

Experimental investigation of biodiesel-n-butanol fuels blends on performance and emissions in a diesel engine

ARTICLE INFO

The paper presents the experimental test results reflecting the comparative changes in the performance efficiency and emissions of the exhaust of a naturally aspirated, four-stroke, single-cylinder, air-cooled diesel engine due to its transition from neat rapeseed oil biodiesel to fuel blends prepared by mixing in various proportion (by volume) rapeseed methyl ester (B) and butanol (Bu). The lubricity properties of biodiesel-n-butanol fuel blends were studied using HFRR method. In contrast to previous works, the undertaken investigation is performed with a totally renewable, binary liquid biofuel blends. The purpose of the research is to reduce simultaneously the production of NO_x emissions and the exhaust smoke with respect to neat biodiesel due to potentially improved homogeneity of combustible mixture and particulate matter emissions benefits suggested by the higher oxygen content (21.62wt%) and the relatively lower carbon-to-hydrogen ratio (4.8) of the normal n-butanol. The tests revealed that the brake specific fuel consumption for the binary biodiesel-n-butanol fuel blends is always higher than that neat biodiesel produces under the same loading conditions. Maximum nitrogen oxide (NO_x) emissions were obtained with the engine running on neat biodiesel (2290 ppm). At full (100%) load conditions, the lowest NO_x emission was obtained with the engine running on a biofuel BBu20 blend. The lowest level of carbon monoxide emissions (CO) was observed, when engine running with the most butanol-oxygenated biofuel blend BBu20. The highest smoke opacity of the exhaust was obtained when the engine was fuelled with neat biodiesel and at full load.

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1. Introduction

In the recent decades, the scientists continue to work on the rational global energy using as well as urgent ecological and environmental problems. The requirements stated by the EU parliamentarians to intensify the development of renewable energy sources, strict environmental requests associated with the reduction of greenhouse gas emissions and wastes in the municipal economy, agricultural and forestry sectors encourage the researchers to investigate alternative and renewable energy strategies including a wider use of biofuels. Up to now, the researchers have not offered new technological solutions that would completely replace internal combustion engines by other mechanical energy sources. For this reason, oil and the natural gas reserves rapidly decrease over the recent decades. Moreover, smoke and exhaust emissions produced by internal combustion engines cause serious damage to the ecological system. The Directive 2009/28/EC of the European Parliament and the Council on the promotion of the use of energy from renewable sources approved a target of a 20% of European energy consumption using renewable fuels in a cost-effective way [1]. This Directive fixes the minimum consumption of renewable fuel used in transport-sector and creates a challenge for both the scientists and the industry. Agriculture and transport sectors are among the largest fossil fuel consumers and therefore can be regarded as the biggest contributors to the environmental pollution. The mineral diesel fuel traditionally remains the most popular among the others motor fuels. Consumption of the diesel fuel has been growing steadily over the last two decades.

The physical properties of the fuel such as density, viscosity and bulk modulus of compressibility affect the deliv-

ery rate and the injection characteristics and thus the quality of the air and the fuel mixture, which in turn affects the combustion process, brake thermal efficiency and the ecological parameters of the diesel engine. Specific properties of alternative and renewable biofuels such as density, viscosity, calorific value, cetane number, freezing point, etc. differ from those of the normal diesel fuel. 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 MBF50, 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. 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 [5].

Normal butanol (CH₃CH₂CH₂CH₂OH) 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°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 CO₂ and CO emissions below the respective values of neat biodiesel or from a straight diesel could be expected. When being used as an oxygenator source in the above tests, anhydrous, 200 proof, ethanol (CH₃CH₂OH – 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]. In contrast to ethanol, 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 [8]. 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].

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 linear 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°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 linear 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 [7].

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.

2. Materials and methods

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). The totally renewable blends BBu10 (11.972 wt% oxygen) and BBu20 (12.336 wt% oxygen) were prepared by mixing 90 vol.% B/10% Bu (BBu10) and 80 vol.% B/20 vol.% Bu (BBu20), respectively.

The experimental investigation was carried out in the Engine testing laboratory of Power and Transport Machinery Engineering Institute, Faculty of Agricultural Engineering of Vytautas Magnus University – Agricultural Academy. For stroke, single-cylinder, direct injection, air cooled DEUTZ FL 511 diesel engine was used for these experiments. Load characteristics of an engine were taken when operating at gradually increasing load and constant engine speed of 2000 rpm at which an engine maximum torque develops. 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.

