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DEPENDENCY OF THE AUTOIGNITION DELAY, COMBUSTION AND EXHAUST EMISSIONS OF A DIESEL ENGINE ON THE CETANE NUMBER OF AVIATION-TURBINE JP-8 FUEL

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The article presents the bench test results of a fully instrumented, four cylinder, naturally aspirated, (60 kW) DI diesel engine running on the normal (class C) diesel fuel (DF) and aviation-turbine (JP-8) fuel. Analysis of changes in the autoignition delay, maximum in-cylinder pressure, performance efficiency of an engine and exhaust emissions caused by the variation of the cetane number of JP-8 fuel was provided. The series of engine tests were conducted running on the normal JP-8 fuel and JP-8 treated with 0.04vol%, 0.08vol%, 0.12vol%, 0.16vol%, and 0.24vol% of 2-ethylhexyl nitrate. Studies on operating characteristics of an engine were carried out for the fully loaded (100%) engine and the two ranges of speed, - 1400 rpm at which maximum torque occurs and rated 2200 rpm speed.

Adding of 2-ethylhexyl nitrate to aviation-turbine fuel in the above proportions the cetane number (CN) of JP-8 fuel improved from 42.3 to 46.1, 47.6, 48.5, 49.4, and 49.8, respectively, enhancing ignition properties of the fuel to adapt it for using in ground-based military transport. The increase of CN from the reference value of 42.3 to optimum value of 48.5 suggested the brake specific fuel consumption lower 1.4%, both total unburned hydrocarbons (THCs) 7.5% and exhaust smoke 5.7% higher with almost unchangeable the NO_x emissions behaviour and 11.9% lower CO emissions when running under a fully (100%) opened throttle at rated 2200 rpm speed. The brake thermal efficiency increased to maximum value of 0.309 (1.3%) for given operating conditions. Analysis of the results revealed that the improved cetane number can be considered as an effective but not the only measure to be applied for an intended use of JP-8 fuel in ground-based diesel engines.

Diesel engine; JP-8 fuel; CN number; autoignition; combustion; performance; emissions, smoke opacity

Introduction

At its autumn meeting in 2004, the NATO Pipeline Committee (NPC) adopted the SFP as the NATO Single Fuel Policy [1]. The aim of the original Single Fuel Concept (SFC) is to simplify the supply chain for petroleum products in the NATO nations and to achieve maximum both aircraft and ground equipment interoperability by using of a single fuel, namely JP-8 (F-34) military jet kerosene produced from the civil fuel Jet A-1. The latter is a light distillate fuel that consists of a mixture of complex hydrocarbons such as 50–65% paraffin, 10–20% aromatics and 20–30% naphthenic [2]. Jet fuel also contains trace amounts of sulphur, nitrogen, and oxygen containing hydrocarbon compounds, which arise from the raw crude oil, known as hetero atoms. At this time the total sulphur content is limited to 3000 ppm by the specification [3]. To satisfy the needs of the USA standard ASTM-D 1655-13a three additives such as static dissipater, anti-icing and lubricating additive 0.1 vol% with long-term corrosion inhibitors are used to improve quality of aviation-turbine JP-8 fuel [4, 5]. Jet fuel has also antifreeze, antimicrobial agents, and corrosion inhibitors to improve performance of aeronautical engines, whose ambient temperature widely varies during flight [6].

The petroleum diesel standard ASTM D975-09a specifies a minimum cetane number of 40, which is 42-45 for fuels D-2 used in the United States, as well as biodiesel standards prescribe a minimum of 47 for neat biodiesel in ASTM D6751-09b and a minimum of 51 in European standard EN 14214 [7]. Whereas aviation Jet-A fuel, which is used mainly in turbine engines, has no minimum cetane rating in ASTM D1655-13a because the ranking of turbine type fuels according to the cetane number value was not used before. This is one of the problems to be solved because a higher cetane number of the jet fuel would improve cold starting properties, reduce the smoke during start up and exhaust emissions, decrease the knocking and noise, increase fuel economy and improve overall durability of an engine. The US military imposed the Single Fuel Forward [8] policy, which allows the use of alternative fuels, such as JP-8 and synthetic aviation S-8 fuels, in CI engines. Since the diesel engines will be used for ground based military vehicles, power generators and associated equipment powering, the cetane number of jet fuels becomes even more important factor in terms of the autoignition and combustion than a decade ago [9,10].

An experimental study carried out in an optically-accessible diesel engine equipped with a common-rail injection system showed that the JP-8 fuel spray tip penetration was shorter by nearly 16% for injection pressure of 30 MPa and 10% for higher injection pressure of 140 MPa compared with normal diesel fuel. The lower spray tip penetration was compensated by 15.9^0 to 6.2^0 wider spray angle of JP-8 under considered fuel injection pressures than that of diesel fuel [11]. The widely differing chemical and physical properties of JP-8 fuel improve atomization and contribute to a higher fuel-air mixing rate, resulting from shorter spray tip penetration and a wider spray angle [12]. The test results of a 558 kW, B-46-6, supercharged, 12-cylinders, CIDI engine showed that the torque and horsepower of diesel fuel 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 [13]. The results obtained with S60 engine showed that the use of JP-8 fuel leads to lower NO_x and PM emissions and shifts the NO_x-PM trade-off favourably for almost all performance conditions [14].

