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RESEARCH OF CHARACTERISTICS OF WORKING CYCLE OF HIGH-SPEED DIESEL ENGINE OPERATING ON BIOFUELS RME–E AND D–RME–E. PART 1. INDICATORS OF FUEL INJECTION SYSTEM AND INDICATIVE PROCESS

Sergejus Lebedevas[a], Galina Lebedeva[b], Ingrida Gudaitytė[a]
[a]*Department of Marine Engineering, Klaipėda University, I. Kanto g. 7, LT-92123, Klaipėda, Lithuania*
[b]*Department of Informatics, Klaipėda University, H. Manto g. 84, LT-92294, Klaipėda, Lithuania*

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Abstract. The article provides the results of an analyses of the characteristics of fuel injection system as well as the processes indicated in diesel engines 1A41 and F2L511, transferred from working with mineral diesel to working with rapeseed methyl ester–ethanol (RME–E) and mineral diesel fuel–rapeseed methyl ester–ethanol (D–RME–E). In biofuel, ethanol takes a part of 10÷40%. It was found that the E part in the fuel causes a lag of fuel injection of 2÷6 CA (greater values of fuel injection lag are common for partial engine loads and greater amount of E in fuel) that does not occur with mineral diesel fuel or RME. The analysis shows how a lag of fuel ignition limits the dynamic parameters (P_{max}, $(dp/d\varphi)_{max}$) of the cycle and specific emission of nitric oxides (e_{NOx}) in exhaust gas. It is possible to convert diesel engines, operating on D to ethanol-containing biofuels without adjusting the fuel injection system parameters. At the same time, it is necessary to increase residual pressure in high-pressure fuel line of diesel engines with fuel injection pressure of 60÷70 MPa.

Keywords: diesel engine; ethanol; biodiesel; fuel injection phases; indicated process.

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Introduction

This publication is dedicated to one of the most urgent issues of the transport sector – transfer of diesel engines designed to work with mineral diesel fuel to working on biofuels, produced from renewable energy sources of plant and animal origin. The standard gradual replacement of mineral diesel fuel with biofuels is governed by international conventions and agreements as well as the EU directives. In particular, according to the Directive 2009/28/EC, the share of biofuels in transport should reach 10% in year 2020. In accordance with new initiatives of the European parliament greenhouse gas emission should be reduced by 50% in 2017 and by 60% in 2018 (Directive 2009/28/EC). In the EU White paper, it is required to halve the use of 'conventionally-fuelled' cars in urban transport by 2030 and phase them out in cities until 2050. Furthermore, the use of low carbon fuels in aviation has to reach 40% by 2050 (White Paper 2011). Obviously, in order to solve these problems it is not only necessary to improve the existing technologies but also to develop and adapt advanced variety of biodiesel that would allow widening of the current base of raw biofuel production materials.

In Lithuania, development of promising types of biofuels and research of their characteristics for the last decade has been provided by the scientific potential of universities – Vilnius Gediminas Technical University, Kaunas University of Technology, Klaipėda University (KU), and Aleksandras Stulginskis University (ASU). The effect of fuel bioadditives on performance of the engine (Bureika 1997; Pikūnas *et al*. 2003, 2006; Pukalskas 2002) and new varieties of multi rapeseed methyl ester–ethanol (RME–E) biodiesel from animal waste have been developed and adapted for practical use in engines (Lebedevas *et al*. 2006, 2007; Lebedevas, Lebedeva 2008) on the basis of new cultures (e.g. *Camelina Sativa*) (Lebedevas *et al*. 2010a). A study of optimal properties of mineral diesel fuel–fatty acid methyl ester of rapeseed oil–ethanol (D–FAME–E) biodiesel for Lithuanian climatic conditions has been conducted (Bazaras, Raslavičius 2008; Raslavičius 2009). It is noteworthy that during the motor bench test an intensive study of diesel fuel–rapeseed methyl ester–ethanol (D–RME–E) was carried out while attempting to develop an analytical analysis of self-ignition properties of biodiesel, based

Corresponding author: Sergejus Lebedevas
E-mail: sergejus.lebedevas@ku.lt

on the theory of stationary combustion (Raslavičius 2009). However, authors of the majority of studies are limited to a comparative analysis of changes in the fuel readings and environmental emissions in the conversion of the diesel engine to biodiesel.

Much wider areas of research on the problems of diesel engines working on biodiesels (especially containing alcohol) taking into account differences of their vaporization, self-ignition properties, and limited solubility in mineral diesel fuel, in comparison with mineral diesel and biodiesel, can be seen in foreign researches (Satgé de Caro *et al.* 2001). Research of the change of exploitation parameters of fuel economy and toxicity of diesel engine has been carried out together with researches of characteristics of fuel injection and working cycle (maximum combustion pressure, rate of pressure rise, differential and integral characteristics of heat release, etc.) (Li *et al.* 2005; Lü *et al.* 2004; Lapuerta *et al.* 2008). Research of the working cycle instability of diesel engines working on low Cetane Number (CN) fuels, allows evaluating the fatigue of cylinder, its piston group, and deterioration of fuel economy and ecologic diesel engine parameters (Rakopoulos *et al.* 2008; Satgé de Caro *et al.* 2001). The influence of E component in multicomponent biodiesels on diesel engine's parameters of fuel injection and indicated processes is an important subject in the most researches. The parameters of two-stroke diesel engine ($n = 450$ °C) working with pure 100% ethanol and diesel fuel have been analyzed (Li *et al.* 2005). The influence of the change of fuel injection phase (from 2 °CA to 28 °CA before Top Dead Center (TDC)) on indicated process and ecological indicators was evaluated. The influence of E component (concentration in biodiesel fuel is up to 40%) on the structure of the fuel torch and dynamics in the cylinder as well as heat emission characteristics was analyzed (Nguyen, Honnery 2008). The influence of E component in D-E biodiesels was analyzed (Lapuerta *et al.* 2008) in a four-stroke, four cylinder, 85 kW ($n = 4000$ min^{-1}) diesel engine. After conducting an analysis of single cylinder 2.8 kW ($n = 1500$ min^{-1}) power Lister Petter diesel engine (Kerihuel *et al.* 2006), the influence of E concentration (increasing concentration of E up to 30% in mixture with animal fat) for induction period was analyzed.

