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THE EFFECT OF FUEL OXYGEN CONTENT ON IGNITION DELAY AND COMBUSTION OF A TURBOCHARGED CRDI DIESEL ENGINE

Key words: diesel engine; diesel-HRD fuel blends; ethanol; biodiesel; autoignition; combustion; heat release, in-cylinder pressure.

Abstract: The article presents the effects caused by the variation of fuel-oxygen mass content and widely differing chemical and physical properties of a fossil diesel (DF) and hydrotreated renewable diesel (HRD) fuel blends involving ethanol (E) or biodiesel (B) on ignition delay, combustion phenomenon, heat release characteristics, and maximum in-cylinder pressure of a turbocharged CRDI diesel engine. The diesel-HRD fuel blends (12 in total) involving anhydrous (200 proof) ethanol OE0-OE5 or rapeseed biodiesel OB0-OB5 in such proportions by mass to assure a wide range of the variation of fuel-bound oxygen mass fraction 0-4.52 wt% (CN = 55.5) were tested for relative air-fuel ratios, λ = 1.30, 1.25 and 1.20, at the respective speeds of 1500, 2000, and 2500 rpm. Analysis of changes in the ignition delay, combustion history, and the peak in-cylinder pressure produced by using purposely designed fuel blends was performed on comparative bases with the corresponding values measured with 'base-line' blends OE0 or OB0 to reveal the potential developing trends. It was found that the reasonably higher fuel oxygen content improved combustion, boosted heat release rates, and shortened burn angle MBF 90, when running mainly at the high engine speed of 2500 rpm. Experiments revealed that fuel-oxygen mass content should be neither too high nor too low, but just enough to assure complete combustion and a low coefficient of the cyclic variation (COV) of operational parameters.

Wpływ zawartości tlenu w paliwie na opóźnienie samozapłonu oraz spalanie w turbodoładowanym silniku wysokoprężnym typu CRDI

Słowa kluczowe: silnik wysokoprężny, mieszanki paliwowe olej napędowy-HRD, etanol, biodiesel, samozapłon, spalanie, uwalnianie ciepła, ciśnienie w cylindrze.

Streszczenie: Artykuł przedstawia wpływ zmian proporcji masowych paliwo–tlen oraz znacznie różniących się właściwościami chemicznymi i fizycznymi oleju napędowego (DF) oraz hydrorafinowanych mieszanek oleju napędowego (HRD) oraz etanolu (E) i biodiesla (B), na opóźnienie samozapłonu, zjawisko spalania, charakterystykę oddawania ciepła oraz maksymalne ciśnienie w cylindrze turbodoładowanego silnika o ZS typu CRDI. Przebadano mieszanki paliwowe: olej napędowy – HRD (łącznie 12), w tym bezwodny etanol OE0-OE5 (próba 200) oraz biodiesel OB0-OB5 na bazie rzepaku w takich proporcjach masowych, aby zapewnić szeroki zakres zmian zawartości masowej tlenu związanego w paliwie w zakresie 0–4,52% (CN = 55,5), dla względnego współczynnika nadmiaru powietrza λ = 1,30, 1,25, 1,20 przy prędkościach obrotowych 1500, 2000 oraz 2500 obr./min. Przeprowadzono analizę porównawczą opóźnienia samozapłonu, sprawności spalania oraz szczytowego ciśnienia wytworzonego wewnątrz cylindra, przy zasilaniu celowo opracowanymi mieszankami paliwowymi, w odniesieniu do odpowiednich wartości zmierzonych dla mieszanek „bazowych" OE0 i OB0, aby wykryć potencjalny trend zmian. Stwierdzono, że odpowiednio wyższa zawartość tlenu w paliwie poprawiła spalanie, podniosła sprawność cieplną oraz zmniejszyła kąt spalania MBF 90, głównie przy pracy na wysokich obrotach 2500 obr/min. Eksperymenty pokazały, że proporcja masowa paliwo–tlen nie powinna być ani zbyt niska, ani zbyt wysoka, ale wystarczająca, by zapewnić całkowite spalanie oraz niski współczynnik zmian cyklicznych (COV) parametrów eksploatacyjnych.