Analysis of literature shows a limited number of in-depth studies on the effects of 2-ethylhexyl nitrate on the cetane number of aviation-turbine JP-8 fuel, autoignition delay, performance efficiency, and exhaust emissions from an engine.

During the autoignition delay the fuel spray tips should be able to penetrate and distribute properly in the combustion chamber before premixed combustion rapidly starts. Since too low cetane number is among the most important problems in terms of JP-8 fuel intended use for military ground-based diesel engine powering, adding 2-ethylhexyl nitrate to JP-8 fuel aims to improve the autoignition properties, combustion, and exhaust emissions. The cetane number is a measure of ignition delay and must be matched to a given engine cycle and injection process [15].

Purpose of the research

The purpose of the research was to study the cetane number effects on operational properties of JP-8 fuel such as autoignition delay, maximum heat release rate, combustion pressure and pressure gradients, performance smoothness and emissions of the exhaust. The two ranges of speed were used for experiments: 1400 rpm at which maximum torque occurs and rated 2200 rpm speed. The study and comparison of engine performance parameters and exhaust emissions mainly for 0.752 MPa (100%) and 0.676 MPa (100%) loads were performed at respective speeds.

The differing chemical and physical properties of JP-8 fuel against those of the normal diesel fuel were considered to improve analysis of the cetane number effects on engine performance, emissions of nitrogen oxides (NO_x), carbon monoxide (CO), total unburned hydrocarbons (THC) and smoke opacity of the exhaust. This experimental work on JP-8 fuel and JP-8 fuel treated with the cetane number improving additive can be regarded as continuity of the diesel engine tests recently conducted at Aleksandras Stulginskis University (ASU) in cooperation with the General Jonas Žemaitis Military Academy of Lithuania [16,17, and 18].

Experimental engine test facilities and measuring apparatus

The tests were conducted on a standard, four-stroke, four-cylinder, 60 kW, DI diesel engine D-243 with a cylinder bore of 110 mm, a piston stroke of 120 mm, a splash volume of 4.75 dm3 and compression ratio of 16:1. Mechanical in-line injection pump PP.4M Motorpal with plunger diameter of 9.0 mm and stroke of 8.5 mm supplied the fuel at static fuel delivery advance of 25^0 CADs before top dead center (BTDC) and needle-valve lifting pressure of 19.0±0.5 MPa through five-hole injector into toroidal type combustion chamber in a piston head. The static delivery timing BTDC was the same for the normal diesel fuel and JP-8 fuels tested at all engine loads and speeds.

The experimental test set up consisted of a diesel engine, an engine test bed, the air and fuel mass consumption measuring tools, the gas analyser and a smoke meter for the exhaust (Fig. 1). A high speed multi-channel indicating system, which consisted of an angle encoder 365C and high performance piezoelectric pressure sensor GU24D coupled to an AVL indicating amplifier IndiModul 622, was introduced for the recording, acquisition and processing of fast crank-angle and time-based gas pressure signals. A piezoelectric uncooled transducer GU24D with the measurements range of 0-280 bar mounted into the head of the first cylinder and connected to the microIFEM piezoelectric amplifier-signal conditioning was used to measure gas pressure for every load-speed setting point with accuracy of ±0.1 bar within the temperature range of 25 °C to 200 °C.

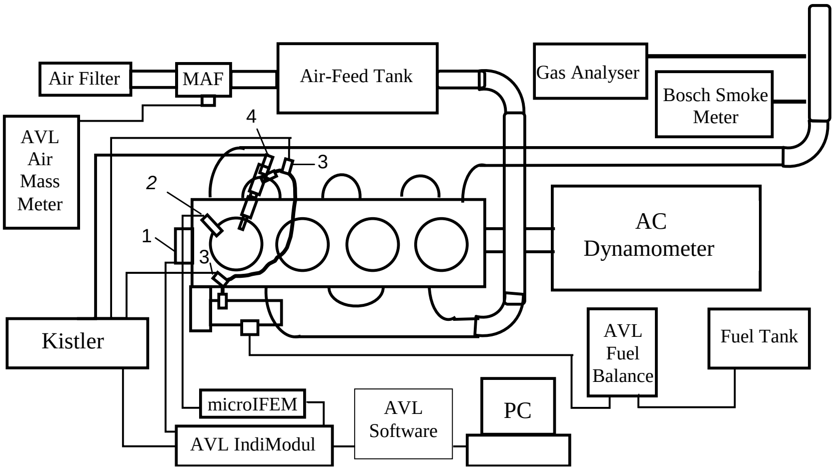

Fig. 1. Schematic arrangement of the engine test stand

The start of fuel injection was determined by using the injector's nozzle-needle-valve lift history recorded with the Wolff Controls Corporation Hall effects position sensor ASMB 470004-1, which was coupled to the Kastler 2-channel charge amplifier-module 5247 mounted on the signals conditioning platform-compact 2854A, with an accuracy of ±0.5% in the needle-valve lift range of 0-0.28 mm. The fuel line high pressure and the needle valve lift signals have been transmitted from the initial conditioning platform 2854A (SCP) to the AVL IndiModul 622 a fast data acquisition and processing system connected to personal computer equipped with the AVL Indicium Mobile software.