The aim of using biodiesels on outdated models of diesel engines made to work on mineral oil fuels (most of these models that are used in Lithuania and were made in the 70 to 80 year of the last century) (Lebedev 2001) widens the research area. In addition, it aims to determine fuel economy, thrust of diesel engine power, and ecological properties of these engines (emissions of CO, HC, NO_x, PM, and SO_x). No less important are the researches on the working properties and fuel injection of diesel engine adjusted to work on new types of fuel. They are a major source of information explaining the observed changes, generalizing energetic and ecological indicators, thermal and mechanical stress of the parts of the test engine and extending these generalizations to other types of operating diesel engines. Here, in particular, one of the important aspects of the research is to approve and clarify the advanced mathematical models for calculating the performance of the diesel engine on computer. This approach reduces the costs of materials and experimental research in solving the problem of using biodiesel in exploitation in fleet-wide biodiesel transportation industry. The principles of the combined approach on the subject of three-component mixed alcohol biodiesel D–FAME–E were implemented in joint research between the Maritime Institute of Klaipėda University (KU) and the ASU (Lebedevas, Lebedeva 2008; Lebedevas *et al.* 2009). The research was implemented in the framework of already completed investigations on concentrative limits of mutual solubility, as well as physical and chemical properties and the optimal ratio of the components of biofuels. Motor properties of FAME–E and D–FAME–E biodiesels were investigated: fuel sustainability performance, environmental performance of diesel engines when using absolute 99.8% and 96% ethanol, alternative energy use to improve performance i.e. indicator efficiency and environmental performance by adjusting partial concentrations of E and FAME and changing control parameters of fuel equipment to improve environmental performance of diesel engine, etc.

The results of the working process features and characteristics research of diesel engine operating on D–RME–E biodiesel are presented in this paper. In addition, solutions to the following tasks are presented:

- Justifying and generalizing the results of earlier experimental studies of operational characteristics of diesel engine (in particular, a significant reduction in specific emission (e_{NOx}) of nitrogen oxides for diesel engines under partial loads, which does not depend on the proportion of E in the fuel mixed by 10–40%; (Lebedevas *et al.* 2010b) (see Fig. 1) carried out.
- Investigating the characteristics of heat release in the cylinder of a diesel engine operating on alcohol biodiesel D–RME–E to refine mathematical models for calculating the indicator processes of diesel engine.
- Working cycle forming the mechanical load on cylinder piston group (CPG) and of engine operating cycle instability.

1. Tested diesel engines, fuels' properties, and research methods

Investigation of energy and environmental characteristics was performed on high-speed single-cylinder four-stroke diesel engine 1A41 with direct fuel injection and

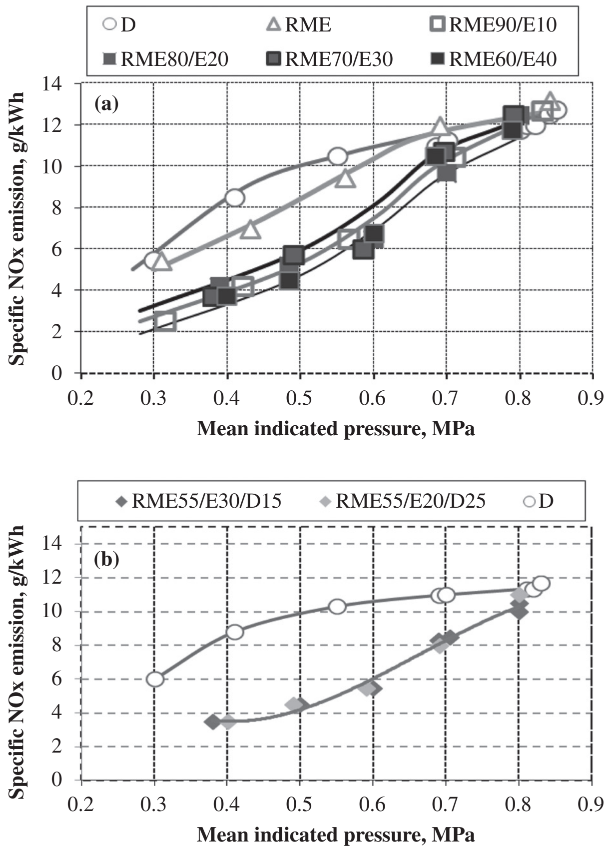


Fig. 1. NO_x emissions of diesel engine 1A41 operating on alcohol-containing biodiesel

two-cylinder high-speed diesel engine 2FL511 manufactured in Mažeikiai Lithuania (ORUVA&CO), licensed by German company DEUTZ. Research on the characteristics of engine operation, fuel injection, and indicators of cyclic instability when working on biodiesels carried out on 1A41 engine. The main parameters of diesel engines 1A41 and 2FL511 are shown in Table 1.

