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THE EFFECT OF AVIATION FUEL JP-8 AND DIESEL FUEL BLENDS ON ENGINE PERFORMANCE AND EXHAUST EMISSIONS

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Abstract

The article presents bench test results of a four-stroke, four-cylinder, naturally aspirated, DI diesel engine operating with neat JP-8 fuel (J) and its blends with Diesel fuel (D) in following proportions by volume: 90/10 (J+10D), 70/30 (J+D30), 50/ 50 (J+D50), 30/70 (J+D70), and 100% diesel fuel (DF). The purpose of the research was to analyse and compare changes occurred in the autoignition delay, combustion events, engine performance efficiency, emissions, and smoke of the exhaust when running on JP-8 fuel, jet-diesel fuel blends, and diesel fuel at a full (100%) engine load and speed of 1400 min^{-1} *at which maximum torque occurs and rated speed of 2200 min*$^{-1}$*. It was found that the start of injection (SOI) and the start of combustion (SOC) occurred earlier in an engine cycle and the autoignition delay decreased by 9.0% and 12.7% due to replacement of aviation JP-8 fuel with diesel fuel at a full load and the latter speeds. Maximum in-cylinder pressure was 6.8% and 4.0% higher when operating with diesel fuel, whereas brake thermal efficiency was 3.3% and 7.7% higher, and brake specific fuel consumption 2.8% and 7.0% lower when using fuel blend J+D50 compared with the respective values measured with neat JP-8 fuel. Emissions of nitric oxide (NO) and nitrogen oxides (*NO_x*) were 13.3% and 13.1% higher from a straight diesel running at speed of 1400 min*$^{-1}$*, and 19.0% and 19.5% higher at a higher speed of 2200 min*$^{-1}$*. The carbon monoxide (CO) emissions and total unburned hydrocarbons (HC) decreased 2.1 times and by 12.3% when running with fuel blend J+D70 at speed of 2200 min*$^{-}$*1 compared with those values measured with jet fuel. Smoke of the exhaust was 53.1% and 1.9% higher when using fuel blend J+D10 than that of 46.9% and 70.0% measured with jet fuel at speeds of 1400 and 2200 min*$^{-1}$*. The engine produced 34.5% more smoke from combustion of fuel blend J+D70 at the low speed of 1400 min*$^{-1}$*, but smoke converted to be 11.3% lower when operating at a higher speed of 2200 min*$^{-1}$*.*

Keywords: *diesel engine, jet fuel, diesel fuel, autoignition, combustion, performance, exhaust emissions*

1. Introduction

At its autumn meeting in 2004, the NATO Pipeline Committee (NPC) adopted the SFP as the NATO Single Fuel Policy [3]. The single fuel selected has been the F-34 (JP-8) military jet kerosene. This light distillate fuel consists of a mixture of complex hydrocarbons such as 50-65% paraffins, 10-20% aromatics, and 20-30% naphthenes [2]. One particular challenge with using global JP-8 fuel is the lack of or too broad a range of specified combustion affecting properties including ignition quality [13]. To satisfy the requirements of the USA standard ASTM-D 1655 additives such as static dissipater, antimicrobial agents, anti-icing inhibitor S-1745, and lubricating additive S-1747 of 0.1 vol% with long-term corrosion inhibitors are used that improves quality of aviation turbine JP-8 fuel [1, 10]. One of the problems is that aviation jet-A fuel, which is mainly used in turbine engines, does not have minimum cetane rating in ASTM D1655 standard because the ranking of aviation turbine fuels according to the cetane number value was not used before [6].

The cetane number of turbine type JP-8 fuel can be improved by adding small amounts of chemical compounds such as 2-ethylhexil nitrate [8]. The test results of a four-cylinder, DI diesel engine showed that as little as 0.12 vol% 2-ethylhexil nitrate added to JP-8 fuel (JP-8-12) its cetane rating improved from 42.3 to 48.5 that resulted in 5.0° CADs shorter autoignition delay time, lower heat release rate in the premixed combustion, higher maximum in-cylinder pressure and pressure gradients. However, too short autoignition delay can produce more CO, HC emissions, and higher smoke opacity. The lubricity of a lighter JP-8 fuel is another problem that may increase the wear of nozzle-needle-valve and plunger-barrel units in a long-term operation. According Graboski et al. [4], adding of biodiesel, lubricity properties of which are excellent, can drastically improve lubricity of the jet fuel. The bench test results of a single-cylinder, Petter engine AV1-LAB showed that the substitution of fuel F-34 with sunflower oil and/or olive oil at proportions from 10% to 50% not only improved lubricity of the fuel blends, but also slightly increased the volumetric fuel consumption and decreased PM emissions [1].

