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Evaluation of the heat release rate during the combustion process in the diesel engine chamber powered with fuel from renewable energy sources

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Abstract. The article describes the results of combustion of a mixture of PCOME (purified cooking oil esters) and bioethanol in the compression ignition Perkins 1104C-44 engine. The engine was prepared for use with the classic type of fuel – diesel oil, not biofuels. That is why bioethanol was added to ester in tests so that the basic physicochemical properties of the obtained mixture were as close as possible to diesel fuel. Thanks to this, the use of such fuel in the future would not require reworking or adjusting the settings of selected elements of the engine power supply system. During this case study, the engine performance and heat release rate were analyzed. For comparison, tests were carried out while powering the engine with ester fuel, 10 and 20 per cent mixtures of bioethanol and PCOME. The speed and load characteristics for each fuel were determined. This article presents selected characteristics where the biggest differences were noticed.

Key words: Heat Release Rate, alternative fuels, compression ignition engine, PCOME, biofuel, bioethanol.

1. Introduction

The world today is based on the use of chemical energy contained in fuels. The vast majority are fossil fuels. Their resources are limited, so there is a huge need to find their replacements. Biodiesel is one of the candidates. Biofuel, in this case, is defined as fatty acid esters from vegetable oils or animal fats [1–3]. These types of oils have significant physicochemical differences compared to traditional diesel fuel; therefore, their processing is required before use [3–5]. The treatment process can bring the physicochemical parameters of biofuels closer to traditional diesel oil only to a limited extent. That is why mixtures and additives of various biofuels are increasingly used [6, 7].

This article tries to explain how the use of bioethanol as an extra component of a mixture of PCOME – purified cooking oil methyl esters, can improve the operational properties of the engine. The physicochemical parameters of the biofuel like PCOME, affect the combustion process, especially fuel spray behaviour and ignition delay. The first parameter is dependent on inter alia fuel density or kinematic viscosity [1, 2]. Variables of fuel spray have influence over the duration of the ignition delay [2, 4]. Operating conditions are also dependent on the physicochemical parameters of the biofuel. Not always good for us as users. This type of fuel has operation problems during the winter period, especially with the cloud point and cold filter blocking temperature [2, 3].

Moreover, when PM decreases at some time NO_X increases. It depends on, inter alia, the heating value of fuel and parameters of the combustion process [1, 8, 9]. The goal of the authors is to find a popular component which can be used and solve a problem. In this case, we chose bioethanol. Firstly, bioethanol combines with methyl ester without any problems, without delamination of the fuel mixture [3, 10]. Furthermore, according to [3, 5, 7, 10] ethanol as part of a mixture with biodiesel can lower the use temperature. Also, the value of NO_X should slightly decrease. To verify the assumptions, the study included PCOME tests and two types of mixture with bioethanol (10% and 20%). Furthermore, performing parameters of the engine and energetic values of combustion process were analysed. Afterwards appointed emission of toxic exhaust components in relation to the EURO STAGE IIG standard in the test C1 ISO 8178. PCOME is one of the types of biofuels which can be qualified as fuel from waste sources. Bioethanol is an easy to produce, widely available fuel, which causes that a mixture of these two products can be a cheaper and common use alternative for diesel fuel.

The novelty of the article is the description and analysis of scientific research on the use of non-schematic fuel mixtures that come from renewable sources (bioethanol) and waste (PCOME). As a whole, they can be perceived as fuels of higher generations (i.e., these, whose development the European Union wants to invest in). Also, the original solution is the possibility of using these types of fuel mixture instead of diesel fuel without modification of the internal combustion engine. Moreover, finding the positive aspects of using these fuels will be carried out by analyzing selected parameters of the combustion process and assessing the emission of selected toxic exhaust components. Besides, the article systematizes the information and fills

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the gap in knowledge about the possibility of using mixtures of methyl ester-bioethanol to power a compression ignition engine.

In this article, authors will consider the analysis of the combustion process, like other researchers, based on thermodynamic parameters of the combustion process and emissions of toxic exhaust components.

