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RESEARCH ARTICLE

Comparable Research of Energy and Ecology Parameters of 1st, 2nd and 3rd Generation Biofuels for Compression Ignition Engines

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Abstract
Paper provides the summarized results of high-speed and direct-injection compression ignition engines (further diesel engines) VALMET 320 DMG (ship gen-set) and Audi 1Z (passenger vehicle) performance research, which was carried out using different kinds and types of biofuel. Main attention focused on energy and environmental characteristics of diesel engine performance using 1st, 2nd and 3rd generation alcohol, fatty acid methyl and butyl esters blends with conventional diesel fuel (EN 590). Results of biofuel blends use instead diesel fuel showed that the efficiency of energy use increases 1–4%; at practically unchanged NO_X concentration unburned product (CO, CH) concentration decreases up to 20% and exhaust gas smokiness – 55–85%.

Keywords
Diesel engine, rapeseed biodiesel, Camelina sativa biodiesel, algae biodiesel, butanol, butyl ester

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1 Introduction

Climate change and warming has forced humankind to focus on the reduction of greenhouse gases emissions and, consequently, on the production and consumption of biofuels. Biomass, which serves as the feedstock for the production of biofuels, assimilates carbon dioxide (CO_2) from the atmosphere by means of photosynthesis during its growth. Particularly large changes related to the consumption of fuels are to be required of the transport sector. The European Commission envisaged new initiatives in this regard in the COM (2011)144 White Paper [1]. One of initiatives involves reducing the pollution in transport sector by 60% through the use of new and stable fuel types. It is planned to reduce the use of vehicles driven by ordinary fuels in cities by half by 2030 and to decrease the number of such vehicles in cities to zero by 2050. In the aviation sector, the objective is to ensure that stable low CO_2-emitting fuels account for 40% of all consumed fuel by 2050. With respect to marine transport in the EU, it is aimed to reduce the amount of CO_2 emissions by 40% by 2050.

A major part of European biodiesel (84%) is obtained from rapeseed oil, while sunflower oil accounts for 13% of the feedstock used for production [2]. Soybean oil, palm oil and other oil types have accounted for only 1% of the feedstock used there. Biodiesel can be produced from many other types of raw materials, including other vegetable oils, lard and animal fat, and waste from catering food enterprises, such as used cooking oil.

Growing biodiesel production and the related increasing demand for feedstock has increased agricultural produce prices and competition with the food sector. Alternative feedstock for biodiesel production has been researched to reduce the negative impact of biodiesel production on the food sector, with new types of oil plants and various fatty wastes being considered as potential options. Production and consumption of biofuel are affected by the European Commission's regulations [3, 4, 5] which promote the production and usage of biofuel, especially made from materials unsuitable for food.

Camelina sativa (CS) is one of oil plant species that may serve this purpose [6]. Due to its high content of unsaturated fatty acids, CS oil (or flaxseed oil) belongs to the group of fast-drying oils. Because of their fatty oil composition (a high amount of polyunsaturated acids) [7], these biofuels fail to comply with the requirements of the EN 14214 standard in terms of their iodine value, which reaches 165–175 g I_2/100 g, while the standard requires a maximum of 120 g I_2/100 g. To use CS oil in the production of diesel fuel, it is necessary to search for possible ways to produce mixtures of CS oil methyl esters with esters of other kinds of oil or fat. Waste fat (pork lard) has a low iodine value (~45 g I_2/100 g). Scientists have determined that mixtures containing 68% spring CS oil and 32% (vol.) pork lard methyl esters meet the requirements of standard EN 14214, and engine tests of blends of this type of biofuel with fossil diesel fuel have been performed [8]. CS biofuel is classified as 2nd generation biofuel.

