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A Study of Energy and Environmental Parameters of a Diesel Engine Running on Hydrogenated Vegetable Oil (HVO) with Addition of Biobutanol and Castor Oil

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Abstract: The article analyses energy and environmental operating parameters of a compression ignition internal combustion engine running on HVO-biobutanol and castor oil fuel blends, also comparing them with parameters of an engine running on convection diesel. Since biobutanol is known for poor lubrication characteristics, it was mixed with 5% of castor oil. The obtained blend of biobutanol and castor oil was mixed with HVO at 2/95, 10/90, and 20/80 v/v and fed to the compression ignition internal combustion engine. The presented physicochemical indicators justified the use of the said fuel blends. Constant engine crankshaft speed of 2000 rpm and a variable load expressed as BMEP of 0.1–0.9 MPa was selected in the research. When using the biobutanol–castor oil additive (hereafter simply biobutanol additive) in HVO, an increase in the rate of heat release (ROHR) and the convergence of its value to that of to conventional diesel fuel was observed. A decrease in BTE values was also observed with increasing biobutanol concentration in the blend. Increasing concentration of biobutanol in blends led to an increase in BSFC both in terms of volume and mass; HC and NO_x emissions grew as well, but smoke emissions declined, and no material changes in CO and CO_2 emissions were observed.

Keywords: hydrogenated vegetable oil (HVO); biobutanol; combustion; pollutant emissions; engine efficiency; mechanical engineering

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1. Introduction

Environmental problems have led to the development of second-generation biofuel production from non-food biomass. The said lignocellulose raw materials are their by-products, such as sugar cane flour, cereal straw, deforestation waste, municipal waste, and vegetative grasses, also fast-growing forests [1]. In order to reduce particulate matter emissions from diesel engines, it is important to develop new fuels, new injection strategies, and highly performing after-treatment devices, i.e., diesel particulate filters [2,3]. Devices that measure particulate matter emitted by cars are currently being renovated [4,5]. The European Union regularly updates permitted pollutant emissions and their limit values [4]. Some countries try to switch from diesel to electric cars as soon as possible due to stricter restrictions on emissions imposed by legislation [6,7].

The EU White Paper and the Europe 2020 Strategy laid down therein provides for the flagship initiative "Resource-Efficient Europe" and the energy efficiency plan of 2011, the main aim of which is to create conditions for promoting European economic progress, increasing competitiveness, providing high-quality mobility services, and making much more efficient use of resources [8–10]. This is the way to increase competitiveness and provide high-quality services and to use resources much more efficiently [11]. This means that the transport sector must use more renewable biofuels of local origin and reduce negative impact on the environment [12]. Moreover, fuels containing biobutanol would be in line with these aims, as their further processing into fuels would increase the share of renewable energy sources in the total energy consumption [13,14]. The use of biodiesel allows significant reduction in environmental pollution with particulate matter [15,16]; thus, its use as a substitute for fossil diesel is very welcome [17]. Even though RME is the dominant type of biodiesel in Lithuania [18,19], trying out second-generation bio-diesel blends (biomass to liquid (BTL) [20,21], hydrogenated vegetable oils (HVO) [22,23], and other blends with biobutanol would be rational. When investing in and improving the technology for the production of second-generation biofuels, the progress of the process towards increasing commercial use can be observed. This would allow stopping the use of first-generation biofuels altogether, switching to second-generation biofuels. The biofuel industry is unlikely to undergo radical changes in the near future. The use of first- and second-generation biofuels will continue to trend, increasing the amounts of second-generation biofuels in line with the established environmental and economic policy [24,25].

Butanol can be of petroleum origin, which is labelled i-bubanol (iso-butanol), and of biological origin (also labelled n-butanol or 1-butanol). N-butanol is one of the most effective additives for reducing NO_X in diesel during combustion [26]. Additionally, a reduction in soot emissions has been observed when mixing diesel with n-butanol [27]. Increasing n-butanol volume in diesel increases NO_X emissions [28]. Exhaust Gas Recirculation (EGR) systems help to reduce NO_X emissions [29,30]. Tests have been performed with diesel and n-butanol blends using different EGR parameters and analysing exhaust gases [31–33]. Cetane number and stability of biodiesel (methyl esters of vegetable oils) are lower compared with HVO (hydrotreated vegetable oil). When adding n-butanol and ethanol to diesel in tests of fuel blends in diesel engines [34], n-butanol showed better results due to a higher cetane number, density, and viscosity. The assessment of homogeneity of the blends revealed that n-butanol mixes with diesel without any additional solvents, unlike ethanol [35,36]. The conducted tests revealed that blends of diesel and alcohol reduce particulate matter emissions [18,37,38]. Ignition delays no longer occur when using n-butanol and diesel blends compared with pure diesel. Using blends of HVO and n-butanol or n-butanol blends (of 30%) reduces particulate matter emissions compared with pure diesel and HVO [13,39].