The engine torque was measured with a three phase asynchronous 110 kW AC stand dynamometer KS-56-4 with a definition rate of ±1 Nm. The engine speed was measured by using the AVL crank angle encoder 365C mounted at the front-end of the crankshaft that guaranteed an accuracy of less than ±0.2% of measured value. The air mass consumption was measured by using an AVL air mass meter (0-400 kg/h) installed downstream the air filter before the air tank to reduce pressure pulsations that guaranteed an accuracy of less than ±1% of measured value. The fuel mass consumption was measured by weighting 100 g of fuel on the AVL dynamic fuel balance 733S flex-fuel with an accuracy of ±0.1%.

The single-cycle and summarized over 100 engine cycles in-cylinder gas pressure versus crank angle diagrams were recorded for every 0.1° crank angle degree (CAD). The autoignition delay was determined as a period in units of time and/or crank angle degrees between start of injection (SOI) and start of combustion (SOC) with an accuracy ±0.1° CAD. As the start of injection was taken crank angle at which the injector-needle-valve moves up about 5% of its total lift. As the start of combustion was taken crank angle at which the curve of the heat release rate crosses the zero line and changes its value from the minus side to plus one.

The heat release rate was calculated by using a single-cycle diagram of the in-cylinder pressure versus crank angle as the input data average over the 100 combustion cycles, instantaneous cylinder volume, and their first order derivative with respect to crank angle. The data post-processing Software AVL CONCERTO™ advanced addition 4.5 was used that significantly increased productivity and improved accuracy of the results.

The emissions of nitric oxide NO (ppm), nitrogen dioxide NO_2 (ppm), carbon monoxide CO (ppm), and total unburned hydrocarbons THC (ppm) were measured by using the electrochemical measuring cells mounted in the Test 350 XL flue gas analyser. The total nitrogen oxide NO_x emissions were calculated as a sum of both the NO and the NO_2 components with an accuracy of ±5 ppm. Whereas a non-dispersive infrared method has been used for measuring the carbon dioxide CO_2 (vol%) emission. The smoke density (%) was measured with a “Bosch” RTT 110 opacity-meter, the readings of which are provided as Hart ridge units (% opacity) in a scale range of 0-100% with an accuracy of ±0.1%.

Experimental procedures and properties of diesel fuel and aviation-turbine JP-8 fuel

The experiments started with the investigation of the engine running on conventional (class C) diesel fuel (DF) to determine the performance efficiency and exhaust emissions constituting the “baseline” level that was used to compare with the respective values of parameters obtained when running on JP-8 fuel. The fuels used were a typical automotive fuel satisfying the EN-590 specification, which according to the EU Directive 2009/28/EC included 5vol% of RME, and aviation-turbine JP-8 fuel (NATO F-34) satisfying the MIL-DTL-83133E specifications.

Five containers of JP-8-04, JP-8-08, JP-8-12, JP-8-16, and JP-8-24 fuels were prepared at the oil refinery “Orlen Lietuva” by adding 0.04vol%, 0.08vol%, 0.12vol%, 0.16vol%, and 0.24vol% 2-ethylhexyl nitrate to JP-8 fuel. Adding 2-ethylhexyl nitrate in the above given proportions the cetane number (CN) of JP-8 fuel improved from 42.3 to 46.1, 47.6, 48.5, 49.4, and 49.8, respectively, enhancing ignition properties of aviation fuel to adapt it for using in ground-based military transport. Chemical and physical properties, including the values of the cetane number of diesel fuel, JP-8 fuel, and JP-8 treated with 2-ethylhexyl nitrate, were measured at the oil refinery’s “Orlen Lietuva” Quality Control Centre, which is approved by NATO (Table 1).

Table 1. Properties of normal diesel fuel and aviation-turbine JP-8 fuel (NATO code F-34)

Property parameters	Diesel fuel test methods	Jet fuel test methods	Diesel fuel (grade C)	JP-8 fuel
Chemical formula	-	-	$C_{13}H_{24}$	$C_{10.17}H_{19.91}$
Density at 15 ^{o}C, kg/m^3	EN ISO 12185:1999	ASTM D 4052-09	843.6	797.2
Kinematic viscosity, mm^2/s	EN ISO 3104+AC:2000 at 40 ºC	ASTM D 445 at -20 ºC	2.89	4.0
Lubricity, corrected wear scar diameter (wsd 1.4) at 60 ºC, µm	EN ISO 12156-1	-	460	611
Flash point, open cup ^{o}C	EN ISO 2719:2003	ASTM D 56-05	59	40.0
Initial / final boiling points, ^{o}C	EN ISO 3405:2011	-	177.8 / 367.0	145.4 / 258.7
Cold filter plugging point, ^{o}C	EN ISO 116/AC:2002	-	-7	-60.4
Cetane number	EN ISO 5165:1999		51.3	42.3
Iodine number, $J_2g/100$ g	EN 14111:2003	-	12	-
Acid value, mg KOH/g	-	ASTM D 3242-11	0.06	0.001
Polycyclic aromatics, %	EN 12916	ASTM D 1319-10	3.0wt%	17.5vol %
Sulphur, total, mg/kg	EN ISO 20846:2004	ASTM D 5453-09	8.9	9.3
Distillation residue, carbonates%	EN ISO 10370:1999	-	0.03 mass%	1.1 volume%
Carbon-to-hydrogen ratio (C/H)	-	-	6.5	6.1
Net heating value, MJ/kg	EN ISO 8217:2007	ASTM D 4529-01	43.10	43.23

The JP-8 fuel is almost exclusively extracted from the kerosene fraction of crude oil, which distillation points are between the gasoline fraction and the diesel fraction [19]. The kerosene has lighter fractions compared with commercial diesel fuel that suggests a more volatile fuel with a higher vapour pressure and faster mixing of combustible mixture. The higher amount of hydrogen in JP-8 composition ensures lower density and viscosity, reduced C/H ratio and slightly (0.3%) increased net heating value of the fuel compared with the diesel fuel. Using a JP-8 fuel with low cetane number may also result in a rough-running of a diesel engine due to the longer autoignition delay and higher amount of the fuel premixed for rapid combustion. The lower lubricity of JP-8 fuel and other related problems create reasonable concern about reliability of diesel engines mounted upon a ground-based military equipment, vehicles and power generators in case of using aviation-turbine fuel with too low cetane rating.

