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Comparison of the Combustion Process Parameters in a Diesel Engine Powered by Second-Generation Biodiesel Compared to the First-Generation Biodiesel

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Abstract: The use of biofuels to power compression–ignition engines makes it possible to reduce emissions of certain harmful components of exhaust gases. The purpose of this study was to determine the influence of second-generation biofuels on the course of indicator graphs and heat release characteristics of the Perkins 1104D-44TA compression–ignition engine. For comparative purposes, the same tests were carried out by feeding the engine with first-generation biofuel and diesel fuel. Babassu butyl esters (BBuE) were used as the second-generation biofuel. The second fuel was a first-generation biofuel—rapeseed oil methyl esters (RME). Analysis of the results made it possible to draw conclusions about the effect of using 2nd and 1st generation biofuels on the parameters of the combustion process. When the DF engine was powered, the lowest fuel dose per work cycle was obtained. In the case of RME and BBuE fuels, it depends on the engine load. For low loads, higher consumption is for RME, and for higher loads, fuel consumption for BBuE in-creases most often. This is due to the lower calorific value of the esters. The results of these tests indicate that feeding the engine with BBuE and RME fuel in most loads resulted in higher maximum combustion pressures compared to feeding the engine with DF which may be directly related to the higher cetane number of these fuels compared to DF and the oxygen content of these fuels. Feeding the engine with BBuE and RME esters compared to DF did not result in large differences in the maximum heat release rates HRmax. However, the values of the first and second maximum heat release rates x_{1max} and x_{2max}, in addition to the type of fuel, are strongly influenced by the operating conditions, especially the engine load. Analyzing the combustion angles of 5, 10, 50, and 90% of the fuel dose, it can be seen that feeding the engine with BBuE and RME esters for most measurement points results in faster combustion of the fuel dose compared to DF.

Keywords: diesel engine; combustion process; heat release characteristics; biodiesel; second-generation biofuel

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1. Introduction

Compression–ignition engines are widely used to power heavy vehicles in road transportation. Such features of their characteristics as higher efficiency, lower fuel consumption and lower operating costs have also resulted in their very widespread use to power passenger cars [1–6]. The main problem of modern compression–ignition engines is the emission of nitrogen oxides and particulate matter. Due to environmental requirements, current compression–ignition engines have been equipped with modern fuel injection systems, turbocharging systems and complex exhaust after-treatment systems [7–9]. The operation of these engines is significantly dependent on the type and quality of fuel burned and this directly affects the combustion process. When looking for alternative fuels to power these engines, it is certainly important to consider their ability to self-ignite by compression in the cylinder [10–12].

The most important process in a reciprocating internal combustion engine is the formation and combustion of the combustible mixture. Evaluation of the quality of this process can be realized on the basis of indicator charts. The form of this graph depends primarily on the course and quality of fuel atomization during the injection process, the amount and aerodynamic properties of the air in the engine cylinder, etc. These quantities determine the quality of the combustible mixture formed and burned. The basic characteristics of the fuel combustion process in the engine are the characteristics of the amount of heat released. The form of the aforementioned characteristics is determined based on the analysis of actual indicator charts, which depends on both the accuracy of the determination of the chart itself and the method of its analysis [13–17].

The publication [18,19] presents the characteristics of heat release, understood as the amount and rate of heat release during the combustion process, taking into account the heat exchanged with the walls of the combustion chamber.

The use of biofuels to power reciprocating internal combustion engines is one way to reduce their negative impact on the environment [20–23]. As biofuels are defined gaseous and liquid fuels for powering internal combustion engines, which are obtained from biomass. Through the development of biofuel production, their division into four generations has been applied [24–30].

First-generation biofuels are made from plants that are primarily grown for food. These primarily include vegetable oil esters and bioethanol. Vegetable cooking oils, which are not converted to esters, can also be used to power diesel engines [17,31–33]. In the case of second-generation biofuels, these are obtained from plants that are not grown for food purposes. They can also be produced from the waste of the agri-food industry, which includes animal fat waste [34–40].

In addition, third- and fourth-generation biofuels can be distinguished. These are the fuels of the future that are being developed. Third-generation biofuels are obtained from organic matter derived from algae or other raw materials obtained from crops modified by molecular biology techniques. The cellular components of algae can be used to obtain biodiesel from algal oil, bioethanol produced by fermentation, biomethane produced by anaerobic digestion of algal biomass and hydrogen separation [29,41]. Fourth-generation biofuels are the result of efforts to close the carbon balance and eliminate its environmental impact.

There are many publications in the literature related to biofuels obtained from various feedstocks. In the implementation of the research presented in this publication, a non-food raw material was used, which is babassu palm oil. Esters were then obtained from this oil. A characteristic feature of this oil is its wide application in the cosmetic industry. An important characteristic of babassu palm oil is the high amount of short-chain fatty acids, which, according to the authors, can significantly affect the combustion process. As the analysis of the literature showed, there are no studies on the effect of babassu oil esters on the combustion process in reciprocating internal combustion engines. The research work presented the possibilities in the use of babassu palm biomass for electricity production. Most of the publications deal with the evaluation of the physical and chemical properties of biodiesel from babassu palm in comparison with biodiesels obtained from other feedstocks [34,42]. There are many publications on the production and the very properties of methyl and ethyl esters produced in babassu palm oil and their effect on emissions of the harmful components of exhaust gas [20,21].

Therefore, an important novelty of this article is the evaluation of the effect of the use of these esters on the combustion process. Base on as cylinder pressure diagrams and heat release characteristics. In publication [43], the authors studied HVO and RME fuel which they compared with diesel fuel. Hydrotreated vegetable oil (HVO) is produced by hydrogenising vegetable oils and wastes. Process uses hydrogen instead of methanol, HVO oil is a better alternative to diesel and more environmentally friendly. The study showed the shortest combustion time for diesel fuel, followed by HVO (hydrotreated vegetable oil) and RME fuel. On the other hand, the paper [44] investigated, among other things, the effect of biodiesel made from waste cooking oil additionally enriched with nanomaterials on the combustion process and emissions of harmful exhaust components. When burning biodiesel, lower combustion pressures were obtained compared to diesel fuel. Authors showed that the rate of heat release and cylinder pressure when burning a biodiesel mixture is lower than diesel fuel alone. This is due to lower fuel consumption and a shorter auto-ignition delay. The authors also pointed out problems with atomization and evaporation of biodiesel blends, which in turn lowered the heat release rate compared to crude diesel. These parameters were improved by adding nanoparticles to the biodiesel. Of the oils, esters derived from coffee husks (CHOME) were studied in [45]. In these studies, for bio-diesel-diesel blends, lower values of heat release characteristics rates were obtained compared to diesel fuel. The authors explain this by the higher viscosity, density, and lower heating value of biodiesel. In publication [46] where RME fuel was studied, the results showed that higher combustion pressures were obtained when burning RME compared to diesel, which the authors explained by the high cetane number and physicochemical properties of this fuel.

In the publication [47], the authors demonstrated the possibility of changing the rates of heat release in the kinetic and diffusion phases by using special additives. They reduced heat release rates in the kinetic combustion phase and increased heat release rates in the diffusion combustion phase. This reduced NOx and PM emissions.

In a publication [48], the authors compared diesel fuel with hydrotreated vegetable oil and biobutanol up to 20%. According to this research, as the concentration of biobutanol in HVO fuel increases, the pressure increment increases, but this value does not reach a higher value than that obtained for pure diesel fuel. The maximum in-cylinder pressure rise during the pre-mix combustion phase was obtained using pure diesel fuel. The publication [49] proposed a mixture of rapeseed oil (Co), n-hexane (Hex) and ethanol (ET). The research showed that feeding the engine with rapeseed oil and the mixtures of n-hexane and ethanol resulted in a smaller heat release rate maximum in the kinetic phase of combustion than DF, which affected the angle of onset of combustion (occurred later relative to DF) and the delay of auto-ignition. Relevant research from the point of view of the use of RME fuel to power compression–ignition engines is presented in [15], where the authors showed that the type of fuel significantly affects the parameters of the injection process and thus the combustion process. In this case, the authors fueled the engine with RME and DF. They showed that feeding the engine with RME fuel resulted in an earlier onset of combustion, higher combustion pressure and higher heat release rates. As the authors suggest, this may be due to the higher cetane number and higher oxygen content of the RME fuel.

The purpose of this article was to determine the effect of feeding the tested engine with babassu oil esters (BBuE) and first-generation biofuel—that is, rapeseed oil methyl esters (RME)—on the indicators of the combustion process. For comparison, the test results of these two fuels were compared with those obtained when the engine was fed with diesel fuel (DF). These indicators were determined from indicator diagrams charts and the characteristics of the amount and rate of heat release during the combustion process, which were prepared on their basis.

2. Experimental Work

The working medium in the cylinder of a compression–ignition engine, before the combustion process begins, is compressed air, into which fuel is injected at very high pressure. A self-igniting fuel–air mixture is formed. During the fuel combustion process, heat is given off, which causes changes in the pressure and temperature of the working medium in the engine cylinder. The heat release affects the rate of pressure build-up during combustion, the maximum values of pressure and temperature in the cylinder, the loads on engine components and engine performance indicators.

Measuring the pressure changes in an engine cylinder as a function of the angle of rotation of the crankshaft or the position of the piston in the cylinder is called engine indexing. Nikolaus August Otto measured such pressure in the first engine he developed [50]. Knowledge of pressure changes in the engine cylinder during successive cycles of its operation, is the primary source of information about the processes occurring in it.

