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PERFORMANCE AND EMISSIONS OF A DIESEL ENGINE OPERATING WITH RENEWABLE BINARY BIODIESEL-N-BUTANOL BIOFUEL BLENDS

This paper presents a comparative analysis of the diesel engine performance and emission characteristics, when operating on rapeseed methyl ester (B) and rapeseed methyl ester -butanol (Bu5, Bu10, Bu15) blends, at various loads and 2000 rpm engine speeds. The experimental tests were performed on a four-stroke, single-cylinder, air-cooled diesel engine FL511. The bench test results showed that the brake specific fuel consumption increased, when operating on biodiesel-butanol fuel blends compared to neat biodiesel. The maximum brake thermal efficiency sustained at the levels from 7.3% to 12.9% lower in comparison with neat biodiesel operating at low engine load. When the engine was running at maximum torque mode using biodiesel-butanol fuel blend Bu15 the total emissions of nitrogen oxides decreased. Thus, the greatest fossil fuel challenge related with the simultaneous reduction of both the NOx emissions and the smoke opacity (PM) could be reasonably solved by switching a diesel engine on totally renewable biodiesel-n-butanol biofuel blends.

Keywords: diesel engine, rapeseed oil derived biodiesel, n-butanol, engine efficiency, brake specific fuel consumption, emissions, smoke opacity.

INTRODUCTION

The Directive 2009/28/EC of the European Parliament and the Council on the promotion of the use of energy from renewable sources [1] approved a target of a 20% of European energy consumption using renewable fuels in a cost-effective way. This Directive fixes at 10% the minimum consumption of renewable fuel used in transport-sector by 2020 and creates a challenge for both the scientists and the industry. Keeping in a track with the newest trends to use lighter and more environment friendly biofuels for a diesel engine powering, Giakoumis et al. [2], Rakopoulos et al. [3], Labeckas et al. [4] tested n-butanol in diesel fuel blends. The research revealed [4], due to the longer auto-ignition delay period of a pilot portion of diesel-n-butanol fuel blends both the fuel-energy conversion efficiency representing burn angle MBF 50, at which burns a half of the injected fuel portion, and the end of combustion occur earlier in an engine cycle after TDC. In result, the brake thermal efficiency increases to maximum value of 0.383 when running with diesel fuel blend involving n-butanol DB3 (3.0 wt% oxygen) at speed of 1800 rpm. While the NO_x, CO and THC emissions decrease by 5.1%, 29.5% and 3,7 times, respectively, when running with the most n-butanol involving blend DB4 (4.0 wt% oxygen) against analogous values a fully loaded straight diesel produces at a higher speed of 2500 rpm. The scientists Sukjit et al. [5] progressed further with totally renewable and environment friendly binary, biodiesel-n-butanol biofuels adding to the intake manifold hydrogen to enhance combustion and drastically reduce CO and particulate matter (PM) emissions in compression ignition engines.

Normal butanol ($CH_3CH_2CH_2CH_2OH$) with molecular weight of 74.12 g/mol. is an alcoholic-origin colourless liquid of medium volatility and a characteristic banana-like odour. It is flammable enough with a flash point of around 35 $^{\circ}$C, contains 21.62 wt.% of fuel-bound oxygen with a boiling point of about 117.40 °C at 760 mm Hg. This renewable biofuel added to widely known rapeseed oil methyl ester (RME) reduces density, viscosity, C/H atoms ratio and provides plenty of fuel-bound oxygen that along with its good evaporative properties improves both the air and fuel vapours mixing rate and the combustion of biofuel blends. Because biodiesel and n-butanol contain a lower number than traditional diesel fuel the carbon atoms in the molecules, the enhanced combustion takes the advantage to reduce the total amount of both CO_2 and CO emissions below the respective values of neat biodiesel or from a straight diesel could be expected. When being used as a oxygenator source in the above tests, anhydrous, 200 proof, ethanol (CH_3CH_2OH – 99.9 vol%) created more concern to the researchers than n-butanol in terms of the blends consistency, auto-ignition delay extension and combustion peculiarities. However, the presence of a lighter n-butanol in biodiesel also reduces the blended cetane number rating, net heating value and thus affects mass of biofuel consumed per unit of energy or effective power developed by an engine. A sensitive interaction between advantageous and disadvantageous operational properties of renewables with a widely differing nature, origin and production technology of biodiesel and n-butanol may lead to ambiguous development trends in the combustion attributes, net heat release rate and engine out emissions [4].

