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Investigation of biofuel combustion process in direct injection diesel engine

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Abstract: In contemporary transport sector and especially in the agricultural production, there is a large possibility of using alternative engine fuels. In the case of agricultural applications, the largest number of agricultural machinery's propulsion engines is diesel, which allows the use of various vegetable oils as propellants. However, this implies that these vegetable oils have been treated by appropriate esterification procedures and adapted for smooth use in engines. Such fuels are generally called biodiesel as well. This paper will present some results of an investigation of the combustion process of rapeseed methyl ester of a single-cylinder direct injection diesel engine designed to drive smaller agricultural machinery, thus engines. The results of the research are presented in the variant of the charged engine, whereby the charging process was performed by an external energy source (electromotor and Roots compressor) under laboratory conditions.

Keywords: Diesel engine, combustion processes, biofuel

1. Introduction

In the last several decades, there had been a large expansion of the use of alternative fuels for exploitation of various agricultural productions and usage of these fuels for agricultural machinery. As the matter of fact, this trend is present in developing countries, although developed countries also invest heavily in technologies for the production and use of agricultural raw materials to produce alternative fuels. Particular attention should be paid to the possibility of producing fuel from raw materials for low cost and environmental reasons. This paperwork will briefly present the results of a combustion process study in a single-cylinder direct injection diesel engine powered by rapeseed methyl ester (RME) and standard for Euro diesel (ED) as diesel.

2. General characteristics of the combustion process of diesel engines

The fuel combustion process in a diesel engine is a fundamental process that determines the quality of the entire duty cycle and the engine [1], [2]. Full knowledge of the physicochemical mechanism of this process is very complex. This is because in this case it is a rather chaotic character of this process, being very sensitive even to relatively small variations of certain influencing factors. This is primarily from the spatial and temporal indeterminacy of a series of physicochemical phenomena and processes, as well as their interactions during combustion. This is because there is a difference in the physical condition of the individual fuel particles, the degree of oxygen concentration in the chamber, and the temperature level in some parts of the combustion chamber. At the same time, knowing the mechanism of the combustion process gives the ability to control this process in the nominal phase.

The standard diesel fuel is Euro Diesel (ED) fuel and the engines are tuned to optimally handle this fuel. However, given the fact that a large number of usable plants that could obtain motor fuels, it is of interest to study the possibility of running engines on these fuels, and the combustion characteristics of these biofuels, as well as their impact on durability and reliability, an also therefore on the environmental performance of the engines. Much research has been done in this regard [3], [4], [5], [6], [7]. In the EU, for the most practical reasons, rapeseed oil in the form of rapeseed methyl ester (MER) is used as biofuel for diesel engines, which must have the characteristics required by EN 14214. This methyl ester is a biodiesel fuel in the RME designation and the results of research into the combustion process of this fuel into diesel the direct injection engine will be discussed below. In general, fatty acid methyl esters, and therefore rapeseed methyl ester RME ($C_{15}H_{31}CO_2CH_3$), can be treated as lucrative fuel for diesel engines.

The difference between fatty acid methyl esters and standard diesel is mainly due to different viscosities. Further, also because of the lower thermal value of fatty acid methyl esters, engine power is generally lower and fuel consumption higher.

3. Laboratory Installation

For the purpose of experimental research, a suitable measuring installation was established at the Institute of Motors, Faculty of Mechanical Engineering in Belgrade. Figure 1 shows the measuring system, containing the test engine, the engine supercharging system components and the dynamometer brake, while measuring devices with sensors and other components and a system for measuring exhaust composition are not shown. The method of processing the indicator diagram, the model of calculating the law of heat release, the method of calculating the amount of recirculated gases and the duration of individual combustion stages, etc., were also developed.

Experimental research has made it possible to acquire fundamental knowledge about the character of the combustion process of various biofuels and their mixtures with standard reference diesel fuels, as well as the characteristics of the exhaust emissions at the engine operation of these fuels. Comparison of combustion and exhaust process characteristics in the supercharged and intake variants of the testing diesel engine duty cycle and the corresponding exhaust emission was also investigated and performed. Since the analysis of the combustion process characteristics is based on a comparison of the process operation of engines with standard diesel fuels and biofuels as well as their mixtures, the basic measuring value on the basis of which this comparison will be made is the pressure flow in the engine cylinder. In addition to recording the flow of pressure as a dynamic fast-variable size, other key parameters of the workflow of the test engine were also recorded, such as:

1. RPM
2. Torque
3. Effective power
4. Volume flow
5. Intake of air
6. Pressure of intake air
7. Critical temperature
8. Derivation and composition of exhaust gaseous
9. Smoke

This paperwork will present the results of a combustion process study with standard diesel engine oil (ED) and rapeseed methyl ester (MER) with a brief analysis of the results obtained. It should also be noted that during long-term operation of the engine on the specified alternative fuel, no harmful effects on the engine or impairment of engine reliability were observed. During the research when changing the operating mode, the engine always operated for 10 to 15 minutes in the selected mode due to the stabilization of all operatinparameters and the thermal state of the engine. After that, the measurement of these parameters wasstarted on the measurement acquisition system ADS2000.

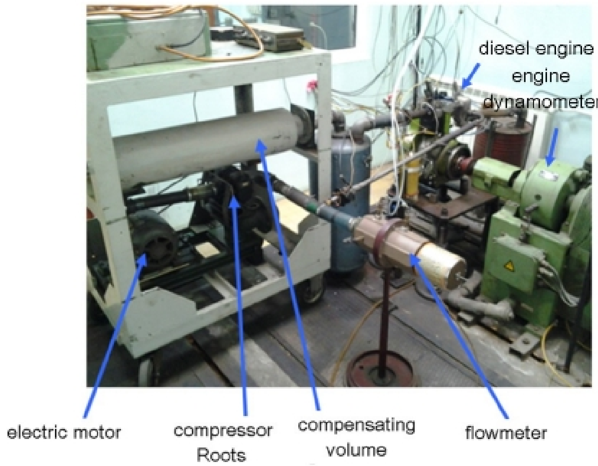

Figure 1. Photo of a laboratory installation formed in Institute of Motors, Faculty of Mechanical Engineering

Calculation of the heat release flow is performed by numerical methods using a mathematical model, based on the measured pressure flow in the cylinder of the engine. Therefore, it is very important that the angular resolution of the pressure flow acquisition resolution be sufficiently high to achieve the accuracy of the calculated heat release law within very acceptable limits with an error of only 0.15%, [1], [8], [9].

Differential flow of heat release $dQ_g / d\alpha$ or the rate of heat release is obtained from Equation:

$$\frac{dQ_g}{d\alpha} = m\frac{du}{d\alpha} + p_z\frac{dV_z}{d\alpha} + u\frac{dm_g}{d\alpha} + (h-u)\frac{dm_{pr}}{d\alpha} + p_z\frac{dQ_w}{d\alpha} \tag{1}$$

and numerical solution of this equation gives an integral or cumulative heat release flow: $dQ_g(\alpha)$. For modeling the heat transfer by convection, the known Newton relation can be used for convective heat transfer in the form:

$$\frac{dQ_w}{dt} = \alpha_w \cdot A_w\left(T_g - T_w\right) \tag{2}$$

where:

$\frac{dQ_w}{dt}$ - the heat flux between the gas and the workspace wall,

α_w - heat transfer coefficient.

A_w - encompassing workspace area.

T_g - The mean temperature of the gas in the workspace

T_w - the mean temperature of the wall (chamber) of the workspace.

The heat flow between the gas and the walls of the working area achieved by radiation can be determined from the equation [2]:

$$\frac{dQ_w}{dt} = \beta \cdot \sigma \cdot A_w \left(\bar{T}_g^4 - T_w^4 \right) \quad (3)$$

Where:

$\sigma = 5.67 . 10^{-8}$ (Wm^{-2} K^{-4}) - Stefan-Boltzmann constant

β - coefficient of proportionality

3.1 Experimental equipment and set up

The engine used for the research was LDA450, domestic production from the factory May 21 - Belgrade, and the technical specifications of the engine are given in Table 1. The engine was powered by a Roots engine-powered compressor system.

Table 1. Main specifications of test engine

Engine type	Diesel 4 stroke, direct injection, air cooled, single cylinder for agricultural application
Bore/stroke	85/80 mm
Compression ratio	1:17,5
Max. power output	5 kW/2500 rpm
Fueling system	High pressure pump, injector with 4 jets, (4 x 0.28 mm)

3.2 Fuel properties

The experimental fuel is produced from crude oil of rapeseed by the transesterification process so that it meets the requirements of EN14214: 2010. In this way, this fuel, by its physicochemical characteristics, approaches the diesel fuel produced according to the standard SRPS EN 519: 2010, which is important especially in terms of viscosity.