Table 1. Main parameters of diesel engines 2FL511 and 1A41

Parameter	F2L511	1A41
Cylinder diameter D, m	0.10	0.13
Piston stroke length S, m	0.105	0.14
Engine displacement V_h, dm^3	1.65	1.115
Compression ratio ε	17	16
Rated output $P_{e\ nom}$, kW	25.7	14
Rated break mean effective (indicated) pressure p_{me} (p_{mi}), MPa	0.62	0.85
Rated speed, rpm	3000	1750
Fuel injection type	Direct	Direct
Type of combustion chamber	Open	Open

It is known (Krahl *et al.* 2005) that the most significant changes in the transferring of diesel engine performance from working with mineral diesel fuel to working with alcohol fuels (due to their poor ignition properties) are characteristic for diesel engine models with direct injection. In addition, diesel engine 1A41 family designed and manufactured since the mid-1970s of the last century in terms of the indicator process are similar to diesel engine, which is now widely exploited in the agricultural sector of Lithuania (LAZ, VMZ, VTZ-VMTZ, Lipeck TG [LTZ] ChTZ, JUMZ). Thus, the choice of research object creates preconditions for the subsequent compilation and dissemination of tests results and recommendations to other types of diesel fuels.

Tested fuels. For comparative tests two-component RME–E, three-component D–RME–E biodiesels and mineral diesel fuel were used. Three-component biodiesel D–RME–E was chosen as the primary type of biofuel for practical use in the operation. During testing, use of two-component biofuels RME–E allowed to increase the concentration limits of alcohol components in biodiesel up to 40% (including unlimited solubility E RME and extremely limited mutual solubility of E and D). Percentages of the components in the composite fuel were chosen based on studies of mutual solubility diesel fuels (D, RME, and E) in different temperatures (simulations made in summer and transient seasons of autumn and spring) and an ethanol (99.8 and 96% of grades E), studies were performed by scientists at ASU. Tables 2 and 3 show the basic properties of the tested fuels. To solve the problems of the practical use of D–RME–E, it is important that the tested biodiesel indicators comply with the requirements of the standards (LST EN 14214:2003; GOST 305–82; LST EN 15376:2008). The properties of biodiesel D–RME–E are described in detail by the authors of this publication and their colleagues from ASU (Lebedevas *et al.* 2009, 2010b).

The analyses of motor characteristics of engines 1A41 and 2FL511 were made on a certified test stand that was supported by modern automated measuring and registration devices to determine the technical and economical (fuel consumption, temperature of exhaust gas (EG), etc.) parameters of emission of harmful components in EG.

To regulate the load, we used a hydraulic brake (Zöllner 20LLNE3N19A) controlled by a computer (FIPS-S486/66-FTFT-635-ES/AT-08-4SER/TM-PLU). A fuel-feeding rate gauge (PLU 401-115W/116 HR) measured the fuel consumption.

The emissions in the EG were measured by an analyzer (MIR 9000) designed to continuously register the harmful components of EG using a method of infrared absorption spectroscopy and a gas filter

Table 2. Basic properties of tested fuels

Fuel	Density at 15 °C, g/cm^3	Viscosity at 40 °C, mm^2/s	Stoichiometric ratio	Lower calorific value, kJ/kg	Lower calorific rate of stoichiometric mixture, kJ/m^3	Cetane number (CN)	Chemical composition % C	H	O
D	0.840	2.5	14.6	42470	3175	46.0	87.0	12.6	0.4
RME	0.890	4.7	12.5	37200	3193	51.6	77.0	12.3	10.7
E	0.78÷0.80	1.08	9.0	27000	3475	8	52.2	13	34.8

correlation. Concentrations of carbon dioxide (CO_2), carbon monoxide, nitrogen monoxide (NO), and hydrocarbons (HC) were measured; also, the smoke opacity of EG was measured with a Bosch analyzer.

A test of diesel engine 2FL511 was carried out in a constant speed ($n = 2800$ min^{-1}) regime. Break mean effective pressure limits (P_{me}) varied from 0.3 MPa up to the nominal value of 0.6 MPa. A test was carried out during summer when the ambient temperature was 25–30 °C. The temperature of the biofuels after preparation and during testing was 20 °C. The accuracy of the measurements of the 1A41 and F2L511 diesel engine parameters during tests is given in Table 4.

The engine 1A41 tests were performed on a certified motor stand that was equipped with an electric brake, automatic fuel consumption, and pressure gauges and temperature sensors in the cooling and lubricating oil systems. A 'Quintox 9106' automatic gas analyzer measured the emissions of harmful components in EG. In all the tested diesel engine regimes, H-2000 digital station and a sensor set to indicate pressure with a needle on a fuel injector nozzle were used to measure the fuel pressure in a high-pressure fuel line, the gas in the diesel engine cylinder, and the actual angles at the start and ending of fuel injection. The data contained an average of over 30 to 100 subsequent diesel engine running cycles. Mean indicated pressure was calculated using data of indicator diagrams.

In order to guarantee that the testing conditions correspond to the real operational conditions of diesel engines, the analyses were made while the 1A41 engine was running at a wide range of loads (mean indicated pressure $P_{mi} = 0.2 \div 0.7$ MPa) and engine speed ($n = 3000$ min^{-1}).

Cyclic instability of the working process of diesel engine running on biodiesel was researched on the basis of statistical data of 50÷60 consequent one-cycle diagrams.

2. Research results

2.1. Characteristics of fuel injection

The self-change of characteristic phases of fuel injection in cylinder: start φ_{f1} and end φ_{f2} of injection, when a diesel engine's work is transferred from D mineral diesel fuel to the two-component RME–E and three-component D–RME–E biodiesels is presented in Figs 2 and 3, respectively.

