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Evaluation of selected combustion parameters in a compression-ignition engine powered by hydrogenated vegetable oil (HVO)

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The article carries out a detailed analysis and evaluation of indicators related to the combustion process (pressure and temperature in the engine combustion chamber, heat release rate, heat release fraction) in a JCB 444 TA4i compression-ignition engine fuelled with diesel and hydrogenated vegetable oil (HVO). During the empirical tests, the operation of the exhaust gas recirculation (EGR) system was stopped, and no other changes were made to the engine settings (factory settings were used). In the first stage, the empirical tests were carried out on the speed characteristics of an engine dynamometer. Then, an experiment was carried out at the engine crankshaft speed corresponding to the maximum torque - which consisted of determining the indicators related to the combustion process at a constant mass flow of fuel: diesel and HVO fuel. This provided information on the effect of hydrogenated vegetable oil on the combustion process in relation to the diesel engine feed. The conclusions drawn from the empirical study can be used to develop guidelines to change the operating map of a compression-ignition engine when it is fed with hydrogenated vegetable oil.

Keywords: *combustion process, compression-ignition engine, hydrogenated vegetable oil*

1. Introduction

Due to the targets set by the EU institutions regarding standards for emissions of toxic components from exhaust gases, the automotive industry will be forced to undergo a decarbonization process. Unfortunately, the time given by EU regulations to carry out this process is very short. This will, of course, force companies and enterprises to make rapid changes in organization and management. The problem is that if the entire process of training, testing, implementation, budgeting, and purchasing in the automotive market is to be carried out reliably, this process takes years. Many companies have fleets of vehicles and are looking for solutions to reduce CO_2 emissions [2, 18, 23]. At the same time, these companies would not want to change the composition of their fleets from internal combustion engine vehicles to electric motor vehicles. One solution could be to fuel internal combustion engines with fuels with similar physical and chemical properties to diesel [4, 6]. Such fuels include those derived from biomass, i.e., from vegetable oils, animal fats, and waste oils. All these components can be used as raw materials for alternative fuels. The group of alternative fuels includes higher fatty acid methyl esters (FAME) [10, 11]. These are fuels produced from oilseed crops such as linseed, rapeseed, or soybeans by transesterification [12, 18]. FAME fuels have several advantages over diesel, such as reduced emissions of hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM) and better ignition [20]. However, FAME fuel applications also come with limitations. FAME fuel can cause corrosion of storage tanks and also has a higher viscosity, which negatively affects fuel injection [4]. An alternative to FAME fuel can be hydrotreated vegetable oil (HVO). It is a synthetic liquid biofuel free of aromatics, oxygen, and sulfur [22]. In terms of chemical structure, it consists of straight-chain paraffinic hydrocarbons. The fuel is produced by hydrotreating vegetable oils, animal fats, or waste oils [17, 24]. Advantages of HVO fuel over FAME fuel include high heating value and cetane value, lower turbidity temperature, and lower viscosity [5, 16]. With fewer unsaturated compounds in its chemical composition, HVO shows better oxidation stability than FAME [1]. HVO fuel consists of straight-chain alkanes, which have a lower activation energy than the aromatic ring-shaped hydrocarbons of which diesel fuel is composed [24]. Therefore, the ignition delay for HVO fuel is shorter than diesel fuel's. This results in an earlier onset of combustion and reduced HC, CO, and PM emissions compared to diesel [15]. This shows that hydrotreated vegetable oil can be the fuel that can allow to plan and manage the reduction of carbon footprint and toxic emissions in the fleet in a professional manner [13]. However, studies are needed to show the effect of feeding an internal combustion engine with HVO fuel compared to diesel fuel on engine performance, power, torque, fuel consumption, efficiency, pressures, HRR, fuel dose burn rate, and combustion chamber temperature.

2. Materials and methods

The main objective of this research is to compare the effects of HVO fuel relative to diesel fuel on the combustion and performance of a JCB 444 TA4i-81 compression-ignition engine located on an engine dynamometer in the Combustion Engine Laboratory at the Institute of Vehicles and Working Machines at Warsaw University of Technology without interfering with the engine's design and control system.

