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ANALYSIS OF THE ECOLOGICAL PARAMETERS OF THE DIESEL ENGINE POWERED WITH BIODIESEL FUEL CONTAINING METHYL ESTERS FROM CAMELINA SATIVA OIL

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Abstract. The article explores the possibilities of using fatty acid methyl esters derived from the oil of a new species of oily plant *Camelina sativa* not demanding on soil. The performed research on the physical and chemical properties of pure methyl esters from *Camelina sativa* show that biofuels do not meet requirements for the biodiesel fuel standard (LST EN 14214:2009) of a high iodine value and high content of linoleic acid methyl ester, so they must be mixed with methyl esters produced from pork lard the content of which in the mixture must be not less than 32%. This article presents the results of tests on combustion emission obtained when three-cylinder diesel engine VALMET 320 DMG was fuelled with a mixture containing 30% of this new kind of fuel with fossil diesel fuel comparing with emissions obtained when the engine was fuelled with a fuel mixture containing 30% of conventional biodiesel fuel (rapeseed oil methyl esters) with fossil diesel fuel. The obtained results show that using both types of fuel, no significant differences in CO and NO_x concentrations were observed throughout the tested load range. When operating on fuels containing methyl esters from *Camelina sativa*, HC emissions decreased by 10 to 12% and the smokeness of exhaust gas by 12 to 25%.

Keywords: biodiesel fuel, *Camelina sativa* oil, diesel engine, ecological parameters.

1. Introduction

The European Commission encourages the use of biofuels in the transport sector. Directive 2003/30/EC (2003) states that the Member States of the EU should gradually increase the consumption of biofuels in transport and by 2010, in total, 5.75% of transport fuels should be replaced by biofuels.

Producing and using biofuels has opened a new area in Lithuania as well as researches in this area (Matijošius and Sokolovskij 2009; Pukalskas *et al.* 2009; Raslavičius and Bazaras 2009; Lebedevas and Lebedeva 2009; Lingaitis and Pukalskas 2008a and 2008b; Butkus *et al.* 2007; Lebedevas *et al.* 2007; Raslavičius and Markšaitis 2007; Lebedevas *et al.* 2006a, 2006b).

However, despite the aspirations set out in the Directive, the development of using biofuels in the EU Member States is still insufficient. The actual average of EU biofuel consumption in the market is only about

3.21% (2009) and is below the target – 5% (EU-27 Bio-Fuels Annual 2008). Meanwhile, the new EU documents 'An EU Strategy for Biofuels' (2006) and 'Biofuels in the European Union. Vision to 2030 and Beyond' (2006) provide for an increase in biofuel consumption to 15% by 2020 and up to 25% by 2030. This will only be possible by increasing the production volumes and consumption of the first generation biofuels and via the introduction of producing the second generation biofuels providing for intensive industrial development after 2020.

In most cases, biodiesel fuel (75% of biofuels in the market) and bioethanol (20%) are used in the EU countries as the first generation biofuels (EU-27 Bio-Fuels Annual 2008). However, the market of raw materials used in producing biodiesel fuel – rapeseed oil – is limited; therefore it is necessary to find new suitable raw materials for producing biodiesel fuel. Certain new kinds of vegetable oil that should have lower prices than

the traditional rapeseed oil would increase the profitability of biodiesel fuel production and attractiveness to producers. In addition, it is necessary to find oil plants not demanding on soil and cultivated on barren lands not suitable for rapeseed cultivation because the potential of the latter process currently both in Lithuania and EU countries is approaching the limit on a lack of suitable land and crop rotation requirements. One of these oil plants recently attracted the interest of scientists is *Camelina sativa* grown as undersowing cereals in order to protect them from weeds without the use of mineral fertilizers and pesticides. The oil content of *Camelina sativa* seed is high and reaches about 43% (Zubr 1997). However, the cultivation of this plant so far is for experimental purposes only and started in Lithuania relatively recently – in 2006. The properties of oil derived from this plant and the possibility of using it for producing fatty acid methyl esters are investigated. The preliminary results of foreign researchers show that due to the high content of polyunsaturated fatty acids, methyl esters from *Camelina sativa* oil could be used as biodiesel fuel only in a mixture with methyl esters from rapeseed oil (RME) (Mittelbach and Remschmidt 2004). Even better results might be obtained by inserting it into the mixtures of methyl esters from animal fat containing much saturated fatty acids.