The use of HVO and n-butanol blends can be concluded to render the best results, including the cetane number, start of combustion, and oxygen content [40–42].

In the assessment of emissions, results of tests of HVO–i-butanol blends revealed a slight decrease in NO_x and a high reduction in particulate matter compared with conventional diesel [43]. The analysis of conventional diesel, diesel–i-butanol, and HVO–i-butanol mixtures revealed higher NO_X emissions in diesel–i-butanol blends (with i-butanol accounting for 30% in diesel) compared with conventional diesel but lower NO_X emissions than that of HVO–i-butanol (with i-butanol accounting for 30% in HVO) [44]. Differences in NO_X emissions of pure diesel and HVO are sufficient, and adding i-butanol in HVO did not lead to any significant and consistent changes in NO_X; thus, statistical assessment of the results received is complicated [45,46]. The increase of oxygen concentration in biodiesel leads to lower CO emissions [47]. Sayin et al. and Gumus et al. tried to prove this phenomenon experimentally [48,49]. The researchers used conventional diesel, pure biodiesel, and blends of diesel and biodiesel: B100, B50, B20, B5 (the figures mean percentage biodiesel content in diesel). At various engine loads, CO emissions decreased by 38.18, 30.90, 20.66, and 13.55%, respectively, using B100, B50, B20, B5 compared with conventional diesel. The results of the research were based on the fact that a higher oxygen content in the used fuels improved the combustion process and its completeness. Gharehghani et al. presented similar results [50]. CO emissions using B25, B50, B75, and B100 (the figures mean percentage biodiesel content in diesel) decreased by an average of 5.2, 11.2, 22.5, and 27%, respectively. Higher oxygen content in the fuel blends used and shorter combustion process also confirm the results obtained. Oxygen contained in biodiesel oxidises with carbon molecules thus reduced CO emissions [26]. Basic fuel properties, such as viscosity and density, become important in order to achieve complete combustion, which would generate CO_2; also, the structure of the engine, engine speed, air-to-fuel ratio, and start of injection (SOI) must be taken into account. The use of conventional fossil hydrocarbon-based fuels would not allow achieving a reduction in CO_2 emissions [51]. Many research reports show that CO_2 emissions decrease using biodiesel compared with diesel. This is due to the low carbon content in biodiesel [52,53].

The conducted research with biodiesel with added alcohol demonstrated a decrease in HC emissions. HC emissions decreased by adding 15% and 20% of n-butanol and pentanol compared with biodiesel without alcohol. This is said to come as a result of increased oxygen content in fuels. On the other hand, the addition of alcohols led to fuel droplets of a larger diameter, resulting in ignition delay, which may increase HC generation during combustion. It has been argued that alcohol as an additive in biodiesel must be considered comprehensively [27].

Pirjola and a team of other researchers presented research results stating that a change in engine load and speed demonstrates the dependence of emissions on the said parameters. The highest content of pollutants is achieved with the engine idling, while the lowest pollutant levels are reached at the engine load of 50%. A further increase of engine load leads to increasing pollutant emissions [43].

Conventional diesel and HVO were used in the analysis of the size of particulate matter (PM) and their amount. When using HVO, smaller particulate matter (below 50 nm) was generated, and PM emissions were also lower [43,54]. Other studies revealed that particulate matter emissions decreased with increasing duration of the pre-injection interval; however, higher volumes of PM have been generated in application of pre-injection ratio compared with the single injection condition. Research of a different nature allowed stating that mixing n-butanol in diesel increased the duration of the ignition delay phase, leading to a better mixing of air and fuel blend during the ignition delay phase and lower PM emissions during combustion [32].