An experimental study conducted with an optically-accessible, single-cylinder, common rail diesel engine showed that replacement of the diesel fuel with JP-8 fuel the spray tip's penetration shortened by approximately 16% at the injection pressure of 30 MPa. The shorter spray tip penetration was accompanied by 15.9° wider spray angle of JP-8 fuel than that of diesel fuel [9]. The widely differing properties of fuel JP-8 may improve atomisation and the air and fuel vapours mixing rate, resulting from shorter spray tip penetration and a wider spray cone angle [11]. The test results of a military 558 kW, B-46-6, 12-cylinders, CIDI engine indicate that the horsepower of diesel engine can be matched with fuel economy penalty lower than 4.5%, by increasing the volumetric fuel delivery to compensate the lower density of JP-8 fuel [12]. Analysis of literature shows that there is a lack of test results with a multi-cylinder diesel engine operating on jet-diesel fuel blends.

2. Purpose of the research

The purpose of this study was to examine the effects of diesel fuel added in various proportions to JP-8 fuel on chemical and physical properties of jet-diesel fuel blends. Thereafter, changes occurring in the autoignition delay, maximum in-cylinder pressure, brake specific fuel consumption (bsfc) obtained with jet-diesel fuel blends were analysed and compared with those parameters developed by the combustion of neat jet fuel at full (100%) engine load and the two ranges of speed: 1400 rpm at which maximum torque occurs and a rated speed of 2200 min^{-1}. Along with changes in the autoignition delay and combustion processes, the NO, NO_2, NO_x, CO, HC emissions, and smoke opacity of the exhaust produced when operating at full (100%) engine load with jet-diesel fuel blends were also examined and compared with „baseline" parameters measured with neat jet fuel at the latter speeds.

3. Objects, apparatus and methods of the research

The tested jet-diesel fuel blends were prepared in following proportions by volume: 100% JP-8 fuel (J), 90% JP-8 / 10% DF (J+D10), 70% JP-8 / 30% DF (J+D30), 50% JP-8 / 50% DF (J+D50), 30% JP-8 / 70% DF (J+D70), and 100% diesel fuel (DF) which included the 5 vol% of RME. The Cloud Points (CP) for diesel fuel, aviation JP-8 fuel, and jet-diesel fuel blends were determined by using standard EN 23015:1994 (ISO 3015:1992) specifications. The Cold Filter Plugging Points (CFPP) were determined according standard EN 116:1997 specifications and Freezing Points (FP) by using test method ASTM D 7153-05. The tested fuels and jet-diesel fuel blends were produced at the oil refinery “ORLEN Lietuva” Ltd., where the property parameters were measured in the Quality Control Centre, which is approved by NATO (Tab. 1).

Tab. 1. Properties of diesel fuel (grade C) and JP-8 fuel (NATO Code F-34)

Property parameters	Test methods for diesel fuel / / turbine type JP-8 fuel	DF EN 590	JP-8 (F-34) ASTM-D 1655
Chemical formula		$C_{13}H_{24}O_{0.6}$	$C_{10.17}H_{19.91}$
Density at 15°C, kg/m^3	EN ISO 12185:1999 / / ASTM D 4052-11	843.6	797.2
Kinematic viscosity at 40°C, mm^2/s	EN ISO 3104 at 40°C / / ASTM D 445 at –20°C	2.89	4.0
Lubricity, corrected wear scar diameter (wsd 1.4) at 60°C, μm	EN ISO 12156-1:2007 / / indeterminable	460	611 –
Flash point, Pensky-Martens closed cup, °C / Flash point by Tag closed cup tester	EN ISO 2719:2003 / / ASTM D 56-05	59.0	40.0
Initial / final boiling points, °C	EN ISO 3405:2011 / –	177.8 / 367.0	145.4 / 258.7
Cold filter plugging point ICFPP), °C / Freezing point, °C	EN ISO 116:1997 / / ASTM D 7153-05	–7	–60.4
Cetane number	EN ISO 5165:1998	51.3	42.3
Acid value, mg KOH/g	– / ASTM D 3242-11	0.06	0.001
Polycyclic aromatics, %	EN 12916 / ASTM D 1319-10	3.0 wt%	17.5 vol%
Sulphur total, mg/kg	EN ISO 20846:2004 / / ASTM D 5453-12	8.9	9.3
Carbon-to-hydrogen ratio (C/H)	– / –	6.5	6.1
Net heating value, MJ/kg	EN ISO 8217:2012 / / ASTM D 4529-01	43.10	43.23

The experimental test setup consisted of a diesel engine, an engine test bed, the air and fuel mass consumption measuring tools, a gas analyser, and a smoke meter for the exhaust. The bench tests were conducted with a naturally aspirated, four-cylinder, DI 60 kW, diesel engine D-243 with a splash volume of 4.75 dm^3 and compression ratio of 16:1. The mechanical in-line injection pump PP4M9P1g-4201 (Czech Republic) supplied the fuel at a static fuel delivery advance of 25° CADs before TDC. The pump injected fuel into toroidal combustion chamber through a five-hole injector at a needle-valve lifting pressure of 19.0±0.5 MPa. Analyses and comparison of engine performance and emission parameters were conducted for full (100%) engine loads of 0.752 MPa and 0.676 MPa at the respective speeds of 1400 and 2200 min^{-1}.

