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EXPERIMENTAL STUDY ON ANTIWEAR PROPERTIES FOR BLENDS OF JET FUEL WITH BIO-COMPONENTS DERIVED FROM RAPESEED OIL

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Abstract

Antiwear properties of jet fuel, two kinds of biocomponents derived from rapeseed oil and their mixtures were investigated experimentally. Antiwear properties were estimated by the value of the scuffing load and the limiting load of scuffing applied to the friction pair working in a fuel medium. Biocomponents, mainly rapeseed oil FAME and rapeseed oil FAME modified via vacuum distillation were used during the study. It is found that lubricity of biocomponents is significantly higher comparing to conventional jet fuel. It is explained by the chemical composition of FAME: highly polarity of molecules stipulate their good adsorption at the surface of friction pair. High viscosity of biocomponents due to chemical structure positively influence on their lubricity. Adding biocomponents into jet fuel results in strengthening boundary film and thus improves antiwear properties of fuel blends. It is determined that FAME modified via vacuum distillation possess better lubricating ability comparing to standard FAME derived from rapeseed oil. Correlation between viscosity and lubricity of fuel is shown.

Keywords: jet fuel, biofuel, FAME, Fatty Acid Methyl Esters, lubricity, wearing, viscosity.

1. INTRODUCTION

Over the last years, increasing attention is paid to the question of traditional energy sources replacement with their alternative analogues [1, 2]. The question is particularly acute for transport sector. Generally, such situation may be explained by the three main reasons:

- usually alternative fuels are produced from renewable biological feedstock that allows decreasing of dependence on exhausting traditional energy sources;
- the use of biofuels provides decreasing exhaust gases toxicity and volume;
- promotion of biofuels helps developing fuel production industry and as a result may provide energy and environmental safety of certain countries [3, 5].

During the last decade alternative fuels have been used not only in motor transport but in aviation as well. Today, a number of international organizations, such as ICAO (International Civil Aviation

Organization), IATA (International Air Transport Association) pay much attention to the issues of making civil aviation "green".

One of the main tasks in the field of production and the use of aviation fuels and lubricants is to expand the resource base and to develop progressive technologies for the production of aviation fuels. Environmentally friendly alternative fuels produced from cheap renewable feedstock may be one of the key directions in solving such questions as energy-, resource saving and environmental safety in aviation [3]. At the same time, alternative aviation fuels must meet a number of requirements related to efficiency, reliability and durability of aviation technics [2, 3].

Today, there is a great variety of alternative jet fuels as well as technologies of their production. Among the most developed and widely used renewable jet fuels, it is necessary to mention hydrogenated synthetic paraffin kerosene. It is produced by processing plant and/or animal fat-containing feedstock by hydrogenation and deoxygenation of mono-, di- and triglycerides of fatty acids, free fatty acids and fatty acid ethers with further application of hydrotreatment, hydrocracking, hydroisomerization and polymerization, isomerization and fractionation processes. Besides, there are some other renewable fuels, for example, made of biomass via FT-synthesis (Fischer-Tropchs synthesis), made of alcohols, various algae and even of industrial and household waste. However, all of these biofuels can be added to conventional petroleum jet fuels in quantity up to 50% [6–9]. This can be explained by the fact that there is not enough experience in the practical use of these kinds of fuels. And perhaps, some properties of new fuels still cannot be adopted by the international standards.

One of the possible ways to replace conventional jet fuels with renewable fuels is to use methyl (ethyl) esters of plant oils or animal fats. Primarily, these biofuels have become popular as a fuel substitute for road transport, mainly for diesel engines. Lately, except being an alternative to diesel fuel, fatty acid esters have been proposed to be used as components for jet fuel [9, 10]. This kind of biofuel is produced via esterification of plant oils with methyl or ethyl alcohols, more rarely butyl alcohol can be also used [3, 7]. According to the developed technology up to 30% (vol.) of biofuel can be added to conventional jet fuel [10]. As it is mentioned in [3, 8, 9] the use of such biofuel can have a number of advantages, among them: substituting conventional oil with renewable resource, decreasing exhaust gases emissions toxicity, improving safety parameters of fuel, decreasing carbon dioxide emissions [6, 7].

However, today properties of various biofuels have not been studied completely. Special attention must be paid to research of exploitation properties of alternative fuels. In other words, it is necessary to study the impact of such fuels on aircraft equipment and details during a long-term use. For example, it is noted [3, 11, 12] that alternative jet fuels, obtained via FT-synthesis are characterized by low lubricity that in future can cause premature wear of engine details. At the same time, there is information about good lubricity properties of plant oils esters [12, 14]. Generally, the observations were made for auto transport where biodiesel was used instead of conventional diesel fuel [14, 18].

Taking into account the data about lubricity properties of plant oil esters, it is interesting to study their impact on antiwear properties of jet fuel. Thus, the aim of the work is to research the antiwear properties of blended jet biofuels containing methyl esters of rape oil.

