ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/01.3001.0012.4325

INFLUENCE OF BIODIESEL ORIGIN ON THE EXHAUST GASSES CONCENTRATION IN COMPRESSION IGNITION ENGINE

Kamil Duda, Michał Śmieja

University of Warmia and Mazury in Olsztyn
Faculty of Technical Sciences
Department of Mechatronics and IT Education
Słoneczna Street 46A, 10-710 Olsztyn. Poland
tel.: +48 89 523 36 23, fax: +48 89 523 34 76
e-mail: mechatronika@uwm.edu.pl

Maciej Mikulski

TNO Automotive
Automotive Campus 30, 5708 JZ Helmond, The Netherlands
e-mail: maciej.mikulski@tno.nl

Jacek Hunicz

Lublin University of Technology
Faculty of Mechanical Engineering
Nadbystrzycka Street 36, 20-618 Lublin, Poland
tel.: +48 81 538 42 84, fax. +48 81 538 42 33
e-mail: j.hunicz@pollub.pl

Abstract

The use of renewable fuels can reduce consumption of fossil fuels as well as diversify the range of alternative energy carriers. The advantage of biofuels is that they can be obtained from waste materials. Biofuels derived from vegetable or animal raw fatty material, as a result of transesterification, are characterized by similar physicochemical properties to mineral diesel fuel in terms of quality standards, however the fatty acid composition of the raw material can significantly influence exhaust gas emissions. The aim of the research is to determine the impact of the origin of various renewable biocomponents on exhaust gasses concentration emitted by compression ignition engine. The tests were conducted on a Common Rail, direct injection engine, operating under steady state conditions. Two kinds of biofuels produced from different fatty raw materials (rapeseed oil and swine lard) were used. All the experiments were performed on fuels containing a total of 50% biocomponent shares admixed to commercial diesel fuel. The tested samples included both: binary and ternary mixtures. During the experiments the differences in: hydrocarbons, carbon monoxide and nitrogen oxides concentrations were examined as a result of different fuel composition. The study shows that the best results were achieved for fuel containing both plant and animal biocomponents.

Keywords: *exhaust gas emission, common rail. biodiesel combustion, animal fat biodiesel mixtures, vegetable oil biodiesel mixtures*

1. Introduction

The ever-increasing number of vehicles powered by combustion engines demands a supply of ever-increasing amounts of fuels to power them. This situation contrasts with the diminishing resources of mineral fuels. In addition to the wide range of economic and ethical concerns centered around ensuring energy security, the issue of the adverse impact of fossil fuel combustion on the natural environment cannot be marginalized. The problem of natural environment pollution caused by the automotive sector was first highlighted in the United States of America where, in the late 1950s, the first regulations concerning the amounts of toxic compounds emitted by motor vehicles were introduced. Over the years, the evolution of legislative conditions was centered around measurements of exhaust gas emissions, with the amount of compounds analysed in exhaust gases being gradually increased while restricting their permissible limits. The currently presented approach includes promoting fuels derived from renewable sources by replacing fossil fuels with their alternative equivalents.

In accordance with the concepts of energy source diversification, becoming independent from fossil fuels, and the pro-environmental aspects, the demand for fuels derived from renewable sources has been on a constant increase. This fact has induced scientists to broaden their knowledge on the use of such fuels to power combustion engines. In this case, particular attention should be paid to Compression Ignition engines, since it has been confirmed that such units can be powered with renewable fuels without the necessity of large-scale hardware modifications [1-3]. In the literature on the subject, a great number of studies have been dedicated to research into the effects of the use of biofuels in emissions of toxic compounds emitted by combustion engines [4-9]. Although various procedures and research facilities affect the observed results [10, 11], the dominant belief in study conclusions is that an inversely proportional relationship exists between the renewable component content of a fuel and the contents of particular toxic compounds in exhaust gases, usually excluding NOx emission, which is characterized by a directly proportional relationship linking the above mentioned factors [11-13].