2.1. Fuel

Two fuels were considered in the present study. Tests were performed for hydrotreated HVO vegetable oil and, comparatively, for diesel fuel. Table 1 summarizes the key physical and chemical parameters of the fuels along with the methods of determination. Table 1 shows the basic physical and chemical properties of the two fuels and provides the basis for the hypothesis that HVO fuel can be used as a replacement fuel for diesel fuel.

Table 1. Selected properties of HVO and diesel oil [8, 9, 20, 23]

Properties	Method	Unit	HVO	Diesel fuel
Density at 15°C	–	kg/m^3	777.8	830.6
Kinematic viscosity	–	mm^2/s	2.646	2.969
Dynamic viscosity	–	Pa·s	$2.06 \cdot 10^{-3}$	$2.47 \cdot 10^{-3}$
Cetane number	ASTM D613	–	79.6	54.6
Pour point	ISO 3016	°C	−58	−39
Flash point	ISO 2719	°C	66.3	70.5
Cold filter plugging point	EN 116	°C	−44	−22
Monoaromatic	–	%v/v	0.50	20.1
Polyaromatic	–	%v/v	0	3.0
Total aromatic	–	%v/v	0	23.1
Flammability	–	°C	60.5	74.0
Lower Heating Value	–	MJ/kg	44.35	42.65
Hydrogen	–	%m/m	15.00	13.72
Carbon	–	%m/m	85.00	85.67
Oxygen	–	%m/m	0	0.61
Sulphur	–	%m/m	0.53	6.50
Ash content	EN ISO 6245	%v/v	0.002	0.014
FAME	–	%v/v	0.05	5.00
Approx. formula	–	–	$C_{13}H_{28}$	$C_{13}H_{24}O_{0.06}$

Hydrogenated vegetable oil is a high-quality diesel product made entirely from renewable raw materials, i.e., vegetable oils and fat waste. HVO is a second-generation biofuel [14]. Hydrotreated vegetable oils are mixtures of paraffin hydrocarbons [3]. These fuels are free of any sulfur and aromatic compounds. As for the physicochemical properties of HVO fuel, special attention should be paid to the lower density value of HVO fuel compared to diesel fuel and the higher cetane number value of HVO fuel compared to ordinary diesel fuel. The main advantages of HVO fuel over diesel fuel are the just-mentioned high cetane number, high energy density, and the absence of oxygen in the molecule of the resulting fuel. An important advantage of HVO fuel is the pour point, which can be as low as –58°C. This, in turn, makes HVO suitable for use in very cold winters and at different geographic latitudes. Importantly, the production and use of HVO is largely climate-neutral if only renewable energy sources are used. HVO is obtained from waste cooking oils, fats, and fat residues, waste fats, and vegetable oil. One solution that will consider the goal of environmental protection and, at the same time, will not make it necessary to reorganize the operations of companies and ordinary households very quickly is to use biofuel as a substitute for diesel. Such a fuel is hydrotreated vegetable oil.

2.2. The engine test

Empirical tests were carried out on an engine dynamometer located at the Faculty of Automotive and Construction Machinery Engineering at the Warsaw University of Technology. The bench was based on a 4-cylinder JCB compression-ignition engine. The engine operates in a four-stroke cycle and has 16 valves (two intake and exhaust valves per cylinder. The crankshaft also drives a high-pressure fuel pump via gears. The pump is part of an electronically controlled common rail fuel injection system. The test engine was installed on a bench equipped with measuring instruments to record engine torque based on the SCHENCK brake (accuracy ±2 Nm), fuel consumption (accuracy 1%) and engine crankshaft speed. The AVL IndiSmart system was used to determine the engine's operating gas pressure. The engine specifications are shown in Table 2.