Table 1. Chemical and physical properties of tested biofuels

Parameter	rapeseed oil biodiesel (B)	n-butanol (Bu)
Density at 15°C, kg/m ³	884.7	810
Kinematic viscosity, mm ² /s	4.8	2.63
Lubricity (HFRR), wear scar diameter (wsd 1.4) at 60°C, µm	205	591
Flash point, open cup, °C	168	35
Initial/final boiling points, °C	346/366	117.7
Auto-ignition temperature °C	~342	~343
Cetane number	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	37.23	33.10

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 $\pm 0.5\%$ of the measured value. The air mass consumption was measured with a turbine type gas meter CGT-02 (10–100 m³/h) with an accuracy of $\pm 1\%$ of the measured value, and fuel mass consumption by using electronic scale SK-1000 with an accuracy of $\pm 0.5\%$.

Emissions of nitric oxide (NO), nitrogen dioxide (NO₂), carbon monoxide (CO) in parts per million (ppm) and carbon dioxide (CO₂) 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 NO₂ pollutants with an accuracy of ± 5 ppm. Exhaust smoke was measured with a Bosch RTT 110 opacity meter with an accuracy of $\pm 0.1\%$ in a scale range of 0–100%. To improve reliability of the measured data the tests have been repeated no less than three times.

Lubricating properties of the fuels were determined by using the HFRR method. Tests were conducted according to the international standard ISO 12156. The temperature of the fuel was maintained to be of a constant value of about 30° C during the lubricity tests.

3. Analysis of the results and discussions

3.1. Lubricity of biodiesel-n-butanol fuel blends

Columns in Fig. 1 show how the average wear scar of the test ball changed when using the neat biodiesel and biodiesel-n-butanol fuels blends.

The test results demonstrate that the average wear scar with maximum increase in the diameter of 0.395 mm was obtained when using biofuel BBU30 blend. While the minimum wear scar with the diameter of 0.280 mm was obtained with neat biodiesel. The Ball On-Cylinder or BOCLE tests showed that biodiesel derived from rapeseed oil has superior lubricity compared to low sulphur diesel fuel [10] and thus the wear-sensitive fuel system designs

such as plunger-barrel and the needle-valve-barrel units are able to tolerate small n-butanol additions to biodiesel.

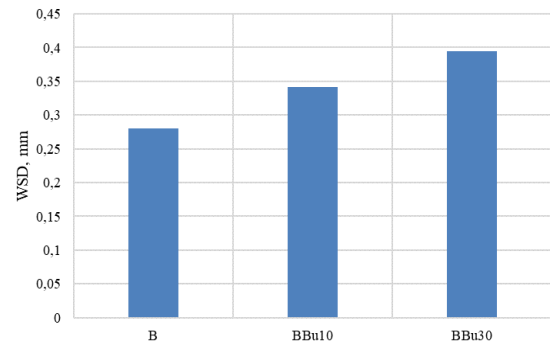


Fig. 1. The dependency of the average wear scar caused by the neat biodiesel and biodiesel-n-butanol fuel BBU10 and BBU30 blends

3.2. Performance efficiency and emissions from an engine powered with biodiesel-n-butanol fuel blends

Figure 2 shows the brake specific fuel consumption (bsfc) variations as a function of engine load. 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 mass 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, 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 BBU10 and BBU20 are up to 12.56% and 16.76% higher than, 798.7 g/kWh, neat biodiesel suggests for light-load operation.

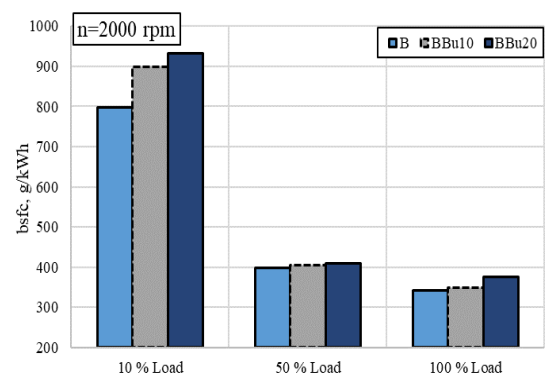


Fig. 2. The brake specific fuel consumption (bsfc) as a function of engine load when running at maximum torque speed of 2000 rpm

As soon as the temperature inside the cylinder increases with engine load increased to about medium (50% of full), the differences in brake specific fuel consumptions are also

less observable and the bsfc values for the respective blends BBU10 and BBU20 sustain at about 1.38%–2.80% 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 1.39%–9.77% higher for n-butanol oxygenated biodiesel blends BBU10 and BBU20 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 BBU10 and BBU20 can be mainly attributed to the lower net heating value of plenty oxygenated biodiesel-n-butanol blends.

Figure 3 shows the brake thermal efficiency variations as a function of engine load.

