetable oil esters for diesel oil.
- There was a higher average COF (coefficient of friction) for vegetable esters, and the highest for SME (ES), which may result in greater wear of the engine injection apparatus when fed with pure vegetable oil esters than in the case of diesel fuel.
- Comparing 90% confidence intervals (ranges built from 5% and 95% quantiles) for COF fuels „ON", „LME (EL)", and „SME (ES)", we can find significant differences in friction between fuels „LME (EL)" and „ON" as well as „SME (ES)" and „ON".
- On the basis of KS and KW tests, COF differences for various fuels were clearly shown.
- Significant differences, disproportionate to the coefficient of friction, in linear wear of cooperating elements for different fuels require further research to demonstrate the dependence of wear on fuel lubricity.
- Due to the observed differences in the coefficient of friction, further research is needed to show what the wear will be of cooperating kinematic pairs in the longer period of operation and what the dependence on the coefficient of friction will be.

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