Wei et al. [6] investigated and compared biodiesel-ethanol (BE) and biodiesel-n-butanol (BBu) blends-made effects on combustion, performance and emissions of a direct-injection diesel engine. Experiments

were conducted on a straight diesel, biodiesel and BE5 (5% ethanol and 95% biodiesel, v/v), BE10, BE15 and BBu5, BBu10, BBu15 biofuel blends, at five engine loads and constant speed of 1800 rpm. The blended fuels lead to higher maximum heat release rate, higher maximum in-cylinder pressure, longer auto-ignition delay, and shorter combustion duration that all in a company evoked adverse effect on combustion noise and stability particularly when running with the BE blends. Moreover, on average of the five engine loads, the BBu and BE blends increased CO emission by 13.7% and 22.8% and HC emission by 5.6% and 29.2%, respectively; but reduced NO_x emission by 6.5% and 28.0%, particle mass concentration by 20.7% and 20.6% and particle number concentration by 22% and 21%, respectively. Thus the BE blends revealed themselves as being more effective in reducing particulate and NO_x emissions, while the BBu blends suggested less increase in CO and HC emissions [6].

Zöldy [7] conducted a wide-range chemical-analytical investigation on properties of butanol, hydrogenated vegetable oil and diesel fuel blends and measured nearly 20 chemical and physical parameters, especially such as flash point, cetane number, viscosity and cold filter plugging point (CFPP) to find out whether or not the three component blends are suitable for compression ignition engines. The researcher estimated that the viscosity decreases within the test range nearly liner and every 1% of butanol mass content (v/v %) added to the blend causes slight 1.4% decreasing effect on viscosity. He also noted that the added butanol decreases the blend's flash point to around 40 ^{o}C that is under the standard DIN EN ISO 2719, revised in 2016, minimum. This decrease is critical from the point of view of transportation fire-safety and logistics security. Because butanol-diesel and/or n-butanol-biodiesel fuel blends are flammable, the security equipment needs to be used as in the gasoline supply chain. Through wide-range experimental tests, the author disclosed that there about a liner relationship exists and the increase by 1 % of butanol in Hydro-treated Vegetable Oil (HVO) content decreases the blended CN rating with an average of 0.4 points.

A lot of the research and development performed on n-butanol using in a diesel engine, however, there is not completely clear what could be the rational renewable biodiesel and n-butanol mixing rate that could be acceptable for diesel-powered machines and power generators. To make a difference, the undertaken research intends to put more light on the changing trends in performance parameters of a diesel engine, biofuels energy conversion efficiency and emissions of the exhaust when running alternately on neat biodiesel (B) derived from rapeseed oil as a 'baseline' fuel and a totally, renewable binary liquid biodiesel-n-butanol blends. Purpose of the research is to improve engine brake thermal efficiency, reduce NO_x, CO, CO_2 emissions and smoke opacity of the exhaust when running a single-cylinder, DI diesel engine on binary biodiesel-n-butanol blends under 5, 10, 15, 20, 25, 30 and 35 Nm loads and maximum torque speed of 2000 rpm. A four-stroke, air-cooled, naturally-aspirated diesel engine operated on a neat biodiesel (B) first, and then with the three totally renewable, binary biodiesel-n-butanol (BBu) blends BBu5 (95 vol.% B/5 vol.% Bu), BBu10 (90 vol.% B/10% Bu) and BBu15 (85vol.% B/15vol.% Bu) under the same loading conditions.

The test results of engine operation with various biodiesel-n-butanol blends are analysed and compared with the respective parameters measured when running with neat biodiesel derived from rapeseed oil at the respective loads, with particular attention to full (100%) engine load, at constant speed of 2000 rpm. Because of the absence of polycyclic aromatic hydrocarbons in renewable biofuel blends, higher brake thermal efficiency, lower maximum NO_x and drastically reduced CO emissions and smoke opacity (PM) could reasonably be expected due to potentially improved homogeneity of combustible mixture and particulate matter (PM) emissions benefits suggested by higher n-butanol-oxygen mass content (21.62 wt%) and much lower carbon-to-hydrogen ratio (4.8).