The engine torque was measured with an asynchronous 110 kW AC stand dynamometer KS-56-4 with a definition rate of ±1 Nm and speed by using the AVL crank angle encoder 365C, which guaranteed an accuracy of less than ±2%. The air mass consumption was measured with the AVL air mass meter (0-400 kg) with an accuracy of less than ±0.1 %. The fuel mass consumption was measured by weighting 100 g of fuel on the AVL dynamic fuel balance 733S (0-150 kg/h) with an accuracy of ±0.1 %. A high-speed multichannel AVL indicating system was used for acquisition of fast crank-angle gas pressure signals with an accuracy of ±0.1 bar. A high-performance pressure transducer GU24D mounted into the first cylinder and connected to the microIFEM piezoelectric amplifier-signal conditioning platform IndiModul 622 were used for recording summarized over 100 engine-cycles average cylinder pressure versus crank angle for every 0.1° CAD with an accuracy of ±0.1 bar.

The start of injection (SOI) and injection duration were found by using the nozzle-needle-valve lifting history recorded with a Wolff Controls Corporation Hall effects position sensor ASMB 470004-1 coupled to the Kistler amplifier-module 5247. The signals then passed through an input channel into the conditioning platform-compact 2854A to record the needle valve lifting with an accuracy of ±0.1°. A higher accuracy of the experimental test results was achieved by the use of the data post-processing software AVL CONCERTO^{TM} advanced edition. The autoignition delay was determined as a period in crank angle degrees (CADs) between start of injection (SOI) and start of combustion (SOC). As the start of injection was taken crank angle, at which the injector's needle valve lifts up about 5% of its total 0.28 mm lift. As the start of combustion was taken crank angle, at which the curve of heat release rate crosses the zero line and changes its value from the minus side to the plus one.

Emissions of nitric oxide (NO), nitrogen dioxide (NO_2), carbon monoxide (CO), and total unburned hydrocarbons (THC) in parts per million (ppm) were measured with electrochemical cells installed into Testo 350 XL flue gas analyser. The NO_x emissions were determined as a sum of both NO and NO_2 pollutants with an accuracy of ±5 ppm. The exhaust smoke was measured with a Bosch RTT 110 opacity meter with an accuracy of ±0.1 % in a scale range of 0-100%.

4. The research results and discussions

The idea to investigate the behaviour of Cloud Point (CP), Cold Filter Plugging Point (CFPP), and Freezing Point (FP) with increasing volumetric amount of JP-8 fuel added to diesel fuel rests on the intention to elaborate recommendations for the Lithuanian Army. As Fig. 1 shows, aviation JP-8 fuel added to diesel fuel in 20%, 40%, 60%, and 80% proportions significantly reduced important temperature points of the fuel blends. The 60 vol% JP-8 fuel added to diesel fuel the CP, CFPP, and FP points from the initial values of –2, –6, and –16°C reduced to about –14, –26, and –50°C, i.e. 7.0, 4.3, and 3.1 times making these fuel blends suitable for the use in winter conditions. The lower viscosity of jet-diesel fuel blends makes it much easier to pump this alternative fuel through the long, often small diameter, fuel delivery lines of the fuelling system arranged upon military diesel powered transport machines. The diesel fuel differs as having 5.8% higher density at the temperature of 15°C and about 2.5 times higher kinematic viscosity at the temperature of 40°C compared with jet fuel. Because the difference in C/H ratio for JP-8 fuel and diesel fuel is not significant, 6.1 and 6.5, the heating values are similar 43.23 and 43.10 MJ/kg (Tab. 1).

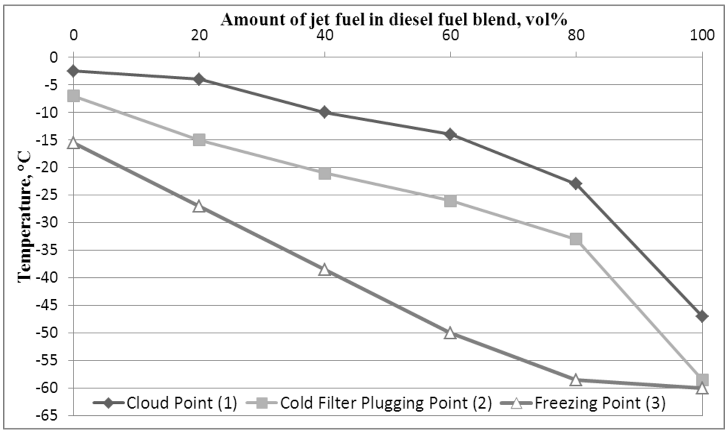

Fig. 1. The dependencies of Cloud Point (1), Cold Filter Plugging Point (2), and Freezing Point (3) of the fuel blends on volumetric percentage of JP-8 fuel added to diesel fuel (grade C)

