УДК 622.625.28
UDC 622.625.28

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COMPARATIVE PERFORMANCE OF A DIESEL ENGINE WITH AVIATION JP-8 FUEL TREATED WITH CETANE IMPROVING ADDITIVE AND RAPESEED BIODIESEL

The paper presents the test results of a DI diesel engine D-243 operating alternately with aviation-turbine JP-8 fuel treated with 0.04.(J04), 0.08 (J08), 0.12 (J12), 0.16 (J16), and 0.24 (J24) vol% with the cetane improving additive and 5 (J5), 10 (J10), 20 (J20), and 30 (J30) vol% rapeseed biodiesel (RME). The effects of 2-ethylhexyl nitrate and biodiesel on autoignition delay, heat release rate, in-cylinder pressure, engine performance efficiency, exhaust emissions and smoke provided for sound interpretation of the test results for 15%, 50%%, and 100% loads at the maximum torque speed of 1400 rpm and 10%, 50%, and 100% loads at rated speed of 2200 rpm. Reduction in ignition delay was achieved at all loads and speeds when using cetane additive- and RME-treated JP-8 fuel, but the shorter ignition delay did not always result to better performance efficiency of an engine. The fuel blend J12 developed brake thermal efficiency 1.4% higher at low 1400 rpm, whereas biodiesel-treated JP-8 suggested 1.0% (J5) to 3.6% (J30) better performance of a fully (100%) loaded engine at 2200 rpm. The higher CN rating of JP-8 fuel did not reduce the HC, CO emissions and smoke (soot) as could be expected due to the limited a real time of each engine cycle to burn the fuel completely, especially at a high speed.

Key words: Diesel engine, JP-8 fuel, cetane improving additive, RME, autoignition, combustion, heat release rate, performance efficiency, emissions, smoke.

The relevance of the problem. In 2004, the North Atlantic Treaty Organisation Pipeline Committee (NPC) adapted the NATO Single Fuel Policy (SPF) [1]. The aim of the Single Fuel Concept (SFC) was to simplify the supply chain for petroleum products for all land-based military aircraft, diesel-powered vehicles, and generators for the use by the army in the NATO nations. Using of a single fuel, namely JP-8 (F-34) military jet kerosene produced from the civil fuel Jet A-1, allows to achieve maximum aircraft and ground equipment interoperability. This light distillate fuel consists of a mixture of complex hydrocarbons (HCs) such as 50-60% paraffins, 10-20% aromatics, and 20-30% naphthenes [2]. Jet fuel also contains trace amounts of sulphur, nitrogen, and oxygen containing hydrocarbon (HC) compounds, which arise from the raw crude oil, known as hetero atoms [3]. The additives such as static dissipater, anti-icing and lubricating additive 0.1 vol% with long-term-action corrosion inhibitors are used to improve quality of JP-8 fuel and satisfy requirements of the standard ASTM-D 1655-13a [4]. Jet fuel often also includes antifreeze, antimicrobial agents, and corrosion inhibitors to improve the performance of aeronautical engines, whose operate during flight at widely varying ambient temperatures [5].

The petroleum diesel standard ASTM D975-09a specifies a minimum cetane number (CN) of 40 for fuels D-2, as well as biodiesel standards prescribe a minimum of 47 for neat RME in ASTM D6751-09b and a minimum of 51 in European standard EN 14214 [6]. Whereas aviation-turbine JP-8 fuel has no minimum cetane rating in standard ASTM D1655-13a because the ranking of turbine type fuels according to the cetane number value was never used before. This is one of the problems to be solved for intended using of JP-8 fuel in a diesel engine. Therefore, the engine test with the cetane number improving additives are important to shorten ignition delay with JP-8 fuel, improve cold starting properties, reduce smoke during start-up and exhaust emissions, decrease the knocking and noise, increase fuel economy, and improve overall durability of an engine [7].

Arkoudeas et al. [8] tested a single-cylinder diesel engine operating with neat JP-8 fuel blended with 10 vol% and 50 vol% of sunflower and olive oil to reduce environment pollution. Researchers found that using of both bio-fuels reduced PM emissions however the HC and CO emissions almost did not change due to the added biodiesel. Nitric oxide NO and NO_x emissions decreased at low (10 vol%) additions, but the NO_x emissions increased at high 50 vol% percentages of biodiesel in the fuel blend. Experiments with 3.8 kW Petter AV1-LAB diesel engine showed that using of neat JP-8 led to large wear scar diameter, however adding of animal fat derived biodiesel, lubricity properties of which are excellent, improved situation [9]. The compatibility tests revealed that biodiesel with short chain esters would be better alternative for mixing it with Jet A-1 fuel rather than long chain polyunsaturates [10]. To put more light on the subject, the research with aviation fuel JP-8 treated with various percentages of rapeseed biodiesel was performed to study combustion phenomenon, engine performance and exhaust emissions [11].