When diesel engine operates in a full-power mode, the phase of the feed injection start φ_{f1} is similar for all tested fuels. However, already at the medium loads (if mean indicated pressure is $P_{mi} \leq 0.7$ MPa, then with the transfer to the low P_{mi}), the replacement of D mineral fuel with biofuels containing E alcohol component causes a lag of φ_{f1} by 2÷3 °CA as compared

Table 3. Properties of three-component biodiesels

Characteristic	LST EN 14214:2003 limit values	Fuel composition (D–RME–E)% 40–2–58	35–9–56	16–7–77	11–31–58	21–46–33	6–65–29
Density, kg/m^3 (15 °C)	860÷900	846.4	844.8	861.5	846	826.4	823.0
Viscosity, mm^2/s at 40 °C	3.5÷5.0	1.72	1.90	1.56	2.41	3.04	3.5
Cetane number	≥51	50	47	48	37	30	22
Ignition temperature, °C	≥120	91	88	102	80	57	47
Ash content % mass	≤0.02	0.01	0.01	0.02	0.01	0.007	0.007
sulfur content mg/kg	≤10	8	8	8	9	10	10
Copper plate corrosion (3 hrs. at 50 °C), rate of corrosion	Class	1a					

Table 4. Measurement accuracy of diesel engine operation parameters

Parameter	Accuracy of parameters recording	
	1A41	F2L511
Torque, N·m	±0.5%	±0.5%
Engine speed, rpm	±0.5%	±10 rpm
Rated brake mean indicated pressure, MPa	±1.0%	±0.5%
Liquid temperature in a cooling and lubricating oil systems, °C	±2°C	±2 °C
Liquid pressure in a cooling and lubricating oil systems, bar	±1%	±2 °C
Fuel-specific consumption, g/kW·h	±0.5%	±0.5%
Fuel pressure in a high-pressure fuel line, MPa	±1%	–
Fuel injection start angle, crank angle (CA) degree	±0.5 °CA	–
Fuel injection end angle, crank angle (CA) degree	±0.5 °CA	–
Cylinder pressure, bar	±1%	–
CO exhaust emission, ppm	±5%	±30 ppm
NO_x exhaust emission, ppm	±5%	±0.5%
HC exhaust emission, ppm	–	±20 ppm
Bosch index	±0.1 unit	±0.1 unit

with D fuel. Thereby, at the identical engine loads (P_{mi} = *idem*) φ_{f1}, values are practically one and the same for all tested biofuels, regardless of the part of alcohol component, ranging from 10 to 40%.

It can be noted readily that the observed nature of the intense drop of NO_x emissions when a diesel engine is running on alcohol biofuels (Fig. 1) correlates well with the trends of φ_{f1} change. The physical mechanism of the impact of φ_{f1} on e_{NOx} is based on the known data of dynamics of the nitrogen oxides formation in the diesel engine cylinder (Lebedev, Nechaev 1999). According to the data of experimental researches, by the time the cycle maximum pressure reaches P_{max}, up to 90% of NO_x is formed in the kinetic phase of fuel combustion in the diesel engine cylinder. In its turn, just the phase φ_{f1} and the value of the ignition induction period φ_i related extensively to it determines the intensity of the kinetic phase of combustion.

The following hypothesis proposed by the authors to explain the lag of φ_{f1} for the alcohol-containing biodiesels:

– The higher pressure of saturated vapor of E alcohol component in biodiesel compared with mineral diesel fuel D (versus 0.16 bar for E) (Thermophysical data website) and 0.01 to 0.1 bar for D (Fuel properties website) at 38 °C may cause the formation of a gas phase – gas-filled cavities in the high-pressure fuel lines (HPFL) of

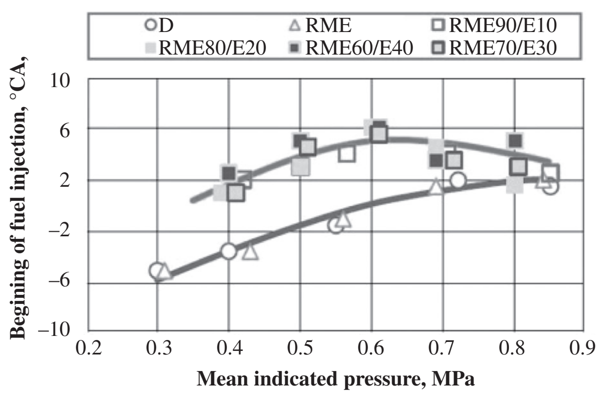


Fig. 2. Phases of fuel injection for 1A41 diesel engine running on RME–E biodiesels

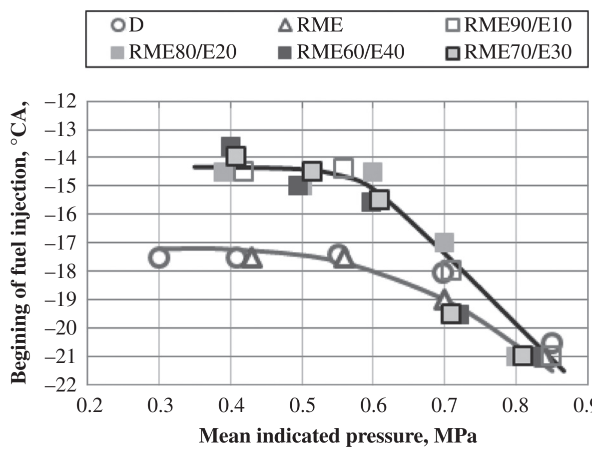


Fig. 3. Phases of fuel injection for 1A41 diesel engine running on D–RME–E biodiesels

