TRANSPORT
ISSN 1648-4142 print / ISSN 1648-3480 online
2013 Volume 28(3): 217–223
doi:10.3846/16484142.2013.828652

RESEARCH OF CHARACTERISTICS OF WORKING CYCLE OF HIGH-SPEED DIESEL ENGINE OPERATING ON BIOFUELS RME–E AND D–RME–E. PART 2. INDICATORS AND CHARACTERISTICS OF HEAT RELEASE IN DIESEL CYLINDER

Sergejus Lebedevas[1], Galina Lebedeva[2], Justas Žaglinskis[1,3], Paulius Rapalis[1], Ingrida Gudaitytė[1]

[1]*Department of Marine Engineering, Klaipėda University, I. Kanto g. 7, LT-92123 Klaipėda, Lithuania*
[2]*Department of Informatics, Klaipėda University, H. Manto g. 84, LT-92294 Klaipėda, Lithuania*
[3]*Department of Automobile Transport, Vilnius Gediminas Technical University, J. Basanavičiaus g. 28, LT-03224 Vilnius, Lithuania*

Submitted 30 November 2012; accepted 26 June 2013

Abstract. This paper presents material about using two-component RME–E and three-component D–RME–E biodiesels in high-speed diesel engines. The results of the analysis of fuel injection parameters described in Part I of this scientific paper – *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* – allow conducting a coherent research of heat release in the cylinder of diesel engines transferred from operation on mineral diesel D to mixed biodiesels containing E. Effects of increased ethanol E in the biodiesel of 1A41 diesel engine have been analysed in a wide range of loads, ranging from 0.25 to 1.0 P_{enom}. It was found that the result of the transfer from two-phase heat release to one-phase heat release is an increase in the fuel's economy of the engine for every 10% increase of E in the fuel (increase of indicative process efficiency makes up 0.4÷0.5%). Dependency of heat release and nitrogen oxide emissions in the exhaust gases remains the same for mineral diesel, RME–E and D–RME–E. Indicators of cyclic stability of the diesel engine, operating on biodiesels containing E $\leq$ 30%, did not exceed those that are common for diesel engines operating on mineral diesel.

Keywords: characteristics of heat release; diesel engine; alcohol biodiesel; nitrogen oxide; cyclic instability; indicated process.

Reference to this paper should be made as follows: Lebedevas, S.; Lebedeva, G.; Žaglinskis, J.; Rapalis, P.; Gudaitytė, I. 2013. Research of characteristics of working cycle of high-speed diesel engine operating on biofuels RME–E and D–RME–E. Part 2. Indicators and characteristics of heat release in diesel cylinder, *Transport* 28(3): 217–223. http://dx.doi.org/10.3846/16484142.2013.828652

1. Kinetics of combustion of alcohol-containing biofuels

The impact of E alcohol component in RME-based blended biodiesels is evaluated by indicators of the differential $dx/d\varphi = f(\varphi)$ and integrated $X = f(\varphi)$ heat release characteristics in the diesel engine cylinder. This researched aspect is important for an effective use of biofuels in the diesel engine. For example, the impact of E on the heat release characteristics and its influence to the two-stroke diesel engine's (150 mm/225 mm) thermal efficiency are analysed by Li *et al.* (2005); the changes of heat release of a 58.5 kW four-cylinder diesel engine (98 mm/105 mm) operating on D–E blend B15 and its influence on the engine's ecological indicators are analysed by Lü *et al.* (2004).

The calculation of $dx/d\varphi$ and X, based on the experimental indicator diagrams, was performed according to prof. Gonchar's method (Gonchar, Matveev 1975). In this article, the mathematical model for ($dx/d\varphi$) calculation is modified to suit fuels with a wide composition of chemical elements (Lebedevas *et al.* 2011).

Material presented in this paper is a continuation of work, presented in paper (Lebedevas *et al.* 2013).
Corresponding author: Sergejus Lebedevas
E-mail: sergejus.lebedevas@ku.lt

The reduction in the intensity of heat release, in the pre-mixed phase of combustion, is a characteristic of RME biodiesel fuels due to the better self-ignition properties compared with D (RME CN is 51 units versus 46 units for D) and the less induction period φ_i caused by it (Lebedevas *et al.* 2006, 2007). However, the appearance of the E alcohol component in RME biodiesel fuels gives rise to the increase of the rate of heat release in the pre-mixed phase $(dx/d\varphi)_{\text{I max}}$ with an increase of E concentration in the mixture. The heat release intensity of the basic diffusion phase of combustion evaluated by $(dx/d\varphi)_{\text{II max}}$ value practically does not change in the main range of tested load regimes (Fig. 1). Only at low P_{mi}, there is a rise of $(dx/d\varphi)_{\text{II max}}$ conditioned by the deformation of the heat release nature from a two phase into a single phase.