When analysing the results of studies concerning the effects of the use of renewable components on exhaust gas emissions, attention is drawn to the small number of studies on the use of multi-component fuel mixtures containing renewable components derived from fatty materials belonging to different groups (plant and animal raw materials). Biofuels derived from plant materials are usually characterized by greater density and more favourable low-temperature properties, while biocomponents derived from animal materials are usually characterized by lower viscosity and lower sulphur content. In addition, the fuels derived from plant materials have a higher energy value, which translates into lower fuel consumption; on the other hand, biofuels derived from animal materials are characterized by a shorter auto-ignition delay [1, 8, 13, 14]. Lower consumption of plant components affects the amounts of emitted exhaust gases, particularly CO_2 content, while shorter auto ignition delay and a higher combustion temperature of animal components affects the contents of such exhaust gas components as THC or CO [1, 6, 15].

Summarizing, the combination of advantages arising from the use of both types of biofuels in the form of a pre-blended ternary mixture with diesel fuel is expected to bring tangible advantages in terms of reducing the amounts of particular components of exhaust gases in relation to both a conventional fuel and to fuels containing renewable components of only one type. Proper blending should further enable achieving similar to standardized-diesel physico-chemical parameters of the bio-fuel mixture, thus enabling efficient engine operation without changing the control maps.

The aim of the present study is to check the feasibility of the above thesis for the state of the art, common rail diesel engine, running on factory controller settings. For this purpose, steady state, test bench measurements are performed at different points of the engine map. Selected, engine-out emission indexes of three different biofuels (two binary mixtures and a ternary mixture) are investigated in relation to standard diesel calibration and assessed with respect to statistical relevance.

2. Materials and methods

Biofuels used in this study have been produced under laboratory conditions. The raw materials used for the biofuel production were swine lard and rapeseed oil. All biofuels were obtained from one-step, base-catalysed transesterification of the fatty raw material with methyl alcohol. The produced biofuels served as a component of fuel mixtures containing identical proportions of renewable biocomponents and commercial Diesel Fuel (DF). The mixture containing 50% biofuel derived from rapeseed oil (RME) mixed with DF was labelled as R50. The mixture containing identical proportions of SLME (swine lard methyl esters) and DF was labelled as S50. The mixture containing 25% SLME, 25% RME and 50% DF was labelled as SR50. The basic physico-chemical properties of the analysed fuels are presented in Tab. 1.

Tab. 1. Physico-chemical properties of the analysed fuels

Sample name	Density at 15ºC [kg/m^3]	Viscosity at 40ºC [mm^2/s]	Water content [mg/kg]	Total contamination [mg/kg]	CFPP [ºC]
DF	824	2.78	59	5.8	-12
R50	851	3.52	160	15.8	-12
S50	848	3.59	230	13.0	0
SR50	850	3.56	199	13.6	-5

Empirical tests were conducted on the Andoria ADCR – a four-cylinder Common Rail compression ignition engine with a cylinder capacity of 2.6 dm^3, described in [13, 16]. During the tests, the engine operation was controlled by a Bosch EDC16C39 control unit with a software containing fuel maps optimized for conventional diesel operation. Basic data for the engine are presented in Tab. 2.

Tab. 2. Specification of the ADCR engine

Engine type	4-stroke, Compression Ignition
Fuel injection system	Common Rail fuel system
Engine layout	4 cylinder inline, vertical
Displacement volume	2636 cm^3
Rated Power / rotational speed	85 kW / 3700 RPM
Max. Torque / rotational speed	250 N·m / 1800-2200 RPM
Injection system	Bosch injection system CR2.0
Turbocharger	Radial with exhaust extraction valve
EGR	High pressure system, pneumatic valve

Other elements of the test stand were based on devices manufactured by AVL:

- eddy-current dynometer AVL Dyno Perform 240,
- engine speed control system AVL THA100,
- fuel balance AVL 735S,
- air mass flow meter AVL SENSYFLOW P,
- emission bench AVL AMA i60,
- test stand control and data acquisition system PUMA Open.

Engine tests to assess the concentrations of particular exhaust gas components in the case of the use of particular fuels were carried out under predefined engine operation conditions for two rotational shaft speeds: n = 1500 RPM and n = 3000 RPM. For both rotational speeds, the tests were carried out for the following loads: 50 N·m (low load conditions) and 200 N·m (high load conditions). After the parameters were set and the engine operation had stabilized to specified values, measurements were taken at each operating point for 120 seconds. During the study, the following emission indexes (concentrations) were recorded: hydrocarbons (THC), carbon monoxide (CO) and nitrogen oxides (NOx). The types of particular analysers used in the measurements, calibrated measuring range, and the accuracy class are listed in Tab. 3.

