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## EFFECT OF THE 2-ETHYLHEXYL NITRATE DOPED RAPESEED OIL AND AVIATION JP-8 FUEL ON THE COMBUSTION PROCESS AND EMISSIONS OF A DIESEL ENGINE

The COP26 Clime Summit brought together Heads of state and ministers from over 200 countries to take urgent actions and protect the planet by limiting global warming to 1.5 degrees Celsius. Low-carbon rapeseed oil (RO) and JP-8 fuel (JF) could be used for diesel engine powering to reduce the climate change. However, at first, too low cetane number related drawbacks of these fuels should be removed to improve the ignition process and achieve efficient and clean combustion. The purpose of the research was to evaluate the cetane improve-made effects on the ignition delay, combustion parameters, thermal efficiency, smoke, and emissions. A naturally aspirated, DI diesel engine operated on the undoped RO and JF to identify the baseline parameters for full (100%) loads corresponding to Indicated Mean Effective Pressures (IMEP) of 0.844 and 0.738 MPa at the most usable speeds of 1400 and 2200 rpm. Then, the engine was fuelled with the cetane improver 2-EHN doped fuels 0.10 (RO-10), 0.30 (RO-30) and 10 (JF-10), 24 vol% (JF-24) to obtain new results important for evaluation of all the benefits and detriments that the use of alternative fuels suggest. It was found that the ignition delay is 10.3% and 44.6% shorter, the Indicated Thermal Efficiency (ITE) is 6.1% higher and 1.2% lower, the NO<sub>x</sub> emissions are a little and 10.3% lower with the doped RO-30 and JF-24 fuels at rated speed of 2200 rpm. Also, the fuels RO-30, JF-24 produce smoke opacity and CO emissions 42.1%, 32.1% and 11.6%, 2.7% higher, THC emissions 1.9 times higher, and 28.6% lower for the respective speeds. The enhanced cetane number differently affects the ignition delay, combustion parameters and emissions because the differing fuel properties play a vital role in the injection, evaporation, and combustion processes. Analysis of the combustion attributes, heat release characteristics, ITE and the NO<sub>x</sub>-smoke trade-off presents new knowledge that is one of the goals of the study.

**Keywords:** Diesel engine; Rapeseed oil; JP-8 fuel; Cetane improver; Combustion process; Cyclic variations

### INTRODUCTION

Extensive usage of traditional fuels in power plants, industry, and the transport sectors reduces natural oil resources and increases the greenhouse effect and global warming leading to the climate change that can damage the nature. The simplest and the most cost-effective way for reducing human-made ecological footprints is a partial or full-scale substitution of fossil-origin fuels with low-carbon, renewable energy sources. The diesel engine tests conducted with vegetable oils, or biodiesel of various origins [1], fossil fuel, and various-vegetable oils, biodiesel, ethanol, n-butanol, and diethyl ether (DEE) blends under steady [2] and transient [3] conditions showed that using of revvable biofuels is feasible and more friendly to nature. However, the experiments also disclosed the existence of differentiation in the ignition delay, the combustion process, maximum heat release rate, thermal efficiency, cyclic irregularity, smoke, and emissions produced by the combustion of biofuel blends.

The Directive (EU) 2018/2001 of the European Parliament and of the Council includes the Union's binding target to cut emissions by at least 40% by 2030 and increase the use of energy derived from renewable sources [4]. That is a motivation why scientists around the world focused attention on cost-efficient, sustainable biofuels and low-carbon alternative fuels, which become a research topic dealing with the main items of sustainability: economic, environmental, and social welfare. Environmental life cycle assessment of RO produced in Latvia, located in the Zemgale region, revealed that total greenhouse gas (GHG) emissions from rapeseed cultivation to processing vary within the range of 203.7-354.7 kg CO<sub>2</sub> eq./t in Slovenia to 828.5-5904.2 kg CO<sub>2</sub> eq./t in Italy depending on the vegetable type, life cycle inventory methods (LCI) and various factors [5]. However, rapeseed possesses a high 37-50% oil content [6] and, therefore, its use in diesel engines is an economically feasible and environment-friendly contribution to the lower CO<sub>2</sub> emissions in a global cycle.

Le et al. [7] investigated the effects of a cetane improver 2-Ethylhexyl nitrate on the two-stage ignition delay (ID) in experimental studies within a rapid compression machine (RCM) assisted by kinetic modelling-works with a mixture of toluene and n-heptane at the doping levels of 0.1 and 1% on a molar basis. The researchers revealed that 2-EHN generates a promoting effect on the surrogate reactivity over the whole temperature range, and the impact is higher the higher are the doping levels of the fuels. This advantageous feature suggests the molecule of 2-EHN containing a weak N – O bond, which breaks rapidly into radicals releasing NO<sub>2</sub> that promotes reactivity of the fuel. Also, the researchers noted that the 1% doped-fuel ensures higher compression temperature, suppresses the negative temperature coefficient behaviour, and lowers both 1st - stage ID and the main ID of the surrogate fuel.