Antiwear properties of jet fuels determine reliability and operational life of fuel system friction pairs in particular [19]. These pairs operate in regimes of rolling friction, sliding friction and combined friction under different loads, temperatures, pressures, speed of relative movement in conditions of liquid and boundary lubricant.

Jet fuel cannot produce a continuous protecting film so aviation components normally operate in the boundary lubrication regime where the load is carried partly by the fluid film and partly by the contacting surfaces. The most likely explanation for wear in aviation systems is a simple corrosive wear process later followed by severe adhesive wear and scuffing as the component dimensions become reduced beyond tolerable limits [19].

Fuel lubricating properties depend on chemical composition, viscosity, thermal-oxidation stability, content of mechanical impurities, presence of surfactants [19, 21]. In the case of high unit loads the semi-liquid friction is usually observed – that is when wearing surfaces are not completely divided by the fuel. In the case of semi-liquid friction the antiwear properties of jet fuels are determined by:

1) fuel viscosity that provides hydrodynamic effect of wearing surfaces division by liquid layer;
2) presence of surfactants in fuel that form high strength absorption layer at the wearing surface and divide wearing surfaces with decreasing of friction coefficient and details wearing.

2. EXPERIMENTAL METHODOLOGY

2.1. Sample characterization

Lubricity of jet fuel, two kinds of biocomponents and their blends with jet fuel were investigated during the experiment. Jet fuel was presented by traditional oil-derived fuel for jet engines of grade Jet A-1 that meets the requirements of ASTM D1655 [22]. Biocomponents were presented by fatty acids methyl esters (FAME) of rape oil, meeting the requirements of EN 14214 [23] and fatty acids methyl esters of rape oil that are specially modified for application as a component of jet fuel. The modification was made by vacuum distillation according to the developed technology [10]. Fuel blends contained up to 50% of biocomponents. The list of tested samples and their designations are presented in table 1.

Table 1. Fuels samples used for lubricity testing [10]

#	Sample description	Sample designation
1	Jet fuel of grade Jet A-1	JFA1
2	Biocomponent – fatty acids methyl esters of rape oil	B100
3	Jet fuel with 10% of biocomponent	JFA1-B10
4	Jet fuel with 20% of biocomponent	JFA1-B20
5	Jet fuel with 30% of biocomponent	JFA1-B30
6	Jet fuel with 40% of biocomponent	JFA1-B40
7	Jet fuel with 50% of biocomponent	JFA1-B50
8	Biocomponent – modified fatty acids methyl esters of rape oil	B100M
9	Jet fuel with 10% of modified biocomponent	JFA1-B10M
10	Jet fuel with 10% of modified biocomponent	JFA1-B20M
11	Jet fuel with 10% of modified biocomponent	JFA1-B30M
12	Jet fuel with 10% of modified biocomponent	JFA1-B40M
13	Jet fuel with 10% of modified biocomponent	JFA1-B50M

2.2. Description of testing device and research methodology

Usually antiwear properties of jet fuels are estimated by the wear value of specific friction pair. Wear of a random friction pair in medium of certain fuel cannot characterize lubricity properties completely. Replacement of details material, testing regimes and other factors may change wear of friction pair significantly. Because of this, estimation of antiwear properties should be made under strictly defined conditions [19, 20].

Traditionally antiwear properties of jet fuels are estimated according to ASTM D5001 [24]. This method was specifically developed for aviation fuel lubricity evaluation. The Ball-on-Cylinder Lubricity Evaluator (BOCLE) test in accordance with ASTM D5001 exhibits oxidative corrosion type wear to produce a measurable wear scar to quantify lubricity. At the same time, researchers found that BOCLE could not be used to predict the scuffing performance of fuels. As a result, the specially intended Scuffing load BOCLE was proposed. Besides, many mechanized test rigs for the determination of jet fuel lubricity have been developed over the past 40 years. However, most of them do not simulate the most important type of wear exhibited in aircraft fuel systems.

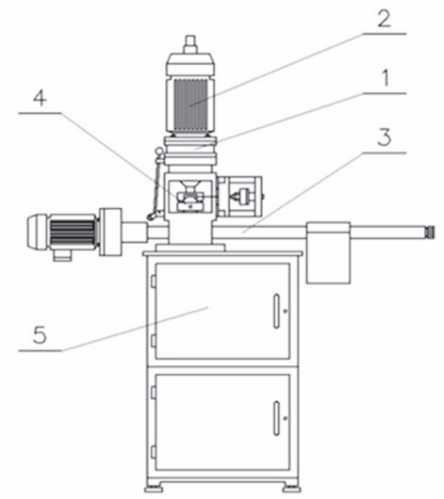


Fig. 1. T-02U four ball tester [25],
1 – body, 2 – power train,
3 – friction pair load bearing drive,
4 – ball cup assembly, 5 – base [25]