2. Materials and Methods

During the implementation of the empirical studies, the authors used purified frying fat, which was the raw material for the esterification process [11]. First, the fat was purified by diluting with hexane, which facilitated the filtration, and also allowed to be washed with a solution of 40% H_2SO_4, H_2O and 20% KOH. After distilling hexane with reduced pressure in the advanced rotary evaporator, the properties of the oil were tested. As a result of the accomplished purification, parameters such as density, viscosity, acid number, and peroxide number were significantly reduced, reached values comparable or even lower than those determined for fresh rapeseed oil [10, 12–14].

Table 1
Basic physicochemical properties of fuel used in research, and for the prepared mixture

Parameter	Unit	PCOME	Bioethanol 99.9%	Diesel fuel
Cetane number	–	51	8	51
Higher heating value	MJ/kg	37.7	27.0	43.2
Density at 15°C	g/cm^3	0.882	0.795	0.820
Kinematic viscosity (∼40°C)	mm^2/s	5.28	0.91	2.92
Surface tension (20°C)	N/m	$3.58 \cdot 10^{-2}$	–	$2.4 \cdot 10^{-2}$
Ignition temperature	°C	170	–	102
Cloud point	°C	–2	–	–17
Cold filter blocking temperature	°C	–7	–	–20
Average elementary composition C H O	%	 76.8 12.2 11	 52.2 13.6 34.2	 87.2 12.7 0.1
Sulfur content S	mg/kg	8.05	–	10
Water content	mg/kg	111	–	200
Solid impurities content	mg/kg	17	–	5
Coke residue in a 10% distillation residue	% (m/m)	0.29	–	0.3
Research on the corrosive effect on copper plates	class	1	–	–

Next, the methyl ester of acids of the purified cooking oil – PCOME was obtained as a result of transesterification with the methanolic catalyst solution [11]. Bioethanol used in research as an addition to the methyl ester was produced by fermentation of the renewable organic material, then by distillation and dehydration. This last process raised the concentration of bioethanol to more than 99% [11, 14, 15].

Principal physicochemical properties of engine fuels used in research are shown in Table 1. For comparison, this table contains diesel fuel parameters. Moreover, Table 2 shows the basic physicochemical properties of fuel mixtures. The first one was a mixture of volume proportions 90% purified cooking oil esters and 10% of bioethanol (PCOME + 10BE), second one 80% of purified cooking oil esters and 20% of bioethanol (PCOME + 20BE).

Table 2
Basic physicochemical properties of mixtures

Parameter	Unit	PCOME + 10BE	PCOME + 20BE
Ignition temperature (Open crucible)	°C	35	31
Cloud point	°C	−2	−2.5
Cold filter blocking temperature	°C	−13	−15
Density at 15°C	g/cm^3	0.874	0.866
Kinematic viscosity at 40°C	mm^2/s	3.61	2.99
Heating value	MJ/kg	36.5	35.7

The test stand was equipped with Perkins 1104C-44 engine. This type of engine achieves Tier 2 for non-road emissions legislation. The parameters of the standard version of the Perkins 1104C-44 engine are shown in Table 3.

Table 3
Parameters of Perkins 1104C-44 engine [16]

Parameter	Unit	Value
Number of cylinders	–	4 Straight
Bore and stroke	mm	105×127
Displacement	dm^3	4.4
Aspiration	–	Natural
Cycle	–	4 Stroke
Combustion system	–	Direct injection
Fuel system	–	Injection pump
Compression ratio	–	19.3:1
Rated power output	kW	64 at 2400 rpm
Rated maximum torque	N·m	308 at 1200 rpm
Fuel injection advance angle	°CA BTDC	11
Injector opening pressure	MPa	29 ±0.5

During the research, it was assumed that engine control parameters could not be changed due to the fuel being tested. Therefore, the combustion process takes place without the fuel dose-volume modification. The authors intended to find a replacement for diesel and biodiesel fuels, that would work at the same factory engine settings. Therefore, such fuel could be used in already existing applications.

The engine tests were carried out for the factory static fuel injection advance angle, and injector type Delphi 2645K016, injection pressure 29 ±0.5 MPa. injection pump BOSCH R927 with a mechanical regulator. Fuel dose injected by volume without correction, according to the engine factory settings for biodiesel fuel.