Algae have frequently been mentioned as a source of oil in recent years. Expanded scientific research has been performed to utilize this raw material for biodiesel production in the most efficient manner. The data from short small scale experiments show that algae biodiesel has economic disadvantage and cannot compete with fossil fuel. However, some authors believe that fuel production from algae can be cost competitive in the next 7–10 years when new strains of algae will be created and more cost effective methods for algae cultivation and conversion will be developed [9]. The use of algae for energy needs has several advantages. Excess CO_2, which causes the greenhouse effect when emitted into the atmosphere, can be used for algae cultivation. Algal biomass can be distributed over vast spaces of land, and its processing would not require additional resources that increase CO_2 emissions. Finally, algae grow faster than ordinary oil plants [10]. All types of algae contain oils, and their oil content is sufficiently high, being 20–40% of the organism's dry mass, and the oil content in some algae strains can be as high as 75% [11]. The fact that microalgae grow much faster than land plants is one of the most compelling reasons for the use of algae in biodiesel production. Moreover, the amount of oil obtained from algae is approximately 7–31 times greater than that obtained from the best land crops, such as palms, cultivated in the same area [12] algae can be cultivated in special water containers, so it is not necessary to allocate agricultural lands currently used for food production. Algae biofuel is classified as 3rd generation biofuel.

Alcohol like bioethanol as a fuel commonly used in spark ignition engines, however scientific practice shows that alcohol could be used as an additive for diesel fuel [13, 14, 15, 16]. Butanol's performance characteristics are better than ethanol's. Butanol blends with diesel fuel are less sensitive for water than ethanol ones [17], which tend to settle in layers when water is present. The calorific value of butanol is higher than that of ethanol or methanol, and the latent vaporific heat is lower than that of ethanol or methanol; therefore, an engine that uses this fuel is easier to start during winters. The good low-temperature properties of butanol fuels are also very significant. Butanol made from biomass containing cellulose is classified as 2nd generation biofuel.

2 Methods and Materials

Research covers 1st, 2nd and 3rd generation biofuel and fossil diesel fuel engine tests. 1st generation rapeseed oil methyl esters (RMEs) were chosen for comparable research. It was purchased from the biodiesel fuel producer JSC "*Mestilla*" (Lithuania). The quality parameters of the esters met the requirements of standard EN 14214. Fossil diesel fuel was purchased from a market, and its quality parameters met the requirements of standard EN 590.

Requirements of standard EN 14214 for 2nd and 3rd generation biofuels were ensured in laboratory of Chemical and Biochemical Research for Environmental Technology (Aleksandras Stulginskis University, Lithuania).

Fuels. C class fossil diesel fuel (D) with a 5% FAME additive complying with requirements for Lithuanian (also EU) standard LST EN 590:2009+A1:2010.

Tested 2nd and 3rd generation biofuels [Butanol (B), Rapeseed butyl (RBE) and methyl (RME) esters of winter (WCME) and spring (SCME) *Camelina sativa* FAME, algae FAME (AME)] were analysed (chemical, physical properties, etc.) by staff of Aleksandras Stulginskis University Laboratory of Chemical and Biochemical Research for Environmental Technology during the cooperated implementation of the international projects: Eureka: Biowaste fuel E!3234, Camelina-Biofuel E!4018, etc. The main properties of tested fuels and their blends are shown in Table 1–3. This data is taken from other 3 author's (with other researchers) publications [18, 19, 20].

Research was carried out using 2 and 3 components FAME, FABE and alcohol based blends:

- B30 (RME) blend of rape methyl ester (RME) and D – blend of 2 components which has volume rate D70/RME30;
- B30 (B) blend of butanol (B) and D – blend of 2 components which has volume rate D70/B30;
- B30 (RME/B), B50 (RME/B) and D blends of rape methyl ester, butanol and D – blends of alcohol and FAME, volume rates are D70/RBE15/B15 and D50/RBE25/B25;
- B30 (RBE/RME) and B50 (RBE/RME) and D blends rape butyl (synthetic) ester butanol and D – blends of alcohol and FABE, volume rates are D70/RBE15/B15 and D50/RBE25/B25;
- B30 (WCME) blend of winter *Camelina sativa*, pork lard methyl esters and D – blend of 3 components which has volume rate D70/WCME30;
- B30 (SCME) blend of spring *Camelina sativa*, pork lard methyl esters and D – blend of 3 components which has volume rate D70/SCME30;
- B30 (AME) blend of micro algae methyl ester (AME) and D – blend of 2 components which has volume rate D70/AME30.