The purpose of the research was to analyse and compare the effects of CN improving additive 2-ethylhexyl nitrate and rapeseed biodiesel added to aviation turbine-type JP-8 fuel in various proportions (by volume) on the autoignition delay, combustion history, heat release characteristics, performance efficiency, NO_x, CO, HC emissions, and smoke of the exhaust at the most common operating conditions.

Engine test facilities and research methodology. The tests were conducted with a naturally aspirated, four-stroke, four-cylinder diesel engine D-243 with a swept volume of 4.75 dm^3 and compression ratio of 16:1 produced at „MMZ" in Belarus Republic. The injection pump PP4M9P1 delivered the fuel with an advance of 25^0 CADs BTDC, which was the same for various loads, speeds, and fuel blends. A high-speed multichannel AVL indicating system was used for recording, acquisition, and processing of fast crank-angle gas pressure signals taken from the first cylinder. The diagrams, which reflected over 100 engine cycles time-averaged in-cylinder pressure versus crank angle and nozzle-needle-valve lift history were in series recorded for every 0.1^0 CAD to detect changes in ignition delay and net heat release rate. Emissions of NO, NO_2, NO_x, CO, and THC (ppm) were measured with electrochemical cells installed into Testo 350 XL flue gas analyser, whereas the exhaust smoke was monitored with a Bosh RTT 110 opacity meter in a scale range of 0-100%.

The engine test results. The turbine type JP-8 fuel with widely differing chemical and physical properties is almost exclusively extracted from the kerosene fraction of crude oil, which distillation points are between the gasoline and the diesel fractions. The lower by nearly 16% spray tip penetration and a wider by 15.9^0 spray cone angle of the JP-8 fuel under the injection pressure of 30 MPa compared with the diesel fuel EN 590 fuel [12] improve atomisation and contribute to a higher fuel-air mixing rate, resulting from shorter spray tip penetration and a wider spray angle [13].

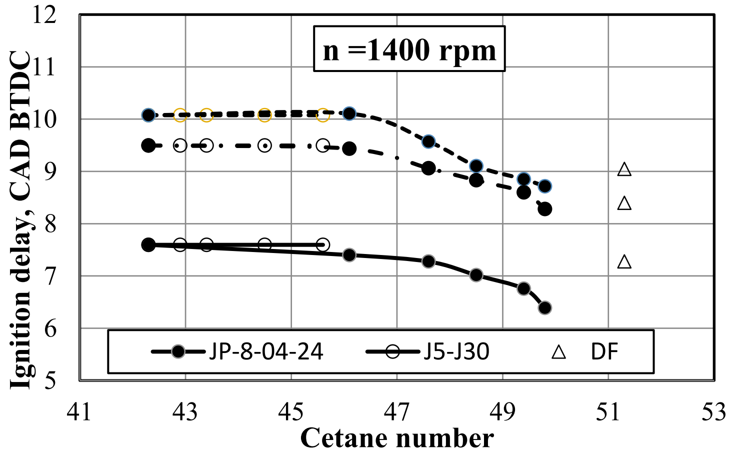

Fig. 1. Dependencies of ignition delay on the cetane number JP-8 fuel treated with CN improving additive and RME for engine loads of bmep = 0.104, 0.376 and 0.752 MPa at speed of 1400 rpm

As Fig. 1 shows, the higher vapour pressure, faster evaporation and thus mixing of a lighter JP-8 fuel with in-cylinder hot air charge did not contribute to sooner autoignition of the JP-8 fuel making delay even longer as compared to normal diesel fuel (DF). This shows that ignition delay is more dominantly affected by the low cetane number of JP-8 fuel, rather than the superior vaporisation and faster mixing with in-cylinder compressed air-charge. The difference in autoignition delay between DF and JP-8 fuels decreased with the increase of load at low speed of 1400 rpm, whereas it increased with load at a higher speed of 2200 rpm. Adding of 2-ethylhexyl in 0.04, 0.08, 0,12, 0.16, and 0.24 vol% proportions the CN rating improved from 42.3 to 46.1 (J04), 47.6 (J08), 48.5 (J12), 49.4 (J16), and 49.8 (J24) enhancing the ignition properties of JP-8 fuel to adapt it for land-based, diesel-powered transport. Adding the maximum 0.24 vol% of the cetane improver to JP-8 fuel the ignition delay shortened by 13.5%, 12.8%, and 15.9% compared with 10.1^0, 9.5^0, and 7.6^0 CADs measured for 15%, 50%, and 100% loads at speed of 1400 rpm. The greatest influence of 2-ethylhexyl nitrate on the reactivity properties of JP-8 fuel was found when using fuel blend J24 at full (100%) load and speed of 2200 rpm.