The engine was installed on the test bench and equipped with measurement apparatus that could measure the engine torque by SCHENCK eddy-current brake, fuel consumption, and engine speed. For the quantification of working fluid pressure in the engine cylinder shown in Fig. 1, the high-speed measurement, and data acquisition system of AVL Indi Smart was used. The test bench was built according to norms BN74/1340-12 and PN-88/S-02005.

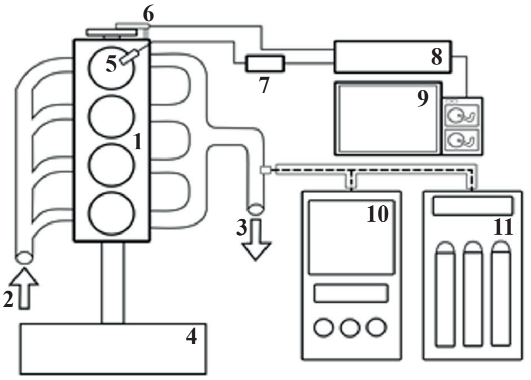

Fig. 1. The test stand [17]: 1 – engine (Perkins 1104-C44), 2 – air intake, 3 – exhaust outlet, 4 – eddy-current brake (Schenck); 5 – piezoelectric pressure sensor (AVL GM 12); 6 – crank position sensor, 7 – amplifier, 8 – system indication (AVL Indi Smart), 9 – data acquisition system, 10 – AVL CEB II, 11 – Horiba Mexa 1230 PM

In the empirical studies, the error of the AVL sensor, the load amplifier, and the A/C converter was calculated according to the method presented in [4]. The relative error of the working medium pressure in the combustion chamber was determined by the equation given in the same method, and the relative error of pressure was $\delta = 0.25\%$ (measuring range $0 \div 25$ MPa).

During the experiments, the speed characteristic of the engine performance was indicated in the range of rotation speed from 1000 rpm to 2200 rpm with the step of 200 rpm and conforming to the norm ISO 15550. Throughout the tests, the injection pump and injectors were non-modified and worked with the factory settings. The injection timing was regulated by the camshaft of the injection pump, and the point of the start of injection was considered as the elevation of the injector needle equal to 0.04 mm. Based on the empirically indicated working pressure in the combustion chamber and AVL software, the course of heat release rate (HRR) was established. It was done in order to indicate the beginning of combustion (rapid growth of work factor pressure in the combustion chamber).

One of the basic parameters of the combustion process in the CI engine is the characteristic of the approximation to the gross heat release rate. The characteristics of heat production during the combustion process mean the quantity and rate of release of the relative amount of heat during the combustion process, considering the heat exchanged with the walls of the combustion chamber. Heat release rate based on the data of the recorded in-cylinder pressure were analyzed at the same brake mean effective pressure. The heat release rate, HRR = dQ/dθ can be calculated by the following equation [2]:

$$HHR = \frac{dQ}{d\theta} = \frac{\gamma}{\gamma - 1} p \frac{dV}{d\theta} + \frac{1}{\gamma - 1} \gamma \frac{dp}{d\theta} \tag{1}$$

where $\frac{c_p}{c_v} = \gamma$, and $R = c_p - c_v$.

In addition, the effects of the combustion process in the form of concentrations of toxic exhaust components have also been determined (at all measuring points in accordance with the C1 test) on the basis of which the specific emissions of toxic exhaust components were obtained in accordance with the ISO 8178 standard for all 3 fuels. Figure 2 presents weight factors depending on rotational speed and load in the above test.

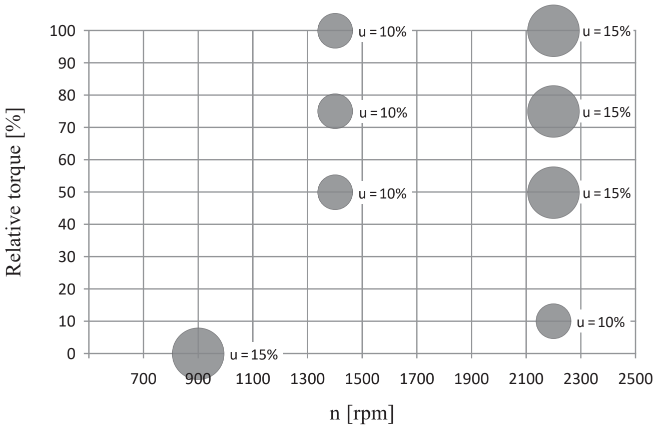

Fig. 2. Weight factors depend on rotational speed [18]

Based on the tests and the equations, hourly (2) and specific (3) energy consumption were also calculated [3]:

$$HEC = MFR \cdot HV, \left[\frac{MJ}{h}\right] \tag{2}$$

where MFR – mass flow rate [kg/h],
HV – heating value [MJ/kg].

$$SEC = SFC \cdot HV, \left[\frac{J}{(W \cdot h)}\right] \tag{3}$$

where SFC – specific fuel consumption [g/(kW·h)],
HV – heating value [MJ/kg].

