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RESEARCH OF USAGE OF RRME AND ALCOHOL BIOFUEL MIXTURE IN DIESEL ENGINE

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Abstract

The paper provides the results of an integrated research of the energy, environmental performance and traction indicators and the characteristics of fuel feed and performance of A41, 2F511, VALMET 320 DMG and Audi 1Z high-speed, direct-injection diesel engines when converting their operation from mineral diesel D to the fatty acid esters (RRME and RRBE) and alcohol biodiesel mixtures. The researches are carried out in cooperation of the Lithuanian and Polish partners within the framework of joint scientific projects under EUREKA international scientific program "E!4018 CAMELINA-BIOFUEL".

In the light of the new EU initiatives ("White Paper" 2011), 30% optimum part of RRME bio-component in the mixture with D (B30) is validated for practical use. The characteristics of fuel supply and heat generation in a diesel cylinder are under investigation; an explanation of a significant reduction in the harmful component emission (EG) and 2 to 4% increase in the fuel efficiency in case of use of B30 and B10 biodiesels is offered. The presence of the ethanol alcohol component (E) in D-RME-E and RME-E biofuel mixtures resulted in reduction of CO and NOx emission by 10 to 12% and EG smokiness – by 20% per each 10% increase of E part. The indicated efficiency of performance was increased by 2-2.5%. The indicators of cyclic instability did not exceed the corresponding indicators in diesel operation on D. It is established that the motor properties of tested B30 and B50 biofuels based on butanol and rapeseed oil butyl ester RBE are similar to RME biodiesels and have important advantages over them: the complete solubility of alcohol component and the possibility of B30 (D-RBE) use at ambient temperature up to -30^{o}C.

The motor characteristics of the second-generation biodiesels produced from the non-food raw material (Camelina Sativa oil methyl esters) are highly competitive with and even exceed by separate indicators the similar indicators of certified RME biodiesels. It is demonstrated that the conversion of diesels, including the automobile diesels with EGR electronic system, to operation on D-RRME (RME, CSME) biodiesels does not require the change of regulation characteristics of the fuel-feed system.

The test of the oxidation stability of D-RME and D-CSME biodiesels performed under operating conditions on

VALMET 320 DMG marine diesel proved the stability of the motor, energy, and environmental performance indicators for 7-8 months' biodiesel storage without the addition of antioxidant and for 13-14 months' storage – with the addition of Ionol BS200 antioxidant.

Keywords: *biodiesel, biofuel, diesel engine, environmental and energy parameters*

1. Introduction

One of the most important strategic aims of the European Union policy is environmental protection. According to the EU Agreement, the economic development policy of member states shall be based on the environmental protection criteria. Recently, a lot of attention has been paid to the reduction of greenhouse gas emissions. Their regulation was started in 1992 according to the United Nations Framework Convention on Climate Change. In 1997, the Kyoto Protocol was signed, which encourages lower the emissions of greenhouse gases. Transport and energy are the main sources of atmospheric pollution using fossil fuel; therefore, EU documents encourage to replace mineral fuel by renewable energy sources and to increase their application in various economic areas.

Analysis of the potential of the raw materials available European union that are required for production of the standard rapeseed oil methyl esters (RME) suggests that fulfilment of the EU prospective norm indices may be problematic. Because of this, the development of new kinds of biofuels is important, as is extension of the raw material base of Lithuania. A new kind of biofuels being widely used in the EU, the USA, Brazil, and other regions of the world such as China, India, Australia, and South America is a multicomponent fuel mixture of fossil fuels composed of fossil diesel fuel (D), fatty acid methyl esters (FAME), and ethanol (E) [1-3].

The production and consumption of biofuel is affected by the European Commission's regulations, which promote the production and usage of biofuels [4-6]. Among the biofuels obtained from biomass containing cellulose, notable ones include bioethanol and the more promising biobutanol.

Biobutanol's properties as a fuel component are better than those ethanol ones. Butanol mixtures with diesel fuel are less sensitive to water than ethanol mixtures, 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 vapourific 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. One of the main weaknesses of the performance of widely used biofuel based on rapeseed oil methyl esters (RME) is its limited possibility of use during intermediate periods as well as during the coldest periods of the year [7].

Another reason for the increasing use of biofuels is insufficient, first of all, in Europe, potential of raw materials of RME as well as moral and political aspects of fuel production from feedstock. One of the reasons for the appreciation is the use of raw materials of food origin in the production of biofuels. One of the possible solutions to the problem is the use of Camelina sativa biofuels complying with the requirements set to the fatty acid methyl esters (FAME), which may grow in the normal environment conditions.

Paper presents the results of various types of biofuel (rapeseed methyl ester (RME), ethanol (E), mixtures with diesel fuel D-RME-E and RME-E; butanol B and rapeseed butyl ester RBE; mixtures of winter/summer Camelina sativa and pork lard methyl esters CSME) tests and researches. Studies were carried out by corporation of Lithuanian and Polish scientists in projects EUREKA E!3234 BIOWASTEFUEL and E!4018 CAMELINA – BIOFUEL.

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2. Materials and Methods

Production process and the main physical-chemical parameters of tested biofuels (rapeseed butyl ester, winter/summer Camelina sativa methyl, Pork lard methyl ester, butanol) were ensured in Laboratory of Chemical and Biochemical Research for Environmental Technology (Aleksandras Stulginskis University). Engine tests were done by researchers of Klaipeda university Maritime institute.

Researches were done using various types of diesel engines: tractor – 1A41, diesel generator – F2L511, vessel's diesel generator – 320 DMG, vehicle – 1.9 TDI 1Z. Engines' main parameters are presented in Tab. 1.

Certificated motor test stands were used in our research, the accuracy of measurement meets requirements of valid standards.

Tab. 1. Main technical parameters of diesel engines F2L511 and 1A41, 320 DMG, 1Z

Parameter	F2L511	1A41	320 DMG	1Z
Cylinder diameter D, m	0.10	0.13	0.108	0.0795
Piston stroke length S, m	0.105	0.14	0.120	0.0955
Engine displacement V_h, dm^3	1.65	1.115	3,3	1.896
Compression ratio ε	17	16	-	19.5
Rated output $P_{e\ nom}$, kW	25.7	14	30	66
Rated break mean effective pressure p_{me}, MPa	0.62	0.85	-	1.19
Rated speed, rpm	3000	1750	1500	4000

3. Research results

3.1. Change into operational characteristics of diesel engines running on RME biodiesel fuel

Types of tested fuels are as follows: mineral diesel fuel as per standard GOST 305, biodiesel fuel RME certified according to standard LST EN 14214 and mixtures: 90/10 – B10, 85/15 – B15, 70/30 – B30 and Bl00 – pure biodiesel.

Modelling of diesel engine technical conditions of different types was an important aspect of these researches. Within an experiment, a failure of fuel injection was simulated in allowable range of said conditions and finally a wide and extensive data, which consist of 87 regimes, were compiled. The above data made available to determine efficiency of biodiesel fuel, which was used on certain level within diesel engine operational conditions and to draw a distinction between the "ideal technical conditions" and the "unideal technical conditions" of diesel engine, i.e. while injector nozzles were gumming up.