MATERIALS AND METHODS OF THE RESEARCH

Regardless of both biodiesel (B) and n-butanol (Bu) are of the same renewable nature, nevertheless, the production of tested biofuels derives from different resources by using dissimilar technologies, therefore, these biofuels differ as having completely different origins with widely differing chemical and physical properties (Table 1). In contrast to ethanol [8], operational properties of n-butanol are much more similar to those of a straight diesel or biodiesel with the exception of lower density, viscosity and about twice as much lower CN rating the improvement of which rests on the higher cetane number of biodiesel. Moreover, n-butanol provides operational advantages because its reasonable addition to biodiesel has the potential to drastically reduce the production of CO and smoke (PM) due to considerably lower C/H atoms ratio and high fuel-bound oxygen mass (wt, %) content. Next, the lower density and viscosity of n-butanol may have positive impact on biofuel injection, atomisation and vaporisation characteristics, the air and fuel vapours mixing rate in the hot in-cylinder compressed air charge, combustion attributes and thus engine out emissions when operating under steady and transient conditions [9].

Table 1. Properties of the tested rapeseed oil biodiesel and n-butanol

Property parameters	Fuel test methods	Rapeseed oil biodiesel (B)	N-butanol (Bu)
Density at 15°C, kg/m^3	EN ISO 12185:1999	884.7	810
Kinematic viscosity, mm^2/s at 40 °C	EN ISO 3104+AC:2000	4.8	2.63
Lubricity (HFRR), wear scar diameter (wsd 1.4) at 60 ^{0}C, μm	EN ISO 12156-1	205	591
Flash point, open cup, °C	EN ISO 2719:2000	168	35
Initial / final boiling points, ^{0}C	EN ISO 3405:2011	346 / 366	117.7
Auto-ignition temperature ^{0}C	-	~342	~343
Cetane number	EN ISO 5165:1999	53.4	25
Oxygen content, max wt%	-	10.9	21.62
Carbon-to-hydrogen ratio (C/H)	-	6.49	4.8
Stoichiometric air/fuel ratio, kg/kg	-	12.62	11.12
Net heating value, MJ/kg	EN ISO 8217:2012	37.23	33.08

The experimental examinations performed in the engine-test laboratory at Power and Transport Machinery Engineering Institute of Vytautas Magnus University - Agricultural Academy. The technical characteristics in more details are listed in Table 2.

Table 2. Engine FL 511 specifications

Type	Deutz FL 511
Number of strokes	4 stroke
Number of cylinders	Single-cylinder
Bore, mm	100
Stroke, mm	105
Displacement volume, cm^3	825
Compression ratio	17
Injection timing advance in CADs before TDC	24°
Maximum power (at 3000 rpm), kW	12.8 ±5%
Injection pressure, bar	175±5 bar
Specific fuel consumption, g/kW·h	255 ±5%
Rated speed, rpm	3000
Engine weight, kg 135	135

Torque of an engine was measured with a magnetic powder brake dynamometer PT40M (0–60 N·m) with a definition rate of ±0.5 N·m and rotation speed with a mechanical tachometer (150–3000 rpm) with an accuracy of ±0.5% of the measured value. The air mass consumption was measured with a turbine type gas meter CGT-02 (10–100 m^3/h) with an accuracy of ±1% of the measured value, and fuel mass consumption by using electronic scale SK-1000 with an accuracy of ±0.5%.

Emissions of nitric oxide (NO), nitrogen dioxide (NO$_2$), carbon monoxide (CO) in parts per million (ppm) and carbon dioxide (CO$_2$) in vol% were measured with electrochemical cells installed in Testo 350 XL flue gas analyser. Total NO$_x$ emissions were determined as a sum of both NO and NO$_2$ pollutants with an accuracy of ±5 ppm. Exhaust smoke was measured with a Bosch RTT 110 opacity meter with an accuracy of ±0.1% in a scale range of 0–100%. To improve reliability of the measured data the tests have been repeated no less than three times.