Table 1 The main properties of tested fuel blends

Parameter	D70/B30	D70/RME15/B15	D70/RBE15/B15	D50/RME25/B25	D50/RBE25/B25
Cetane number	46.2	50.5	51	50.2	51.8
Density (15˚C), kg/m^3	833	835	832	838	833
Viscosity (40˚C), mm^2/s	3.45	3.29	3.39	3.15	3.32
Elemental composition, %					
C	80.4	80.9	81.1	78.2	78.4
H	12.9	14.2	14.2	13.6	13.7
O	6.7	4.9	4.7	8.2	7.9
Lower heat. value, MJ/kg	39.8	41.5	41.6	39.6	39.8
Cold filter plug point, ˚C	-36	-29	-33	-27	-29

Table 2 The main properties of tested methyl esters

Parameter	SCME (68%)+PME (32%)	WCME (68%)+PME (32%)	RME
Cetane number	52	52	53.1
Density (15˚C), kg/m^3	890	896	883.1
Viscosity (40˚C), mm^2/s	4.7	4.7	4.425
Cold filter plug point, ˚C	-5.5	-5.5	-12

Table 3 The main properties of tested fuel blends

Parameter	B30 (AME)	B30 (RME)	Diesel fuel
Density at 15 ^{0}C, kg/m^3	851.1	853.4	0.840
Viscosity at 40 ^{0}C, mm^2/s	2.96	2.99	2.52
C/H/O, %	81.42/13.67/3.91	80.98/13.49/4.46	86.5/13.1/0.1
Lower heating value, MJ/kg	40.78	40.92	43.44

Engines. Engine tests carried out during cooperation between Klaipeda University Maritime Institute, Lithuanian Navy and Vilnius Gediminas Technical University.

Blends of biofuels and fossil diesel fuel were tested using two different engines: VALMET 320 DMG and Audi 1Z. Fuel blends containing RME butanol, Camelina sativa and micro algae fuels were tested on VALMET 320 DMG. The 1Z engine was used for CS and RME fuel blends with D research only.

To approximate the results of tests of actual operating conditions, tests were performed in a VALMET 320 DMG diesel gen-set on board a ship. Engine VALMET 320 DMG (manufactured by AGCO SISU POWER, Finland), intended for running on a wide range of fuels, including pure (100%) biodiesel, which by itself ensures the optimal operating characteristics of the engine to prevent changing the adjustment parameters for running on biofuels. The main operating parameters of the engine are provided in Table 4.

Table 4 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
Rated power, kW	30 (1500 rpm), 35 (1800 rpm)
Rated speed, rpm	1500
Starting pressure of fuel injection, MPa	23.5 ± 0.5
Fuel injection	Direct
High pressure pump	Sectional Bosch

The tests also included control test points for technical condition of the engine: during the biofuel tests, engine tests were repeated two or three times periodically while running on fossil diesel fuel. Engine tests were performed on the engine operating under its main operating characteristic: the load characteristic

(n=1500 min^{-1}, in modes from idle to next-to-maximum running, meeting the requirements of test cycle D2 according the ISO 8178 standard (Table 5).

Table 5 Weighting factors of ISO 8178 test cycle D2

Speed, %	100	100	100	100	100
Load, %	100	75	50	25	10
Weighting factor	0.05	0.25	0.30	0.30	0.1

The derivative values of the diesel engine parameter *P* under the test cycle mode were determined using the following equation:

$$P_{cycle} = \sum_{i=1}^{n} P_i \times w_i \qquad (1)$$

where P_{cycle} is the integral parameter value; P_i is the parameter value when the engine operates in the i^{th} test cycle mode and w_i is the weighting factor of the i^{th} mode.

Table 6 provides data on the measurement accuracy tolerances of the portable equipment used for VALMET 320 DMG engine tests.

Other research object was 4 stroke four cylinder 1.9 litre TDI passenger vehicle Audi engine 1Z. The engine with an open combustion chamber, direct fuel injection system, containing a turbo compressor and exhaust gas recirculation systems, also electronic engine control unit, was tested in VGTU's laboratory. Main technical data of the engine are presented in Table 7.