Whereas the added RME, CN rating of which is high enough (53.4), the cetane number of fuel blends J5, J10, J20, and J30 increased from 42.3 to 42.9, 43.4, 44.5, and 45.6, respectively. RME not only improved the cetane number of JP-8 fuel, but it also increased volumetric fuel delivery per engine cycle to compensate for the lower heating value of biodiesel that extended the end of injection. The stoichiometric air-fuel ratio of RME is 15% lower than that of JP-8 fuel and biodiesel needs less atmospheric air-born oxygen, but it is less volatile than jet fuel, as specified by the higher flash point of 178 ^{0}C. Small amount of CN improving agent did not change physical properties and injection / atomisation characteristics of JP-8 fuel, whereas the higher density, viscosity, surface tension, C/H ratio, and autoignition temperature (~362 ^{0}C) of RME may reduce evaporation of the blend and extend the end of combustion. Sensitive interaction between many influencing factors resulted in the combustion of biodiesel-treated fuels starting up to 1.3^0 (J20), 1.4^0 (J10), and 0.6^0 (J5) later in an engine cycle than the respective values of 7.2^0, 7.1^0, and 6.9^0 CADs BTDC measured with neat jet fuel at 15%, 50%, and 100% loads and speed of 1400 rpm (Fig. 1). Whereas, at a high 2200 rpm, the combustion started 0.9-1.0^0 earlier for the highest CN rating having blend J30 than those values of 1.6^0 and 4.4^0 CADs BTDC measured with neat jet fuel at 10% and 100% engine loads.

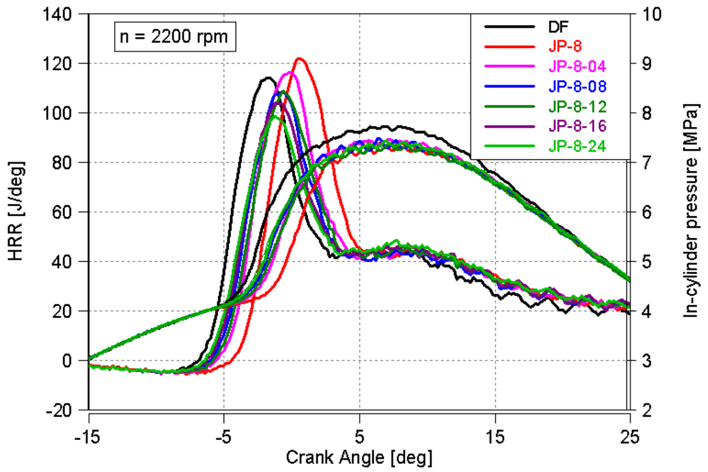

Fig. 2. The heat release rate and in-cylinder pressure versus CADs for diesel fuel, neat JP-8 and fuel JP-8 treated with the cetane improving additive for full engine load and speed of 2200 rpm

Replacement of the normal diesel fuel with a lighter JP-8 retarded the start of injection (SOI) by 1.0^0 CADs compared with the initial value of 16.6^0 CADs BTDC of a straight diesel operating at full (100%) load and speed of 2200 rpm. The later SOI and a longer ignition delay shifted the start of combustion (SOC) towards TDC that considerably increased maximum heat release (HRR_{max}) because of the faster vaporization and superior mixing rate of JP-8 fuel with the in-cylinder air and thus more fuel premixed for rapid burning at nearly constant volume combustion. This in turn, reduced in-cylinder pressure, and relocated the following diffusion processes and the end of combustion towards a bigger cylinder volume in the expansion stroke.

