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Environmental Aspects of a Common Rail Diesel Engine Fuelled with Biodiesel/Diesel Blends

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ABSTRACT

The purpose of the study was the research concerning the emissions of limited exhaust gas components of the AVL research engine equipped with common rail injection system, fuelled with different biodiesel blends and diesel fuel as reference. In details, the engine was powered with mixtures of rapeseed methyl esters with diesel fuel in the volumetric ratios of 10:90, 20:80, 30:70, 40:60 and 50:50. The tests were performed at: 1200, 1700 and 2200 rpm and the torque T = 5–35 Nm (step 5 Nm). The analysis of the obtained results showed that the emissions of hydrocarbons from the tested engine fuelled with biodiesel are lower than that of diesel fuel. Carbon monoxide emissions are also lower, except for low rotational speeds and low engine load T = 5–20 Nm. As for nitrogen oxides emissions, it is also lower than that for the diesel fuel, except for high engine loads, in the range above 25 Nm, for each rotation speed of the engine load characteristics. Moreover, in this research it was confirmed that emission of particulate matter is also slightly reduced for the engine fuelled with tested blends.

Keywords: common rail, emissions, diesel, fuel injection, combustion.

INTRODUCTION

Historically, a compression ignition engine was powered by a biofuel for the first time at the World EXPO 1900 in Paris. It was a Rudolf Diesel engine adapted to run on the peanut oil. The energy crisis in the 1970s made it clear that countries that do not have their own fossil energy sources must change their approach to the economic strategy used so far. An additional important argument in the global assessment of climate phenomena was a noticeable phenomenon of climate warming. It has now been revealed that the largest oil companies in France and the United States were strictly hiding the fact. Therefore, since the beginning of the seventies, intensive research on the use and production of biofuels has been undertaken. In Europe, the research subjects were not only methyl esters of rapeseed oil fatty acids, but also other oils obtained from sunflower seeds and soybeans [1]. These studies were conducted on a large scale in Poland (including the Radom University of Technology since 1989), Germany, Austria, France and other countries. In the USA, the studies included only soybeans and corn, whereas in Brazil and Argentina only sugarcane was studied [2, 3]. Corn oil has been produced in the USA since 2013 according to the Edeniq Oil Plus technology.

The studies have not been discontinued and are being carried out on new raw materials obtained from the seeds of camelina, salicornia, jatropha, jajoba and karanja that occur in Mexico, Brazil, Bolivia, Peru, Argentina, Paraguay, India, China, Japan [4]. The fuel containing vegetable oils obtained from these seeds is produced in the factories in the Philippines, Pakistan and Brazil [2].

The increase in the cultivated area for the production of oilseeds for biofuels raises concerns in terms of a sustainable economy. Therefore, recently, new technologies are being developed and other solutions are being sought for the use of animal waste fats [5] and cooking oils [6]. In addition, research is carried out on the use of waste from the pulp industry as well as algae cultivation on an industrial scale [7]. New technologies of diesel fuel components make production processes more efficient and improve the profitability of the investment.

Contemporary research on complex fuel resources for powering internal combustion engines clearly confirms the interest in biofuels. It mainly concerns methyl esters obtained from various oilseeds. It has been found that carbon dioxide (CO_2) plays a decisive role in warming of the Earth's climate. A special feature of vegetable based fuels is the fact that CO_2, which is emitted into the atmosphere, is absorbed by biofuels and consumed in the process of photosynthesis. Consequently, it does not block the heat radiation from the Earth into the atmosphere. Therefore, it can be assumed with some simplification that in this case we are dealing with a closed CO_2 cycle.

The purpose of the study was the research concerning the emission of limited exhaust gas components: carbon dioxide (CO_2), hydrocarbons (HC), nitrogen oxides (NOx) and particulate matters (PM). Most of the previous researches have been carried out on a compression-ignition engine equipped with mechanical injection and fuel control regulation systems [8]. They were no longer able to reach the expectations in terms of vehicle driving dynamics, economics and exhaust emissions in accordance with the applicable EU standards. As a result, more attention is being paid to more modern fuel supply systems, like common rail, that will replace obsolete, previous-generation fuel systems in the future.

Several researches are published with common rail fuel systems using biodiesel fuel. Mainly this is a biodiesel produced from different sources, not only rapeseed, but also palm, sunflower, used fried oil, etc. Main part of these researches are dedicated to different blends with fossil diesel with the aim to find out engine efficiency, fuel consumption, as also emissions. It is well known that some properties of biodiesel leaves an impact on main performance parameters of the engine. Lower heating value stimulates increase of fuel consumption, higher oxygen content helps to reduce amount of some components in exhaust gases, higher viscosity and surface tension leaves impact on atomization and better penetration. In case of common rail systems composition of mentioned properties are especially important for reaching of appropriate injection and performance characteristics.

For example, Kousoulidou [9] has been tested palm oil and rapeseed oil methyl esters in blends at ratio of 10 vol.% in the common rail (CR), direct injection, turbocharged and intercooled engine tests and Renault Laguna 1.9 dCi common-rail turbocharged vehicle tests. Author observed that biodiesel have not had a serious impact on CO and CO_2 emissions, while NOx ranged from –6% to +4% regardless of the type of used biodiesel. Another research [10] with 5 different biodiesels (rapeseed, soy, sunflower, palm and used fried oils) in ratio of 10% vol. in CR passenger car showed increase of CO and HC emission by 10–25%, CO_2 ranging from –2% to +4%, and NOx ranging from –7% to +11% depending on the origin of feedstock.

