COMBUSTION, PERFORMANCE AND EMISSION CHARACTERISTICS OF DIESEL ENGINE OPERATING ON JET FUEL TREATED WITH CETANE IMPROVER

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Abstract: The article presents the bench testing results of a four stroke, four cylinder, unmodified, naturally aspirated DI diesel engine running on diesel fuel (DF) and Jet A-1 fuel (JF) treated with various percentage 0.04 %, 0.08 %, 0.12 %, 0.16 % and 0.24 vol % of cetane number (CN) improver. The purpose of the research is to conduct analysis of the autoignition delay, performance, combustion, and emissions of diesel engine running on diesel fuel as a starting point version and fuel Jet A-1 to recommend this alternative kerosene based fuel for using in battlefield military equipment. Replacing diesel fuel with Jet A-1 increases the autoignition delay and reduces both the maximum cylinder pressure by 6.5 % and maximum pressure gradient by 9.3 % at maximum torque. The maximum cylinder pressure is 4.4 % lower, however the maximum pressure gradient increases by 2.2 % when running at rated power. The additive 2-ethylhexyl nitrate does not actually affect the maximum cylinder pressure, however, it reduces the maximum pressure growth in the cylinder. The brake specific fuel consumption (BSFC) of the fully loaded engine decreases by 1.8 % at 1400 rpm speed and increases by 2.5 % at 2200 rpm speed compared to normal diesel. The effect of CN improver (0.12 %) on the BSFC is small at maximum torque, but the BSFC of the fully loaded engine increases by 2.3 % and 1.2 %, respectively, at 1800 rpm and 2200 rpm speeds. The maximum NO emissions reduce by 11.5 %, 11.8 % and 17.1 % when running the engine on fuel Jet A-1 at 1400, 1800 and 2200 rpm speeds. The influence of 2-ethylhexyl nitrate on the NO emission is ambivalent enough, – because of adding cetane improver 0.12 % by mass the NO emission increases by 5.0 % at 1400 rpm speed and reduces by 1.1 % and 0.8 % at higher 1800 and 2200 rpm speeds. When running of the fully loaded engine on fuel Jet A-1, the maximum CO emission reduces 2.8 times, by 15.0 % and increases by 15.7 % at 1400, 1800 and 2200 rpm speeds. The maximum HC emission reduces 6.1 times, does not change and increases 3.0 times at considered loading conditions. Adding the cetane improver into fuel Jet A-1 increases the CO and HC emissions almost for all loads and speeds. The maximum smoke opacity of the exhaust produced by Jet A-1 fuel is up to 31.0 % lower over the whole speed range, however, it also shows a tendency to increase slightly under the influence of the cetane improver.

Keywords: diesel engine, fuel Jet A-1, cetane improver, autoignition, combustion, performance, emissions, smoke opacity of the exhaust.

Introduction

The MC-473 Directive provides guidance to NATO and national authorities on the policies, principles, and characteristics of the NATO Petroleum Supply Chain. The aim of the single fuel idea is to simplify the supply chain for petroleum products in the NATO nations and to achieve maximum versatility of equipment by using of a single fuel, namely JP-8, on the battlefield for land-based military aircrafts, vehicles, and equipment. At its autumn meeting in 2004, the NATO Pipeline Committee (NPC) adopted the SFP as the NATO Single Fuel Policy [1]. The single fuel selected has been JP-8 military jet kerosene, which is based upon the civil jet fuel Jet A-1, which is widely available in Europe. The fuel Jet A-1 meets the needs of the USA standard ASTM-D 1655. Anti-icing and lubricating additive 0.1 vol % with long-term corrosion inhibitors are used in aviation fuel Jet A-1 to improve the quality of military jet fuel JP-8 [2].

The bench tests of a single cylinder, DI Petter engine show that the volumetric fuel consumption slightly increases, PM emissions strongly recede and the nitrogen oxide emissions decrease or increase because of replacement of commercial aviation fuel JP-8 with sunflower oil and olive oil at parts from 10 % to 50 % [2]. An experimental study carried out in an optically accessible single cylinder heavy duty diesel engine equipped with a common-rail injection system showed that the spray tip penetration of JP-8 was shorter than that of diesel fuel by nearly 16 % when the injection pressure was 30 MPa and 10 % with increased injection pressure at 140 MPa. The decreased spray tip penetration was accompanied by 15.9º to 6.2º wider spray angle of JP-8 under considered fuel injection pressures than that of diesel fuel [3]. These and other properties of fuel JP-8 contribute to higher fuel-air mixing rate and improve atomisation, resulting from shorter spray tip penetration and a wider spray angle [4].