Emission tests of toxic exhaust components were carried out on the AVL CEB II and Horiba Mexa 1230 PM analyzers. Table 4 shows the measurement ranges and measurement errors of toxin components AVL CEB II analyzer.

Table 4
The error associated with the AVL CEB II Emissions bench readings based on instrument specification

Species	Range	Analyzer Error
THC	10 ppm ÷ 5%	± 1 ppm
CO	Low: 50 ÷ 2500 High: 0.5 ÷ 10%	± 2 ppm ± 100 ppm
NO_X	Low: 30 ÷ 5000 High: 50 ÷ 10,000	± 1 ppm ± 2 ppm

Particulate matter (PM) was determined by an analyzer designed for continuous real-time measurements. Its measuring range was 0–300 mg/m^3.

3. Results

The first part of the discussed scientific research presents basic performance parameters in internal combustion engine powered by tested fuels (Figs. 3–8). The further part of the research presents the course of HRR (the most important parameter characterizing the combustion process) determined based on speed and load characteristics of the engine. The load characteristics were determined for 10, 25, 50, 75 and 100% of the load. The chapter presents selected results in which the largest changes were noticed. The last part of results contains a comparative graph of a specific emission of toxic exhaust components in relation to the EURO STAGE IIG standard in the test C1 ISO 8178.

Figure 3 shows torque parameter for three tested fuels described in the previous chapter – PCOME, mixture PCOME and 10% of bioethanol, mixture PCOME and 20% of bioethanol. The best result achieved pure PCOME, and the worst outcome reached mixture of PCOME and 20% of bioethanol. The most significant difference of torque is for point 2200 rpm and reaches 17 per cent, the smallest difference is for point 1400 rpm and is 7 per cent.

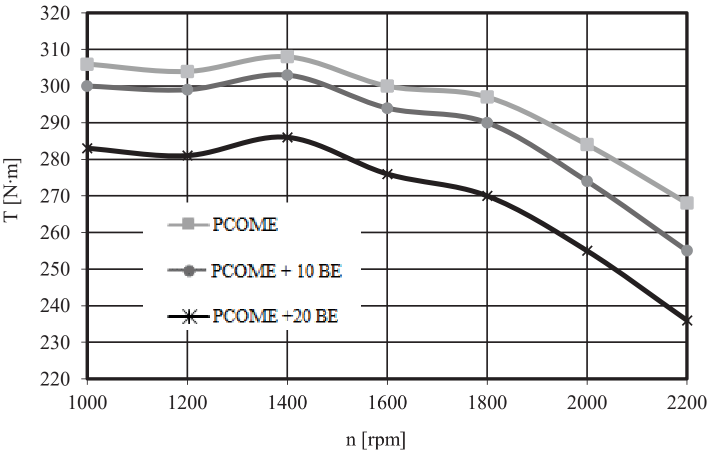

Fig. 3. Engine crankshaft torque (T) – speed characteristic

Figure 4 shows the power parameter for three tested fuels described in the previous chapter – PCOME, mixture PCOME and 10% of bioethanol, mixture PCOME and 20% of bioethanol. The best result achieved pure PCOME, and the worst outcome was reached by the mixture of PCOME and 20% of bioethanol. The smallest difference in power is for point 1400 rpm and is 6 per cent and the highest difference is for point 2200 rpm and reaches 9 per cent.