The lower density and viscosity of the JP-8 fuel lead to earlier start of distillation curve at the temperature of 145.4 °C and sooner vaporisation end at the temperature of 258.7 °C, - both parameters are much lower than the respective values of 177.8 °C and 367.0 °C of the normal diesel fuel. These beneficial features of JP-8 fuel may quicken the air and fuel vapours mixing and improve homogeneity of flammable mixture. Better atomization of JP-8 fuel and lower latent heat of vaporization (250 kJ/kg) may also contribute to faster evaporation and air-fuel mixing [11]. However, the 17.5% lower cetane rating of JP-8 fuel against that (51.3) of the normal diesel fuel may lead to longer ignition delay and bigger portion of the fuel premixed for rapid combustion. This may increase the maximum heat release rate in a premixed combustion phase and lead to more intensive pressure growth in the engine cylinder. According Schihl et al. [20], the premixed phase vapour fraction trends are similar, even though JP-8 (CN = 49) showed a shorter ignition delay in comparison to DF-2, due in part to the much faster evaporation rate of JP-8 fuel.

Results on changes of the autoignition delay and combustion parameters

The autoignition delay in CADs decreased with the increase of engine load for both fuels tested at both ranges of speed. However, the measured autoignition delay was always longer for JP-8 fuel than the normal diesel fuel tested at all engine loads and the two ranges of 1400 and 2200 rpm speed because of low cetane rating of aviation turbine fuel. The autoignition delay was 8.3%, 7.4%, and 4.3% longer for JP-8 fuel compared with the respective values of 9.3^0, 8.8^0, and 7.3^0 CADs of normal diesel running at 15%, 50% and 100% loads and 1400 rpm speed. In contrast to the low speed range, the difference in autoignition delay between both fuels increased by 10.5%, 13.3%, and 15.3% with the increase of engine load when running at rated 2200 rpm speed. As a result, the autoignition delay for JP-8 fuel sustained at much higher levels compared with corresponding values of 11.8^0, 10.8^0 and 9.7^0 CADs of the reference diesel fuel used at respective 10%, 50%, and 100% loads.

The investigation conducted in an optically-accessible diesel engine revealed that the ignition delay of JP-8 is longer than that of diesel fuel by about 0.5^0–0.8^0 CADs even though one could expect that JP-8 may have shorter ignition delay due to superior vaporisation and, thus, faster mixing [11]. These results show that ignition delay is more dominantly influenced by the low cetane number, rather than improved volatility of JP-8 fuel and better mixing properties. The longer autoignition delay for JP-8 fuel matches well with the test results of JP-8 fuel on both DI and IDI diesel engines obtained by other researchers [13,21-24].

When running on maximally 0.24vol% treated JP-8-24 fuel (CN = 49.8) the ignition delay decreased by 13.5%, 12.8% and 15.9% compared with corresponding values of 10.1^0, 9.5^0 and 7.6^0 CADs measured for 15%, 50% and

100% loads at low 1400 rpm speed. This preignition reactions period further decreased even with a higher intensity 36.9%, 37.2% and 44.8% against the reference values of 13.0^0, 12.3^0 and 11.2^0 CADs of JP-8 fuel measured for 10%, 50% and 100% loads at rated 2200 rpm speed.

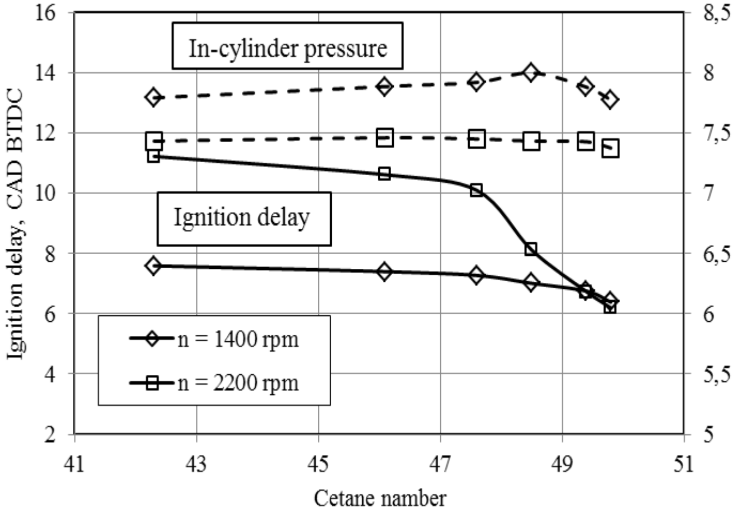

Fig. 2. Effect of the cetane number JP-8 fuel on the autoignition delay and maximum in-cylinder pressure for various engine loads (bmep) at speeds of 1400 and 2200 rpm

Fig. 2 shows, the autoignition delay for the fully loaded (100%) engine changes inversely proportional to the cetane number of JP-8 fuel. Evaluating the effectiveness of 2-ethylhexyl nitrate on reactivity properties of JP-8 fuel one can state that the biggest reduction of the autoignition delay was achieved when running on maximally treated JP-8-24 fuel (CN = 49.8) at full (100%) engine load and high 2200 rpm speed. The test results show that the biggest effect of the cetane number of JP-8 fuel is obtaimed when running under heavy (100%) load at high speed, namely, because the time-span intended to complete fuel injection and overall engine cycle is a major limiting factor.