The test results of a 558 kW, B-46-6, supercharged, 12-cylinders, CIDI engine show 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. The lower cetane number (CN) of JP-8 fuel caused a slight increase in ignition delay but improved the combustion at load conditions, thus lowering the combustion noise [5]. Experimental studies showed that JP-8 fuels have the potential for lowering NO_x, CO, HC emissions and smoke compared to diesel fuel. The test results obtained at the Detroit Diesel Corporation with S60 engine outfitted with exhaust-gas recirculation show that torque and fuel economy of diesel fuel can be improved without smoke or NO_x penalty. This goal can be achieved by increasing the duration of injection to compensate for the lower fuel density. The lower cetane number of JP-8 causes an increased ignition delay and increased premixed combustion, and their cumulative effect led to relatively unchanged combustion phasing. Under almost all conditions, JP-8 led to lower NO_x and PM emissions and shifted the NO_x-PM trade-off favourably [6].

Purpose of the research

The purpose of the research is to examine the effect of cetane improver on the autoignition delay, combustion, performance, emission composition, including nitrogen oxides NO_x, carbon monoxide CO, total unburned hydrocarbons HC and smoke opacity of the exhausts of direct-injection diesel engine running over a wide range of loads and speeds.

Apparatus and methods of the research

The tests were conducted on a four-stroke, four-cylinder, DI diesel engine D-243. The fuel was delivered by an in line fuel injection pump through five holes (0.34 mm) injection nozzles with the fuel injection advance of 25° before the top dead centre (TDC).

The needle valve lifting pressure was set to 17.5±0.5 MPa. The load characteristics were taken at 1400, 1800 and 2200 rpm speeds when working on diesel fuel (class C), Jet A-1 fuel (JF) and Jet A-1 fuel treated with the CN improving additive 2-ethylhexyl nitrate 0.04 %, 0.08 %, 0.12 %, 0.16 % and 0.24 % by mass. The engine torque was measured with AC stand dynamometer with an accuracy of ±1 Nm. The fuel mass consumption was measured with the AVL fuel balance with an accuracy of ±0.10 % and the air mass consumption was measured by using the AVL air metering equipment with an accuracy of ±0.25 %. The brake specific fuel consumption was determined with an uncertainty of ±2.5 %.

Single-cycle and summarised over 100 engine cycles in-cylinder gas pressure diagrams versus the crank angle were recorded at every 0.1 crank angle degree (CADs) by using the AVL indication and data acquisition system. A piezoelectric un-cooled transducer GU24D mounted into the first cylinder and connected to the MICROIFEM piezoelectric amplifier-signal conditioning with the AVL crank angle encoder 365C (±0.1°) have been used to record gas pressure for every load-speed setting point with an accuracy of ≥±0.1 bar.

The start of injection and injection duration were determined by recording of the nozzle-needle-valve lifting and its history by using the Hall effects position sensor ASMB 470004-1. The needle-valve lifting signals have been transmitted to the Kistler type 5247 amplifier module mounted on the signal conditioning platform Compact 2854 A. The AVL IndiModul 622 was introduced as a multi-channel indicating system for the acquisition and processing of fast crank-angle based cylinder pressure, and nozzle-needle-valve lift signals. For analysis and calculation of the heat release rate the average in-cylinder gas pressure of 100 engine cycles was used.

The autoignition delay was determined as the period in degrees (φ_i) and/or units of time (τ_i) between the start of fuel injection and the start of combustion. As the start of injection the point, at which the needle-valve lifts about 5 % of its total 0.28 mm stroke, was taken. As the start of combustion the point, at which the heat release differential curve crosses the zero line and changes its value from minus to plus one, was taken. These critical points were determined with an accuracy ±0.1° of the crank angle degrees.

The amounts of nitric oxide NO (ppm), nitrogen dioxide NO_2 (ppm), carbon monoxide CO (ppm) and total unburned hydrocarbons HC (ppm) in the exhausts were measured with the Testo 350 XL gas analyser. The smoke density D (%) of the exhausts was measured with a Bosch RTT 100/RTT 110 opacity-meter, which readings are given as Hartridge units in a scale ranging from 0 to 100 % with an accuracy of ±0.1 %. Temperature of the exhausts was measured by using of chromel-kopel thermocouple and indicator N20 that guaranteed an accuracy of ±0.2 ºC.