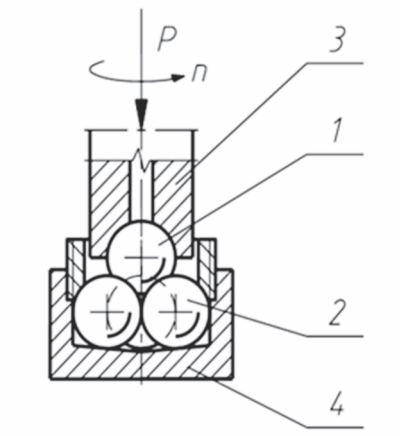


Fig. 2. Four ball tester friction pair [25],
1 – top ball, 2 – bottom balls,
3 – spring clamp, 4 – balls cup [25]

Antiwear properties of fuel samples were investigated using a T-02U four-ball tester that consists of the testing device and a metering-control system. The mechanical part (testing device) is shown in figure 1 and includes body, power train, friction pair load bearing drive, ball cup assembly and a base. The friction pair (Fig. 2) consists of three lower balls fixed in a clamp and loaded with appropriate force applied by the top ball mounted on a spindle rotating with a determined speed [25].

The typical ball bearings of 1/2" diameter were used for the tests. The bearings are made of GCr15 bearing steel with hardness of 60÷65 HRC. The mechanical system allows linear increasing of the load applied to the friction pair during a test. The metering-control system consists of a dedicated microprocessor based controller, asynchronous motor controller and a computer with special control software [25].

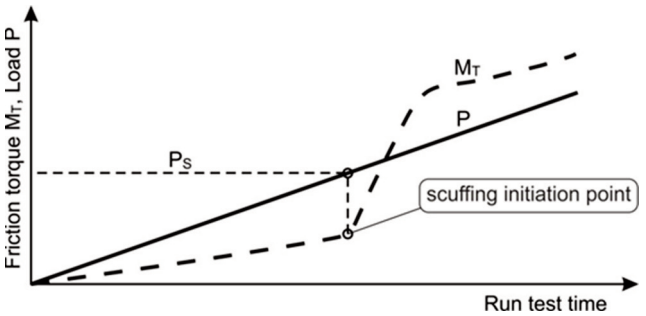


Fig. 3. The method for determining the scuffing load P_S [26]

The tests were conducted under conditions of gradual load increase. The rotation speed during tests was 500 rpm, with the load increase rate of 409 N/s. The initial temperature of the fuel sample at the start of the test run was 60 ± 1.0°C. Within the scope of this test, by definition a friction pair seizure is said to have occurred once the boundary friction torque M_T, of 10 Nm is exceeded. This value is determined by the durability of the top ball shank in the friction pair. The friction torque M_T and the linearly increasing friction pair load P were recorded during testing.

The principle of the method is determining of the scuffing load applied to the friction pair (fig. 3) [26]. Load P where the friction torque value starts to increase rapidly is called the scuffing load and denoted as P_S. The values of P_S were reading from files recorded during the run test. The reading errors of P_S have been estimated to be ±20 N. Thus, the fuel sample with the highest value of applied scuffing load is considered to have the best antiwear properties. In other words, it means that the boundary film of this fuel sample demonstrated the highest resistance to breaking.

4. DISCUSSION OF RESULTS

The following figures (4–17) depict the friction torque, friction pair load and friction coefficient that were recorded during tests. The scuffing load describing the criteria for lubricity assessment in the chosen test methodology is marked.

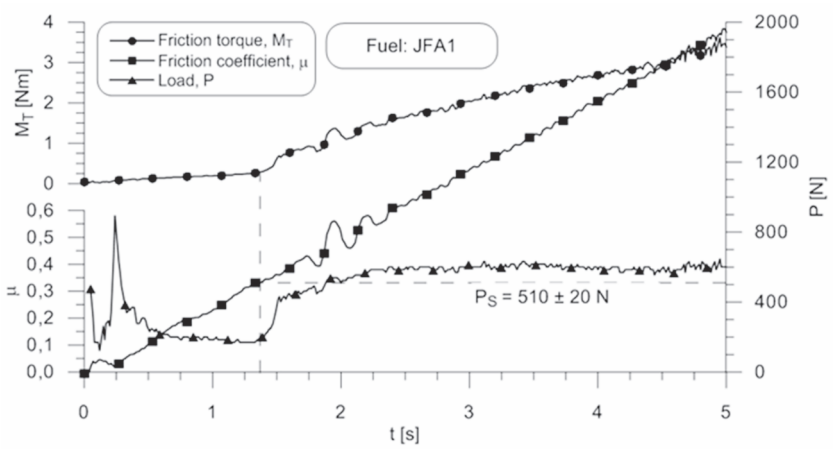


Fig. 4. Friction pair loading force P, friction torque M_T and friction coefficient μ as a function of testing run time t for pure jet fuel of grade Jet A1 fuel: P_S – scuffing load [Vovk, 2014]