In producing the new types of biodiesel fuel, it is necessary to evaluate not only its physical and chemical characteristics but also to carry out comparative performance tests on the engine assessing its motor and environmental performance in comparison with the properties of conventional biodiesel fuel. Literature and data about engine performance research on biodiesel fuel derived from *Camelina sativa* oil is relatively low and can be linked with recently launched experiments on cultivating and using this plant. Therefore, the aim of our work was to carry out comparative performance tests on the engine assessing the motor and ecological characteristics of fuels containing fatty acid methyl esters from *Camelina sativa* oil.

2. Methodical Aspects of Researches

2.1. Object of Research

The object of research was 3-cylinder diesel engine VALMET 320 DMG manufactured by AGCO SISU POWER which is a part of vessel diesel generator STAMFORD UC.M224C2 alternating the current of 28 kW.

The main parameters of the diesel engine are given in Table 1.

Diesel engine design provides for its operation using fatty acid methyl esters (FAME) produced from rapeseed oil or cabbage oil.

During testing, the engine load has been ensured by gradually increasing electricity consumption produced by the diesel generator in the ship. With the diesel engine operating with all types of fuel, its load was increased from the modes close to idle to nominal modes (P_{enom}): 5–10% P_{enom} , ~25% P_{enom} , ~55% P_{enom} ,

Table 1. The main parameters of diesel engine VALMET 320 DMG

Parameter	Value
Number of cylinders	3
Operational volume, dm ³	3.3
Cylinder diameter, mm	108
Stroke, mm	120
Fuel injection method	Direct injection
High pressure pump	Sectional Bosch
Starting pressure of fuel injection, MPa	23.5±0.5
Nominal power (P_{enom}), kW	30
Nominal rpm (n_{nom}), min ⁻¹	1500

65–70% P_{enom} and 80–85% P_{enom} at nominal rotation speed, $n = 1500 \text{ min}^{-1}$. In order to ensure the repeatability of results and the stability control of engine technical condition at the beginning and end of the tests, they were carried out using fossil diesel fuel.

2.2. Fuel Used for Researches

Camelina sativa oil was obtained by mechanical pressing using Skeepsta Maskin Type 40A press (Sweden). Oil transesterification with methanol was carried out using laboratory equipment and applying a conventional method of rapeseed oil transesterification. Analytically pure methanol (*Aldrich Chemical Company, Inc.*) was used for transesterification and analytically pure KOH (*Aldrich Chemical Company, Inc.*) was used as a catalyst. Transesterification was carried out at two stages during the first of which, 11% of methanol was inserted into oil using 0.9% KOH content while during the second stage 6% of methanol and 0.4 KOH were used. After passing through each stage, glycerol fraction was separated and the esters obtained after the second stage had been over were washed using 10% of ester content with a 5% of phosphoric acid solution (*Aldrich Chemical Company, Inc.*). Following the process of washing with phosphoric acid, solution esters were washed twice using 10% of water. The traces of water from the esters were evaporated in a vacuum.

Pork lard methyl esters were produced from pork lard purchased from the market (Poland). After the evaporation of moisture, transesterification and the ester cleaning procedure of lard were carried out in the same way as the process of producing fatty acid methyl esters from *Camelina sativa* oil.

