Research Article

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Research on the combustion process in the Fiat 1.3 Multijet engine fueled with rapeseed methyl esters

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Abstract: The aim of the paper is to analyze and evaluate the basic parameters of the combustion process in a modern Fiat 1.3 Multijet diesel engine, fuelled esters (FAME) and diesel oil. During the tests on an engine test bed, the pressure waveforms in the cylinder were measured, on the basis of which the averaged actual indicator graphs were established in the determined engine operating conditions. On their basis, the pressure increase rates were determined and heat release characteristics were prepared based on the equation of the first principle of thermodynamics. The characteristics of the relative amount of heat released and the characteristics of the relative heat release rate were determined. The use of rapeseed methyl esters to supply the engine had an impact on the parameters of the combustion process as compared to its supply with diesel oil. Differences in the waveforms of heat release characteristics of the engine powered by the tested fuels are significantly greater at low loads. At the lowest engine loads, esters burn much faster than diesel oil. With the increase in engine load, the differences in the waveform of heat release characteristics during combustion of these fuels were significantly smaller.

Keywords: compression ignition engine, combustion process, engine fuels, rapeseed oil methyl esters, harmful exhaust components, heat release characteristics

1 Introduction

Conventional fuels used for powering internal combustion diesel engines are diesel oils, consisting of hydrocarbons, *i.e.* elements of carbon and hydrogen. The trace presence of other elements is the effect of impurities or additives introduced into the oil to improve its properties. Alternative fuels with similar physicochemical properties are fatty acid esters of vegetable oils. They are a renewable fuel consisting of molecules, the structure of which includes elements of carbon, hydrogen and oxygen. Esters are obtained by chemical modification of vegetable oils by transesterification [1–3]. Vegetable oils are composed of large and heavy particles and have a much higher density and viscosity compared to diesel oil, which makes their use as diesel fuel difficult. Compared to pure vegetable oils, physicochemical properties of esters obtained by transesterification are more similar to those of diesel oil. Esters, in comparison with raw vegetable oil, are characterized by lower cloud and freezing point and contain much less compounds causing the formation of deposits in the combustion chamber.

The best known raw material for obtaining esters, which can then be used to power diesel engines, are oils obtained from various types of oil plants [4–12]. The choice of raw material for the production of esters depends to a large extent on its availability, which in turn depends on climatic conditions and the possibility of cultivating certain plant species. Esters can also be obtained from animal fats [5, 13–16]. Usually, waste from the agri-food industry can be used for this purpose. This makes it possible to obtain fuel from waste that needs to be managed or disposed of anyway. Fats from food production and preparation processes, for example used fats from restaurants, can also be used as the source of raw material for obtaining esters [5, 17–19]. Another future raw material for the production of esters may be algae [20–22]. Esters are utilised to fuel engines in the road transport. Investigations have also been conducted into the use of esters in air transport [23]. Lapuerta and Canoira discussed the process of obtaining esters from different raw materials [24]. Then, the properties of fuel blends for jet engines and of esters were examined. The authors demonstrated that the presence of oxygen in methyl esters

