EFFECT OF THE RME BIODIESEL ON THE DIESEL ENGINE FUEL CONSUMPTION AND EMISSION

Dariusz Kurczyński

Department of Automotive Vehicles and Transportation, Faculty of Mechatronics and Automotive Engineering, Kielce University of Technology, Kielce, Poland

*E-mail of corresponding author: kdarek@tu.kielce.pl

Resume

Road transport is the primary source of atmospheric air pollution, thus posing a threat to human health and life. The aim of the study was to determine the impact of fuel obtained from plants on the ecological properties of a compression ignition engine. The article reports the results of investigations into a modern engine with a Common Rail system, powered by the RME (rapeseed methyl esters) biodiesel and their blends with diesel. For comparison, the engine was also fuelled with conventional diesel oil without ester addition. When powering the engine with blends and pure biodiesel, brake specific fuel consumption increased. The concentrations of nitrogen oxides and carbon dioxide in the engine exhaust gas also slightly increased. At the same time, a clear reduction in average concentrations of carbon monoxide, hydrocarbons and particulates matter was obtained.

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1 Introduction

Transport is a large source of harmful effects on the environment. It has a significant impact on people's health and lives. The main, noticeable example of the impact transport has on the environment are road accidents. Transport also causes the introduction of various types of chemical compounds and elements harmful to human health into the Earth's atmosphere. Their main contributors are the exhaust gases emitted by engines used in most means of transport. The road transport sector in 2017 was the largest source of total NO_X emissions and the second largest source of soot, CO emissions and an important source of $PM_{2.5}$ and Pb emissions [1]. According to data from the European Environment Agency, the road transport in the European Union in 2017 was responsible for emissions of: 39% nitrogen oxides, 28% carbon black, 19% carbon monoxide, 11% $PM_{2.5}$ particles, 11% PM_{10} particles and 8% non-methane volatile organic compounds. In addition, transport in the European Union accounts for around 25% of all the greenhouse gas emissions [2-3]. Estimates presented in [1] indicate that in the European Union countries, premature deaths related to exposure to $PM_{2.5}$, NO_2 and O_3, in 2016 amounted to 374000, 68000 and 14000 respectively. The $PM_{2.5}$ particles are the pollutants with the greatest impact on people's lives.

Transport is an energy-consuming sector of the economy. At present, the demand for energy in transport is met mainly by using fossil fuels, which are non-renewable energy sources. Combustion creates harmful compounds and carbon dioxide, which is the basic greenhouse gas that contributes to climate change. Renewable fuels, obtained from organic matter, can be a source of energy that reduces CO_2 and other harmful components of flue gas released into the atmosphere [4-8]. Fatty acid esters are biofuels that can be used in a pure form or as an additive to diesel fuel. They have similar properties to diesel fuel. They can be obtained from various raw materials [9-11]. Esters produced from vegetable oils are well recognized [12-17]. Inedible plants are currently being sought for ester production [18-19]. Such a raw material for obtaining fuels should not affect food prices. Research is also being carried out on development of new technologies for obtaining biofuels, including esters from algae [20-23]. Another important raw material for production of esters [24-27] may be organic waste from agriculture, the agri-food industry and food processing. Using them to produce fuels can also be a way to get rid of waste that is difficult to manage. For the production of esters, waste cooking oil can also be used [28-31]. Uddin et al. produced esters from oil from used coffee [32].

The use of esters to power compression ignition engines is the subject of numerous studies assessing their impact on emission of harmful exhaust components and carbon dioxide. Ozcanli et al. studied B100 methyl castor oil esters and their blends with diesel fuel: B5,

***Table 1** Basic physicochemical properties of commercial diesel fuel DF and rapeseed methyl esters RME [36-37]*

parameter	unit	diesel fuel	biodiesel RME
fatty acid methyl ester (FAME) contents	-	<0.05% (V/V)	97.9% (m/m)
density at a temperature of 15 °C	kg/m^3	833.4	883.1
kinematics viscosity at a temperature of 40 °C	mm^2/s	2.596	4.55
cetane number	-	51.0	51.3
cloud point	°C	-10	-6
cold filter plugging point	°C	-29	-22
ignition point	°C	63.5	above 111
sulphur (S) content	mg/kg	8.3	6.4
water content	mg/kg	84	180
particulate contents	mg/kg	7.3	18
10% distillation residue coking residue	% (m/m)	0.01	0.21
testing for corrosive action on copper (3 hours at 50 °C)	assessment	class 1	class 1