Introduction

Limited oil reserves, air pollution, and climate change encourage researchers to intensify investigations on the autoignition and combustion of renewable biofuels derived from a biomass of various origins and their blends with a fossil diesel fuel. However, the added ethanol (E) or biodiesel (B) to diesel fuel changes the cetane number, fuel oxygen mass content, and the chemical and physical properties of fuel blend in the most common test conditions [1–3]. Whereas, the majority of the investigations were performed for the simultaneous variation of cetane number, fuel-oxygen content, relative air-fuel ratio, engine load, speed, and fuel properties related variables. Because the effects of many influencing factors interfered with each other, it was difficult to reveal which of them played a key role in the ignition delay and combustion characteristics. Until recently [4,5], there still was a lack of evidential clues on how the variation of fuel-oxygen mass content or widely differing chemical and physical properties of the fuel affects the ignition delay, combustion characteristics, maximum heat release rate, and the cyclic variation of parameters.

Zannis et al. [6] have used the multi-zone combustion model to describe the effect of fuel-oxygen fraction on DI diesel engine performance, soot, and NO emissions. The comparison of the modelling results with measurements obtained from a Lister LV1 engine revealed the advantages of the fuel-oxygen in creating higher maximum in-cylinder pressures, bulk gas temperatures, and NO emissions, and reducing exhaust soot as compared to intake air-born oxygenation. Whereas, a high cetane fuel, such as HRD, is needed for blending with less flammable diesel fuel and ethanol or biodiesel to keep the cetane number value of oxygenated fuel blends the same. Using of the HRD technology allows one to produce the best quality, high-cetane diesel fuel from various vegetable oils, including palm, soybean, and rapeseed oils, as well as waste animal fats. Even the production of aviation bio-jet fuel of the future is possible with the hydro-treated vegetable oil (HVO) process [7]. A new diesel NExBTL fuel matches well with the EU Directive 2009/28/EC, which approved a target of 20% share of renewable fuels to be introduced in the overall automotive transport sector by 2020.

The presence of anhydrous ethanol in diesel-HRD fuel blends may reduce the penetration of the fuel sprays due to its lower density, viscosity, and faster evaporation at the temperature of 78°C that may reduce the development of liquid phase sprays. It can be expected that the shorter spray length will be compensated by a wider spray cone angle that may contribute to the faster mixing rate of ethanol-fuel vapours with the in-cylinder compressed air-charge. Whereas, a heavier, viscous, and less volatile biodiesel in diesel-HRD fuel blends may have the diametrically opposite effect on the fuel spray tips' penetration and atomization characteristics. Experiments carried out on the fuel spray of a multi-jet CR injection system in an optically accessible diesel engine showed that the soybean methyl ester shows a denser liquid core with respect to the reference diesel and a higher average tip penetration because of the highest density and viscosity [8].

When ethanol or biodiesel is added to diesel-HRD fuel blends, it is not a case where only fuel-oxygen ratio works, but the cetane number also comes into action with its own contribution. This fact makes it difficult to reveal which of the influencing factors plays a key role in the ignition and combustion processes [9]. Thus, the cetane number must be kept constant for various diesel-HRD fuel blends involving ethanol or biodiesel components. The purpose of the research was to reveal the developing trends in the ignition delay, combustion characteristics, maximum heat release rate, burn angles MBF 50, MBF 90, and the peak in-cylinder pressure caused by the individual variation of oxygen-mass content in the fuel blends involving ethanol or biodiesel, while still possessing the same cetane number value of about 55.5. The widely differing properties of diesel-HRD fuel blends involving biofuels are derived from the biomass of various origins, but possessing the same blended cetane number and fuel-oxygen mass content will provide evidential clues to find out which of them, - a single-bound with the carbon atoms ethanol-oxygen or double-bound biodiesel-oxygen, contribute more in the combustion reactions.

1. Engine test set up, apparatus and research methodology

The experimental tests were conducted on a turbocharged, four-stroke, four-cylinder, common rail (CR), direct-injection (DI), diesel engine (1.9 JTD 8V) with a splash volume of 1.91 dm^3 and compression ratio of ε =18:1. The moving vanes of a garret variable geometry GT1749V turbocharger were taken under control and the air charge pressure (p_k) and temperature (T_k) sensors were fitted into the manifold to the know density of the intake air and volumetric efficiency of an engine. The uncooled air entered the capacity chamber and the cylinder at a boost pressure of 0.160 MPa and a temperature of 85°C. An OMEGA-shaped combustion chamber in the piston crown improved air-fuel mixing and combustion efficiency. The electronic control unit EDC-15C7 CR governed the timing and the duration of the fuel injection to make the test conditions more manageable. The test setup consisted of a diesel engine, an engine test bed, the AVL indicating system, air and fuel mass consumption measuring equipment, a gas analyser, and a smoke meter.