Fig. 2a gives a schematic representation of the dynamics of transfer from a two-phase to a single-phase combustion of RME–E with an increase of E concentration in biodiesel fuels. Thus, the single-phased nature of combustion with E not exceeding 20% is only observed at low P_{mi} that does not exceed 40% of the rated P_{mi} values. With an increase of E concentration up to 30%, and especially up to 40%, the nature of combustion becomes single phased in the basic range of loads, including the nominal one.

The comparison of differential characteristics of heat release when using tested fuels D, RME and RME60/E40 ($P_{mi} = 0.7$ MPa) is given in Fig. 2b. It allows defining a set of characteristic features of the impact of alcohol component on the combustion process. Given E, the rate of $dx/d\varphi$ at the early stage of combustion process (3÷4 °CA from the onset time) is noticeably lower than that at the two-stage heat release at combustion of mineral diesel fuel D and rapeseed methyl ester RME. However, the lack of reduction of the rate of heat release between two maximums – $(dx/d\varphi)_{\text{II max}}$ and $(dx/d\varphi)_{\text{II max}}$ – is typical for a two-stage process, and the high intensity of heat release at its final stages determines the reduced period of combustion of the alcohol-containing biodiesel. When interpreting the heat release characteristic using parameters of I. Vibe's model (Vibe 1970), the following values of the heat release (combustion) period φ_z were obtained: 120÷170 °CA

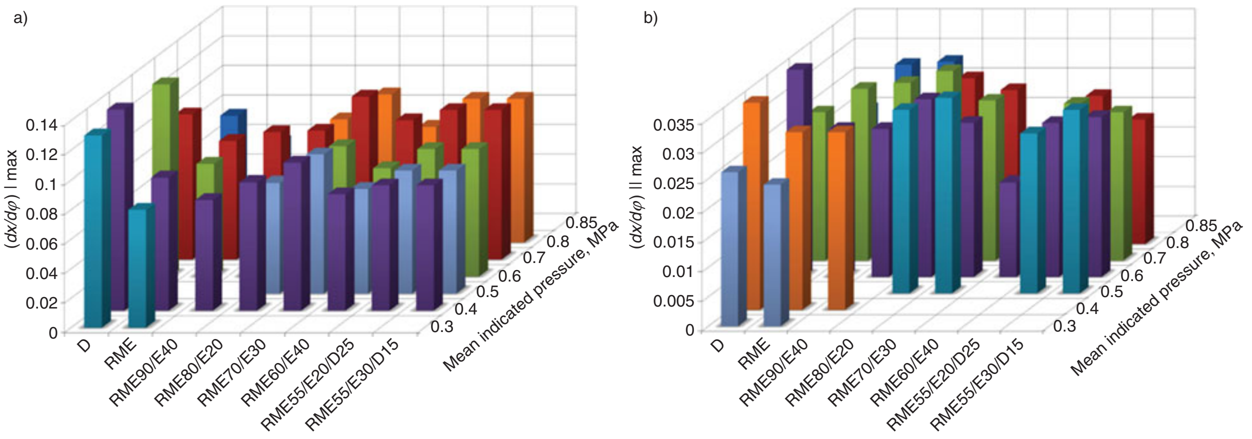

Fig. 1. Indicators of heat release dynamics in 1A41 engine cylinder when running on RME–E and D–RME–E biodiesel fuels