One of the biggest problems creates too long autoignition delay when using low cetane jet fuel in a diesel engine. Therefore, the added diesel fuel, the cetane number of which is 21.3% higher than that (42.3) of JP-8 fuel, has potential to improve ignition properties of the fuel, lead to constant-volume combustion and more fuel-efficient engine performance with jet-diesel fuel blends. Another serious problem is poor lubricity of turbine type JP-8 fuel, which according HFRR tests produces the biggest wear of 611 µm (no additives) as compared with that (460 µm) of diesel fuel according corrected wear scar diameter (wsd), 1.4 µm at the temperature of 60°C. The lubricity problem can also be solved by the use of jet-diesel fuel blends because of higher density, viscosity and the presence of 0.51 wt % of fuel bound oxygen (RME) in diesel fuel according the EU Directive 2009/28/EC. Lubricity tests for the ULSD and GTL blends conducted on a HFRR showed that as little as 5% RME improves the lubricity of ULSD/GTL blends dramatically [14].

The lower density and viscosity of JP-8 fuel along with the earlier start of distillation curve at the temperature of 145.4°C and vaporization end at the temperature of 258.7°C compared with the respective values of 177.8°C and 367.0°C of the normal diesel fuel propose faster evaporation and higher the air and fuel vapours mixing rate. The lower latent heat of vaporization (250 kJ/kg) of JP-8 fuel may also contribute to sooner autoignition and combustion. However, the low cetane number of JP-8 fuel may lead to the longer autoignition delay, more fuel premixed for rapid combustion and thus higher maximum heat release rate, pressure and temperature in the cylinder.

The autoigtinion delay time depends on the cetane number of the fuel, engine load and speed, which affect the temperature inside the cylinder and turbulence intensity of combustible mixture [13]. As Fig. 2 shows, both the start of injection (SOI) and the start of combustion (SOC) occurred earlier in an engine cycle due to a bigger volume of diesel fuel added to jet fuel when operating under full engine load at speeds of 1400 and 2200 min^{-1} because of the higher density and the cetane rating of the tested fuels. The higher density, earlier injection and better cetane number of jet-diesel fuel blends contributed to sooner autoignition of the air and fuel mixture. Under the influence of main control factors, the autoignition delay from 8.9° and 12.6° CADs measured with neat JP-8 fuel decreased to minimum of 8.1° and 11.0° CADs with increasing volume of diesel fuel in the blend, i.e. the pre-ignition period became 9.0% and 12.7% shorter when operating with neat diesel fuel. The obtained autoignition delay's behaviour matches well with the test results of a heavy-duty diesel engine operating with JP-8 fuel, which is comparable with military F-34 fuel [9].

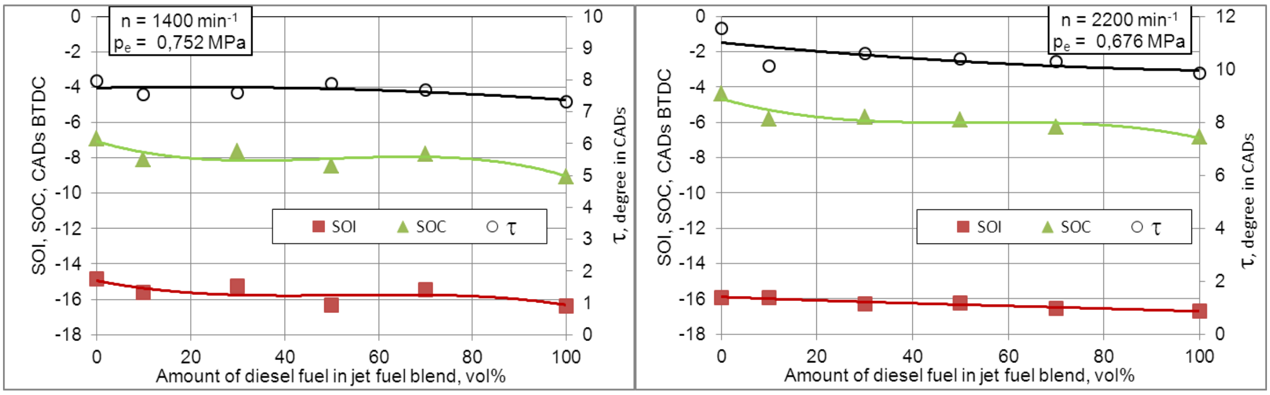

Fig. 2. Dependencies of the start of injection (SOI), start of combustion (SOC), and autoignition delay in CADs on the amount of diesel fuel added to JP-8 fuel at full (100%) load (bmep) and speeds of 1400 and 2200 min^{-1}