For each of the measurement point, the time-sampled (1 Hz) emission indexes were averaged across the recording window (120 s). Standard deviation was used to assess the measurement uncertainty of individual indexes. The species concentrations were presented in relation to standard diesel calibration results. The measurement uncertainty level for the presented relative values ($\Delta[X]_{relative}$) was calculated using the exact differential method, following the approach of McClintock [17]:

$$\Delta[X]_{relative} = \sqrt{\left(\frac{\partial[X]_{relative}}{\partial[X]_{DF}} \cdot \Delta[X]_{DF}\right)^2 + \left(\frac{\partial[X]_{relative}}{\partial[X]_{BF}} \cdot \Delta[X]_{BF}\right)^2}. \quad (1)$$

Tab. 3. Data concerning the exhaust gas analysers used in the tests

Component	Device	Analyser	Range	Unit	Accuracy [% of max range]
THC	AVL AMA i60	Flame Ionization Detector (FID)	3-1000	ppm	< 1
NOx		Chemiluminescence Detector (CLD)	10-10000	ppm	< 1
CO		Infrared Detector (IRD)	50-5000	ppm	< 0.5

Either standard deviation or device accuracy (Tab. 3) – whichever was higher – was taken as maximum uncertainty of individual emission indexes for diesel ($\Delta[X]_{DF}$) and biofuel ($\Delta[X]_{BF}$) respectively.

To support the emission results, the brake fuel conversion efficiency (*BFCE*) was calculated as a ratio of mechanical work performed by the engine and energy input with the fuel. Additionally, volumetric efficiency (V_e) was introduced to provide information on turbocharger response. This was calculated as the mass of aspirated air relative to the amount of air, which would fill the cylinder, swept volume under ambient conditions.

3. Results and discussion

As already mentioned, the engine was operated using the original control maps, optimized for diesel fuel combustion. The mass of fuel required to achieve set torque was corrected via setting of the accelerator pedal input signal. It should be noted however that due to different content of oxygen and different auto-ignition properties of fuels, excess air ratio and heat release rates were different. It resulted in variations of both, exhaust emissions and engine efficiency.

All the experimental data presented in this study are presented as percentage changes with relation to conventional diesel fuel (DF). To provide reference values, Tab. 4 shows the results of *BFCE,* V_e and concentrations of gaseous exhaust compounds for diesel calibration.

Tab. 4. Engine operating parameters for diesel fuel

Engine parameters		V_e [%]	BFCE [%]	Concentrations		
RPM	Load [N·m]			HC [ppm]	CO [ppm]	NO_X [ppm]
1500	50	60	23	121	303	388
	200	94	33	75	474	1164
3000	50	54	17	172	740	496
	200	86	30	74	459	1028

Figure 1 shows that under all conditions except high RPM and high load the changes in BFCE are negligible (within 1%). However, at 3000 RPM and under high engine load substantial deterioration of the efficiency was noted. It can be ascribed to the differences in mixture formation process, due to differences in physiochemical properties of fuels (Tab. 1) as well as differences in quantity of fuel introduced into combustion chamber [18]. At 3000 RPM, the fuel was introduced into the cylinder in a single dose, whereas at 1500 RPM the controller moved to the split injection strategy with small pilot injection for mixture conditioning. Thus, considering the higher viscosity and slower vaporization of biofuels, single injection of large amount of fuel could result in higher fuel stratification and delayed combustion. This thesis is also supported by relative HC emissions shown in Fig. 2. The 3000/200 case is the only one where an increase in HC emissions was noted, indicating deterioration of combustion.

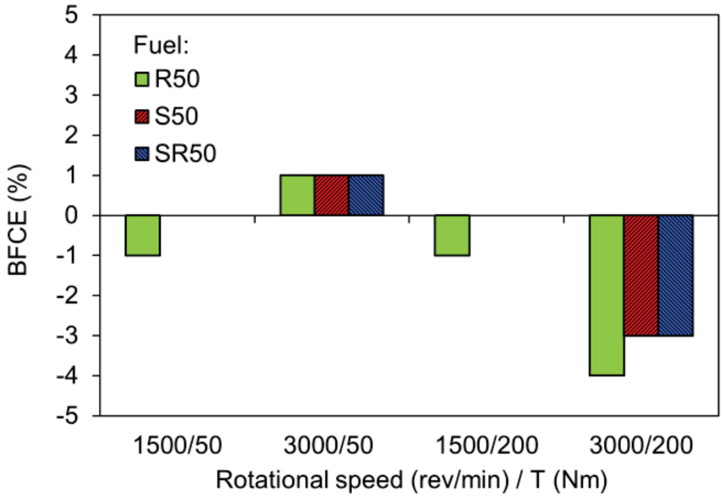

Fig. 1. Changes of brake fuel conversion efficiency in relation to DF for investigated fuel mixtures and operating conditions