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makes it possible to reduce soot emissions, and thereby particulate emissions. According to Schäfer, advanced biofuels can offer the possibility of substantial reduction in carbon emissions over the plane service life [25]. Fatty acid esters of vegetable oils (FAME) are now virtually the only alternative fuel that can be used to power diesel engines in their pure form or as additives to diesel oil without the need for engine design changes. This is due to the similar physicochemical properties between these esters and diesel oil. Esters obtained from vegetable oils are characterized by good self-ignition properties, *i.e.* high cetane number. FAME esters have a higher density and more than twice as high viscosity compared to diesel oil [26]. This affects the process of injection and the formation of the air-fuel mixture in the engine cylinders. Moreover, esters are characterized by a narrow boiling range and a significantly higher ignition temperature than diesel oil [27]. Greater viscosity of esters ensures better lubricating properties. Esters have a lower calorific value than diesel oils, which results from the fact that they contain about 12% oxygen in the elementary composition. The beneficial effect of a higher oxygen content in FAME esters is their greater tendency to spontaneous ignition and their more intensive and complete combustion. This has the effect of reducing the concentrations of carbon monoxide, hydrocarbons and particulates in exhaust gases and reducing the smoke level of an engine powered by esters or their mixtures with diesel oil. At the same time, there is usually an increase in the concentration of nitrogen oxides in the exhaust gases of an engine powered by esters or their mixtures with diesel oil. Moreover, the disadvantages of esters include their higher tendency to absorb water and the presence of unsaturated bonds in molecules. The presence of water and oxygen in esters favors the development of microorganisms, which also adversely affects fuel quality and stability. Esters have worse low-temperature properties. Under winter conditions they can only be used with special additives reducing their cold filter plugging point (CFPP). In addition, technical solutions for pre-heating of the engine fuelling system could be employed. The possibility of using esters obtained from various raw materials to power diesel engines in their pure form or in mixtures with diesel oil has been confirmed by numerous studies presented in scientific publications. Slightly different properties of FAME esters and diesel oil cause differences in the process of combustion of these fuels. Qi *et al.* studied the process of combustion in a single-cylinder diesel engine powered by esters obtained from soybean oil and, for comparison, by diesel oil [27]. They showed that the combustion process of soybean oil methyl esters has similar combustion stages as for diesel oil. However, when powering an engine with esters, the combustion process started earlier than when powering

the engine with diesel oil. Comparing the combustion process of both fuels, attention was drawn to the engine load. At lower engine loads, the maximum cylinder pressure values, maximum pressure increase rate and maximum heat release rate values were higher for esters than for diesel oil. At higher engine loads, the maximum cylinder pressures in the engine when supplied with soybean oil esters were similar to those obtained in the engine when supplied with diesel oil. In turn, the maximum pressure increase rate and maximum heat release rate values were lower for esters than for diesel oil. Furthermore, Qi D.H. *et al.* [27] demonstrated that the maximum values of the above indicators for an ester-fueled engine were obtained earlier than for a diesel oil-fueled engine. Moreover, they stated that regardless of the engine load, the combustion process starts earlier when the engine is supplied with esters, which is a result of a shorter auto-ignition delay and a different course of fuel injection. Qi D.H. *et al.* obtained similar results when supplying the same engine with soybean oil methyl esters and their mixtures with diesel oil with the ester volume content of 30%, 50%, 80% and, for comparison, with diesel oil only [28]. Aldhaidhawi *et al.* conclude from literature analysis that pure biodiesel or its mixtures with diesel oil have lower heat release rates, lower self-ignition delay and lower thermal efficiency [29]. They found that heat release rate of an engine powered by biodiesel or its mixtures with diesel oil could be slightly lower than for powering with diesel oil, due to lower calorific value, lower volatility and higher viscosity. On the other hand, the shorter self-ignition delay may be the result of lower compressibility and higher cetane number of rapeseed biofuel. Can *et al.* carried out tests on a naturally aspirated, single-cylinder diesel engine powered with mixtures of rapeseed esters and diesel oil with volumetric ester content of 5%, 10%, 15% and 20%, and for comparison with diesel oil only [30]. The engine ran at a constant speed of crankshaft of 2200 rpm and four different loads: low, high and two intermediate. The mechanical injector was opened with fuel pressure. When powering the engine with mixtures, an earlier start of fuel injection was obtained compared to diesel oil. In the case of the engine running on mixtures, earlier combustion starts and shorter self-ignition delay periods were also achieved. With the increase in the share of esters in the mixture with diesel oil, the increase in pressure in the cylinder took place earlier, the maximum values of heat release rates were lower, and the points of their reaching were earlier. The maximum values of the pressure increase rates were also reduced. Maximum values of pressures for engine fueling with mixtures were comparable or slightly lower than for diesel oil, while for high load the differences of these pressures were slightly higher. Chen *et al.* powered a six-cylinder engine