However, if the autoignition delay decreases below observed critical limit, which is important for penetration and distribution across the combustion chamber of the fuel sprays, it may not always convert into clean combustion as could be expected. Since maximum and average injection pressures decrease with the speed of the mechanical in-line injection pump boosted up beyond certain critical limit, the penetration distance of the fuel spray tips decreases even for the normal diesel fuel [25]. Mechanical injection pump develops lower penetration of the JP-8 fuel compared with common rail injection system that may reduce the total surface area of the fuel sprays exposed to hot in-cylinder compressed air charge. Thus, if the cetane number of the JP-8 fuel is too high, the autoignition delay can be too short and combustion may start too soon in the engine cycle before the air and fuel mixture of acceptable quality is prepared.

Replacement of the diesel fuel with a lighter JP-8 fuel the start of injection (SOI) retarded by 1.5^0 and 1.0^0 CADs compared with initial values of 16.3^0 and 16.6^0 CADs BTDC of normal diesel running at full (100%) load and respective 1400 and 2200 rpm speeds. Both the late start of injection and the long ignition delay retarded the start of combustion (SOC), increased maximum heat release rate HRR_{max} in premixed combustion phase that affected overall process, and relocated the end of combustion towards a bigger cylinder volume in the expansion stroke. The observed increase of heat release intensity was further promoted by a faster vaporization and superior mixing rate of JP-8 fuel vapours with the in-cylinder air. The higher maximum heat release rate HRR_{max} shows that premixed burn portion of JP-8 fuel was greater than that of fossil diesel fuel tested at the same performance conditions.

Both the autoignition delay and the heat release intensity decreased, whereas the first maximum of heat release rate HRR_{max} moved closer to the area traditionally occupied by the combustion of the normal diesel fuel due to the added 2-ethylhexyl nitrate to JP-8 fuel. The decrease of autoignition delay and the transfer of HRR_{max} in premixed combustion phase towards constant-volume combustion occurred about directly proportional to the cetane number value of the tested fuel. Whereas the diffusion combustion phase almost did not respond to 2-ethylhexyl nitrate added to JP-8 fuel and the second heat release maximum HRR_{max} took place at about $7\text{-}9^0$ CADs ATDC for all fuels tested. A slight increase of net heat released in the diffusion burning phase can be soundly acknowledged as a pay-off for the reduced heat release rate during premixed combustion phase.

The higher maximum heat release rate in premixed combustion phase does not always leads to high maximum in-cylinder pressure produced for similar combustion conditions as could be expected (Fig. 2). The engine performance on JP-8 fuel was a bit smoother and quieter compared with normal diesel operation under full (100%) load at both 1400 and 2200 rpm speeds, regardless of a higher premixed fuel portion and intensive heat release rate in the premixed combustion phase. This occurred because the maximum heat release rate and thus the peak in-cylinder pressure took place later in the expansion stroke within a bigger cylinder volume. The obtained results match well with those observed for a DI engine running on JP-8 fuel at all 1500, 2000, and 2500 rpm speeds and part load conditions. In that research [22], the in-cylinder pressure rise also was lower compared with the normal diesel fuel case.

The maximum in-cylinder pressure increased to a certain extent reaching the highest value of 8.0 MPa (2.6%) for CN = 48.5 fuel tested at full (100%) engine load and 1400 rpm speed (Fig. 2). This occurred since using of JP-8 fuel with a higher cetane rating reduced autoignition delay and shifted the location of maximum heat release rate towards constant volume process. As a result, higher in-cylinder pressure was produced by greater than before maximum pressure gradients 0.590 MPa/^{0}, which were up to 10.7% higher compared with untreated JP-8 fuel case

(0.533 MPa/^{0}). Whereas, the peak in-cylinder pressure and maximum pressure gradients almost did not respond to the increase of the cetane number of JP-8 fuel at a higher 2200 rpm speed. Both the in-cylinder pressure and pressure growth rate reached the biggest values of 7.46 MPa and 0.757 MPa/^{0} for CN = 46.1 fuel case and, afterwards, decreased smoothly for higher cetane ratings of the JP-8 fuel.

Comparative results of engine performance on JP-8 fuel

Using of JP-8 fuel suggested the brake specific fuel consumption 5.5% higher, 1.0% and 1.8% lower than the reference values of 483, 269 and 252 g/kWh of normal diesel running under 15%, 50% and 100% loads at low 1400 rpm speed. Better atomisation of a lighter JP-8 fuel, faster vaporisation, and superior mixing of the fuel vapours with the in cylinder compressed air ensured complete combustion and thus lower brake specific fuel consumption for medium (50%) and full (100%) loads. To better fuel-economy contributed also slightly higher (0.3%) calorific value of JP-8 fuel. Whereas the bsfc increased by 5.6%, 0.8% and 2.5% against baseline values of 589, 274 and 267 g/kWh of the normal diesel fuel used at 10%, 50% and 100% loads and high 2200 rpm speed.