Results and discussion

The technical properties of diesel fuel, Jet A-1 fuel and Jet A-1 treated with the cetane improver by the addition 0.12 vol % of 2-ethylhexyl nitrate have been evaluated at the Quality research centre "ORLEN Lietuva" Ltd., Mažeikiai, which is accredited according to the standard EN ISO/IEC 17025-2005. The test results are shown in Table 1.

Table 1

Quality parameters of diesel fuel and Jet A-1 fuel

Quality parameters	Diesel fuel test methods	Jet fuel test methods	Diesel fuel (class C) EN 590	Jet A-1 fuel	
				Without additive	0.12 % of 2-ethylhexyl nitrate
Density at 15 ºC, kg·m^3	EN ISO 12185	ASTM D 4052	843.6	797.2	797.2
Kinematic viscosity, mm^2·s	EN ISO 3104 at 40 ºC	ASTM D 445 at -20 ºC	2.893	4.0	4.0
Lubricity, corrected wear scar diameter (wsd 1.4) at 60 ºC, μm	EN ISO 12156	–	460	611	729
Cold filter plugging point CFPP, ºC / Freezing point, ºC	EN ISO 116	AC:2002	-7	-58	-58
Cetane number	EN ISO 5165		51.3	42.3	48.5
Net heating value, MJ·kg^{-1}	ISO 8217:2007 / ASTM D 4529-01		43.10	43.30	43.27

Because of lower density and viscosity, the lubricating properties of fuel Jet A-1 are slightly worse compared with diesel fuel (Table 1). The fuel Jet A-1 is also oxygen free and its net heating value is 0.5 % higher than that of diesel fuel. On the one hand, the lower density and viscosity of jet fuel lower the start of distillation curve at temperature of 145.4 ºC compared to diesel fuel (177.8 ºC) and the vaporization end at temperature of 258.0 ºC against 345 ºC of normal diesel improve fuel evaporation and preparation of flammable mixture. The improved atomisation of Jet A-1, reduced the aromatics content (19.3 %) compared to diesel fuel (27.5 %) [3], and lower latent heat of vaporization (250 kJ·kg^{-1}) also might contribute to faster evaporation and air-fuel mixing. On the other hand, the 17.5 % lower cetane number of jet fuel compared with diesel fuel may lead to longer autoignition delay and bigger fuel portions premixed for rapid combustion. This may affect the heat release rate during the kinetic phase, lead to higher cylinder pressure and faster pressure growth in the cylinder. It was shown that adding of the cetane improver (0.12 vol %) into fuel Jet A-1 its cetane number increases from 42.3 to 48.5 making this aviation fuel better adapted for using in diesel engine vehicles [7].

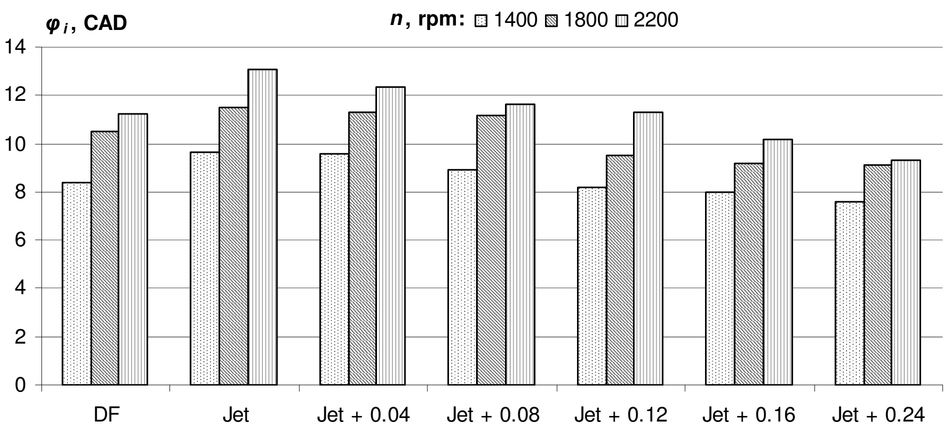


Fig. 1. **The effect of CN improver on the autoignition delay φ_i of the fully loaded engine**