with Common Rail system with clean esters from used oil and inedible vegetable oils and with diesel oil, and they also showed shorter self-ignition delay and better flammability of esters compared to diesel oil [31]. The research by Özener *et al.* has also shown a reduction of self-ignition delay and maximum heat release rates when powering a single-cylinder engine with a mechanical injection pump with soybean esters and their mixtures with diesel oil with a volumetric content of esters of 10%, 20% and 50% [32]. Kousoulidou *et al.* tested a four-cylinder turbocharged engine with Common Rail system used in passenger cars [33]. During tests on an engine test bed, the engine was powered by a mixture of 10% (V/V) palm oil esters and 90% (V/V) diesel oil. They showed that the use of 10% ester addition to diesel oil has an inconclusive influence on the combustion process and depends on the engine operating conditions. The start of combustion can be either earlier or later than for diesel oil. However, in most cases, the combustion of a mixture of esters and diesel oil is faster than for diesel oil in the initial phase of the combustion process. The possibilities of using mixtures of diesel fuel with esters and alcohols as well as mixtures of esters and alcohols are also investigated [34–37].

2 Heat release characteristics

The working medium in the cylinder of a diesel engine, before the start of the combustion process, is compressed air, into which fuel is injected under very high pressure. A self-igniting air-fuel mixture is formed. During the fuel combustion process, heat is released, which causes changes in pressure and temperature of the working medium inside the engine cylinder. The course of heat release has an impact on the speed of pressure build-up during combustion, maximum values of pressure and temperature inside the cylinder, loads of engine components and indicators of the engine's operation. Heat release characteristics are defined as the quotient of heat released until the present moment of time and the total amount of heat delivered to the cylinder with fuel in the analyzed work cycle [38]. The above relation can be presented in a mathematical form:

$$HR = \frac{Q(\alpha)}{g_c \cdot W_u} \quad (1)$$

where: $Q(\alpha)$ – the amount of heat released until the present, g_c – the dose of fuel supplied in one engine work cycle, W_u – the calorific value of fuel.

Heat release characteristics are determined on the basis of indicator graphs and the equation of the first principle of thermodynamics for processes occurring in the engine

cylinder, which can be expressed as follows:

$$dQ_{HR} = dU + pdV + dQ_{str} \quad (2)$$

where: dQ_{HR} – amount of heat released in the cylinder until the present, dU – change of internal energy of the working medium in the cylinder, pdV – work performed in the cylinder by the working medium, dQ_{str} – heat lost, among others, to the cylinder walls as a result of incomplete combustion and as a result of dissociation phenomena.

The amount of heat released in the cylinder until the current time can be calculated from the relationship:

$$dQ_{HR} = g_c \cdot W_u \cdot dHR \quad (3)$$

The total amount of heat that can be released during the combustion process in the cylinder can be calculated with the equation:

$$Q = g_c \cdot W_u \quad (4)$$

Dividing the equation (2) by $g_c W_u$ provides a relationship allowing to determine the relative characteristics of the indicated amount of net heat released during the combustion process [39]:

$$dHR = dHR_i + dHR_{str} \quad (5)$$

The above equation can be written in the following form:

$$HR_i = HR - HR_{str} \quad (6)$$

In equation 7 the value HR_i is the indicated characteristic of the relative release of heat consumed for the conversion of internal energy of the working medium and the execution of the absolute work [38]. The relative amount of heat released during the combustion process in the engine cylinder is calculated from the relationship:

$$HR_i = \frac{U_i - U_{ps} + \int_{V_{aps}}^{V_i} pdV}{g_c \cdot W_u} \quad (7)$$

where: U_i – current value of internal energy of the working medium, U_{ps} – internal energy of the working medium at the beginning of the combustion process, V_i – current volume of the cylinder, V_{aps} – volume of the cylinder at the beginning of the combustion process.