B10, B25 and B50 [33]. The measurements were carried out for a three-cylinder, naturally aspirated compression ignition engine with direct fuel injection. For pure esters and blends of esters and diesel oil, a reduction in CO and CO_2 concentrations was obtained compared to diesel fuel. At the same time, NO_x concentrations for B100, B5, B10, B25 and B50 were higher than for diesel. Raheman and Ghadge carried out tests using mahua oil (B100) methyl esters and its blends with diesel fuel B20, B40, B60 and B80 to supply the CI engine [34]. A single-cylinder diesel engine, operating at constant speed under varying loads, was used for the tests. The authors showed that the increase in the content of esters in the blend with diesel fuel resulted in a decrease in CO emissions and smoke opacity. The growing share of biodiesel in the tested fuels slightly increased the NO_x concentrations in comparison to the pure diesel oil. Ozener et al. studied biodiesel from soybean oil and its blends with diesel fuel: B10, B20, B50. The measurements were carried out for a single-cylinder, naturally aspirated compression ignition engine, operating at different rotational speeds of the crankshaft, at maximum load [35]. By supplying the engine with biodiesel and its blends, compared to diesel, reduced CO, HC and smoke opacity and increased CO_2 and NO_x concentrations. Raman et al. conducted tests of rapeseed oil methyl esters and their blends with diesel fuel: B25, B50 and B75 and for comparison pure diesel oil [12]. The tests were carried out for a stationary, single-cylinder diesel engine operating at a constant crankshaft rotational speed and variable load. They achieved a reduction in HC, CO emissions and an increase in NO_x and smoke opacity for fuels: B25, B50, B75 and B100 compared to DF.

In contrast to the above-presented analyses, the studies of RME rapeseed methyl esters and their blends with diesel fuel, presented in this work, were carried out using a modern compression ignition engine, with the Common Rail power supply system and electronically controlled electromagnetic injectors. This engine is typically used to power passenger cars. It is a construction designed in accordance with the direction of development of piston internal combustion engines called "downsizing". The purpose of this study was to determine the effect of use of the RME biodiesel and its blends with diesel fuel: B20, B40, B60 and B80 on the ecological indicators of the tested engine.

2 The tested fuels

The tests were conducted with the engine being fed either with rapeseed methyl esters (RME) and with commercial diesel oil containing no plant oil esters. The rapeseed methyl esters (RME) constitute a renewable fuel of plant origin. The RMEs are obtained in the process of transesterification of rape oil triglycerides with methanol. The requirements imposed on esters intended for feeding self-ignition engines are specified in standard PN-EN 14214. The second fuel was the diesel fuel. It is a mixture of hydrocarbons obtained via various petroleum processing routes. The requirements for diesel fuel intended for feeding compressed ignition engines are specified in standard PN-EN 590. In the diesel oil purchased for performing the tests, there were no FAME esters. As compared to diesel oil, the RMEs are distinguished by higher density and viscosity, higher water and solid impurity contents, higher turbidity and cold filter blocking temperature, as well as a higher oxygen content in the elementary fuel composition, among other characteristics. Selected properties of the diesel fuel and the RME are presented in Table 1.

3 Experimental setup

Experimental tests were carried out on an engine test bed stand built in the Heat Engine Laboratory at the Kielce University of Technology. The test stand