Fig. 1 shows that the autoignition delay φ_i is 15.5 %, 9.5 % and 17.0 % longer against normal diesel 8.4º, 10.5º and 11.2º of CADs when running the fully loaded engine on Jet A-1 fuel at 1400, 1800 and 2200 rpm speeds. The increase in the autoignition delay matches well with the test results of JP-8 fuel on both DI and IDI diesel engines measured by other researchers [3; 5; 6]. Adding 2-ethylhexyl nitrate, which increases the cetane number of the jet fuel, reduces the autoignition delay φ_i for all engine loads and speeds. The effect on the autoignition delay increases with the percentage of cetane improver added in Jet A-1 fuel, therefore, the self-ignition process occurs much faster. Adding 0.12 % of 2-ethylhexyl nitrate into fuel Jet A-1 the autoignition delay reduces to the level, which roughly suits normal diesel needs. Further addition of the cetane improver leads to the autoignition delay φ_i of Jet A-1 even shorter than that of diesel fuel.

When the engine runs on diesel fuel at 1400 rpm speed, the maximum cylinder pressure is 84.1 bar and maximum pressure gradient 6.6 bar·(º)$^{-1}$. Replacing diesel fuel with fuel Jet A-1, the maximum cylinder pressure decreases by 6.5 % and maximum pressure gradient by 9.3 %. However, the pressure gradient increases from 9.7 to 12.3 bar·(º)$^{-1}$ (by 28.8 %) when running at 1800 rpm speed, When running the fully loaded engine at 2200 rpm speed, the maximum cylinder pressure decreases from 82.5 to 78.9 bar (by 4.4 %), however, the maximum pressure gradient increases from 13.7 to 14.0 bar·(º)$^{-1}$ (by 2.2 %).

The addition 0.04 % and 0.08 % of CN improver does not change the maximum cylinder pressure and pressure gradient variation tendencies at 1400 rpm speed. The higher percentages 0.12 %, 0.16 %, and 0.24 % of cetane improver added in fuel Jet A-1 result into the maximum pressure gradients nearly the same, 16.1 % and 24.7 % lower, respectively, compared to normal diesel operation. The maximum pressure gradients reduce by 14.3 %, 16.9 %, and 23.7 % due to addition 0.12 %, 0.16 %, and 0.20 % of 2-ethylhexyl nitrate at 2200 rpm speed as well.

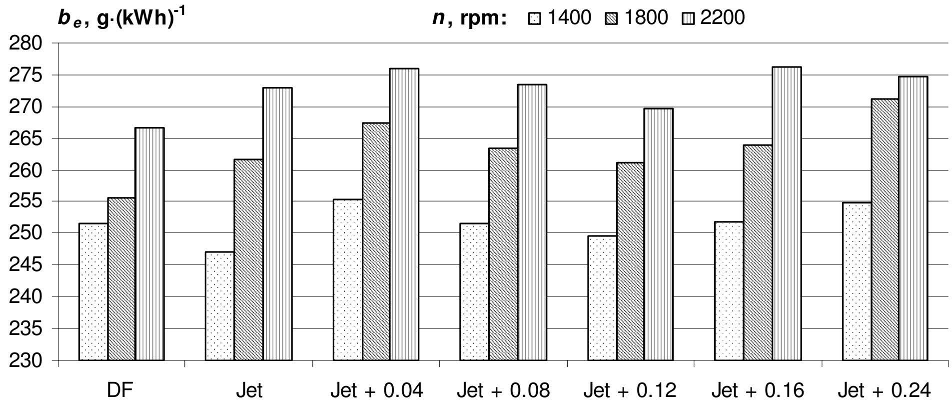
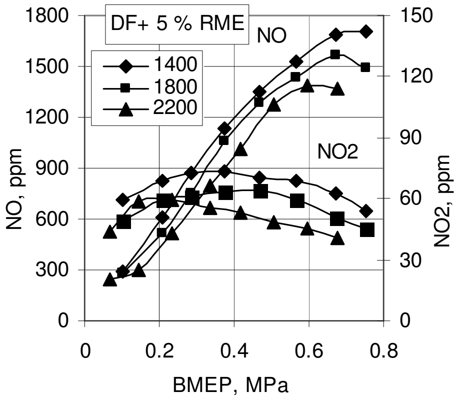


Fig. 2. **The effect of CN improver on BSFC when operating at full load and various speeds**

As the columns of Fig. 2 show, the brake specific fuel consumption of the fully loaded engine running on fuel Jet A-1 decreases by 1.8 %, increases by 2.4 % and 2.5 % against that of normal diesel, respectively, at 1400, 1800 and 2200 rpm speeds. At maximum torque 1400 rpm speed, the brake specific fuel consumption for diesel fuel and treated (0.12 %) fuel Jet A-1 is nearly the same, whereas the BSFC values increase by 2.3 % and 1.2 %, respectively, at higher 1800 rpm and 2200 rpm speeds.