Using of JP-8 fuel with the improved cetane rating may not have straight effect on the brake specific fuel consumption of an engine, however the bsfc values decreased for all JP-8 fuels treated with the cetane number improving additive. The biggest 4.7% improvement of fuel economy was achieved when running on JP-8-12 (CN = 48.5) at light 15% load and low 1400 rpm speed. However, the brake specific fuel consumption for higher CN ratings was up to 8.7% (CN = 49.4) and 3.2% (CN = 49.8) bigger compared with the reference JP-8 fuel used at medium (50%) and full (100%) loads. Only the use of JP-8-12 fuel suggested the bsfc about the same or slightly (1.0%) higher than the respective values of 266 and 247 g/kWh of neat JP-8 fuel.

The brake specific fuel consumption for JP-8 with CN = 48.5 was slightly 0.6%, 0.4% and 1.4% lower than corresponding values of 622, 276 and 273 g/kWh of the reference JP-8 fuel used at all 10%, 50% and 100% loads and rated 2200 rpm speed too. To better fuel economy contributed both, - reasonably shorter autoignition delay and lower maximum heat release rate of the premixed combustion phase, which occurred earlier in the engine cycle. The positive changes shifted subsequent combustion phases towards more energy-saving constant-volume process closer to TDC that is important to have efficient performance of an engine. Since the CO_2 emissions directly depend on the amount of fuel burned, the use of properly treated JP-8-12 fuel in ground-based diesel-powered military vehicles would be an effective measure to reduce the fuel consumption and controlled emissions.

The brake thermal efficiency changed in the reverse manner as the bsfc responded to adding the cetane improving agent to JP-8 fuel (Fig. 3). This occurred because the difference in net heating values of the normal diesel fuel (43.10 MJ/kg) and JP-8 fuel (43.23 MJ/kg) was below 0.3% computed uncertainty (±1.5%) of the bsfc value. To be precise, the brake thermal efficiency for JP-8 fuel varied within the range of 5.2% lower to 1.5% higher level compared with values of 0.173 and 0.332 of normal diesel running at 15% and 100% loads at 1400 rpm speed. However, the brake thermal efficiency for JP-8 fuel always was 5.6% and 2.6% lower compared with values of 0.142 and 0.313 developed by the normal diesel fuel for respective 10% and 100% loads at rated 2200 rpm speed.

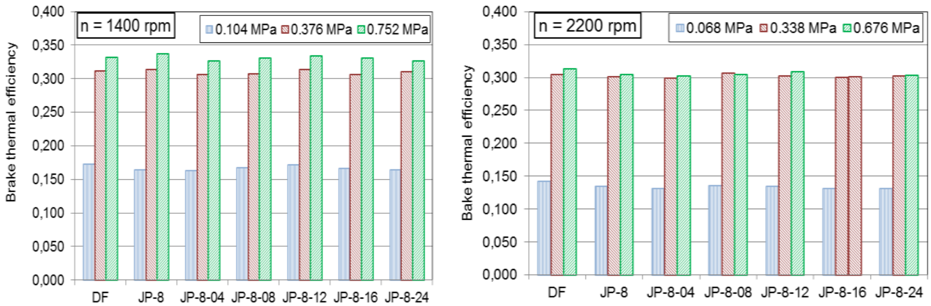

Fig. 3. Effect the cetane number of JP-8 fuel on the brake thermal efficiency (bte) for various engine loads (bmep) at 1400 and 2200 rpm speeds

Overall performance efficiency of a fully (100%) loaded engine did not change much with adding 2-ethylhexyl nitrate to JP-8 fuel (Fig. 3). The use of JP-8-12 fuel suggested the brake thermal efficiency 0.9% lower when running at a fully opened throttle and 1400 rpm, but it converted to be 1.3% higher at rated 2200 rpm speed compared with the respective values of 0.337 and 0.305 of untreated JP-8 fuel. The analysis of changes in heat release characteristics, maximum in-cylinder pressure, and brake specific fuel consumption shows that adding about 0.12vol% of 2-ethylhexyl nitrate to JF-8 fuel would be effective measure to improve operational properties of an engine.

Comparative results of engine emissions on JP-8 fuel

According to EU Directive 2009/28/EC diesel fuel used has included about 0.57wt% of the fuel bound oxygen due to the presence of the 5vol% of RME in its composition. Despite of this, using of a lighter, oxygen-free JP-8 fuel showed benefits in reducing of all harmful species, - the NO_x, CO, HC emissions, and smoke of the exhaust. The presence of more sulphur in aviation-turbine fuel did not result in a higher PM emissions and smoke density due to of formed sulphates [26]. The fuel JP-8 was especially environmentally friendly when running at a fully (100%) opened throttle and 1400 rpm speed at which maximum torque occurs.

Using of JP-8-12 fuel with about optimal CN = 48.5 rating the NO_x emission increased by 5.1% compared with the reference JP-8 fuel used at full (100%) engine load and 1400 rpm speed (Fig. 4). However the NO_x emissions almost did not respond to the increase of the cetane number of JP-8 fuel up to CN = 48.5 when running at rated 2200 rpm speed. The NO_x emissions reduced by 3.3% and 9.2% for both speeds due to further improvement of the cetane number to 49.4 and 49.8, respectively. The higher NO_x emissions measured at 1400 rpm speed and almost unchangeable NO_x values at 2200 rpm speed, with the increase of the cetane number up to the value of 48.5, match well with better performance efficiency of an engine on treated JP-8-12 fuel.