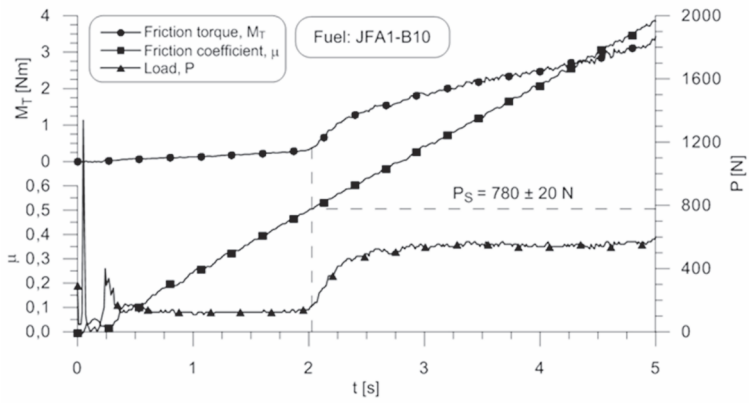


Fig. 5. Friction pair loading force P, friction torque M_T and friction coefficient μ as a function of testing run time t for blend fuel Jet A1 with 10% of biocomponent: P_S – scuffing load [Vovk, 2014]

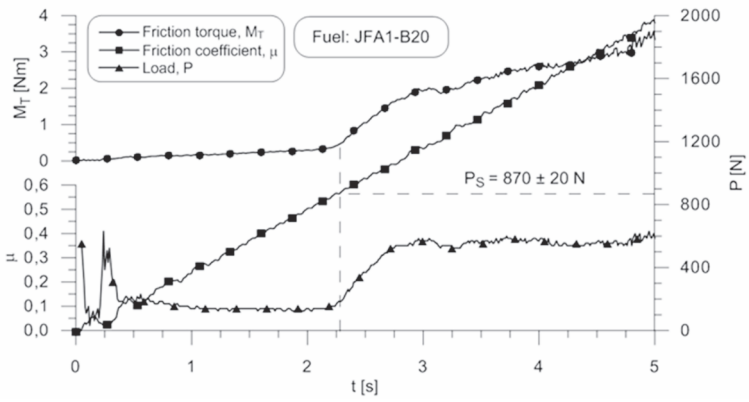


Fig. 6. Friction pair loading force P, friction torque M_T and friction coefficient μ as a function of testing run time t for blend fuel Jet A1 with 20% of biocomponent: P_S – scuffing load [Vovk, 2014]

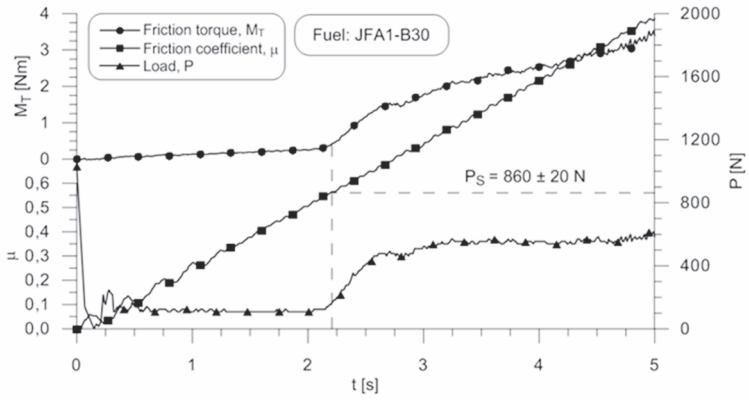


Fig. 7. Friction pair loading force P, friction torque M_T and friction coefficient μ as a function of testing run time t for blend fuel Jet A1 with 30% of biocomponent: P_S – scuffing load [Vovk, 2014]

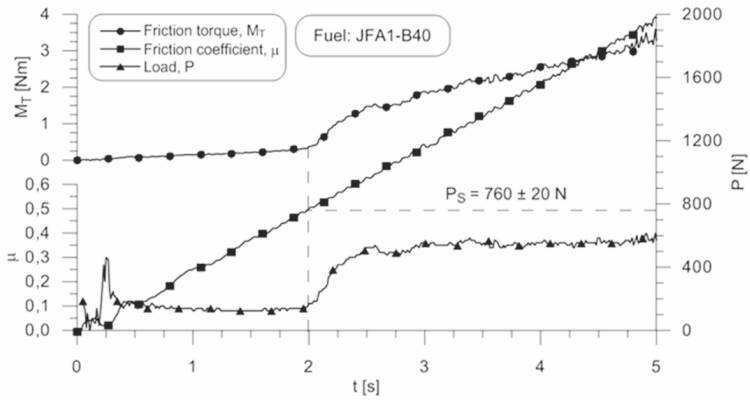


Fig. 8. Friction pair loading force P, friction torque M_T and friction coefficient μ as a function of testing run time t for blend fuel Jet A1 with 40% of biocomponent: P_S – scuffing load [Vovk, 2014]