The autoignition delay and first maximum of heat release rate decreased and moved closer to the position traditionally occupied by the combustion of normal diesel fuel due to the added 2-ethylhexyl nitrate to the JP-8 fuel. As Fig. 2 shows, the decrease in autoignition delay and the transfer of HRR_{max} towards constant volume combustion occurred about directly proportional to the amount of the cetane improving agent added to JP-8 fuel. Whereas, the diffusion combustion almost did not respond to 2-ethylhexyl nitrate adding to JP-8 fuel and the second maximum of heat release emerged at about 7-9^0 CADs after TDC for all fuels tested. Maximum heat release rate and its location with regard to TDC did not change greatly due to a small 5 vol% RME addition to JP-8 fuel too. It decreased only when operating with fuel J10 and blends with higher CN ratings. Maximum heat release rate in the diffusion combustion changed little when using biodiesel-treated JP-8 fuel blends and the second maximum of heat release took place at about 7-9 CADs beyond TDC. The higher HRR_{max} in the premixed combustion phase did not result in a higher in-cylinder pressure as could be expected [14]. Therefore at 2200 rpm, a fully (100%) loaded engine operated smoother and quieter with JP-8 fuel compared to a straight diesel. The added CN improving agent (J12) and biodiesel (J5) increased maximum in-cylinder pressure, but using of fuel blends (J24) and (J30) with the highest CN ratings tended to reduce maximum heat release rate and in-cylinder pressure for both engine speeds.

Small amounts of 2-ethylhexyl nitrate added to JP-8 did not have much effect on the brake specific fuel consumption, whereas bsfc progressively increased with the increasing percentage of biodiesel in JP-8 fuel because of a lower heating value of RME. The brake thermal efficiency was a bit (0.9%) lower when using J12 fuel at full load and 1400 rpm, but it converted to be 1.3% higher at rated speed of 2200 rpm than those values of 0.337 and 0.305 developed by the combustion of neat JP-8 fuel. When using biodiesel-treated JP-8 fuel, the brake thermal efficiency was from 0.3% to 1.8% lower than that developed with neat jet fuel. However, it progressively 1.0%, 1.6%, 2.6%, and 3.6% increased for fuel blends J5, J10, J20, and J30 against the reference value of 0.304 developed when using neat jet fuel at 2200 rpm. This shows how the fuel-bound oxygen is important for burning of very non-homogeneous the air and fuel mixture at limited real time available to complete combustion at a high speed.

Replacement of diesel fuel with a lighter JP-8 fuel significantly reduced harmful engine pollutants. As can be seen in Figs. 3 and 4, the NO_x emissions and exhaust smoke (soot) were 11.6% and 31.0% lower than the respective values of 1760 ppm and 68.0% of the normal diesel running at full load and a low speed of 1400 rpm. The added 0.12 vol% 2-ethylhexyl nitrate the NO_x emission increased by 5.1% compared with neat JP-8 fuel used at the same test conditions. Further increase of the cetane number to 49.4 (J16) and 49.8 (J24) tended to reduce production of NO_x. Whereas maximum NO_x emission increased by only 2.4% when running with biodiesel treated fuel J10 with a tendency to produce even less NO_x from combustion of a higher J20 and J30 blends at the maximum torque speed of 1400 rpm.

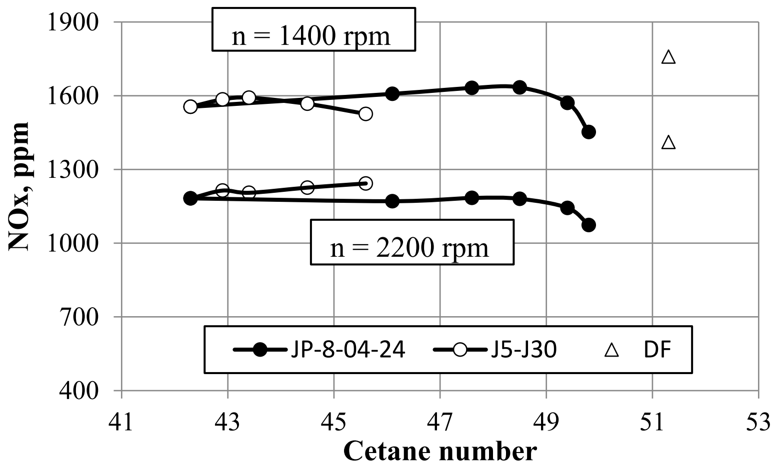

Fig. 3. The effect of CN improving agent and RME added to JP-8 fuel on maximum NO_x emission for full engine load and speeds of 1400 and 2200 rpm