Load characteristics with a fossil diesel fuel (DF) and hydrotreated renewable diesel (HRD) fuel blends involving ethanol (E) or biodiesel (B) components were taken at the maximum torque speeds of 2000 rpm, 1500, and 2500 rpms to improve the interpretation of the obtained results. The performance parameters taken with diesel fuel EN590 as a "baseline" fuel and various fuel blends as a function of load (bmep) were plotted as a function of overall air-fuel ratio (λ), which decreased with increasing engine load [10]. Changes in ignition delay, combustion, total heat release characteristics, and the peak in-cylinder pressure revealed with oxygenated fuel blends OE0-OE5 or OB0-OB5 were compared with those obtained with the reference blends OE0 or OB0 for relative air-fuel ratios of λ = 1.30, 1.25, and 1.20 at the respective speeds of 1500, 2000, and 2500 rpm. The selected air-fuel ratios were computed by using the measured air-mass flow and fuel mass flow at each load-speed setting point and the stoichiometric air-fuel ratio for each fuel blend to establish direct relation with a real engine performance conditions. Identical air-fuel ratio predicts that the fuel-energy input per each engine cycle and a common air-born and fuel-bound oxygen availability in the cylinder for each fuel blend involving ethanol or biodiesel will be almost the same. This creates proper preconditions to directly observe how the ignition delay and combustion history change due to the individual variation of fuel-oxygen mass content and widely differing properties of diesel-HRD fuel blends oxygenated with ethanol or biodiesel components.

A high-speed multichannel indicating system, which consisted of the AVL angle encoder 365C and high-performance pressure transducer GU24D coupled to the AVL microIFEM piezoelectric amplifier and signal acquisition platform IndiModul 622 was introduced for the recording, acquisition, and processing of fast crank-angle gas pressure signals in the first cylinder. The single indicator diagrams, which reflected in-cylinder individual pressure signals over 100 engine cycles versus crank angle, were recorded in series for each fuel blend at every load-speed setting point to improve the accuracy of the research. The data post-processing Software AVL CONCERTO™ advanced version 4.5 was used to increase the productivity and improve accuracy of the measured test results. The total heat release rate was calculated using the AVL BOOST program and summarized over the 100 engine-cycles averaged in-cylinder pressure data, instantaneous cylinder volume, and their first order derivative with respect to crank angle.

2. Results and discussions

Automotive fossil diesel fuel (Class 1) was produced at the oil refinery "Orlen Lietuva" and its quality satisfied the requirements of standard EN-590:2009 + A1. Its composition consisted of C/H = 0.8608/0.1299 and the remaining 0.0093 belonged to water, sulphur, and other impurities. The NExBTL fuel, which satisfied the diesel fuel EN-590 specifications, was donated by the Finish NESTE Oil Ltd., and was brought from Finland with the certificate of analysis. The composition of renewable hydrotreated diesel fuel was C/H = 0.8480/0.1520, and the biomass source used for HRD production was primarily rapeseed oil. Biodiesel (RME), brought from Ltd. "Rapsoila", Mažeikiai consisted of C/H/O = 0.7720/0.1190/0.1084, and its quality satisfied the standard EN 14214:2012. Anhydrous ethanol (CH3CH2OH – 200 proof) was produced in Germany (Seelze) at Ltd. "Sigma-Aldrich," and its quality satisfied the requirements of standard EN 15376:2015.

