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INFLUENCE OF CONTRIBUTION OF BIOFUELS DERIVED FROM RENEWABLE MATERIALS IN THE FUEL ON THE COMBUSTION PROCESS AND TOXIC COMPOUNDS EMISSION OF COMPRESSION IGNITION ENGINE

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Abstract

The use of liquid fuels as an energy source for internal combustion engines is unavoidable nowadays, further consumption increases with the development of industry and economic growth of the country. The abundance of the world in fossil fuels is a highly controversial issue; however, irrespective of forecasts concerning deposits of mineral fuels, undisputable fact is that these are resources, which will deplete. Economic, environmental and legislative issues also impose a limitation of use of fossil fuels. Under the problems associated with fossil fuels, an interesting alternative may be fuel derived from renewable sources. Biodiesel understood as a renewable energy source, used to feed compression ignition engines seem to be the ideal solution to meet energy needs, facing so called economic circulation era. Many research results confirm that combustion of pure biofuels in the currently highly advanced injection systems causes many problems. Different biofuel properties from diesel, such as viscosity or density directly influences on combustion process and emission of toxic components in the exhaust gases. Therefore, biodiesel blends with diesel fuel in all proportions; the combustion of such mixtures carries a number of benefits, from consumption reduction of non-renewable resources to reduction of harmful components in the exhaust gases. In this paper, the effect of doping methyl esters on the process of combustion and exhaust gases emissions in a compression ignition engine feed with mixtures of esters and diesel was examined. Tests were performed on four-cylinder, CI Andoria ACDR engine equipped with Common Rail fuel injection system. In order to investigate the combustion process, cylinder pressure and toxic components in exhaust gases steady state measurements were performed.

Keywords: *Engines, Fuel, Oils & Lubrication, Exhaust Emission & Ecology*

1. Introduction

Biodiesel is understood as an alternative fuel used for feeding CI engines obtained from renewable raw materials. The use of biodiesel is gaining recognition worldwide due to promising results relating to toxic exhaust component emissions compared to mineral diesel fuel. Biodiesel usually has a higher cetane number; it does not contain sulphur or aromatic compounds, and is also characterized by good lubricating properties compared to mineral fuels with reduced sulphur content [1]. Such properties as the stability, non-toxicity or biodegradability of the fuel also weigh in its favour. Biodiesel is also compatible with mineral diesel distribution infrastructure and, because of a higher flash point, is even safer in storage than mineral diesel. The most popular biodiesel types are esters of fatty acids and low molecular weight alcohols. The esters owe their popularity to properties close to mineral diesel and the multitude of plant and animal fatty raw materials from which they can be obtained.

Depending on the type of fatty raw material, its quantity and quality, economic aspects or the expected quality of final product, the transesterification reaction can be carried out in many ways using many methods [2-4]. Esters obtained from different raw materials or by different methods can differ in various properties, but they all mix with one another and with mineral diesel in any proportions, forming homogeneous, non-stratifying mixtures, due to which they can be used as an autonomous fuel, mixtures of different esters or as a bioadditive to mineral diesel fuel.

The use of biodiesel mixtures with mineral diesel for fuelling CI engines can be introduced without far-reaching modifications to existing engines. Compared to mineral diesel, combustion of Biodiesel emits less harmful gases such as sulphur oxide, carbon monoxide and dioxide, hydrocarbons [2, 5], thus providing a huge advantage over the vanishing fossil fuel resources used so far.