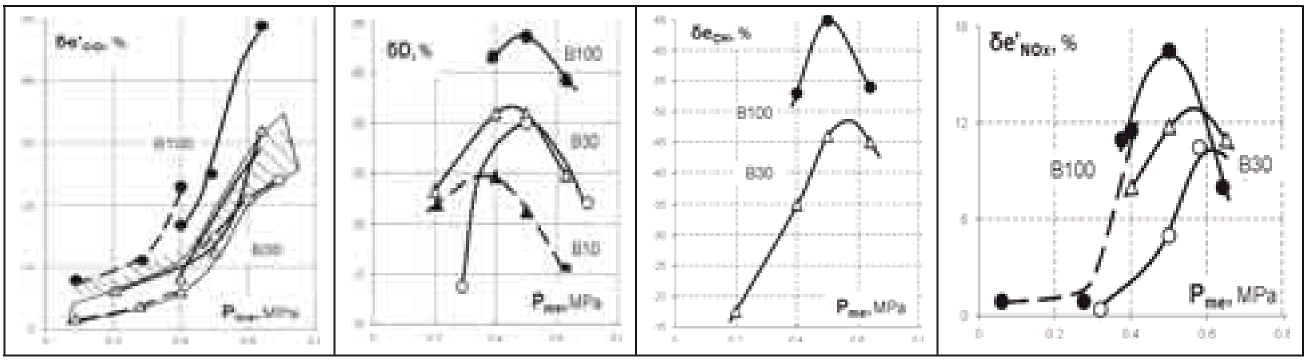

Fig. 1. The ecological parameters relative change of diesel engines F2L511 and 1A41 while running on biodiesel fuel: —●— B100 (F2L511, n=3000 rpm, unideal technical condition); –●–B100 (1A41, n=1750 rpm); —△—B30 (F2L511, n=3000 rpm, unideal technical condition); –○–B30 (F2L511, n=2000 rpm, unideal technical condition); ———B30 (F2L511, n=3000 rpm, ideal technical condition); –△–B30 (1A41, n=1750 rpm);–▲–B10 (F2L511, n=3000 rpm, unideal technical condition)

CO emission

The decrease of B100 CO emission 1.5–1.6 times more than the same of B30 while RME concentration is increased therefore more (see Fig. 1). This proportion remains constant in the completely researched range of brake mean effective pressure.

HC emission

The decrease of HC emission is about 20% by use of B30 and up to 50% at rated load. HC emission is decreased up to 65% by use of B100 within entire researched range of loads and 1.2–1.5 times more than of B30.

Smokiness

B30-biodiesel fuel smoke emission in exhaust gases decreases up to 50-55% at medium load and is 25-30% at low and rated loads. Maximal effect of the decrease of B100 smoke emission is 75%, relation of smoke emission of B100 and B30 is l.5–l.8. To be noted that the smoke emission absolute decreasing is at rated load or in other words: the more is load, the less is smoke emission.

NO_x emission

Relation of change of NO_X emission by the use of B100 and B30 at medium and rated loads is 1.3–1.4.

Complex improvement of ecological parameters by fuel injection timing optimization

Reduction of fuel injection timing in its turn reduces the intensity of combustion within the primary kinetic timing and positively influences on reduction of NO_X emission [7].On the contrary emission of incomplete combustion products is increased, but this increase as a whole is much less than the decrease of emission if mineral diesel fuel is in use.

The increase of CO emission being calculated for injection timing changed by 1° of crank angle (CA). It was determined for mineral diesel fuel, B30 by 3% and for Bl00 by 2%. At the same time reduction of NO_X emission is 3-4% fold for mineral diesel fuel and Bl00 – 8%, for B30 – 11%. Thus, the main task of injection timing optimization was done i.e. the decrease of NO_x emission is more than the increase of CO emission.

Fuel consumption

Results of both 1A41and F2L511 diesel engines experimental researches were qualitative identical i.e. fuel consumption, taking into account measurement error, remained practically unchanged for B10, B15, increased by 2-2.5% for B30 and by 10±2% for B100 (see Fig. 2). The use of parameter $b_{e\ eqv}$, which as a matter of fact is analogous of indicated efficiency factor, makes available to evaluate relative overall efficiency factor within operating conditions and by admissible method.

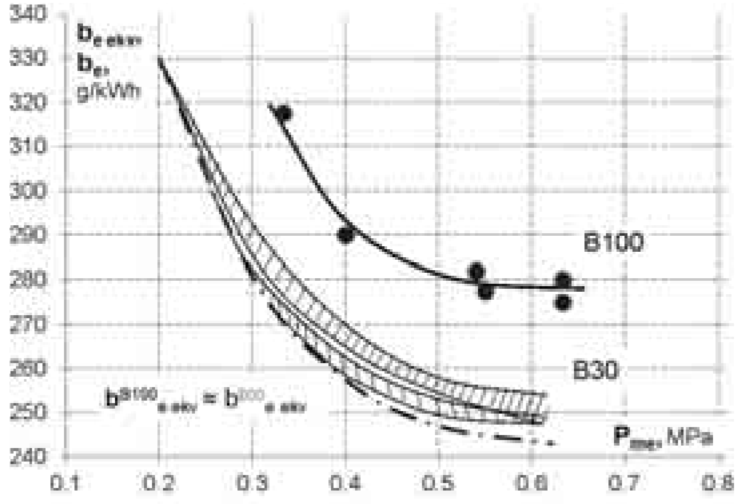

Fig. 2. Diesel engines F2L511 and 1A41 fuel consumption change while running on different fuels: —○— mineral diesel fuel (▥- summary of 87 regimes); —△— biodiesel B30 (▨- summary of 87 regimes); —×— biodiesel B10 (1A41, B15); —●—biodiesel B100; –·–·–·–$b^{B100}_{e\ ekv}$; –··–··–$b^{B30}_{e\ ekv}$

Concentration of biodiesel fuel up to and equal 30% in mixture with mineral diesel fuel is optimal to be used practically in respects of fuel consumption change and effect of ecological parameters improvement. Ecological parameters were changed from 30% up to 55% and maximal possible ecological parameters improvement effect 70% was obtained if B100 is used.

Thrust characteristics

As to conventional viewpoint, thrust characteristics are comprehended as relation of torque M_t (brake mean effective pressure P_{me}) to diesel engine speed by maximum quantity of fuel portion – q_{cycle}, within fuel cycle. Biodiesel fuels are characterized by higher density ρ^B and lower calorific value H_u^B. When speed of engine and brake mean effective pressure is constant, the above can be evaluated by indicated overall efficiency factor η_i. Relative divergence of brake mean effective pressure - torque, can be evaluated by formula:

$$\delta p_{me} = 1 - \frac{p_{me}^B}{p_{me}^D} = 1 - \frac{\eta_i^B \times q_{cycle}^B \times H_u^B}{\eta_i^D \times q_{cycle}^D \times H_u^D} = 1 - \frac{b_e^D}{b_e^B} \times \frac{q_{cycle}^B}{q_{cycle}^D}. \quad (1)$$

If:

$$V_{cycle} = idem: \frac{q_{cycle}^D}{q_{cycle}^B} \approx \frac{\rho^D}{\rho^B}. \quad (2)$$

(1) and (2) being solved simultaneously are transformed into final form:

$$\delta p_{me} = 1 - \frac{b_e^D}{b_e^B} \times \frac{\rho^B}{\rho^D}. \quad (3)$$

Reduction of brake mean effective pressure of naturally aspirated diesel engines within range of boost does not exceed 1% by the use of B30 and B100 by 5-6. There is no necessity to regulate parameters q_{cycle} and injection timing while running on B30.