Erman et al. [8] investigated the influence of the ignition delay and fuel properties on the combustion process and emissions in a single-cylinder, naturally aspirated DI diesel engine. The fuel ignitibility was controlled in two different ways: naturally, using seven fuels possessing various cetane numbers and artificially, with an CN improver 2-EHN blended into a single base fuel. The researchers made an important conclusion that the change in a natural cetane number has a much wider influence on combustion attributes and exhaust emissions than additive-boosted cetane alone, even though the two types of fuel have the same value cetane number. The valuable findings revealing the ignition delay's behaviour, the in-cylinder pressure, combustion process, PM formation, smoke, NO<sub>x</sub>, CO, and THC emissions are of importance when dealing with low-cetane fuels related issues.

The auto-ignition and clean combustion of rapeseed (canola) oil as potential diesel fuel extender related issues are not fully examined even though its production and the use are popular in Europe, North America, and Canada. The two factors determined the fuels taken for the experiments. At first, the CN ratings of both alternatives are slightly too low but of similar value that still can be accepted by a diesel engine. Secondly, analysis of the results obtained with fuels of different origins, nature and the widely differing chemical-physical properties allows to look deeper at the processes trying to extract information helpful for revealing the correlated relationships between the combustion parameters and the factors affecting them. The purpose of the research was to evaluate the cetane enhancer-made effects on the ignition delay, combustion attributes, the coefficients of cyclic variations (COVs) of the IMEP, the in-cylinder maximum pressure, its increment rate, the ITE, smoke, and exhaust emissions. Analysis of the results may provide a new knowledge and essential help in solving the problem how to reduce the existing drawbacks and increase the share of veg.-oils as a cheap, locally available, and safe to handle, green-energy source to accomplish "decarbonization" of the power sector.

#### **ENGINE TEST FACILITIES, MEASURING APPARATUS AND METHODOLOGY OF THE RESEARCH**

The research was carried out in the Engine testing laboratory, Department of Mechanical, Energy and Biotechnology Engineering at Faculty of Engineering of Vytautas Magnus University-Agricultural Academy. The tests were conducted on a fully instrumented, four-stroke, DI, naturally aspirated, 60 kW at 2200 rpm diesel engine D-243 with a bore 110 mm, piston stroke 125 mm, displacement 4.75 dm<sup>3</sup>, and compression ratio of 16.0:1. The in-line, injection pump type PP4M9P1g-4201 with plunger diameter x stroke of 9 x 8.5 mm supplied the fuel at the needle-valve lifting pressure of 19.0±0.5 MPa through a five-hole injector with the nozzle type DOP122S532-4164 MP 5 x 0.34 into the toroidal-shape combustion chamber in a piston head. The static fuel delivery advance angle was fixed at 25 crank angle degrees (CADs) before TDC and was kept the same for the various 2-EHN additions to the fuels tested at full (100%) engine loads and the two ranges of speed.

The experimental test setup consists of a diesel engine, an engine testbed, the air- and fuel mass measuring tools, a gas analyser, and a smoke meter for the exhaust. A high-speed indicating system, an angle encoder 365C with an accuracy of ± 0.1° CAD and pressure sensor GU24D with an accuracy of ± 0.1 bar coupled to an AVL indicating amplifier IndiModul 622 are used for the recording, acquisition, and processing of fast crank-angle and time-based gas pressure traces in the first cylinder. Start of injection (SOI) was defined using the injector nozzle-needle-valve lift history, which was recorded using the position sensor ASMB 470004-1 with an accuracy of ± 0.5% in the needle-valve lift range of 0–0.28 mm. The position sensor is connected to the Kistler charge amplifier-module 5247 mounted on the signals conditioning platform-compact 2854A. The needle-valve lift signals from Signal Conditioning Platform (SCP) proceed to the AVL IndiModul 622, a fast data acquisition and processing system, which is connected to a PC equipped with the AVL Indicom Mobile software. The data post-processing software AVL CONCERTO advanced edition 4.5 increased productivity and improved the accuracy of the results.

The engine torque was measured using a 110 kW AC stand dynamometer KS 562-4 with a definition rate of ± 1 Nm and speed with AVL crank angle encoder 365C installed at the crankshaft's front-end with an accuracy of ± 0.2% of the measured value. The air mass flow was measured with an AVL air mass meter installed downstream of the air filter in front of the air tank to reduce pressure pulsations. This method guarantees the stability of the airflow and accuracy of ± 1% of the measured value. The fuel mass-flow was measured by weighing 100 g on the AVL dynamic fuel balance 733S flex fuel with an accuracy of ± 0.10%. The engine power, ISFC and ITE values were identified with the respective ±1 (kW), ±0.1 (g/kWh) and ±1.5 (%) uncertainties.