RESULTS AND DISCUSSION

The summarised effect of the widely differing chemical and physical properties and net heating values of the biofuels studied along with the changes in the auto-ignition and combustion peculiarities have

influence on the fuel mas burned over an hour (kg/h) and the fuel mass consumed per unit of effective power (g/kWh) developed by an engine. As can be seen in graphs of Figs. 1a and b, both the mass of the fuel consumed over an hour (B_d) and the brake specific fuel consumption (bsfc) for neat biodiesel are lower over the whole load-range tested compared to the engine running on less calorific biodiesel-n-butanol blends. The noted differences in the bsfc values are mainly observable when running at a light load, low pressure and temperature in the cylinder because the auto-ignition delay extends due to the presence of more volatile n-butanol with both the cooling effect and the reduced CN rating that may negatively affect the combustion of the blends. For the above reasons and slightly lower calorific value, the brake specific fuel consumptions for the respective blends BBu5-BBu15 are up to 1.08% - 14.80% higher than, 798.7 g/kWh, neat biodiesel suggests for light-load operation.
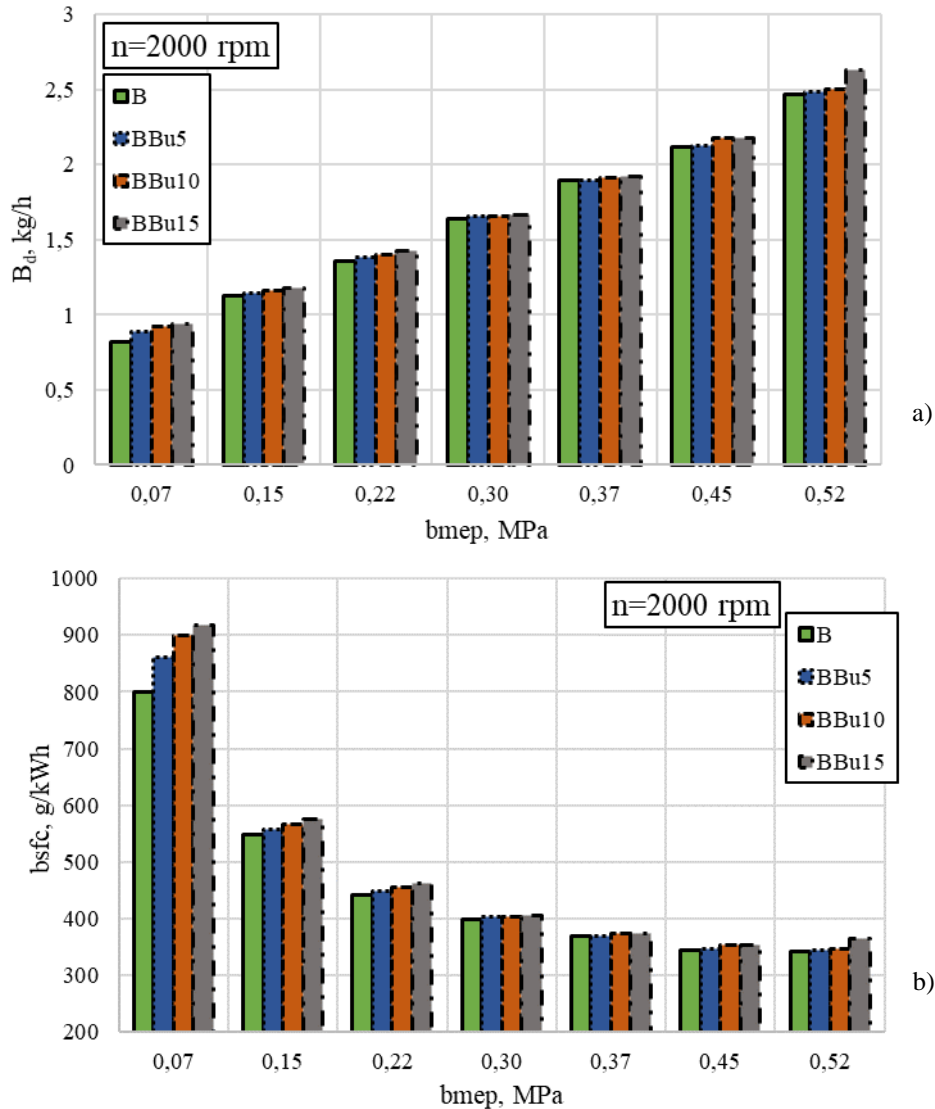

Fig. 1. The fuel mass consumption per hour (B_d) and brake specific fuel consumption (bsfc) as a function of engine load when running at maximum torque speed of 2000 rpm.