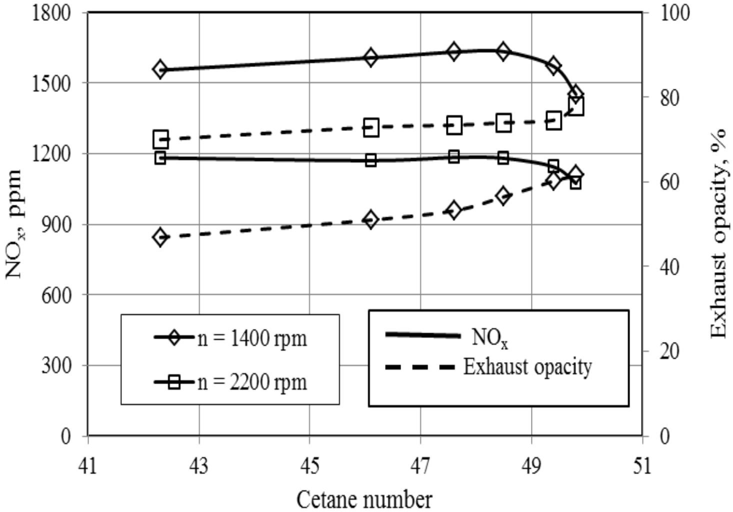

Fig. 4. Effect of the cetane number of JP-8 fuel on the total NO_x emission and smoke opacity of the exhaust for full (100%) load at 1400 and 2200 rpm speeds

Smoke opacity of the exhaust increased with a higher 8.7%, 13.4%, 20.5%, 28.4%, and 31.1% intensity than the cetane number 9.0%, 12.5%, 14.7% 16.8%, and 17.7% of JP-8 fuel treated with 2-ethylhexyl nitrate was improved for full (100%) engine load and 1400 rpm speed (Fig. 4). Despite the fact that the time-span was just enough to convert all carbon in the jet fuel to CO_2 and all hydrogen to H_2O, the shorter autoignition delay resulted into stable growth of the exhaust smoke (soot) at low 1400 rpm speed, with the increase being higher the higher the cetane rating of JP-8 fuel. The higher volatile PM emissions along with increased incomplete combustion products CO and THC match well with slightly lower performance efficiency of an engine on treated JP-8 fuel.

Using of the JP-8 fuels with a higher cetane ratings increased the smoke opacity when running a fully (100%) loaded engine at rated 2200 rpm speed too. However, in this case, the visible smoke increased with the increase of the cetane number of JP-8 fuel up to three times smoother 4.1%, 4.9%, 5.7%, 6.6%, and 11.1% than at low engine speed. Even though the exhaust smoke increased with a lower increment rate, overall opacity level at which the fully loaded engine operated was greater than before treatment of JP-8 fuel with 2-ethylhexyl nitrate for both ranges of 1400 and 2200 rpm speed.

The CO and the HC emissions decreased by 63.7% and more than 6 times compared with the values of normal diesel running at full (100%) load and 1400 rpm speed. Positive changes in the unburned hydrocarbons behaviour occurred because using of a lighter JP-8 fuel increased the fuel spray cone angle and improved homogeneity of combustible mixture. The fact that less HC and CO were produced matches well with a better brake thermal efficiency (Fig. 3) and lover exhaust smoke at maximum torque of an engine (Fig. 4). It is important to note that the CO and the HC emissions depend on fuel aromatic content, which is greater for JP-8 fuel (Table 1). Regardless of this, the CO, HC and smoke (soot) produced by a fully loaded engine is almost always lower if combustion of the fuel goes normally.

Advantages obtained by the use of alternative JP-8 fuel for diesel engine powering disappeared after transition to a higher 2200 rpm speed. The fully (100%) loaded engine emitted the CO, HC and exhaust smoke 15.7%, 19,7% and 1.4% more consuming 2.5% more JP-8 fuel per unit of energy developed than an engine running on the normal diesel fuel. The potential to form a locally over-lean mixture due to higher vaporization rate and longer autoignition delay of JP-8 fuel may lead to incomplete burning in some combustion chamber parts.

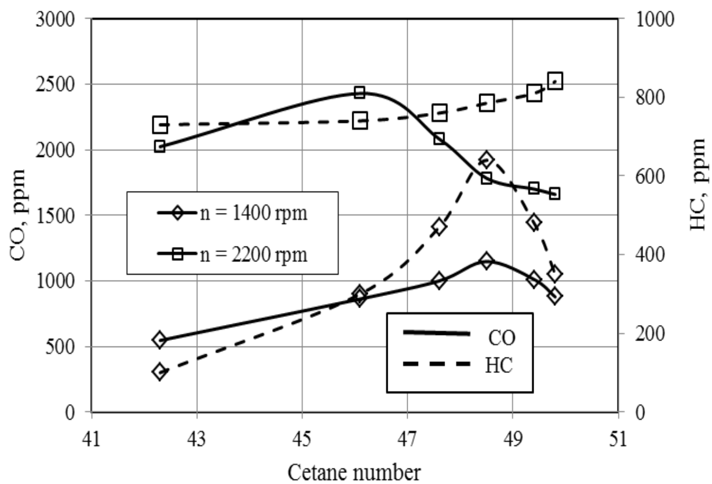

Fig. 5. The effect of the cetane number of aviation-turbine JP-8 fuel on the CO and the HC emissions for full (100%) engine load at 1400 rpm and 2200 rpm speeds