The goals of ensuring energy security, independency of fossil fuels and diversifying sources of obtaining energy, causing the demand for renewable fuels to increase rapidly. This has encouraged further interest in obtaining biodiesel and its use in CI engines. Numerous studies on the changes in fuel consumption, exhaust emissions and thermodynamic effectiveness of a biodiesel-fuelled engine have shown that compared to mineral diesel, fuel consumption generally rises, with an increasing biocomponent percentage, while a rise in the engine's thermodynamic efficiency is observed [6-10]. For low biodiesel admixtures in the fuel (< 20%), several authors have recorded a decrease in fuel consumption [11-13]. Different proportions of esters with mineral diesel have been tested, from several percent admixtures of esters [14] to tests on pure biodiesel [15]. Since the performance, characteristics of an engine fuelled with pure biodiesel or mixtures with mineral diesel depend on many factors, different for different engine models. It is important carefully analyse the test results. Due to such parameters as: engine capacity, fuel injection method, pressure and time, supercharging pressure and air quality and temperature, the test results can differ depending on the engine used in the tests or their methodology. Fatty material characteristics, transesterification efficiency and the quality of the obtained biofuels also significantly affect the results of the analysed studies. Regardless of the engine type, test type used proportions or the biodiesel type, the authors of all the studies confirm reductions in toxic component emissions and decreased exhaust smoke levels, which indicates that it is possible to fuel CI engines fitted with modern injection systems with renewable fuel mixtures, without any engine modifications [16].

2. Characteristics of the research material

Mixtures of mineral diesel and swine lard methyl esters obtained in the process of transesterification using an alkaline catalyst and methyl alcohol were tested. Transesterification was carried out under atmospheric pressure in laboratory conditions. Based on experimental tests and data in the literature [17], the proportions of the components used in the process were selected as follows: methyl alcohol in a molar ratio of 6:1 to the fatty material, potassium hydroxide was added in an amount of 0.9% by weight relative to weight of the fatty material. The process temperature was set at 60°C, the stirrer revolutions were set at min. 600 rpm and the process was conducted for 60 minutes. After the end of transesterification, the post-reaction mixture was subjected to the collection of excess alcohol, in a reduced pressure still. After alcohol collection, the mixture of esters and glycerol was separated by sedimentation in a separation funnel. The ester phase was additionally purified by filtering through a car fuel filter. The purified esters were then used to create mixtures of esters with mineral diesel with an ester content of 75%, 50% and 25%, respectively. All of these mixtures were tested concerning the most important physicochemical characteristics bearing on the possibility of their use for fuelling CI engines. The characteristics were analysed based on the PN-EN 14214 standard for esters and mixtures and PN-EN 590 for mineral diesel. The requirements set out by the standards were met by both pure esters and mixtures with mineral diesel. Tab. 1 presents the analysis results.

3. Test stand and methodology

The tests described below analysed the effect of mixtures of swine lard methyl esters on an engine controlled by a standard modern common rail fuel system. The tests were conducted on a four-cylinder ADCR CI engine manufactured by Andoria-Mot (Tab. 1). The engine has a standard CR 2.0 injection system, developed by Bosch and an EDC16C39 controller controls it. Depending on the engine's operating conditions, this controller carries out two different fuel injection strategies. At low revolutions and small loads in the medium speed range, divided injection is performed. In the remaining range, a single fuel charge is injected.

Tab. 1. Properties of obtained mixtures

Sample	Density at 15°C [kg/m^3]	Viscosity at 40°C [mm^2/s]	Flash point [°C]	Sulphur content [mg/kg]	Total contamination [mg/kg]	Oxidation stability [h]	Acid number [mg KOH/g]	CFPP [°C]
Pure esters	895.49	4.4528	134	1.44	22.5	1.32	0.14	13
75% Esters	879.79	3.924	80	2.31	17.6	6.64	0.13	8
50% Esters	869.59	3.5937	71	2.74	11.0	8.22	0.10	4
25% Esters	857.09	3.168	63	3.70	8.2	>19	0.10	1
Mineral diesel	844.49	2.8798	58	4.09	5.0	>19	0.11	-1

Tab. 2. Technical data of the ACDR engine

Engine	ADCR
Type	diesel, 4-stroke, turbocharged with intercooler
Fuel injection	Common Rail fuel accumulator system
Engine layout	4 cylinder inline, vertical
Cylinder diameter / piston travel	94 / 95 mm
Piston displacement volume	2636 cm3
Compression ratio	17.5 : 1
Rated power* / rotational speed	85 kW / 3700 rpm
Max. torque* / rotational speed	250 Nm / 1800-2200 rpm
Min. idle rotational speed	750 rpm
Fuel consumption at torque peak*	210 g/kWh
Injection system (Bosch)	accumulator injection system (Common Rail) CR2.0
Turbocharger	radial, with exhaust extraction valve
EGR system	pneumatic EGR valve with exhaust cooler

The tested engine was installed on a test bed stand available at the Department of Mechatronics and IT education of the UWM in Olsztyn. The test stand was described in detail in previous reports by the author [18].