As soon as the temperature inside the cylinder increases with engine load increased to about 0.30 MPa, the differences in brake specific fuel consumptions are also less observable and the bsfc values for the respective blends BBu5-BBu15 sustain at about 1.15% - 1.85% higher levels than, 398.4 g/kWh, the neat biodiesel consumes at considered test conditions. As could be reasonably expected, the bsfc values remain relatively up to 0.69% - 6.57% higher for n-butanol oxygenated biodiesel blends BBu5 – BBu15 when running at a full (100%) load as well than, 343.1 g/kWh, neat biodiesel suggests for the same loading conditions at maximum torque speed of 2000 rpm. The relatively higher brake specific fuel consumption of binary biofuels BBu5 - BBu15 can be mainly attributed to the lower net heating value of plenty oxygenated biodiesel-n-butanol blends.

The biggest relative decrease in the brake thermal efficiency of an engine reasonably obtained when running with neat biodiesel and biofuel blends tested under the low loads and thus not as high as would be needed for fuel-efficient operation the temperature inside the cylinder. As shown in Fig. 2a, an engine develops the lowest brake thermal efficiency value of 0.107 (11.6% lower) when running with the most n-butanol oxygenated blend BBu15 and the maximum one of 0.121 with neat biodiesel at the lowest 0.07 MPa load. The obtained energy conversion efficiencies of biofuel blends match well with obvious differences in the cetane number, negative changing trends in the combustion noise, engine performance stability and the respective bsfc values (Fig. 2b) measured when running with blend BBu15 at the lowest load. The brake thermal efficiency gradually increased with engine load and the temperature inside the cylinder to reach for neat biodiesel and slightly n-butanol oxygenated blend BBu5 the same maximum value of 0.282 remaining 1.4% and 4.3% lower engine efficiencies, 0.281 and 0.270, for the respective n-butanol blends BBu10 and BBu15 when running under full (100%) load conditions.
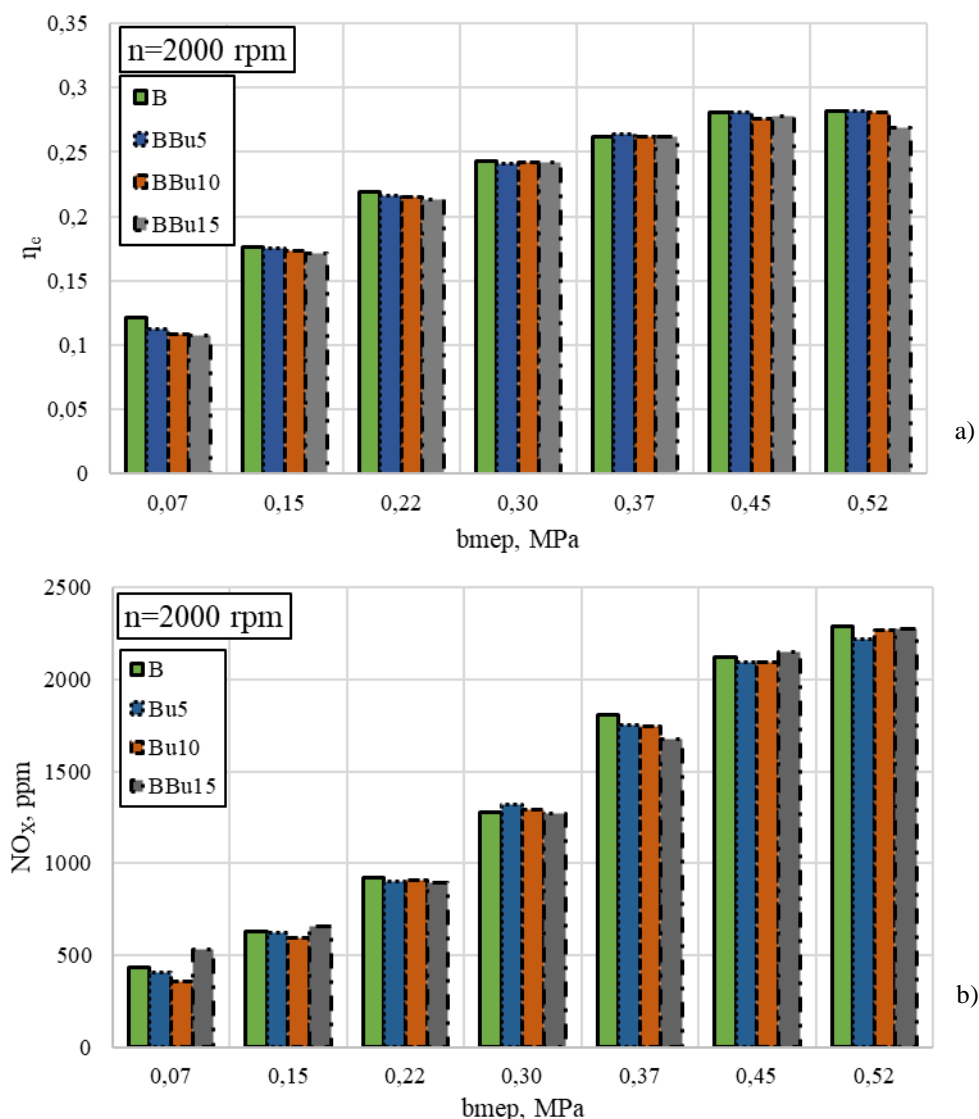