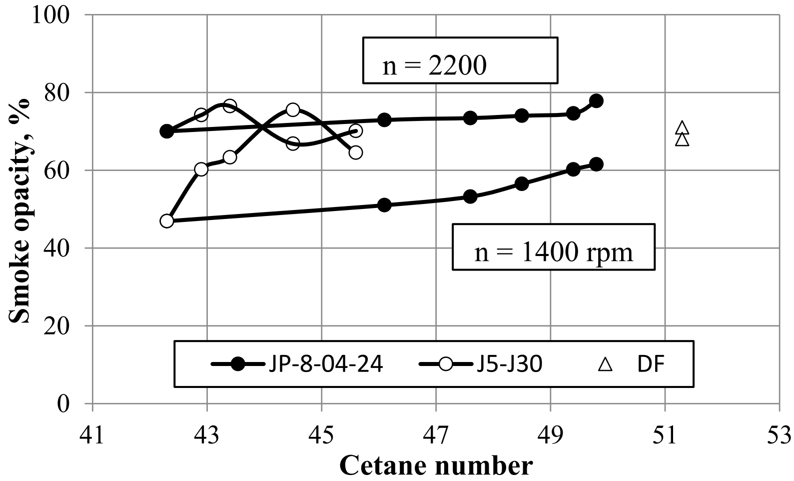

Fig. 4. The effect of the cetane number on exhaust smoke for full engine load at speeds of 1400 and 2200 rpm

The smoke opacity (soot) progressively 8.7%, 13.4%, 20.5%, 28.4%, and 31.1% increased when running a fully (100%) loaded engine with CN treated fuels J04, J08, J12, J16, and J24 at speed of 1400 rpm (Fig. 4). The exhaust smoke with CN treated fuels increased at a high speed of 2200 rpm too. Similar smoke behaviour was measured when using biodiesel-treated JP-8 fuel at both engine speeds. The higher was the percentage of 2-ethyhexyl nitrate and RME added to jet fuel and thus the cetane number of the blend, the greater smoke opacity was produced at the same test conditions. Complicated interaction between the autoignition delay period and proper mixing of the air and fuel vapours does not always improve combustion and what ends up in the exhaust.

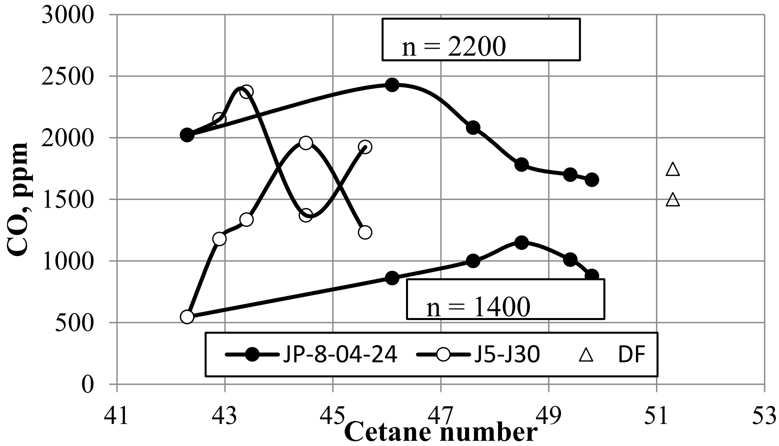

Fig. 5. The effect of the cetane number on CO emissions for full engine load at speeds of 1400 and 2200 rpm

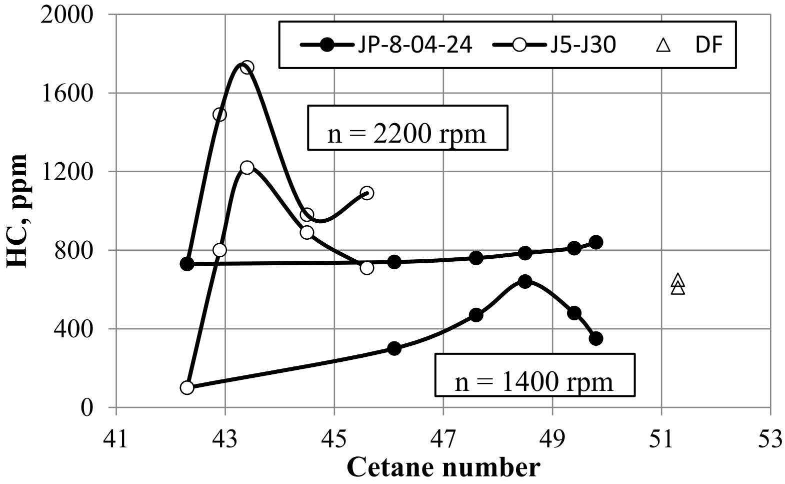

Fig. 6. The effect of the cetane number HC emissions for full engine load at speeds of 1400 and 2200 rpm