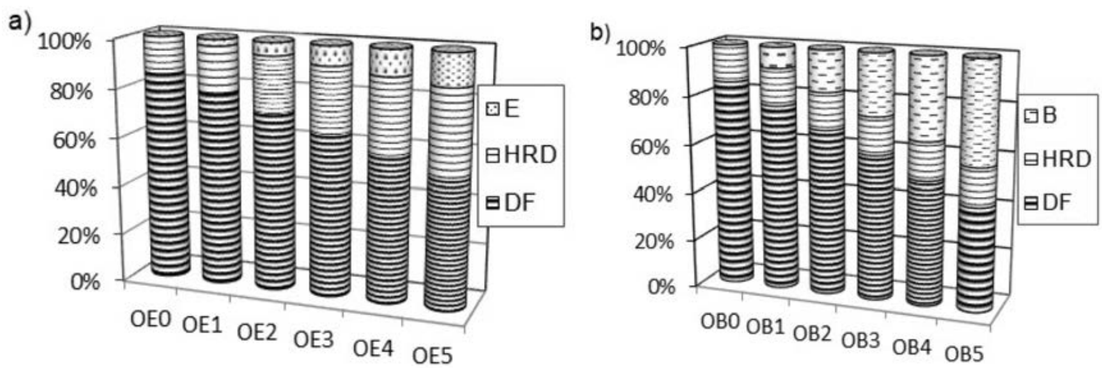

Fig. 1a, b. Composition of fuel blends involving ethanol (a) or biodiesel (b) components (by mass) designed to have a wide variation range of fuel-oxygen (O) content 0–4.52 wt%, but still possessing the same CN rating of about 55.5

The compositions of fuel blends prepared for the engine tests are shown in Figs. 1a and b. The fuel blends designed from a fossil diesel, HRD fuel, and biofuels derived from the biomass of various origins created proper preconditions for the analysis and comparison of the test results aiming to reveal the individual role of fuel oxygen on the ignition delay and combustion phenomenon in the cylinder. To make the analysis of engine parameters more manageable, the fuel-energy inputs per the respective engine cycles were maintained as identical as possible. Specified test conditions are important to find out what changes in the ignition delay and combustion characteristics occurred, to disclose what potentially caused them, and to examine the existing trends and relationships between the key factors to explain why the obtained results are possible.

This strategy allowed providing the engine tests with oxygenated fuel blends of various origins; whereas, extra-quality, high-cetane, oxygen-free, renewable, biomass based HRD fuel was an excellent tool just as needed to start the engine tests. The HRD fuel and HVOs belongs to the group of hydrocarbons that are miscible with a hydrocarbon matrix of a fuel blend; therefore, it mixes well with diesel fuel [7]. Then, ethanol (200 proof) or biodiesel was added to diesel-HRD fuel blends in pre-calculated amounts to satisfy the needed fuel oxygen content while keeping the cetane number at the same value of 55.5. Having the experimental cetane number data of each fuel-component, a blending cetane number for oxygenated fuel blends was computed by using typical methodology developed in the U.S. at the National Renewable Energy Laboratory [11].

The density of HRD fuel is 6.4% lower at the temperature of 15°C, but kinematic viscosity is nearly 37.0% higher than that of diesel fuel at the temperature of 40°C. The HRD fuel provides the high-energy content and a reasonable distillation range without high boiling fractions compared to diesel fuel. This advantages feature of HRD fuel rests on the fact that oxygen, nitrogen, and much of the sulphur containing chemical compounds are removed during the refining process to replace them with more calorific hydrogen (15.2 wt%) compared to 13.0 wt% of diesel fuel. In such a case, less fuel mass is needed to provide the same energy inputs per engine cycle. A lighter HRD added to diesel fuel enhanced the cetane number and heating value, reduced C/H atoms ratio, polycyclic aromatics, sulphur, water, ash content, acid value, and autoignition temperature, deepened cloud and cold filter plugging points of the tested fuel blends.

Ethanol has the lowest C/H atoms ratio and plenty of fuel-oxygen that is essential to complete combustion at critical relative air-fuel ratios of 0.7–1.25 [12]. Thus, less air-born oxygen will be needed which may save ambient air and improve the quality of the air in municipal cities. The viscosity of ethanol is 34.3% lower than that of a fossil diesel and 52.0% lower than HRD fuel at the temperature of 40°C. This, along with low surface tension, high volatility, and saturated vapour pressure, improved injection, the atomisation characteristics of blends involving ethanol, and enhances the mixing rate of the air and fuel; whereas, the low cetane number of ethanol oxygenated blends was restored by adding a pre-calculated amount of high-cetane HRD fuel.