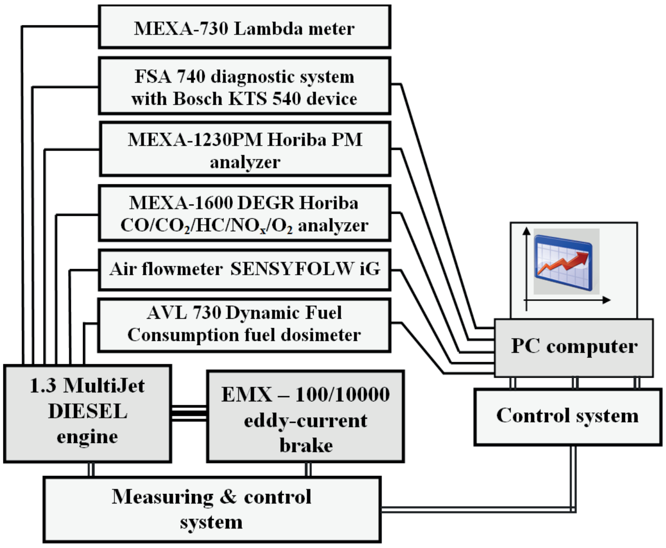

Figure 1 *A block diagram of the dynamometer test stand*

Table 2 *Basic metrological parameters of the test stand*

measured parameter	measuring ranges	accuracy	measurement resolution
rotational speed	0 - 10000 rpm	≤ 1 rpm	1 rpm
torque	0 - 240 Nm	1% of full scale	0.001 Nm
fuel consumption	0 - 150 kg/h	0.12% of measured value	0.001 g/s
air consumption	0 - 2000 kg/h	0.2% of measured value	0.001 kg/h

Table 3 *Metrological parameters of exhaust gas analyzers*

measured component	measuring ranges min/max	repeatability	measurement resolution
CO	0-100/3000 ppm	± 1% of full scale	0.1 ppm
CO_2	0-1/16%	± 1% of full scale	0.01%
THC	0-100/20000 ppm	± 1% of full scale	0.1 ppm
NO_x	0-100/5000 ppm	± 1% of full scale	0.1 ppm
O_2	0-10/25%	± 1% of full scale	0.01%
PM	0-300 mg/m^3	± 1% of full scale	0.01 mg/m^3

consisted of: a Fiat 1.3 MultiJet compression ignition engine, an eddy-current brake type EMX - 100/10 000, a control cubicle with a control system by AUTOMEX, a PC with software to control the test stand during the testing and to archive the test results. The fuel consumption measurement on the testing stand was done by the gravimetric method with an AVL 730 Dynamic Fuel Consumption fuel dosimeter. The air consumption during the testing was measured using an FMT500-IG (SENSYFOL iG) air flowmeter. The test stand control cubicle consists of: an AMX 202 brake power panel, an AMX 211 engine-brake assembly control module, an AMX212 PMO measuring module to measure the most important parameters describing the engine operation conditions (the crankshaft rotational speed and the torque) and a temperature and pressure measurement panel. Furthermore, the test stand was equipped with a FSA 740 diagnostic system complete with a Bosch KTS 540. The block diagram of the engine test stand on which the tests were performed is shown in Figure 1. Basic metrological parameters of the research stand are summarised in Table 2.

The test stand included also a MEXA-1600 DEGR combustion gas analyzer and a MEXA-1230PM particulate matter analyzer. The MEXA-1600DEGR analyzer is designed for the continuous real-time measuring of the concentrations of five internal combustion engine exhaust gas components, namely: carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (THC), nitrogen oxides (NO_x) and oxygen (O_2). Moreover, this analyzer enables the assessment of the exhaust gas recirculation rate by the measurement of EGR-CO_2. All the subassemblies, needed for carrying out measurements, such as analyzer modules, a gas sampling and sample preparation system, an incorporated industrial-type computer and gas and electric connections, are all housed

Table 4 *Basic technical specification of the FIAT 1.3 Multijet*

parameter	unit	value
cylinder arrangement	-	in-line
number of cylinders	-	4
injection type	-	direct, multi-stage fuel injection
cylinder operation order	-	1 - 3 - 4 - 2
compression ratio, ε	-	17.6
cylinder bore, D	m	$69.6 \cdot 10^{-3}$
piston stroke, S	m	$82 \cdot 10^{-3}$
engine cubic capacity, V_{ss}	m^3	$1.251 \cdot 10^{-3}$
engine rated power, P	kW	66
rotational speed at rated power, n_P	rpm	4000
maximum engine torque, T	Nm	200
maximum torque rotational speed, n_T	rpm	1750
idling rotational speed	rpm	850±20