The auto-ignition delay as a time interval between the SOI and the start of combustion (SOC) was determined with an accuracy of ± 0.1° CAD. Here the SOI represents the crank angle at which the injector-

needle-valve moves up about 5% of its total lift. Whereas the SOC represents the crank angle at which the heat release rate crosses the zero-line and changes from the negative to the positive value. The heat release rate was calculated using the in-cylinder pressure traces versus crank angle as the input data average during the 100 consecutive combustion cycles, the instantaneous cylinder volume, and their first-order derivatives along the crank angle for every load-speed setting point.

Emissions of nitric oxide NO (ppm), nitrogen dioxide NO<sub>2</sub> (ppm), carbon monoxide CO (ppm), dioxide CO<sub>2</sub> (vol%), and total unburned hydrocarbons THC (ppm) were measured using the electrochemical sensors installed into Testo 350 XL flue gas analyser. The total nitrogen oxide NO<sub>x</sub> emissions were estimated as a sum of both NO and NO<sub>2</sub> components with an accuracy of ± 5 ppm. The exhaust smoke (%) was measured with a “Bosch” RTT 110 opacity-meter, the readings of which are provided as Hartridge units (% opacity) in a scale range of 0–100% with an accuracy of ± 0.1%. The temperature of the exhausts was measured with a K-type thermocouple and an indicator N20 that guaranteed the accuracy of ±0.2 °C within the temperature range of 0-650 °C.

The experimental tests started by registering load characteristics running an engine alternately on the undoped rapeseed oil (RO) and JP-8 fuel (JF) to identify the combustion characteristics, smoke and exhaust emissions at a maximum torque speed of 1400 rpm and rated speed of 2200 rpm. The engine operation-related data with the reference fuels were taken at first to identify the baseline parameters for full (100%) engine loads, IMEP = 0.844 and 0.738 MPa at these speeds. Then, the doped both rapeseed oil-sets RO-10, RO-30 and JF-10, JF-24 fuel-sets were prepared by adding 0.10, 0.30 and 0.10, 0.24 vol% of 2-EHN into fuel containers and the engine tests were repeated with all the doped fuel-sets under the same test conditions to accomplish the stated tasks. Mixing of RO with 2-EHN is vital to maintain the homogeneity of the doped fuel-sets because oil possess higher molecular weight, density, viscosity, and pour point that requires careful handling of the samples.

## RESULTS AND DISCUSSION

Cold-pressed, decanted, and safely filtered RO was brought from the oil refinery Orlen Lietuva (Mažeikiai). Rapeseed oil is renewable, sustainable, economically feasible, environmentally friendly, low-sulphur, non-toxic, and safe for transportation. However, it possesses lower volatility and net heating value due to fuel-bond oxygen in the molecular compared to JP-8 fuel. Chemical-physical properties of the fuels of both origins were found at the oil refinery’s Quality Control Centre according to the ISO and ASTM test methods as listed in Table 1. It is evident, the density, viscosity, flash- and initial/final boiling points, the cetane number, iodine number, acid value, C/H atoms ratio, and other data are all the fuel-composition related properties.

The main drawbacks of RO are the high molecular weight, density, viscosity, initial/final boiling points that may clog the fuel filters, feeding lines and affect the injection quality leading to incomplete combustion at light loads and low speeds. Whereas the injectors coking and piston rings sticking may occur due to the higher density, viscosity, and lower volatility of RO even though the temperature in the cylinder is high enough at the high loads. Also, the air and still liquid oil-droplets mixing quality is vital for starting characteristics of an engine. Molecular formulas of RO and JP-8 fuel were used to calculate the fuel-oxygen mass content, C/H atoms ratio and stoichiometric air/fuel ratio.

**Table 1.** Basic properties of rapeseed oil and aviation turbine JP-8 fuel

Property parameters	Test methods of RO and JP-8	RO	JP-8 (JET A-1)
Chemical formula	-	C <sub>57</sub> H <sub>105</sub> O <sub>6</sub>	C <sub>10.17</sub> H <sub>19.91</sub>
Density at 15 °C, kg/m <sup>3</sup>	EN ISO 12185:1999 / ASTM D 4052-09	0.916	797.2
Kinematic viscosity, mm <sup>2</sup> /s	EN ISO 3104:2000 at 40 °C / ASTM D 445 at -20 °C	38.0	4.0
Flash point, open cup, °C	EN ISO 2719:2003 / ASTM D 56-05	220-280	40.0
Initial/final boiling points, °C	EN ISO 3405:2011 / -	340 / 375	145.4 / 258.7
Auto-ignition temperature, °C	-	320	238 [45]
Cold Filter Plugging Point, °C	EN ISO 116/AC:2002 / -	+15	-60.4
Cetane number	EN ISO 5165:1999	44-48	42.3
Iodine number, J <sub>2</sub> /100 g	EN 14111:2003 / -	111	-
Acid value, mg KOH/g	EN ISO 14104:2003 / ASTM D 3242-11	2.0	0.001
Oxygen content, max%	-	10.8	-
Polycyclic aromatics, %	EN 12916 / ASTM D 1319-10	≥ 36vol%	17.5vol%