Knowing the characteristics of HR_i relative amount of net heat released during the combustion process, the relative heat release rate during the combustion process is calculated [39]:

$$HRR = \frac{HR_i - HR_{i-1}}{\alpha_i - \alpha_{i-1}} \quad (8)$$

where: HR_i – relative amount of heat at point i , HR_{i-1} – relative amount of heat at point $i-1$, α – engine's crankshaft rotation angle at point i , α_{i-1} – engine's crankshaft rotation angle at point $i-1$.

Table 1: Basic technical specification of the FIAT 1.3 Multijet SDE 90 HP engine

Parameter	Unit	Value
Cylinder arrangement	–	in-line
Number of cylinders, c	–	4
Injection type	–	direct, multi-stage fuel injection (od 3 do 5)
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, N_e	kW	66
Rotational speed at rated power, n_N	rpm	4000
Maximum engine torque, M_e	Nm	200
Maximum torque rotational speed, n_M	rpm	1750
Idling rotational speed, n_{bj}	rpm	850 ± 20

3 Object of the study

The object of the study was Fiat 1.3 Multijet SDE 90 HP four-cylinder compression-ignition internal combustion piston engine. The basic technical data of the engine are presented in Table 1. The engine was designed with the so-called “downsizing” in mind, *i.e.* the direction of development of engines with smaller geometric dimensions and lighter weight while maintaining or improving economic, energy and ecological indicators. It is a very good reflection of the directions of development of modern diesel engines used in passenger cars. The tested Fiat 1.3 Multijet SDE 90 HP engine is equipped with Common Rail fuel supply system with electronically controlled solenoid injectors. The dose of fuel injected into the cylinder during a single work cycle is divided into up to three parts. The fuel injection process is electronically controlled and depends on the load and speed of the engine crankshaft. The maximum pressure of the injected fuel in the fuel tank of the tested version of the engine is 160 MPa. In the air intake system, a variable geometry turbocharger and an air cooler are used. The use of such a turbocharger allows to improve the process of filling cylinders in the whole range of crankshaft speed. In order to improve the process of changing the working medium, the engine is equipped with four valves per cylinder controlled by two camshafts. The processes taking place in the engine and its systems are controlled by an electronic ECU controller.

4 Test stand and measuring equipment

The tests were carried out on an engine test bed built in the Heat Engine Laboratory at the Kielce University of Technology. The block diagram of the test stand is presented in Figure 1. The test stand included the EMX 100/10 000 brake made by ELEKTROMEX CENTRUM, a control cabinet controlling the operation of the test bed with an AUTOMEX control system, a PC with software to control the test stand during testing and archive the test results, AVL Dynamic Fuel Consumption fuel meter series 730, and ABB SENSYFLOW iG gas-mass flow meter that allows to accurately determine the air consumption of the engine. In addition, the test stand was equipped with the FSA 740 diagnostic system with Bosch KTS 540 device for viewing and controlling the selected motor parameters. AVL IndiSmart measuring system was used to measure the fast-changing values. The system made it possible to measure the pressure waveforms of the working medium in the Fiat 1.3 Multijet engine cylinder and the fuel pressure in the injection line as a function of the crankshaft rotation angle. It consisted of the AVL IndiSmart 612 data acquisition system, a piezoelectric pressure sensor in the engine cylinder, a tensometric pressure sensor in the injection line, and an engine crankshaft rotation angle encoder AVL 365C.