Table 2. Technical data of JCB engine [27]

Description	Unit	JCB SH Engine
Engine variants	–	Turbocharged with intercooler
Emission compliance	–	US-EPA Tier 4i, EU Stage IIIB
Rated speed	rpm	2200
Weight (dry)	kg	496
Number of cylinders	–	4
Nominal bore size	mm	103
Stroke	mm	132
Cylinder arrangement	–	In line
Combustion cycle	–	4-stroke
Firing order	–	1-3-4-2
Compression ratio	–	16.7:1
Direction of rotation (viewed from front {crankshaft pulley} end)	–	Clockwise
Valves	–	4 per cylinder
Valve clearances measured at the tappet end of the rockers (measured cold)		
– Inlet	mm	0.04–0.23
– Exhaust	mm	0.04–0.6
Lubricating oil pressure (dependent on engine temperature and speed)	MPa	0.16–0.65
Filter type	–	Screw-on canister (with drain facility)
Pressure to open by-pass valve	MPa	0.16
Oil pressure relief valve setting	MPa	0.6
Oil pressure switch setting	MPa	0.06 (falling)
Oil pump	–	Integral unit with relief valve
Combustion system	–	Common rail direct injection
High pressure fuel pump	–	High pressure with electron cally controlled fuel metering

The engine dynamometer stand is based on a JCB engine. The main internal and external components of the JCB engine assembly are shown below. The structure of the JCB engine is shown in Fig. 1–3.

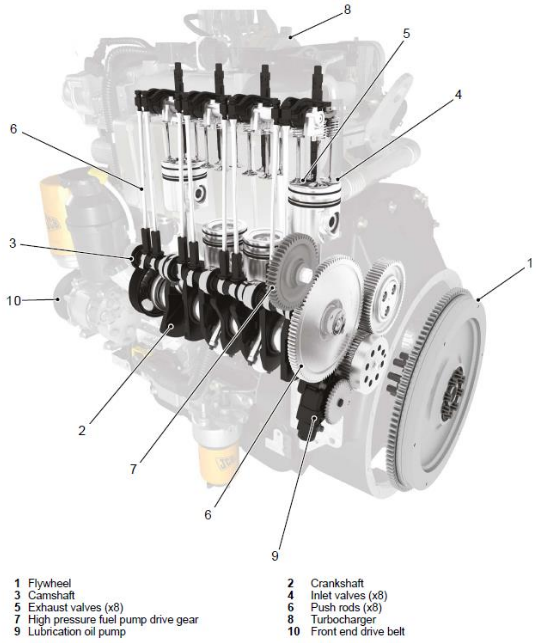

Fig. 1. JCB engine design [27]

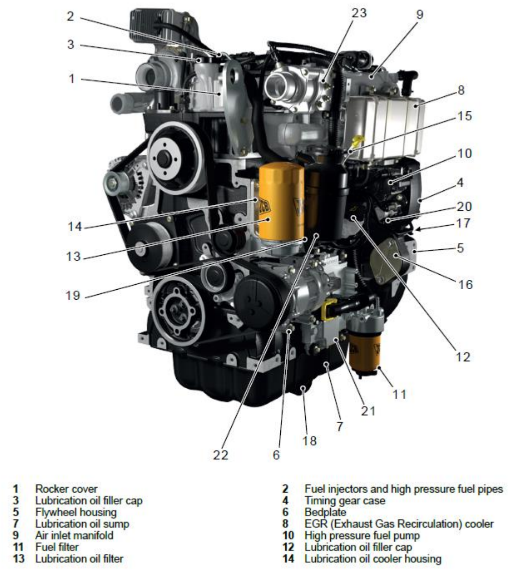

Fig. 2. JCB engine design [27]

2.3 Methods

The empirical tests on the JCB engine were planned so that during their implementation, the exhaust gas recirculation (EGR) system was not operating, and, in addition, no other changes were made to the engine settings (factory settings were used). In the first stage, empirical research was carried out on the speed characteristics. Then, an experiment was performed at the rotational speed of the engine crankshaft corresponding to the maximum torque – consisting of determining indicators related to the combustion process at a constant mass flow of fuels [kg/h]: diesel fuel (DF) and hydrogenated vegetable oil (HVO). In this way, information can be obtained about the impact of HVO on the combustion process in relation to the power supply of the DF engine.