Cylinder pressure changes were recorded during the tests. A piezoelectric pressure sensor (Type 6056A from Kistler) installed in one of the cylinders, in place of the heater plug, was used for pressure recording.

The sensor combined with a Type 5018A charge amplifier was connected via a DAQ card to a PC. The software for pressure measurement result acquisition was written based on the National Instruments LabVIEW environment. The measurement of dynamic pressure with respective rotation angle values was provided by an optical encoder, mounted on the crankshaft. The angle-marking gauge resolution was 720 points/revolution, which enabled pressure recording every 1° of crankshaft revolution, in the full range of the engine's work cycle.

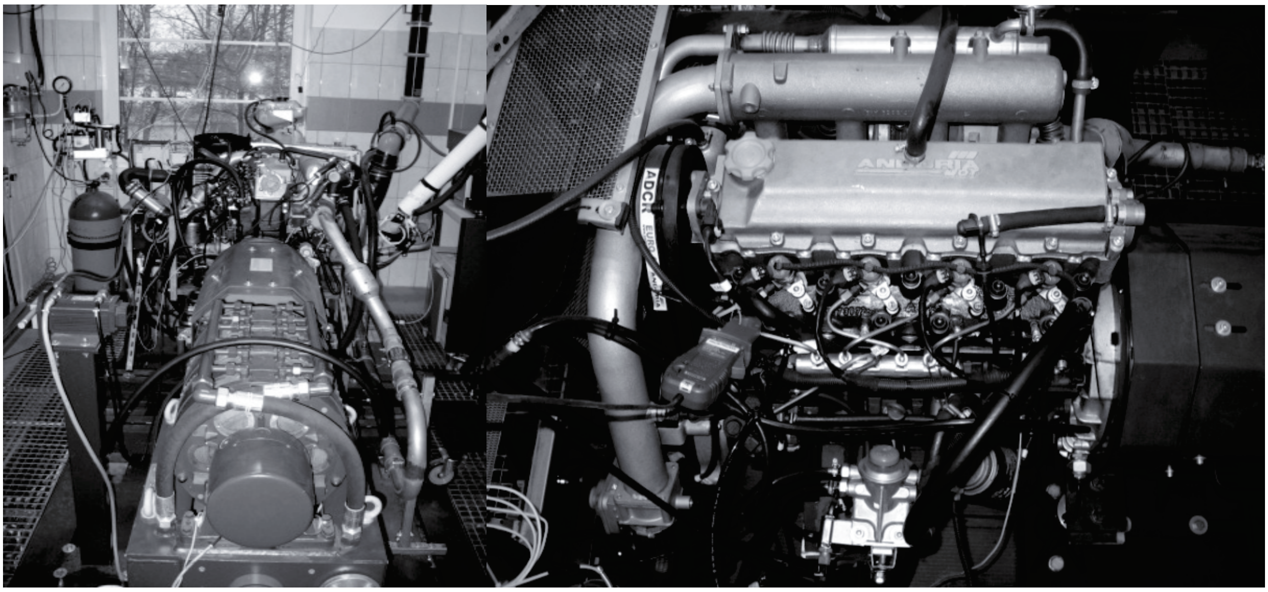

Fig. 1. Test stand with the ADCR engine installed on the test bed

Additionally, to determine the moment of injection, a current clamp was mounted on the injector of the indicated cylinder, which allowed recording the current changes at the injector coil.

The ignition start angle was established from the analysis of second pressure derivative changes [19]. Maximum pressure rise acceleration indicated the moment when ignition had occurred.

Engine speed during the measurements was stabilized by an AVL THA100 engine speed control system.