The mechanical and thermal load of diesel engine

The thermal and mechanical load of parts of cylinder – piston group can be evaluated by widely used in practise indirect criterions, what is allowable at comparative researches. The following indirect criterions were used: maximum in-cylinder pressure P_{max}: for evaluation of mechanical load; maximum in-cylinder temperature T_{max} and medium temperature of compression – power stroke T_{cycle}: for evaluation of thermal load;

Replacement of mineral diesel fuel with biodiesel up to concentration of B100 do not increases mechanical load of parts of cylinder-piston group of diesel engine. The identical value of maximum pressure P_{max} is obtained independently on sort of fuel at constant rated output P_e=idem. Divergence from generalized curves is about ± 1–1.5 bar. The determined change of criterions T_{max} and T_{cycle} confirms that does not increase thermal load and heat transferring into cooling system at the same level of rated output.

Characteristics of fuel injection and combustion kinetics

The comparative research on characteristics of indicated work of diesel engine forms the base to choose the proportions of biocomponents of new biodiesels what practically realises the engineering of fuel. It is also allows to evaluate the optimum and critical values of parameters of biodiesel and to take compromise decisions regarding optimisation of regulation parameters of diesel engine.

Characteristics of fuel injection

The replacement of mineral diesel fuel by biodiesel practically does not change the phases of fuel injection (φ_{f1} – start of injection and φ_{f2} – end of injection) and duration of injection at the same fuel injection timing and rated output (see Fig. 3).

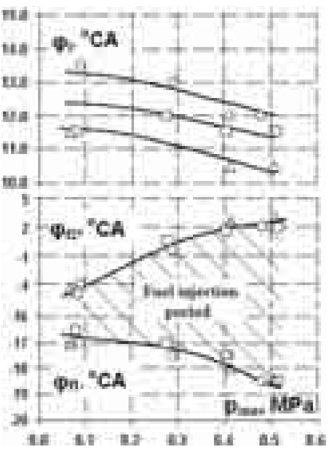

Fig. 3. Phases of fuel injection of 1A41 while running on biodiesel: : ○ - diesel fuel, □ - RME biodiesel B30, △ - RME biodiesel B100

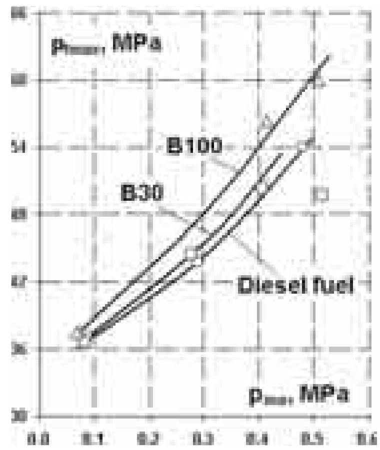

Fig. 4. The change of maximum pressure before fuel injector P_f of diesel engine 1A41 while running on biodiesel: ○ - diesel fuel, □ - RME biodiesel B30, △ - RME biodiesel B100

The replacement of mineral diesel fuel with biodiesel ensuring the same level of rated output of diesel engine is related with increase of cycle quantity of fuel q_{cycle} because of lower calorific value H_u of biodiesel. The constancy of duration of fuel injection $\varphi_{f\,inj}$ confirms that the intensiveness of injection or pressure of injection (speed of volume and mass injection) increases by using of biodiesels. The increase of fuel pressure before fuel injector P_f is determined within the completely researched range of loads (see Fig. 4).

The higher pressure before fuel injector P_f of biodiesels stabilizes characteristic of fuel injection. The real timing of lifting of injector needle is earlier for 1-1.5º CA up to dead top centre (see Fig. 5).

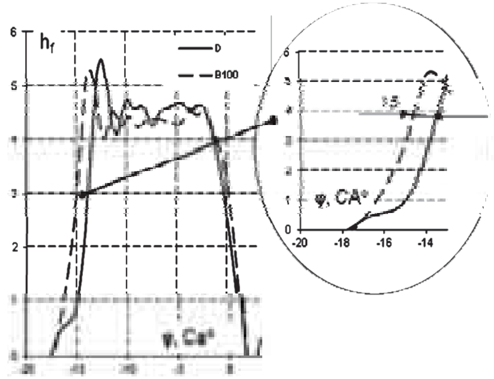

Fig. 5. The characteristic of lifting of injector needle hf of diesel engine 1A41: ▬▬ - diesel fuel, ▬ ▬ ▪ - RME biodiesel B100

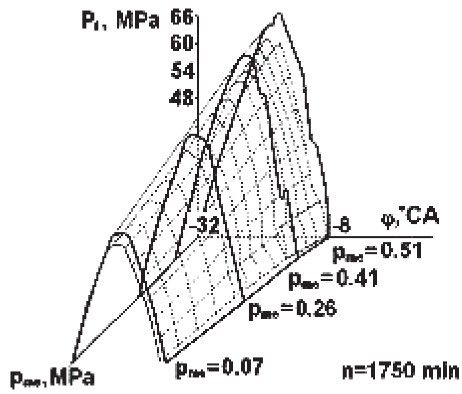

Fig. 6. The characteristic of fuel injection pressure Pf of diesel engine 1A41: ▬▬ - RME biodiesel B100, ▬ ▬ ▪ - diesel fuel

The front of characteristic of fuel pressure before fuel injector remains unchanged (see Fig. 6). Is it known that the increase profile and maximum value of P_f significantly influences the quality of fuel injection, period of induction φ_i and kinetic phase of combustion.

The characteristics of heat release

The characteristics of evaporation of biodiesel are worse also as dispersity: temperature of start of evaporation of RME – 299ºC, when the same of mineral diesel fuel - 178ºC and higher value of specific enthalpy of evaporation [9]. The influence of working fluid of biodiesel into work process is evaluated by characteristics of heat release X, $dX/d\varphi=f(\varphi)$ (see Fig. 7, 8). The analysis of characteristics of heat release is accented on the first - kinetic $(dX_I/d\varphi)_{max}$ and the second - diffusion $(dX_{II}/d\varphi)_{max}$ maximums of speed of heat release.

$(dX_I/d\varphi)_{max}$ forms the dynamic parameters of work process: ratio of pressure speed $(dp/d\varphi)_{max}$, pressure ratio λ, maximum pressure of cycle p_{max} and emission of nitric oxides NO_x. The character of fuel combustion in the second – diffusion phase influences parameters of fuel economy and emission of products of non-complete combustion: (carbon monoxide CO, hydrocarbons CH and smoke).

The reduction of induction period by ~ 7% and 15% while running on biodiesel (B30 and B100 respectively by 1 and 2ºCA) influences the reduction of heat release in kinetic phase $(dX/d\varphi)^{I}_{max}$ by ~ 30%. It is also reduces the mechanical load of parts of cylinder-liner group: ratio of pressure speed $(dp/d\varphi)_{max}$ reduces from 0.9 MPa/º CA down to 0.85 MPa/º CA for biodiesel B30 and down to 0.7 MPa/º CA for biodiesel B100 at the regime of load p_{mi} = 0.73-0.83 MPa.

The increase of heat release at diffusion phase of combustion $dX/d\varphi)^{II}_{max}$ by ~ 55% positively influences the increase of indicated efficiency factor η_i ~ 2% and partly compensates the increase of fuel consumption.