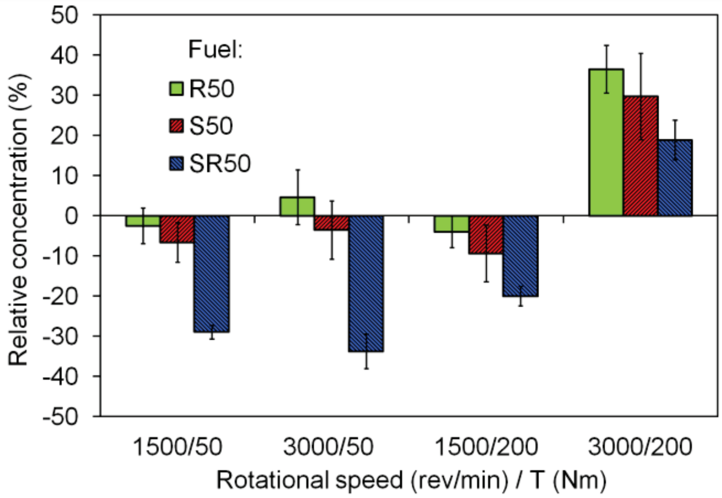

Fig. 2. Hydrocarbons concentration in relation to DF for specific fuel mixtures

The results presented in Figs. 2-4 clearly indicated that the concentration of particular compounds in exhaust gases was determined by operating conditions of the engine. As regards the experiments carried out under low load conditions, the use of fuels containing one of the renewable components resulted in the concentration of THC and CO in exhaust gases at a level comparable to that of DF. The slightly higher THC and CO contents for R50 and S50 in particular cases can be explained by the higher viscosity of alternative fuels, which hinders the proper spraying of the fuel stream (particularly when small amounts of fuel were fed into the cylinder – low load conditions). It appears, however, that the use of a fuel containing both types of renewable components resulted in a considerable reduction in the contents of both compounds concerned in exhaust gases. Tangible advantages arising from the use of SR50 in terms of THC and CO contents under low load conditions could have resulted from the differences in the operation of the injection system whose controller optimally adjusted the injection parameters to physico- and thermo-chemical properties of the fuel.

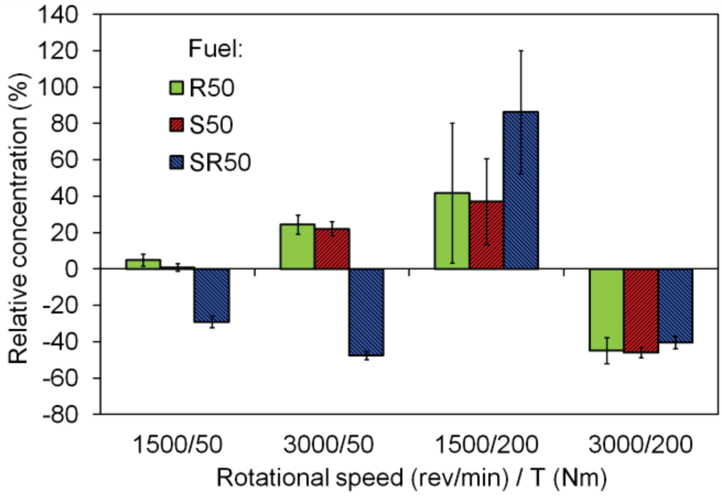

Fig. 3. Carbon monoxide concentration in relation to DF for specific fuel mixtures