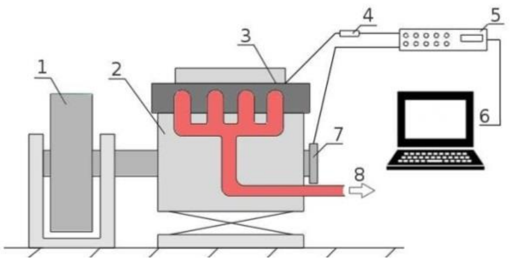

Fig. 3. Test stand: 1 – Schenck eddy current engine brake, 2 – JCB engine, 3 – pressure sensor, 4 – signal amplifier, 5 – AVL Indismart, 6 – computer for acquisition data, 7 – crankshaft position sensor, 8 – exhaust gases

The research engine was installed on a stand equipped with measuring instruments enabling the registration of engine torque based on the SCHENCK eddy current brake, fuel consumption, and engine crankshaft rotation speed. The AVL IndiSmart data acquisition system was used to determine the operating gas pressure in the engine cylinder. Relative error the gas pressure in the combustion chamber of the tested engine is δ = 0.25% (measuring range 0–25 MPa). The test stand was built in accordance with the standards BN74/1340-12 and PN-88/S-02005.

One of the main characteristics of the fuel combustion process in an CI engine is the characteristic of the relative amount of heat released. Thanks to it, we can present the amount and rate of release of the relative amount of heat in the combustion process [10]. The rate of heat release based on data recorded in cylinder pressure was analysed as a function of crankshaft rotation angle at a crankshaft speed of 1400 rpm (speed corresponding to maximum torque). The heat release rate (HRR), can be calculated using the following formula [10]:

$$\mathrm{HRR} = \frac{\kappa}{\kappa-1} p \frac{dV}{d\varphi} + \frac{1}{\kappa-1} V \frac{dp}{d\varphi} \quad \text{[J/CAD]} \tag{1}$$

where $\frac{c_p}{c_v} = \kappa$.

The temperature can be determined from the ideal gas equation of state when the pressure and volume are known, and the mass is assumed to be constant at a given point in the characteristic.

The specific fuel consumption (SFC) was determined based on the hourly fuel consumption (HFC) measured during the experiment and the determined effective power (EP) at a given engine operating point:

$$\mathrm{SFC} = \frac{\mathrm{HFC}}{\mathrm{EP}} \cdot 1000 \text{ [g/(kW·h)]} \tag{2}$$

$$\mathrm{HFC} = \frac{m_f}{t} \text{ [g/h]} \tag{3}$$

where: m_f – fuel mass [g], t – fuel mass consumption time [h].

The useful power was determined on the basis of the torque (T) and angular speed of the crankshaft (ω):

$$\mathrm{EP} = \frac{T \cdot \omega}{1000} \text{ [kW]} \tag{4}$$

where: T – torque crankshaft torque [Nm], ω – angular speed of the crankshaft [rad/s].

3. Results

This chapter presents the waveforms of torque and effective power. The following figures show the specific fuel consumption curves in the conditions described in section 2.3. The chapter ends with drawings regarding the combustion process, including the pressure and temperature of the working medium, heat release rate, and heat release factor. All of them were concerned with powering the engine with two HVO fuels and diesel fuel.

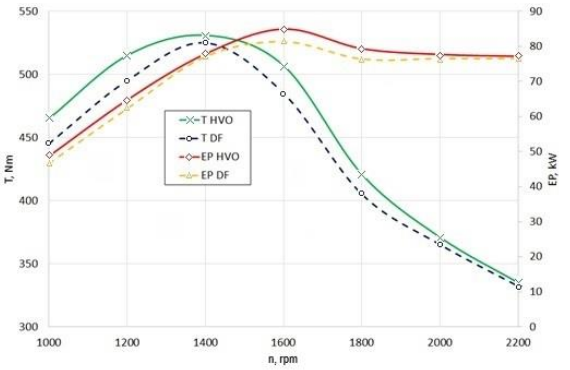

Fig. 4. Speed characteristics. Curves of the effective power and torque of the engine crankshaft as a function of the crankshaft rotation angle when the engine is powered by two fuels: diesel fuel (DF) and hydrogenated vegetable oil (HVO)