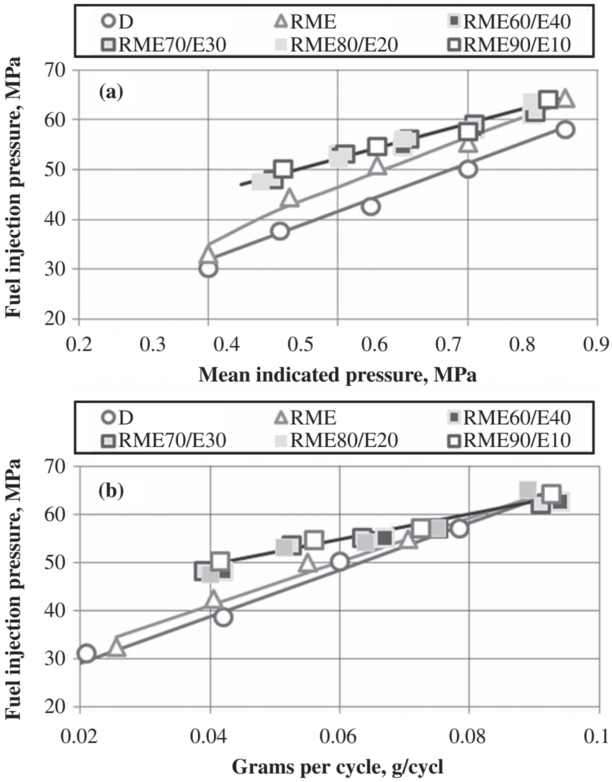


Fig. 4. Change of fuel injection maximum pressure $P_{f\max}$ when 1A41 diesel engine is running on biofuels RME and RME–E

diesel engines with the relatively low maximum fuel injection pressure, especially, in the part-load modes. The tested 1A41 diesel engine is precisely this type: the maximum values of pressure pulse $P_{f\max}$ of D in HPFL do not exceed 60÷70 MPa.

- The gas-filled cavities formed in the process of HPFL discharge (with reduction in P_f) result in the breach of the fuel liquid phase continuity and due to the higher compressibility cause a respective fuel injection start lag φ_{f1} as compared with D.
- In its turn, the further collapsing of gas-filled cavities causes the increase of $P_{f\max}$ as compared with D in the diesel engine partial-load mode.

The viscosity of tested biodiesels should not affect the change of fuel injection phase. The viscosity of tested biodiesels RME55/E20/D25 (2.97 mm^2/s) and RME55/E30/D15 (2.79 mm^2/s) is practically the same for mineral diesel fuel (according to standard (EN 590:2009), the viscosity of mineral diesel fuel is 2.0÷4.5 mm^2/s). The data of registration of the fuel pressure characteristic in HPFL, the fuel injection nozzle lift defining the real phase of the fuel injection start, and the indicator diagram presented in Fig. 4 allege for the advanced hypothesis.

The transfer of diesel engine to work on the RME–E biodiesel does not result in the change of the start of phase of the pressure rise P_f in HPFL as compared with D mineral diesel fuel. It indicates a zero lag in fuel injection by the high-pressure fuel pump (HPFP). At the same time, there is a lag of the real phase at the start of fuel injection into the diesel engine cylinder (H_f) for RME-E biodiesel compared with D with a shift by 2÷3 °CA toward top dead point (TDP). The indicator diagram of the working medium pressure in the diesel engine cylinder is also shifted by an expansion stroke.

Thus, an explanation of φ_{f1} lag is to be sought in the features of the hydrodynamic processes of injection of the alcohol-containing fuels into the HPFL.

The risks caused by the spontaneous changes of φ_{f1} are connected with the probability of the cyclic instability of diesel engine operation, followed by the degradation of mileage rating, the increase of toxic emissions in EG, and the increase of dynamic loads on the parts of the cylinder-liner group (reduction in the fatigue strength of spare parts).

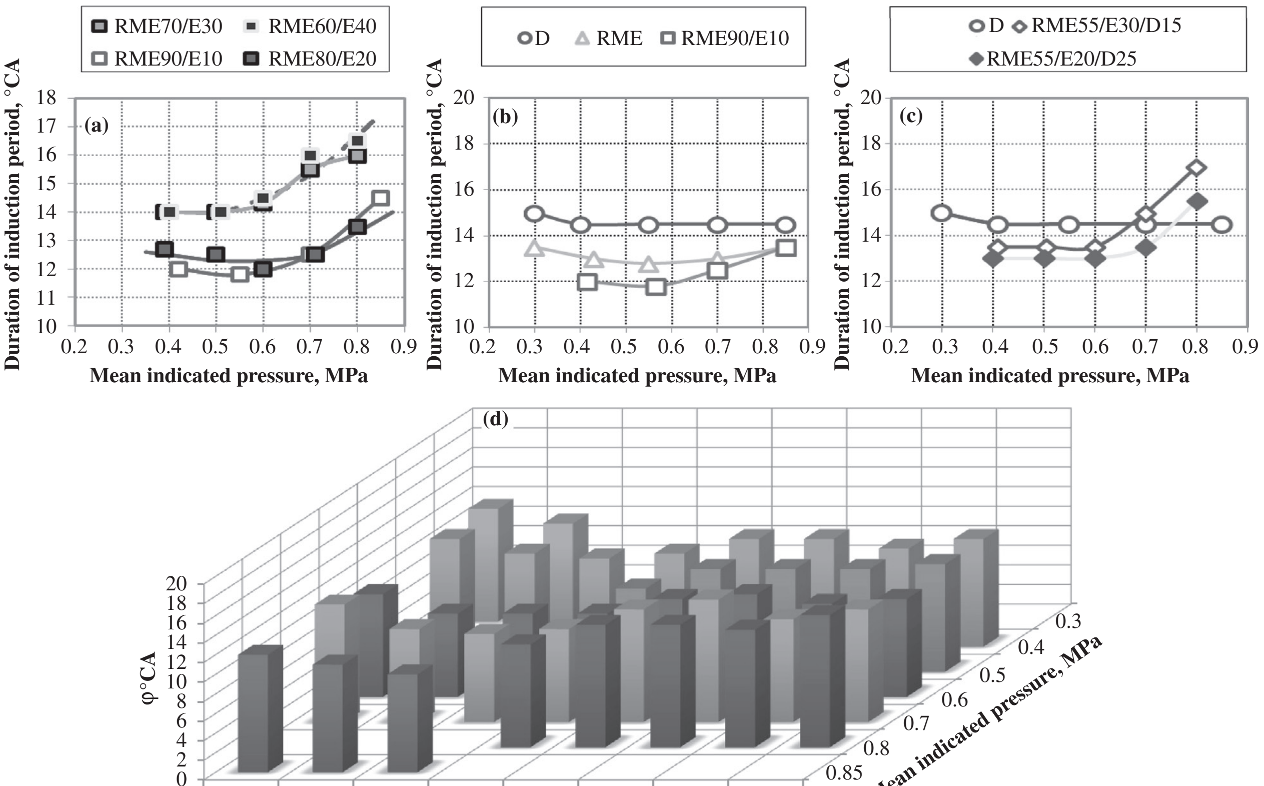
In this regard, the cyclic instability of operation of diesel engine running on the alcohol-containing biodiesel was evaluated within the scope of the integrated researches carried out by the authors.