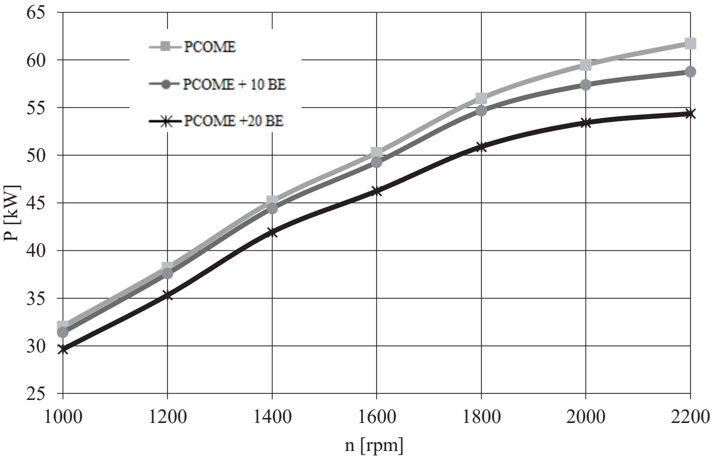

Fig. 4. Effective power (P) – speed characteristic

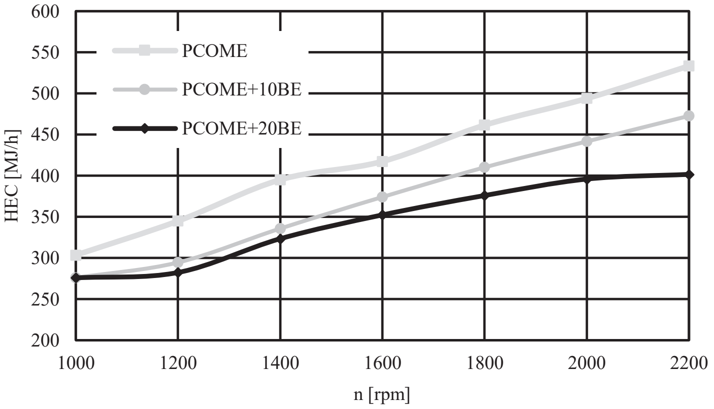

Fig. 5. Hourly energy consumption (HEC) – speed characteristic

Because of the large difference between the heating value of components used to preparation of mixtures, is better to use energy indicators such as hourly energy consumption and specific energy consumption. These two parameters were calculated based on Equation 2 and 3.

Figures 5 and 6 show the HEC and SEC parameters for PCOME, mixture PCOME and 10% of bioethanol, mixture PCOME and 20% of bioethanol. The highest energy consumption achieved pure PCOME for both characteristics. The lowest

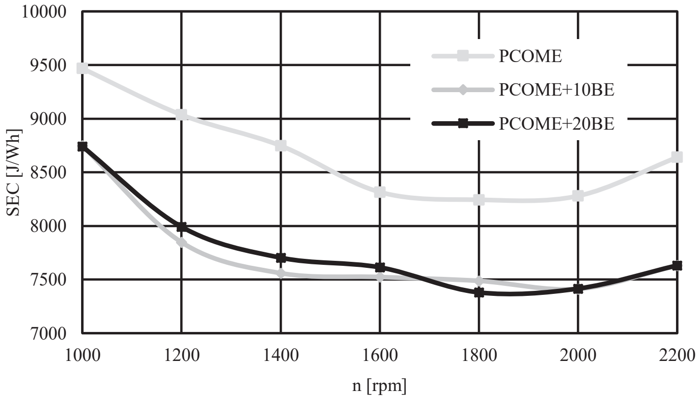

Fig. 6. Specific energy consumption (SEC) – speed characteristic

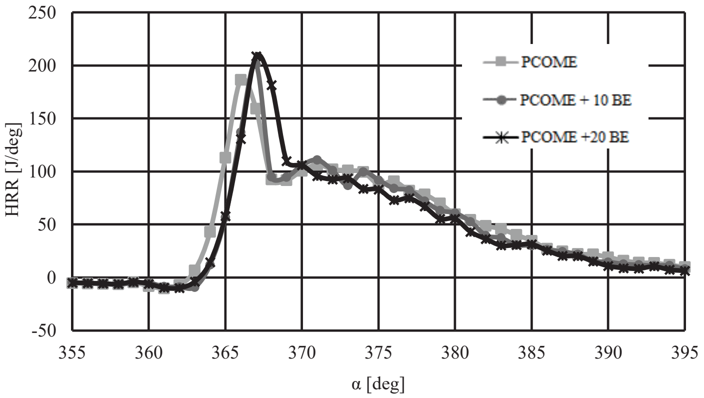

Fig. 8. Heat release rate (HRR) – load characteristic 1400 rpm – 50% load

outcome reached the mixture of PCOME and 20% of bioethanol, but for 2200 rpm difference between this mixture and PCOME and 10% of bioethanol are inconclusive.