The mass of air inducted by the engine (G_{air}), fuel consumption (G_{fuel}) and air temperature in the suction manifold (T_{air}) were recorded during the tests. The temperatures of the engine coolant and lubricating oil were stabilized at 85°C and 95°C, respectively.

4. Results

The tests were conducted for two speeds:

- 1500 rpm – at which the engine controller injects two diesel fuel charges (pilot and main charge),
- 3400 rpm – at which the controller injects a single fuel charge regardless of the load.

Engine tests at the given speeds were conducted for different loads and proportions of biofuel admixtures to mineral diesel (presented in Tab. 1). The scope of the performed tests with the basic engine operating parameters has been compiled in a table:

Tab. 3. Scope of the performed tests with the basic engine operating parameters

	N [RPM]	T [Nm]	P [kW]	G_{air} [kg/h]	T_{air} [°C]	G_{fuel} [l/h]	Exhaust gasses opacity [%]
ON	1500	50	7.9	99	34	3.1	1.3
		100	15.8	106	38	5.6	3.8
		150	23.6	146.6	43	7.3	2.5
	3000	50	15.8	188	53	8.8	2.3
		100	31.5	270	69	13.8	5.7
		150	47.5	304	86	17.1	8.3
25%E	1500	50	7.9	98	34	3.1	0.45
		100	15.9	106	36	5.5	1.5
		150	23.6	146	41	7.3	0.8
	3000	50	15.7	187.5	50	8.6	0.3
		100	31.4	273	63	12.4	0.9
		150	47.1	308	80	18.0	2.5
50%E	1500	50	7.9	86.5	35	3.4	0.65
		100	15.8	109	37	5.5	0.8
		150	23.8	145	42	7.5	0.8
	3000	50	15.7	190	52	8.4	0.4
		100	31.5	275.5	60	12.9	0.7
		150	47.1	311	82	17.1	1.4
75%E	1500	50	7.9	90	34	3.5	0.5
		100	15.8	111	36	5.8	0.5
		150	23.6	145	41	7.8	0.7
	3000	50	15.4	194	51	8.6	0.3
		100	31.4	280	65	13.3	0.5
		150	46.9	316	85	18.9	0.85

The recorded cylinder pressure changes, selected injector excitation current changes, and standard deviation changes for the pressure signal under individual cycles, as the measure of engine operation unrepeatability, are presented below.

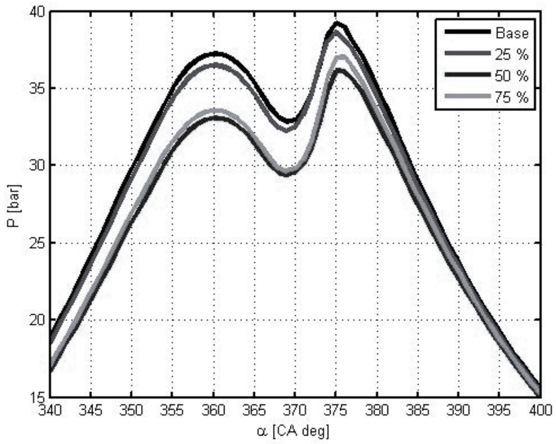

Fig. 2. Average cylinder pressure changes for N = 1500 rpm, T = 50 Nm and different ester percentages in the used fuel

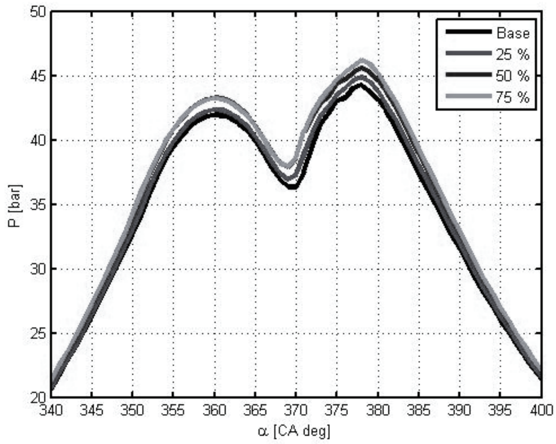

Fig. 3. Average cylinder pressure changes for N = 1500 rpm, T = 100 Nm and different ester percentages in the used fuel