Sulphur content, mg/kg	EN ISO 20846:2004/ASTM D 5453-09	2	9.3
C/H atoms ratio	-	6.5	6.1
Net heating value, MJ/kg	EN ISO 8217:2007/ASTM D 4529-01	36.87	43.23
Stoichiometric air/fuel ratio	-	12.63	14.85
Latent heat of vaporisation (Enthalpy), kJ/kg	-	209 [9] at (T <sub>boil.</sub> )	343 [8] at 20 °C
Ash content, mass-%	-	0.01	0.007
Total contamination, mg/kg	EN ISO 12662:2014/-	25	0.2

Whereas JP-8 fuel, which satisfies the MILDTL-83133E specifications, is a kerosene-type, the civil fuel Jet A-1, which includes special additives: a static dissipater additive, corrosion inhibitor, lubricity improver, and fuel system icing suppressant. The aviation turbine JP-8T fuel is produced in a crude oil refining process and its price fuel is inherently lower than that of petroleum diesel because it does not require any enhancement of the cetane number. The boiling points of JP-8 fuel are between those of gasoline and diesel fuel. This fuel is lighter than diesel fuel and retains lower viscosity than RO that suggests real advantages in evaporation and the air-fuel mixing processes.

If the ignition conditions are improved, the rapid premixed combustion and the mixing-controlled diffusive-flame burning of the fuels will proceed smoother with a lower engine noise and less harmful pollutants. Thus, the ignition delay plays an essential role in a CI engine operation, depending on the in-cylinder temperature, fuel chemical-physical properties and engine load-speed conditions. The fuel CN value, iodine number, and latent heat of vaporization impact the ignition delay. It was noted that the 2-EHN doping level enhanced up to 0.12 vol% reduces the ignition delay, improves premixed combustion, engine efficiency, and the in-cylinder pressure, retains the CO production, but increases the level of NO<sub>x</sub>-smoke trade-off and THC emissions [10]. Kumar et al. [11] used additives such as nitrates, peroxides nitrates, aldehydes, and tetra-azoles to enhance the cetane number of the fuel.

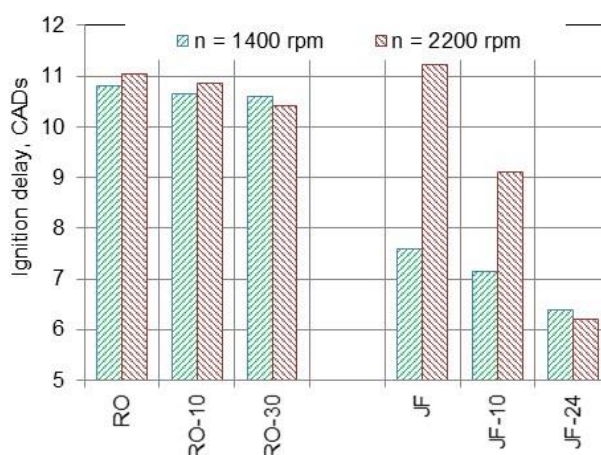


Fig. 1. Ignition delay (CADs) as a function of the doping level of rapeseed oil (RO) and JP-8 fuel (JF) for full engine loads, IMEP = 0.844 and 0.738 MPa, at speeds of 1400 and 2200 rpm

As can be seen in Fig.1, the ignition delay for the undoped RO and the doped oil-sets RO-10, RO-30 is 3.2° (42.1%) and 3.6° (50.7%), 4.2° (65.6%) longer than those values of 7.6° (JF) and 7.1° (JF-10), 6.4° (JF-24) CADs obtained with jet fuel sets at a speed of 1400 rpm. It was unpredicted and not completely understood why the ignition delay decreased by 1.9° only even though the highest doping level was applied in the fuel-set RO-30. Most likely that the reduction in the ignition delay is not as large as could be expected because of dissimilar chemical composition and the high-molecular-weight of RO, smaller spray cone angle, poor atomisation of oil droplets, and thus imperfect air-oil-vapours mixing quality. The high density, viscosity, and initial/final boiling points of RO minimised the expected effect of the 2-EHN on the ignition delay.

It was showed that the spray length of a JP-8 fuel is 16% shorter, but its cone angle is 15.9° wider than that of diesel fuel at the injection pressure of 30 MPa [12]. The wider spray cone angle contributes to a larger surface area of the fuel spray plume exposed to the hot-in-cylinder air charge. This promotes the evaporation process and improves the air-fuel-vapours mixing quality leading to a lower local equivalence ratio. This fact can be one of the reasons why the ignition delay of the undoped JF and the doped jet fuels is almost always



shorter than that of RO, and it diminishes rapidly with increasing doping level of the fuel. The ignition delay decreased with a different rate of intensity even though the doping level for both fuels was identical of 0.10 vol% and even higher in RO-30 case. The ignition delay was affected by the higher initial/final boiling points and lower heating value of rapeseed oil. Also, the high iodine value of RO indicates the high number of double bonds and thus unsaturation degree in oil components that does not contribute to a better quality of rapeseed oil.