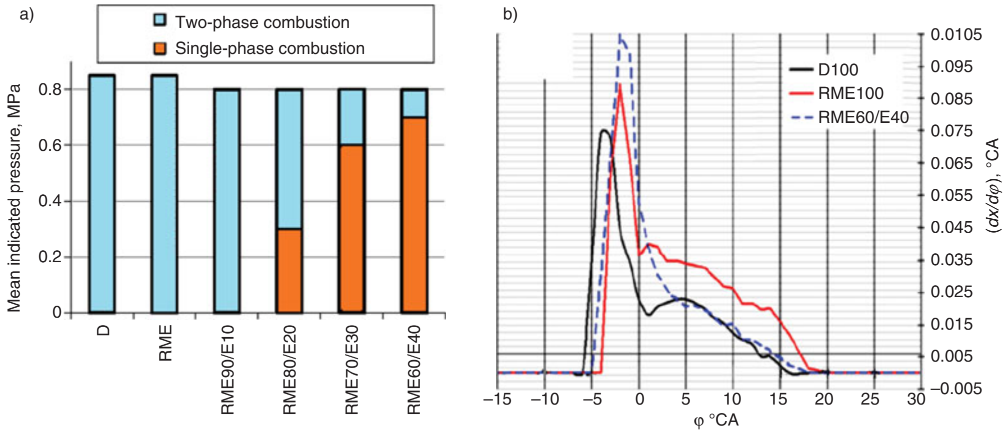

Fig. 2. Dynamics of heat release characteristic $dx/d\varphi$ with increase of E alcohol component

for RME; 75÷100 °CA for RME90/E10 and RME80/E20; and 40÷70 °CA for RME60/E40. Similar to the traditional D, the lower φ_z was obtained in the partial-load mode and the high φ_z – in the nominal-load modes of a diesel engine. As a result, the form of the integral curve of heat release $X = f(\varphi)$ is shifted to TDC as compared with combustion of D and RME fuels. Consequently, the centroid of the area under curve $X = f(\varphi)$ is also shifted to TDC. According to the theoretical justification of academician Stechkin (1960) and considerable evidence of experimental researches, this fact provides the reduction of the combustion delay losses and the upgrading of the cycle indicated efficiency η.

Therefore, the kinetics of combustion of alcohol-containing fuels and the oxygen content, which is higher than the one of RME and, especially D (34.8% versus 10.7% and 0.4%, respectively), are characterised by the transfer to the single-stage combustion process, the increase of its intensity and the improvement of the energy indicators of a diesel engine. The data in Fig. 3 given to prove this shows an ~0.5÷0.15% increase of η_i for every 10% increase of E in biodiesel fuels.

In this regard, the spontaneous lag of the fuel injection phase, when a diesel engine is transferred to using the alcohol-containing RME–E and D–RME–E biofuels, should be considered as a positive factor limiting the rise of $P_{\max}$ and $dP/d\varphi_{\max}$ and reducing the emission of $\mathrm{NO_x}$ in exhaust gases (EG) while maintaining a high mileage rating. Such self-regulation of a diesel engine, when it is transferred to use the alcohol-containing biodiesels, is similar to one of the efficient complex ways to improve the operational characteristics of the high-speed diesel engines implemented at the end of the 1980s of the last century by the leading diesel engine construction companies including the German Company 'Motoren und Turbien Union' (Friedrichshafen) (Kruggel 1989). At the creation of the second development stage of diesel engines of '396' series, the increase in the fuel injection intensity and, correspondingly, its combustion characteristics were matched with the lag of the fuel injection phase that resulted in a significant reduction of $\mathrm{NO_x}$ emission and limitation of $P_{\max}$ with 50% boosting of the mean effective pressure.

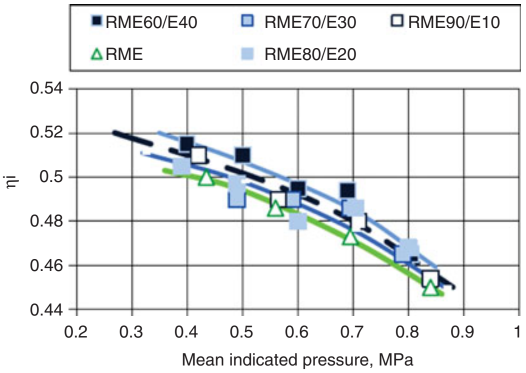

Fig. 3. Rise of 1A41 engine η_i with increase in E component in RME–E biodiesel fuel

2. Relationship of heat release nature and $\mathrm{NO_x}$ emission

Unlike the incomplete combustion's toxic products (CO, HC and PM), the $\mathrm{NO_x}$ concentration is primarily influenced by the conditions of fuel combustion in the cylinder: temperature and reagent concentrations in the burned mixture zone. The influence of the elemental chemical composition C/H/O of the fuel is less.

Zeldovich (1946) investigated and determined the predominant thermal nature of nitrogen oxide generation. The flame temperature and the concentration of the air oxygen O_2 and nitrogen N_2 in the combustion reaction zone are the main influencing factors. The follow-up researches confirmed the substantially smaller influence of the mechanisms on the generation of 'prompt nitrogen oxides' and 'fuel nitrogen oxides' in the total $\mathrm{NO_x}$ emission budget (Kavtaradze 2007).