Cardenas [11] also has been tested different biodiesel fuels (rapeseed, sunflower, soybean) in a common rail diesel engine on a test bench under New European Driving Cycle. Author observed increase of nitrogen oxides, total hydrocarbons and carbon monoxide for biodiesel and its blends in comparison to conventional diesel, and concluded that the main reason could be connected with the impact of fuel properties on the electronic control unit response tuned for diesel operation by the car maker [11]. It was also confirmed in another research [12] after detailed analysis of a light duty CR diesel engine fuelled with rapeseed methyl ester, concluding that Electronic Control Unit calibrations must done to reach the best compromise between performance and emissions, if it is used in diesel engine with a fuel with different characteristics to conventional diesel. In the same time How [13] concluded that engine load had a significant effect on brake specific emissions realizing tests with coconut biodiesel in a high pressure common rail diesel engine – reduction of carbon monoxide and increase of nitrogen oxide emissions was observed with the increase of engine load and blending ratio.

Meanwhile, Serrano [14] in the tests with low biodiesel blends (7 vol.% (B7) and 20 vol.% (B20) addition to fossil diesel) in a Renault Megane 1.5 dCi NEDC cycle and performance tests observed that small blends like B7 shows very small difference in NOx emissions in comparison to fossil diesel while B20 corresponds to almost 20% of decrease. At the same time authors concluded that increase of researches on combustion of engines equipped with recent technologies and usage of biodiesel are required to obtain the knowledge on the exhaust emission technologies in case of newest fuel tendencies.

Tests with higher biodiesel blends mainly have been performed with less common types of biodiesel, like fish-oil biodiesel. For example, Jiaqiang [15] have been tested diesel / fish oil biodiesel blends at ratio of 10, 20, 30, 40 and 50 vol.% in AVL-5402 naturally aspirated single-cylinder engine, where he observed reduction of CO, HC and smoke emissions, but increase of NOx emissions with increase of biodiesel content.

In general, an analysis of the literature suggests that attention needs to be paid to the use of higher concentrations of biodiesel in common rail engines to assess the environmental benefits of using these blends. It should be recalled that since 2020 the EU Directive, requiring the use of 10% biofuels in relation to fuels consumed annually in the country, has been in force. And while pollution from internal combustion engines on a larger scale has not been fully addressed through the use of electrical or hybrid technologies, increasing the concentration of biodiesel in blends can also be considered as an appropriate solution.

In overall, the publication presents the ecological aspect of the research results concerning limited components of exhaust gases such as: HC, NOx, CO, PM of the AVL-5402 engine powered by mixtures of diesel oil with rapeseed oil methyl ester.

MATERIALS AND METHODS

Tested fuels

The research included diesel fuel (DF) and mixtures of DF with rapeseed oil methyl ester (RME), respectively, with the addition of 10% to 50% RME in a volumetric mixture (v/v) containing 5 blends:

- 10% of RME with 90% of DF (mixture code: 10RME);
- 20% of RME with 80% of DF (mixture code: 20RME);
- 30% of RME with 70% of DF (mixture code: 30RME);
- 40% of RME with 60% of DF (mixture code: 40RME);
- 50% of RME with 50% of DF (mixture code: 50RME);

Tested blends were prepared just before the experiments by splashing mixing technique in the proportions mentioned before. Measurements of selected physicochemical properties of mentioned blends were also carried out in Kazimierz Pulaski University of Technology and Humanities in Radom, and these properties are listed in Table 1. The numerical values concerning DF and RME contained in this table are consistent with the data for DF with the quality certificate no. 21BMK/A/321 PKN ORLEN S.A. Płock of 06th February 2021 [16], and for RME in accordance with the presented by PKN ORLEN Południe S.A. Trzebinia: Certificate of Quality no. 21TBIO/A/41 of 2nd March 2021 [17].

Currently, fuel stations in Poland sell diesel fuel with an addition of 7% (v/v) FAME or RME. The product quality certificates show that both esters are characterized by the same basic physicochemical parameters. The only difference is that FAME may additionally contain fatty acids of other vegetable based fuels, e.g. sunflower whereas RME esters are derived only from rapeseed [18].

Table 1. Selected physicochemical properties of the tested fuels

Properties	Fuel type						
	DF	RME	10RME	20RME	30RME	40RME	50RME
RME content, % (v/v)	-	100.0	10.0	20.0	30.0	40.0	50.0
Density at temp. 15 °C, kg/m^3	825.3	882.7	831.2	836.6	841.7	846.5	852.6
Kinematic viscosity at 40 °C, mm^2/s	2.50	4.47	2.66	2.83	3.13	3.24	3.40
Surface tension at 20 °C, mN/m	27.32	31.45	27.29	27.38	27.70	27.79	28.77

According to the quality certificate of PKN ORLEN Południe S.A. 21TBI0/41 of 4th February 2021 this product corresponds to WTO EG/83/2019 based on the PN–EN 14214 standard as amended and the Regulation of the Minister of Economy of 17th December 2010 with subsequent amendments [19].

Research engine

The test object was a single-cylinder, supercharged diesel engine AVL-5402 engine equipped with the Common Rail fuel supply system. It is used for preliminary tests in the development of new prototypes of the AVL LIST G.m.b.H engines in Graz, Austria.

The following are basic technical characteristics of the AVL-5402 engine: single-cylinder engine, bore – 85.01 mm, stroke – 90 mm, displacement – 511.0 cm^3, combustion type – compression ignition, compression ratio – 17.0–17.5, fueling system – direct injection, single injector, Common Rail system, maximum effective power with supercharging – 16 kW, rated engine speed – 4200 rpm, injection pressure – 110.0 MPa. The main technical data of the AVL research engine are listed in Table 2.