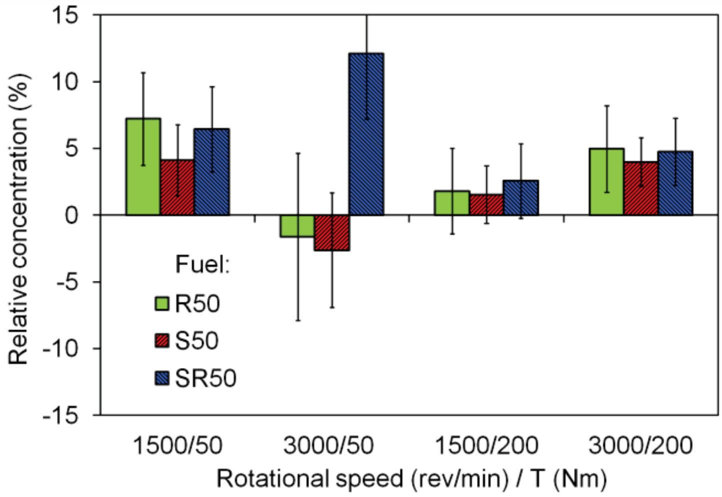

Fig. 4. Nitrogen oxides concentration in relation to DF for specific fuel mixtures

For experiments conducted under high load conditions and engine rotational speed n = 1500 RPM, the THC concentration for SR50 mixture was lower in relation to DF; at the same time, a higher CO content was noted. The other fuels resulted in similar trends yet the level of significance was beyond the measurement accuracy. During the experiments carried out at n = 3000 RPM, a reversal of the relationship linking the contents of both mentioned compounds found in exhaust gases was observed. The above observations can be explained by differences in the ways the fuel is fed into the cylinder. For experiments carried out at n = 1500 RPM, the fuel was fed into the cylinder in 2 doses for each engine operating cycle, while for experiments carried out at n = 3000 RPM for each engine operating cycle, the fuel was fed in the form of a single injection. It appears that the strategy of fuel injection division, applied during the engine operation at n = 1500 RPM, has a positive effect on efficiency of the process of alternative fuel combustion, which is reflected in the reduction in THC content (Fig. 2) and, at the same time, in the increase in CO content (Fig. 3).

Nitrogen oxide content of exhaust gases is related, inter alia, to the course of combustion process (i.e. combustion duration, the temperature inside the combustion chamber and oxygen concentration). Given that alternative components burn at higher temperatures than DF and contain additional oxygen in their molecules, an increased concentration of these compounds is usually observed in exhaust gases from an engine powered by fuels containing renewable components [1-3, 7, 8, 10-14]. The results confirm that the use of fuels containing renewable components results in an increased concentration of the compounds concerned. NOx content of exhaust gases being lower than that of DF was only noted for R50 and S50 during experiments carried out at n = 3000 RPM under low load conditions. For these fuels, under the above-mentioned conditions an increased CO concentration (as well as an increased THC content for R50) was noted at the same time, which may suggest the previously mentioned reduction in efficiency of the process of R50 and S50 combustion under these conditions.

4. Conclusions

The results presented in this study indicate that the use of fuels containing renewable components offers a number of tangible advantages as regards the concentration of particular toxic compounds present in exhaust gases. The use of fuels containing renewable components did not result in a considerable reduction in engine efficiency either. However, the observed advantages arising from the use of fuels containing renewable components are substantially determined by both the operating conditions and the response of an engine control unit.

Physico-chemical properties of renewable components (greater viscosity and density compared to DF) may affect the quality of spraying the fuel stream inside the combustion chamber, particularly when small amounts of fuel are fed into the cylinder. This may manifest itself in reduced efficiency of the fuel combustion process, which, in turn, is reflected in increased contents of hydrocarbons and carbon monoxide in exhaust gases. In turn, a higher temperature of the combustion of alternative components translates into a higher content of nitrogen oxides.

Of all the analysed fuels containing renewable components, the most favourable results in terms of reducing THC and CO concentrations were obtained for the use of the mixture containing both types of biocomponents. At the same time, the use of this fuel resulted in the greatest increase in nitrogen oxide content. The most favourable results (in relation to DF) for the composition containing both types of renewable components appears to result from optimal physico-chemical properties of components of plant origin as well as from favourable properties associated with the combustion process, related to the use of components derived from animal materials.

References

[1] Kleinová, A., Vailing, I., Lábaj, J., Mikulec, J., Cvengroš, J., *Vegetable oils and animal fats as alternative fuels for diesel engines with dual fuel operation,* Fuel Processing Technology, Vol. 92, pp. 1980-1986, 2011.