in a single cubicle. The computer software enables the control of the analyzer subassemblies, including the gas sampling and sample preparation system and the calibration gas connection system for performing calibrations. Moreover, it performs the collection of data and its archiving, editing and transmitting. The MEXA-1230PM analyzer is designed for the continuous real-time measurements of the particulate matter (PM) concentrations in the exhaust gas of compression ignition engine. The analyzer enables the separate and simultaneous measurement of the two particulate matter components: the Soluble Organic Fraction (SOF) and the Soot. It is able to sample exhaust gas either directly from the exhaust system or after it has been diluted in the measuring tunnel. The measurement of the Soot is done by measuring the quantity of electric charge transferred by soot particles charged in the electric field. The Soluble Organic Fraction (SOF) is measured using two FID detectors as the difference of their signals for the exhaust gas tested, at temperatures of 47 ºC and 191 ºC. Metrological parameters of the analysers used in the tests are shown in Table 3. The exhaust gases paths of these analysers comply with the requirements of ISO-8178.

The Fiat 1.3 MultiJet engine has been designed based on an engines development direction, aimed at designing engines with smaller geometrical dimensions and smaller mass, while maintaining or improving their ecological and energy indices. The basic technical specification of this engine is given in Table 4. The engine block is cast of cast iron and has an aluminium support plate and in-cast cast iron main bearing bushes. This provides the required rigidity of the engine with limited dimensions. The timing gear system uses two distribution shafts. The engine head incorporates four valves per cylinder: two inlet valves and two exhaust valves. This solution has been adopted to increase the cylinder filling ratio. The tested engine was equipped with a variable-geometry vane turbocompressor and a cooler for air delivered to the cylinders. The engine was furnished with an exhaust gas recirculation system with an exhaust gas cooling capability. The engine under investigation is equipped with the Common Rail MJD 6JF fuel feed system with electromagnetic injectors. The fuel injection process is electronically controlled. The feed system of the Fiat 1.3 Multijet engine allowed the fuel dose injected to the cylinder during one cycle to be divided into a maximum of three parts.

4 Research methodology

Engine tests were carried out to determine the exhaust gas composition and fuel consumption of the FIAT 1.3 Multijet engine, powered successively by blends of diesel oil and RME esters with an increasing volume of RME in the blends. The tests were conducted on the following RME and DF blends: B20, B40, B60 and B80. In addition, the engine was also powered by pure RME esters and, for comparison, diesel fuel that contains no esters. The tests were carried out at a constant crankshaft rotational speed of 3000 rpm. The engine load was changed from the smallest to the largest set value. Measurements were taken for the following torque values: 10, 20, 40, 60, 80,100, 120, 140, 160 and 180 Nm. At each measuring point, the results were recorded after establishing the speed-load and thermal conditions of engine operation. At the same time, the hourly fuel consumption, torque, effective power, hourly air consumption, excess air coefficient were measured as well as concentrations of the basic exhaust components: carbon monoxide CO, carbon dioxide CO_2, nitrogen oxides NO_x, total hydrocarbons THC, particulates matter PM and oxygen O_2. These concentrations were measured continuously under established engine operating conditions for approximately 60 seconds at a sampling rate of ten measurements per second. The quantity of the PM particles in exhaust gases was also measured. This measurement was also carried out for about 60 seconds with a sampling rate of one measurement per second. Measurements of gaseous exhaust components and particulates were taken simultaneously. The results of the exhaust gas composition measurements presented in the graphs are the averaged values at individual measurement points.

5 Results and discussions

The basic indicator, measured during the tests of the work of the FIAT 1.3 Multijet engine fuelled with: RME, B20, B40, B60, B80 and DF, was its hourly fuel consumption FC. The engine was operated at a constant crankshaft speed and variable loads. The results of these measurements are shown in Figure 2. Fuel consumption increased with the increase of the RME share in the blends with DF. The highest fuel consumption was obtained for the RME. The average increase in fuel consumption for B20, B40, B60, B80 and RME fuels in relation to DF was: 6.6, 6.8, 8.6, 12.7 and 13.2%, respectively. The increase in fuel consumption is a result of the lower calorific value of esters containing oxygen in their elemental composition. Brake specific fuel consumption BSFC was determined by dividing the values of hourly consumption by engine's power. The calculated BSFC values for the tested fuels are shown in Figure 3. Similar BSFC changes were obtained for B20, B40, B60, B80 and RME fuels in relation to DF, as in the case of FC. Other researchers also obtained an increase in BSFC when engines were run on esters or their blends with diesel oil compared to diesel oil [12, 17, 38].