While preparing fuel for engine testing, in addition to the experimentally derived fatty acid methyl esters (FAME), fossil diesel fuel (D) purchased from the trade network and conforming to the requirements of LST EN 590 was used. According to the standard, it contained 5% (vol.) of rapeseed oil methyl esters (RME). Given the fact that pure biodiesel fuel still has no perspectives to be used as fuel in Lithuania for our tests, we took 30%

(vol.) of biological origin fuel mixtures with fossil diesel fuel. This concentration was chosen taking into account a fact that foreign authors carried out tests on diesel engines (Lebedevas et al. 2006a, 2007) and found out that 30% of FAME mixture with D was of optimal concentration, in a view of improving diesel fuel economy and ecological indicators.

The quality indicators of fatty acid methyl esters and their mixtures were evaluated applying the procedures specified in the standard LST EN 14214:2009. The physical and chemical parameters of the tested fuels (methyl ester mixtures with fossil diesel fuel) were determined applying standard methods:

- density was defined following ISO 12185:1996;
- viscosity – ISO 3104:1994;
- cetane number – ISO 5165:1998;
- sulfur content – ISO 20846:2004;
- copper strip corrosion – ISO 2160:1998;
- flash point – ISO 3679:2004;
- ash content following ISO 6245:2001.

2.3. Engine Testing

The temperature mode of the diesel engine during the test was controlled using stationary devices for diesel generator on the control panel.

The power consumed by the generator was identified according to electrical current and voltage indications and was measured with portable device MINI AC/DC CLAMP METER: current in the range of up to 40 A had the resolution of 0.01 A with the accuracy of $\pm 2.5\%$; in measuring the voltage range of up to 400 V, resolution was 0.1 V and accuracy made $\pm 1\%$. On this basis, the accuracy of sensing power consumption was $\pm 3.5\%$ and was rated as satisfactory for research operation.

The parameters of measurement devices for the harmful components of engine exhaust gas are given in Table 2.

3. Results and Discussions

3.1. Physical and Chemical Parameters of Fuel

The performed analysis on the quality of methyl esters from *Camelina sativa* oil (KSME) demonstrated that such methyl esters did not meet requirements for the

standard LST EN 14214:2009 of the quality indicators of biodiesel fuel. These fuels have too high iodine value – 143 g I₂/100 g while the standard specifies a maximum of 120 g I₂/100 g. Because of the large content of polyunsaturated fatty acids in *Camelina sativa* oil, the resulting methyl esters have too high linolenic acid methyl esters content making 44.8%, whereas the maximum limit under the standard is 12%. For these reasons, pure KSME could not be used as fuel. On the contrary, pork lard has low unsaturated fatty acid content, and therefore the iodine value of pork lard methyl esters (KME) is low and makes 64.9 g I₂/100 g. They don't contain linoleic acid methyl esters at all. The assumption was made that when mixing KSME and KME considering an appropriate ratio, biofuel meeting the requirements of standard LST EN 14214:2009 could be obtained. After testing, it was found that such mixtures had to contain 68% (vol.) of *Camelina sativa* oil and 32% (vol.) of pork lard methyl esters. The quality indicators of such mixture and their compliance with the requirements of the standard are given in Table 3.

The data show that the mixture of KSME and KME meets quality requirements for biodiesel fuel, so in this composition it was used for producing fuel to test the engine. As mentioned above, this fuel included 30% (vol.) of the fuel of biological origin which accounted for 5% of methyl esters from rapeseed oil (RME) mandatory included into mineral diesel fuel (D) in the marketing network. The composition of fuel used for comparative tests on the engine was as follows: fuel No. 1 – 70% D, 30% RME; fuel No. 2 – 70% D, 17% KSME, 8% KME, 5% RME.

Quality indicators of such mixtures are presented in Table 4.

The presented data indicate that the mixtures containing KSME have characteristics slightly different from those containing RME and according to the main regulated characteristics of fuel for diesel engines, are in full compliance with the standard of biofuels. They have slightly higher viscosity and density and a lower Cetane number. Compared with pure D, it can be noted that the mixtures of biofuels also have higher density, viscosity, Cetane number and flash point.