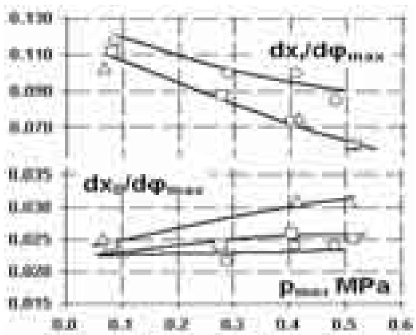

Fig. 7. The parameters of heat release of diesel engine 1A41 while running on biodiesel: ○ - diesel fuel, □ - RME biodiesel B30, △ - RME biodiesel B100

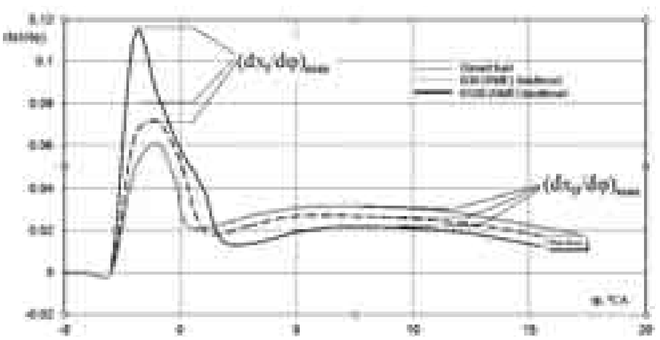

Fig. 8. The change of characteristics of heat release (dXI/dφ)max and (dXII/dφ)max of diesel engine 1A41 while running on biodiesel: ▬▬▬ - diesel fuel, ▬ ▬ ▬ - RME biodiesel B30, ▬▬▬ - RME biodiesel B100

The reduction of intensiveness of heat release $(dX/d\varphi)^{I}_{max}$ in kinetic phase of combustion and the increase of intensiveness of heat release $(dX/d\varphi)^{II}_{max}$ in diffusion phase of combustion at the same time predetermines the constancy of heat quantity Q_{Pmax} released until the moment the maximum cycle pressure is reached. In the result the running of diesel engine on biodiesel do not increase maximum in-cylinder pressure p_{max} and characteristics temperatures of gases which forms mechanical and thermal load of parts of cylinder-piston group.

3.2. Usage of fuel mixtures containing ethanol and rapeseed oil methyl esters

Ethanol use in the diesel engine cycle is hampered by the poor motor-fuel characteristics of lower alcohols and, primarily, the limited solubility of ethanol in fossil diesel fuel and its low self-ignition characteristics. In practice, these shortcomings are surmounted by using higher alcohols, acetates, aromatic amine hydrocarbons, ethers, and admixtures as the ethanol solvent [10-12].

Another alternative is a three-component fuel mixture containing fossil diesel fuel-ethanol-rapeseed oil methyl esters (D-RME-E) [11]. RME provides solubility of ethanol in diesel fuel, mutual compensation of polar characteristics, such as self-ignition, viscosity, and many other important motor characteristics, and also a considerable increase of the sum of (RME+E) biocomponents in a blend with diesel fuel.

Parameters of the diesel engine running on RME-E mixtures

In the initial stage of our research using the three-component mixture, D-RME-E, in diesel engines, we carried out exploitation tests of RME-E. The increase in the ethanol portion in the RME-E mixture because of the lower Hu of ethanol compared to RME (26.8 MJ/kg against ~37.2 MJ/kg) leads to an increase in be. Increase of be is is average 3.5% for every 10% increase in the E portion in RME (see Fig. 9).

While increasing the amount of ethanol E in the mixture RME-E, the stable trend of η_i increase is observed (see Fig. 10). The increase of E amount up to 40% increases η_i ~ up to 2.5% within the completely analysed range of loads P_{mi}.

The Parameters of the Indicator Process

In a regime of low P_{mi}, the values $P_{\max}$ are lower than those obtained using RME and D; for medium P_{mi}=0.55-0.6 MPa, they are practically equal; and for nominal P_{mi}, they are considerably ~14% higher (see Fig. 11). However, the obtained result is not critical. For fuels B30, which are used in practice and in which the summarized portion of biocomponents constitutes 30%, the degree of the $P_{\max}$ increase will be considerably lower because of a significantly lower portion of E in the three-component mixed biodiesel fuel D-RME-E.

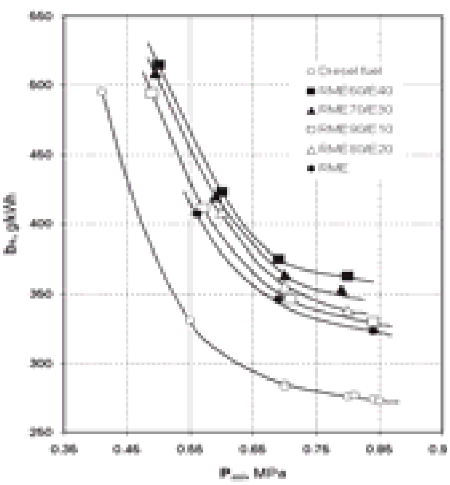

Fig. 9. Parameters of fuel economy of diesel engine 1A41

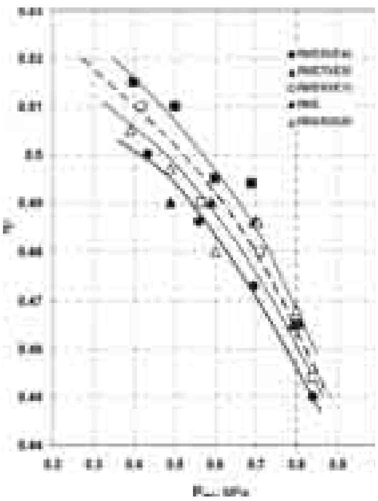

Fig. 10. Efficiency index of diesel engine 1A41

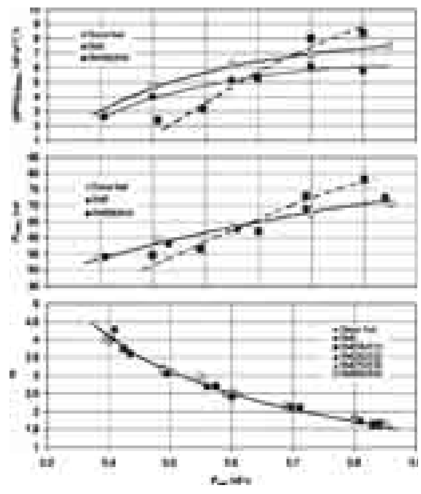

Fig. 11. Parameters of the indicator process of diesel engine 1A41

Ecological Parameters

The increase in the oxygen portion of ethanol composition from 11% for RME, less than 1% for mineral diesel fuel D, and up to 36% for E promotes a large decrease of CO emission in exhaust gases (see Fig. 12). The greatest CO decrease with an increasing E portion in mixed biodiesel fuel RME-E is reached at rated loads: for P_{mi}≈0.8-0.85 MPa on average for each 10% of E portion increase, the values e_{co} and decrease by 7-8%.