The view of the test stand is shown in Figure 1. Main elements of this stand are: AVL-5402 engine, AVL eddy current brake, air and fuel conditioning systems, fuel scale, Atlas Copco screw compressor, air temperature control system, automated supply system for the AVL + EC station, a measuring station: CO, HC, NOx and PM. Fundamental data on the particulate matter analyzer are listed in Table 3.

The measuring apparatus used for the tests were in conformity with the requirements of the following normative documents: Directive 1999/96/EC of the European Parliament and of the Council of 13th December 1999, Regulation (EC) No. 715/2007 of the European Parliament and of the Council of 20th June 2007, as well as Commission Regulation (EC) No. 692/2008 of 18th July 2008.

Table 2. Technical data of the AVL 5402 research engine

Engine type	4-stroke, single cylinder
Cooling system	liquid
Fuel injection type	Common Rail, BOSCH CP4.1
Maximum injection pressure	180 MPa
Maximum power without turbocharging	6.25 kW at 4200 rpm
Compression ratio	17,5:1
Engine controller	AVL-RPEMS + ETK7 BOSCH
Displacement	510.7 cm^3
Valves per cylinder	2 inlet, 2 exhaust

RESULTS

The emission values of exhaust components (CO, HC, NOx, and PM) obtained during the tests are shown in Fig. 2–4. The AVL-5402 engine worked on the load characteristics with a) n = 1200, b) 1700, c) 2200 rpm and with torques T = 5–35 Nm every 5 units. The summary of CO emissions for these three characteristics is shown in Fig. 2a–c. The engine speeds which were taken into consideration will be defined as: low, medium and high, respectively. In the range of low rotational speeds when the torque of the engine is T = 5–20 Nm the CO content in the exhaust gases for n = 1200 rpm ranges from 140–350 ppm, for n = 1700 rpm it ranges from 170–510 ppm and for n = 2200 rpm it ranges 160–870 ppm, respectively.

For low engine speeds, the smallest share of CO in exhaust gases is when the engine is loaded with a higher torque than T = 20 Nm. The nature of changes in the CO emission function for the average and high rotational speed is comparable, different than for n = 1200 rpm (Fig. 2a–c).

With a great approximation, it can be assumed that CO emission with engine load decreases to its value T = 30 Nm in a comparable manner for all RME fuels with DF. Only under the maximum torque load, the values of CO emission of all the tested fuels increase, but in a similar manner. A greater share of RME in a mixture with DF causes a decrease of CO emission.

The HC hydrocarbon emission values for the load characteristics of the AVL-5402 engine with n = 1200, 1700 and 2200 rpm are in the

Table 3. Technical data of the AVL Micro Soot Sensor

Parameter	Value
Measuring range	0.001–50 mg/m^3
Display resolution	0.01 mg/m^3
Detection limit	1 $\mu g/m^3$
Sample flow	4 L/min
Data rate	10 Hz