Experimental researches of kinetics of $\mathrm{NO_x}$ generation in the diesel engine cylinder (Smailys, Bykov 1990) established that the main part (up to ~90%) of nitrogen oxides is generated at the moment of reaching the maximum combustion pressure $\varphi_{P\max}$. The authors of the present article carried out an analysis of the relationship $e'_{\mathrm{NO_x}} = f\left(Q_{P_{\max}}\right)$, where $e'_{\mathrm{NO_x}}$ is the specific emission of nitrogen oxides, in g/kg fuel; $Q_{P_{\max}}$ is the released heat at the moment of reaching the maximum combustion pressure, in kJ, for a wide range of high-speed transport diesel engines (Lebedev, Nechaev 1999).

Based on this, a mathematical model enabling the evaluation of the changes of $e'_{\mathrm{NO_x}}$ as a function of design and adjustment parameters and the indicators of the in-cylinder process (Lebedev, Nechaev 1999) was developed and successfully applied to practice. The investigation of relationship $e'_{\mathrm{NO_x}} = f\left(Q_{P_{\max}}\right)$ for biodiesels will enable to significantly simplify the assessment of environmental efficiency of the transferring the fleet of diesel engines operating on D to biodiesels and, along with it, the development of $\mathrm{NO_x}$ emission reduction technologies.

As is known, the replacement of D by RME causes an increase in the emission of one of the most toxic substances, namely, nitrogen oxides $\mathrm{NO_x}$ (Sarin 2012). Through the researches made, a marked improvement of the diesel engine's environmental performance when using the alcohol-containing fuels was recorded (Lebedevas *et al.* 2009) (Fig. 4).

Mostly, the change of the fuel's chemical composition contributes to the reduction in CO emission and smoke (SM) in the EG. The fraction of carbon (C), the major source of CO and SM generation in

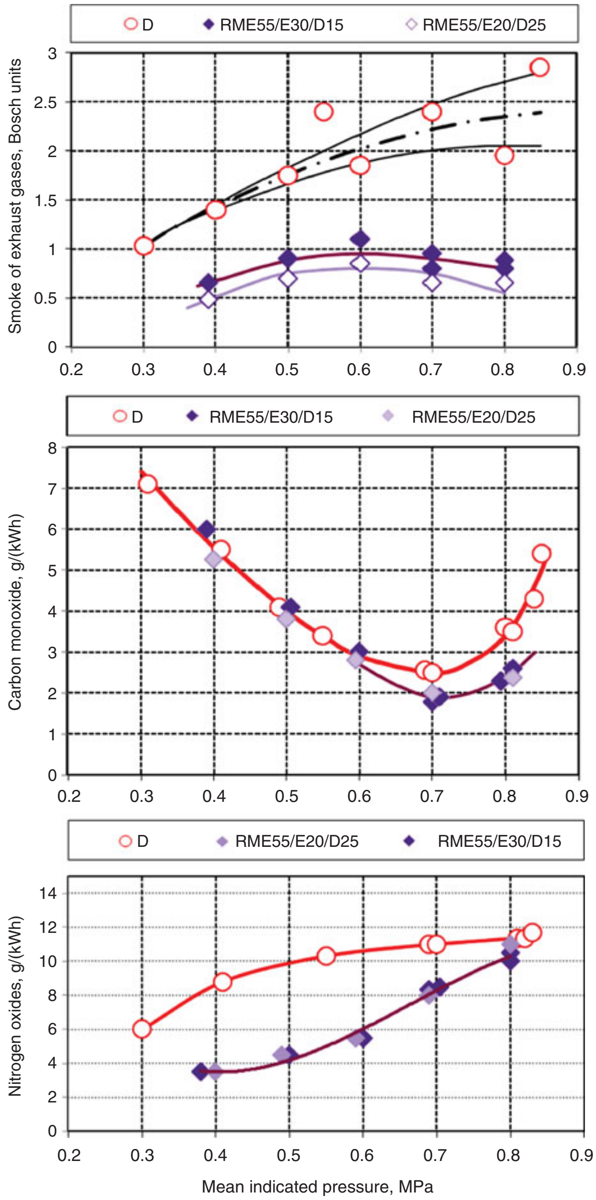

Fig. 4. Change of emission of toxic components in engine EG running on alcohol-containing biodiesels

the elemental composition of the tested alcohol-containing biodiesel fuels, is decreased up to 67.0÷74.5% versus 87% and 77% for D and RME, respectively. At the same time, a fraction of oxygen stimulating the combusting efficiency increased from 0.4% and 10.7% for D and RME, respectively, to 13÷20%. According to research data (Choi *et al.* 1997), a significant fraction of the combustion-generated fine soot particulates, having time to burn out at the opening of the cylinder exhaust units, is an additional factor of SM reduction. The 50% and 70% reduction in CO emission and SM, respectively, even with a spontaneous lag of the fuel injection phase, may be held responsible for the influence of these factors. The $\mathrm{NO_x}$ emission behaviour is evaluated using $Q_{P\max}$ factor. Fig. 5 presents a comparison of $Q_{P\max}$ values and the diesel engine load for all tested fuels.