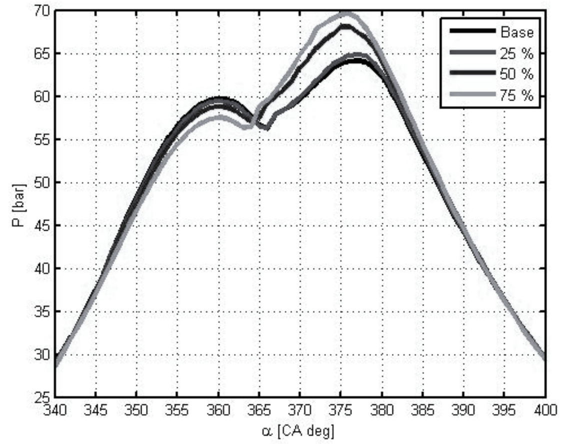

Fig. 4. Average cylinder pressure changes for N = 1500 rpm, T = 150 Nm and different ester percentages in the used fuel

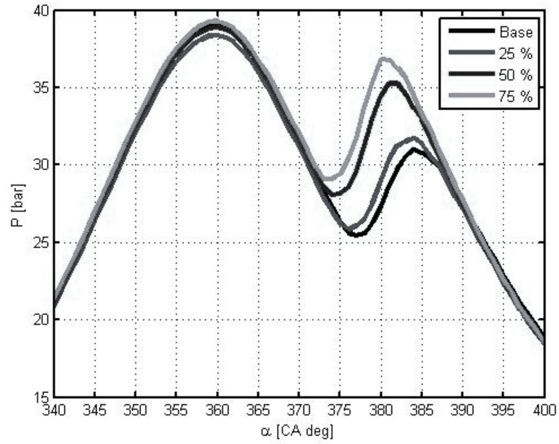

Fig. 5. Average cylinder pressure changes for N = 3000 rpm, T = 50 Nm and different ester percentages in the used fuel

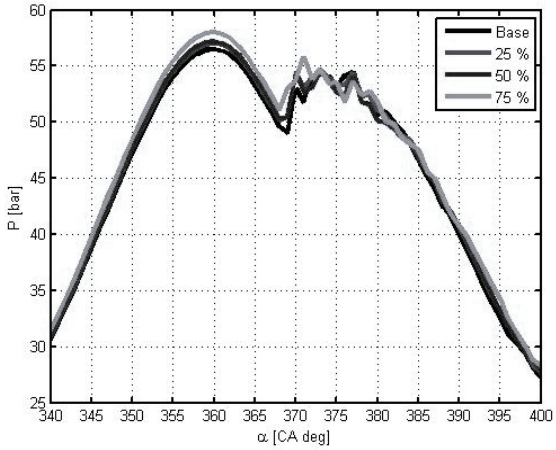

Fig. 6. Average cylinder pressure changes for N = 3000 rpm, T = 100 Nm and different ester percentages in the used fuel

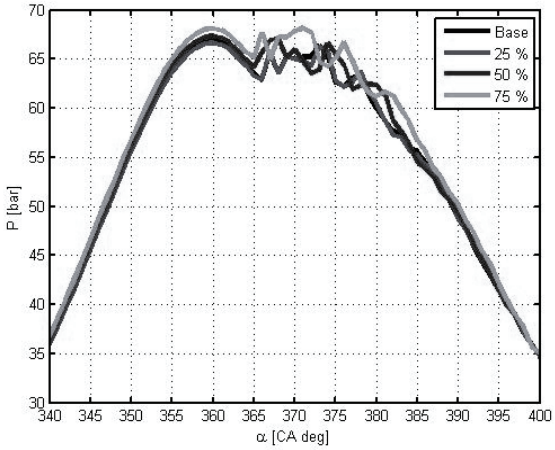

Fig. 7. Average cylinder pressure changes for N = 3000 rpm, T = 150 Nm and different ester percentages in the used fuel