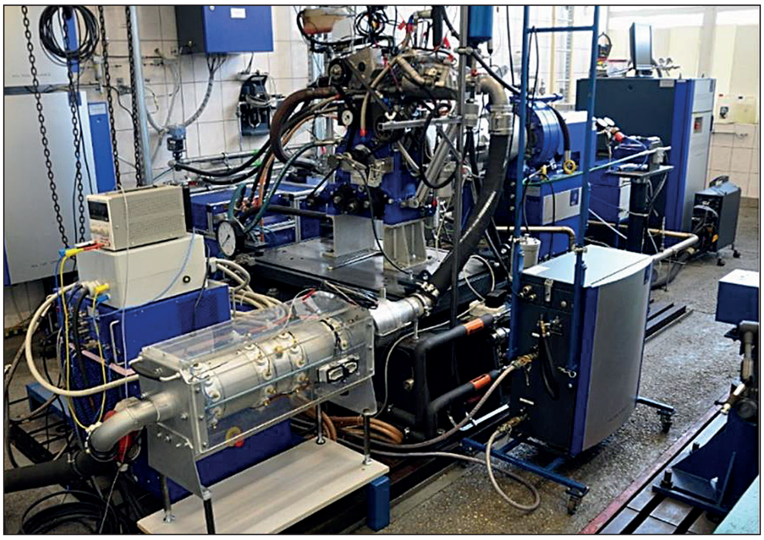

Figure 1. A general view of the test stand with the AVL-5402 engine

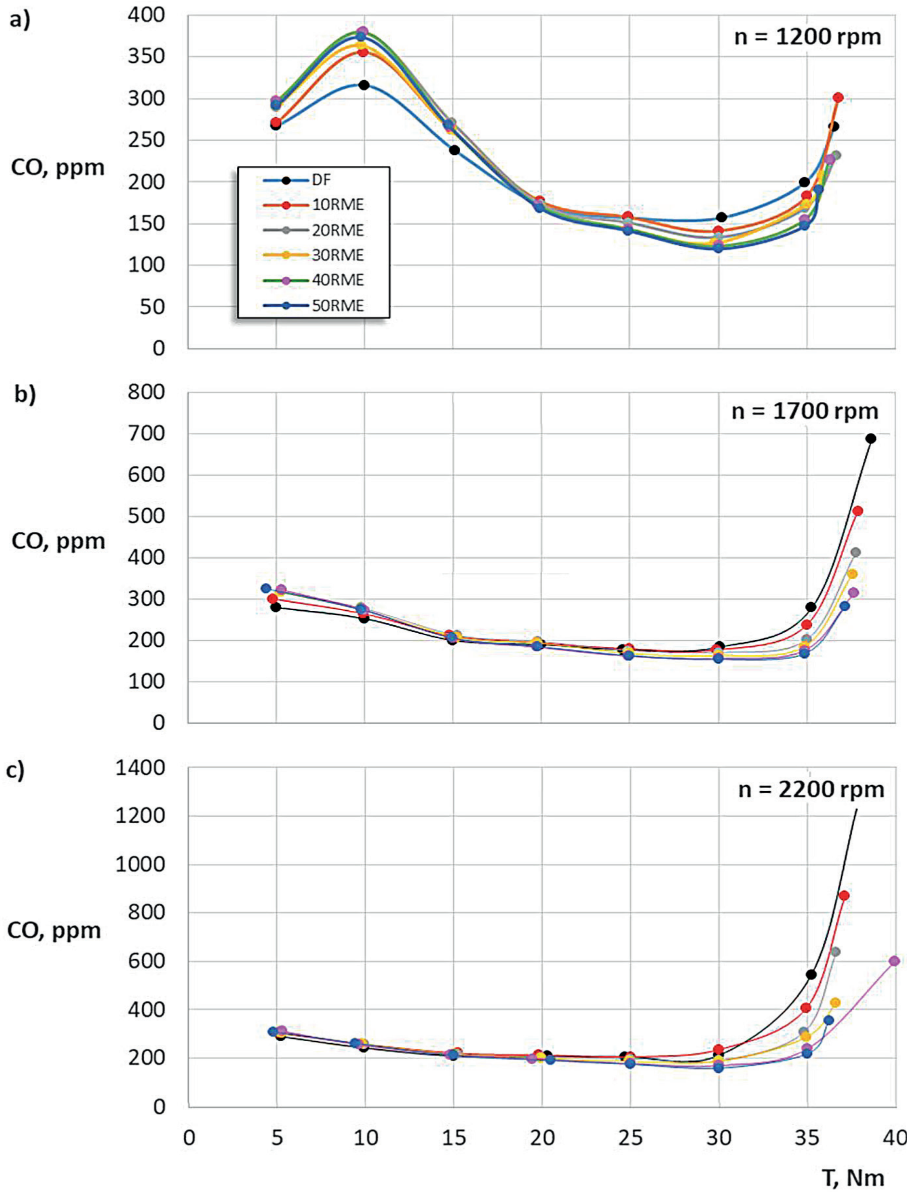

Figure 2. The impact of tested fuels on the emission of carbon monoxide (CO) from the AVL-5402 engine

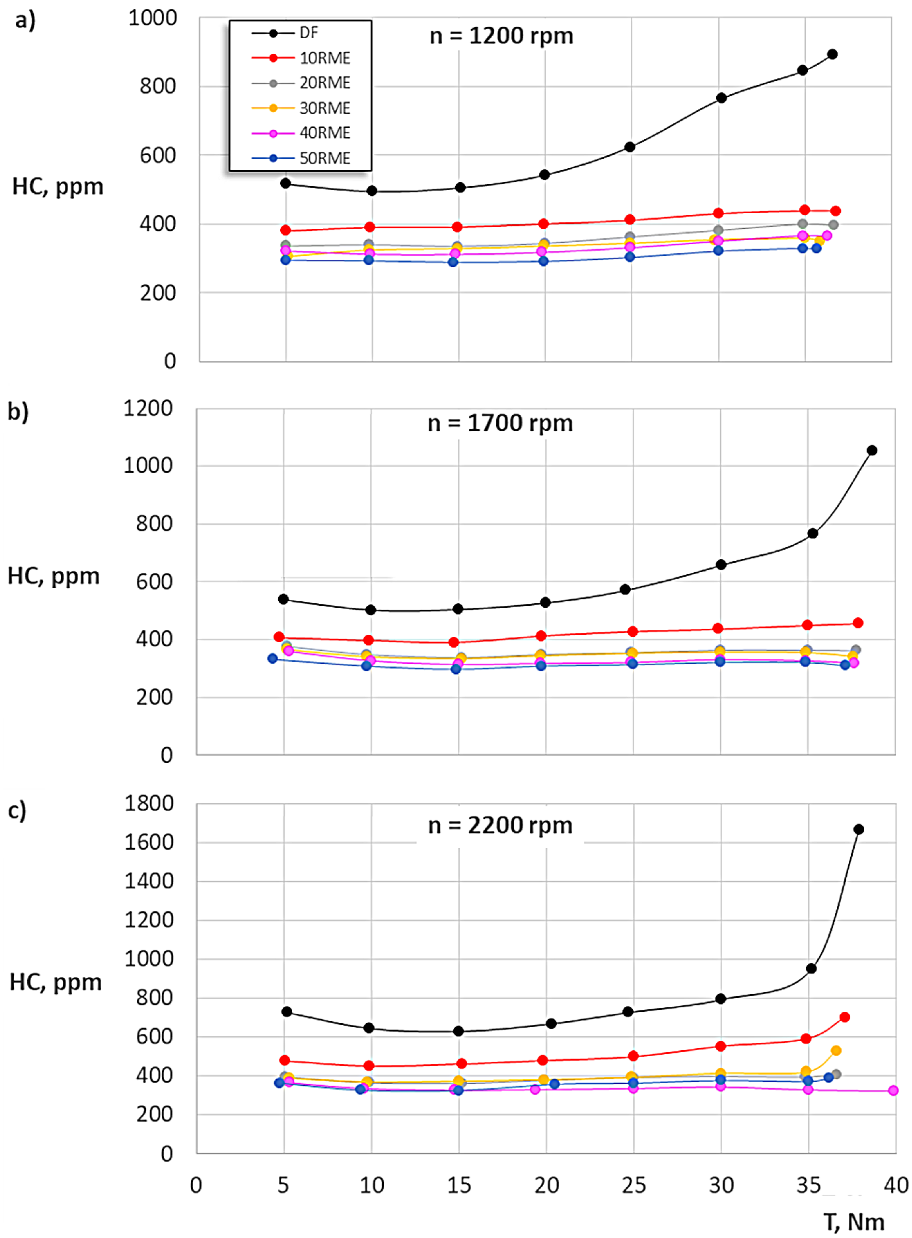

Figure 3. The impact of tested fuels on the emission of unburned hydrocarbons (HC) from the AVL-5402 engine