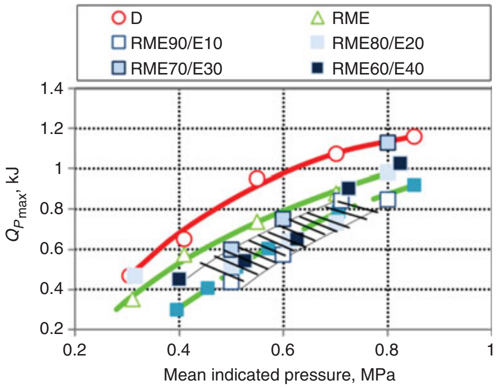

Fig. 5. $Q_{P\max}$ behaviour of transferred engine from D to biodiesels

The graphical dependences of $Q_{P\max}$ correlate well and provide a qualitative explanation of the test values of $\mathrm{NO_x}$ emission in EG (Fig. 5). For D, the highest value of $Q_{P\max}$ corresponds to the highest $e'_{\mathrm{NO_x}}$ values in the rated load regime. As for RME–E biodiesels, the curves $e'_{\mathrm{NO_x}} = f(P_{mi})$ and $Q_{P\max} = f(P_{mi})$ are practically character-identical, irrespective of E in the mixture. The obtained levels of $e'_{\mathrm{NO_x}}$ and $Q_{P\max}$ values are also identical for different fuels: the highest $e'_{\mathrm{NO_x}}$ and $Q_{P\max}$ values are obtained for D, then followed by RME and the alcohol-containing RME–E biodiesels.

The results of testing the engine running on D and RME fuels and their blends enable summarising the quantitative relationship of $e'_{\mathrm{NO_x}}$ and $Q_{P\max}$ (Fig. 6).

The value of $\delta_{xy} = 0.947$ indicator counts in favour of a strong correlation between $e'_{\mathrm{NO_x}}$ and $Q_{P\max}$. The maximum ratios of experimental values of the smoothing graphical dependence $e'_{\mathrm{NO_x}} = f\left(Q_{P_{\max}}\right)$ do not exceed $\pm 7 \div 10\%$. The obtained solution for the practical tasks of evaluation of $e'_{\mathrm{NO_x}}$ performance of diesel engines when transferring them to biodiesels is assessed positively. For the follow-up research, it is planned to expand the experimental evaluations of $e'_{\mathrm{NO_x}}$ and $Q_{P\max}$ relationship, as well as, to adapt the

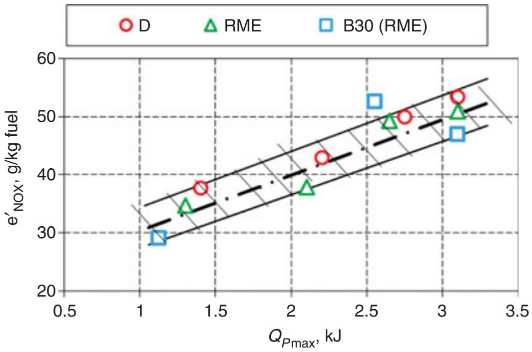

Fig. 6. Relationship of and $Q_{P\max}$ when a diesel engine is running on D and biodiesels

mathematical model of the NO_x emission evaluation developed by the authors for the cases of engine running on the alcohol-containing biodiesels.

3. Evaluation of cyclic instability of a diesel engine running on alcohol-containing biodiesels

The cyclic instability of the diesel engine is the imbalance of a series of indicator chart parameters (main parameters are maximum pressure $P_{\max}$ and start of combustion ($\varphi_{P\max}$). Fragments of the results of statistical analysis are shown in Figs 7 and 8 and in Table 1.