It can be seen in graphs of Fig. 3 that maximum in-cylinder pressure p_{max} slightly increased with increasing amount of diesel fuel in JP-8 fuel when operating at a full (100%) engine load and both speeds of 1400 and 2200 min^{-1}. To be precise, the peak in-cylinder pressure increased from 77.9 and 74.3 MPa measured with neat JP-8 fuel to maximum of 83.2 and 77.3 MPa due to replacement of jet fuel with the normal diesel fuel at speeds of 1400 and 2200 min^{-1}. This means that the peak in-cylinder pressure increased by 6.8% and 4.0% due to JP-8 fuel replacement with diesel fuel. Maximum pressure gradients also were 11.6% and 5.6% higher when operating with diesel fuel than those values of 5.33 and 7.52 MPa/° produced by the combustion of jet fuel at the latter speeds. Pressure $p_{\max}$ and its gradients $(dp/d\varphi)_{\max}$ increased with a higher intensity when running at the low speed of 1400 min^{-1}. This occurred because the position of maximum pressure shifted by 1.4° CADs towards constant volume combustion with increasing up to 100% amount of diesel fuel in the blend at a low speed. Whereas, the burn angle $Ap_{\max}$ moved away from TDC, i.e. it slightly shifted in apposite-direction towards a bigger cylinder volume that did not contribute to developing of higher $p_{\max}$ when running at a full engine load and high speed of 2200 min^{-1}.

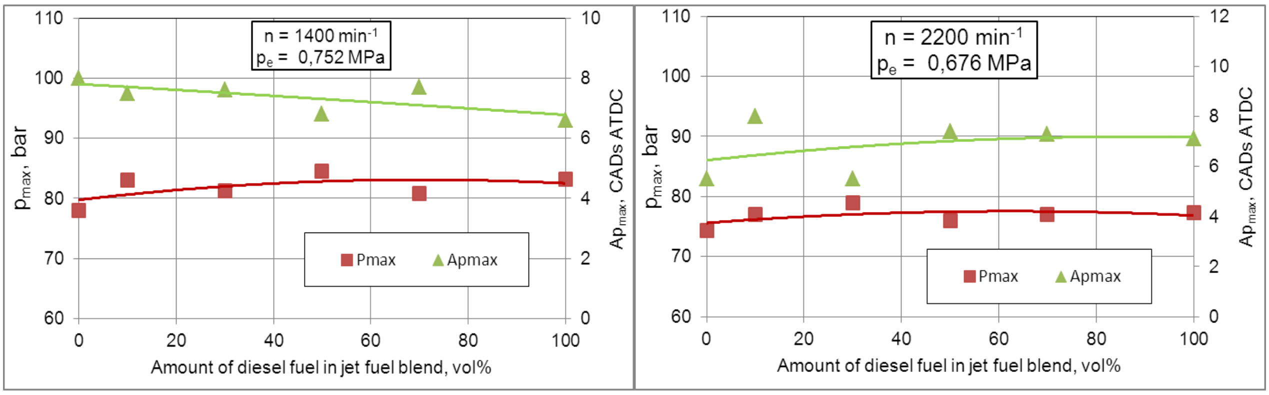

Fig. 3. Dependencies of the peak in-cylinder pressure (p_{max}) and pressure gradients $(dp/d\varphi)_{max}$ on the amount of diesel fuel added to JP-8 fuel at full (100%) load (bmep) and speeds of 1400 and 2200 min^{-1}

A bigger amount of diesel fuel added to jet fuel did not have significant effect on brake thermal efficiency and brake specific fuel consumption when operating at full load and the low speed of 1400 min^{-1} (Fig. 4). Nevertheless, the brake thermal efficiency increased to maximum of 0.348 (3.3%) and brake specific fuel consumption decreased to minimum of 240 g/kWh (2.8%) when operating with fuel blend J+D50 with regard to those values measured with neat jet fuel. The brake thermal efficiency increased to maximum of 0.327 (7.7%) and brake specific fuel consumption decreased to minimum of 254 g/kWh (7.0%) when powering a fully (100%) loaded engine with fuel blend J+D70 compared with those values of 0.304 and 273 g/kWh measured with neat jet fuel at a high speed of 2200 min^{-1}. Thus, the 70% of diesel fuel added to JP-8 fuel improved the cetane rating of the fuel blend, shortened the autoignition delay, and thus led to sooner combustion with lower heat losses to the cooling system [12].