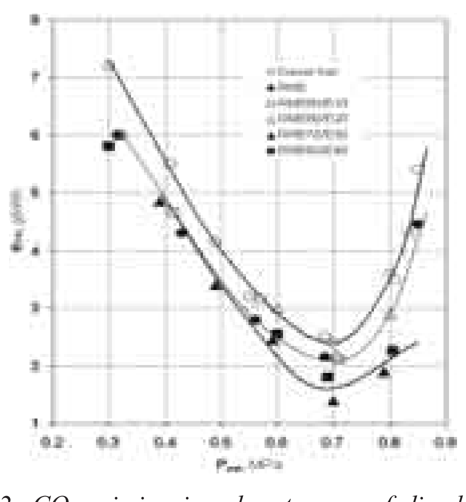

Fig. 12. CO emission in exhaust gases of diesel engine 1A41

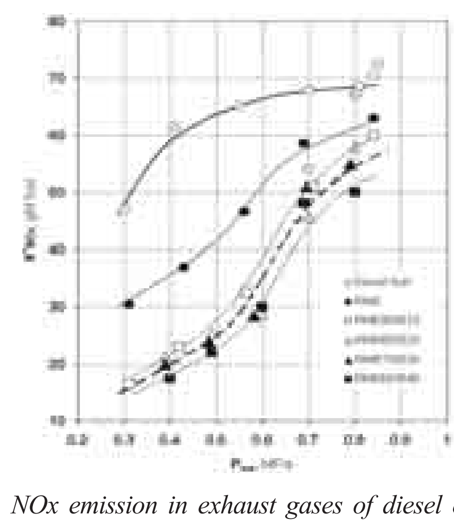

Fig. 13. NOx emission in exhaust gases of diesel engine 1A41

In contrast to CO emission at low and medium loads, the effect of $e'NOx$ reduction is significantly higher because of deterioration of the indicator process dynamic indices (λ) and, consequently, the indicator process temperature characteristics, while a diesel engine is running on RME-E biodiesel fuels. Thus, for example, when P_{mi}) 0.4 MPa, the value e'_{NOx} from 60 g/kg of mineral diesel fuel decreases up to 35 g/kg of RME and 20 g/kg of RME-E mixtures.

Investigation of the characteristics of multicomponent biodiesel fuel (D-FAME-E)

In order to evaluate the influence of ethanol on engine performance characteristics and emissions of harmful components in exhaust gases, engine tests of stable three-component mixtures containing 4.7-28% ethanol, 15.2-66.2% fossil diesel fuel, and 26.3-56.8% FAME were performed. The results of engine performance tests in diesel engines F2L511 and 1A41 demonstrate the improvement of the operating characteristics when ethanol concentrations up to 30% are used in three-component D-FAME-E biofuels. An approximately proportional improvement of D-FAME-E biofuel effectiveness and a decrease of toxic emissions were observed when absolute 99.8% alcohol or 96% alcohol was used.

The types of tested fuels are as follows: fossil diesel fuel (D) and three-component mixtures D25/RME55/E20 and D15/RME55/E30.

Fuel Consumption Indices

An increase of ethanol concentration from 20% to 30% the indicated efficiency increased by about 1.5-2.0%. The result with respect to the influence of the portion E on be and ηi is consistent with results of tests with biofuels containing 5-10% E.

Ecological Indices

Increase of the concentration of E in the biofuel to 10% did not significantly influence emissions of NO_X or CO. The decrease of smoke density was 0.2-0.25 Bosh units. At the same time, unlike the results of tests with biofuels containing 5-10% E, the use of diesel engine F2L511 demonstrated a significant improvement of ecological indices compared with fossil diesel fuel. We observed a 3-fold decrease of smoke density, a decrease of e_{CO} by 30-40% on rated loads, and a 2-fold decrease in emissions of NO_X on a partial load. Significant improvements of diesel engine ecological indices compared with the use of D were connected with the sufficient portion of oxygen containing components, i.e., the total portion of RME and E in the biofuels tested, 70% and 80%, respectively. At the same time, the influence of E on emissions of NOx was practically the same and did not depend on the value of the proportion of E.

Indices of fuel injection and indicated process

For RME-E testing [13], the portion of E increased from 10% to 40% of the volume (see Fig. 13). Similar studies have reported that a small portion of E (5%, 10%, 15%) causes a decrease of the crank angle by about 2^o, i.e., a decrease of the real injection phase of injection timing on partial loads of the diesel engine [14].

At the same time, the maximum fuel injection pressure into a high-pressure line is significantly higher on partial loads when the diesel engine is operating on E than when it is operating on D and FAME [15]. On a rated power regime, the spontaneous change in fuel feed does not occur. The fuel feed phase lag can be explained by the high pressure of saturated alcohol vapour compared with D and RME. At the moment of discharge of the high-pressure line after the next fuel injection, the vapour locks (vacuum cavities) are formed into a high-pressure line as E is evaporated. This in turn disturbs continuity of fuel flow and increases compressibility, causing a delay at the beginning of fuel feed. The cavities collapse when the next injection begins and can cause so-called water hammering, consequently leading to an increase of pressure in the high-pressure line on partial loads.

Analogous demonstrations of significant improvement of the indices studied here related to exhaust gas toxicity when ethanol is added to diesel biofuel have been reported by authors testing RME-E (see Fig. 14).

When three-component fuel contained 10% of ethanol, maximum fuel feed pressure increased by ~9% from 50 to 54.5 MPa. Real fuel injection angle determined from the beginning of injector needle rise hf (see Fig. 14, Fig.5) decreased by ~2°CA. As a result, ~2°CA decreased the fuel burning beginning phase and gas pressure in a cylinder. Therefore, we recommend an increase of the residual fuel pressure into the high-pressure line when the diesel engine fleet is converted to operate on alcohol-containing fuels.

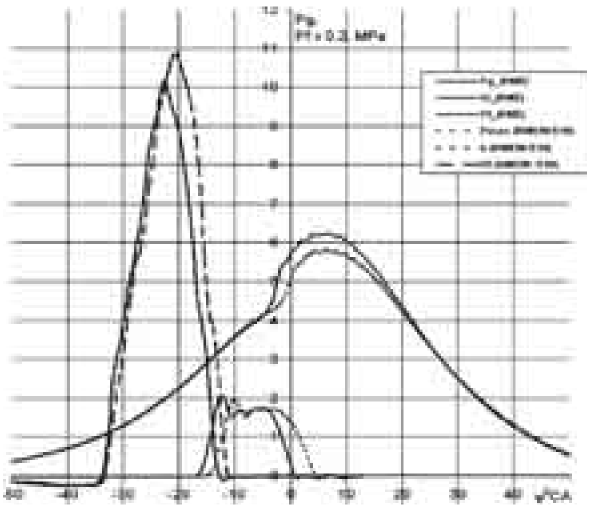

Fig. 14. Lag of phase of diesel engine 1A41 injection timing while running on RME60/E40 (P_{mi} = 0.8 MPa)

3.3. Investigation of the performance and emission characteristics of biodiesel fuel containing butanol

On the basis of the existing usage of B30 fuels in some EU countries, the possibility of using mixtures containing 70% fossil diesel fuel was analysed. The possibility of increasing the quantity of biocomponents to 50%, where the rapeseed butyl ester RBE (rapeseed methyl ester RME) and B ratio is 1:1, was also investigated. Two-component mixtures containing fossil diesel fuel D and butanol B at ratio 7:3 were analysed as well.

The CFPP (Cold Filter Plugging Point) of butanol is equal to -36ºC, lower than that of fossil diesel fuel. An advantage of using three-component mixtures is that multicomponent fuels would have better properties, as compared to separate components.

Multicomponent fuels D70/B30, D70/B15/RME(RBE)15, and D50/B25/RME(RBE)25 meet the standards for fossil diesel fuel and biodiesel fuel, according to the main indicators of quality. One of the most significant operational advantages of multicomponent fuel D-RBE-B is its good low-temperature properties: in the case of 30% concentration of biocomponents, they could be used for diesel engines at temperatures down to -33ºC.