The ignition delay of the doped fuels JF-10, JF-24 decreased by 6.6%, 15.8%, and 18.7%, 44.6% compared with 7.6 and 11.2 CADs needed for ignition of the undoped fuel JF at speeds of 1400 and 2200 rpm (Fig.1). Analysis of the results shows that the chosen doping level (0.24 vol%) of JF-24 fuel is even too high and the ignition delay time is already too short to prepare the air-fuel mixture of the highest quality during an extremely limited time left for evaporation and mixing, less than 0.0005 seconds at speed of 2200 rpm. On the contrary, the ignition delays of the doped RO-10 and RO-30 were only 0.7 (6.0%) and 1.2 (10.3%) shorter than that value of 11.6 CADs (about 0.0009 seconds) during which straight RO ignited at this speed. The estimated effect of the CN improver to RO was negligible therefore the ignition delay decreased by only 0.2 CADs (1.9%) even with the doped (0.30 vol%) RO-30 oil-set at a speed of 1400 rpm. Thus, if fuel properties are not truly ideal for a diesel engine, the cetane improver is no longer as active as can be expected and comes with only a little help in reducing the ignition delay even though the temperature inside the cylinder is very high under full-load conditions.

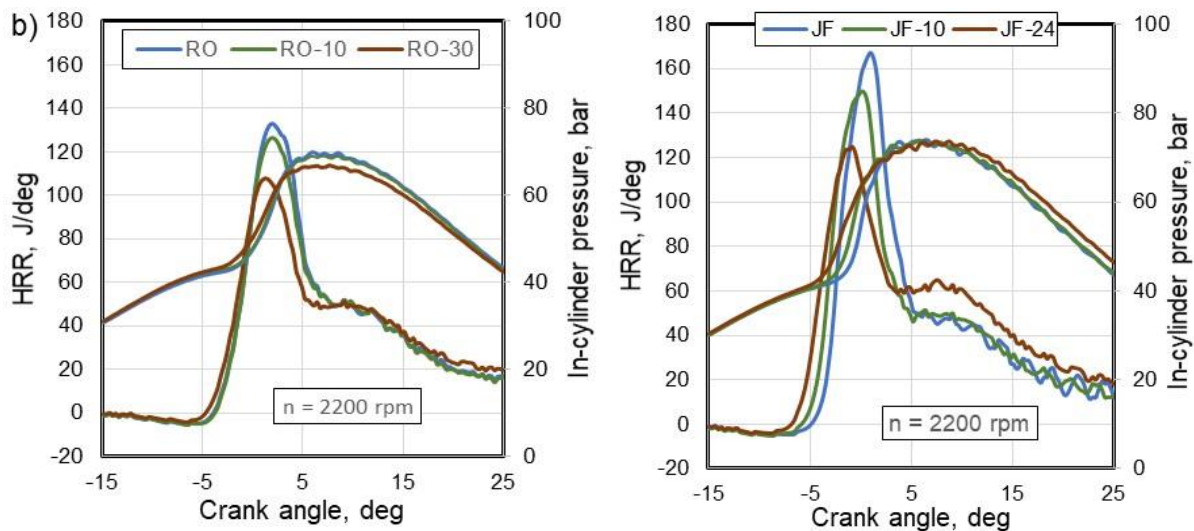


Fig.2. Changes of the in-cylinder pressure and heat release rate (HRR) versus crank angle from combustion of rapeseed oil (RO) and jet fuel (JF) as well as the doped oil-sets RO-10, RO-30, and jet fuel-sets JF-10, JF-24 recorded for a full (100%) load, IMEP = 0.738 MPa, at speed of 2200 rpm

Superimposed illustrations in Fig.2 present an average heat release rate (HRR) and the in-cylinder pressure traces during consecutive 100 engine cycles from combustion of the undoped and the doped rapeseed oil (RO) and jet fuel (JF) versus crank angle. Since the ignition delay converted to be shorter and the SOC took place earlier before TDC with increasing doping level of the fuels, the  $HRR_{max}$  in the premixed combustion phase decreased by 5.0% (RO-10), 19.0% (RO-30) and 10.8% (JF-10), 25.5% (JF-24) at a speed of 2200 rpm. Whereas the angle  $AHRR_{max}$  shifted less (RO) or more (JF) towards constant-volume combustion (Fig.2). The decrease in  $HRR_{max}$  was reasonable but not proportional to the ignition delay's changing behaviour (Fig.1). Reduction in the  $HRR_{max}$  matches well with the differing chemical-physical properties of the fuels and the mass of the air-fuel mixture taking an active part in the rapid premixed combustion. The  $HRR_{max}$  and the resulting in-cylinder pressure depend on the fuel distribution in the combustion chamber volume and near the parietal zone (near-wall mixture formation process) on which the rapid premixed combustion relays, but not always on the duration of ignition delay and even on the fuel mass injected during mixing of the fuel and air prior to ignition process starts up [13].