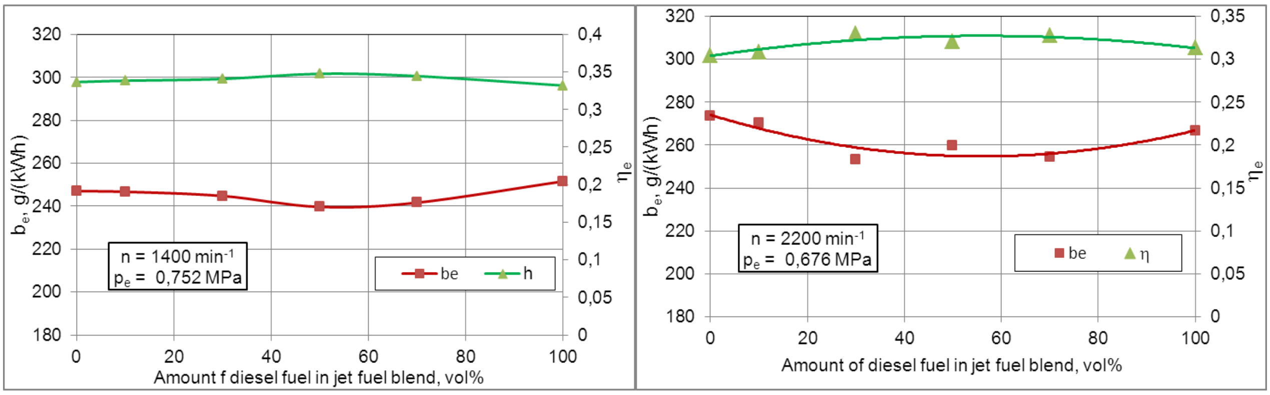

Fig. 4. Dependencies of brake thermal efficiency (η_e) and brake specific fuel consumption (b_e) on the amount of diesel fuel added to JP-8 fuel at full (100%) engine load (bmep) and speeds of 1400 and 2200 min^{-1}

Emissions of nitric oxide (NO) and total nitrogen oxide (NO_x) increased with increasing volume of diesel fuel added to jet fuel and reached maximum values of 1705 ppm (13.3%) and 1759 ppm (13.1%) when operating with diesel fuel at full (100%) load and the low speed of 1400 min^{-1} (Fig. 5). The NO and NO_x emissions increased more significantly after transition to a higher speed of 2200 min^{-1}. Despite overall level of harmful pollutants was lower because of the lower volumetric efficiency and in-cylinder pressure, the NO and NO_x emissions increased from 1152 ppm and 1182 ppm measured with jet fuel to maximum of 1371 ppm (19.0%) and 1412 ppm (19.5%) when operating with neat diesel fuel. The increase in NO and NO_x emissions can be attributed to changes in fuel atomisation and thus homogeneity of the air and diesel fuel mixture that resulted in more uneven temperature distribution in the combustion chamber. Next reason of a higher NO_x was that diesel fuel included 5 vol % of RME, which contains 10.9 wt% of fuel-oxygen.

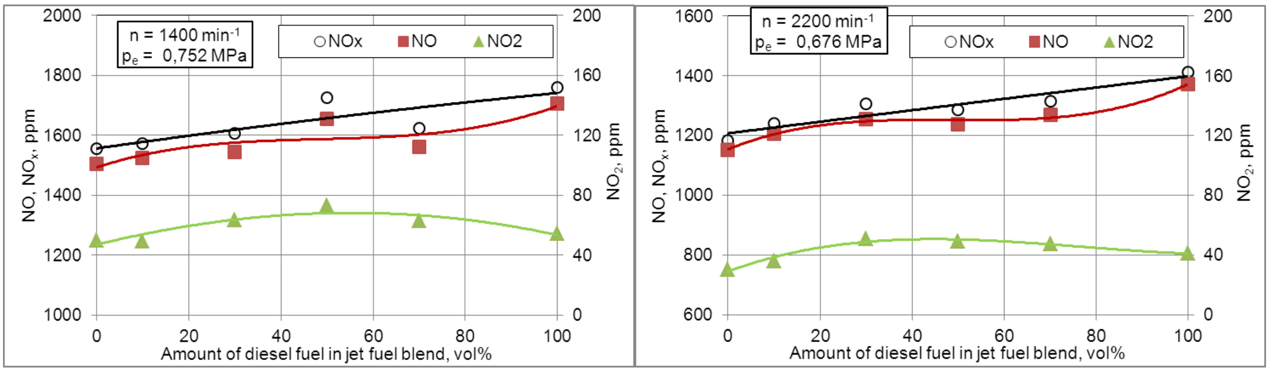

Fig. 5. Dependencies of nitric oxide (NO), nitrogen dioxide (NO_2), and total NO_x emissions on the amount of diesel fuel added to JP-8 fuel at full (100%) engine load (bmep) and speeds of 1400 and 2200 min^{-1}

As the test results show, the NO_x emissions produced from vegetable oil derived fuels [4] and rapeseed oil methyl ester [7] are almost always higher than those produced from combustion of the normal diesel fuel and neat jet fuel [8]. It should be noted that the higher NO and NO_x emissions match well with a better performance efficiency of a fully (100%) loaded engine and lower brake specific fuel consumption (Fig. 4), higher maximum in-cylinder pressure (Fig. 3), and thus temperature on which the NO_x production mostly depends [5]. The nitrogen dioxide (NO_2) emissions increased to a certain extent and reached maximum values of 73.0 ppm (46.6%) and 49.1 ppm (62.6%) when using fuel blend J+D50 compared with those values measured with neat JP-8 fuel at the respective speeds of 1400 and 2200 min^{-1}.