In the case of the 50% biocomponent in the mixture with fossil diesel fuel, the maximum increase of engine's VALMET 320 DMG break specific fuel consumption b_e does not exceed 3-3.5% for the fuel D50/B25/RBE25, and reaches 8% in the case of the fuel D50/B25/RME25. The increase in specific fuel consumption (b_e) is 3-4% for all tested fuel mixtures with the biocomponents' volume of 30%, except for D70/B15/RME15. In the case of fuel D70/B15/RME15, b_e increased by 8% in the heavy-load modes.

For a mixture with 30% of biocomponents, the coefficient of efficiency (ηe) is as good as that of fossil diesel fuel; an increase of biocomponents to 50% causes an increase of η_e by up to 4% compared to D (see Fig. 15).

Ecological parameters

Causes 25% decreased concentration of CO and HC in exhaust gases at NO_X-idem, when the engine was running on mixture D70/B15/RBE15. Investigated fuel mixtures containing RBE and RME (D70/B15/RBE15 and D70/B15/RME15) demonstrated nearly the same fuel economy and ecological properties (see Fig.16).

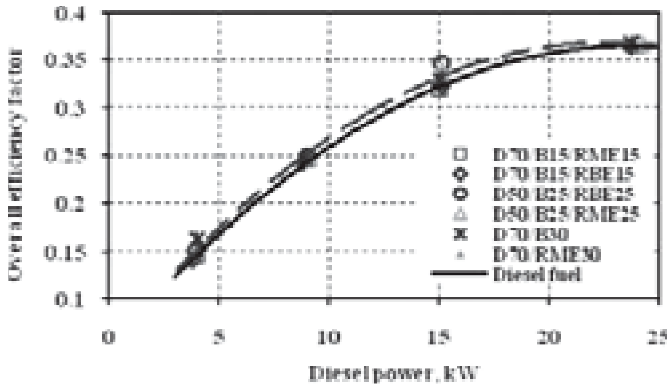

Fig. 15. Overall efficiency factor of diesel engine VALMET 320 DMG (n=1500 min-1)

Mixtures containing 30% of biocomponents are characterized by better ecological properties than fuel containing higher content of biocomponents: an increase of biocomponents from 30% to 50%causes an increase of CO emissions by 20-25% for low and moderate load and an increase of HC emissions by 30-35% (for NO_X idem) over the entire range of tested diesel engine loads.

It was observed that the usage of mixtures containing fossil diesel fuel and butanol (D-B) is less attractive compared with that of three-component mixtures D-B-RBE. When the engine was fuelled with all sorts of tested multicomponent fuel, the smokiness of exhaust gases was 5-7 times less than that for D over the entire range of tested diesel engine loads; therefore, further investigation of fuel containing butanol is purposeful.

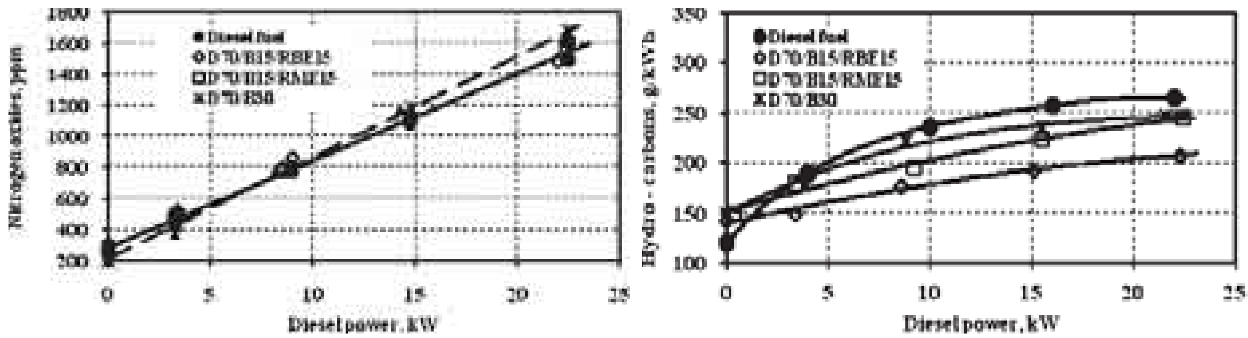

Fig. 16. Harmful component (NO_x, CH) in diesel engine's VALMET 320 DMG exhaust gases

3.4. Operating parameters of the diesel engine fuelled with Camelina sativa oil biodiesel

The tests on operating diesel engines DMG 320 and 1.9 TDI 1Z demonstrate favourable motor characteristics of the new type of biofuel containing methyl esters from *Camelina sativa* (CS) oil.

Due to its high content of unsaturated fatty acids, Camelina Sativa oil (False flax seed oil) belongs to the group of fast-drying oils. Because of their fatty oil composition (a high amount of polyunsaturated acids) [16], 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 Camelina Sativa in the production of diesel fuel, it is necessary to search for possible ways to produce mixtures of Camelina Sativa methyl esters with esters of other kinds of oil or fat. Waste fat (pork lard) has a low iodine value (approximately 45 g I_2/100 g). Scientists have determined that mixtures containing 68% spring Camelina sativa oil and 32% (vol.) pork lard methyl esters (PME) meet the requirements of standard EN 14214 [17]. However, they could be used only in warm climate areas when CFPP is expected to be not lower than minus 5ºC.

The tests on operating diesel engine VALMET DMG 320 manufactured by the company AGCO SISU POWER and used in the vessel, demonstrate favourable motor characteristics of the new type of biofuels.

The obtained results show that using both types of fuel, no significant differences in CO and NOX concentrations were observed throughout the tested load range (see Fig. 17). When operating on fuels containing methyl esters from CS, HC emissions decreased by 10 to 12% and the smokiness of exhaust gas by 12 to 25%.

In terms of 1.9 TDI 1Z engine‘s power parameters, standard rapeseed methyl ester RME and new winter CS methyl ester WCME and summer CS methyl ester SCME biofuels are evaluated almost equally (see Fig. 18).

In terms of their power properties, new types of winter and summer Camelina sativa methyl ester biofuels (WCME and SCME) are equal to standard RME biodiesel. Energetic parameters, first of all, Overall efficiency factor, of a diesel are practically equal throughout the total tested range of load. If compared with B30 (RME), biofuel B30 (WCME) is characterized by ~15% lower emission of the most harmful component NO_X at the load of ~65-70% from maximum. Biofuels B30 (RME), B30 (WCME) and B30 (SCME) are characterized by the same smokiness of engine exhaust gases, which throughout the whole range of engine load is approximately 20% lower compared with diesel fuel (see Fig. 19).