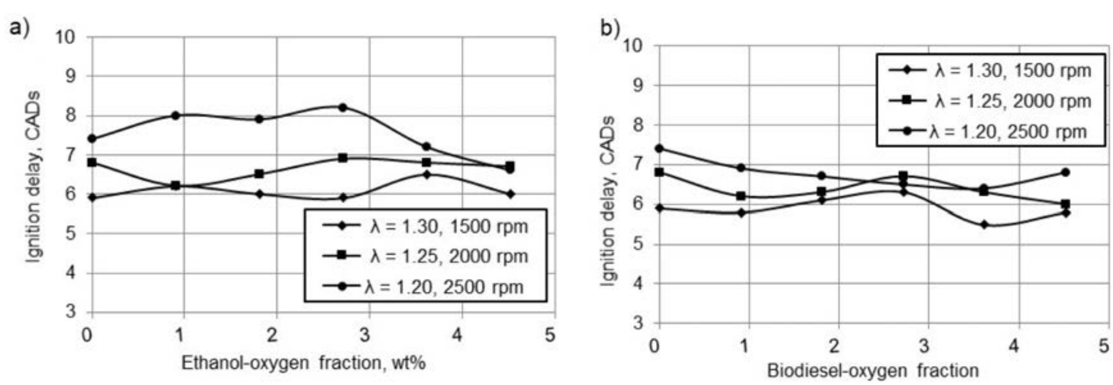

Fig. 2a, b. The ignition delay as a function of ethanol (a) or biodiesel (b) fuel-oxygen (wt%) content in diesel-HRD fuel blends for relative air-fuel ratios, λ = 1.30, 1.25 and 1.20, at the respective speeds of 1500, 2000 and 2500 rpm

Biodiesel as ethanol and HRD fuel has a negligible content of polycyclic aromatics and provides extra fuel-oxygen that may improve the local fuel air-fuel ratios in the fuel-rich zones, accelerate combustion at close to stoichiometric conditions, and reduce emissions [13]. In the normal loading conditions, biodiesel-oxygen, being in double bounds with the hydroxyl -OH group, proved itself to be more active in the combustion reactions than ethanol [2]. However, better spray penetration and a smaller initial spray cone angle may reduce the air and fuel vapours mixing rate and lead to the enrichment of the local air-fuel mixtures in some combustion chamber 'zones' due to higher density, viscosity, droplets size, and the low volatility of biodiesel [14]. Using diesel-HRD fuel blends involving biodiesel components may retard mixing control combustion, diffusive burning, and extend the end of combustion when running at close to stoichiometric conditions at a high speed.

As Fig. 2a, b shows, the ignition delay did not change greatly with increasing ethanol (a) or biodiesel

(b) oxygen mass content in diesel-HRD fuel blend when running at a relative air-fuel ratio of λ = 1.30 at the low speed of 1500 rpm. However, the autoignition delay started to increase more intensively with increasing ethanol-oxygen mass content and reached the highest values of 8.2 (1.5%) and 6.9 (10.8%) CADs when running with diesel-HRD fuel blend CE3 (2.71 wt% oxygen) under λ = 1.25 and 1.20 at the high speeds of 2000 and 2500 rpm. It is interesting to note that the ignition delay was almost always longer when running with fuel blends oxygenated with ethanol than with biodiesel possessing the same CN = 55.5 rating at identical both relative air-fuel ratio and engine speed. The autoignition delay was longer probably because of a nearly threefold higher latent heat of vaporisation and a greater cooling effect caused by the added ethanol.

Despite the fact that 3.2 times more biodiesel was added to diesel-HRD fuel blends to maintain the same fuel-oxygen mass content, higher density, kinematic viscosity, total contamination, and slower evaporation of biodiesel droplets, this did not create significant difficulties for the ignition process. As a result, the autoignition delay was always shorter when running with fuel blends involving biodiesel than with their respective ethanol-oxygenated counterparts at identical fuel-energy inputs per cycle and engine speed. The autoignition delay increased by 6.8% (6.5), then decreased by 11.8% (6.0) and 13.5% (6.4) CADs when running with biodiesel oxygenated blends OB4 (3.61 wt% oxygen), OB5 (4.52 wt% oxygen) and again OB4 under relative air-fuel ratios of λ = 1.30, 1.25, and 1.20 at the respective speeds of 1500, 2000 and 2500 rpm.