The AVL IndiSmart 612 system was used to record indicator graphs, while AVL Indicom mobile 2012 software [51] was used to plot heat release characteristics and other combustion process parameters. As part of the study, in addition to the indicator charts, the heat release characteristics and their basic parameters were determined (such as maximum heat release HRmax, maximum heat release rate during combustion according to the kinetic x_{1max} and the diffusion combustion mechanism x_{2max}). Maximum combustion pressures, maximum pressure build-up stages were determined, and 5, 10, 50, and 90% fuel dose burnout stages. The parameters of the combustion process obtained when feeding the engine with BBuE fuel were compared with the results obtained when feeding the engine with first-generation biofuel, RME and on DF. Diesel fuel met the requirements of PN-EN590+A1, while RME and BBuE met the requirements of PN-EN 14214. The tests were carried out with engine operation according to load characteristics at two engine speeds: 1400 and 2200 rpm. At 1400 rpm, the engine achieves maximum torque while at 2200 rpm it achieves maximum power. Measurements of the basic parameters of the combustion process were carried out over the entire range of engine loads for the above-mentioned rotational speeds. The first measurement was carried out at a load expressed as a torque T of 20 Nm, the next measurements at T = 50 Nm. Subsequent measurements were carried out by increasing the load in 50 Nm increments up to the maximum value possible for a given crankshaft speed. Under the same engine operating conditions as for all tested fuels, basic engine operating parameters such as power, fuel consumption, temperatures in the basic functional systems of the engine were recorded. In addition, indicator charts were recorded from which heat release characteristics and their basic parameters such as maximum heat release values and maximum heat release rates were determined.

2.1. Engine Description

Experimental tests were carried out on an engine dynamometer bench with a Perkins 1104D-44TA compression–ignition engine equipped with a Delphi DP310 rotary injection pump. The engine on the dynamometer bench is shown in Figure 1.

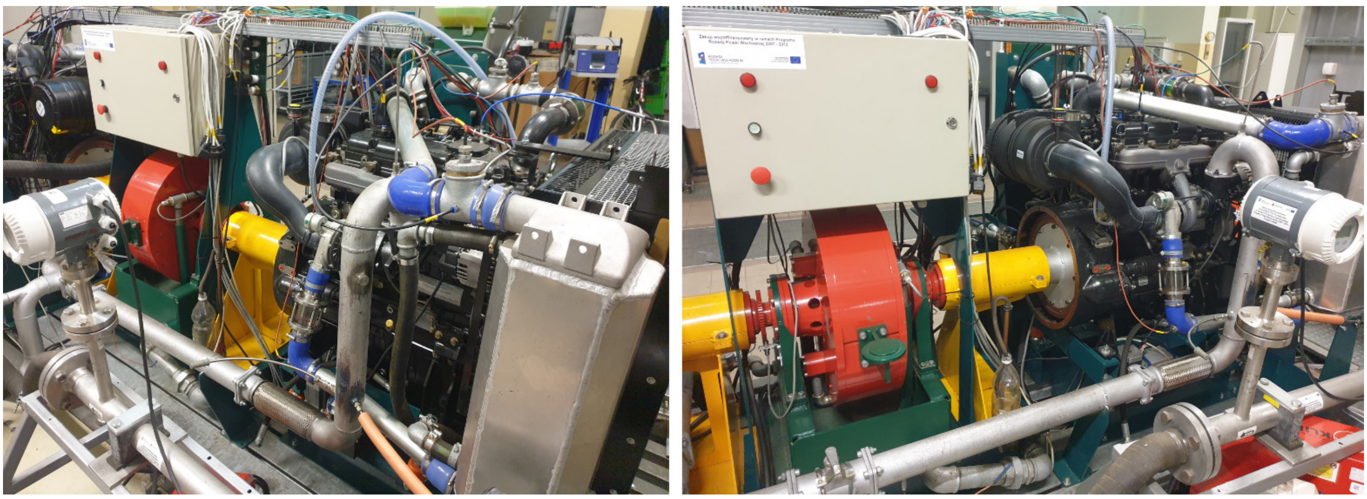

Figure 1. Braking stand with Perkins 1104D-44TA engine.

The engine has off-road applications in agricultural tractors or construction machinery. The Perkins 1104D-44TA engine meets Stage IIIA and EPA Tier 3 emission standards and develops 75 kW at a crankshaft speed of 2200 rpm and a maximum torque of 416 Nm at 1400 rpm. The basic specifications of the engine under test are shown in Table 1.

Table 1. Basic technical data of the engine.

Parameter	Value
Cylinder layout	Inline
Cylinder count	4
Injection type	Direct
Type of injection type	Delphi DP310 rotary pump
Rated power engine	75 kW
Rated power speed	2200 rpm
Rated torque engine	416.0 Nm
Rated torque speed	1400 rpm
Engine displacement	4.4×10^{-3} m^3
Cylinder diameter	105 mm
Piston stroke	127 mm
Compression ratio	18.2:1
Air supply system	Turbocharger, intercooler

2.2. Engine Testing Facilities

On the dynamometer bench, the engine is connected by a shaft to an electrospinning load brake of the AMX-200/6000 type. It can receive power of 200 kW from the engine and transmit torque of 700 Nm. The test stand is equipped with a computer to control the implementation of the tests and to acquire the measurement results. A strain gauge ATMX2040 fuel dosimeter was used to measure fuel consumption. Air consumption was measured using a thermal mass air flow meter from ABB. An IndiSmart 612 measurement system from AVL was used to measure the high-speed quantities. This system made it possible to measure the pressure profiles of the working medium in the engine cylinder as a function of the crankshaft rotation angle. In addition to the AVL IndiSmart 612 data acquisition system, the measurement system consisted of an AVL piezoelectric engine cylinder pressure sensor, an AVL 365C engine crankshaft angle encoder with a resolution of 720 electrical pulses per engine crankshaft revolution. This means that the next measurement took place, every specified angular value of $\Delta\alpha = 0.5$ °CA. The system allows multiplication of this signal, which gives the possibility of increasing the resolution of the measurement to $\Delta\alpha = 0.1$ °CA. In addition, the measurement system included AVL Indicom Mobile 2012 software for operating the entire system, including recording engine cylinder pressure profiles, and producing heat release characteristics during the combustion process. A schematic of the engine test stand on which the tests were conducted is shown in Figure 2.

All tests were carried out by changing the load from zero to full load at two constant speeds of 1400 and 2200 rpm for the duration of the experiment. Before the actual measurements, the engine was warmed up without load until the constant exhaust gas temperature was obtained. Finally, the readings were recorded after stabilization of the measurements was achieved. Measurements of the basic engine operation parameters were recorded on a computer using the Automex software.

2.3. Tested Fuels

Fuels for powering compression–ignition engines should be characterized by good atomization, evaporation and mixing properties with air, which affect the quality of the combustible mixture formed and its combustion under various load and speed conditions of engine operation [52,53]. The basic requirements for diesel fuel include ease of self-ignition and ensuring complete and total combustion. Ensuring these requirements is significantly influenced by such fuel properties as fractional composition, volatility, viscosity, density, surface tension, cloud point, water content and the number of mechanical impurities present in the fuel. Three types of fuels were used to carry out the study, two of which (RME) and (BBuE) were fatty acid esters of vegetable oils. The comparison fuel was standard DF diesel used to power compression–ignition piston internal combustion engines. The BBuE esters used in the study were obtained from by refining babassu palm oil. The babassu palm grows in the tropical forests of Brazil in the northeastern part of the country. Of great importance is the fact that babassu palm oil is not used in food production. For this reason, the esters obtained from this oil are a second-generation biofuel. The situation is different for the second biofuel intended for testing, which was rapeseed methyl ester (RME). In their pure form, rapeseed oil esters are used as fuel and as an additive to diesel fuel. On the other hand, rapeseed itself is also an edible crop, used for food production for this reason, which is why esters derived from rapeseed are first-generation biofuels. The esters used in the study were produced using a GW-200 reactor constructed by one of the co-authors of this publication G. Wcisło at the Malopolska Renewable Energy Center "BioEnergia".

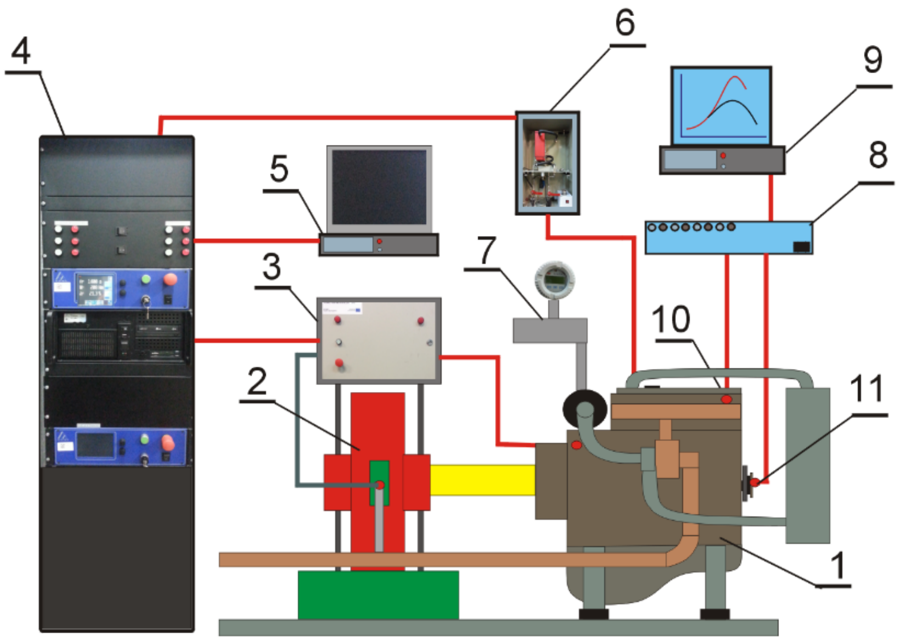

Figure 2. Set-up of the test stand: 1—Perkins 1104D-44TA engine, 2—Automex AMX-200/6000 brake, 3—measurement module, 4—measurement cabinet with the control system, 5—computer used to control the stand parameters and to archive test results, 6—fuel mass dosing device, 7—air flow meter, 8—AVL Indicom 612 system, 9—computer used to control the measurements, 10—engine cylinder pressure sensor, 11—engine crank angle encoder.