For both normal diesel fuel and fuel Jet A-1, the maximum NO emissions suspend over the entire load range on the highest level when running at low 1400 rpm speed (Fig. 3). The NO emissions reduce with 1400, 1800 and 2200 rpm speed and reach the maximum values of 1705, 1567 and 1389 ppm for diesel fuel and 1509, 1382 and 1152 ppm for Jet A-1, i.e., the NO amounts decline by 11.5 %, 11.8 % and 17.1 %. The maximum nitrogen dioxide NO_2 emissions range from 60 to 70 ppm and suspend at nearly the same level for diesel fuel and fuel Jet A-1. The maximum NO emission increases by 3.6 %, 5.0 %, 5.0 %, 0.9 %, and reduces by 6.2 % compared with normal Jet A-1 fuel when using the treated jet fuels JF + 0.04 %, JF + 0.08 %, JF + 0.12 %, JF + 0.16 % and JF + 0.24 % at 1400 speed. The NO emissions stimulating effect becomes less significant when working at higher 1800 and 2200 rpm speeds, so the NO emissions decrease by 7.7 % to 1.9 % (JF+0.16 %) and 9.5 % to 9,9 %

(JF+0.24 %), respectively. The NO_2 emission changes are minor and remain in the accuracy limits from 2 to 3 ppm.



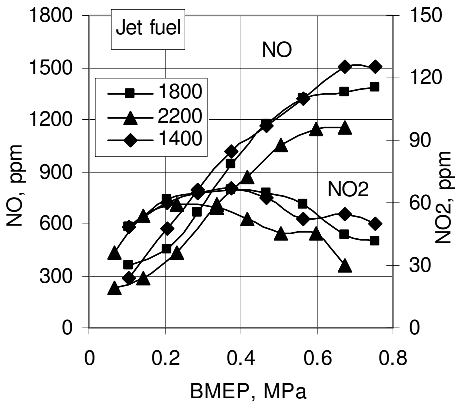
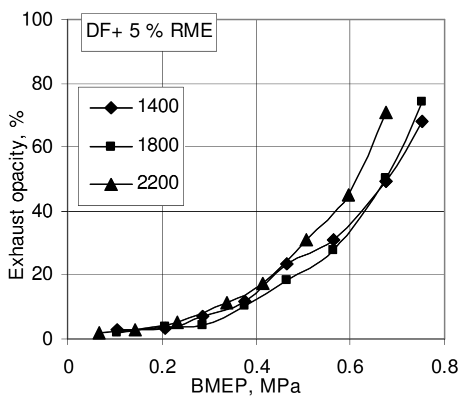


Fig. 3. **Dependencies of nitric oxide NO and nitrogen dioxide NO_2 emissions on engine load when running at various speeds on normal diesel and Jet A-1 fuel**

Fuel Jet A-1 suggests the CO emission 2.8 times lower compared to normal diesel (1502 ppm) produced at full load and 1400 rpm speed. The CO emission of the fully loaded engine still is 15 % lower when running on fuel Jet A-1 at 1800 rpm speed, however, the CO emissions increase over the entire load range up to 15.7 % compared with that produced by normal diesel at rated 2200 rpm speed. The maximum CO emission increases 2.1 times, reduces by 35.7 % and 46.5 % when running of the fully loaded engine on treated fuel JF + 0.12 % at respective 1400, 1800 and 2200 rpm speeds. When running on treated fuels JF + 0.04 %, JF + 0.08 %, JF + 0.16 % and JF + 0.24 %, the maximum CO emissions increase at all performance modes of the engine, except the CO decrease (18.0 %) achieved by using the most treated fuel JF + 0.24 % at rated 2200 rpm speed.