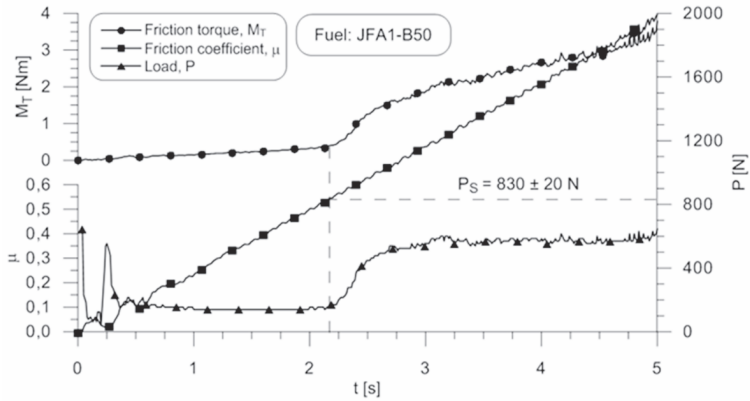


Fig. 9. Friction pair loading force P, friction torque M_T and friction coefficient μ as a function of testing run time t for blend fuel Jet A1 with 50% of biocomponent: P_S – scuffing load [Vovk, 2014]

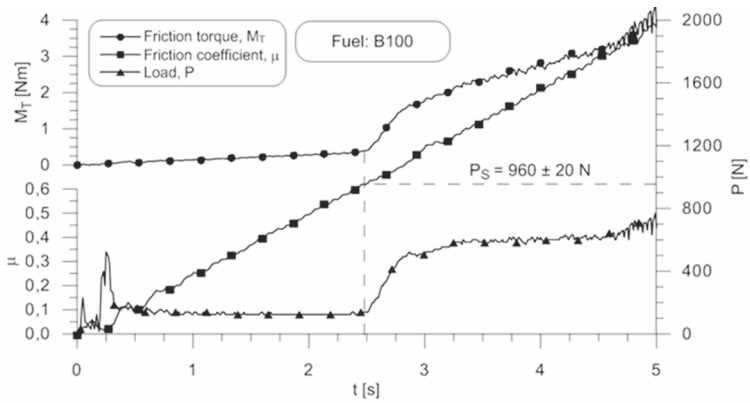


Fig. 10. Friction pair loading force P, friction torque M_T and friction coefficient μ as a function of testing run time t for pure biocomponent: P_S – scuffing load [Vovk, 2014]

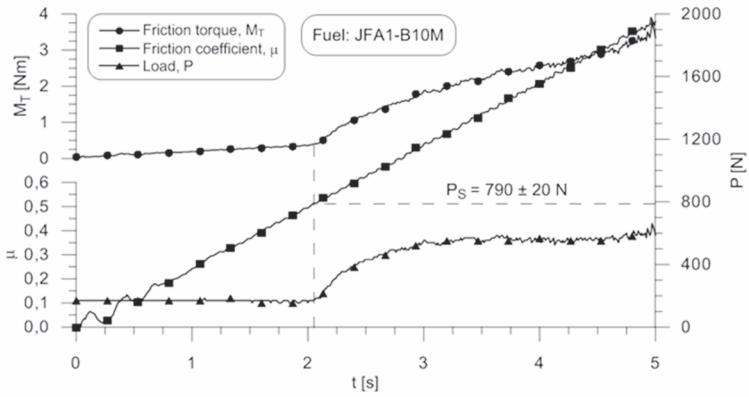


Fig. 11. Friction pair loading force P, friction torque M_T and friction coefficient μ as a function of testing run time t for blend fuel Jet A1 with 10% of modified biocomponent: P_S – scuffing load [Vovk, 2014]

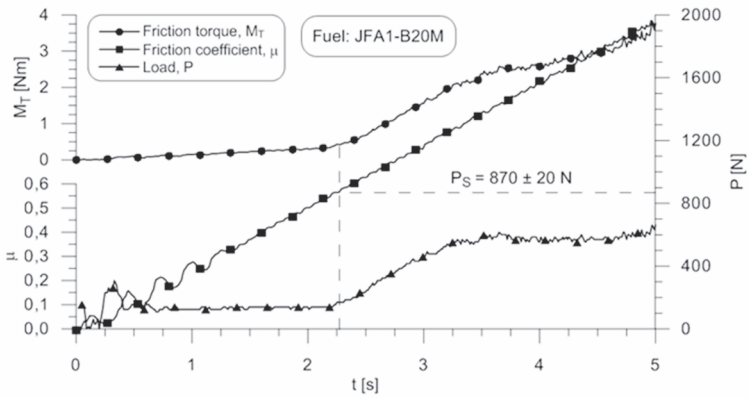


Fig. 12. Friction pair loading force P, friction torque M_T and friction coefficient μ as a function of testing run time t for blend fuel Jet A1 with 20% of modified biocomponent: P_S – scuffing load [Vovk, 2014]