following ranges: 290–440 ppm, 300–550 ppm and 330–700 ppm, respectively. The nature of changes in HC emission, depending on the engine load throughout the entire range can be assumed to be linear (Fig. 3a–c). The lowest share of HC emission in exhaust gases for these two characteristics was obtained for the fuel with 50% of RME in the mixture with DF. It practically did not depend on the engine load. The engine speed had a minimal impact on its emission. For three load characteristics, HC emission in the exhaust gases for diesel fuel was higher by approximately 50%.

The increase of RME content in the mixture with DF results in the lower HC emission. As far as the emission of nitrogen oxides NOx is concerned, it was found that for the three load characteristics, the emission of nitrogen oxides was comparable to that of the diesel fuel. Only for the maximum load of the AVL-5402 engine, the emission of nitrogen oxides was by a few percent higher (Fig. 4a–c). It concerned a fuel mixture containing 50% RME (v/v) in the diesel fuel. It was due to the higher oxygen content in the RME fuel, better fuel atomization and caused easier ignition as well as more complete combustion, which could increase the local temperatures in the combustion chamber and the formation of larger amounts of nitrogen oxides.

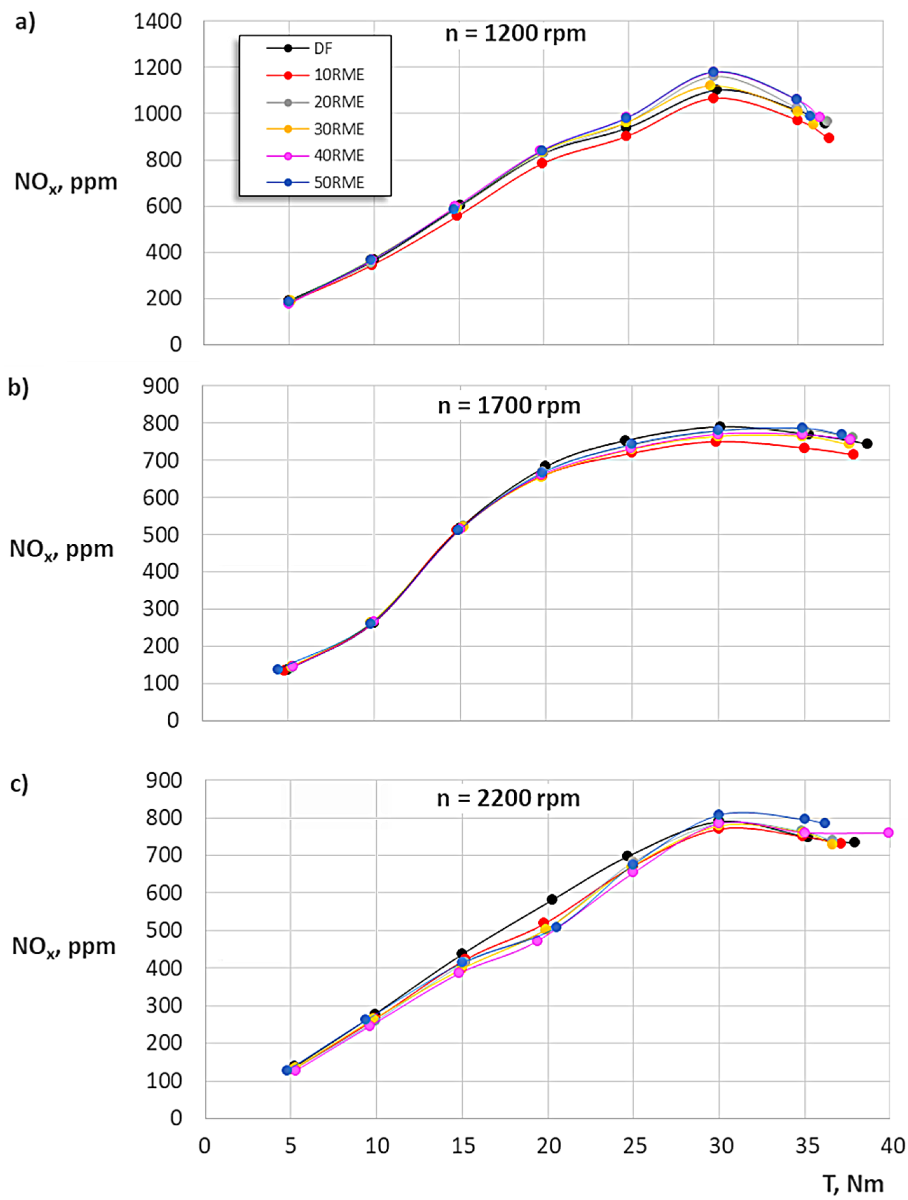

Figure 4. The impact of tested fuels on the emission of nitrogen oxides (NOx) from the AVL-5402 engine

The results of the particulate matter emission of the AVL-5402 engine are presented in Figure 5a–c. The analysis of the values in the graphs shows that at the engine speed n = 1200 rpm, the emissions of particulate matters in the exhaust gases was slightly lower for RME mixtures with DF.