The main objective of this study was to determine the impact of the increased participation of RME in blends with DF and to assess the effect of using the pure RME on concentrations of the basic measured components in the engine exhaust. Figure 4 compares the concentrations of the carbon monoxide in the engine exhaust gases when fuelled by: B20, B40, B60, B80, RME and DF. For all the blends tested and for biodiesel B100, concentrations of CO in the exhaust gases were reduced, as compared to diesel. The average CO reduction for B20, B40, B60, B80, RME compared to DF was 13.4, 13.7, 17.1, 21.2 and 27.4%, respectively. This is the result of the oxygen content of the elementary composition of biodiesel, which promotes the firing of fuel and oxidation of CO to CO_2. Many publications indicate CO reductions in exhaust gases when using biodiesels obtained from various raw materials [39-42].

The results of measurements of carbon dioxide concentrations in the exhaust gases of engines powered by the B20, B40, B60, B80, RME and DF are shown in Figure 5. When supplying the engine with blends and pure RME biodiesel, an average increase in CO_2 concentrations in the exhaust gas was obtained by about 2.0% - 5.7%. A slight increase in CO_2 concentrations in exhaust gases may be the result of increased fuel consumption and better CO-burning for CO_2. Other researchers also show an increase in carbon dioxide emission using esters to power engines [35, 43-44].

The results of various studies presented in the literature indicate an increase in nitrogen oxide concentrations using different biodiesels to power compression ignition engines [45-48]. This article also

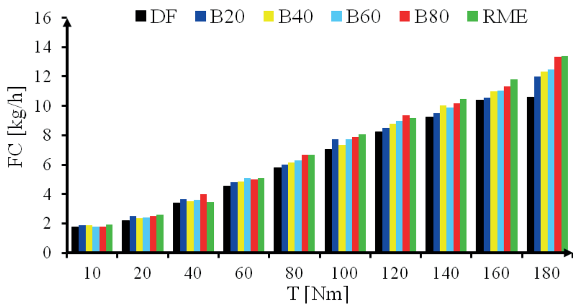

***Figure 2** Engine fuel consumpion as a function of its load, when fuelled: DF, B20, B40, B60, B80, RME*

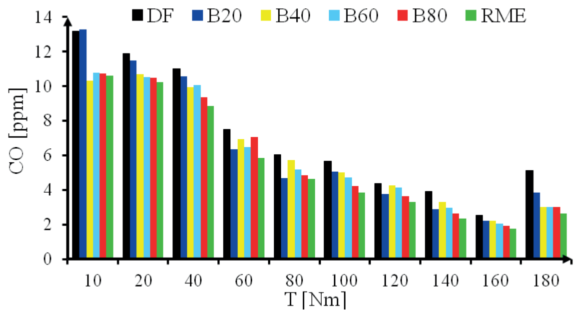

***Figure 4** Variation of the CO concentrations in engine exhaust gas as a function of its load, when fuelled: DF, B20, B40, B60, B80, RME*

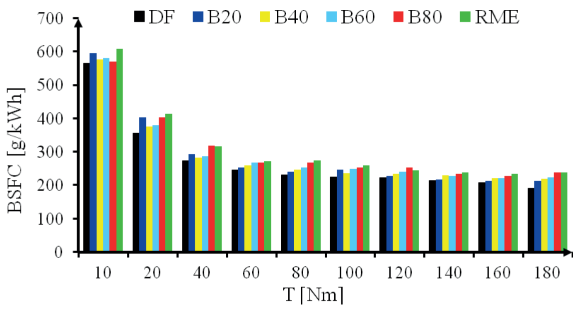

***Figure 3** Brake specific fuel consumption of the engine as a function of its load, when fuelled: DF, B20, B40, B60, B80, RME*