Table 2. Parameters of measurement devices

		Measured components						
		CO	CO ₂	HC	O ₂	NO ₂	NO	NO _x
Gas analyzer HGA 400	Limits	0–10% vol	0–20% vol	0–20000 ppm	0–22% vol	–	–	0–5000 ppm
	Accuracy	$\pm 5\%$	$\pm 5\%$	$\pm 5\%$	$\pm 5\%$	–	–	± 1 ppm*
Gas analyzer TESTO 330 XL	Limits	0–20000 ppm	0–25% vol	–	0–25% vol	0–500 ppm	0–3000 ppm	–
	Accuracy	$\pm 5\%$	$\pm 0.3\%$ vol	–	$\pm 0.2\%$ vol	$\pm 5\%$	$\pm 5\%$	–
Smoke meter MDO-2	Limits	Smokeness, % 0÷100			Coefficient of absorbance, 0–9.99 m ⁻¹			
	Accuracy	$\pm 2\%$			$\pm 2\%$			

* resolution

Table 3. Quality indicators of the mixture containing 68% of *Camelina sativa* oil and 32% of methyl esters from pork lard and their compliance to the requirements of LST EN 14214:2009

Parameter	Unit	Requirements of LST EN 14214		Mixture of KSME and KME
		min	max	
Ester content	% (mass)	96.5		97.1
Density at 15°C	kg/m ³	860	900	865
Viscosity at 40°C	mm ² /s	3.50	5.00	4.8
Flash point	°C	120	–	185
Sulfur content	mg/kg	–	10	18
Conradson carbon residue	% (mass)	–	0.30	0.2
Cetane number		51.0	–	51.5
Sulfated ash content	% (mass)	–	0.02	0.02
Water content	mg/kg	–	500	350
Total impurities	mg/kg	–	24	12
Oxidation stability at 110°C	h	6.0	–	7.6
Acid value	mg KOH/g	–	0.50	0.38
Iodine value	g I ₂ /100 g	–	120	118
Linoleic acid methyl ester content	%	–	12	12
Polyunsaturated fatty acid methyl esters content (≥ 4 double bonds)	% (mass)	–	1	–
Methanol content	% (mass)	–	0.20	0.15
Monoglycerides	% (mass)	–	0.80	0.48
Diglycerides	% (mass)	–	0.20	0.1
Triglycerides	% (mass)	–	0.20	0.1
Free glycerol	% (mass)	–	0.02	0.05
Total glycerol	% (mass)	–	0.25	0.30
Potassium (K) content	mg/kg	–	5.0	4.5
Phosphorus content	mg/kg	–	10.0	8.0

Table 4. Quality indicators of fuels

Parameter	Unit	Fuel No. 1	Fuel No. 2	D	RME	KSME	KME
Ester content	% (vol)	30	30	–	96.5	97.1	97.0
Density at 15°C	kg/m ³	848	849	840	890	864	866
Viscosity at 40°C	mm ² /s	2.97	3.2	2.5	4.7	3.7	5.4
Cetane number		49	48	46.0	51.6	51.3	51.6
Ash content	% (mass)	0.007	0.01	0.01	0.02	0.02	0.01
Copper strip corrosion (3 hours at 5°C)	°C	1	1	1	1	1	1
Flash point	°C	101	103	68	185	180	190

3.2. Comparative Analysis of Environmental Indicators for the Diesel Engine

Carbon monoxide. The nature of CO emissions changes when changing the engine load is equal for all tested fuels: minimum emission values are ~150 ppm, reached at 60–70% P_{enom} ; at a lesser and higher load from 60–70% P_{enom} , CO emission increases (see Fig. 1). The authors obtained a similar dependence of CO emission on P_e was during 1A41 and 2FL511 diesel engine tests on RME (Lebedevas et al. 2006b). Differently from those mentioned in the previous studies, a markedly less intensive growth of CO is close to the nominal one within the load modes. This could be explained by the improved operational process of engine 320 compared with the previously tested engines, especially with the obsolete model 1A41.