Table 5 presents indicators of the combustion process for all tested fuels.

Table 5
Parameter of the combustion process – fuel injection advance angle (FIAE), the center of combustion angle (AI50)

Fuel	Parameter	rpm	1400			2200		
		% load	100	50	25	100	50	25
PCOME	FIAE	°CA	12.2	13.3	14.4	11.3	12.1	12.4
	AI50		15.8	14.1	12.3	17.5	16.2	13.6
PCOME + 10BE	FIAE		13.2	14.3	15.1	13.2	14.1	14.4
	AI50		15.2	12.4	11.6	16.8	15.5	13.5
PCOME + 20BE	FIAE		13.3	14.4	15.2	13.4	14.1	14.5
	AI50		14.4	12.1	11.2	16.5	15.3	12.9

Subsequently, Figs. 7–12 present the heat release rate (HRR) determined under different engine operating conditions. This parameter was calculated based on Eq. (1). Variables of this mathematical problem such as the working medium pressure (p) in the combustion chamber or the exponent of the polytropy (γ) and the instantaneous value of the volume of the combustion chamber were determined as part of the experiment.

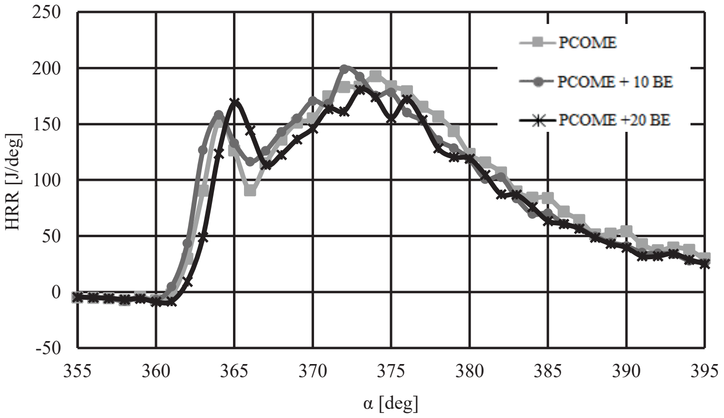

Fig. 7. Heat release rate (HRR) – load characteristic 1400 rpm – 100% load

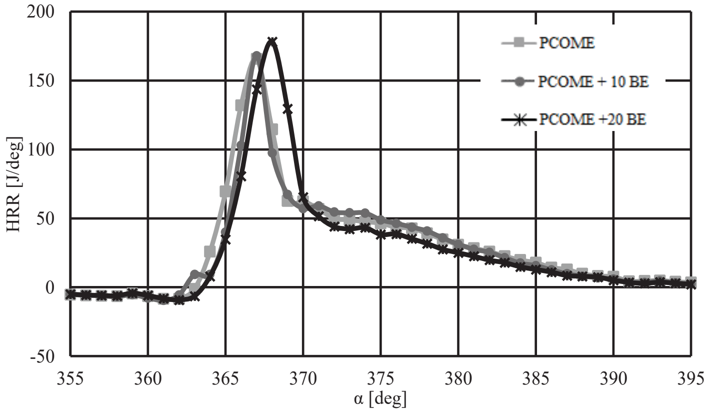

Fig. 9. Heat release rate (HRR) – load characteristic 1400 rpm – 25% load

Figures 7–9 show the HRR parameter for PCOME, mixture PCOME and 10% of bioethanol, mixture PCOME and 20% of bioethanol obtain at load 100%, 50%, 25% and speed 1400 rpm. The highest peak of energy achieved a mixture of PCOME and 20% of bioethanol. For this fuel we can observe a drift of self-ignition delay and it reached a maximum 2 degree after PCOME.