Table 2. Test fuel properties

	Diesel (ED)	MER100
Density [kg l^{-1}]	0.828	0.88
Lower caloric value [kJ kg^{-1}]	41494	37631
Kinematic viscosity [mm^2 s^{-1}]	3.16	4.59
Stoichiometric air mass [kg kg^{-1}]	15.08	12.64
$O_2/C/H_2$ content [kg kg^{-1}]	0.0/0.8496/0.1504	0.120/0.772/0.12

4. Results and discussion

Characteristics of the combustion process were determined first when working with diesel fuel and then with the specified alternative fuel - rapeseed methyl ester, after which the obtained results were compared. During engine operation, very quiet operation was observed with relatively low noise levels, especially during biofuel operation. Occasional disassembly of the injector did not reveal any increased soot deposits on the nozzle. Also, no increased contamination of engine oil with soot or acid particles was noted.

4.1 Examination and derivation of result

Figure 1 shows the pressure flows in the cylinder of the engine, as well as the mean cycle temperatures for biodiesel of 100% rapeseed methyl mercury (REM100) at the rated engine load, that is, for the nominal cycle fuel quantity. Appropriate comparative diagrams for reference diesel fuel (ED) are also given.

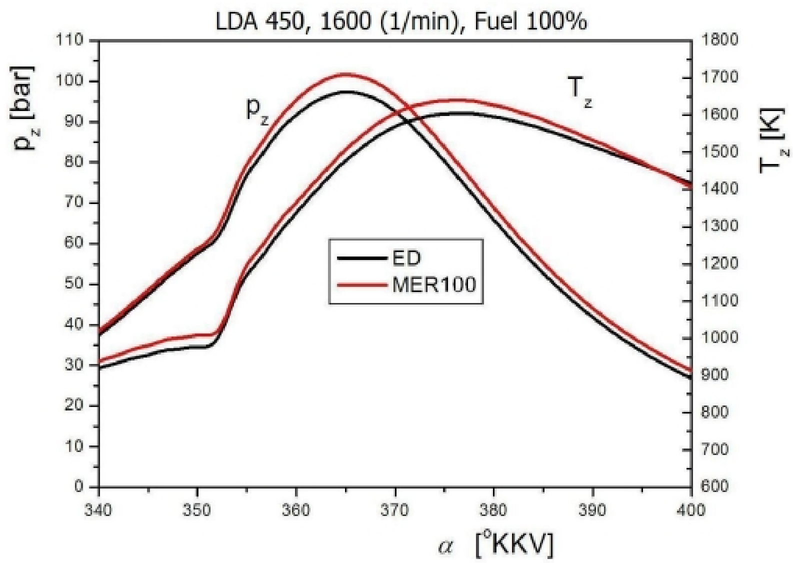

Figure 1. Pressure flows - pz and temperatures - Tz in the cylinder of the engine when operating with pure diesel fuel (ED) and pure rapeseed methyl ester (RME100)

It can be seen from the figure that when operating with the RME100 the maximum cycle pressure is slightly higher than when operating with the reference diesel fuel. Specifically, the values are 101.61 bar at 4.8 $^o CA$ behind TDC for RME100 biodiesel versus 97.38 bar at 5 $^o CA$ behind TDC for reference diesel. The difference in the value of the maximum of the cylinder pressure is relatively small and is 4.3% at practically the same angle of the crankshaft of the engine. It can be observed that the maximums of pressure in the cylinder are reached quite early behind the TDC, indicating the need to optimize the injection angle. Attention should be paid to this because the operation of a cylinder with a cylinder pressure that is too close to the TDC can shorten its service life.

The mean cycle temperature is higher for the RME100 than for the reference diesel engine. In the first case, the maximum value is 1669.8 K to 376.6 $^o CA$ compared to the diesel use case when this value is 1605.1 K to 377.2 $^o CA$. This fact can have a negative effect on the NOx emission during engine operation on this biofuel due to the known sensitivity of the rate of formation of nitric oxides to the temperature level of the engine life cycle as well as to the temperature values in individual local zones of the combustion chamber.