Figure 1: Block diagram of the test stand

5 Fuels selected for testing

The test were carried out while the Fiat 1.3 Multijet SDE 90 HP engine was powered by commercial diesel oil containing no FAME vegetable oil esters and by rapeseed fatty acid methyl esters produced in Trzebinia Refinery (Rafineria Trzebinia S.A.) Selected properties of fuels used to supply the engine are shown in Table 2. Diesel oil is a mixture of hydrocarbons obtained from various petroleum processing operations. For this fuel, intended for supplying high-speed diesel engines, the requirements are specified in the PN-EN 590 standard [40]. The standard specifies that no more than 7% (V/V) of FAME esters may be present in diesel oil. In the diesel oil purchased for testing, there were no FAME esters or their amount was negligibly small. Rapeseed fatty acid

methyl esters are a renewable fuel of plant origin. Compared to diesel oil, they are characterized by higher density and viscosity, higher water and solids content, higher cloud and cold filter blockage point, as well as higher oxygen content in the elementary fuel composition. The esters used in the tests were obtained by transesterification of triglycerides of rapeseed oil with methanol. Requirements for esters intended for supplying diesel engines are specified in the PN-EN 14214 standard [41].

6 Results of combustion process tests in an engine fueled with FAME esters

The aim of the paper was to determine the effect of supplying the tested engine with rapeseed methyl esters (FAME) and, for comparison, with DF diesel oil on the basic indicators of combustion process in the Fiat 1.3 Multijet engine cylinder. The numerical values of the determined indicators are presented in Tables 3 and 4.

These indicators were determined from the indicator graphs and the characteristics of the relative heat release rate during the combustion process, prepared on their basis. Figure 2 shows a comparison of exemplary pressure waveforms in the cylinder during the combustion process with the engine supplied with the following fuels: FAME and diesel oil and its operation according to the load characteristics for crankshaft speed $n = 1750$ rpm and loads $T = 20, 60, 100$ and 140 Nm. As shown in the graphs presented in Figure 2, the greatest differences in the waveforms of the indicator graphs occur for the load $T = 20$ Nm. At higher

Table 2: Basic physicochemical properties of commercial diesel oil and rape oil fatty acid methyl esters as stated in the Quality Certificates of these fuels [42, 43]

Parameter	Unit	Diesel oil	FAME
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
Kinematic 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

Table 3: The maximum combustion process pressure values $p_{\max}$, maximum pressure increase rate in the cylinder $(dp/d\alpha)_{\max}$ and maximum values of the first and second maximum of the relative heat release rate $HRR_{1\max}$, $HRR_{2\max}$ during the combustion process in the cylinder of the Fiat 1.3 Multijet engine, working according to the load characteristics for $n = 1750$ rpm, supplied with the following fuels: FAME, DF

Load, Nm	$p_{\max}$, MPa		$dp/d\alpha_{\max}$, MPa/°CA		$HRR_{1\max}$, 1/°CA		$HRR_{2\max}$, 1/°CA	
	DF	FAME	DF	FAME	DF	FAME	DF	FAME
10	4,476	4,374	-0,167	0,039	0,006	0,022	0,107	0,142
20	4,424	4,352	-0,517	0,034	0,002	0,009	0,060	0,110
40	4,729	4,846	0,290	0,344	0,002	0,006	0,124	0,134
60	6,178	5,881	0,441	0,332	0,012	0,011	0,103	0,082
80	7,270	7,275	0,366	0,338	0,009	0,007	0,069	0,068
100	8,489	8,324	0,288	0,262	0,007	0,008	0,065	0,067
120	9,745	9,557	0,265	0,265	0,007	0,008	0,061	0,060
140	10,789	11,038	0,315	0,334	0,010	0,007	0,057	0,054
160	11,603	11,946	0,308	0,312	0,008	0,006	0,053	0,048
171	-	12,446	-	0,318	-	0,006	-	0,047
180	12,311	-	0,303	-	0,008	-	0,048	-
200	13,110	-	0,301	-	0,006	-	0,044	-
209	13,047	-	0,300	-	0,006	-	0,042	-

Table 4: Angular values of crankshaft rotation of the engine at which 5, 10, 50 and 90% of the fuel dose was burned in the Fiat 1.3 Multijet engine cylinder working according to the load characteristics for $n = 1750$ rpm, supplied with the following fuels: FAME, DF