Numerous studies on biodiesels obtained from various raw materials can be found in the literature. In this study, a non-food raw material was selected—babassu palm oil, from which the esters were then obtained. The use of babassu palm oil in the cosmetics industry is growing steadily. This oil contains a lot of short chain fatty acids, ranging from C-8 to C-12, which are not found in e.g., rapeseed oil [54]. The authors assumed that the high content of short-chain esters should positively affect the combustion process. Butyl alcohol was used to produce esters from babassu oil, and sulfuric acid was used as a catalyst in the transesterification process. In this way, butyl esters of babassu oil (BBuE), which constitute a second-generation biofuel, were obtained. The use of butyl alcohol and sulfuric acid as a catalyst allowed to obtain high esterification efficiency of babassu oil. The transesterification process was carried out at the temperature of 390 K. Gas chromatography was performed for the produced biofuels. The aim of the research was to determine which fatty acid esters make up BBuE and RME biodiesels. A TRACE GC Ultra gas chromatograph by Thermo Scientific was used for the tests. The identification range of the butyl esters in BBuE and the methyl esters in RME was set from C6: 0, i.e., a hexanoic acid ester, to C24: 1. The produced BBuE contained 99.2% (m/m), while RME contained 99.1% (m/m) of higher fatty acid esters. A comparison of the fatty acid profiles of both biofuels shows substantial differences.

In the case of BBuE, the C6: 0 to C14: 0 fatty acid esters dominate, constituting 68% (m/m), while the RME biofuel does not contain them at all. When it comes to the composition of RME (the main biofuel used in transport in Europe), esters of fatty acids C18: 1, C18: 2 and C18: 3, which together constitute 90% (m/m) of all esters, predominate. On the other hand, in the BBuE biodiesel, the content of the above-mentioned three fatty acid esters is only 15.4% (m/m). Table 2 shows a comparison of the fatty acid profiles of BBuE and RME.

Table 2. Average fatty acid ester composition in BBuE and RME biodiesel.

Fatty Acids	Usage of Acid	Esters % (m/m)
	BBuE	RME
C 6:0	0.47	-
C 8:0	6.02	-
C 10:0	4.85	-
C 12:0	39.17	-
C 14:0	17.52	-
C 16:0	10.05	4.49
C 16:1	0.10	0.36
C 18:0	6.17	1.91
C 18:1	12.23	60.91
C 18:2	2.19	19.25
C 18:3	1.03	8.98
C 20:0	-	0.75
C 20:1	-	1.72
C 22:0	-	0.36
C 22:1	-	0.72
C 24:0	-	0.22
C 24:1	-	0.33

Research indicates that second generation biodiesel (BBuE) differs significantly from first generation biodiesel (RME) with regard to the content of different fatty acid esters. BBuE mainly contains short fatty acid esters, while RME contains medium length esters. BBuE esters are expected to self-ignite faster and to burn and burn off more efficiently.

Selected physicochemical properties of the BBuE and RME biodiesels, as well as the DF used in this study, are shown in Table 3.

Table 3. Selected physicochemical properties of BBuE, RME and DF fuel.

Property	BBuE	RME	DF	Standard
Density at 15 °C; g/cm^3	0.884	0.872	0.839	PN-EN ISO 3675
Cetane number	57.4	56.1	52.2	PN-EN ISO 5165
Calorific value; MJ/kg	38.2	37.8	42.7	ISO 1928:2009
Dynamic viscosity 40 °C; mPa·s	9.7	11.1	6.9	EN ISO 3104
Flash point; °C	94	100.5	56	PN-EN ISO 3679
Start of distillation temperature; °C	249	280	155	PN-EN ISO 3405
End of distillation temperature; °C	351	354	348	PN-EN ISO 3405
Esters content; % (m/m)	99.2	99.1	0	
Mass Percentage, % (m/m) [11,54]				PN-EN 14103
H	12.2	12–13	13–14	
C	74.7	75–77	86–87	
O	13.1	10–11	0	

3. Test Results and Analysis

The realization of the tests was carried out with the engine operating according to two load characteristics at 1400 and 2200 rpm. The tests were realized when feeding the Perkins 1104D-44TA engine with three fuels DF, BBuE and RME. During the tests, the basic indicators of engine operation such as effective power Ne, effective torque Mo, hourly fuel consumption, hourly air consumption were recorded.

When running the engine for 1400 rpm feeding the engine with DF and RME fuels, a maximum torque of T = 440 Nm was obtained. When feeding the engine with BBuE, the maximum torque is T = 400 Nm. For 2200 rpm feeding the engine with BBuE and RME esters, a lower torque of T = 300 Nm was obtained compared to DF where T = 350 Nm.

Figure 3 shows the dose per cycle q, calculated on the basis of hourly fuel consumption. As the diagram shows, the fuel dose depends on the engine load and rotational speed. As the load increases, the fuel dose increases. When the DF engine was powered, the lowest fuel dose per work cycle was obtained. In the case of RME and BBuE fuels, it depends on the engine load. For low loads, higher consumption is for RME, and for higher loads, fuel consumption for BBuE increases most often. This is due to the lower calorific value of the esters.

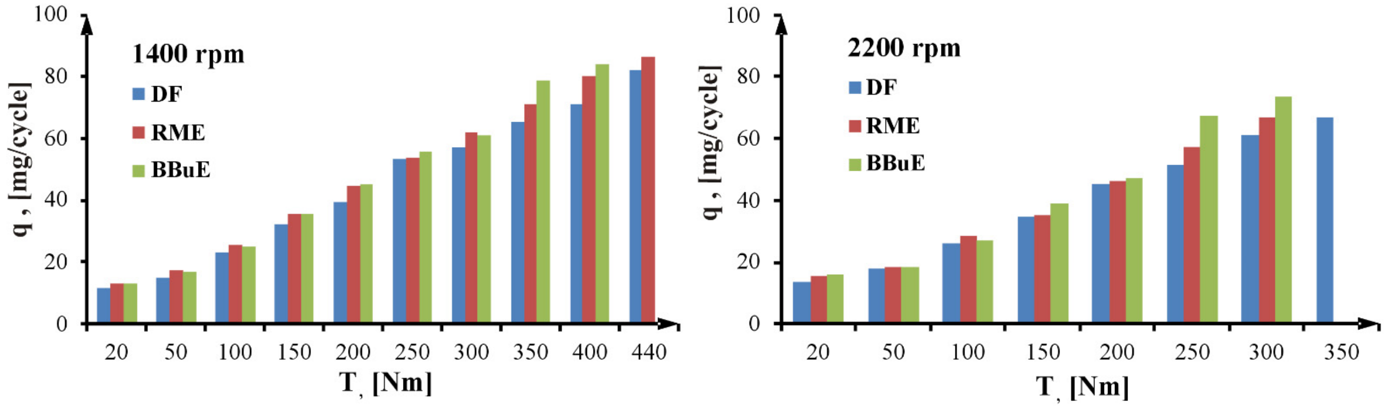

Figure 3. Fuel dose per cycle, with the engine running according to the load characteristics for 1400 and 2200 rpm.

In addition, pressure profiles for two hundred consecutive operating cycles as a function of crankshaft rotation angle were recorded under the engine operating conditions established above and analyzed. Graphs averaged over two hundred consecutive duty cycles were used for analysis. From the averaged indicator charts, the maximum values of combustion pressure pmax and the crankshaft rotation angles at which they occurred αpmax were determined. In addition, the maximum values of pressure build-up during the combustion process dp/dαmax were determined.

Figure 4 shows example pressure profiles in the cylinder of a Perkins 1104D-44TA engine operating according to load characteristics at a crankshaft speed of 1400 rpm and loads T = 50, 200, 250 and 300 Nm. Meanwhile, Figure 5 shows example pressure profiles in the cylinder of an engine operating according to load characteristics at a crankshaft speed of 2200 rpm and loads T = 50, 100, 150 and 300 Nm. As can be seen on the pressure profiles in the cylinder, Figures 4 and 5, feeding the engine with RME and BBuE esters causes, at low engine loads, a faster pressure increase compared to DF. This may be related to the higher cetane number of these esters. With higher loads, the tendency is the opposite.