4.1.1 The effect of biofuels on the law of heat release (HRR)

Figure 3 shows the heat release law for pure biodiesel - MER100 and for reference diesel fuel. The co-firing period - pps for the MER100 biodiesel is shorter than for the reference diesel fuel, Figure 3. The start of combustion, where the reference line is zero, is at 350.85 $^o CA$ for the MER100 and at 351.2 $^o CA$ for the diesel fuel. Taking into account the start of injection for these two fuels, *i.e.* the moment of needle withdrawal followed by the appropriate sensor, it can be calculated that the co-combustion period - pps for the MER100 is shorter by 0.55 $^o CA$ than for the diesel fuel, which can be easily seen in Figure 4 which is an enlarged area of the HRR diagram in the area of combustion onset.

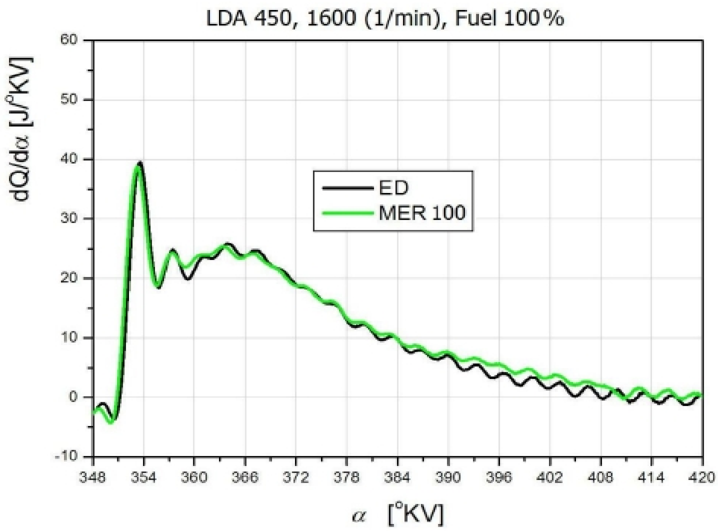

Figure 3. Law RME100 combustion of diesel fuel and reference

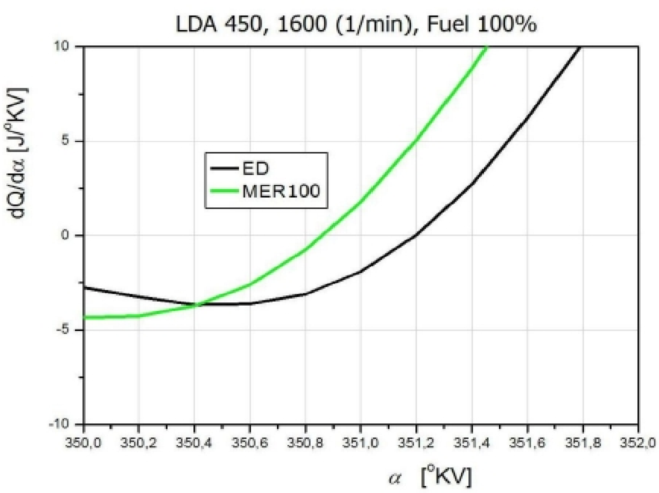

Figure 4. The difference in the start of combustion and MER100 reference diesel fuel

The maximum values of the differential law of combustion of biodiesel RME100 and its mixture RME50 are lower than when working with diesel fuel. Specifically, for RME100 fuel, this value is 38.8 $J/^{o}CA$ at 353.2 ^{o}CA versus diesel when 39.5 $J/^{o}CA$ at 353.6 ^{o}CA. Otherwise, the maximum heat release law for biodiesel is also achieved slightly earlier in this case than for diesel.

This is because, as stated earlier, the cooldown - pps for RME100 biodiesel is shorter than for diesel fuel, so that the second combustion phase, ie unregulated combustion period, is less pronounced when working on biodiesel. On the other hand, due to the slightly longer pps when working with diesel fuel, the accumulated amount of fuel in the combustion chamber increases during this period, resulting in a slightly higher value of the maximum of the combustion law.

Conclusion

The results of the research briefly presented in this paper indicate that there are no particularly large differences in the dynamics of the combustion process if biodiesel produced from rapeseed oil is used as the engine fuel compared to that obtained with diesel fuel. Also, the reliability of the engine is not compromised, and the amount of soot deposited on the injector nozzles and in the combustion, area is within acceptable limits. From this it can be concluded that rapeseed methyl ester is an excellent fuel for the propulsion of engines of agricultural machinery, if it is manufactured to the applicable standards for this type of fuel.

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