Fig. 2. The brake thermal efficiency (η_e) and total nitrogen oxide (NO_x) emissions as a function of engine load when running at maximum torque speed of 2000 rpm.

High evaporative cooling effect and low calorific value of n-butanol can be realised in practise bearing in mind that the production of NO_x relies primary on the temperature inside the cylinder, local oxygen concentration, the residence time limited by the combustion reactions, and relative (overall) air/fuel ratio [10], but less depends on the availability of the local oxygen [11]. The total NO_x emissions sustain at a reasonable levels when running at the lowest 0.07 MPa load varying within the narrow range from 397 ppm for neat biodiesel to 476 ppm for the biggest mass content of n-butanol containing biofuel BBu15. The relatively 19.9% higher NO_x emissions emanating from the combustion reaction of the most n-butanol

involving blend BBu15 can be reasonably attributed to the fact that the temperature inside the cylinder is too low to keep smooth operation of an engine on plenty n-butanol oxygenated biodiesel blend at the lowest load. Therefore, the increased combustion instability accompanied by the high noise levels and the in-cylinder pressure oscillations contributed to the production of more NO_x emissions in this particular low-load conditions (Fig. 2b).

The production of NO_x emissions gradually increases with engine load and thus the temperature inside the cylinder reaching the lowest value, 1121 ppm, for neat biodiesel and the biggest one, 1219 ppm, (8.7% higher) for the combustion of blend BBu5 when running at about medium (50% of full) load. As could be expected, the NO_x emissions increase to the maximum value of 2132 ppm for neat biodiesel sustaining at relatively 3.0%, 0.9% and 0.5% lower levels for the respective biodiesel-n-butanol blends BBu5, BBu10 and BBu15 when running under the full (100%) load conditions. It is challenging to define the reasons, but in fact, the obtained result provides excellent finding revealing that the higher n-butanol mass content (v/v %) is added to biodiesel blend, the lower actually its contribution to the reduction intensity of maximum NO_x emissions can be expected. The potential answer to this intriguing question lies perhaps beyond the fact that the NO_x emissions emerge mainly during the first kinetic combustion phase under the high temperatures above 2000 K where a key role in the NO_x production plays the air-borne oxygen.
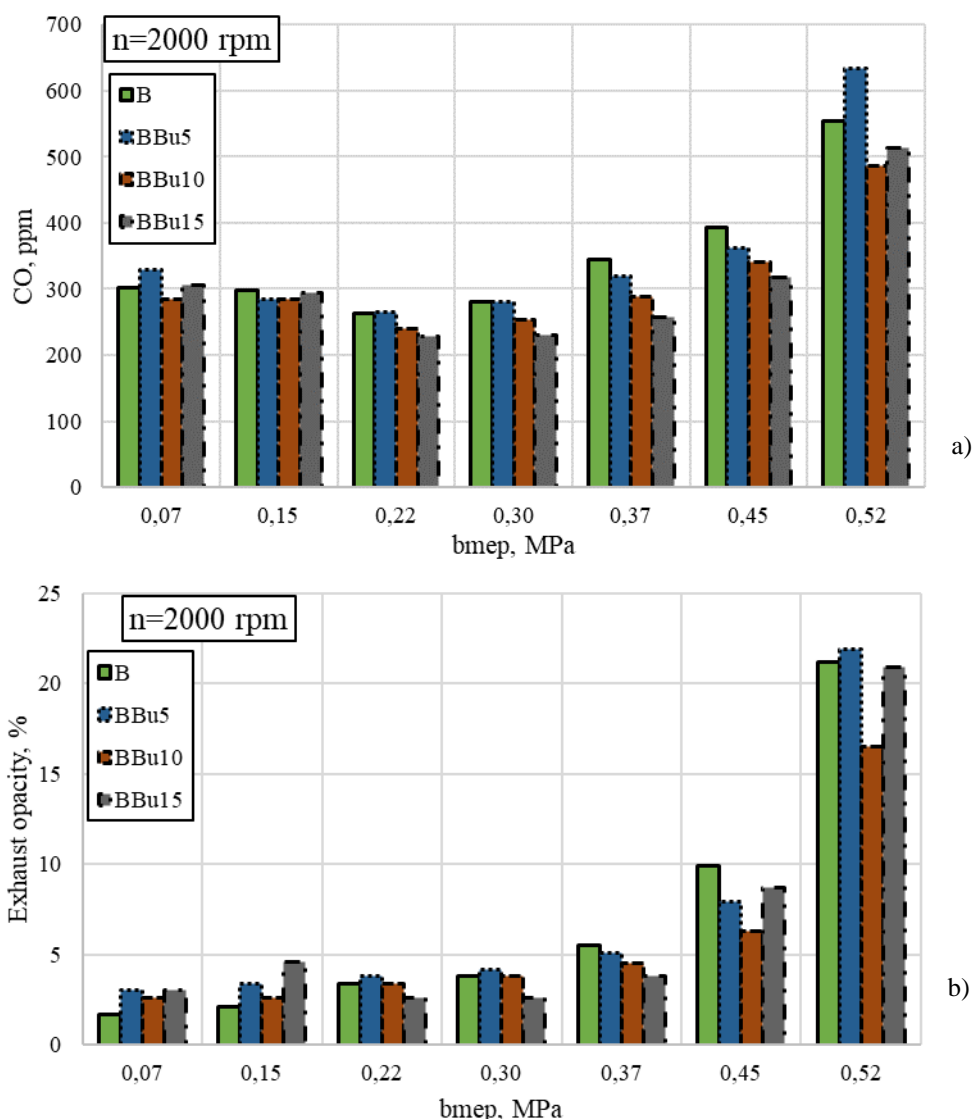