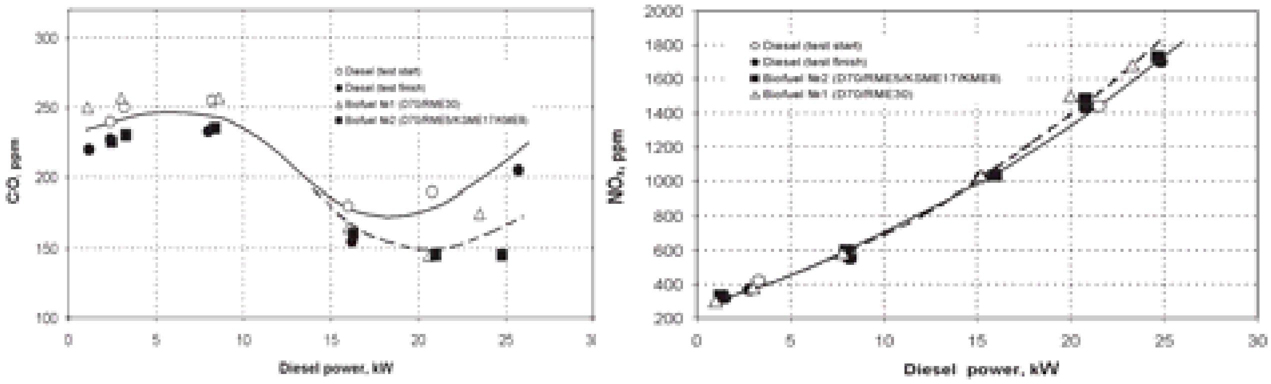

Fig. 17. Emissions of carbon monoxide (CO) and nitrogen oxide (NO_x)

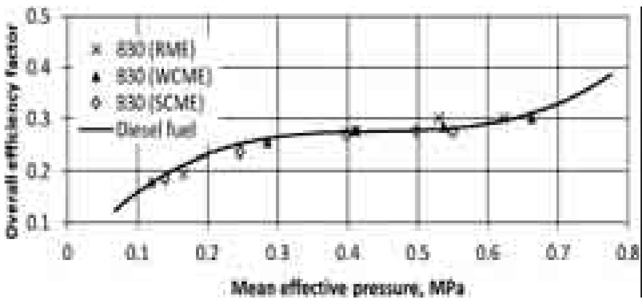

Fig. 18. Overall efficiency factor η_e of engine‘s 1.9 TDI 1Z

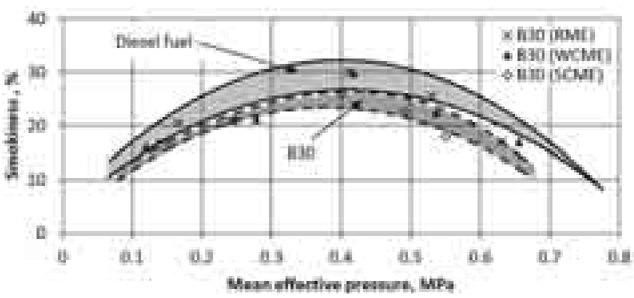

Fig. 19. Smokiness SM of engine‘s 1.9 TDI 1Z

Based on the findings of the conducted tests, it is stated that engine‘s control parameters shall not be modified when diesel engine 1.9 TDI 1Z and models similar to it according to their structure with ECS and recirculation of exhaust gases, taking into consideration both ecological and energetic parameters, are powered by B30 FAME (RME and Camelina sativa) biofuels.

3.5. Oxidation stability of biofuel containing *Camelina sativa* oil methyl esters and its impact on energy and ecological indicators of diesel engine

Motor tests were performed on the engine VALMET 320 DMG 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 under the ISO 8178.

The stability of energy and ecological indicators for an engine driven by fossil diesel fuel (when performing tests in different periods of time) during characteristic test stages demonstrates the stability of the technical condition of the engine, which is especially important when performing tests in this direction (see Fig. 20).

Energy parameters

In terms of the energy consumption efficiency, the overall efficiency factor is η_i; or, when comparing the parameters under identical operating modes, the effective performance factor η_e is a more informative indicator. The change in η_e ($\Delta\eta_e$) during the biofuel storage period is presented in Fig. 21.

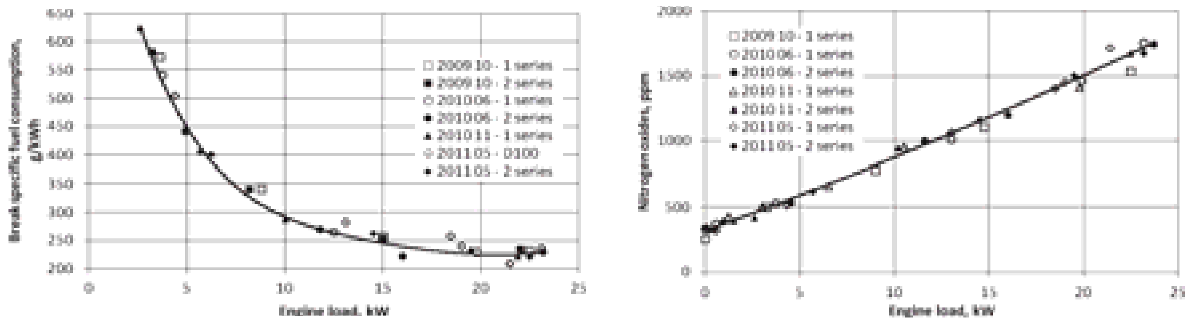

Fig. 20. VALMET 320 DMG Engine parameters when performing tests in different periods using fossil diesel fuel

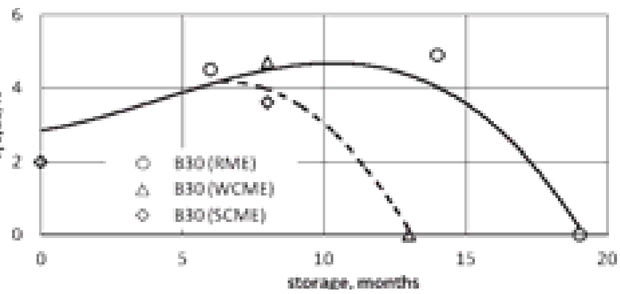

Fig. 21. Impact of the period of storage of B30 fuel on the overall efficiency factor

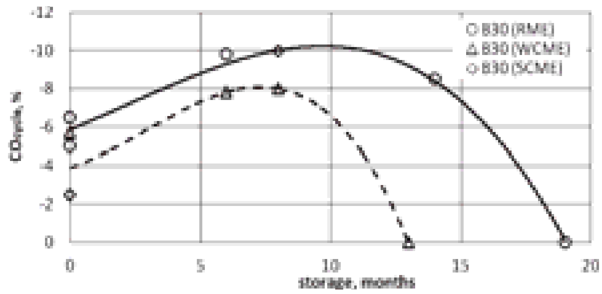

Fig. 22. Impact of the period of storage of B30 on carbon dioxide emissions in exhaust gas

One of the causes of the improvement of η_e may be related to the increase of the peroxide value in the biofuel, which improves the self-ignition properties of the fuel in the cylinder and shortens the ignition induction period [18].

A reduction in the duration of the induction period correspondingly decreases heat emissions in the first, kinetic phase and, in most cases, increases the heat emission intensity in the second, diffusion phase of fuel combustion in the cylinder. As a result, the energy consumption efficiency η_i (η_e) improves, and emissions of the products of incomplete oxidation (CO, HC, and SM) of fuel decrease. The character of the changes in η_e when using B30 (WCME and SCME) biofuel is similar to what is observed when using B30 (RME). The maximum η_e improvement effect of ~ 4% is observed when the storage duration is 8 months, and equalization with the η_e data of mineral diesel fuel occurs when the storage period reaches 13 months.

Ecological indicators

When using B30 (RME) stored for up to 14 months and B30 (SCME) or B30 (WCME) stored for up to 8 months, compared to fossil diesel fuel, the maximum reduction of CO reaches 8-10% (see Fig. 22); the smokiness SM of the exhaust gas decreases by 20-25%(see Fig. 23); and the changes in CH and NO_X (see Fig. 24) emissions are not considerable.