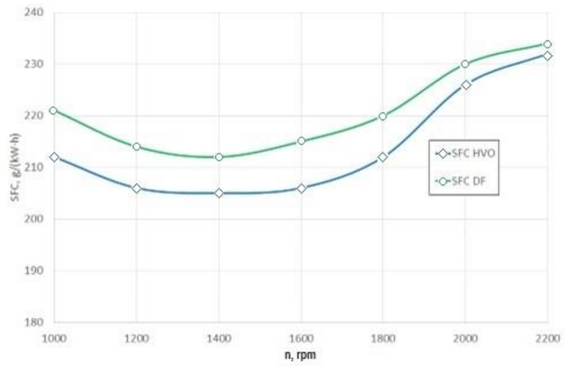

Fig. 5. Speed characteristics. Specific fuel consumption (SFC) curves as a function of the crankshaft rotation angle when the engine is powered by two fuels: diesel fuel (DF) and hydrogenated vegetable oil (HVO)

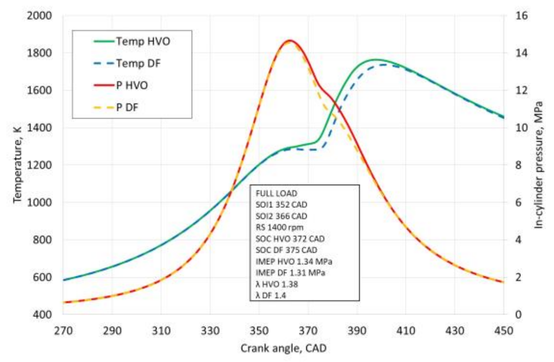

Fig. 6. Curves of pressure and temperature of the working medium in the combustion chamber as a function of the crankshaft rotation angle. Measurement made at maximum load and engine crankshaft speed of 1400 rpm

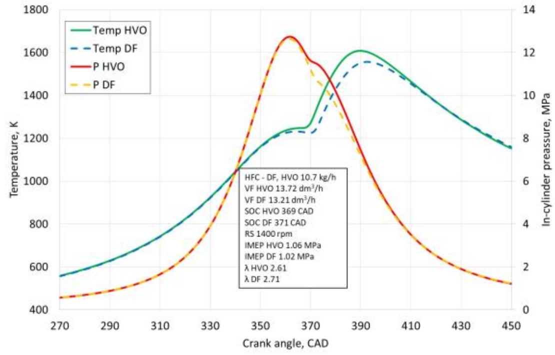

Fig. 7. Curves of pressure and temperature of the working medium in the combustion chamber as a function of the crankshaft rotation angle. Measurement made at a constant fuel mass flow of 10.7 kg/h and at an engine crankshaft speed of 1400 rpm

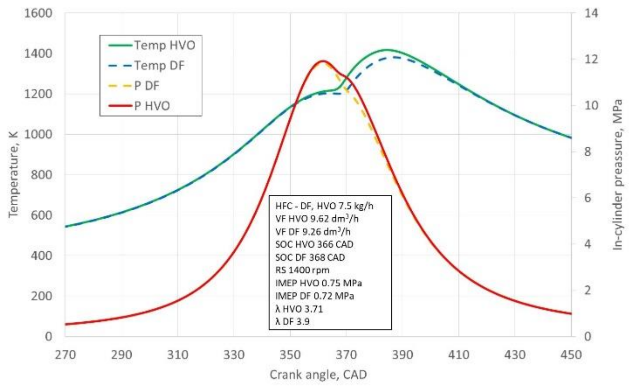

Fig. 8. Curves of pressure and temperature of the working medium in the combustion chamber as a function of the crankshaft rotation angle. Measurement made at a constant fuel mass flow of 7.5 kg/h and at an engine crankshaft speed of 1400 rpm

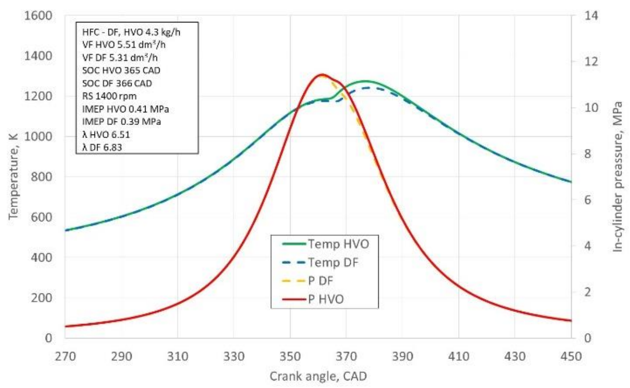

Fig. 9. Curves of pressure and temperature of the working medium in the combustion chamber as a function of the crankshaft rotation angle. Measurement made at a constant fuel mass flow of 4.3 kg/h and at an engine crankshaft speed of 1400 rpm

4. Conclusions and summary

Conclusions from the drawings presented in chapter 3:

1. The speed characteristics at the maximum volumetric fuel dose HVO (in the entire engine crankshaft rotational speed range) result in higher engine crankshaft torques and effective powers. Up to a maximum of 5% (Fig. 4).