The 1Z engine tests were conducted on the automated mounted stand KI-5543 with weight dynamometer to identify the torque generated by an internal combustion engine. The electric asynchronous engine with wound rotor, liquid rheostat and dynamometer was used as an engine brake on the mounted stand. The stand is universal: when engine‘s revolutions fall within the range of 600–1400 min^{-1}, the stand runs as an electric engine, and when resolutions fall within the range of 1600–3000 min^{-1} – it operates as a brake in the electric generator's mode. The stand‘s torque operating in the engine‘s and generator‘s modes is controlled by the electromechanical drive liquid rheostat. Maximal stand‘s brake torque reaches 186 Nm, and the maximum measured torque is 440 Nm. Torque‘s measuring error makes up 0.8% from the maximal value of torque.

The engine is connected to the stand directly (without gearbox), via shaft.

Fuel consumption was measured by electronic SK – 5000 scales, the maximum limit of which is – 5000 g, the value of mark being 1 g. The accuracy of measuring fuel consumption per hour is 0.5%.

To analyse engine‘s exhaust gas harmful components, the exhaust gas analyser AVL DiCom 4000 was used. The measuring ranges and accuracy of harmful components in exhaust gases are presented in Table 8.

The rates of exhaust gas temperature were measured in the following two ways:

- Infrared thermometer Emsitest IR 8839, within the range of measured temperature of 50–1000 ˚C, when measuring error limit is ±2 ˚C.
- Thermocouple TP-02A, which was connected with the data registering measuring module Datalogger DL 2000, within the range of measured temperature 0–650 ˚C.

3 Engine test results

To maintain the stability of engine thermal condition, its parameters were measured in 5–10 min. after work regime set at the selected loads. To enhance the accuracy of measuring, the parameters were measured approximately 3 times in each testing regime of the engine thus identifying the mean value of the obtained data. To control the technical condition of the engine in the test start, run and finish, the parameters of the engine running on fossil diesel fuel were registered.

A number of diesel engine tests were carried out in different periods. Table 9 shows a part of results of biofuel blends tests during PhD studies.

Table 6 Technical specifications of measurement equipment

<table>
<tr><th colspan="2">Device</th><th>CO</th><th>CO_2</th><th>HC</th><th>O_2</th><th>NO_2</th><th>NO</th><th>NO_x</th></tr>
<tr><td rowspan="2">HGA 400</td><td>Limits</td><td>0–10% vol.</td><td>0–20% vol.</td><td>0–20000 ppm</td><td>0–22% vol.</td><td rowspan="2">–</td><td rowspan="2">–</td><td>0–5000 ppm</td></tr>
<tr><td>Accuracy</td><td>±5 %</td><td>±5 %</td><td>±5 %</td><td>±5 %</td><td>±1 ppm</td></tr>
<tr><td rowspan="2">Horiba PG-250</td><td>Limits</td><td>0–5000 ppm</td><td>0–20% vol.</td><td rowspan="2">–</td><td>0–25% vol.</td><td>0–2500 ppm</td><td>0–2500 ppm</td><td>–</td></tr>
<tr><td>Accuracy</td><td>±5 %</td><td>±3 % vol.</td><td>±0.2% vol.</td><td>±5 %</td><td>±5 %</td><td>–</td></tr>
<tr><td rowspan="2" colspan="2">MDO-2 LON</td><td colspan="2">Limits</td><td colspan="2">Smoke, 0–100 %</td><td colspan="3">Absorbance coef., 0–9.99 m^{-1}</td></tr>
<tr><td colspan="2">Accuracy</td><td colspan="2">± 2%</td><td colspan="3">± 2 %</td></tr>
<tr><td rowspan="2" colspan="2">AIC-888</td><td colspan="2">Flow limits, *l*/h</td><td colspan="2">Nominal temp., ˚C</td><td colspan="3">Accuracy, %</td></tr>
<tr><td colspan="2">1–200</td><td colspan="2">-30–90</td><td colspan="3">0.5–1.0</td></tr>
</table>

An accuracy of voltage and ampere measurement by clamp meter Kyoritsu KEW 6300 is ±0.3 % for each (V and A)