N-butanol had an impact on the combustion speed in diesel and bio-diesel blends, while the combustion temperature differed slightly. Having added N-butanol to the fuel resulted in a smaller diameter of soot particles [55]. N-butanol increased the duration of the ignition delay and slowed down the combustion phase, which was especially evident at low loads. The results achieved allow stating that with NO_x staying the same, n-butanol–diesel blends reduce particulate matter content and smoke, but heat efficiency also decreases compared with pure diesel [33]. More detailed studies show that during combustion, when the i-butanol ratio in diesel is below 17.5%, the combustion flame propagates back and forth, while with i-butanol ratio above 17.5%, the combustion flame propagates in a jumping-crawling motion [56].

When using HVO–n-butanol and i-butanol blends, no significant changes were observed in the heat release rate at low and high engine loads; thus, the obtained results of fuel blends can be compared based on the measurement uncertainty [39]. The results received when using blends of diesel and n-butanol revealed that brake thermal efficiency (BTE) decreased significantly at low engine loads, but an increase of about 7.08% was observed at high engine loads [57]. The comparison of diesel and HVO-brake-specific fuel consumption (BSFC) revealed that HVO fuel consumption decreased by 1% at low rotational speed, which is an insignificant result; meanwhile, BSFC increased when using a diesel with n-butanol and i-butanol blend [38]. A 10% i-butanol content (in the diesel–i-butanol blend) demonstrated an increase in BTE (brake thermal efficiency) and a decrease in BSFC (brake-specific fuel consumption), which is assumed to be due to decreased injection pressure [58]. Additionally, when using this fuel blend, exhaust gas temperature (EGT) was lower compared with that of conventional diesel [59].

In summary, biobutanol and HVO blends can be said to be very promising and can completely replace fossil diesel. In addition, such a fuel mix is 100% biological; thus, it is in line with EU policy objectives. However, a relatively small field of research on these fuels raises a number of questions about the analysis of its combustion process, as the conducted research has mostly focused on summarizing characteristics of fuel consumption and environmental properties. A comprehensive assessment of both energy-environmental and the combustion process analysis would allow for a better substantiation of the use of such fuels in compression ignition engines, without any additional modifications in the engine structure and with biobutanol concentration ranging from 0% to 20% in terms of volume in fuel blends with HVO.

2. Equipment, Methodology, and Fuel

Tests were conducted using the 1.9 TDI diesel engine (type 1Z) equipped with an electronic control unit BOSCH VP37. Test engine had a rotary fuel pump and a turbocharger. Selected technical data of the 1.9 TDI engine are shown in Figure 1.

Parameter	Value
• Power	• 66 kW (4000 rpm)
• Torque	• 182 Nm (2000-2500 rpm)
• Piston diameter, mm	• 79.5 mm
• Piston stroke, mm	• 95.5 mm
• Copression ratio	• 19.5
• Displacement	• 1896 cm^3
• Number of cylinders	• 4/OHC
• Fuel injection	• Direct (single)
• Nozzle type	• Hole-type
• Nozzle opening pressure	• 190 bar
• Nozzle and holder assembly	• Two spring
• Cooling system	• Liquid cooling

Figure 1. The main parameters of the test engine (1.9 TDI type: 1Z).

Figure 2 presents fundamental data of the measurement equipment used in this research.

Configuration of the test stand is shown in Figure 3. The engine crankshaft was coupled with the eddy current brake. Fuel consumption was measured with the fuel scale and emissions sampled with the AVL DiCom 4000 gas analyser and smoke opacity meter. Smoke measurement is performed by determining the extinction of a light beam by scattering and absorption.

Experimental tests were conducted at a constant crankshaft rotation speed of n = 2000 rpm. These revolutions were set closest to the most economical operating mode of a laboratory engine (1.9 TDI, type 1Z). During the tests, engine loads of 30 Nm, 60 Nm, 90 Nm, and 120 Nm were selected, simulating engine speeds of ~50 km/h, ~80 km/h, ~100 km/h, and ~110 km/h at the said loads.

Equipment	Accuracy of measurement	Purpose of use
• Load bench *KI-5543*	• 1.2 Nm	• brake torque
• Scale SK-500	• 1.0 g	• fuel consumption
• Air mass meter BOSCH HFM 5	• ≤2%	• air mass
• VAG-COM diagnostic equipment	• -	• Fuel injection timing, the start of injection (SOI)
• Piezo pressure sensor AVL GH13P	• ±0.11 (%FCO)	• In-cylinder pressure
• Encoder A58M- F	• 0.1758 crank angle degrees (CAD)	• Crankshaft position
• Oscilloscope AVL DiSTEST DPM 800	• -	• in-cylinder pressure and CAD transmit
• Delta OHM HD 2304.0, sensor TP704-2BAI	• ±0.0002 MPa	• intake air pressure
• K type thermo couple	• ±0.5%	• intake air and the exhaust gas temperature
• AVL DiCom 4000 gas analyser	• CO_2, 0.1% vol.; CO, 0.01% vol.; HC, 1 ppm; NOx, 1 ppm; smoke, 0.01 m^{-1}	• CO_2, CO, HC, NO_x, smoke absorption coefficient

Figure 2. Laboratory equipment.