These differences deepened with the increase in the content of RME fuel in a mixture with DF and were within the range of 0.6–2.4 mg/m^3. On the other hand, for the load characteristics at n = 1700 and 2200 rpm, the PM emission was similar in terms of the engine load. However, numerical values increased with the increase of the AVL-5402 engine speed and were in the range 1.40–7.80 mg/m^3 and 1.40–14.70 mg/m^3, respectively.

A key impact of the engine speed and multiple increase of PM emission at the maximum engine load T = 35 Nm and n = 2200 rpm can be clearly seen. For all load characteristics, PM emission for the tested fuels in the entire engine load range was lower than for DF, with the exception of NOx emission for high engine loads at low engine speed n = 1200 rpm. It should be noted that the differences in the emission of limited exhaust fumes components are also insignificant, and their difference in ± 100 ppm value is within the measurement error.

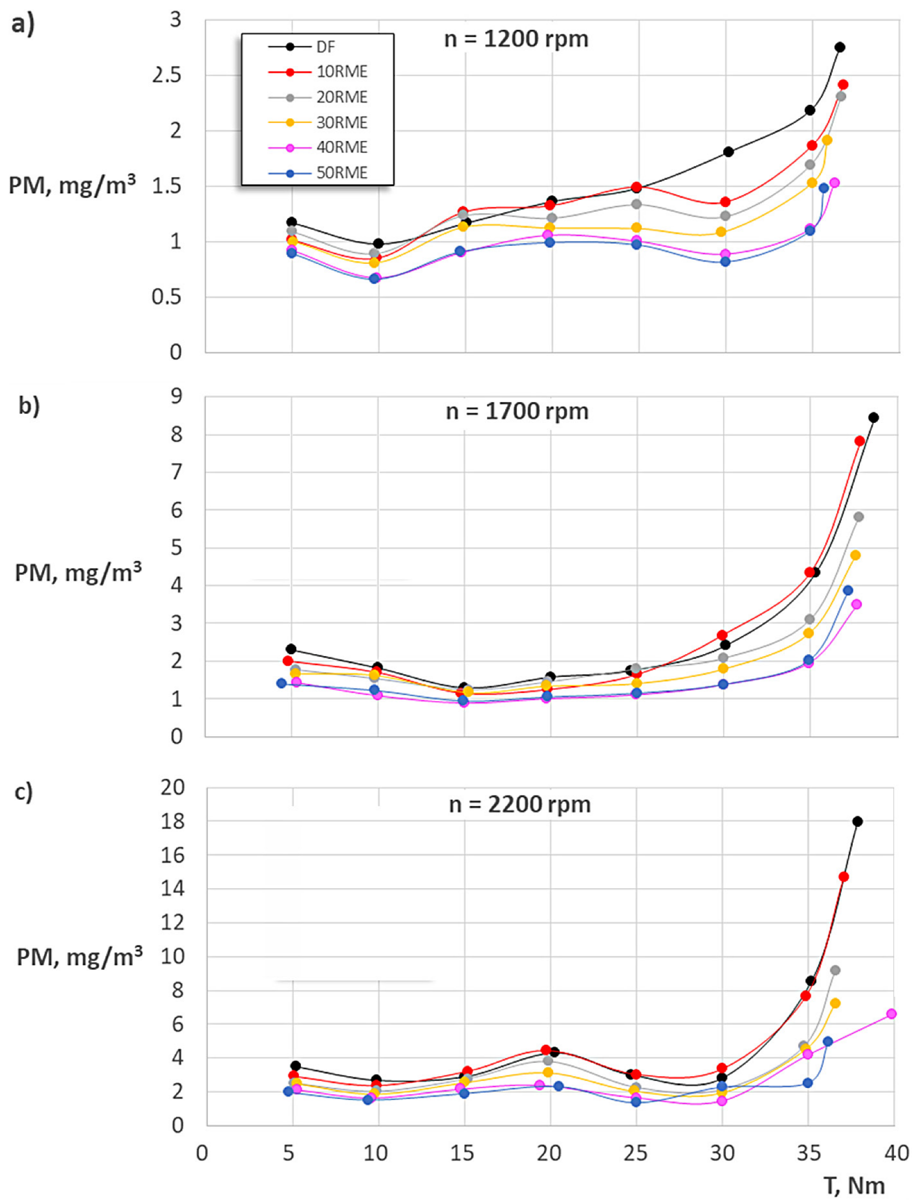

Figure 5. The impact of tested fuels on the emission of particulate matter (PM) from the AVL-5402 engine

CONCLUSIONS

Studies on the use of biofuels, including their esters for fueling internal combustion engines, are still carried out in numerous research centres around the world. In Europe, research on the use of rapeseed oil fatty acids and their mixtures with diesel fuel is still dominant.

RME which have a slightly different calorific value and different physicochemical values, viscosity, surface tension as well as higher density than diesel fuel has the impact on the combustion process and emissions. This is an important fact as the injection pump realize fuel delivery. Therefore, for the same volume, the amount of energy supplied from RME to the cylinder will be lower than that of DF due to the lower calorific value of RME. However, higher viscosity of RME esters than DF can result in the fact that the energy balance may be comparable to DF due to a smaller fuel leakage in the process of its pressing through the pump and the injector. Additionally, the oxygen content, higher by approx. 12%, and unsaturated bonds contribute to a better ignition and more complete combustion of RME.