Fig. 3. Dependencies of carbon monoxide (CO) emissions (a) and smoke opacity of the exhaust (b) on engine load when running at maximum torque speed of 2000 rpm.

While the biofuel-bound oxygen takes only a second-rate role coming into effect too late in the expansion stroke during the diffusion-controlled combustion phase and thus with a little help to contribute to the NOx production. For this reason, the effect of the fuel-bound oxygen on the NOx emissions changing trends can be ambiguous enough, hardly predictable and dependable on the feedstock materials, origin and

production technology of the biofuel as well as on the combustion chamber type and the test conditions of an engine, particularly on the relative (overall) air/fuel ratio.

In contrast to ambiguous the NO_x emissions behaviour, the positive effect of the lower C/H atoms ratio strongly supported by both the absence of polycyclic aromatic hydrocarbons in the composition of biodiesel-n-butanol biofuels and the increased n-butanol-oxygen mass (wt, %) content, significantly contributes to enhance combustion and thus drastically reduce CO, CO_2 emissions and visible smoke of the exhaust. At the beginning of engine loading, the CO emissions relatively decrease to be 5.6% lower mainly for the blend's BBu10 case, while unstable combustion of the respective blends BBu5 and BBu15 produce CO emissions 9.3% and 1.3% higher than neat biodiesel suggests, 302 ppm, when running at the lowest 0.07 MPa load (Fig. 3a).

As soon as the engine load increases to about medium (50% of full) value and the temperature inside the cylinder boosts up, both most n-butanol oxygenated blends BBu10 and BBu15 reveal themselves as having strong potentials to drastically reduce the carbon monoxide (CO) emissions by 8.9% and 17.5%, respectively. The noted positive CO emissions changing trends with using the most n-butanol oxygenated biodiesel blends BBu10 and BBu15 actually remain in value after transition to full (100%) load operation as well. The enhanced combustion of the respective blends BBu10 and BBu15 produces the CO emissions 12.4% and 7.4% lower than, 555 ppm, the neat biodiesel emits under full (100%) load operation. Only the combustion of the blend BBu5 produces the CO emissions relatively 14.1% higher, most likely, due to an inevitable pay off required to compensate for the merits experienced with having the relatively lowest NO_x production when running under full (100%) load at maximum torque speed of 2000 rpm (Fig. 2b).