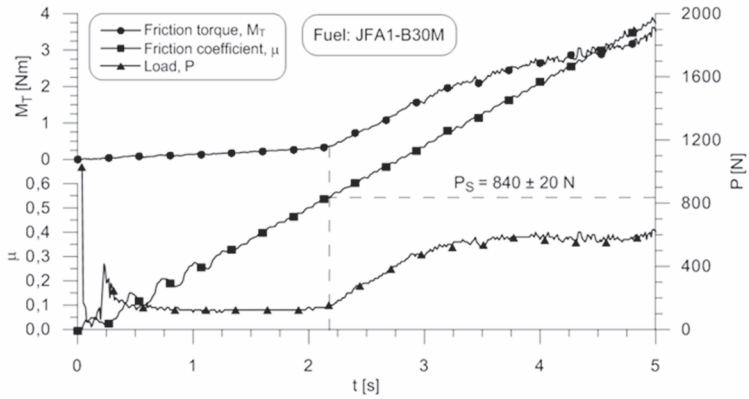


Fig. 13. Friction pair loading force P, friction torque M_T and friction coefficient μ as a function of testing run time t for blend fuel Jet A1 with 30% of modified biocomponent: P_S – scuffing load [Vovk, 2014]

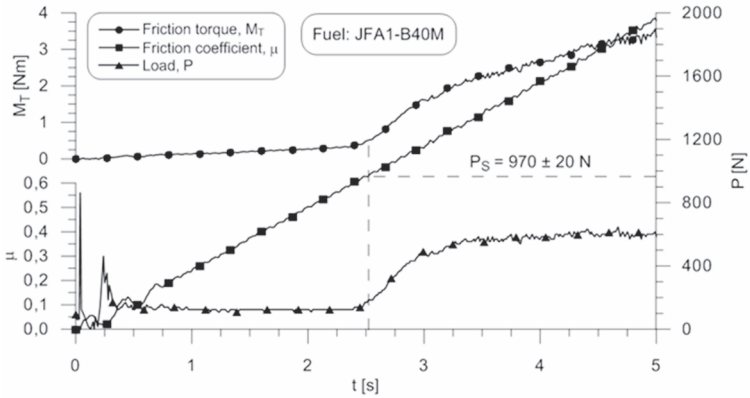


Fig. 14. Friction pair loading force P, friction torque M_T and friction coefficient μ as a function of testing run time t for blend fuel Jet A1 with 40% of modified biocomponent: P_S – scuffing load [Vovk, 2014]

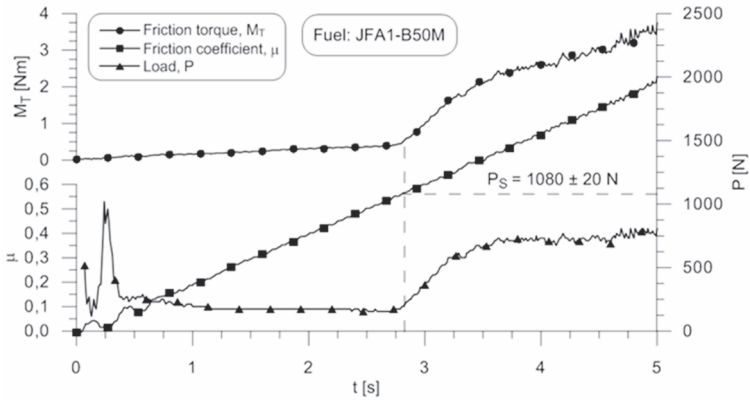


Fig. 15. Friction pair loading force P, friction torque M_T and friction coefficient μ as a function of testing run time t for blend fuel Jet A1 with 50% of modified biocomponent: P_S – scuffing load [Vovk, 2014]

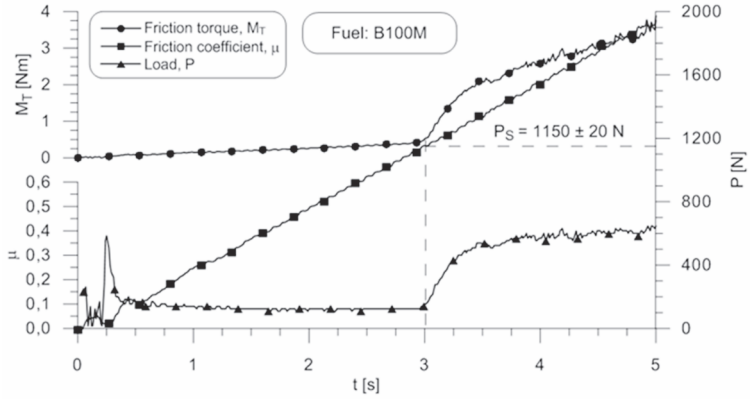


Fig. 16. Friction pair loading force P, friction torque M_T and friction coefficient μ as a function of testing run time t for pure modified biocomponent: P_S – scuffing load [Vovk, 2014]

In order to summarize the obtained results, the values of scuffing load P_S for each fuel sample were recorded and shown in figure 17.