Figures 10–12 show the HRR parameter for PCOME, mixture PCOME and 10% of bioethanol, mixture PCOME and 20% of bioethanol obtained at load 100%, 50%, 25% and speed 2200 rpm. The highest peak of energy achieved again the mixture of PCOME and 20% of bioethanol. Once again for this fuel, we can observe a drift of self-ignition delay but this time it reached almost 4 degrees after PCOME.

Figure 13 shows the test results for specific exhaust emissions from a Perkins engine powered by three fuels. These tests were carried out according to the recommendations of the C1 test of ISO 8178.

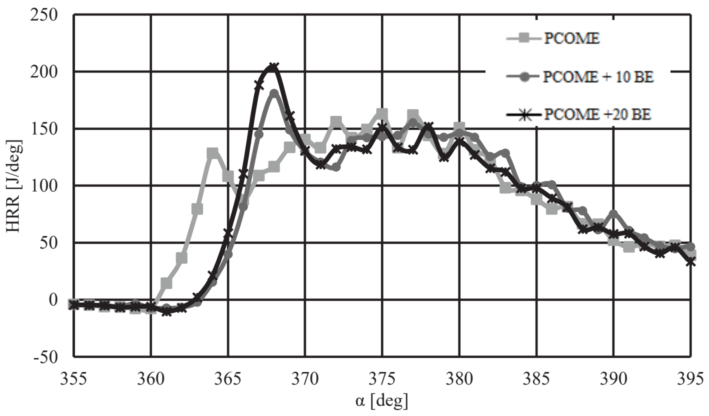

Fig. 10. Heat release rate (HRR) – load characteristic 2200 rpm – 100% load

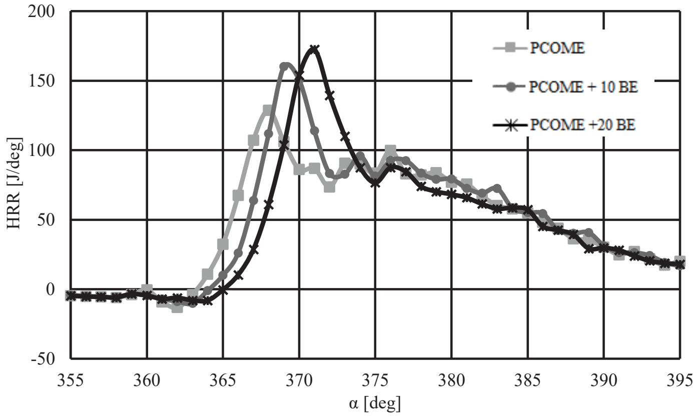

Fig. 11. Heat release rate (HRR) – load characteristic 2200 rpm – 50% load

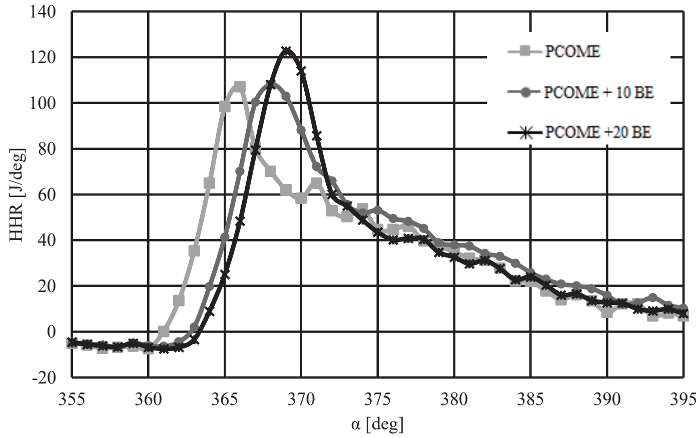

Fig. 12. Heat release rate (HRR) – load characteristic 2200 rpm – 25% load

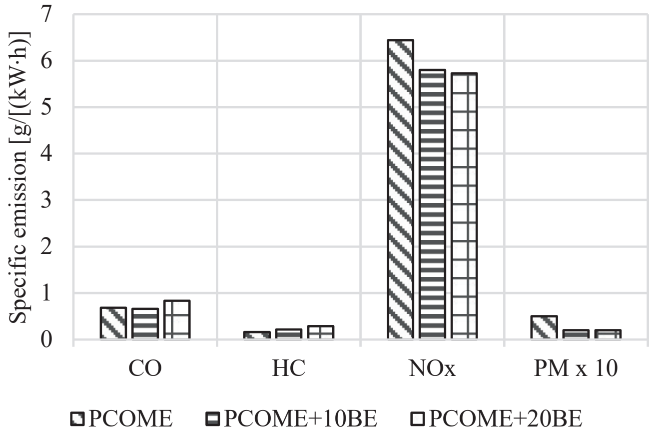

Fig. 13. Specific emission of toxic exhaust components in relation to the EURO STAGE IIG standard in the test C1 ISO 8178 when fueling the engine with 3 types of fuels