Emissions of carbon monoxide (CO) and total unburned hydrocarbons (HC) produced by the combustion of fuel blend J+D10 increased to maximum values of 1407 and 910 ppm, i.e. 2.6 and 9.1 times, compared with those values measured with neat JP-8 fuel at a full engine load and the low speed of 1400 min^{-1} (Fig. 6). The increase in unburned hydrocarbons probably occurred because the air and fuel mixture was more heterogeneous due to the presence of a small amount of diesel fuel in jet fuel. Adding 30-vol % of diesel fuel to jet fuel improved the cetane rating of the blend and reduced the autoignition delay that resulted in less the CO and the HC emitted at a full (100%) engine load. In this case, the CO and the HC emissions were 1.7 and 3.9 times higher compared with very low levels of 546 and 100 ppm of the respective pollutants produced from combustion of neat JP-8 fuel. The increased presence of diesel fuel in JP-8 fuel did not contribute to considerable reduction in CO and HC emissions and the measured data ambiguously varied for every next engine test.

The air swirl, squish, and turbulence intensity increased at speed of 2200 min^{-1}, therefore the CO emissions became slightly (3.9%) lower, but the HC emissions increased 2.2 times when operating with fuel blend J+D10 compared with those values of 2023 and 730 ppm measured with JP-8 fuel (Fig. 6). In contrast to low speed operation, the CO and the HC emissions decreased 2.1 times and by 12.3% when using fuel blend J+D70 compared with the respective values of 2023 and 730 ppm produced by the combustion of neat JP-8 fuel at a full engine load. Because a time-span needed to complete combustion is very limited at a high 2200 min^{-1} speed, the use of jet-diesel fuel blends with higher cetane ratings shortened the autoignition delay time and suggested some advantages in engine performance.

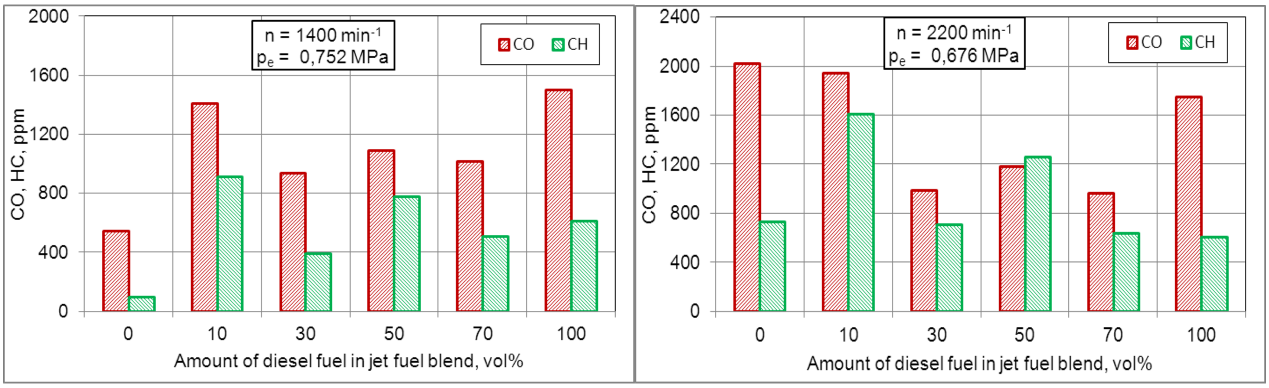

Fig. 6. Dependencies of carbon monoxide CO and total unburned hydrocarbons HC emissions on the amount of diesel fuel added to JP-8 fuel at full (100%) engine load (bmep) and speeds of 1400 and 2200 min^{-1}

The exhaust smoke changed with the increasing amount of diesel fuel in the fuel blend almost the same way as the CO and the HC emissions did because production of considered pollutants caused incomplete combustion of the tested fuels (Fig. 7). To be precise, smoke opacity produced by a fully loaded (100%) engine increased when operating with fuel blend J+D10 and was 53.1% and 1.9% higher compared with the initial values of 46.9% and 70.0% measured with neat jet fuel at speeds of 1400 and 2200 min^{-1}. Using of jet-diesel fuel blend J+D70 for a fully (100%) loaded engine powering resulted in smoke opacity 34.5% higher at the low speed of 1400 min^{-1}, however it converted to be 11.3% lower at a high speed of 2200 min^{-1} compared with the respective values of 46.9% and 70.0% produced by the combustion of neat jet fuel.