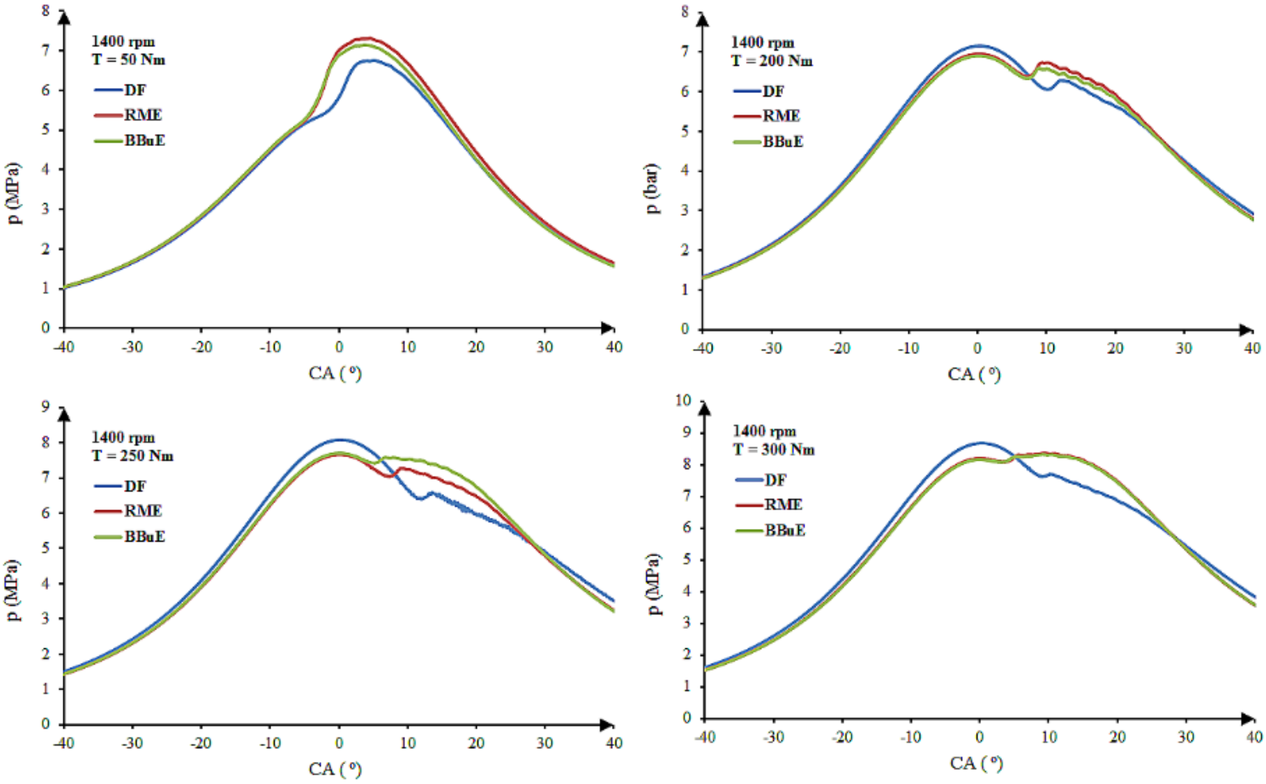

Figure 4. Examples of pressure profiles during the combustion of the tested fuels in the engine cylinder at its operation according to load characteristics.

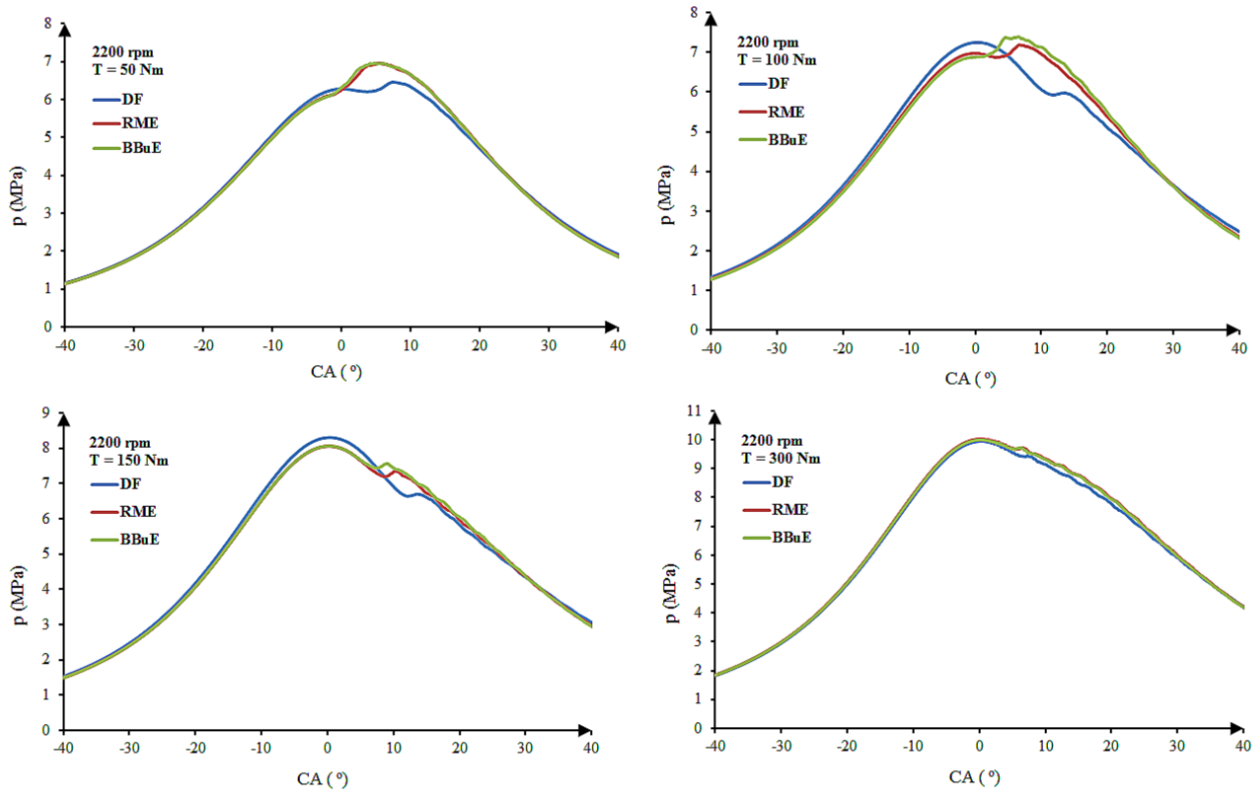

Figure 5. Examples of pressure profiles during the combustion of the tested fuels in the engine cylinder at its operation according to load characteristics.

Figure 6 shows a comparison of maximum engine cylinder pressures p_{max}, for crankshaft speeds of 1400 and 2200 rpm. In addition, the crankshaft angular values at which the maximum combustion pressures occurred were determined and are shown in Figure 7. Feeding the engine with BBuE and RME fuel in the low load range from 20 to 100–150 Nm and rotational speeds of 1400 and 2200 rpm, higher maximum combustion pressures were obtained compared to feeding the engine with DF. This is in line with studies [46]. At maximum engine load for 1400 and 2200 rpm, the highest combustion pressure was obtained for RME fuel. This is also consistent with the work of [15]. On the other hand, some literature [55–57] states that feeding the engine with RME fuel reduces the maximum combustion pressure. The reason for this is the shorter auto-ignition delay period.

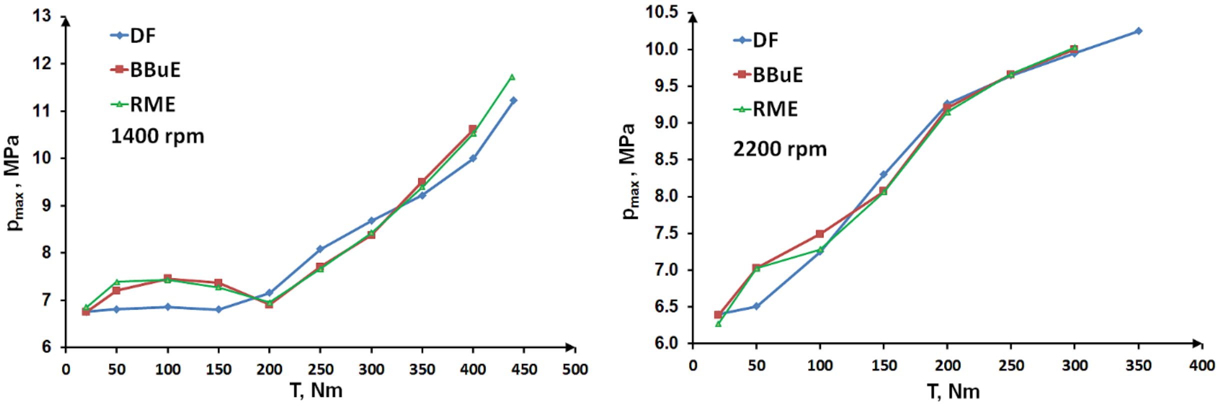

Figure 6. Maximum in-cylinder pressures during the combustion process.