The level of CO emission in low and medium load modes are the same when using D and its mixtures containing only RME (D70/RME30) and the mixtures containing KSME (D70/RME5/KSME17/KME8). For the load exceeding 60 to 70% P_{enom} , the consumption of biofuel with the types of methyl esters (B30) allows to reduce the emissions of CO by ~20 to 25% compared with fossil diesel fuel (D). Maximum CO emission was ~250 ppm recorded under low load conditions.

Nitrogen oxides. When increasing the load of the diesel engine, NO_x emissions are monotonously growing from 170 ppm to ~1800 ppm under nominal load conditions. A physical mechanism of NO_x and CO formation in the engine cylinder is different (Kruggel 1989; Звонов 1981). Therefore, in most cases, the conversion of the diesel engine to work using different types of fuel is related to contrary changes in CO and NO_x emissions (Lebedevas et al. 2006b; Chen et al. 2008; Al-Hasan and Al-Momany 2008; He et al. 2003). Similar results are obtained in the current tests. Unlike CO emission, the NO_x emission of the diesel engine operating on both fuel containing 30% of RME, pure RME and fuel containing KSME increases by 7 to 8% in the nominal power modes, compared with pure fossil diesel fuel (see Fig. 2). With the diesel engine operating on D70/RME30 and D70/RME5/KSME17/KME8 fuels, nearly the same NO_x emission was obtained within the entire range of load.

Hydrocarbons HC. The general positive characteristics of HC emission of all tested fuels features a strong increase in idle up to 30% P_{enom} modes, and further stabilization of their values under medium and nominal load conditions (see Fig. 3). HC emissions do not differ when the diesel engine operates on fossil diesel fuel and 30% RME mixtures with D. The use of a new kind of diesel fuel D70/RME5/KSME17/KME8 based on *Camelina sativa* oil reduces HC emissions by ~25 to 30 ppm or by 10 to 12% within the main load range. This is one of the recorded advantages of the motor features of the new fuels.

Smokeness. The second advantage of fuel containing *Camelina sativa* oil methyl esters is reducing the smokeness of exhaust gas (SM) where the diesel engine operates on D70/RME5/KSME17/KME8. The reduction of SM content was recorded across the entire range of

P_e and was equal to 12–25% (K factor values decrease to 0.025–0.05 units at its maximum level of ~0.35 units) compared with D and D70/RME30 (see Fig. 4).

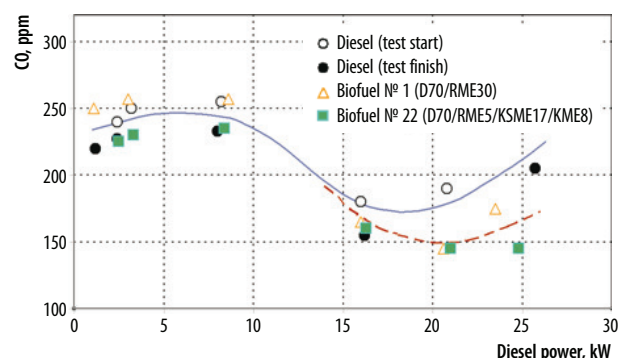


Fig. 1. Emissions of carbon monoxide from diesel engine VALMET 320 DMG operating on different types of fuels