The highest HC emissions continue over the entire load range when running on diesel fuel at low 1400 rpm speed, which matches to maximum torque mode. Replacing of diesel fuel with Jet A-1 the maximum HC emission reduces from 610 to 100 ppm, i.e., 6.1 times at low 1400 rpm speed, it does not change (570 ppm) at moderate 1800 rpm speed and increases 3.0 times at rated 2200 rpm speed. The same as with CO, treatment of the Jet A-1 with the cetane improver leads to the maximum HC emission higher for all loads and speeds, except the HC decrease (11.4 %) measured when running on the most treated fuel JF + 0.24 % at rated speed. The biggest (6.4 times) HC emission increase is registered when working under full load on treated fuel JF + 0.12 % at low 1400 rpm speed.



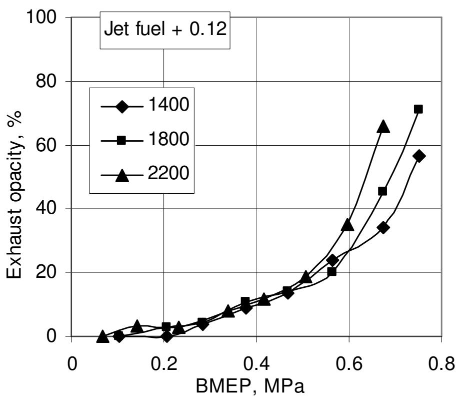


Fig. 4. **Dependencies of smoke of the exhaust on engine load when running on diesel fuel and treated aviation fuel JF + 0.12 % at 1400, 1800 and 2200 rpm speeds**

Replacing of diesel fuel with a lighter Jet A-1 fuel, the maximum smoke opacity reduces by 31.0 %, 9.8 % and 1.4 % at 1400, 1800 and 2200 rpm speeds. The smoke opacity reduces from 70.0 % to 66.0 % (by 5.7 %) for full load and rated 2200 rpm speed only due to addition into Jet A-I fuel 0.12 % of 2-ethylhexyl nitrate (Fig. 4). Other percentages of the cetane improver lead to higher maximum smoke opacity of the exhaust over all load-speed ranges. The biggest increase (by 31.1 %)

of the smoke opacity was measured when running on the most treated fuel JF + 0.24 % at rated 2200 rpm speed under full load at low 1400 rpm speed. The higher smoke opacity of the exhaust agrees with the well-known Soot/NO_x trade-off in classic diesel combustion.

Conclusions

1. Replacing of diesel fuel with aviation fuel Jet A-1 the autoignition delay period φ_i increases from 11.2º to 13.1º CADs (17.0 %) when running at full (100 %) load and rated 2200 rpm speed. Addition 0.12 % of 2-ethylhexyl nitrate in fuel Jet A-1 decreases the autoignition delay to 11.3º CADs, which matches normal diesel needs.
2. The maximum cylinder gas pressure and its maximum gradient reduce by 6.5 % and 9.3 % when running the fully loaded engine on fuel Jet A-1 at low 1400 rpm speed. Addition 0.12 % of 2-ethylhexyl nitrate does not affect the cylinder pressure and pressure gradient at maximum torque, however, the maximum pressure gradient reduces by 14.3 % at rated 2200 rpm mode.
3. The brake specific fuel consumption of the fully loaded engine running on fuel Jet A-1 decreases by 1.8 %, increases by 2.4 % and 2.5 % against that of normal diesel running at 1400, 1800 and 2200 rpm speeds. The BSFC for diesel fuel and treated fuel JF + 0.12 % is nearly the same at 1400 rpm speed, whereas the BSFC values increase by 2.3 % and 1.2 % at higher 1800 and 2200 rpm speeds.
4. The maximum NO emissions suggested by Jet A-1 are 11.5 %, 11.8 % and 17.1 % lower compared to those produced by normal diesel running at 1400, 1800 and 2200 rpm speeds. In case of using Jet A-1 treated with 0.12 % of 2-ethylhexyl nitrate, the maximum NO emissions further reduce by 7.0 %, 12.8 % and 17.7 % against those 1705, 1567 and 1389 ppm of normal diesel running at respective speeds.
5. When using fuel Jet A-1 the CO and the HC emissions reduce 2.8 and 6.1 times compared with normal diesel working at maximum torque mode. Replacing of diesel fuel with a lighter fuel Jet A-1 the maximum smoke opacity reduces by 31.0 %, 9.8 % and 1.4 % at 1400, 1800 and 2200 rpm speeds. However, the CO, the HC emissions and smoke opacity of the exhausts increase almost for all loads and speeds when running on Jet A-1 fuel treated with 2-ethylhexyl nitrate.

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