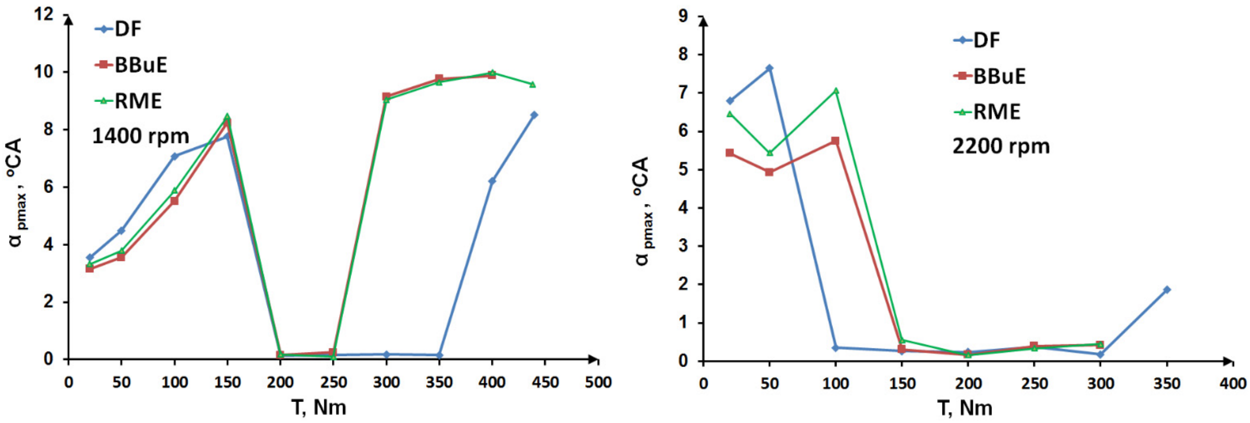

Figure 7. Angular values of the engine crankshaft at which the maximum combustion pressures.

The chemical reactions that occur during biodiesel injection at high temperatures break down high-molecular-weight esters into lower-molecular-weight esters, allowing the volatile compounds ignited earlier to burn, thereby reducing the auto-ignition delay period, which is in line with studies [55,56].

At loads of 200 to 300 Nm and rotational speeds of 1400 rpm, higher combustion pressures were obtained when feeding the engine with DF fuel. At further load increases from 350 to 450 Nm, higher combustion pressures were obtained by feeding the engine with BBuE and RME fuel compared to feeding the engine with DF fuel. When operating the engine according to load characteristics for an engine crankshaft speed of 2200 rpm for loads from 20 to 100 Nm, the maximum p_{max} pressures occurred when feeding the engine with BBuE fuel. For higher loads, the p_{max} values for all tested fuels are similar.

For BBuE fuel, when the engine was operated according to load characteristics at 1400 rpm and loads from 20 to 100 Nm, the maximum combustion pressure occurred slightly earlier than for RME and DF diesel. For successive loads from 150 Nm to the maximum load at this rpm, the maximum combustion pressure for BBuE and RME fuels occurred at virtually the same crankshaft rotation angles. From a load of 250 Nm to the maximum load when feeding the engine with BBuE and RME, the maximum combustion pressures occurred much later compared to feeding the engine with DF fuel especially in the range from 250 to 400 Nm. When operating the engine according to the load characteristics for 2200 rpm, these differences in the values of crankshaft rotation angles at which the maximum combustion pressures occurred are no longer as pronounced as at 1400 rpm.

Based on the graphs of pressure profiles as a function of crankshaft rotation angle, the graphs of the degree of pressure increment during the combustion process $dp/d\alpha$ were prepared. Based on these, the maximum values of the degree of pressure increase in the cylinder during the combustion process were determined as $(dp/d\alpha)max$, which are shown in Figure 8. Feeding the engine with BBuE fuel results in higher maximum combustion pressure increases compared to DF diesel fuel, but lower compared to the values obtained by feeding the engine with RME esters. This tendency is particularly pronounced for 1400 rpm. At 2200 rpm, the trend is very similar, only at a load of 100 Nm the highest $(dp/d\alpha)max$ occurred when feeding the engine with BBuE fuel. An increase in pressure increments when feeding the engine with biofuels was also observed by the authors in [58].

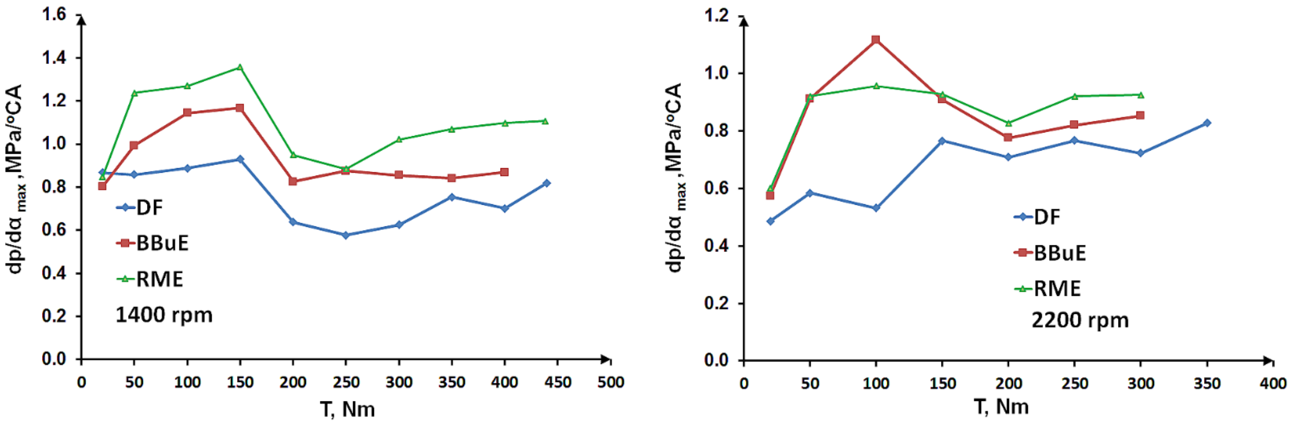

Figure 8. Maximum values of the degree of pressure increase $(dp/d\alpha)max$ during the combustion process.

Feeding the engine with BBuE and RME fuel resulted in higher combustion pressure values than when the engine was fed with DF fuel. Higher in-cylinder pressure values mean higher temperature values. The higher in-cylinder pressure values when the engine was fueled with BBuE and RME biofuels can be attributed to the higher cetane number, among other factors. The higher auto-ignition capability of these fuels leads to earlier ignition than diesel as the piston approaches top dead center. This results in higher maximum pressure values during biofuel combustion. As engine load increased, the differences in combustion pressure between the fuels tested decreased. These results are consistent with the work of [59].

Based on the averaged pressure profiles in the cylinder, the characteristics of the amount and rate of heat release during the combustion process were determined. Moreover, their basic parameters were determined, such as maximum heat release HRmax, maximum heat release rate during combustion according to the kinetic x_{1max} and the diffusion combustion mechanism x_{2max}.

The course of the heat release rate is divided, in the physical sense, into two stages: the combustion phase according to the kinetic mechanism and the combustion course according to the diffusion mechanism, as shown in Figure 9. Kinetic combustion takes place after the fuel self-ignition. It is characterized by a sharp increase in the rate of heat release and a large increase in pressure in the cylinder. In older diesel engines, it was basically uncontrolled. In new generation diesel engines, the maximum kinetic combustion rate may be limited by using, for example, fuel pre-injections to shorten the auto-ignition delay period.

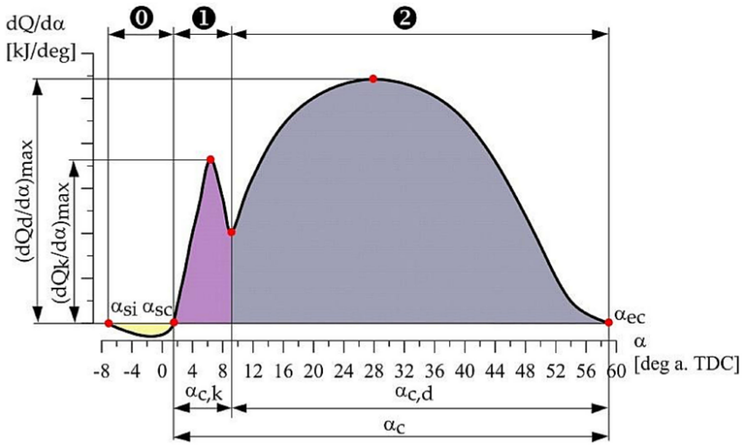

Figure 9. Characteristics of the heat release rate in a compression ignition engine divided into kinetic and diffusion combustion, where [46]: 0—auto-ignition delay period, 1—kinetic combustion, 2—diffusion combustion.

Figure 10 shows a comparison of example characteristics of the amount of heat release during the combustion process when the engine is fueled with DF, BBuE and RME and its operation according to load characteristics for 1400 rpm and load T = 20, 100, 250 and 400 Nm. On the other hand, Figure 11 shows the maximum amounts of heat release when the engine is fueled with the tested fuels and when it operates according to load characteristics for 1400 and 2200 rpm. As can be seen from these graphs, for low loads up to 150 Nm, the HR_{max} values for the tested fuels are very similar, while above this load, higher amounts of heat release occurred when the engine was fed with DF diesel.