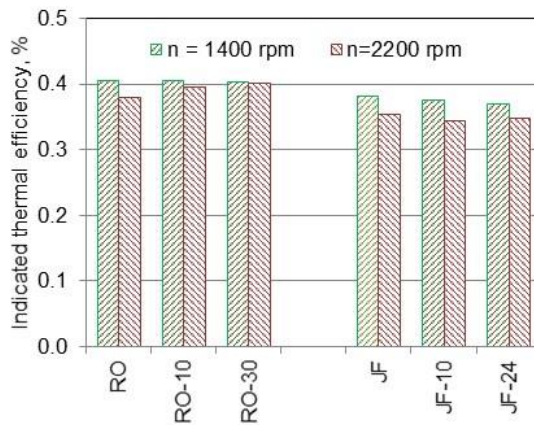


Fig. 3. Indicated Thermal Efficiency (ITE) as a function of the 2-EHN doping level of rapeseed oil (RO) and jet fuel (JF) for full (100%) engine loads, IMEP = 0.844 and 0.738 MPa, at speeds of 1400 and 2200 rpm

The combustion of the doped oil-sets RO-10 and RO-30 developed the ITE a bit 0.2% and 0.5% lower than that efficiency of 0.406 measured with the undoped RO at a speed of 1400 rpm. Though the engine thermal efficiency converted to be 4.2% and 6.1% higher with these oil-sets than that value of 0.379 the combustion of the undoped RO has produced at speed of 2200 rpm (Fig.3). The ITE of an engine increased with increasing doping level of a dense and viscous RO, most likely, due to the small (not too much) reduction of the ignition delay and, consequently, the SOC occurred a bit earlier at the end of the compression process (Fig.2). The earlier SOC suggest more time available to preheat, evaporate, and burn RO-30 completely during the limited combustion cycle. On the contrary, in the JF fuel case, even a lower doping level of 0.24 vol% was already too high and the SOC started too early before TDC with a resulting loss in engine power. That is the answer to the question of why the engine ITE decreased, and smoke opacity increased with the increment rate higher, the higher engine speed (Fig.4b). This occurred due to too short ignition delay time to premix and burn the fuel completely during a limited engine cycle. Because the doping level of the doped fuels JF-10 and JF-24 was slightly too high for given test conditions, the ITE was 1.8%, 3.4% and 2.5%, 1.1% lower than those values of 0.382 and 0.353 the combustion of the undoped jet fuel developed at speeds of 1400 and 2200 rpm. Unfavourable changes in the SOC advanced AHRR<sub>max</sub> and reduced the HRR<sub>max</sub> late in the compression stroke that, in turn, triggered too early growth of the in-cylinder pressure requiring more negative work to complete the cycle (Fig.2).

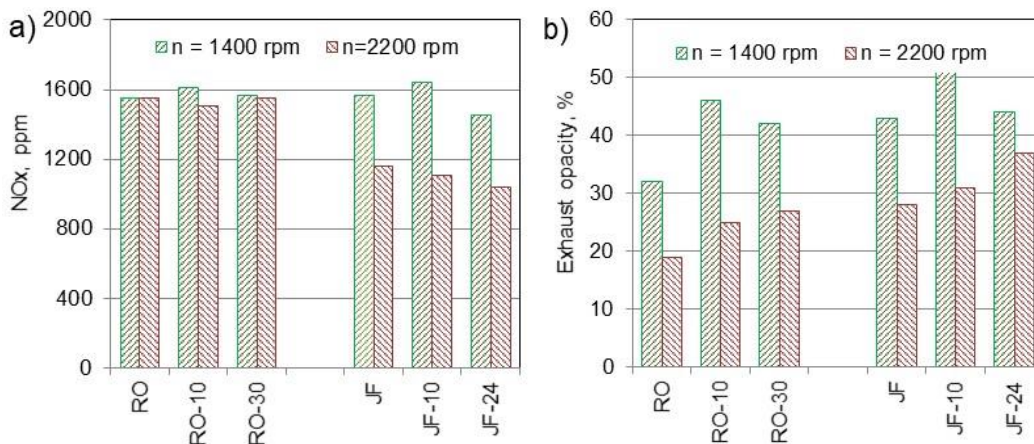


Fig. 4. The NO<sub>x</sub> emissions (a) and smoke opacity (b) as a function of the 2-EHN doping level of rapeseed oil (RO) and jet fuel (JF) for full (100%) engine loads, IMEP = 0.844 and 0.738 MPa, at speeds of 1400 and 2200 rpm