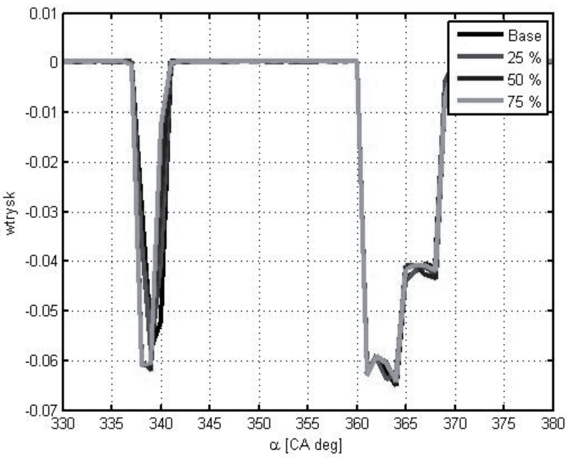

Fig. 8. Average injector coil current changes for N = 1500 rpm, T = 100 Nm and different ester percentages in the used fuel

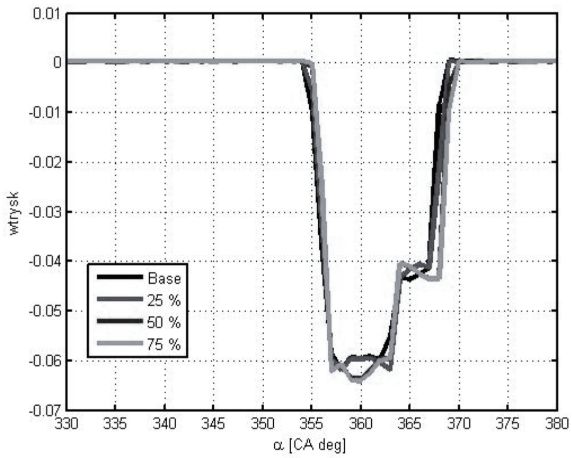

Fig. 9. Average injector coil current changes for N = 3000 rpm, T = 1000 Nm and different ester percentages in the used fuel

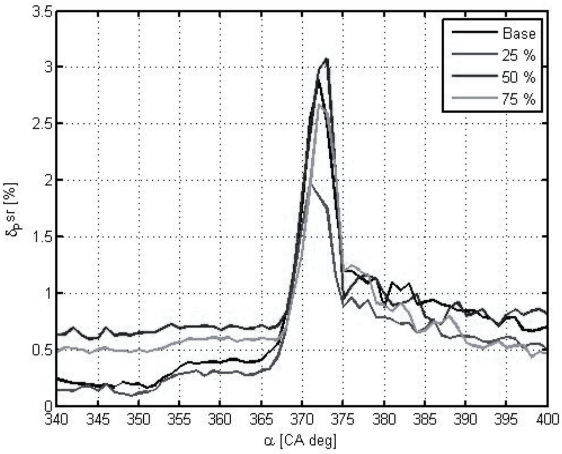

Fig. 10. Cylinder pressure signal standard deviation changes for N = 1500 rpm, T = 50 Nm and different ester percentages in the used fuel

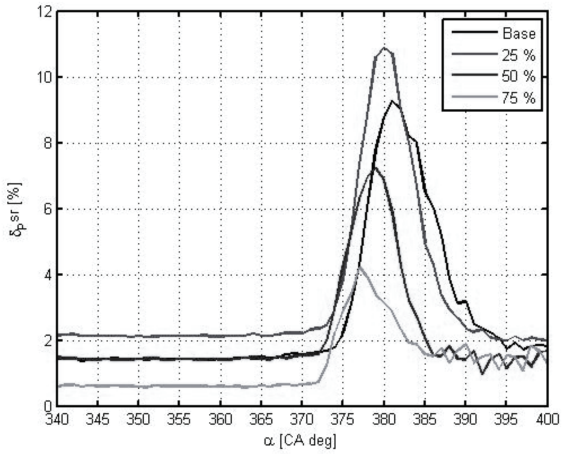

Fig. 11. Cylinder pressure signal standard deviation changes for N = 3000 rpm, T = 50 Nm and different ester percentages in the used fuel