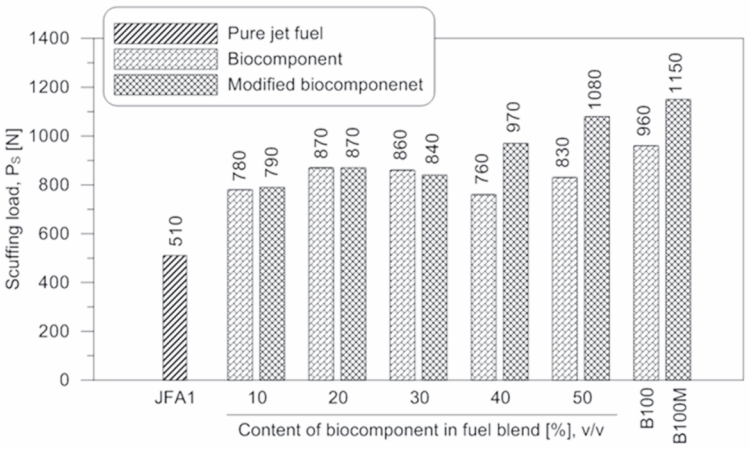


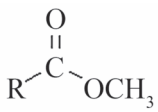
Fig. 17. Change of friction pair scuffing load depending on the content of biocomponent in jet fuel blends [Kuszewski, 2014]

The presented results show that the conventional jet fuel of grade Jet A1 has demonstrated the lowest value of scuffing load – 510 N. At the same time, the highest values of scuffing load were observed for both types of biocomponents: 960 N – for rape oil FAME and 1150 N – for modified rape oil FAME. Taking conventional jet fuel as a reference sample, we can easily conclude that the use of rape oil esters positively influences the lubricity properties of jet fuel.

Let us consider the mechanism of this effect. As it was said before, antiwear properties of jet fuels are determined by fuel viscosity and presence of surfactants in fuel [27]. Surfactants in fuel cause its surface activity – ability of fuel or its components to absorb at the surface of metal, form the boundary film and thus prevent dry friction of details. Solid bodies are characterized by high surface tension and their surface contacting to multicomponent liquid adsorbs substances that decrease this tension [27, 28]. Physical mechanism of adsorption at solid surface is explained by electrostatic interaction of polar molecules with electric field of particles that form solid surface, for example, metal ions [20, 21].

Fuel hydrocarbons are non-polar and almost do not protect friction pairs from wear. Substances, which may be contained in jet fuel naturally and which are considered to be surface active, are gums, organic acids and other oxygen-containing compounds, sulfur-organic and nitrogen-organic compounds. At the same time, the presence of the mentioned substances is undesired from the point of view of thermal stability and corrosion properties of fuel [29].

Biocomponents used in jet biofuel blends are the products of reaction between complex esters of glycerine and higher fatty acids (triglycerides) and simple alcohol (methanol or ethanol). Molecules of biocomponents are complex esters, which contain residuals of fatty acid and alcohol. Fatty acids esters have a different number of carbon atoms in the chain and a different number of double bonds [30, 31]. General formula of FAME looks as follows:



where R – radical of fatty acid.

Fatty acids radical are non-polar, but the presence of carboxyl group in molecule stipulates strong polarity of complex esters. Such a structure of biocomponents provides their surface activity and thus, ability to form a boundary film.

Basing on the data, we can assume that increasing biocomponent content in blends causes increasing surfactants quantity and, as a result, strengthening of boundary film between friction pair.

Another property that influences details wear is fuel viscosity [21,29]. Conventional jet fuels with lower viscosity are composed of compounds with smaller molar mass. Their molecules have smaller sizes and thus a smaller dipole moment. As a result, the boundary film formed at the solid surface possesses less strength comparing to fuels with higher viscosity values. Except that, decreasing of molecules' size causes the increase of average speed of their chaotic heat movement and promotes destruction (desorbtion) of the boundary film.

In order to verify theoretical data about viscosity influence on lubricating properties, the kinematic viscosity of investigated fuel blends was measured. Because the lubricity properties of jet fuel blends were tested at temperature 60°C, the kinematic viscosity n_{60} was measured at the same temperature regime. The measurement results are presented in table 2.

Table 2. Kinematic viscosity of tested fuel samples [29]

Sample name	Viscosity at 60 °C, mm^2/s
JFA1	0.9500
JFA1-B10	0.99289
JFA1-B20	1.11510
JFA1-B30	1.25760
JFA1-B40	1.46030
JFA1-B50	1.70560
B100	3.06220
JFA1-B10M	0.99992
JFA1-B20M	1.13090
JFA1-B30M	1.26790
JFA1-B40M	1.42880
JFA1-B50M	1.59570
B100M	2.92630

In table 2 we can see that kinematic viscosity of conventional oil-derived jet fuel is much lower comparing to viscosity of biocomponents. Such high values of FAME viscosity are explained by their chemical structure. Viscous characteristics of conventional jet fuel depends on their hydrocarbon composition: the content of alkanes (paraffins), cycloalkanes (naphthens), mono- and bicyclic arenes with average number of carbon atoms in molecule from 5 to 16. At the same time, hydrocarbon chain of ester molecules contains about 14 – 23 carbon atoms [30, 31]. This influences molecules' size and thus decreases the speed of their chaotic movement. It is clearly seen from the table 2 that increasing biocomponent content in blends causes an increase of their viscosity. Figure 18 depicts the dependence of viscosity and scuffing load increment with increasing biocomponents content in fuel blends.