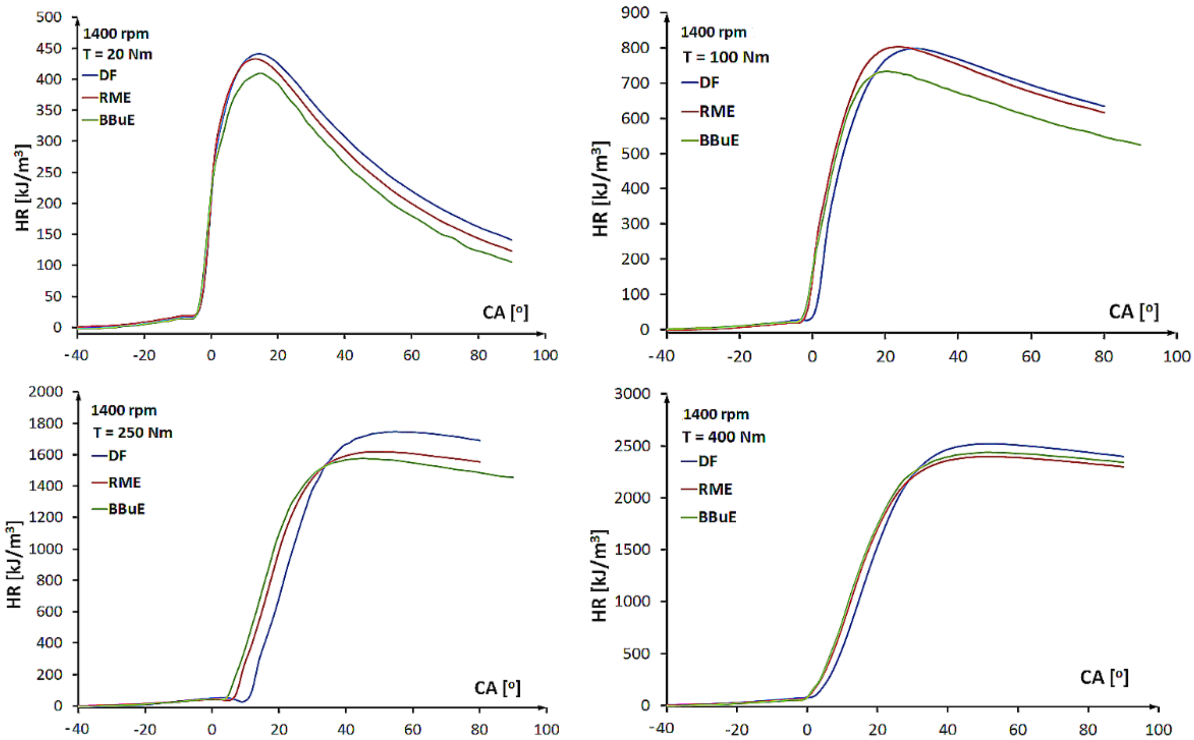

Figure 10. Examples of heat release characteristics of the combustion process.

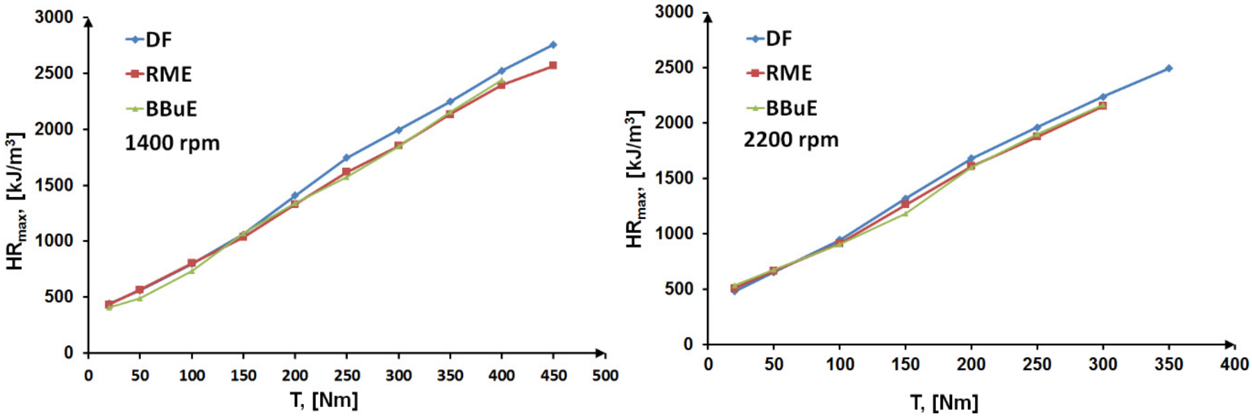

Figure 11. Maximum values of the amount of heat release HRmax during the combustion process.

Examples of heat release rate characteristics are shown in Figure 12. They were drawn up when the engine was operated according to load characteristics for 1400 rpm and loads T = 20, 50, 100 and 200 Nm. The determined maximum heat release rates during the combustion process occurring according to the kinetic mechanism x_{1max} and the diffusion mechanism x_{2max} are shown in Figures 13 and 14.

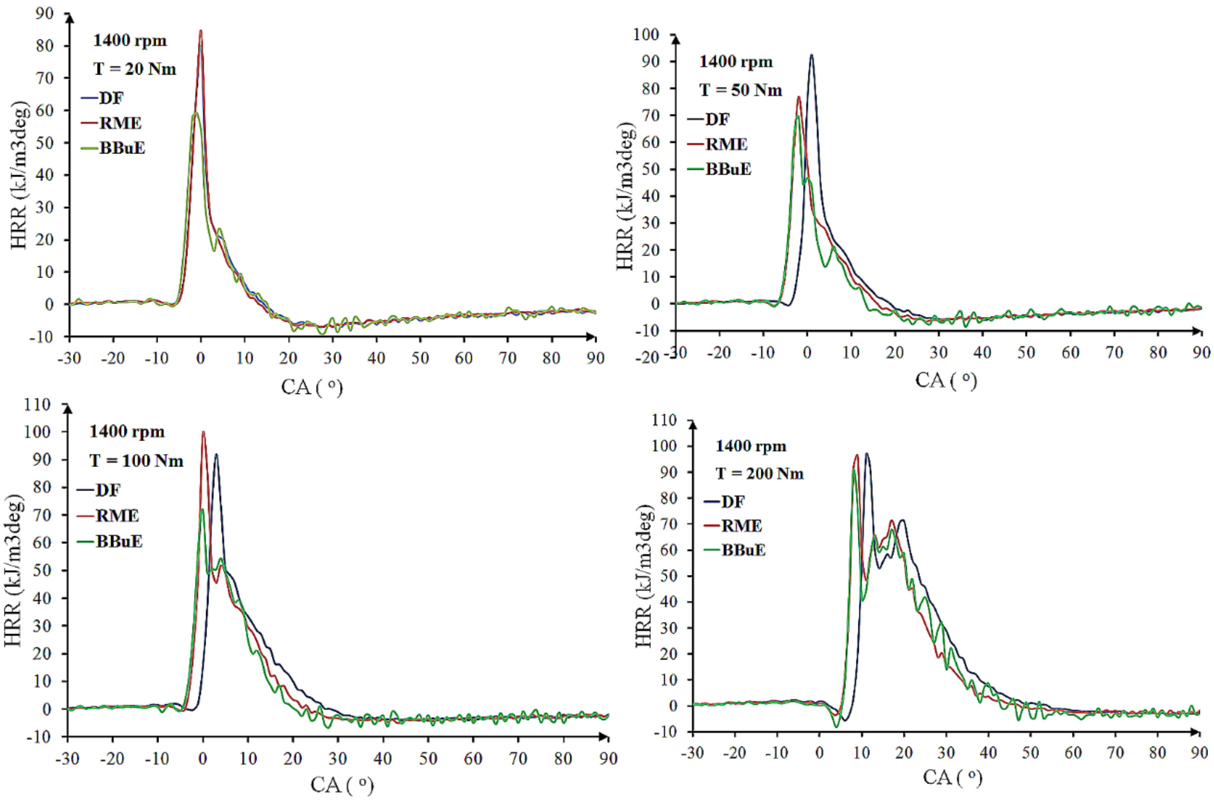

Figure 12. Example characteristics of the heat release rate during the combustion process.

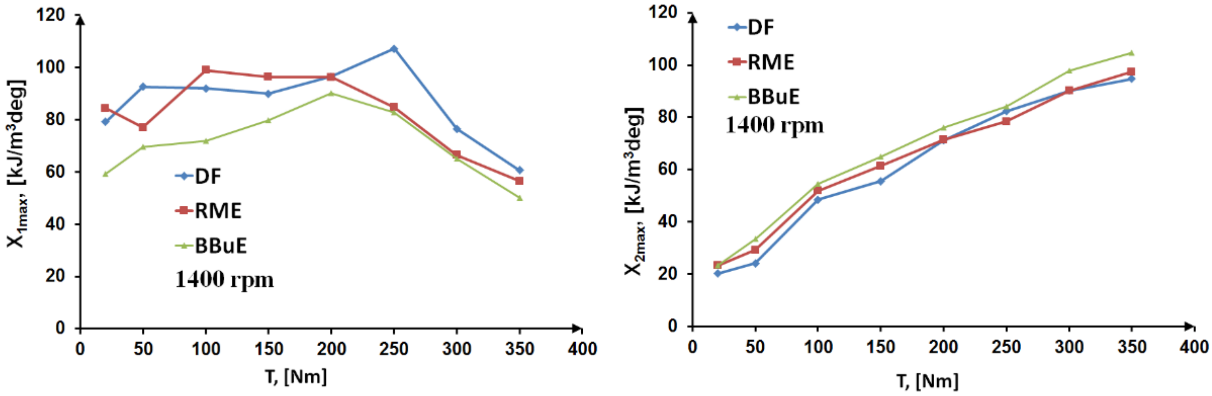

Figure 13. Maximum values of the first rate of heat release during the combustion process occurring according to the kinetic mechanism x_{1max} and the second rate of heat release during the combustion process occurring according to the diffusion mechanism x_{2max} when the engine is operated according to the load characteristics at a crankshaft speed of 1400 rpm and fed with the tested fuels.