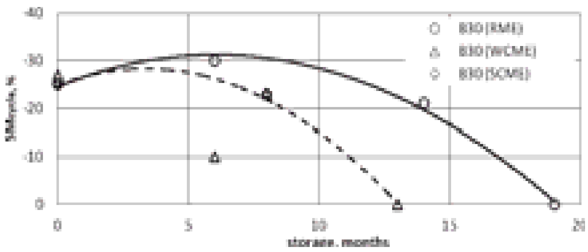

Fig. 23. Impact of the period of storage of B30 on the smokiness of exhaust gas

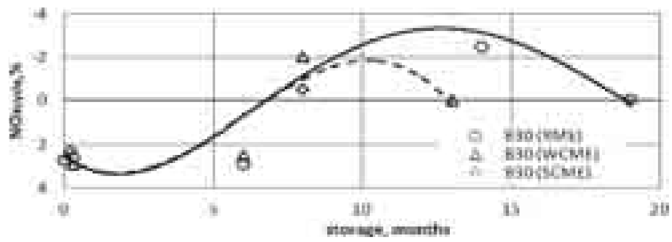

Fig. 24. Impact of the period of storage of B30 on nitrogen oxide emissions in exhaust gas

B30 (RME) containing 0.02 g/kg$_{RME}$ of the antioxidant Ionol BF200 stored for 14 months under normal conditions (in tight 30 dm^3 canisters at ambient temperatures of +12±3^{o}C to +20±3^{o}C) did not exhibit loss of motor properties regarding both energy (η_e) and environmental (CH, SM, NO_X, and CO) parameters of the engine. It is claimed that the oxidation processes occurring in the tested biofuel blends stored for periods of 19 or 13 months do not have any negative impact on the energy and environmental indicators of the engine, respectively.

Evaluation of cyclic instability of a diesel engine running on alcohol-containing biofuels

The cyclic instability of diesel performance has a negative impact on the fuel efficiency, emission of toxic substances in exhaust gas and diesel reliability indexes. The instability of the fuel injection and air supply characteristics is its main cause.

The spontaneous changes of phase of the fuel injection start recorded during the conducted researches served as a ground for a comparative assessment of the cyclic instability of a diesel engine running on D and alcohol biodiesel fuels.

The maximum combustion pressure Pmax is an indicator of engine working cycle considerable determines the mechanical loads on the cylinder-piston group parts, the NOx emission and the specific fuel consumption was selected as the test parameter of cycle.

According to the data of an array of Pmax values of the successively recorded 40-60 diesel cycles, a mean value of Pmax and a normal deviation δPmax of the maximum combustion pressure were calculated. The comparison of Pmax stability factors was made for the load mode Pmi=0.4-0.85 MPa when running on D and RME, RME/E biofuels.

Pmax data dispersion, which corresponds to the normal law of data distribution, presented in Fig. 17 and 18.

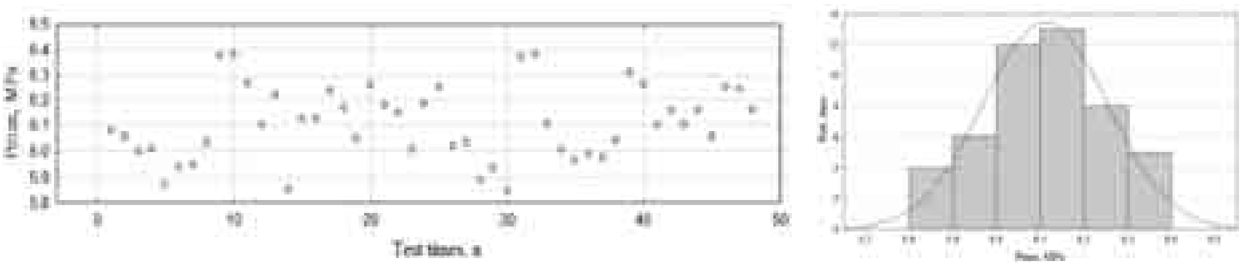

Fig. 17. Statistical data of P_{max} dispersion while 1A41 engine running on D (P_{mi} = 0.4 MPa)

There was no significant difference in a case of change of statistical evaluation criteria P_{max}. Using fossil diesel fuel, RME and biocomponent RME-E mixtures (E concentration up to 30%): standard deviation in a range from 0.09 to 0.14 MPa; standard average deviation in a range from 0.013 to 0.02 MPa. The dispersion of parameter P_{max} increases in the case of using RME60/E40, standard deviation reaches up to 0.21 MPa.

Conclusions

The limited raw material resources for the perspective increase of rapeseed oil methyl ethers (RME) production in Lithuania and new initiatives of EU Parliament stipulates the necessity of the scientific research in the field of elaboration of production technologies and effective utilization of new biodiesel fuel grades including blended diesel-alcohol fuels D – RME – E, B, RBE, CSME in the transport sector.

The best improvement of ecological parameters (reduced: CO by 20-40%, CH – 30-50%, SM – 50-80%, NOX up to 30%) was reached when the concentration of certified RME and new biocomponents was increased in the mixture with fossil diesel fuel up to 30%, and that makes their practical exploitation meaningful; little difference of low temperature characteristics to compare with fossil diesel fuel was observed.

The energy and environmental indicators of the diesel engine when running on mixtures of new biofuels with fossil diesel fuel (B30 (WCME) and B30 (SCME)) are scarcely inferior to the values of the diesel engine parameters when it runs on the certified RME and fossil diesel fuel blend (B30 (RME)).

One of the most significant operational advantages of multicomponent fuel D-RBE-B is its good low-temperature properties: In the case of 30% concentration of biocomponents, they could be used for diesel engines at temperatures down to -30-35°C.

The increase of efficiency index by 2%-4% while increasing the ethanol portion up to 40% in biodiesel fuel RME and new biofuel mixtures is one of the trends regulated by the European Parliament and Council to realize the strategic increase of the efficiency of energetic resources' utilization in the countries-members of the EC.

B30 (RME) containing 0.02 g/kg_{RME} of the antioxidant Ionol BF200 stored for 14 months under normal conditions (in tight 30 *l* tanks at ambient temperatures of +12±3ºC to +20±3ºC) did not exhibit loss of motor properties regarding both energy (η_e) and environmental (CH, SM, NO_X, and CO) parameters of the engine:

– when the diesel engine VALMET 320 DMG was switched to running on biofuel that had been stored for 6-14 months, an increase of 4-4.5% in the effective performance factor (which is characterized based on the efficiency of energy transformation in the cylinder of the diesel engine) compared to fossil diesel fuel is observed,
– when using B30 (RME) stored for up to 14 months and B30(SCME) or B30 (WCME) stored for up to 8 months, compared to fossil diesel fuel, the maximum reduction of CO reaches 8-10%; the smokiness of the exhaust gas decreases by 20-25%; and the changes in CH and NO_X emissions are not considerable.

It is claimed that the oxidation processes occurring in the tested biofuel blends stored for periods of 19 or 13 months do not have any negative impact on the energy and environmental indicators of the engine, respectively.

The new data of dynamic of biodiesel combustion were obtained by complex researches into characteristics of fuel injection and indicated work of the 1A41diesel engine. The results of researches had allowed substantiating the conformity with the law of change of main operational parameters of diesel engine while running on biodiesel fuel. The following principal propositions for replacement of mineral diesel fuel by biodiesel in operated fleets of diesel engines were formulated.

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