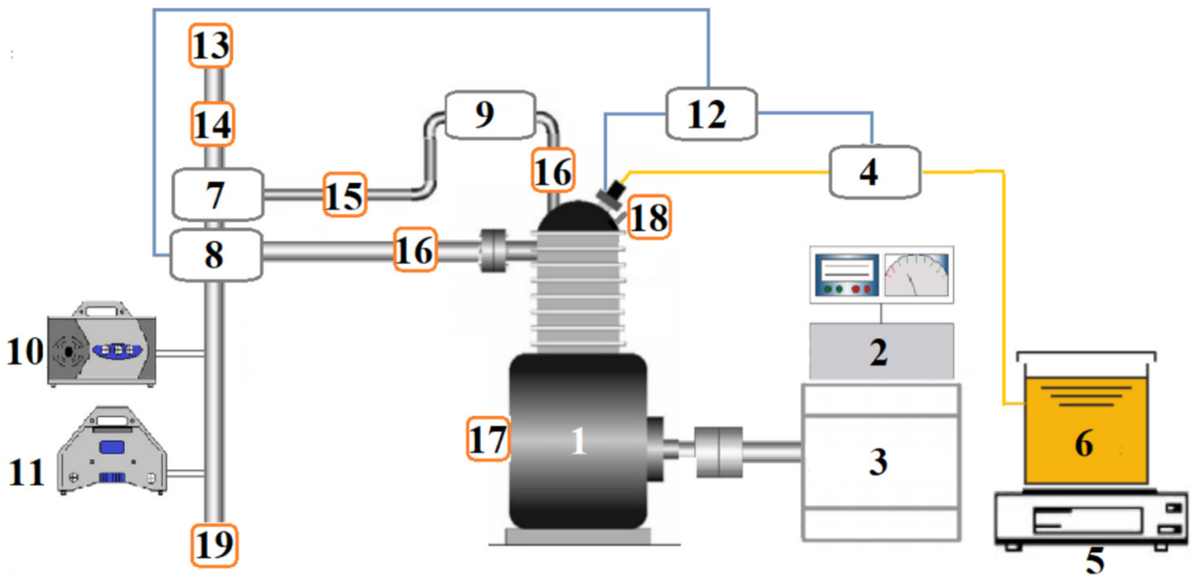


Figure 3. Engine test equipment. 1–engine, 2–measurement output gauges, 3–engine load unit, 4–high pressure pump, 5–scales, 6–fuel tank, 7–compressor, 8–turbocharger, 9–intercooler, 10–exhaust gas analyser, 11–smoke analyser, 12–electronic control unit, 13–air mass meter, 14–intake air temperature sensor, 15–pressure sensor, 16–temperature sensor, 17–crankshaft position sensor, 18–in-cylinder pressure sensor, 19–exhaust pipe.

Experimental tests were conducted with the engine running on conventional diesel fuel (labelled D100), hydrotreated vegetable oil (labelled HVO100), hydrotreated vegetable oil, and biobutanol blends of 95/5, 90/10 and 80/20 (% vol/% vol) (labelled HVOB5, HVOB10, and HVOB20). An amount of 5% of castor oil was added to fuel blends with biobutanol for better lubrication. Selected physicochemical properties of base fuels were tested and the results are listed in Table 1.

Table 1. Properties of 100% pure diesel, hydrotreated vegetable oil, biobutanol, and castor oil.