Load range	Angular values of crankshaft rotation of the engine at which 5, 10, 50 and 90% of the fuel dose was burned, °CA							
	5%		10%		50%		90%	
Mo, Nm	DF	FAME	DF	FAME	DF	FAME	DF	FAME
10	373,81	371,95	374,29	371,95	378,11	375,48	388,80	387,34
20	378,49	373,75	379,69	373,75	387,15	378,01	400,64	390,27
40	374,97	372,92	375,76	372,92	379,27	376,75	398,70	395,36
60	371,16	370,73	371,86	370,73	377,12	377,22	399,46	397,74
80	369,59	369,34	370,38	369,34	377,08	376,82	398,84	396,19
100	368,98	369,26	370,17	369,26	377,32	377,15	399,02	395,80
120	368,71	368,85	370,02	368,85	377,25	377,47	397,78	396,67
140	368,21	367,76	369,57	367,76	377,20	377,12	396,89	396,67
160	367,72	367,50	369,14	367,50	377,24	377,84	397,93	398,50
171	-	367,50	-	367,50	-	378,35	-	400,01
180	367,61	-	369,14	-	378,09	-	400,88	-
200	367,37	-	369,01	-	378,74	-	403,13	-
209	367,49	-	369,18	-	379,31	-	404,69	-

Figure 2: Comparison of pressure waveforms during the combustion process in the Fiat 1.3 Multijet engine cylinder supplied with the following fuels: FAME, DF, operating according to the load characteristics for $n = 1750$ rpm, with loads $T = 20, 60, 100$ and 140 Nm

loads, these differences are much smaller. For loads $T = 20, 60$ and 100 Nm, higher maximum pressures occur when the engine is powered with diesel oil. For load $T = 140$ Nm, higher value of the maximum pressure in the engine cylinder occurs when the engine is powered with FAME esters.

On the basis of the measured pressure waveforms during the combustion process, their maximum values were determined, which are shown in Figure 3. As can be seen from the graph, supplying the engine with the FAME fuel reduces the maximum combustion process pressure $p_{\max}$ at low and medium loads, until the torque $T = 140$ Nm is reached. For high engine loads, the maximum combustion process pressure values $p_{\max}$ are slightly lower for diesel oil than for esters.

Indicator graphs made it possible to prepare graphs of the pressure increase rates during the combustion process $dp/d\alpha$. Examples of their waveforms are shown in Figure 4. For load $T = 20$ Nm and powering the engine with diesel oil, there is a slight change in pressure due to the combustion of a small dose of fuel at low engine load. This is also confirmed by the indicator graphs shown in Figure 2. For the other loads, the maximum values of $dp/d\alpha$ are much higher. As can be seen on the $dp/d\alpha$ graphs, two or three maxima are visible, which result from the multiphase fuel

Figure 3: Comparison of the maximum combustion process pressure values $p_{\max}$ in the cylinder of the Fiat 1.3 Multijet engine working according to the load characteristics for $n = 1750$ rpm and supplied with the following fuels: FAME, DF

injection in the tested engine and combustion of its subsequent doses: two consecutive small doses and the main dose.

Based on the waveforms of pressure increase rate in the cylinder $dp/d\alpha$, its maximum values $(dp/d\alpha)_{\max}$ were determined, which are shown in Figure 5. As can be seen

Figure 4: Waveforms of pressure increase rate dp/da during the combustion process in the Fiat 1.3 Multijet engine cylinder supplied with the following fuels: FAME, DF, operating according to the load characteristics for $n = 1750$ rpm, with loads $T = 20, 60, 100$ and 140 Nm