As can be seen in Figs. 5 and 6, both CO and HC emissions increased to maximum values of 1148 ppm (2.1 times) and 640 ppm (6.4 times) when running a fully (100%) loaded engine with J12 fuel at 1400 rpm with a tendency to produce the CO and the HC emissions less from combustion of J16 and J24 fuels with higher CN ratings. The CO and the HC emissions increased even more intensively 2.2, 2.4, 3,6, 2.3 and 8.0, 12.2, 8.9, 7,1 times, respectively, when using biodiesel treated J5, J10, J20, J30 JP-8 fuel blends at the same test conditions. This, probably, occurred because the biodiesel transition from the liquid phase to gas phase advanced slowly that aggravated combustion and contributed to emergency of more unburned end-products in the exhaust. Similar HC emissions behavior was registered at high speed of 2200 rpm however the CO emissions slightly reduced when using J20 and J30 fuels with a higher CN ratings.

Conclusions. Replacement of diesel fuel EN 590 with aviation-turbine JP-8 fuel resulted in a longer autoignition delay, lower maximum in-cylinder pressure and pressure gradient leading to overall smother engine performance with less NO_x, CO, HC emissions and smoke produced at the low speed of 1400 rpm. Using of 2-ethylhexyl nitrate for JP-8 fuel treatment proved itself as an effective measure to shorten ignition delay, relocate the maximum heat release rate closer to constant volume combustion, increase in-cylinder pressure, and engine efficiency at slightly higher NO_x emissions. Small amounts of 2-ethylhexhyl added to JP-8 did not affect physical properties of the fuel, whereas biodiesel increased density, viscosity, surface tension, initial/final boiling points, autoignition temperature, fuel-oxygen mass fraction of JP-8 blend. It was noted, if the autoignition delay is too short, the premixed combustion starts too early in an engine cycle that may convert to long-lasting diffusion combustion within a bigger cylinder volume with more HC and smoke (soot) produced by a fully loaded engine at speed of 2200 rpm. Whereas, the NO_x emissions increased by 5.1% with J12 fuel and 2.4% with J10 fuel blend compared to operation with neat JP-8 fuel at the maximum torque speed of 1400 rpm. The 5 vol% of RME added to JP-8 significantly improved lubricity properties of the fuel, brake thermal efficiency increased by 1.0-3.6% when using bio-fuels J5-J30 at speed of 2200 rpm.

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Лабецкас Г., Славинскас С., Вилутиенė В., Мицкявичюс Т., Канапкиенė І. **Сравнительная оценка работы дизельного двигателя на авиационном топливе JP-8 с добавками цетановое число улучшающей присадки и метилового эфира рапсового масла.**

Проанализировано влияние авиационного турбинного топлива JP-8 на показатели и эмиссию отработавших газов (ОГ) дизельного двигателя. Выполнена сравнительная оценка влияния цетановое число улучшающей присадки (нитрата 2-этилгехила) и метилового эфира рапсового масла на период задержки самовоспламенения, скорость тепловыделения, максимальное давление в цилиндре, скорость его нарастания, эффективность двигателя, эмиссию ОГ и дымность. Цетановая присадка практически не изменило физические свойства топлива JP-8, а значительные добавки метилового эфира увеличили фракцию кислорода в топливе, плотность, вязкость, поверхностное натяжение, начальную и конечную точки кипения и температуру самовоспламенения. Сокращение периода задержки самовоспламенения привело к более раннему началу сгорания, уменьшению максимальной скорости тепловыделения, более длительному диффузионному сгоранию и, как следствие, к большей эмиссии несгоревших углеводородов и дымности ОГ, особенно на номинальной частоте вращения 2200 мин$^{-1}$. В то же время, выбросы окислов азота (NO_x) при полной нагрузке могут увеличиться от 2.4% (J10) до 5.1% (J12) по сравнению с чистым реактивным топливом на частоте вращения 1400 мин$^{-1}$ соответствующей максимальному крутящему моменту двигателя.

Ключевые слова: дизельный двигатель, топливо JP-8, цетановая присадка, ЭРМ, самовоспламенение, сгорание, тепловыделение, эффективность двигателя, эмиссия, дымность.

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Стаття надійшла в редакцію 29.03.2016р.