Smoke opacity characteristics proceed at the low levels compiling only 3.4%, 2.6% and 4.6%, however transparency of the exhausts for the respective n-butanol oxygenated blends BBu5, BBu10 and BBu15 is relatively 61.9%, 23.8% and 2.2 times not as good as that, 2.1%, neat biodiesel produces when running at 0.15 MPa load and maximum torque speed of 2000 rpm (Fig. 3b). This phenomenon of smoke is the evidential fact that biofuel vapours do not burn completely at the low load, so they additionally affect transparency of the exhaust if or when the temperature inside the cylinder is not as high as would be needed to support efficient combustion and take under control the cyclic variability of operational parameters. As could be reasonably expected, the lowest smoke opacity produces the combustion of most n-butanol oxygenated blend BBu15 that is 31.6% lower than, 3.8%, neat biodiesel suggests when running at about medium (50% of full) load. While less n-butanol oxygenated biodiesel blend BBu10 took real advantage to enhance combustion and reduce smoke opacity by 20.9% than that, 21.2%, neat biodiesel produces under full (100%) load at maximum torque speed of 2000 rpm.

CONCLUSIONS

1. The brake specific consumption of biodiesel-n-butanol blends BBu5-BBu15 is 1.08% - 14.80%, 1.15% - 1.85% and 0.69% - 6.57% higher than the respective bsfc values, 798.7, 398.4 and 343.1 g/kWh, neat biodiesel suggests for studied loading conditions of 0.07, 0.30 and 0.52 MPa at maximum torque speed of 2000 rpm. The main reason of having relatively higher the bsfc for oxygenated blends is much lower net heating value of the added n-butanol.

2. The brake thermal efficiency suffered relative decrease to 0.107 (11.6% lower) when running with the most n-butanol oxygenated blend BBu15 at the lowest load of 0.07 MPa. However, thermal efficiency increased to reach the same maximum of 0.282 for neat biodiesel and blend BBu5 remaining, 0.281 and 0.270, that is relatively 1.4% and 4.3% lower for more n-butanol containing blends BBu10 and BBu15 when running under full (100%) load conditions.

3. The highest total NO_x emissions, 2132 ppm, produces the combustion of neat biodiesel, while the positive effect of n-butanol oxygenated biodiesel blends on the NO_x suppression is not as huge as could be expected. This is because the NO_x reduction intensity decreases 3.0%, 0.9% and 0.5% when running an engine with n-butanol oxygenated biodiesel blends BBu5, BBu10 and BBu15 under the full (100%) load at maximum torque speed of 2000 rpm.

4. Both most n-butanol oxygenated biodiesel blends BBu10 and BBu15 revealed themselves as having strong potentials to drastically reduce the carbon monoxide (CO) emissions by 8.9% and 17.5%, respectively, when running at about medium (50% of full) load. The enhanced combustion of the carbon-limited, plenty oxygenated blends BBu10 and BBu15 emitted the CO emissions 12.4% and 7.4% less than, 555 ppm, the neat biodiesel produces for full load conditions as well.

5. The lowest smoke opacity produces the combustion of plenty n-butanol oxygenated biodiesel blend BBu15, which is 31.6% lower than, 3.8%, neat biodiesel suggests running at about medium (50% of full) loading conditions. While less n-butanol oxygenated biodiesel blend BBu10 took advantage the

enhanced combustion of which reduces smoke opacity by 20.9% than, 21.2%, neat biodiesel produces under full (100%) load at maximum torque speed of 2000 rpm.

Taking into account the above merits, renewable binary biodiesel-n-butanol blends are suitable for diesel engine powering to replace fossil-origin diesel fuels, reduce the climate change and safe the untouched nature for future generations. The Ball On-Cylinder or BOCLE tests showed that biodiesel derived from rapeseed oil has superior lubricity compared to low sulphur diesel fuel [12] and thus the wear-sensitive fuel system designs such as plunger-barrel and the needle-valve-barrel units are able to tolerate up to 15 vol% n-butanol additions to biodiesel.

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