from the graph, the engine power supply with FAME fuel increases the rate of pressure increase at low loads until the torque $T = 40$ Nm is reached. For the other engine loads, the values $(dp/da)_{\max}$ obtained when powering the engine with Diesel oil and FAME are similar. These results also confirm the insignificant changes in pressure during the combustion process with the engine running at $T = 10$ and 20 Nm loads and diesel oil supply. Under such conditions, the charges of injected fuel are small. When being injected, they are divided into three portions. The combustion onset occurs after the Top Dead Centre during the expansion. The combustion process is mild. When the engine is fuelled by diesel oil, pressure increment due to combustion is almost not perceivable in the indicator diagram (Figure 1 for $T = 20$ Nm). Under the same conditions, a visible pressure increase in the indicator diagram is found for engines fuelled with esters. Esters ignite earlier because of a slightly higher cetane number and combustion proceeds more rapidly due to the presence of oxygen in the ester molecule.

Figure 6 shows a comparison of exemplary characteristics of the relative amount of heat released during the combustion process, with the engine powered by FAME and DF fuels and its operation according to the load char-

Figure 5: Comparison of the maximum pressure increase rate in the cylinder $(dp/da)_{\max}$ of the Fiat 1.3 Multijet engine working according to the load characteristics for $n = 1750$ rpm and supplied with the following fuels: FAME, DF

acteristics for crankshaft speed $n = 1750$ rpm and loads $T = 20, 60, 100$ and 140 Nm. As the results show, the greatest differences in the characteristics of the relative amount of heat release occur for load $T = 20$ Nm. For the other engine loads, the waveforms of the relative heat release amount characteristics obtained when supplying the engine with diesel oil and FAME are similar.

Figure 6: Characteristics of the relative amount of heat released during the combustion process in the cylinder of the Fiat 1.3 Multijet engine supplied with the following fuels: FAME, DF, operating according to the load characteristics for $n = 1750$ rpm, with loads $T = 20, 60, 100$ and 140 Nm

Figure 7: Characteristics of the relative heat release rate (HRR) during the combustion process in the cylinder of the Fiat 1.3 Multijet engine supplied with the following fuels: FAME, DF, operating according to the load characteristics for $n = 1750$ rpm, with loads $T = 20, 60, 100$ and 140 Nm

Figure 8: The maximum values of the first and second maximum of the relative heat release rate HRR_{1max} , HRR_{2max} during the combustion process in the cylinder of the Fiat 1.3 MultiJet engine, working according to the load characteristics for $n = 1750$ rpm, supplied with the following fuels: FAME, DF

Figure 9: Angular values of crankshaft rotation of the engine at which 5, 10, 50 and 90% of the fuel dose was burned in the Fiat 1.3 MultiJet engine cylinder working according to the load characteristics for $n = 1750$ rpm, supplied with the following fuels: FAME, DF

Figure 7 shows a comparison of exemplary characteristics of the relative heat release rate during the combustion process, with the engine powered by FAME and DF fuels and its operation according to the load characteristics for crankshaft speed $n = 1750$ rpm and loads $T = 20, 60, 100$ and 140 Nm. As the test results show, when supplying the engine with FAME fuel for $T = 20$ Nm, a much higher value of the first and second maximum heat release rate HRR_{1max} , HRR_{2max} was obtained compared to the values obtained

when supplying the engine with diesel oil. For loads $T = 60$ and 100 Nm, the HRR_{1max} , HRR_{2max} values are only slightly higher when the engine is supplied with FAME esters. For load $T = 140$ Nm higher values of HRR_{1max} , HRR_{2max} were obtained when the engine was supplied with diesel oil.

Figure 8 shows graphs of the values of the first and second maximum HRR_{1max} , HRR_{2max} of the relative heat release rate during the combustion process, with the Fiat 1.3 MultiJet engine operating according to the load char-

acteristics for $n = 1750$ rpm and supplied with DF diesel oil and FAME esters. As shown by tests at low loads in the range from $T = 10$ Nm to $T = 40$ Nm, supplying the engine with FAME fuel results in a higher value of the first maximum relative heat release rate $HRR_{1\max}$. For heavy loads, the $HRR_{1\max}$ values are higher when the engine is supplied with diesel oil. The values of the second maximum relative heat release rate $HRR_{2\max}$ at low loads from $T = 10$ to 40Nm and engine supplied with FAME fuel are also higher than for engine supplied with DF. For the other engine loads, the $HRR_{2\max}$ values obtained when powering the engine with FAME and DF are similar.