The CO and the HC emission increased and reached the maximum values of 1148 ppm (2.1 times) and 640 ppm (6.4 times) when running on treated JP-8-12 fuel at full (100%) load and 1400 rpm speed (Fig. 5). Using of the JP-8 fuels with a higher than CN = 48.5 rating resulted in slight reduction of the CO and the HC emitted. However, overall level of smoke opacity and incomplete combustion products always was higher than in case of using neat JP-8 fuel. The CO emissions reached the highest value of 2430 ppm (20.1%) when running on JP-8 fuel with CN = 46.1 at full (100%) load and high 2200 rpm speed too with following decrease to 1660 ppm (18.0%) for a higher CN = 49.8 ratings.

The HC emissions increased from 730 ppm to 840 ppm (15.1%) with steady growth (11.1%) of the exhaust smoke caused by the improvement of the cetane number of jet fuel within the range of 42.3 to 49.8. The main reason of producing more unburned hydrocarbons is too high cetane number of over treated fuel that leads to sooner than before start of combustion resulting in less time available for the air and fuel vapours mixing and, therefore, the CO and the HC emissions are high. The test results show that diesel engine would be able to work properly on aviation-turbine JP-8 fuel at low 1400 rpm speed mainly as it would not be longer at full efficiency if running at a fully opened throttle and high speed.

It is possible to reduce the brake specific fuel consumption of an engine by adding about 0.12vol% of 2-ethylhexyl nitrate to JP-8 fuel. However too low autoignition delay often results in less efficient combustion producing more CO, HC emissions and smoke (soot). Therefore, the improvement of the cetane number of JP-8 fuel cannot be the only measure to be used to reduce unburned THC, CO and soot. It is important to note that mixing of the air and fuel vapours weakens if the cetane number of JP-8 fuel becomes increased to the extent that it is no longer acceptable. This topic should be thoroughly considered while adapting aviation-turbine JP-8 fuel for land-based diesel generators and military transport.

Conclusions

The low cetane number and the long autoignition delay are among major causes, which retarded combustion of JP-8 fuel, increased brake specific fuel consumption and what ends up in the engine exhaust. The late start of combustion resulted in more the CO and the HC emitted at rated 2200 rpm speed, however maximum NO_x emissions and visible smoke were decreased for both 1400 and 2200 rpm speeds that can be regarded as an environmentally friendly behaviour.

Using of JP-8 fuels with higher CN ratings led to the resulting performance and emissions changes of a fully (100%) loaded engine:

1. Reduction of the autoignition delay for all engine loads and speeds. The autoignition delay became 1.2^0 and 5.0^0 CADs shorter compared with corresponding values of the reference JP-8 fuel used under full (100%) load at both 1400 and 2200 rpm speeds due to the use of JP-8-24 fuel with the highest cetane rating of CN = 49.8.

2. Reduction of the maximum heat release rate HRR_{max} in premixed combustion phase and its slight growth in the diffusion burning phase with overall transfer of the combustion towards a constant-volume process that is important for efficient engine performance on JP-8 fuel.

3. Increase of the peak in-cylinder pressure and maximum pressure gradients by 2.7% and 10.3%, 0.4% and 0.7% for JP-8-12, JP-8-04 fuels against the values of JP-8 fuel used at 1400, 2200 rpm speeds with tendency to run smoother with a higher than 48.5, 46.1 CN ratings, respectively.

4. Increase of the brake specific fuel consumption by 1.0% at low 1400 rpm speed and its following decrease by as much as 1.4% when running on JP-8-12 fuel (CN = 48.5) at rated 2200 rpm speed against corresponding values of the reference JP-8 fuel.

5. Increase of the brake thermal efficiency up to the maximum values of 0.334 and 0.309 when running on treated JP-8-12 fuel (CN = 48.5) at both 1400 and 2200 rpm speeds.

6. Increase of the NO_x emission for the CN = 48.5 rating by 5.1% against the respective value of 1555 ppm of the reference JP-8 fuel (CN = 42.3) used at 1400 rpm speed. About unchangeable the NO_x behaviour with the increase of the cetane number up to 48.5 at rated 2200 rpm speed and its smooth decrease for fuels with higher CN ratings at both 1400 and 2200 rpm speeds.

7. Increase of the CO and the HC emissions by 33.2% and 2.1 times for JP-8-12 fuel (CN = 48.5) against corresponding values of the reference JP-8 fuel with following decrease of both harmful species for fuels with higher CN ratings at 1400 rpm speed.

8. Increase of the CO emission to the maximum value of 2429 ppm for JP-8-04 fuel (CN = 46.1) with its following decrease for higher CN ratings and stable growth of the HC emission by as much as 15.1% for JP-8-24 fuel (CN = 49.8) at 2200 rpm speed; increase of the exhaust smoke opacity by as much as 31.1% at 1400 rpm speed and its smooth (11.1%) growth at 2200 rpm speed for JP-8-24 fuel with the highest CN = 49.8 cetane rating.

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