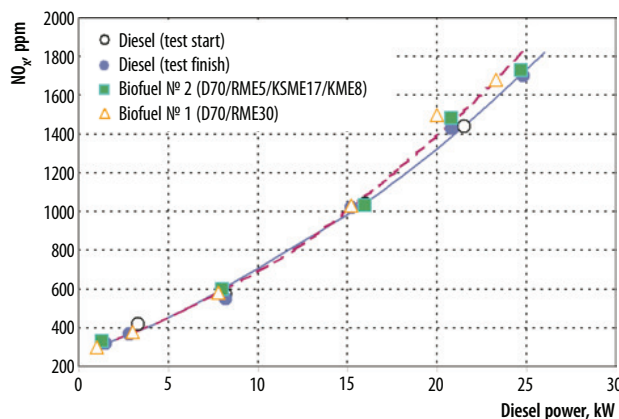


Fig. 2. Emissions of nitrogen oxide from diesel engine VALMET 320 DMG operating on different types of fuels

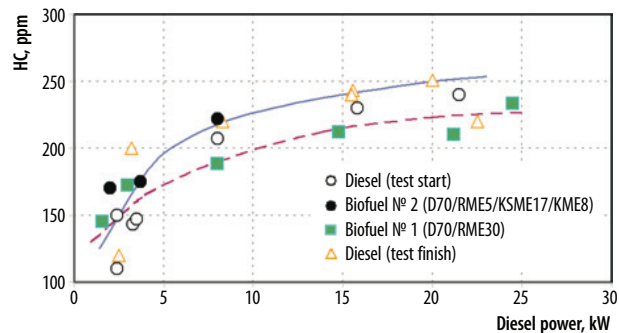


Fig. 3. Emissions of hydrocarbons from diesel engine VALMET 320 DMG operating on different types of fuels

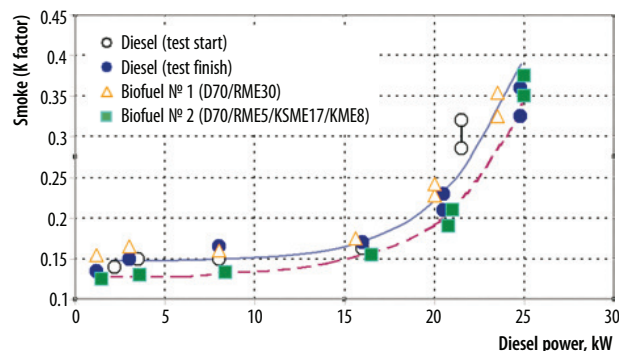


Fig. 4. Smokeness of exhaust gas from diesel engine VALMET 320 DMG operating on different types of fuels

4. Conclusions

1. Methyl esters produced from pure *Camelina sativa* oil do not meet quality requirements applied for biodiesel fuel due to a high iodine value and the high content of linoleic acid methyl esters, and therefore cannot be directly used as fuel for diesel engines.
2. In order to use methyl esters from *Camelina sativa* oil in the diesel engine, they must be mixed with methyl esters from pork lard. A mixture containing methyl esters from *Camelina sativa* oil and pork lard complies with the requirements of LST EN 14214 at the ratio of 68:32 regarding the iodine value and the content of linolenic acid methyl esters.
3. The tests on operating diesel engine 320 manufactured by the company AGCO SISU POWER and used in the vessel, demonstrate favourable motor characteristics of the new type of biofuel containing methyl esters from *Camelina sativa* oil (KSME) in the mixture with methyl esters from pork lard (KME) at the determined optimum ratio of 68:32:
 - when compared with fuel containing 30% of RME in the mixture with fossil diesel fuel, the use of KSME-based biofuel (D70/RME5/KSME17/KME8) features the same CO and NO_x emissions within the entire investigated range of loads from idle travel and makes up to 80% P_{enom} in comparison with fossil diesel fuel at the load greater than 60% of the nominal where CO emissions decrease from 20 to 25% and NO_x increase from 7 to 8%;
 - the use of fuels D70/RME5/KSME17/KME8 reduced HC emissions by ~10 to 12% within the main load range and the smokiness of exhaust gas by 12 to 25% compared with D and D70/RME30.
4. Diesel fuel cost-saving and traction characteristics of the engines operating on KSME and based on the new types of biofuels will be tested on the motor test stand.

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