5. Analysis of results

In analysing the current changes in the injector coil, it can be concluded that regardless of the used fuel, the engine controller used the same fuelling strategy for individual working points. Example changes are presented in (Fig. 8 and 9). For a speed of 1500 rpm, a small fuel charge was applied as the preliminary injection to prepare the conditions for the combustion of the main charge injected near TDC. For a speed of 3000 rpm, only the main injection was performed. The factory-mounted engine controller did not react to the fuel change with an observable individual charge injection angle displacement for any working point. This fact also provides a comparative evaluation of the combustion process itself (Fig. 2-7). For all the measurement samples except for N = 1500 rpm, T = 50 Nm (Fig. 2), increasing the swine lard methyl ester percentage in the fuel generated higher maximum pressure values for individual working points. This shows that an admixture of the tested esters to diesel fuel causes faster fuel combustion, which generates higher heat emission rates and, consequently, higher maximum pressure. Fig. 2 seems to confirm this thesis because of a visible, significant pressure rise in the main charge combustion phase for fuels with ester percentages of 50% and 75%. In this case, the globally lower pressure values recorded for these fuels, compared to pure diesel fuel and a 25% ester admixture, result from a reduced degree of supercharging, which can be easily observed when comparing the respective air consumption values. This is most likely the controller's reaction to an excessively rapid combustion of mixtures with high ester content. On a smaller scale, similar engine controller behaviour can be observed by analysing Fig. 4.

The use of animal fat admixtures clearly improves the fuel's ability to self-ignite. For a speed of 1500 rpm and a load of 50 Nm (Fig. 2), the fuel self-ignites 1 degree of crankshaft revolution earlier than diesel fuel for a 75% animal ester mixture, despite much lower cylinder temperatures and pressures at the time of injection (resulting from the reduced degree of supercharging).

Analogically, when similar pressure and temperature values are reached in the compression process (Fig. 5), the shortening of the self-ignition delay relative to pure diesel fuel can reach 5° of crankshaft revolution for a 75% ester admixture.

Operation repeatability was similar for all the sample (Fig. 10 and 11). No tendency for uneven combustion, mistiming or knocking combustion was observed. The engine worked evenly even when fuels with 75% of animal fat esters were used.

Fuel consumption remained at a similar level for all the tested fuels. Without knowledge of the calorific value of the tested mixtures, a conclusion on efficiency was not possible.

6. Summary

It was demonstrated that it is possible to combust fuels with a very high content of esters of fatty acids of animal origin, reaching 75%. The engine worked correctly for all working points. No adverse phenomena related to misfiring or knocking combustion were observed. The working method was similar to work on the base fuel.

It was also demonstrated that the fuel admixed with esters of fatty acids of animal origin is characterized by higher heat release rates during combustion. It is expected that this will increase combustion efficiency for specific fuel compositions, with proper selection of the engine's control parameters. On the other hand, lack of such control can lead to excessively high thermal and mechanical loads in engine components. It has been demonstrated that the controller of the tested engine reacts to an increased combustion rate with a reduced degree of supercharging, which decreases the maximum pressure indicated in the cylinder. The fuel with an admixture also has a better ability to self-ignite, which leads to a considerably reduced self-ignition delay.

The exhaust smoke level decreased with an increasing percentage of esters in the mixture used for fuelling the tested engine. The obtained results concern the set engine operating conditions, tests in intermediate states should be conducted for a full conclusion on the emission properties of the analysed mixtures.

Pure esters were not used in this research due to a high level of impurities (Tab. 1), which could cause damage to the injection system. It appears that after proper filtration it is possible to use 100% diesel fuel substitution with esters of fatty acids of animal origin in modern engines with electronic injection, without modification of the engine's control program.

This bodes well for the possibility of using meat industry waste for biofuel or biocomponent production. An evaluation of engine emission performance using this fuel remains a separate issue, which will be the subject of another publication.

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