It is known that the greatest cyclic instability occurs when the engine is running on low loads or idling. Based on this, the analysis comprises of two regimes: mean indicated pressure of 0.4 MPa and maximum load of 0.85 MPa. Statistical analysis confirmed that there is a normal distribution of ($P_{\max}$) data. This facilitates the task of evaluation of cyclic instability using standard deviation and dispersion (Table 1). Up to 30% concentration of E in D–RME composition has no influence on the cyclic instability (on energetic and ecological parameters of engine as well) through all of the engine load ranges. With an increase in E reaching 40%, the cyclic instability exceeds the normal level of cyclic instability for D (the highest measured value of maximum pressure as well). Standard deviation grows from 0.13 to 0.21 MPa and the dispersion grows from 0.016 to 0.045 MPa.

The cyclic instability of engine performance has a negative impact on the fuel efficiency, emission of toxic components in EG and engine reliability indexes (Rakopoulos *et al.* 2008). The cyclic instability of 10 kW diesel engines D80 (100 mm/85 mm) and 50 kW Renault (80 mm/93 mm) operating on D–E biodiesels were analysed by Satgé de Caro *et al.* (2001).

The instability of the fuel injection and air supply characteristics are its main cause. The spontaneous changes of the fuel injection start phase 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 biodiesels.

The maximum combustion pressure $P_{\max}$, an indicator of 1A41 engine, to a considerable degree, determines the mechanical loads on the cylinder-liner group parts, NO_x emission and the specific fuel consumption selected as the test parameter of cycle.

According to the data of an array of $P_{\max}$ values of the successively recorded 40 ÷ 60 engine cycles, a mean value of $P_{\max}$ and a standard deviation $\delta_{P\max}$ (dispersion) of the maximum combustion pressure were calculated. The comparison of $P_{\max}$ stability factors was conducted for the load mode $P_{mi}=0.4\div0.35$ MPa, when running on D and RME–E biodiesels.

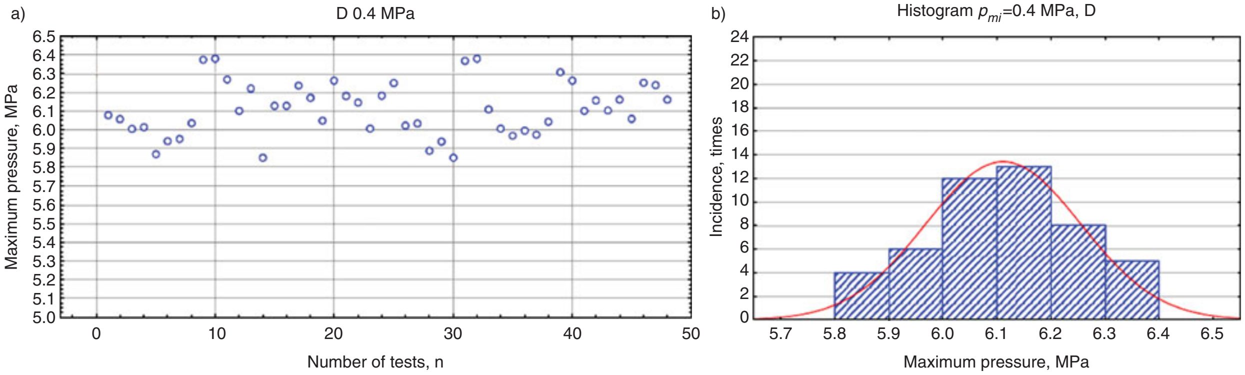

Fig. 7. Statistical analysis of cyclic instability of engine working on mineral diesel

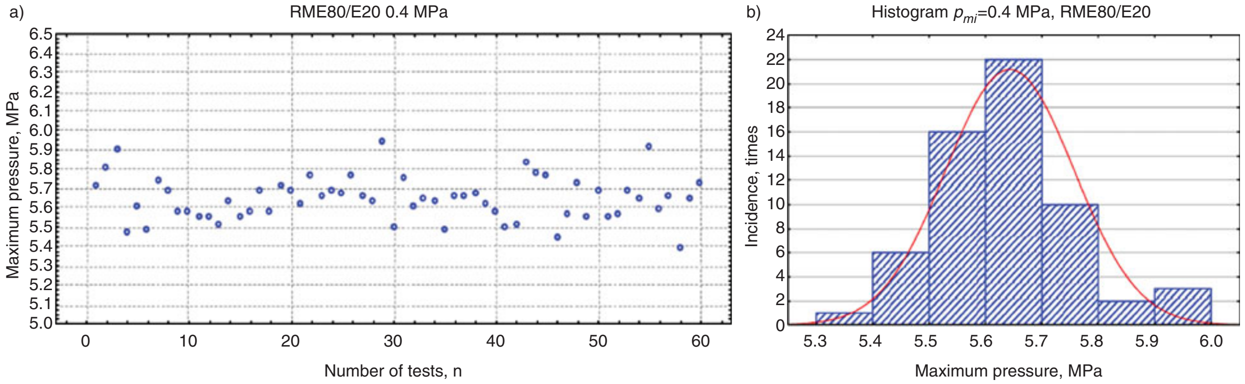

Fig. 8. Statistical analysis of cyclic instability of engine working on RME80/E20 biodiesel