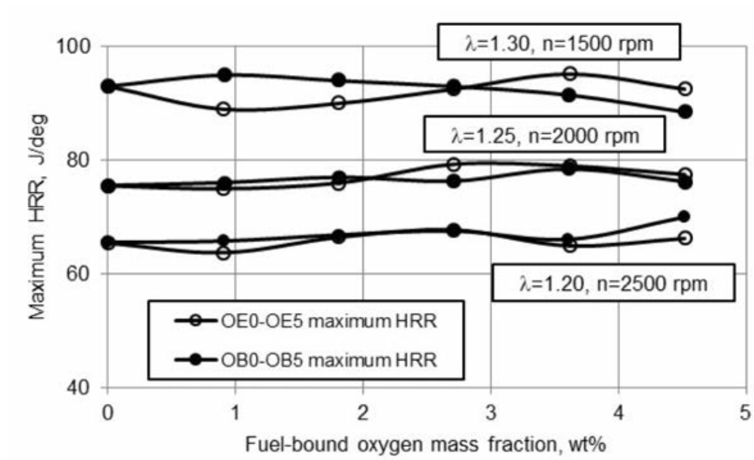

Fig. 3. Maximum heat release rate HRR_{max} as a function of ethanol (E) or biodiesel (B) fuel-oxygen (wt%) content in fuel blends for air-fuel ratios, λ = 1.30. 1.25 and 1.20, at the respective speeds of 1500, 2000 and 2500 rpm

As can be seen in Fig. 3, the HRR_{max} increased when the fuel-oxygen content increased up to the rational level, which varied under the simultaneous influence of both air fuel ratio and engine speed-dependant combustion conditions in the cylinder. The maximum heat release rate increased to remain 2.3% (3.61 wt%), 5.0% (2.71 wt%), and 3.5% (2.71 wt%) higher when using ethanol-oxygenated blends against, 93.0, 75.5, and 65.5 J/deg., the combustion of oxygen-free blend OE0 develops for λ = 1.30, 1.25, and 1.20 at the respective speeds of 1500, 2000 and 2500 rpm. Thus, an almost constant 3.61–2.71 wt% ethanol-oxygen content was needed to maintain rapid combustion and produce a high maximum heat release rate under close to stoichiometric conditions. The content of ethanol-oxygen needed to sustain proper combustion slightly decreased with the increasing speed, because ethanol with a very high vapour pressure evaporated more readily than the biodiesel fraction and produced a more homogeneous air-ethanol-fuel mixture. Whereas, the biodiesel-oxygen content should be progressively increased 0.91, 3.61, and 4.52 wt% with increasing engine speed to maintain a maximum heat release rate 2.2% (OB1), 4.0% (OB4), and 6.9% (OB5) higher than that the combustion of oxygen-free blend OB0 develops for identical test conditions.

As columns in Figs. 4a, b, c show, the percentage of fuel-bound oxygen of both ethanol and biodiesel origins did not greatly affect the burn angle MBF 50 and thus the performance efficiency of an engine. Only a smooth reduction of up to 0.2–1.0° CADs in MBF 50 occurred due to the rationally increased ethanol-oxygen mass content when running under relative air-fuel ratios of λ = 1.25 and 1.20 at the high speeds of 2000 and 2500 rpm. Whereas, the burn angle MBF 90 was much more sensitive to the presence of fuel-bound oxygen in the cylinder and widely differing chemical and physical properties of diesel-HRD fuel blends involving ethanol