Parameter	Diesel	Hydrotreated Vegetable Oil	Biobutanol	Castor Oil
Density at 15 °C, kg/m^3	830.4	780.0	810.0	964.0
Carbon content, % m/m	86.20	84.55	65.00	73.60
Hydrogen content, % m/m	13.80	15.45	13.50	11.55
Oxygen content, % m/m	0	0	21.50	14.85
Stoichiometric AFR	14.79	15.18	11.30	11.91
Cetane number	51	70	18	28
Lower heating value, MJ/kg	43.1	44.1	33.0	41.3
Lower heating value, MJ/l	36.09	34.17	26.73	39.81
Purity, %	N/A	N/A	99.5	100
Manufacturer, country	Orlean Lietuva, Lithuania	Neste, Finland	Carl Roth GmbH, Germany	Biochemlit, Lithuania

In order to maintain the accuracy of the tests, the fuels used and their additives were kept at the same temperature to avoid differences in temperature and density that can be affected by temperature. Fuel blends (hydrotreated vegetable oil and biobutanol) were mixed on the day of the study just before use. They were stored at the same temperature and mixed to avoid delamination of components and to maintain homogeneity of the blend for different densities. The properties of fuel blends used during tests are presented in Table 2.

Table 2. Properties of fuel mixtures.

Properties	HVOB5	HVOB10	HVOB20
Density at 15 °C, kg/m^3	780.4	782.4	786.4
Carbon content, % m/m	83.55	82.55	80.57
Hydrogen content, % m/m	15.34	15.24	15.03
Oxygen content, % m/m	1.11	2.21	4.40
Stoichiometric AFR	14.98	14.77	14.38
Cetane number	67.3	64.6	59.3
Lower heating value, MJ/kg	43.54	42.98	41.87
Lower heating value, MJ/l	33.98	33.63	32.93

The numerical analysis of the combustion process was conducted using AVL FIRE software. The rate of heat release (ROHR) during combustion was calculated using cylinder pressures measured during tests, air and fuel consumption, properties of the fuel used, and engine parameters. The following combustion process indicators were set: start of combustion (SOC), in-cylinder temperature, in-cylinder temperature rise, and in-cylinder pressure rise. The said combustion process parameters helped to establish environmental and energy indicators using conventional diesel, hydrotreated vegetable oil, and hydrotreated vegetable oil and biobutanol blends.

3. Research Results and Discussion

Graphs illustrating changes in environmental and energy indicators are presented based on the results of the experimental research of CI engine running on conventional diesel D100, HVO100, and HVOB5, HVOB10, HVOB20 blends. The discussion of the said indicators and trends of their changes are presented based on the properties of the fuel used, the numerical analysis of the combustion process, and conclusions of other researchers.

3.1. Combustion Indicators

Experimental research was conducted at a constant engine crankshaft speed of n = 2000 rpm and three different engine loads (M_B = 30 Nm, M_B = 60 Nm, M_B = 90 Nm, and M_B = 120 Nm), which correspond to the brake mean effective pressure *BMEP* = 0.2 MPa, *BMEP* = 0.4 MPa, *BMEP* = 0.6 MPa, *BMEP* = 0.8 MPa.

Figure 4 illustrates the rate of heat release. According to the presented graph, under the same brake mean effective pressure of fuels and their blends, the start of combustion (SOC) varies: D100 ~0.7 CAD ATDC; HVO100 ~0.3 CAD BTDC; HVOB5, HVOB10, and HVOB20 ~0.1 CAD BTDC. The start of injection (SOI) in this mode of engine operation was set at ~4 CAD BTDC. The duration of the ignition delay phase of the said fuels also differed: D100 ~4.7 CAD ATDC; HVO100 ~3.7 CAD ATDC (which is 1 CAD less compared with D100); HVOB5, HVOB10, and HVOB20 ~3.9 CAD ATDC (which is 0.8 CAD less compared with D100). The analysis of combustion duration (CD) revealed that the longest combustion duration was with pure diesel: D100 ~50.7 CAD; HVO100 ~4.2 CAD less compared with D100; and CD decreased respectively when adding biobutanol: HVOB5- ~4.3 CAD less, HVOB10- ~3.9 CAD less, and HVOB20- ~5.2 CAD less. The maximum ROHR value was achieved in premixed combustion phase when using pure diesel at 5 CAD ATDC–35.0 J/CAD. When using hydrotreated vegetable oil (HVO), the maximum ROHR value was at 3 CAD ATDC–21.5 J/CAD (a decline of ~39%), while having added in HVO biobutanol at 5, 10, and 20%, the maximum ROHR decreased respectively in the premixed combustion phase at 4 CAD ATDC by ~28, ~21, and ~10% when comparing with pure diesel. When using pure diesel (D100), the maximum ROHR value in the controlled combustion phase was 32.4 J/CAD at 10 CAD ATDC. When using HVO, the maximum ROHR value in this phase was –34 J/CAD at 9 CAD ATDC (an increase of ~4.9%). Having added biobutanol to HVO, the value of ROHR in the controlled combustion phase was the following: HVOB5–an increase of ~5.9% at 9 CAD ATDC; HVOB10–an increase of ~6.8% at 10 CAD ATDC; HVOB20–an increase of ~5.4% at 9 CAD ATDC; and the said ROHR value was compared with pure diesel. A growth in the controlled combustion phase when increasing biobutanol concentration improved soot oxidation but had a negative impact on the energy efficiency of the engine [60]. ROHR significantly decreasing in the premixed combustion phase reduced the intensity of NO_x generation [61].