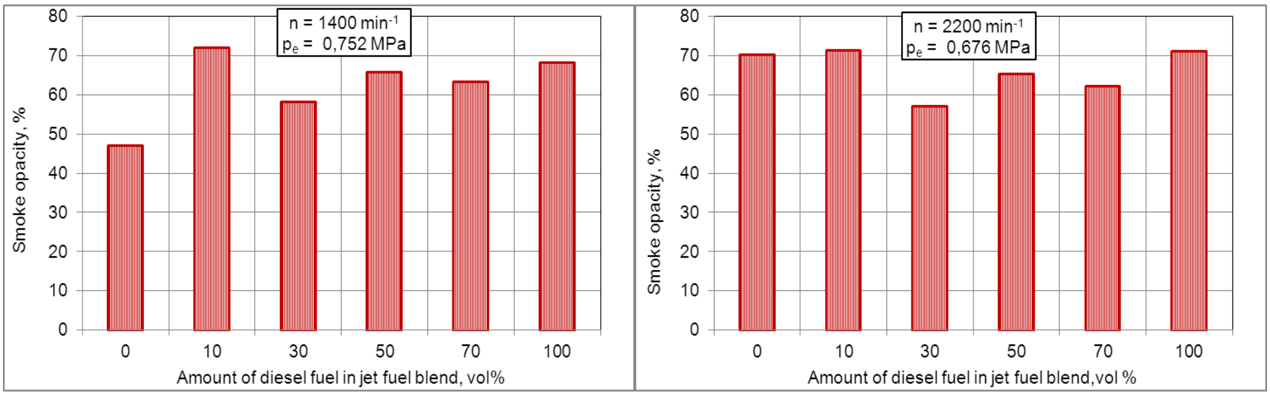

Fig. 7. Dependencies of smoke opacity of the exhaust on the amount of diesel fuel added to JP-8 fuel at full (100%) engine load (bmep) and speeds of 1400 and 2200 min^{-1}

5. Conclusions

1) The start of injection (SOI) and the start of combustion (SOC) occurred earlier in an engine cycle and the autoigtinion delay time decreased from 8.9° and 12.6° CADs measured when operating with neat JP-8 fuel to minimum of 8.1° (9.0%) and 11.0° (12.7%) CADs BTDC when running on diesel fuel at a full (100%) engine load and speeds of 1400 and 2200 min^{-1}.
2) Maximum in-cylinder pressure increased from 77.9 MPa and 74.3 MPa when operating with neat JP-8 fuel to maximum of 83.2 MPa and 77.3 MPa when using diesel fuel at full engine load and speeds of 1400 and 2200 min^{-1}. Maximum pressure gradients also were 11.6% and 5.6% higher when operating with diesel fuel compared with those values of 5.33 and 7.52 MPa/° produced by the combustion of neat jet fuel at the latter speeds.
3) The brake thermal efficiency increased to maximum of 0.348 (3.3%) and brake specific fuel consumption decreased to minimum of 240 g/kWh (2.8%) when operating with fuel blend J+D50 at full engine load and the low speed of 1400 min^{-1}. Whereas, the respective parameters

increased to maximum of 0.327 (7.7%) and decreased to minimum of 254 g/kWh (7.0%) when running at a high speed of 2200 min^{-1} compared with values of 0.304 and 273 g/kWh measured with jet fuel.

4) Emissions of nitric oxide (NO) and total nitrogen oxide (NO_x) produced by a fully (100%) loaded engine increased to maximum of 1705 ppm (13.3%) and 1759 ppm (13.1%) when operating with diesel fuel at the low speed of 1400 min^{-1}. Both pollutants also increased from 1152 ppm and 1182 ppm measured with neat jet fuel to maximum of 1371 ppm (19.0%) and 1412 ppm (19.5%) when operating on neat diesel fuel at a high speed of 2200 min^{-1}.
5) Emissions of carbon monoxide (CO) and total unburned hydrocarbons (HC) increased to maximum of 1407 and 910 ppm, i.e. 2.6 and 9.1 times, when using fuel blend J+D10 compared with the respective values measured with neat JP-8 fuel at a full engine load and speed of 1400 min^{-1}. However, both emissions decreased 2.1 times and by 12.3% when using fuel blend J+D70 at rated speed of 2200 min^{-1} compared with 2023 and 730 ppm measured with neat JP-8 fuel.
6) The exhaust smoke produced by a fully loaded (100%) engine was 53.1% and 1.9% higher when operating with fuel blend J+D10 compared with those values of 46.9% and 70.0% measured with neat jet fuel at speeds of 1400 and 2200 min^{-1}. Using of fuel blend J+D70 resulted in smoke opacity 34.5% higher at the low speed of 1400 min^{-1}, but it converted to be 11.3% lower at a high speed of 2200 min^{-1} compared with those values produced by the combustion of neat jet fuel.

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