The results of this research showed positive tendency in RME addition to DF in case of CO, HC, PM, and even NOx emission reduction, which usually was considered as a problem. The modernization of the existing engines with mechanical control systems for the injection process enabled CR the control of the parameters of the injection and combustion process, reduced uniqueness [20–22] as well as the amount of exhaust gas components [23].

The physicochemical properties (density, viscosity, surface tension, calorific value, flash point, atomic number and the structure of the molecule bond chain [24]) of the tested mixtures of RME with DF were different from conventional DF. Here it is possible to mark that the molecules with the number of double bonds have a positive impact on the parameters of the injection process: initial velocity of fuel injection, critical speeds of secondary fuel droplet breakup, critical diameters fuel droplets, microstructure of the fuel stream, vertical angle of the injected fuel stream. The impact of the tested fuels on the above-mentioned parameters of the injection process for the AVL-5402 engine has been discussed in the publication [21, 25] and consequently, the improvement of the combustion process and the reduction of emissions of limited exhaust gas components: CO, HC, NOx and PM occurred.

Apart from the previously used traditional methods of assessing the parameters of injection and combustion of mixtures of RME with diesel fuel [26–29], attempts are made to use new phenomena of numerical modelling to develop the impact of fuel properties on the course of mechanism reaction in the combustion chamber [30]. Model studies are also carried out on the impact of the fuel injection pressure on the delay of auto-ignition, the fuel atomization and combustion processes [31]. Research is also carried out on the development of an oxy-fuel flame with the use of a test burner [32–33].

REFERENCES

1. Chong, C.T., Chiong, M.C., Ng, J., Lim, M., Tran, M. Valera-Medina, A., Chong, W.W.F. Oxygenated sunflower biodiesel: Spectroscopic and emission quantification under reacting swirl spray conditions. Energy. 2019; 178: 804–813. http://dx.doi.org/10.1016/j.energy.2019.04.201
2. Patil, V.V., Patil, R.S. Experimental investigations to predict optimistic biodiesel(s) and its optimistic operating conditions by varying ignition delay period and fuel spray pressures for lower emissions and better performance. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science. 2020; 234(19): 3890–3902. https://doi.org/10.1177/0954406220917693
3. Biodiesel. Biodiesel – Tankstellen im Deutschland. 3 Auflange Union Zur Forderung Von Oel-Und Proteinptlanzen. Im Jahr 2016.
4. Raport Grupy Energii Odnawialnej (REG) z 2009r. (in Polish)
5. Graboski, M.S., McCormick, R.L. Combustion of fat and vegetable oil derived fuels in diesel engines. Progress in Energy and Combustion Science. 1998; 24(2): 125–164. DOI: 10.1016/S0360-1285(97)00034-8
6. Marchese, A.J., Vaughn, T.L., Kroenlein, K., Dryer, F.L. Ignition delay of fatty acid methyl ester fuel droplets: Microgravity experiments and detailed numerical modeling. Proceedings of the Combustion Institute. 2011; 33(2): 2021–2030. https://doi.org/10.1016/j.proci.2010.06.044
7. Anas, M.I., Khalid, A., Zulkifli, F.H., Hushim M.F., Manshoor, B., Zaman, I. Analysis of the Effect of Injection Pressure on Ignition Delay and Combustion Process of Biodiesel from Palm Oil, Algae and Waste Cooking Oil. Journal of Physics: Conference Series. 2017; 914(1): 012008. https://doi.org/10.1088/1742-6596/914/1/012008
8. Caresana, F., Bietresato, M., Renzi, M. Injection and Combustion Analysis of Pure Rapeseed Oil Methyl Ester (RME) in a Pump-Line-Nozzle Fuel Injection System. Energies. 2021; 14: 7535. https://doi.org/10.3390/en14227535
9. Kousoulidou, M., Fontaras, G., Ntziachristos, L., Samaras, Z. Biodiesel blend effects on common-rail diesel combustion and emissions. Fuel. 2010; 89: 3442–3449. http://dx.doi.org/10.1016/j.fuel.2010.06.034
10. Fontaras, G., Kousoulidou, M., Karavalakis, G., Tzamkiozis, T., Pistikopoulos, P., Ntziachristos, L., Bakeas, E., Stournas, S., Samaras, Z. Effects of low concentration biodiesel blend application on modern passenger cars. Part 1: Feedstock impact on regulated pollutants, fuel consumption and particle emissions. Environmental Pollution. 2010; 158(5): 1451–1460. https://doi.org/10.1016/j.envpol.2009.12.033
11. Cardenas, M.D., Armas, O., Mata, C., Soto, F. Performance and pollutant emissions from transient operation of a common rail diesel engine fueled with different biodiesel fuels. Fuel. 2016; 185: 743–762. http://dx.doi.org/10.1016/j.fuel.2016.08.002
12. Senatore, A., Cardone, M., Buono, D., Rocco, V. Combustion study of a common rail diesel engine optimized to be fueled with biodiesel. Energy Fuels. 2008; 22(8): 1405–1410. https://doi.org/10.1021/ef7004749
13. 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. 2014; 69: 749–759. http://dx.doi.org/10.1016/j.energy.2014.03.070