Figure 9 shows the angular values of the crankshaft rotation of the tested engine, at which 5, 10, 50 and 90% of the fuel dose was burned. Analyzing the angular values of the burnout of 5, 10 and 50% of the fuel dose one can notice that engine supply with FAME fuel, in comparison with diesel oil supply in the load range from $T = 10$ to about $T = 60$ Nm results in shortening the combustion time of the injected fuel dose. This is particularly evident with the load of $T = 20$ Nm, where the differences between DF diesel oil and FAME esters are between 5 and 9° of crankshaft rotation. For higher loads, the differences are small and amount to a maximum of approximately 1° of crankshaft rotation. Analyzing the results of burnout of 90% of the fuel dose, which can be interpreted as the end of the combustion process, it can also be noted that engine supply with FAME esters, compared to diesel oil in the load range of $T = 10$ to 120 Nm causes a reduction in the combustion time of the injected fuel dose. The greatest differences in burnout of 90% of the fuel dose occur at the load of $T = 20$ Nm and amount to approximately 10° of crankshaft rotation. For loads above $T = 120$ Nm, the angular values of burnout of 90% of the fuel dose obtained with engine powered by FAME and DF are similar.

7 Conclusions

The results of the tests presented in this paper allowed to determine the influence of supplying the tested engine with rapeseed methyl esters (FAME) on the basic indicators of the combustion process, in comparison to the indicators determined when supplying the engine with DF diesel oil. Power supply the engine with FAME esters in comparison to the supply with diesel oil results in a reduction of the maximum combustion process pressure $p_{\max}$ at low and medium loads. At higher engine loads, the $p_{\max}$ values are slightly lower when the engine is supplied with diesel than when it is supplied with FAME esters. For the waveforms of

pressure increase rate and their maximum values, engine power supply with FAME esters at low engine loads resulted in an increase in the pressure increase rate. For higher engine loads above $T = 40$ Nm, the values $(dp/d\alpha)_{\max}$ obtained for the engine supplied with diesel oil and FAME are similar. The $dp/d\alpha$ graphs show two or three maxima, which result from the combustion of subsequently injected two small doses and the main dose. Moreover, supplying the engine with FAME esters did not cause any significant differences in the waveforms of relative heat amount characteristics compared to the characteristics obtained when supplying the engine with DF. They are only visible at low loads. Then the increase in the relative amount of heat released takes place much earlier when the engine is supplied with FAME esters than when it is supplied with DF. The relative heat amount release rates with engine supplied with FAME esters, at low loads, have higher values of the first and second maximum $HR_{1\max}$, $HR_{2\max}$ than those obtained for engine supplied with diesel oil. For the other engine loads, the $HR_{1\max}$ and $HR_{2\max}$ values obtained when powering the engine with FAME and DF are similar. The results of the fuel dose burnout percentage tests showed that engine supply with FAME esters, compared to DF supply, results in a reduction of the combustion time of the injected fuel dose in the low load range. For higher engine loads, the angular values of fuel dose burnout obtained when supplying the engine with FAME and DF are similar.

To sum up, it can be stated that by powering a modern diesel engine with Common Rail system with FAME esters, differences were obtained in the values of combustion process indicators at low and possibly medium load values, compared to its powering with diesel oil. At higher and heavy loads, FAME and diesel fuel combustion process indicators are more similar. Differences in the combustion process indicators determined for the tested fuels are the effect of different properties of these fuels, especially higher density and viscosity of esters and oxygen content in esters. For heavy loads of the tested engine, different properties of the tested fuels have a significantly smaller effect on the values of the determined combustion process indicators.

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