Table 1. Results of statistical evaluation of cyclic instability

P_{me}, MPa	Fuel type	Standard deviation	Dispersion	Mean standard deviation	Median
0.4	D	0.142675	0.020356	0.020593	6.101624
	RME	0.100168	0.010034	0.013041	5.912842
	RME90/E10	0.112887	0.012743	0.014574	5.468079
	RME80/E20	0.113110	0.012794	0.014602	5.644775
	RME70/E30	0.087041	0.007576	0.012696	5.606324
	RME60/E40	0.131550	0.017306	0.017126	5.595337
0.85	D	0.127503	0.016257	0.016461	7.282288
	RME	0.141436	0.020004	0.018259	7.441773
	RME90/E10	0.126044	0.015887	0.016410	7.620848
	RME80/E20	0.127722	0.016313	0.016628	7.620848
	RME60/E40	0.213091	0.045408	0.027510	8.089234

Conclusions

The presented material is dedicated to one of the most urgent issues of the transport sector – transfer of diesel engines designed to work with D to working with biodiesels produced from renewable energy sources of plant and animal origin:

1) The conducted researches of the fuel injection and in-cylinder process characteristics of 1A41 high-speed diesel engine have confirmed that its transfer from D to RME–E and D–RME–E alcohol-containing biodiesels (with E up to 40%) has a favourable effect on the improvement of the energy and environmental performance, while maintaining at admissible level the mechanical loads on the parts of the cylinder-liner group:
    a) Higher rates of heat release in the premixed phase at combustion of alcohol-containing fuels provide ~15% reduction of combustion time, every time increasing the alcohol component part (ethyl alcohol) by 10%. As a result, the energy performance improves: the increase of the diesel engine's indicated (effective) efficiency in the full range of tested loads (0.30÷0.85 MPa) amounted to 5÷6 for every 10% increase in E;
    b) Maximum combustion pressure ($P_{\max}$) of the cylinder creates a level of mechanical load of the cylinder-liner group parts. $P_{\max}$ is lower in the range of low and medium load regimes. Meanwhile, at the rated power, with a part of E $\leq$ 20% in the blend, it does not exceed the level of mineral diesel fuel. With an increase up to 30÷40% of the alcohol component part in biodiesel fuel it exceeds the $P_{\max}$ level of the fossil diesel.
2) Increase of ethanol part in biodiesel resulted in the qualitative improvement of the indicative process of conversion of heat release from a two-phased (common to mineral diesel and RME) to a single-phased form. A 10% increase of ethanol part in the fuel results in increased indicated efficiently by 0.5÷0.4%.
3) Optimisation of the fuel injection phase φ_{f1} is an effective way of the complex improvement (with regard to the incomplete combustion products and NO_x) of the environmental performance (by 50÷70%) of the operating fleet of high-speed diesel engines, when converting them from working with the mineral diesel fuel to working with D–RME–E alcohol biodiesel fuels.
4) Indicators of the cyclic instability of a diesel engine evaluated by $P_{\max}$ value are practically the same when running on mineral diesel fuel and alcohol biodiesel fuels. The largest dispersion of $P_{\max}$ fixed for the diesel engine mode of 60% load of the rated one does not exceed 0.045 MPa when E = 40% and at maximum increase of $P_{\max}$ does not exceed 10% in comparison with D.

References

Choi, C.; Bower, G.; Reitz, R. 1997. Effects of biodiesel blended fuels and multiple injections on D. I. diesel engines, *SAE Technical Paper* 970218. http://dx.doi.org/10.4271/970218

Gonchar, B. M.; Matveev, V. V. 1975. Metodika chislennogo modelirovaniya perehodnyh processov dizelej, *Trudy CNIDI* 68: 3–26 (in Russian).

Kavtaradze, R. Z. 2007. *Lokal'nyj teploobmen v porshnevyh dvigatelyah*. MGTU im. N. Je. Baumana. 472 s. (in Russian).