2. Based on the speed characteristics at the maximum volumetric fuel dose, specific fuel consumption was reduced by up to 4% in the entire crankshaft speed range of the engine fueled with HVO fuel (Fig. 5).

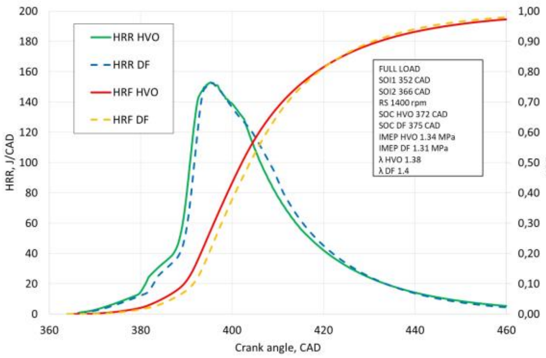

Fig. 10. Heat release rate (HRR) and heat release fraction (HRF) as a function of the crankshaft rotation angle. Values determined at maximum load and engine crankshaft speed of 1400 rpm

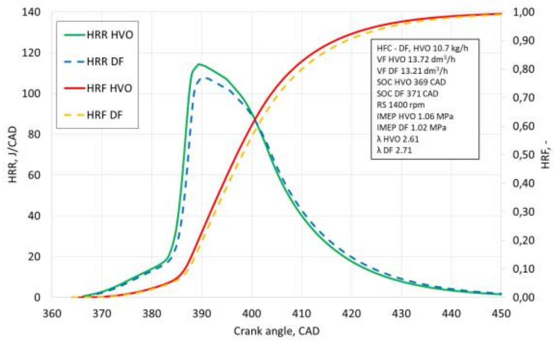

Fig. 11. Heat release rate (HRR) and heat release fraction (HRF) as a function of the crankshaft rotation angle. Values determined at a constant fuel mass flow of 10.7 kg/h and at an engine crankshaft rotation speed of 1400 rpm

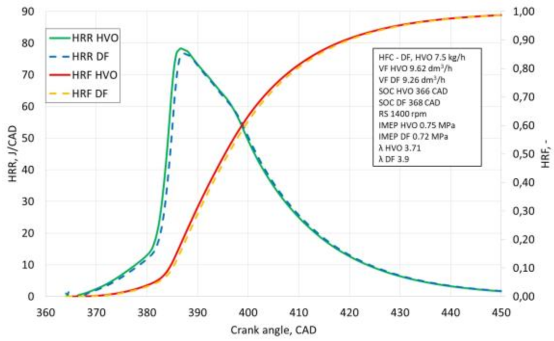

Fig. 12. Heat release rate (HRR) and heat release fraction (HRF) as a function of the crankshaft rotation angle. Values were determined at a constant fuel mass flow of 7.5 kg/h and at an engine crankshaft speed of 1400 rpm

3. Analyzing the course of pressure and temperature of the working medium in the combustion chamber as a function of the crankshaft rotation angle, one can notice in the case of the engine fueled with HVO fuel:

   – earlier start of the combustion process by 3 degrees CA, resulting in an increase in the maximum temperature in the combustion chamber by approximately 40 K and maintaining a similar level of maximum pressure at the engine operating point corresponding to the maximum load and crankshaft rotation speed of 1400 rpm (Fig. 6).