4. Discussion

The research presented in this article concerns selected, widely described problems of the combustion process in a diesel engine powered by new generation biofuels [6–7, 11–14]. Their application does not always result in maintaining engine operating parameters at the level that it could achieve with classic fuel supply [2–4, 9, 17]. However, their use is beneficial in terms of environmental protection by reducing the emission of toxic exhaust components to the atmosphere [3, 6, 8, 17]. The tests were carried out in accordance with the standards in force on engine braking systems [2, 3]. During the tests, the volumetric fuel dose was constant for given operating conditions so as to check the advisability of using mixtures of biofuel and bioethanol in real conditions at standard engine settings.

As a result of the analysis of the research, it was noticed that the value of the torque decreased with the concentration of bioethanol in the fuel mixture. Approximately averaging eleven and almost twenty-two per cent reductions compared to PCOME fuel (Fig. 3). The changes in maximum power are identical, i.e. an almost 5 and 12 per cent decrease compared to PCOME (Fig. 4). Regarding the speed characteristic of hourly energy consumption (Fig. 5), the decrease was the highest for 20% of the bioethanol concentration amounting to almost 22 per cent for the maximum speed and almost 15 per cent for 1000 rpm. Specific energy consumption in Fig. 6. The biggest difference is between PCOME and a mixture of PCOME and 10% bioethanol at 1400 rpm and is about 14 per cent. For a mixture of PCOME and 20% bioethanol close to 12 per cent.

A tendency to increase the auto-ignition delay was also observed along with the increase of bioethanol content, which is caused by other physicochemical properties of ester-bioethanol mixtures such as self-ignition ability, calorific value (Table 1). The parameters of the atomized fuel stream, which are affected by density, viscosity and surface tension, indirectly affect the auto-ignition delay.

Ethanol has a low ability to auto-ignite, so as an additive to fuel it extends the ignition delay, which was intentionally not corrected in these tests by non-standard settings of the fuel supply system (injector opening pressure, fuel injection angle/time).

The maximum difference of fuel injection advance angle is achieved at the maximum load at 2200 rpm and is about 2 degrees (Table 5). This has an impact on the combustion process presented on the HRR charts and the AI50 parameter. This parameter indicates that fuels with bioethanol, despite the prolonged self-ignition delay, achieve half the combustion process by up to 2 degrees of crankshaft rotation later compared to a pure ester (Table 5).

Subsequent charts of load characteristics (Figs. 7–12) showed an increase in HHR for higher concentrations of bioethanol in the tested fuel – by up to 36% in places (Fig. 10). In addition, in all the charts showing HRR processes, it can be seen that in the first period of the combustion process (kinetic combustion) the increase in HRR was greater in the case of an ester with the addition of bioethanol. However, in the second, longer part of the combustion process (diffusion combustion), the amount of heat generated is usually higher for pure ester. Such differences in HRR mileage, AI50 parameter and auto-ignition delay have an impact on the emission of toxic exhaust components in test C1 ISO 8178. A positive effect of using PCOME with the addition of bioethanol was the simultaneous reduction of specific NO_X and PM emissions with a slight increase in CO and HC emissions (Fig. 13).

Despite the worse selected engine performance indicators (Figs. 3–4), the above studies indicate that the addition of bioethanol to biofuel (PCOME) can be used in compression-ignition engines. Thanks to this solution, we obtain biofuel with better low-temperature properties (Tables 1–2) and unattainable among other single-component fuels, simultaneous lower emission of selected toxic exhaust components (NO_X, PM), which cannot be observed comparing these studies with the results of works [3, 6, 8, 9].

However, it is worth looking at future tests on the durability of the engine power supply system when using this type of fuel. The authors of this article want to solve this problem in the future.

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