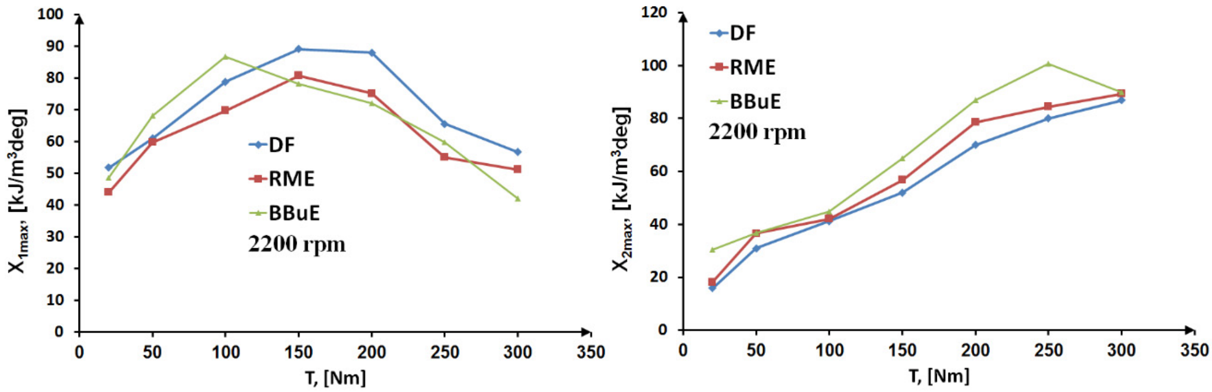

Figure 14. Maximum values of the first rate of heat release during the combustion process occurring according to the kinetic mechanism x_{1max} and the second rate of heat release during the combustion process occurring according to the diffusion mechanism x_{2max} when the engine is operated according to the load characteristics at a crankshaft speed of 2200 rpm and fed with the tested fuels.

The values of the first and second maximum heat release rates x_{1max} and x_{2max}, in addition to the type of fuel with which the engine is fed, are strongly influenced by the operating conditions and, above all, the engine load. This is confirmed by Figures 10 and 11. For the load characteristic curve at 1400 rpm with BBuE fuel, the lowest heat release rates occurred during the combustion process occurring according to the kinetic mechanism x_{1max}. On the other hand, for the maximum rate of heat release occurring according to the diffusion mechanism, the relationship is reversed where the highest values of x_{2max} occurred for BBuE fuel. In the case of the load characteristic of 2200 rpm feeding the engine with BBuE fuel, the values of x_{1max} compared to RME and DF fuels change as a function of engine load without a clear trend. The situation is different in the case of the maximum heat release rate proceeding according to the diffusion mechanism x_{2max}, where, as for 1400 rpm, the largest values of x_{2max} occurred for BBuE fuel and the smallest for DF diesel fuel, the reasons for which are the same properties of the fuels that cause higher combustion pressures when the engine is fed with biofuels. In this case, these results are similar to those of [15]. There, the authors unambiguously obtained higher combustion pressures and higher heat release rates when feeding the engine with RME fuel compared to diesel. When comparing the x1 max results for DF and RME, they coincide at most measurement points with the work [60] where the authors obtained lower heat release rates for biofuels relative to diesel.

But for x_{2max} the results are the opposite, where higher values of x2 max were obtained for RME fuel for most loads. A similar relationship is found for BBuE fuel. Similar relationships are confirmed by other studies [61], where it was observed that the amount of heat released in the pre-combustion phase X1 max for RME is always lower than for diesel. This may be due to the fact that this fuel has a higher cetane number than diesel. In contrast, the heat released in the diffusion combustion phase for RME is always higher than for diesel. This may also be related to the higher oxygen content of these fuels compared to DF.

Using the AVL IndiCom Mobile 2012 program, the values of crankshaft rotation angles were determined at which the fuel dose injected per cycle of the Perkins 1104D-44TA engine was burned to a certain degree: $\alpha_{5\%}$—5% of the burned total fuel dose, $\alpha_{10\%}$—10% of the burned total fuel dose, $\alpha_{50\%}$—50% of the burned total fuel dose and $\alpha_{90\%}$—90% of the burned total fuel dose. The beginning of the combustion process is defined as the burning of 5% of the fuel dose, while the burning of 90% of the fuel dose is defined as the end of the combustion process. The methodology for determining the angle of rotation of the crankshaft of the tested engine at which the fuel dose burned to a certain degree is shown in Figure 15.

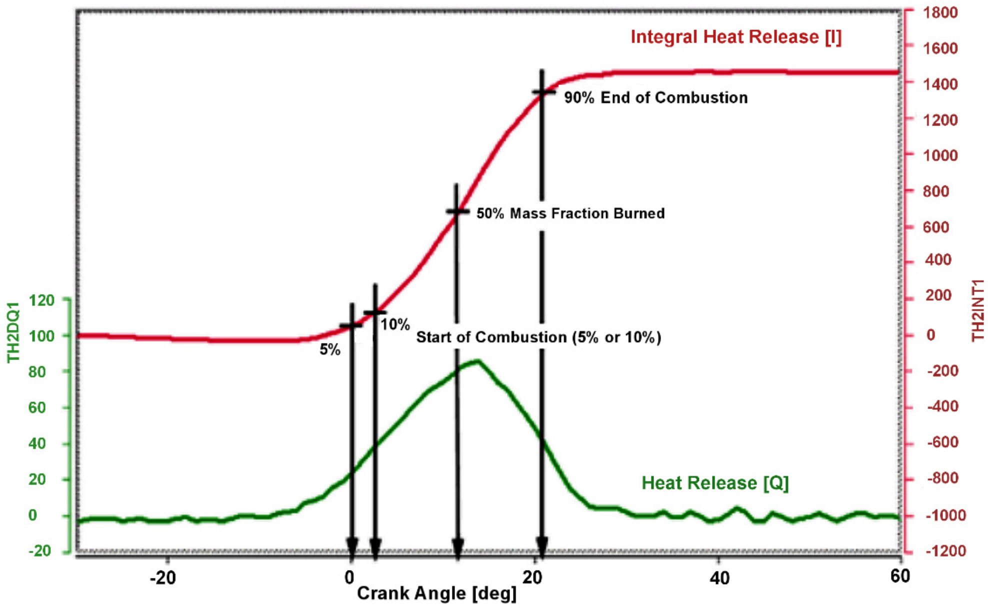

Figure 15. Methodology for the determination of the engine crankshaft rotation angles, at which the fuel dose has been burned out to the degree of 5, 10, 50 and 90% of the total fuel dose injected to the cylinder.

Figure 16 shows the angular values of the crankshaft revolutions of the tested engine at which 5, 10, 50 and 90% of the fuel dose was burned when it was operated according to load characteristics at 1400 rpm. Analyzing the angular values of burning 5, 10, 50, and 90% of the fuel dose for 1400 rpm, it can be seen that feeding the engine with BBuE and RME esters results in faster burning of the fuel dose compared to DF. Only for the 20 Nm load were values the same for all fuels.

This is due to the shorter auto-ignition delay for biofuels, but also to the composition and these fuels and above all to the high oxygen content. These results are consistent with the work of [62], where a shorter auto-ignition delay, i.e., an earlier start of combustion, was obtained for biofuels. In this case, the onset of combustion is identified with the burning of 5 or 10% of the fuel dose.

The results also indicate a shorter combustion period for RME and BBuE fuel compared to DF, which is in contrast to the results in the [61] paper.

Similar relationships are found when the engine is operated according to the load characteristic at 2200 rpm, where the fastest combustion of 10, 50 and 90% of the fuel dose was obtained when the engine was fed with BBuE esters. In the case of RME esters, these results are very similar to those for BBuE. In the case of DF fuel, the burning of the fuel dose occurred much later. For the crankshaft angle values for which a 5% fuel dose burnout occurred at loads between 20 and 150 Nm, feeding the DF engine, there is a faster fuel dose burnout. For loads greater than 200 Nm, the trend is reversed, and a faster 5% fuel dose firing occurs when feeding the BBuE and RME engine compared to the DF. The firing of 10, 50, and 90% of the fuel dose for 2200 rpm is similar to the 1400 rpm characteristic, occurring faster feeding the engine with BBuE and RME esters compared to DF.