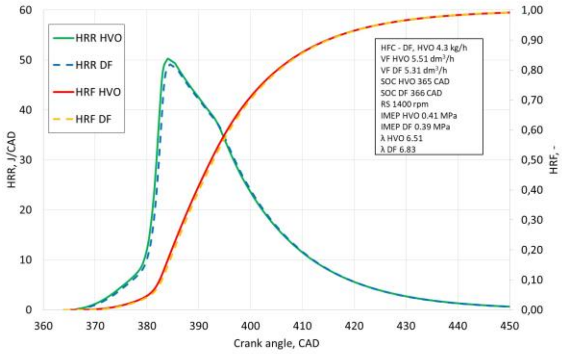

Fig. 13. Heat release rate (HRR) and heat release fraction (HRF) as a function of the crankshaft rotation angle. Values determined at a constant fuel mass flow of 4.3 kg/h and at an engine crankshaft speed of 1400 rpm

   – earlier start of the combustion process by 2 degrees CA, resulting in an increase in the maximum temperature in the combustion chamber by approximately 45 K and maintaining a similar level of maximum pressure at the engine operating point with a constant fuel mass flow of 10.7 kg/h for the tested fuels and at the crankshaft rotation speed engine speed of 1400 rpm (Fig. 7).
   – earlier start of the combustion process by 2 degrees CA, resulting in an increase in the maximum temperature in the combustion chamber by approximately 35 K and maintaining a similar level of maximum pressure at the engine operating point with a constant fuel mass flow of 7.5 kg/h for the tested fuels and at the crankshaft rotation speed engine speed of 1400 rpm (Fig. 8).
   – earlier start of the combustion process by 1 degree CA, resulting in an increase in the maximum temperature in the combustion chamber by approximately 10 K and maintaining a similar level of maximum pressure at the engine operating point with a constant fuel mass flow of 4.3 kg/h for the tested fuels and at the crankshaft rotation speed engine speed of 1400 rpm (Fig. 9).

4. Analyzing the heat release rate (HRR) and heat release fraction (HRF) as a function of the crankshaft rotation angle, it can be seen that in the case of fueling the engine with HVO fuel, one can notice an earlier start of the combustion process, higher maximum HRR values and the completion of the combustion process in a shorter time. The same crankshaft rotation angle.

In all measurement cases, the engine powered by HVO fuel showed increased IMEP. The indicated mean effective pressure in a compressor ignition engine is determined by various factors related to the combustion process. In all research cases, the average temperature in the combustion chamber was higher (on HVO fuel). According to point 3 from chapter 4 – the earlier start of combustion – lower ignition delay can increase IMEP value. The increase of IMEP may result from better fuel atomization. The lower kinematic viscosity of the HVO fuel and the lower ignition temperature may improve the combustion process, which is noticeable by increasing IMEP. Lambda's value for HVO fuel was higher than that of diesel fuel. Due to the higher temperature and pressure in the combustion chamber, the kinetic energy of the exhaust gases increases. This may cause an increase in the amount of air forced into the engine by the turbocharger and, therefore, increase the excess air ratio.

The differences in combustion process indicators noticed during the tests result mainly from different physicochemical properties of the tested fuels. The most important of them are fuel calorific value, fuel density, and cetane number. HVO fuel has a higher cetane number compared to diesel fuel, which results in a shorter auto-ignition delay period and an earlier start of the fuel combustion process. Moreover, HVO fuel has a higher calorific value compared to diesel oil, which has a significant impact on the engine operating parameters. In the case of fueling the JCB engine with HVO fuel, no significant differences were noticed in the engine operating parameters or the combustion process. Therefore, according to the authors, the fuel can be a replacement for diesel oil even without major modifications or changes to engine settings. Based on the results and literature analysis, modern compression-ignition engines can use mixtures of HVO and diesel fuel in various concentrations without loss of engine performance. Thanks to modern fuel injectors with a fuel injection start sensor, the engine management units are able to correct the settings regarding the fuel injection process to eliminate differences in the physicochemical properties of the tested fuels. Thanks to the method of obtaining HVO fuel, it is possible to reduce CO_2 production by up to 90%, which is a particularly important parameter that may contribute to the popularization of this fuel, especially in heavy transport.

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Nomenclature

EP	effective power
DF	diesel fuel
FAME	fatty acid methyl esters
HRF	heat release fraction
HRR	heat release rate
HVO	hydrogenated vegetable oil
RS, n	engine crankshaft rotation speed
SFC	specific fuel consumption
SOC	start of combustion
T	engine crankshaft torque
VF	volume flow

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