14. Serrano, L., Lopes, M., Pires, N., Ribeiro, I., Cascao, P., Tarelho, L., Monteiro, A., Nielsen, O., Gameiroda Silva, M., Borrego, C. Evaluation on effects of using low biodiesel blends in a EURO 5 passenger vehicle equipped with a common-rail diesel engine. Applied Energy. 2015; 146: 230–238. https://doi.org/10.1016/j.apenergy.2015.01.063
15. Jiaqiang, E., Pham, M., Deng, Y., Nguyen, T., Duy, V.N., Le, D.H., Zuo, W., Peng, Q., Zhang, Z. Effects of injection timing and injection pressure on performance and exhaust emissions of a common rail diesel engine fueled by various concentrations of fish-oil biodiesel blends. Energy. 2018; 149: 979–989. https://doi.org/10.1016/j.energy.2018.02.053
16. Certyficate of Quality Nr 21BMK/A/321. Polski Koncern Naftowy ORLEN S.A. Płock, 06.02.2021.
17. Certyficate of Quality no 21TBIO/A/41 Methyl ester of higher fatty acids RME. PKN ORLEN Południe S.A. Polska 04.02.2021.
18. Certyficate of Quality no 21TBIO/A/274 Methyl ester of higher fatty acids FAME. PKN ORLEN Południe S.A. Polska 25.08.2020.
19. PN-EN 16709+A1:2018-12 Paliwa do pojazdów samochodowych o wysokiej zawartości FAME (B20 i B30) – Wymagania i metody badań.
20. Allen, C., Toulson, E., Tepe, D., Schock, H., Miller, D., Lee, T. Characterization of the effect of fatty ester composition on the ignition behavior of biodiesel fuel sprays. Fuel. 2013; 111: 659–669. https://doi.org/10.1016/j.fuel.2013.03.057
21. Longwic, R., Sen, A.K., Lotko, W., Górski, K., Litak, G. Cycle to-Cycle Variatons of the Combustion Process in the Diesel Engine Power by Different Fuels. Journal of Vibroengineering. 2011; 13(1): 120–127.
22. Lotko, W. Self-Ignition Delay and Control Parameters of Diesel Engines for Different Vehicle Feeding Systems and Different Fuels. Advances in Science and Technology Research Journal. 2021; 15(1): 245–254. https://doi.org/10.12913/22998624/132474
23. Geng, L., Bi, L., Li, Q., Chen, H., Xie, Y. Experimental study on spray characteristics, combustion stability, and emission performance of a CRDI diesel engine operated with biodiesel–ethanol blends. Energy Reports. 2021; 7: 904–915. https://doi.org/10.1016/j.egyr.2021.01.043
24. Harrington, K.J. Chemical and physical properties of vegetable oil esters and their effect on diesel fuel performance. Biomass. 1986; 9(1): 1–17. https://doi.org/10.1016/0144-4565(86)90008-9
25. Lotko, W. The Impact of Rapeseed Oil Methyl Esters on Fuel Injection Parameters in a Diesel Engine Equipped with the Common Rail Injection System. Advances in Science and Technology Research Journal. 2021; 15(3): 76–87. https://doi.org/10.12913/22998624/138725
26. Agarwal, A.K., Dhar, A., Gupta, J.G., Kim, W.I., Choi, K., Lee, C.S., Park, S. Effect of fuel injection pressure and injection timing of Karanja biodiesel blends on fuel spray, engine performance, emissions and combustion characteristics. Energy Conversion and Management. 2015; 91: 302–314. https://doi.org/10.1016/j.enconman.2014.12.004
27. Nguyen, T., Pham, M., Anh, T.L. Spray, combustion, performance and emission characteristics of a common rail diesel engine fueled by fish-oil biodiesel blends. Fuel. 2020; 269. https://doi.org/10.1016/j.fuel.2020.117108
28. Ramirez-Verduscol, P. Predicting cetane numer, kinematic viscosity, density and higher heating value of biodiesel from its fatty acid methyl ester composition. Fuel. 2012; 91: 102–111. https://doi.org/10.1016/j.fuel.2011.06.070
29. Sudarmanta, B., Mahanggi, A.A.K., Yuvenda, D., Soebagyo, H. Optimization of injection pressure and injection timing on fuel sprays, engine performances and emissions on a developed DI 20c biodiesel engine prototype. International Journal of Heat and Technology. 2020; 38(4): 827–838. https://doi.org/10.18280/ijht.380408
30. Raghu, P., Sakthivel, B., Linkesh Kumar, V.V., Pradeep Raj, J., Niranjan Suresh, S. An optimization of spray and performance emission characteristic of biodiesel and its blends by varying injection timing in diesel engine. International Journal of Mechanical and Production Engineering Research and Development. 2019; 9(3): 165–170.
31. Ashkezari, A.Z., Divsalar, K., Malmir, R., Abbaspour, I. Emission and performance analysis of DI diesel engines fueled by biodiesel blends via CFD simulation of spray combustion and different spray breakup models: a numerical study. Journal of Thermal Analysis and Calorimetry. 2020; 139(4): 2527–2539. https://doi.org/10.1007/s10973-019-08922-1
32. El-Kelawy, M., Bastawissi, H.A.E., El-Shenawy, E.S.A., Panchal, H., Sadashivuni, K., Ponnamma, D., Al-Hofy, M., Thakar, N., Walvekar, R. Experimental investigations on spray flames and emissions analysis of diesel and diesel/biodiesel blends for combustion in oxy-fuel burner. Asia Pacific Journal of Chemical Engineering. 2019; 14(6): e2375. https://doi.org/10.1002/apj.2375
33. Shen, C., Zhang, S., Hou, J., Chang, W., Lee, C. The effects of spray angles on soot emissions of diesel and biodiesel engines. ICLASS 2015 – 13th International Conference on Liquid Atomization and Spray Systems 2015. Tainan, Taiwan.