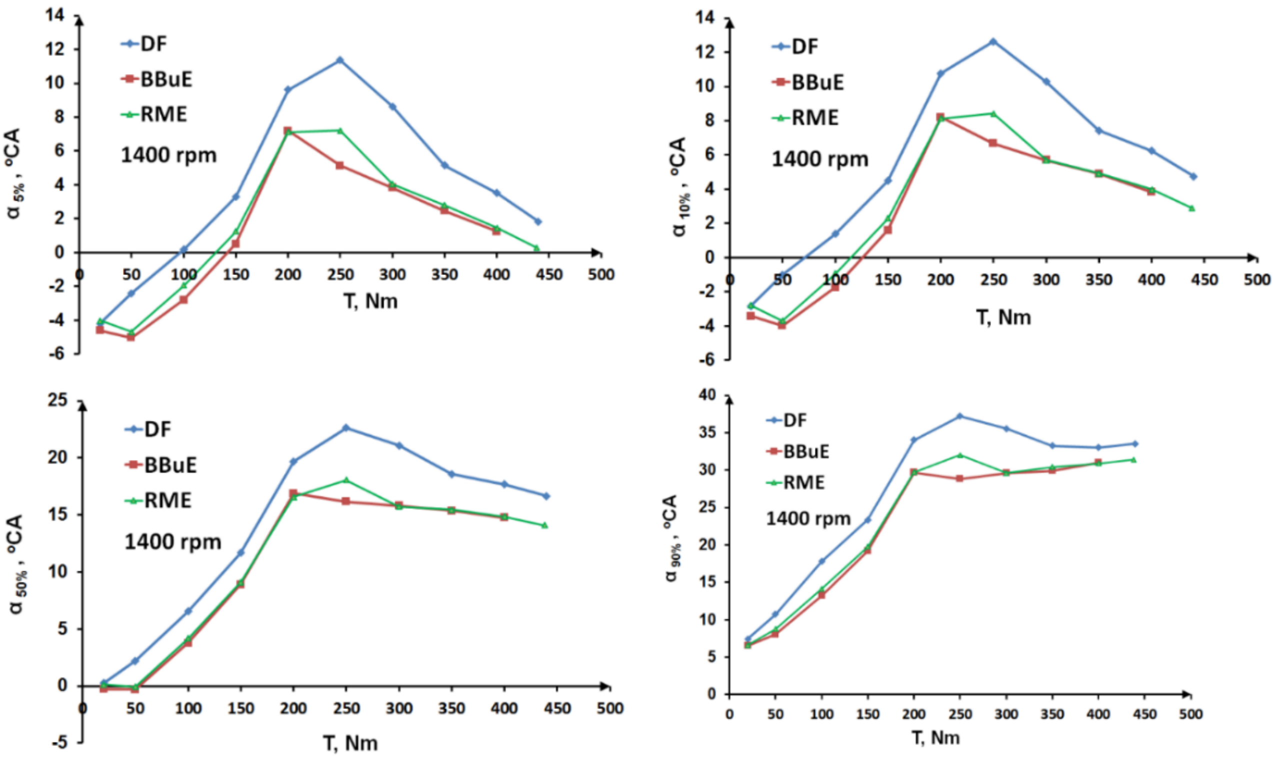

Figure 16. Angular values of crankshaft rotation of the engine at which 5, 10, 50, and 90% of the fuel dose was burned.

Figure 17 shows the angular values of the crankshaft revolutions of the tested engine, at which 5, 10, 50 and 90% of the fuel dose was burned when it was operated according to load characteristics at 2200 rpm.

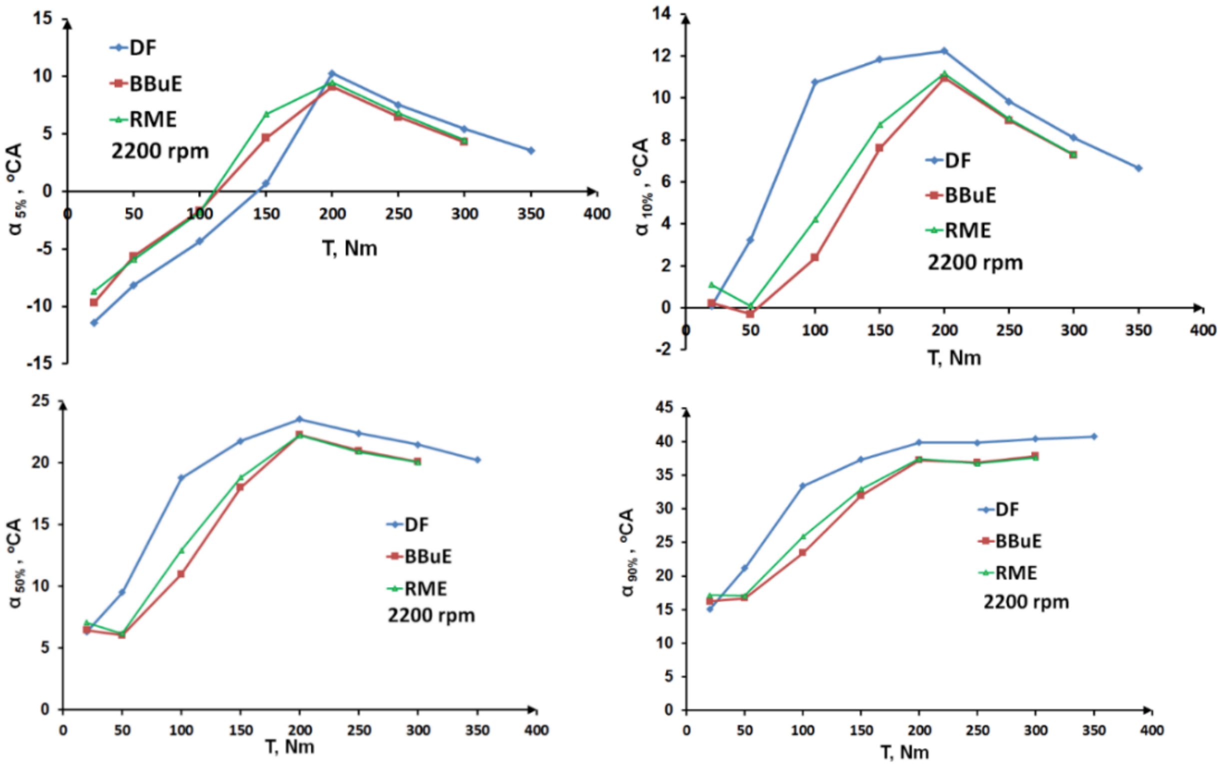

Figure 17. Angular values of crankshaft rotation of the engine at which 5, 10, 50 and 90% of the fuel dose was burned.

4. Conclusions

The results of the tests presented in this article have made it possible to determine the effect of feeding the engine under study with babassu butyl esters (BBuE), a second-generation biofuel, compared to feeding it with first-generation RME and, DF, on the combustion process.

The results of this study indicate that feeding the engine with DF resulted in the lowest fuel dose per duty cycle. For RME and BBuE fuels, this depends on the engine load. For low loads the consumption is higher for RME, while for higher loads the fuel consumption tends to increase for BBuE. This is due to the lower calorific value of the esters. In addition, feeding the engine with BBuE esters resulted in a reduction of the maximum torque. For 1400 rpm, the T value for BBuE was 400 Nm. For DF and RME, 440 Nm was obtained. At 2200 rpm, feeding the engine with BBuE and RME esters resulted in a decrease in torque to T = 300 Nm compared to DF T = 350 Nm. Feeding the engine with BBuE and RME fuel at most loads resulted in higher maximum combustion pressures compared to feeding the engine with DF fuel, which may be directly related to the higher cetane number of these fuels compared to DF and the oxygen content of these fuels.

The crankshaft rotation angular values at which the maximum combustion pressures occurred varied with load and engine speed, but without any clear effect of the type of fuel the engine was fed. When feeding the engine with BBuE fuel for most loads, larger increments in maximum combustion pressures were obtained compared to DF diesel, but smaller compared to the values obtained when feeding the engine with RME esters.

The analysis of the maximum heat release rates HRmax shows that feeding the engine with BBuE and RME esters compared to DF does not result in large differences. However, the values of the first and second maximum heat release rates x_{1max} and x_{2max}, in addition to the type of fuel, are strongly influenced by the operating conditions, especially the engine load.

At an engine speed of 1400 rpm and BBuE fuel, the lowest heat release rate values occurred during the combustion process following the kinetic mechanism of x_{1max}. For

x_{2max}, the relationship is reversed, where the highest values occurred for the BBuE fuel. For the 2200 rpm load characteristic, feeding the engine with BBuE fuel, the x_{1max} values compared to RME and DF fuels vary with engine load without a clear trend. In the case of x_{2max}, the re-location is similar to that for 1400 rpm, where the highest values occurred for the BBuE fuel and the lowest for the DF diesel.

Analysing the combustion angles for 5, 10, 50, and 90% of the fuel dose for most measurement points, feeding the engine with BBuE and RME esters results in faster combustion of the fuel dose compared to DF.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

CA	crank angle, deg
$dp/d\alpha$	degree of pressure build-up, MPa/deg
HR	heat release, kJ/m^3
HRR	heat release rates, kJ/m^3 deg
p	cylinder pressure, MPa
p_{max}	Maximum combustion pressure, MPa
T	torque, Nm
q	fuel dose per cycle, mg/cycle
x_{1max}	first maximum heat release rate, kJ/m^3 deg
x_{2max}	second maximum heat release rate, kJ/m^3 deg
α_{SI}	start of inection, deg
α_{SC}	start of combustion process, deg
αe_C	end of combustion process, deg
α_C	combustion duration, deg
$\alpha_{C,K}$	kinetic combustion phase, deg
$\alpha_{C,d}$	diffusion combustion phase, deg
$\alpha_{5\%}$	The angle of rotation of the crankshaft at which 5% of the fuel dose has been burned off, deg
$\alpha_{10\%}$	The angle of rotation of the crankshaft at which 10% of the fuel dose has been burned off, deg
$\alpha_{50\%}$	The angle of rotation of the crankshaft at which 50% of the fuel dose has been burned off, deg
$\alpha_{90\%}$	The angle of rotation of the crankshaft at which 90% of the fuel dose has been burned off, deg
$\alpha pmax$	the angle of rotation of the crankshaft at which the maximum combustion pressure occurred, deg
Abbreviations	
BBuE	babassu butyl esters
DF	diesel fuel
HVO	hydrotreated vegetable oil
RME	rapeseed methyl esters

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