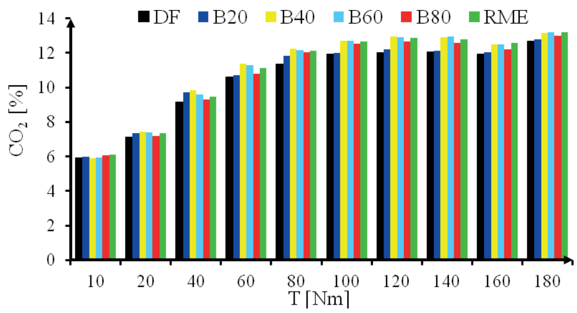

***Figure 5** Variation of the CO_2 concentrations in engine exhaust gas as a function of its load, when fuelled: DF, B20, B40, B60, B80, RME*

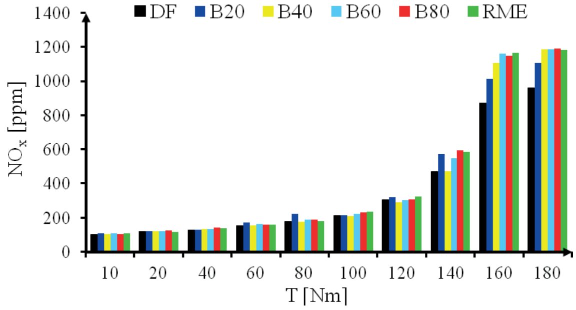

Figure 6 *Variation of the NO_x concentrations in engine exhaust gas as a function of its load, when fuelled: DF, B20, B40, B60, B80, RME*

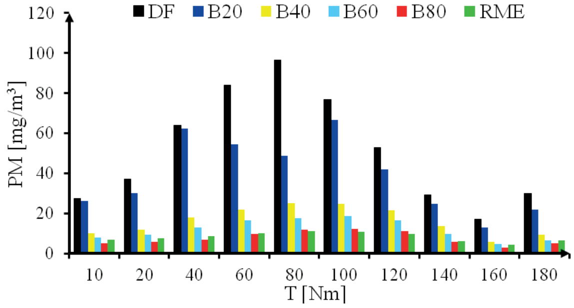

Figure 8 *Variation of the PM concentrations in engine exhaust gas as a function of its load, when fuelled: DF, B20, B40, B60, B80, RME*

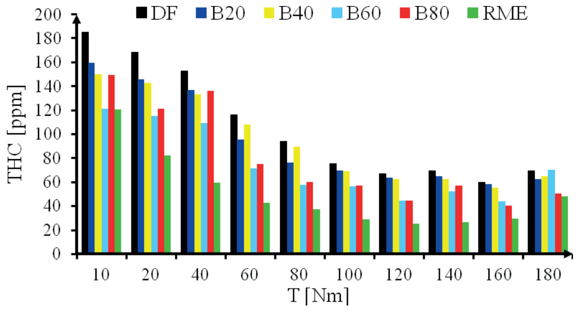

Figure 7 *Variation of the THC concentrations in engine exhaust gas as a function of its load, when fuelled: DF, B20, B40, B60, B80, RME*

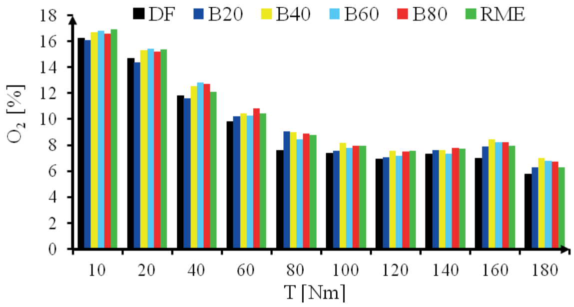

Figure 9 *Variation of the O_2 concentrations in engine exhaust gas as a function of its load, when fuelled: DF, B20, B40, B60, B80, RME*