[2] Lin, C. Y., Li, R. J., *Engine performance and emission characteristics of marine fishoil biodiesel produced from the discarded parts of marine fish*, Fuel Processing Technology, Vol. 90 (7-8), pp. 883-888, 2009.

[3] Selvam, P. D. J., Vadivel, K., *Performance and emission analysis of DI diesel engine fuelled with methyl esters of beef tallow and diesel blends*, Procedia Engineering, Vol. 38, pp. 342-358, 2012.

[4] Atadashi, I. M., Aroua, M. K., Abdul Aziz, A., *High quality biodiesel and its diesel engine application: A review*, Renewable and Sustainable Energy Reviews, Vol. 14, pp. 1999-2008, 2010.

[5] Bocheński, C. I., *Biodiesel paliwo rolnicze*, Wydawnictwo SGGW, Warsaw 2003.

[6] Graboski, M. S., McCormick, R. L., *Combustion of fat and vegetable oil derived fuels in diesel engine*, Progress in Energy and Combustion Science, Vol. 24 (2), pp. 125-164, 1998.

[7] How, H. G., Masjuki, H. H., Kalam, M. A., Teoh, Y. H., *An investigation of the engine performance, emissions and combustion characteristics of coconut biodiesel in a high-pressure common-rail diesel engine*, Energy, Vol. 69, pp. 749-759, 2014.

[8] Mofijur, M., Atabani, A. E., Masjuki, H. H., Kalam, M. A., Masum, B. M., *A study on the effects of promising edible and non-edible biodiesel feedstocks on engine performance and*

emissions production: A comparative evaluation, Renewable and Sustainable Energy Reviews, Vol. 23, pp. 391-404, 2013.

[9] Prasad, C. V., Krishna, M. M., Reddy, C. P., Mohan, K. R., *Performance evaluation of nonedible vegetable oils as substitute fuels in low heat rejection diesel engines*, Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, Vol. 214 (2), pp. 181-187, 2000.

[10] Kruczyński, S., Ślęzak, M., Gis, W., Żółtowski, A., Gis, M., *Comparative studies of diesel engine powered by diesel and B100 fuel*, Combustion Engines, Vol. 170 (3), pp. 126-130, 2017.

[11] Karavalakis, G., Johnson, K. C., Hajbabaei, M., Durbin, T. D., *Application of low-level biodiesel blends on heavy-duty (diesel) engines: Feedstock implications on NOx and particulate emissions*, Fuel, Vol. 181, pp. 259-268, 2016.

[12] Wojs, M. K., Orliński, P., Lasocki, J., *The effect of alternative fuels injection timing on toxic substances formation in CI engines*, Combustion Engines, Vol. 168 (1), pp. 73-76, 2017.

[13] Duda, K., Wierzbicki, S., Śmieja, M., Mikulski, M. *Comparison of performance and emissions of a CRDI diesel engine fuelled with biodiesel of different origin*, Fuel, Vol. 212, pp. 202-222, 2018.

[14] Mikulski, M., Duda, K., Piętak, A., Wierzbicki, S., *Influence of contribution of biofuels derived from renewable materials in the fuel on the combustion process and toxic compounds emission of compression ignition engine*, Journal of KONES, Vol. 21 (4), pp. 344-351, 2014.

[15] Mikulski, M., Duda, K., Wierzbicki, S., *Performance and emissions of a CRDI diesel engine fuelled with swine lard methyl esters diesel mixture*, Fuel, Vol. 164, pp. 206-219, 2016.

[16] Mikulski, M., Wierzbicki, S., *The concept and construction of the engine test bed for experiments with a multi-fuel CI engine fed with CNG and liquid fuel as an ignition dose*, Journal of KONES, Vol. 19 (3), pp. 289-296, 2012.

[17] Kline, S. J., McClintock, F. A., *Describing uncertainties in single-sample experiments*, Mechanical Engineering, Vol. 75 (1), pp. 3-8, 1953.

[18] Rybak, A., Hunicz, J., Krzaczek, P., et al., *Effect of different biofuels on common rail injector flow rate*, Combustion Engines, Vol. 171 (4), pp. 39-43, 2017.

Manuscript received 21 May 2018; approved for printing 31 August 2018