The registration of pressure P_f in high-pressure pipeline showed that in the full tested range of loads, with the exception of the rated power, the maximum values of $P_{f\max}$ are 20÷30% higher for a diesel engine running on RME and blended biodiesels with an alcohol component, than for D mineral diesel fuel (Fig. 4a). The heating value of RME and E as compared with D is significantly lower and that makes the increase of the cyclic fuel portion necessary to realize the identical capacities of engine operations.

In order to balance out the impact of the increased cyclic fuel portion q_{cikl} on $P_{f\max}$, when running on RME and RME–E biodiesels compared with D fuel, the functional relationships $P_{f\max} = f(P_{mi})$ are rearranged into functions $P_{f\max} = f(q_{cikl})$ (Fig. 4b). As expected, the values of $P_{f\max} = f(q_{cikl})$ for D and RME are practically the same (Lebedevas *et al.* 2007).

When using RME–E biodiesel, the values of maximum pressure $P_{f\max}$ for low and average q_{cikl} remained ~15÷20% higher compared with D and RME fuels, therefore, the E part in fuel does not have an effect on the value of $P_{f\max}$. For the nominal cyclic fuel portion, the differences in $P_{f\max}$ are not observed. The obtained data validate the proposed hypothesis of formation of gas phase-cavities in HPFL with a relatively low $P_{f\max}$ <60÷70MPa in the cases of use of the alcohol-containing blended fuels D–RME–E even with an insignificant E part.

At the same time, the obtained results serve as a confirmation of the reduction in EG NO_x emission of diesel engines with a lag of the fuel injection phase φ_{f1} for RME biodiesel. It is commonly known that the



MIP	D	RME	RME90/E10	RME80/E20	RME70/E30	RME60/E40	RME55/E20/D25	RME55/E30/D15
0.85	12	11	10					
0.8				10.5	12.5	12.5	12	13.5
0.7	12	9.5	9	9.5	11.5	12.5	10.5	11.5
0.6	10.5	8.5	8.5	8.5	10	10.5	9.5	10
0.5				8.5	10.5	10.5	10.5	11
0.4	11	9.5	9	9.5	11	11	10	11
0.3	11.5	10						

Fig. 5. Change of ignition induction period when 1A41diesel engine is running on RME–E and D–RME–E biodiesels

conversion of a diesel engine from D mineral fuel to RME biodiesel is associated with an increase of emission of the most toxic substances in EG – nitrogen oxides NO_x, while the emission of smoke (emissions of particulate matters – PM), CO, and HC decreased (Krahl *et al*. 2005). Therefore, a lag of the fuel injection phase φ_{f1} is simultaneously a method of the complex reduction of harmful emissions from a diesel engine into the environment, when it is transferred from D to D–RME–E biodiesel as far as the emission of all major toxic substances is concerned.

2.2. In-cylinder process indicators

The above-determined changes of the fuel injection performance indicators, first, have an effect on the ignition lag phase, which is the most important for the whole combustion process or the period of the induction (φ_i) in the diesel engine cylinder. At the same time, the deterioration with an increase of E part of the self-ignition properties evaluated by CN has an impact on the value of φ_i. Thus, with the increase of the alcohol part E from 9 to 46% in RME–E mixture, the value of CN decreases from 47 to 30 units (see Table 3). The cumulative effect of these factors cause the following changes of φ_i:

– Lag of fuel injection (φ_{fi}) results in a reduction of φ_i, as the fuel is injected at the higher values of pressure P and temperature T of the air in cylinder (Tolstov 1955; Kavtaradze 2007):

$$\varphi_i = B \cdot C^{0.5} \left(\frac{T_k}{p_k}\right)^{0.5} \cdot \exp\left(\frac{E \cdot C^{m-1}}{\tilde{R} \cdot T_k}\right), \quad (1)$$

where: E is the fuel activation energy that is higher at the low values of CN; B is the coefficient, $B = 12 \cdot 10^{-3} \cdot (1 - 1.6 \cdot 10^{-4} \cdot n)$; n is the engine speed (min^{-1}); and $\tilde{R}$ is the molar mass of gas;

$$C = \frac{1}{\varepsilon} \cdot \left(1 + 0.5 \cdot \frac{\delta}{\beta} \cdot (\varepsilon - 1)\right),$$

where: β is the coefficient of volume which is nonparticipating in the compression process; T_k is the temperature in the cylinder; p_k is the