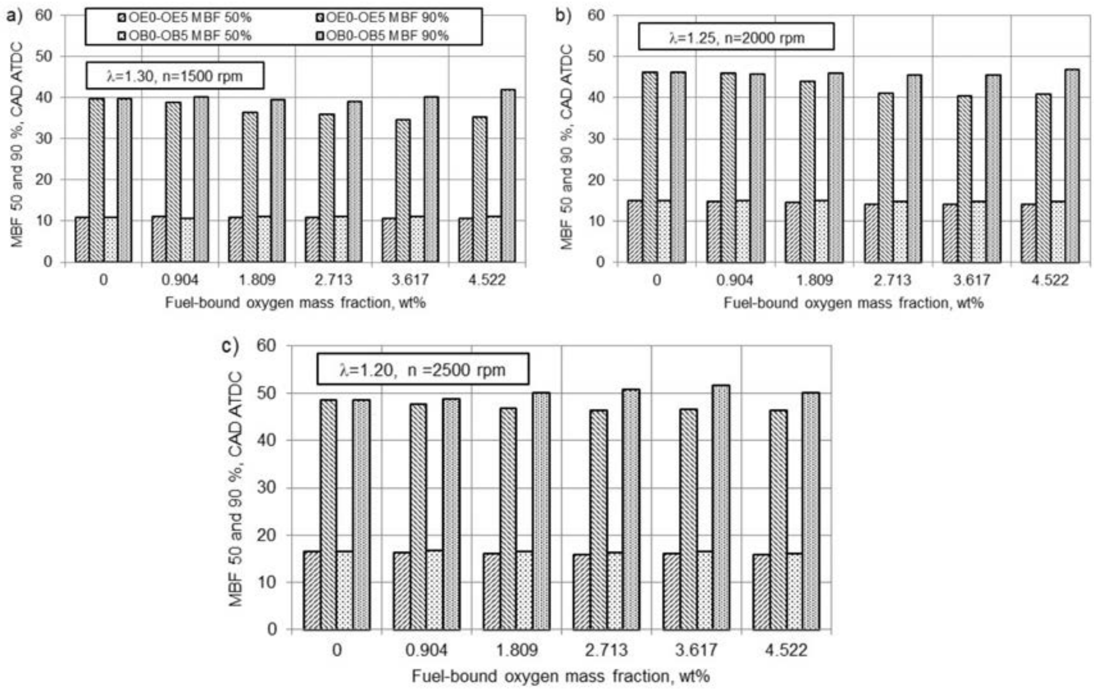

Fig. 4a, b, c. Burn angles MBF 50 and MBF 90 as a function of ethanol (E) or biodiesel (B) fuel-oxygen (wt%) content in fuel blends for air-fuel ratios, λ = 1.30, 1.25 and 1.20, at the respective speeds of 1500, 2000 and 2500 rpm

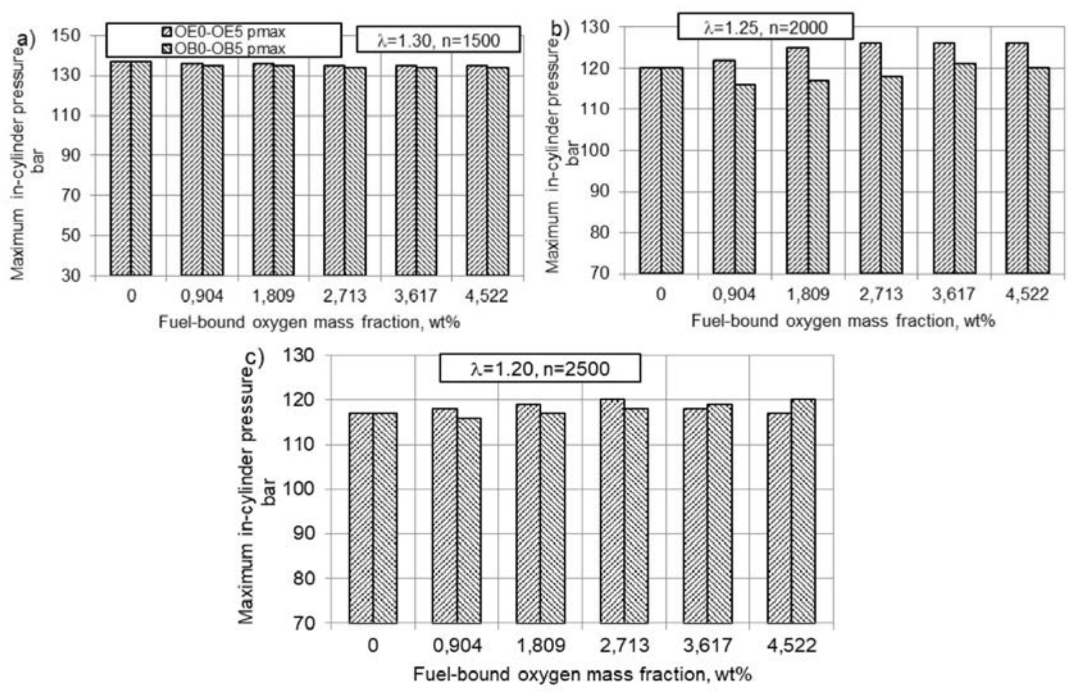

Fig. 5a, b, c. Maximum in-cylinder pressure p_{max} as a function of ethanol (E) or biodiesel (B) fuel-oxygen (wt%) content in fuel blends for air-fuel ratios, λ = 1.30, 1.25 and 1.20, at the respective speeds of 1500, 2000 and 2500 rpm

or biodiesel components. The fuel oxygen increased up to the rational extent, which depended on engine speed and air turbulence intensity inside the cylinder, improved the combustion process, and significantly reduced burn angle MBF 90 for both ethanol (E) and biodiesel (B) test series.