Table 7 Main parameters of diesel engine Audi 1Z

Parameter	**Value**
Engine displacement, cm^3	1896
Number of cylinders	4
Compression ratio	19.5
Rated power, kW	66 (4000 min^{-1})
Torque, Nm	180 (2000–2500 min^{-1})
Mean effective pressure, MPa	1.19 (180 Nm)
Cylinder bore, mm	79.5
Piston stroke, mm	95.5

Table 8 Measuring range and resolution of device AVL DiCom 4000

	Measuring range	**Resolution**
Smokiness:		
Smoke opacity	0–100 %	0.1 %
Absorption (K – factor)	0–99.99 m^{-1}	0.01 m^{-1}
Nitrogen oxides	0–5000 ppm (vol.)	1 ppm
Hydrocarbons	0–20 000 ppm (vol.)	1 ppm
Carbon monoxide	0–10% (vol.)	0.01% (vol.)
Carbon dioxide	0–20% (vol.)	0.1% (vol.)

Table 9 Results of engine tests

Fuel blend	Relative deviation comparing with fossil diesel fuel, %						
	NO_X	CO	CO_2	HC	SM	b_e	η_e
D70/RME30	~ +2.9	-7–-16	~ 0	–	-3,5–-7 times	+3–+4	~ +1^{sc}
D70/B30	~ +3	-10–-20		-7–-8		~ +6	
D70/RME15/B15	+4–+5	-6–-14		~ -15		~ +8	
D50/RME25/B25		-7–-16	~ -4	+7–+13			~ +4^{sc}
D70/RBE15/RME15	~0	-10–-20	~ 0	-10–-20		+3–+4	~ +1^{sc}
D50/RBE25/B25			~ -4	+20–+40			~ +4^{sc}
D70/RME30	-2.5*	-8.5*	–	+4*	-21.0*	–	+4.95^{sc,*}
D70/WCME30	-2*	-8.0*		-1.2*	-23*		+4.6^{sc,*}
D70/SCME30	-0.5*	-10.0*		+7.5*	-23.2*		+3.6^{sc,*}
D70/RME30	+2.6– -2.7*	-5.0 – -6.5*	–	+4*	-25*	–	+3.0^{sc,*}
D70/WCME30	+2.95*	-5.5*		-1.2*	-27*		+3.0^{sc,*}
D70/SCME30	+2.4*	-2.5*		-8.0*	-25*		+2.0^{sc,*}
D70/RME30	0*	0*	–	0*	0*	–	0^{sc,*}
D70/WCME30							
D70/RME30	~ 0^{S}	–	~ 0^{S}	-15–-18^{S}	-5–-20	–	~ 0^{sc,S}
D70/WCME30				~ 0^{S}			
D70/SCME30				-15–-18^{S}			
D70/RME30	0*	0*	–	0*	0*	–	~ 0^{sc,*}
D70/RME30	+4–+7	–	–	< -3 ppm	-0.5–-1.2^{sc}	1–+3.5	~ 0^{sc}
D70/RME30	-3–+10^{E}	–	±2^{E}	-24–+10^{E}	-7– -24^{E}	-2–+8^{E}	-3–+6$^{sc, E}$
D70/RME30	~ 0	0–-10	–	-5–-25	-10– -75	+3– +3.5	+2.5–+3^{sc}
D70/DME30				-12–-15	-10–-55		

* – cyclic (or average operational) change determined according D2 cycle requirements of standard ISO 8178;

– – not analysed/not measured;

~0 – change is close to zero or less than accuracy of measurement device;

^{sc} – assessed scale's values in %;

^{E} – tests carried out without exhaust gas recirculation (but system is provided);

^{S} – tests carried out with exhaust gas recirculation.

Table 10 The summarized results of diesel engines tests

Parameter	δ from diesel fuel			
	Positive		Negative	
	Dominant	Maximum	Dominant	Maximum
NO_X	0– -2%	~ -3%	+3–+5%	+10%
CO	–5– -16%	~ -20%	–	+5%
SM	–20– -30%	3,5–7 times	–	-0.5–0
HC	–8– -15%	–10– -15%	+ 4– +7%	+20–+40%
b_e	–	–	+3–+8%	+8%
η_e	+2–+4%	~ +6%	–3–0%	-3%

Tests were carried out in 4 year period. Bolded biofuel blend names mark the tests carried out on 1.9 TDI engine and not bolded – 320 DMG. It should be noted that results (of 320 DMG engine tests) of CO HC, SM and NO_X, which are very close or equal zero, are related to strongly oxidized (long stored) biofuel use. In order to evaluate the change of parameter of engine working on different blends, a number of results could confuse. Due to this, it's better to pick out the ranges of dominant and maximal values for each engine work parameter. These steps are carried out in Table 10.