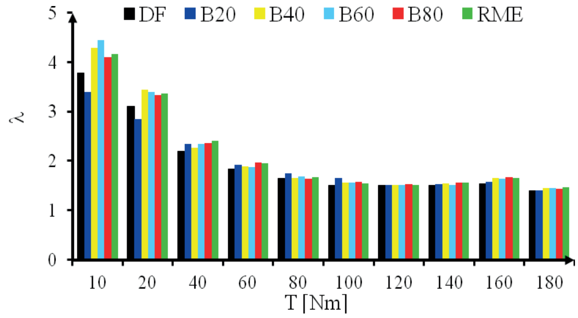

Figure 10 *Values of the excess air ratio λ as a function of engine load, when fuelled: DF, B20, B40, B60, B80, RME*

presents the results of studies that resulted in an increase in NO_x concentrations when supplying the CI engine with common rail power supply system, with RME and DF blends and pure RME. The NO_x concentrations for test fuels are shown in Figure 6. Powering by B20, B40, B60, B80 and RME fuels increases average NO_x concentrations as compared to diesel reaching 11.9, 7.5, 11.5, 13.1 and 13.4%, respectively. The increase in NO_x emissions using esters is a result of the higher temperatures when burning them, compared to the combustion of diesel fuel.

Figure 7 shows the results of measuring the THC concentrations when supplying the engine with tested fuels. The average THC reduction for B20, B40, B60, B80, RME compared to DF was 10.6, 9.9, 28.1, 26.7 and 53.8%, respectively. There was also a clear reduction of the PM concentrations in the exhaust gases of the engine fuelled with RME and blends of RME and DF. Results of the PM measurements for the engine supplied with tested fuels are shown in Figure 8. The average reduction in PM concentrations for B20, B40, B60, B80 and RME fuels was from 21.1% to even 84.3%. Merkisz et al. also showed a large reduction in the concentration of solid particles in the exhaust gas of a ZS engine with a Common Rail supply system fuelled by RME esters and blends of B20 and B50 [49]. Lemaire et al. showed that the carbon black arising from the combustion of diesel oil with the addition of RME esters oxidizes faster [50]. The reduction in both THC and PM concentrations in the exhaust gas is a result of the higher oxygen content and higher temperatures when burning B20, B40, B60, B80 and RME fuels. Figure 9 presents the results of measurements of the oxygen concentrations in the exhaust gases of an engine powered by tested fuels. For B20, B40, B60, B80 and RME fuels, average O_2 concentrations in flue gas were higher about 5.3% to 10.9%, compared to DF. This is also reflected in the measurements of the excess air coefficient, which are shown in Figure 10. They are higher for B20, B40, B60, B80 and RME fuels compared to diesel.

6 Conclusions

Based on the research carried out on the FIAT 1.3 Multijet SDE 90 HP engine, operating at variable loads and a constant speed of the crankshaft, fed with RME esters and their blends with diesel oil, the following conclusions can be drawn:

- By powering the engine with B20, B40, B60, B80 and RME fuels, an increase in hourly fuel consumption and brake specific fuel consumption was obtained. The increase in RME's share in DF resulted in an increase in FC and BSFC.
- Carbon monoxide concentrations in the exhaust gas, when the engine was fuelled with B20, B40, B60, B80 and RME fuels, were lower compared to diesel fuel. Along with the increase in the amount of esters in the blend with diesel oil, lower concentrations of CO were obtained. The lowest CO values were for pure biodiesel.
- Carbon dioxide concentrations were slightly higher when fuelling the engine with B20, B40, B60, B80 and RME fuels. The highest increase was obtained for B40 fuel - 5.7%, the smallest for B20 fuel - 2.0%.
- By powering the engine with fuels: B20, B40, B60, B80 and RME, the concentrations of nitrogen oxides in the exhaust gas increased in comparison to the diesel fuel. The biggest increase was obtained when the engine was powered by the RME biofuel.
- For the engine fuelled with B20, B40, B60, B80 and RME, the hydrocarbon concentrations in the exhaust gas are significantly reduced. By powering the engine with pure RME esters, this reduction was, for the conducted tests, over 50% on average.
- The concentrations of particulate matter were significantly lower when feeding the engine with esters and their blends with diesel fuel. For B80 and RME fuels, the average PM concentrations reductions for the study were over 80%.
- When the engine was fuelled with B20, B40, B60, B80 and RME fuels, the fuel-air mixture composition showed higher excess air ratios than those measured for diesel.
- Oxygen concentrations in the exhaust gas were higher when the engine was fuelled by blends of RME and DF and pure RME.

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