The doped jet fuels suggested NO<sub>x</sub> emissions like that RO-sets produced varying from 4.5% higher (JF-10) to 7.6% lower (JF-24) compared with 1570 ppm, which the combustion of the undoped JF fuel generates at a speed of 1400 rpm (Fig.4a). Overall leaner air-fuel mixtures of  $\lambda = 1.26$  (RO) – 1.20 (JF) suggested emissions high enough for both fuels because peak NO<sub>x</sub> occurs at slightly lean conditions, where the combustion temperature is high and there is an excess of oxygen to react with hydrogen [14]. NO<sub>x</sub> emissions

from combustion of the doped, oxygen-free JF-24 fuel were lower and demonstrated the reduction tendencies, while these emissions almost did not change for most doped RO-30 at both engine speeds. The enhanced cetane number of jet fuel reduced the ignition delay and the air-fuel mass premixed for the combustion that suppressed the production of NO<sub>x</sub>, especially at high speeds. The matter is that a little NO will form during the fuel-rich premixed burning phase; almost all the NO will form in the mixing-controlled diffusion-flame burning process [14]. Therefore, as the ignition delay decreases (Fig. 1), so do NO<sub>x</sub> emissions due to the lower maximum pressure (temperature) inside the cylinder, on which the NO formation mainly depends.

The high doping levels of a denser and more viscous RO neither reduced the ignition delay nor effectively suppressed NO<sub>x</sub> emissions at both engine speeds. Even though the maximum pressure and hence the in-cylinder temperature were somewhat higher at a speed of 2200 rpm (Fig. 2), the NO<sub>x</sub> emissions did not increase due to the homogeneous air-jet-fuel mixture and the temperature evenly distributed in the cylinder. As shown in Fig.4a, the doped jet fuel sets are more effective in reducing NO<sub>x</sub> emissions. The NO<sub>x</sub> production decreased by 4.3 % (JF-10) and 10.3% (JF-24) compared with that value of 1160 ppm (JF) that produces less damage to nature. As the doping level of jet fuel increased to 0.24 vol%, much shorter ignition delay (Fig.1) and lower the in-cylinder pressure (Fig.2) contributed to the reduction of NO<sub>x</sub> at both engine speeds. Therefore, the cetane enhancer 2-EHN is a more effective in reducing NO<sub>x</sub> emissions from combustion of jet fuel rather than RO. However, the NO<sub>x</sub> reduction does not occur for free, - an engine consumes more jet fuel in grams per unit of energy developed due to slightly lower ITE (Fig.3).

The combustion of oxygenated RO and all the doped RO-sets produced more transparent smoke-flow for full-load operation at both speeds (Fig.4b). This advantageous feature emerged even though the content of polycyclic aromatics and the ratio of the C/H atoms in oil composition are higher than in jet fuel-sets, The first reason is that the molecule of RO possesses fuel-bond oxygen, which is always on the spot ready to accelerate the oxidation reactions when availability of air-bone oxygen is limited in the mixing-controlled combustion phase. Also, the combustion of RO proceeded at a bit higher air-fuel ratio of  $\lambda = 1.26$  than that of  $\lambda = 1.20$ , at which jet fuel burned at a speed of 1400 rpm. Finally, the combustion of jet fuel generated more soot (PM) due to more sulphur in JP-8 fuel composition (Table 1). As a result, the smoke increased by 43.8% (RO-10) and 20.9% (JF-10) reaching maximum values of 46% and 52% at a speed of 1400 rpm. The increment rate in smoke opacity decreased for both fuel types as the doping level increased to 0.30 (RO-30) and 0.24 vol% (JF-24) at this speed.

Though, this strategy did not work at a higher speed because even a bit shorter ignition delay (Fig.1) does not contribute to cleaner combustion during the short time available to complete each engine cycle [10]. The combustion of fuels RO-30 and JF-24 continued longer due to the poor air-fuel mixture quality. As a result of undermixing, the smoke increased by 42.1% and 32.1% against those values of 19% and 28%, which the burning of the undoped fuels suggested at a speed of 2200 rpm (Fig.4). The enhanced cetane rating shortened the ignition delay and reduced the heat release rate in the premixed combustion phase together with NO<sub>x</sub>, but increased smoke, as an unavoidable penalty. Since the ignition delay was too short to improve the quality of air-fuel mixture, even the earlier SOC (Fig.2) does not manage to cope with a delicate task. Therefore, it is difficult to overcome the smoke-NO<sub>x</sub> trade-off, which is the most useless and disappointing problem in diesel engines [2].