Kruggel, O. 1989. Progress in the combustion technology of high performance diesel engines toward reduction of exhaust emissions without reduction of operation economy, in *Proceedings of Baden–Wurttemberg Technology Conference*. 14 p.

Lebedev, S. V.; Nechaev, L. V. 1999. *Sovershenstvovanie pokazatelej vysokooborotnyh dizelej unificirovannogo tiporazmera*. Monografiya. Altajskij gosudarstvennyj tehnicheskij universitet. 112 s (in Russian).

Lebedevas, S.; Lebedeva, G.; Bereišienė, K. 2011. Modifying mathematical models for calculating operational characteristics of diesel engines burning RME biofuels, *Transport* 26(1): 50–60. http://dx.doi.org/10.3846/16484142.2011.561528

Lebedevas, S.; Lebedeva, G.; Gudaitytė, I. 2013. 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, *Transport* 28(2): 204–213. http://dx.doi.org/10.3846/16484142.2013.806346

Lebedevas, S.; Lebedeva, G.; Makarevičienė, V.; Janulis, P.; Sendžikienė, E. 2009. Usage of fuel mixtures containing ethanol and rapeseed oil methyl esters in a diesel engine, *Energy and Fuels* 23(1): 217–223. http://dx.doi.org/10.1021/ef800512z

Lebedevas, S.; Vaicekauskas, A.; Lebedeva, G.; Makarevičienė, V.; Janulis, P. 2007. Change in operational characteristics of diesel engines running on RME biodiesel fuel, *Energy and Fuels* 21(5): 3010–3016. http://dx.doi.org/10.1021/ef060314t

Lebedevas, S.; Vaicekauskas, A.; Lebedeva, G.; Makarevičienė, V.; Janulis, P.; Kazancev, K. 2006. Use of waste fats of animal and vegetable origin for the production of biodiesel fuel: quality, motor properties, and emissions of harmful components, *Energy and Fuels* 20(5): 2274–2280. http://dx.doi.org/10.1021/ef060145c

Li, X.; Qiao, X.; Zhang, L.; Fang, J.; Huang, Z.; Xia, H. 2005. Combustion and emission characteristics of a two-stroke diesel engine operating on alcohol, *Renewable Energy* 30(13): 2075–2084. http://dx.doi.org/10.1016/j.renene.2004.05.014

Lü, X.-C.; Yang, J.-G.; Zhang, W.-G.; Huang, Z. 2004. Effect of cetane number improver on heat release rate and emissions of high speed diesel engine fueled with ethanol–diesel blend fuel, *Fuel* 83(14–15): 2013–2020. http://dx.doi.org/10.1016/j.fuel.2004.05.003

Rakopoulos, D. C.; Rakopoulos, C. D.; Giakoumis E. G.; Papagiannakis, R. G.; Kyritsis, D. C. 2008. Experimental-stochastic investigation of the combustion cyclic variability in HSDI diesel engine using ethanol–diesel fuel blends, *Fuel* 87(8–9): 1478–1491. http://dx.doi.org/10.1016/j.fuel.2007.08.012

Sarin, A. 2012. *Biodiesel: Production and Properties*. Royal Society of Chemistry. 288 p.

Satgé de Caro, P.; Mouloungui, Z.; Vaitilingom, G.; Berge, J. Ch. 2001. Interest of combining an additive with diesel–ethanol blends for use in diesel engines, *Fuel* 80(4): 565–574. http://dx.doi.org/10.1016/S0016-2361(00)00117-4

Smailys V. I.; Bykov V. Yu. 1990. Optimizaciya jekonomicheskih jekologicheskih pokazatelej dizelej ChN21/21 pri forsirovanii po srednemu jeffektivnomu davlenyu, *Dvigatelestroenie* 4: 44–46 (in Russian).

Stechkin, B. S. 1960. O kojefficiente poleznogo dejstviya ideal'nogo cikla bystrogo sgoraniya pri konechnoj skorosti vydeleniya tepla, *Teoriya, konstrukciya, raschet i ispytaniya dvigatelej vnutrennego sgoraniya: Trudy laboratorii dvigatelej AN SSSR* 5: 61–67 (in Russian).

Vibe, I. I. 1970. *Brennverlauf und Kreisprozess von Verbrennungsmotoren*. Berlin: VEB Verlag Technik, 286 S (in German).

Zeldovich, Y. B. 1946. The oxidation of nitrogen in combustion and explosions, *Acta Physiochimica URSS* 21(4): 577–628.