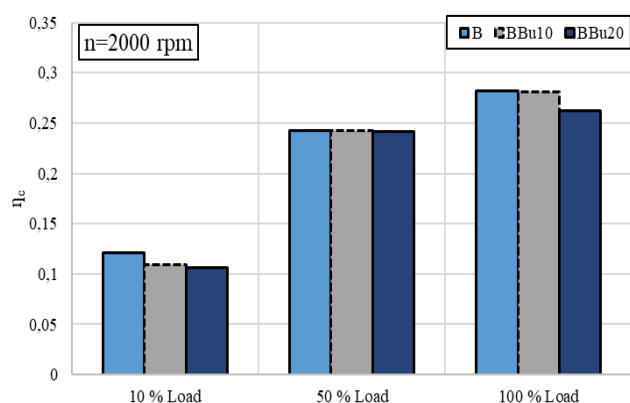


Fig. 3. The brake thermal efficiency as a function of engine load when running at maximum torque speed of 2000 rpm

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 combustion the temperature inside the cylinder. As shown in Fig. 3, an engine develops the lowest brake thermal efficiency value of 0.106 (14.15% lower) when running with the most n-butanol oxygenated blend BBU20 and the maximum one of 0.121 with neat biodiesel at the lowest (10%) 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. 2) measured when running with blend BBU20 at the lowest load. The brake thermal efficiency gradually increased with engine load and the temperature inside the cylinder to reach for neat biodiesel the same maximum value of 0.282, remaining 3.28% and 7.33% lower engine efficiencies, 0.273 and 0.263, for the respective n-butanol blends BBU10 and BBU20 when running under full (100%) load conditions.

The variation of total emissions of nitrogen oxides (NO_x) with as a function of engine load and different biofuel blends is presented in Fig. 4. The total NO_x emissions sustain at a reasonable level when running at the lowest engine load varying within the narrow range from 434 ppm for neat biodiesel to 489 ppm for the biggest mass content

of n-butanol containing biofuel BBU20. The relatively 12.5% higher NO_x emissions emanating from the combustion reaction of the most n-butanol involving blend BBU20 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. 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 [11], but less depends on the availability of the local oxygen [12].

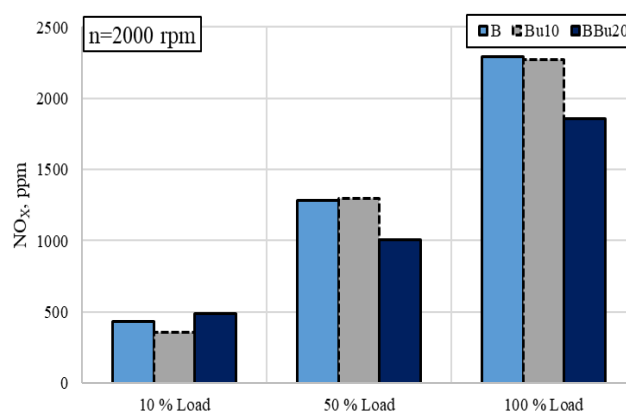


Fig. 4. The total nitrogen oxide (NO_x) emissions as a function of engine load when running at maximum torque speed of 2000 rpm

The production of NO_x emissions gradually increases with engine load and thus the temperature inside the cylinder reaching the lowest value, 1280 ppm, for neat biodiesel and 1273 ppm, for the combustion of biofuel blend BBU10 when running at about medium (50% of full) load.

As could be expected, the NO_x emissions increase to the maximum value of 2290 ppm for neat biodiesel sustaining at relatively 0.7% and 23.5% lower levels for the respective biodiesel-n-butanol blends BBU10 and BBU20 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. 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 NO_x production. For this reason, the effect of the fuel-bound oxygen on the NO_x 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.

The dependencies of carbon monoxide (CO) emission of engine load is shown in Fig. 5. At the beginning of engine loading, the CO emissions relatively decrease to be 6.0 and 25.3% lower mainly for the blends BBU10 and BBU20 case, than neat biodiesel, when running at the lowest load.

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 BBU20 reveal themselves as having strong potentials to drastically reduce the carbon monoxide (CO) emissions by 10.7% and 27.3%, respectively. The noted positive CO emissions changing trends with using the most n-butanol oxygenated biodiesel blends BBU10 and BBU20 actually remain in value after transition to full (100%) load operation as well. The enhanced combustion of the respective blends BBU10 and BBU20 produces the CO emissions 486 ppm and 374 ppm lower values than, 555 ppm, for the neat biodiesel under full (100%) load operation.