The end of combustion representing angle MBF 90 took place 5.1°, 5.7°, and 2.1° CADs earlier in an engine cycle than 39.8°, 46.1° and 48.7° CADs ATDC, and the combustion of oxygen-free blend OE0 ends up at given test conditions. Thus, the rationally increased content of ethanol-bound oxygen created potentials to improve the combustion process by using a single blend OE4 over the wide speed range of 1500–2500 rpm. It should be noted that the end of combustion representing the angle MBF 90 always took place earlier in an engine cycle when running with ethanol-oxygenated blends than with their respective counterparts involving the same amount of biodiesel-oxygen under identical air-fuel ratios and speeds. The combustion of biodiesel-oxygenated diesel-HRD fuel blends was longer probably because the fuel-spray containing biodiesel droplets of a bigger size evaporate slower and delay burn [14]. The higher C/H atoms ratio and more carbons in fuel composition also contributed to the longer combustion of fuel blends involving biodiesel compared to their respective ethanol-oxygenated counterparts.

The peak in-cylinder pressure decreased by 1.5% or 2.2% due to ethanol or biodiesel oxygen mass content increased to 3.61 wt% (OE4) or 2.71 wt% (OB3) against, 137 bar, the combustion of oxygen-free blends OE0 or OB0 develops at speed of 1500 rpm. The small descent in the peak in-cylinder pressure with increasing fuel-oxygen content occurred at the low speed 1500 rpm, mainly because its location shifted by 0.6–0.4° CADs away from TDC towards a bigger cylinder volume. The matter is that oxygenated blends burned consuming less air-born oxygen due to the presence of fuel-bound oxygen (chemical effect). Next, the increased ignition delay resulted in the gaseous fuels diluted more than it was experienced with oxygen-free fuels OE0 (dilution effect) [15].

Both chemical and dilution factors affected the flame velocity, maximum heat release rate, and the peak in-cylinder pressure, because the heating value (energy effect) was eliminated from the analysis owing to the identical air-fuel ratios of the fuels of both origins. This helps to find the answer to why the combustion of the fuel involving ethanol OE4 with fuel-oxygen content of 3.61 wt% developed the peak in-cylinder pressure 4.1% higher, and it was located 0.9_ CADs earlier in an engine cycle than its biodiesel-oxygenated counterpart OB4 produces (121 MPa) under similar burning conditions at a maximum torque speed of 2000 rpm.

Conclusions

The ignition delay increased by 10.2% (OE4), 1.5% (OE3), and 10.8% (OE3) or by 6.8% (OB3), then decreased by 11.8% (OB5) and 13.5% (OB4) when running with the respective blends at, $\lambda = 1.30$, 1.25 and 1.20, and speeds of 1500, 2000 and 2500 rpm.

Maximum heat release rate increased by 3.5% (OE3) or 6.9% (OB5), the burn angle MBF 50 decreased by 0.6^0 (OE3) or 0.5^0 CADs (OB5), and the combustion (angle MBF 90) ended by 2.2^0 (OE5) earlier or a bit later at 1.5^0 CADs (OB5) in an engine cycle when running at a relative air-fuel ratio of $\lambda = 1.20$ and the high speed of 2500 rpm.

The peak in-cylinder pressure increased by 2.6% when using ethanol (OE3) and biodiesel (OB3) oxygenated fuel blends, and the engine operated smoother with fuel blends of both OE5 and OB5 origins with a coefficient of variation ($COV_{pmax} = 0.6\%$), Whereas, the COVs of $(dp/d\varphi)_{max}$ were 8.7% and 8.2% when running at air-fuel ratio of $\lambda = 1.20$ and the high speed of 2500 rpm.

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