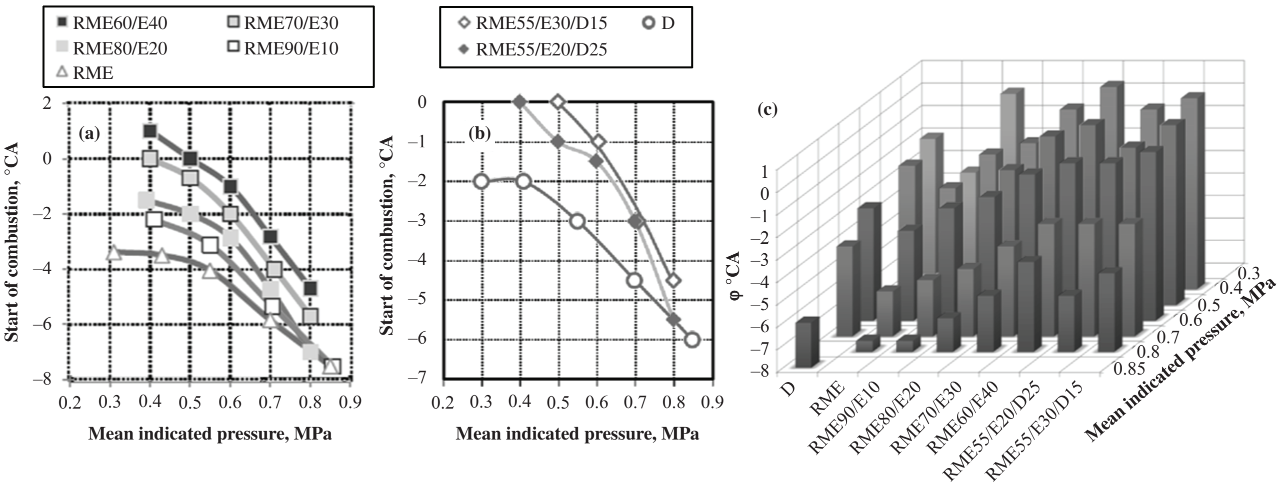


Fig. 6. Change of onset phase when 1A41 diesel engine is running on RME–E and D–RME–E biodiesels

pressure in the cylinder; ε is the compression ratio.

$$\varphi_i = 18.165 \cdot p^{-1.196} \cdot \exp\left(\frac{1640}{T}\right), \quad (2)$$

where: p is the pressure in cylinder; T is the temperature in cylinder.

– Reduction in biofuel CN with an increase of the alcohol component part (associated with the increase of E in Eqns (1), (2)), on the contrary, causes the increase in φ_i. Therefore, the resulting nature of φ_i change is determined by the dominant effect of change of either φ_{fi} or CN.
– In fact, according to the data obtained (see Fig. 5b), φ_i values for RME90/E10 biodiesel compared with the ones for RME decreased by ~ 1°CA in the full range of loads, except for the mode of nominal P_{mi}. It is obvious that with a slightly different CN for RME and RME90/E10 (due to a small E part), ~2÷3 °CA lag of the fuel injection phase had a determining impact on φ_i. The values of φ_i for RME80/E20 biodiesel are the same as for RME, while with the bigger E part (20%), they are increased and especially intensive at the high loads of a diesel engine. At the low and medium P_{mi} (mean indicated pressure), the rise of φ_i does not exceed 1÷1.5 °CA and reaches 3÷4 °CA at the near-nominal loads. Similar φ_i change trends were revealed during the research of the three-component D–RME–E biodiesel (see Fig. 5c).

Onset phase. In consequence of the combination of the effect of φ_{fi} lag and the predominant increase of the induction period φ_i, when transferring diesel engine from using D to using the alcohol-containing RME–E and D–RME–E biodiesels, the onset time φ_{ost} is moved toward TDC (see Fig. 6a, c):

– The least change of φ_{ost} is observed in the mode of nominal loads: it is near zero for RME90/E10 and RME80/E20 and does not exceed 2÷2.5 °CA for RME70/E30 and RME60/E40.
– When a diesel engine is operated at the partial P_{mi}, a shift of φ_{ost} is approximately proportional to E part in biofuel, lagging by ~1÷1.25 °CA for each 10% increase of E; as a result, for a 30÷40% part of E, the onset time starts at TDC and at the expansion stroke after TDC, respectively (+1 °CA after TDC). A qualitatively similar result was received for the three-component D–RME–E biofuels.

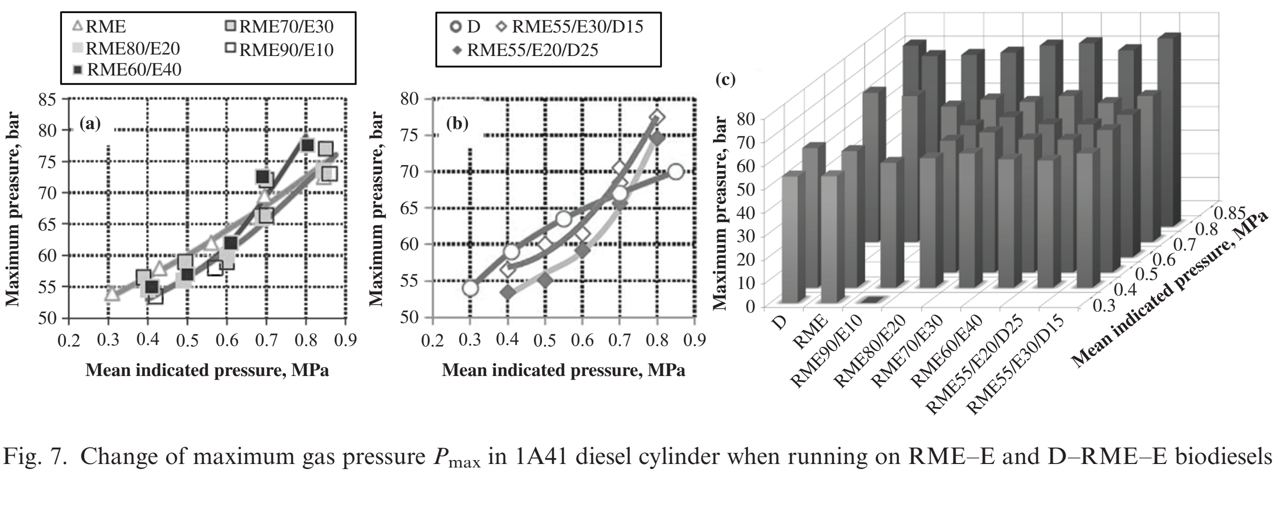


Fig. 7. Change of maximum gas pressure P_{max} in 1A41 diesel cylinder when running on RME–E and D–RME–E biodiesels