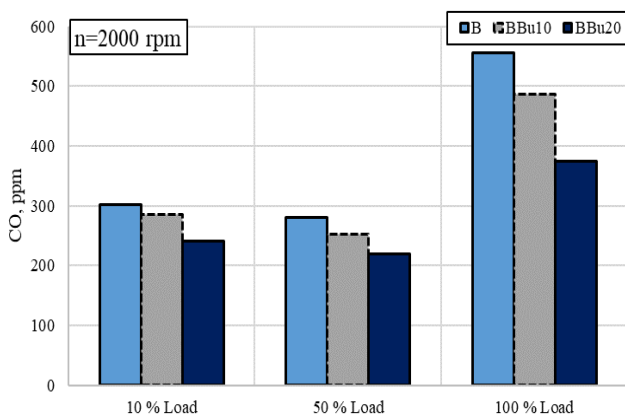


Fig. 5. Dependencies of carbon monoxide (CO) emissions on engine load when running at maximum torque speed of 2000 rpm

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, CO₂ emissions and visible smoke of the exhaust.

Figure 6 shows dependencies of smoke opacity of the exhaust of engine load. Smoke opacity characteristics for the respective n-butanol oxygenated blends BBU10 and BBU20 is 52.9% and 23.5% higher comparison to the neat biodiesel produces, when running at low load and maximum torque speed of 2000 rpm. 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 BBU20 that is 26.7% lower than, neat biodiesel suggests when running at about medium (50% of full) load.

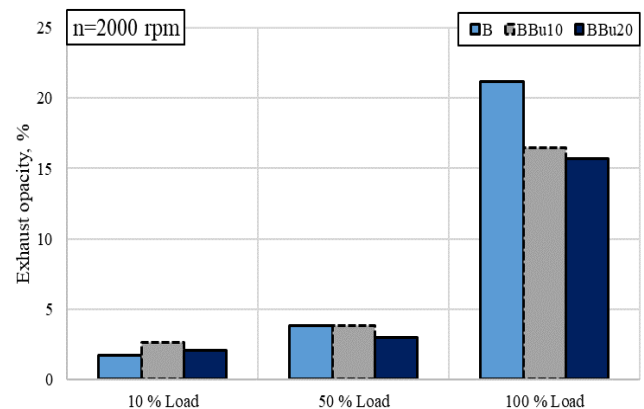


Fig. 6. Dependencies of smoke opacity of the exhaust on engine load when running at maximum torque speed of 2000 rpm

When running the engine on biofuel blends BBU10 and BBU20 at full (100%) load at maximum torque speed of 2000 rpm, the smoke opacity decreased by 28.5% and 35%, respectively, compared to the cases of using neat biodiesel.

Conclusions

1. Maximum mean diameter of the wear scar was equal to 0.395 mm when using biodiesel-n-butanol fuel BBU30 blend and the minimum value of the wear scar was measured when running with the neat biodiesel.
2. The brake specific fuel consumption using biodiesel-n-butanol fuel blends increased across at over the whole load range. At full engine load biofuel BBU10 and BBU20 blends, the break specific fuel consumption increased by 1.39%, and 9.77%, respectively, compared to neat biodiesel. The main reason of having relatively higher the bsfc for oxygenated blends is much lower net heating value of the added n-butanol.
3. Using a biofuel BBU20 blend, the break thermal efficiency was 7.33% lower, compared to the engine running on neat biodiesel, at full engine load.
4. The highest total NO_x emissions, 2290 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. At full engine load and using biofuel BBU20 blend, the most environmentally and human harmful total emissions of nitrogen oxides decreased 23.5%, respectively.
5. When the engine running at low load, the highest the carbon monoxide emissions were obtained with the engine running on neat biodiesel (302 ppm) and the lowest using the biofuel BBU20 blend (241 ppm). Both most n-butanol oxygenated biodiesel blends BBU10 and BBU20 revealed themselves as having strong potentials to drastically reduce the carbon monoxide (CO) emissions for full load.
6. At the full engine load, using biofuel BBU10 and BBU20 blends, the smoke opacity was 28.5% and 35% lower, compared to the engine running on neat biodiesel.

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 save the untouched nature for future generations. Because of the absence of polycyclic aromatic hydrocarbons in renewable biofuel blends, 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).

Nomenclature

CN	cetane number	WSD	wear scar diameter
B	rapeseed methyl ester	bsfc	brake specific fuel consumption
Bu	n-butanol	bte	brake thermal efficiency
BBu10	10 vol% n-butanol/80 vol% rapeseed oil methyl ester	NO _x	total nitrogen oxides
BBu20	20 vol% n-butanol/90vol% rapeseed oil methyl ester	CO	carbon monoxide

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