Figure 18 shows the dependence between friction pair scuffing load and fuel viscosity. Increasing fuel viscosity causes strengthening of boundary film at the surface of the friction pair that results in increasing scuffing load. Thus, the obtained results prove that antiwear properties of jet fuels are directly dependant on fuel viscosity that provides wearing surfaces division by liquid layer and presence of surfactants in fuel that form high strength absorption layer at the wearing surfaces that provides decreasing of friction coefficient and details wearing.

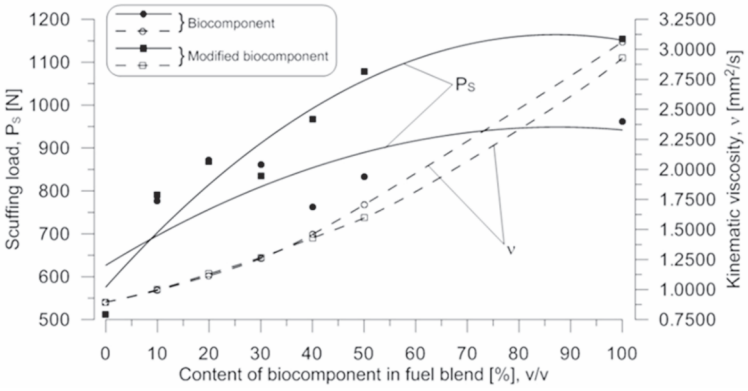


Fig. 18. Friction pair scuffing load P_S, fuel viscosity n as a function of biocomponent content in fuel blends [Boichenko, 2014]

5. CONCLUSIONS

The durability of the boundary film of the wearing surfaces of a friction pair may be one of the lubricity assessment criteria for fuels. It is obvious that the smaller the durability of the film, the smaller the value of the seizure load. These relationships can be used to compare the lubricating characteristics of different fuels.

A four-ball tester with a facility for a continuous load increase was used for estimation lubricity properties of conventional jet fuel and its blends with rape oil derived biocomponents.

The comparative tests of fuel blends indicated that rape oil FAME exhibit better permanent boundary film creation properties comparing to conventional jet fuel within the scope of the tested friction pair. This effect is explained by surface activity of FAME molecules and its high viscosity. The results of the tests have shown that increasing biocomponent content in fuel blend caused strengthening of the boundary film of friction pair surface. Thus, it can be assumed that alternative jet fuels which contain rape oil derived biocomponent are characterized by better antiwear properties. In other words, rape oil esters positively affect lubricity properties of conventional jet fuels and may be used as an improvement of jet fuel antiwear properties.

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BADANIA EKSPERYMENTALNE NA WŁAŚCIWOŚCI PRZECIWZUŻYCIOWYCH DLA MIESZANEK PALIWA DO SILNIKÓW ODRZUTOWYCH O BIOKOMPONENTACH POCHODZĄCYCH Z OLEJU RZEPAKOWEGO

Streszczenie

W pracy przebadano doświadczalnie właściwości przeciwzużyciowe paliwa do silników odrzutowych, dwa rodzaje biokomponentow pochodzących z oleju rzepakowego, oraz ich mieszaniny. Właściwości przeciwzużyciowe oszacowano przez wartość obciążenia zacierania i obciążenia granicznego zacierania przyłożonego do pary tarcia obrotowego w środowisku paliwa. Biokomponenty, głównie rzepakowe FAME - oleju rzepakowego i oleju zmodyfikowanego poprzez destylację próżniową zostały przebadane. Stwierdzono, że właściwości smarne biokomponentów są znacznie wyższe w porównaniu z tradycyjnym paliwem do silników odrzutowych. Należy wyjaśnić skład chemiczny FAME: wysoka polaryzacja cząsteczek dobra adsorpcja na powierzchni par tarcia. Wysoka lepkość biokomponentów ze względu na ich strukturę chemiczną, pozytywnie wpływa na ich smarowność. Dodawanie biokomponentów ma wpływ na wyniki paliwa lotniczego we wzmacnianiu folii granicznej, a tym samym poprawia właściwości przeciwzużyciowe mieszanek paliwowych. Stwierdzono, że FAME zmodyfikowany przez destylację próżniową posiada lepszą zdolność smarowania w stosunku do standardowego FAME pochodzącego z oleju rzepakowego. Korelacja między lepkością i smarnością paliwa jest wykonana.
Słowa kluczowe: paliwa do silników odrzutowych, biopaliwa, smarność, lepkość.