The maximum temperature rise value can be achieved with conventional diesel ~53° K/CAD, at 4 CAD ATDC) (Figure 5). When using HVO100, the maximum temperature rise decreased by ~22% at 8 CAD ATDC compared with conventional diesel. Additionally, HVOB5 dropped by ~24% 8 CAD ATDC, HVOB10 by ~19% at 4 CAD ATDC, and HVOB20 by ~4% at 4 CAD ATDC. With increasing biobutanol concentration in HVO, a difference in the temperature rise in the premix combustion phase was observed to decrease compared with conventional diesel and came close to the value of the reference fuel. These trends are in line with previously published works by the authors [12,62].

The assessment of the in-cylinder temperature graph (Figure 6) revealed that when increasing biobutanol concentration in HVO, the in-cylinder temperature in the controlled combustion phase also increased. The highest temperature of HVO100 was 1392 K, D100–1400 K, and HVOB20–1424 K. With increasing biobutanol concentration in HVO, the combustion process was also longer. This is why the temperature and the pressure of turbo-compressor increased during compression, emitting more energy along with exhaust gases, but resulting in better soot combustion.

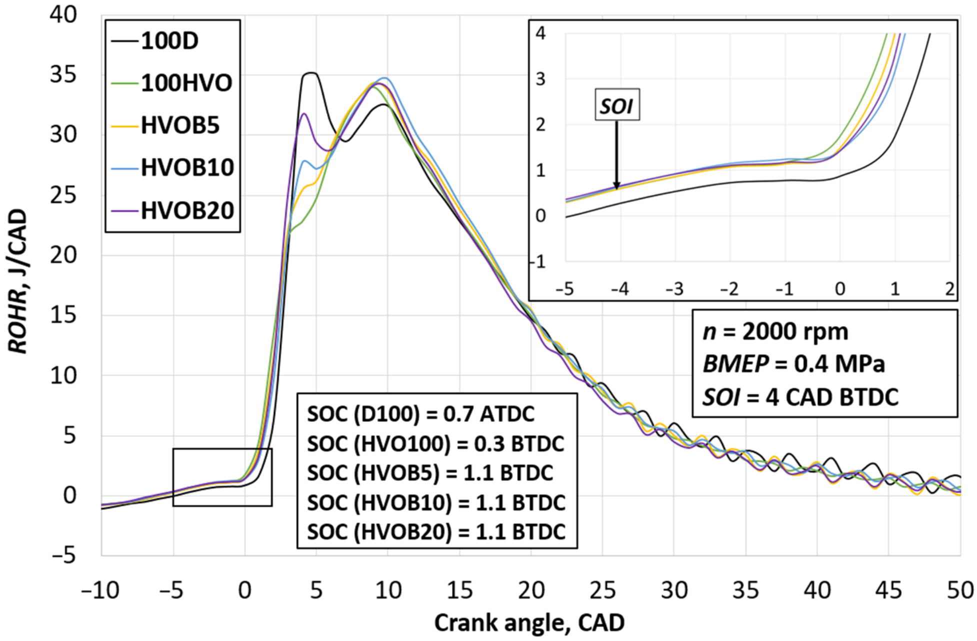


Figure 4. Rate of heat release in-cylinder depending on fuel composition.