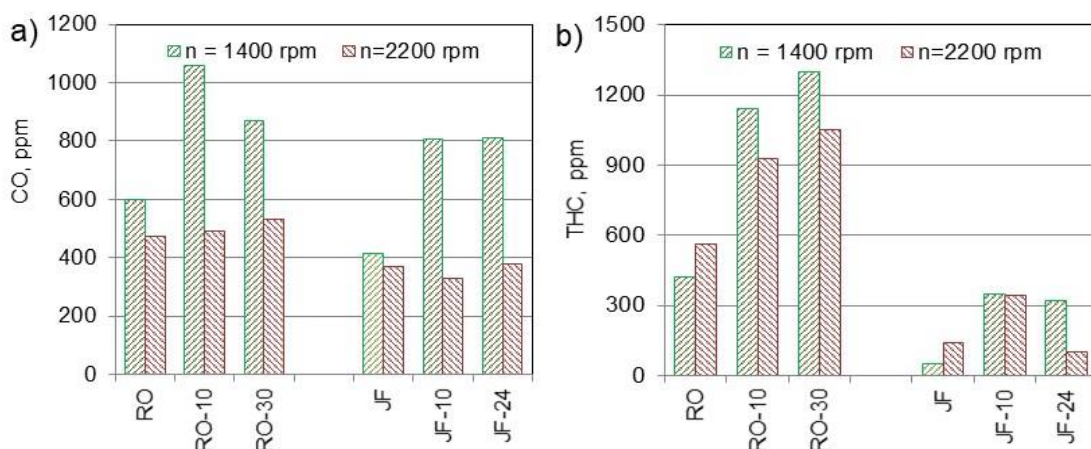


Fig. 5. The CO (a) and THC (b) emissions as a function of the 2-EHN doping level of rapeseed oil (RO) and jet fuel (JF) for full (100%) engine loads, IMEP = 0.844 and 0.738 MPa, at speeds of 1400 and 2200 rpm



Despite the combustion of oxygenated RO sets should demonstrate cleaner exhaust, but this did not occur. In general, CO and THC emission were always higher than the combustion of oxygen-free jet fuel sets produced for the same doping levels, loads, and speeds (Fig.5). This drawback can be caused by a deficiency or excess of the air-borne oxygen in some local combustion chamber zones and incomplete burning due to poor evaporation of oil droplets and undermixing or overmixing problems. Too much shortened ignition delay converted the combustion conditions to be even worse. Therefore, CO and THC emissions increased 1.8 (RO-10) and 3.1 times (RO-30) against 600 and 420 ppm, at which the combustion of straight RO ends up at a speed of 1400 rpm.

CO and THC emissions increased with increasing doping level to 0.30 vol% (RO-30) reaching the highest values of 530 ppm (11.6%) and 1050 ppm (1.9 times) compared with those emissions of 475 and 560 ppm emanating from combustion of the undoped RO at a speed of 2200 rpm. The higher emissions of unburned hydrocarbons can be a reason (among others) why even the high doping level did not improve energy conversion efficiency from combustion of the fuels (Fig.3). Interestingly, CO emissions from combustion of jet fuel were 10.8% lower, while THC emissions converted to be 2.4 times higher (JF-10) than those values of 370 and 140 ppm measured with the undoped JF fuel at a speed of 2200 rpm. Nevertheless, the combustion of a lighter jet fuel emitted comparably lower THC emission levels at both engine speeds.

### CONCLUSIONS

1. The ignition delay almost did not change with the doped RO, neither at maximum torque speed of 1400 rpm nor at 2200 rpm, while it was 5.8% and even 44.6% shorter with the doped JF-24 fuel at these speeds. Since RO properties are not truly ideal for a diesel engine, the cetane enhancer is a little helpful in reducing the ignition delay even with the high doping level of 0.30 vol% applied.
2. The maximum heat release rate was 19.0% (RO-30), 25.5% (JF-24) relatively lower and the angle  $AHRR_{max}$  took place closer to TDC due to the shorter ignition delay at a speed of 2200 rpm. However, when using fuel JF-24 the  $HRR_{max}$  was 15.9% higher than in RO-30 case showing its strong dependence on the fuel mass burned rapidly near TDC rather than on the ignition delay.
3. The ITE with the doped RO-30 was 0.5% lower than that of 0.406 (RO) at a speed of 1400 rpm but it converted to be 6.1% higher against that value of 0.379, which RO suggested at a speed of 2200 rpm. Whereas the ITE decreased by 3.4% and 1.1% with the doped (too much) JF-24 fuel against that efficiency of 0.382 and 0.353 achieved with the undoped JF fuel at both speeds.
4. Maximum  $NO_x$  and smoke were 3.9% and 43.8% (RO-10) or 4.5% and 20.9% (JF-10) higher than, 1555 ppm and 32% or 1570 ppm and 43%, the combustion of straight RO or JF fuel emits at 1400 rpm.  $NO_x$  emissions did not change, and smoke was 42.1% higher with RO-30, while  $NO_x$  converted to be 10.3% lower and smoke 32.1% higher with JF-24 fuel at a speed of 2200 rpm.
5. CO and THC emissions were 1.8 (RO-10) and 3.1 times (RO-30) or 2.0 (JF-24) and 7.0 times (JF-10) higher with the doped fuels than, 600 and 420 ppm or 415 and 50 ppm, the combustion of RO or JF fuel emitted at 1400 rpm. While both pollutants were 11.6% and 1.9 times higher (RO-30) or converted to be 10.8% lower and 2.4 times higher (JF-10) at a speed of 2200 rpm.

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