The generalized assessment of all tested fuel blends was carried out using rate of O_2 content in the fuel. Data shown in Fig. 1 covers results carried out on engine DMG 320 tests only. Table 11 specifies the rate of O_2 content for fuel blends.

Figure 1 shows the harmful components emission rates dependence on O_2 content in tested fuels on engine 320 DMG.

Results show that the highest value of NO_X concentration comes with the highest value of oxygen (O_2) content in fuel. B50 blends have the highest content of O_2, this reduces smokiness very effective due to lower content of carbon in blends. The opposite results observed in case of incomplete combustion product concentration in exhaust gases. When B50 is used, HC and CO concentration reaches the values higher than fossil diesel fuel. This opposite result is related to the high content (25% vol.) of alcohol, used in B50 blends. This could be explained that the high content of alcohol makes influence to cylinder combustion process due to higher value of vaporific heat.

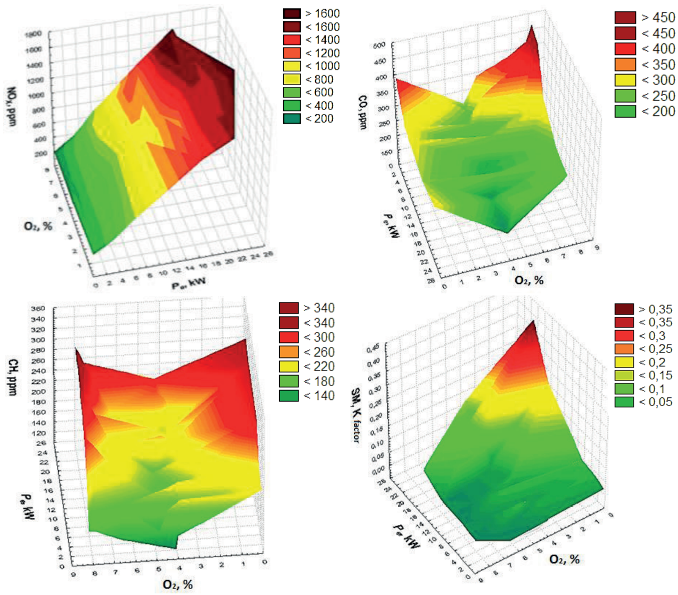

Fig. 1 The dependence of 320 DMG engine harmful components concentration on oxygen content in fuel

4 Conclusion

The 2nd and 3rd generation biofuel blends (2 and 3 components) containing FAME, FABE, alcohol and fossil diesel fuel were tested on two different type engines. The results of diesel engine energy and ecology parameters research showed that properties (NO_X, CO, CH, SM and b_e, η_e) of diesel engine fueled by tested fuel blends are as good as properties of certificated RME blends and comparing to diesel fuel the efficiency of energy use increases 1–4%; at practically unchanged NO_X concentration the decrease of unburned products (CO, CH) concentration reaches up to 20% and exhaust gas smokiness – 55–85%.

The summarized results of diesel engine VALMET 320 DMG showed that considering to the concentration of incomplete combustion products the B30 blends are more advantageous comparing to D and B50. The disadvantage of B50 associated with a use of relatively large amount of alcohol which changes the kinetics of combustion process.

Table 11 Oxygen content in tested fuel blends

Blend:	**D**	**D70/B30**	**D70/RME15/B15**	**D50/RME25/B25**	**D70/RBE15/B15**
O_2, %	~0.1	6.7	4.9	8.2	4.7
Blend:	**D50/RBE25/B25**	**D70/RME30**	**D70/DME30**	**D70/WCME30**	**D70/SCME30**
O_2, %	7.9	4.5	3.9	4.1	4.0

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