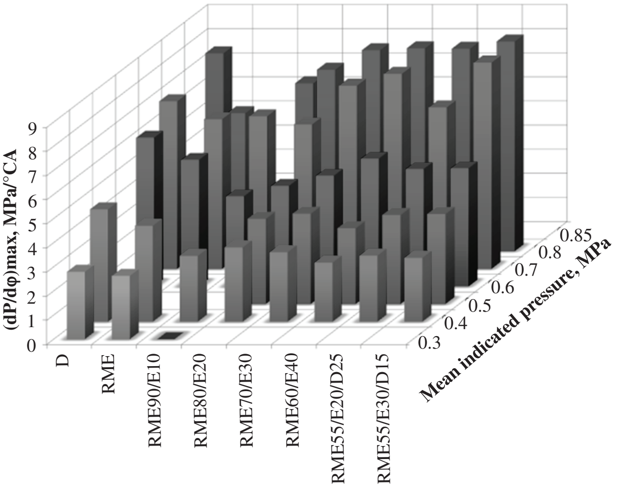


Fig. 8. Change of maximum rate of pressure rise $(dP/d\varphi)_{max}$ in 1A41diesel engine cylinder when running on biodiesels

2.3. Indexes of in-cylinder process dynamics

The relevance of evaluation of the in-cylinder process dynamic indexes (P_{max} is the maximum pressure of gas in cylinder, λ is the pressure increase ratio, ($(dP/d\varphi)_{max}$ is the maximum rate of pressure rise) is conditioned by their determining influence on the mechanical intensity of the most vital parts of the diesel engine CPG and its reliability in whole when replacing mineral diesel fuel by the alcohol-containing biodiesels. Fig. 7 gives the results of P_{max} registration when a diesel engine is running on the tested fuels.

For both the tested alcohol-containing biodiesels, RME–E and D–RME–E, P_{max} behaviors are similar: the presence of alcohol component E in the fuel mixture leads to a reduction in P_{max} by $\sim 3 \div 4$ bar at the low and medium loads. While E part in the mixture is over 20%, it leads to the increase of P_{max} by $7 \div 8$ bar or $\sim 10\%$ of the rated value if running on the D, at the rated loads. The determined trends fully correspond to the change of the fuel injection phases, the induction period, and the onset phase in the tested P_{mi} range for RME–E and D–RME–E biodiesels. In particular, the shift of φ_{ost} to TDC at small P_{mi} with the hardly varying phase of reaching the maximum cycle pressure $\varphi_{P\max}$ gives rise to the reduction of the amount of heat released ($Q_{P_{max}}$) by the time of $\varphi_{P_{max}}$. As P_{max} for the naturally aspirated diesel is determined by $Q_{P_{max}}$, the value of P_{max} has to decrease, as evidenced by the obtained experimental data. Along with this, in the high-load modes, with the alcohol component part in the biodiesel $>20\%$, the increase of φ_i has to cause the increase of intensity of kinetic phase of the combustion process (as with the increase of φ_i, the fuel quantity prepared for combustion in kinetic phase is correspondingly increased). P_{max} behavior can be seen in Fig. 7.

For the naturally aspirated diesel, which is the object of the research, λ behavior is identical to the behavior of P_{max}. Fig. 8 presents the changes of $(dP/d\varphi)_{max}$ values.

The excess of $(dP/d\varphi)_{max}$ parameter level typical for running on D is observed for biofuels with $30 \div 40\%$ E composition in the nominal-load modes. Thus, $(dP/d\varphi)_{max} = 7.48$ MPa/°CA for RME60/E40, while for D, it amounts to 8.42 MPa/°CA.

The obtained data shows that the use of the alcohol-containing biodiesels, including up to 20% alcohol component, is not associated with the increase of mechanical load on the parts of CPG.

Conclusions

The transfer of diesel engine with relatively low fuel injection pressure of $60 \div 70$ MPa to work on biodiesel containing E $\leq 30\%$ does not require adjustment of fuel injection system parameters:

(1) A shift of the phases of biodiesel injection does not depend on the part of E component in range of tested concentrations: $10 \div 40\%$ and makes up $2 \div 3$ °CA in normal loads. When operating in partial loads, maximum lag occurs up to $5 \div 6$ °CA. At the same time, peak cyclic fuel pressure in high-pressure fuel line, in comparison to D and RME, increases by $25 \div 30\%$.

(2) An increase of E part in biofuel causes dual effect on fuel combustion period: on one side, the lag of fuel injection shortens induction period φ_i, while on the other side, it lowers the CN of E in comparison with D, then RME increases φ_i. Increase of E part by 10% increases φ_i by 0.5 °CA in nominal loads and by 1.5 °CA in partial loads. In addition, a lag of beginning of visible combustion ranges from 1.5 °CA with nominal loads to $4 \div 4.5$ °CA with partial loads.

(3) Ethanol part in fuel of up to 30% does not cause any critical irregularities of diesel engine indicated process parameters with all tested loads.

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