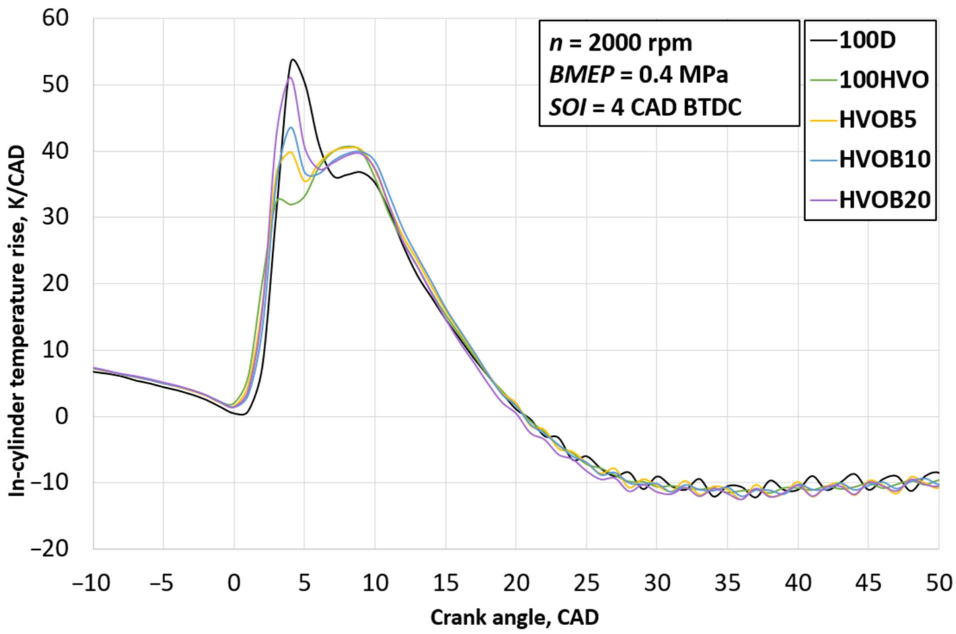


Figure 5. Temperature rise in-cylinder depending on fuel composition.

The highest in-cylinder pressure rise in the premix combustion phase was reached when using pure diesel: ~0.21 MPa/CAD, (Figure 7). The pressure rise of HVO100 in the premix combustion phase declined by ~48%, with HVOB5 decreasing by ~30%, HVOB10 by ~30%, and HVOB20 by ~11%. The greatest in-cylinder pressure rise was reached with D100, HVOB10, and HVOB20 fuel blends at 4 CAD ATDC, with HVO100 and HVOB5 fuel blend at 3 CAD ATDC. When increasing biobutanol concentration in HVO, the pressure rise also increased, but the result was not higher than that of conventional diesel.

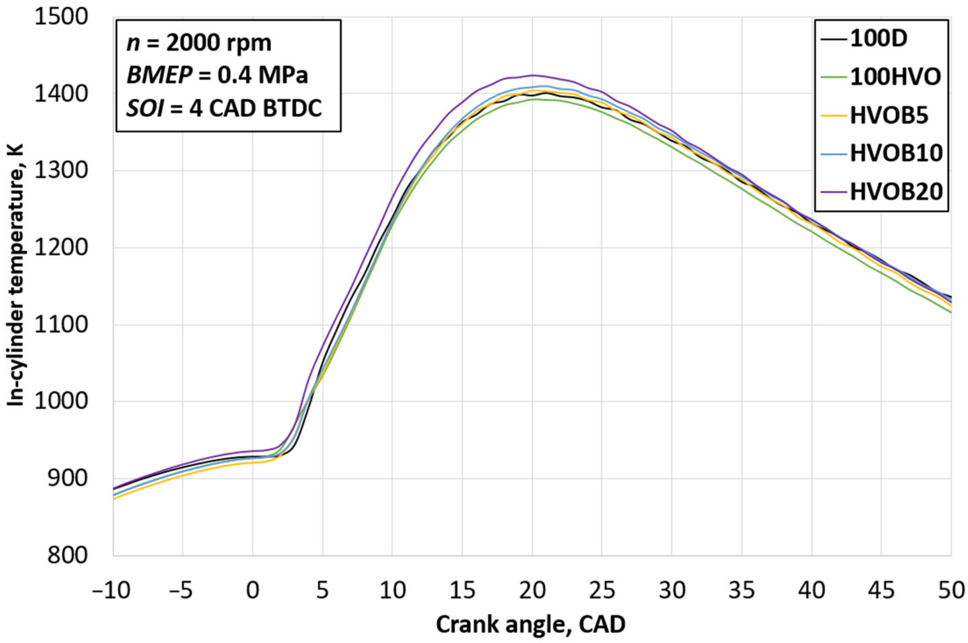


Figure 6. In-cylinder temperature depending on fuel composition.

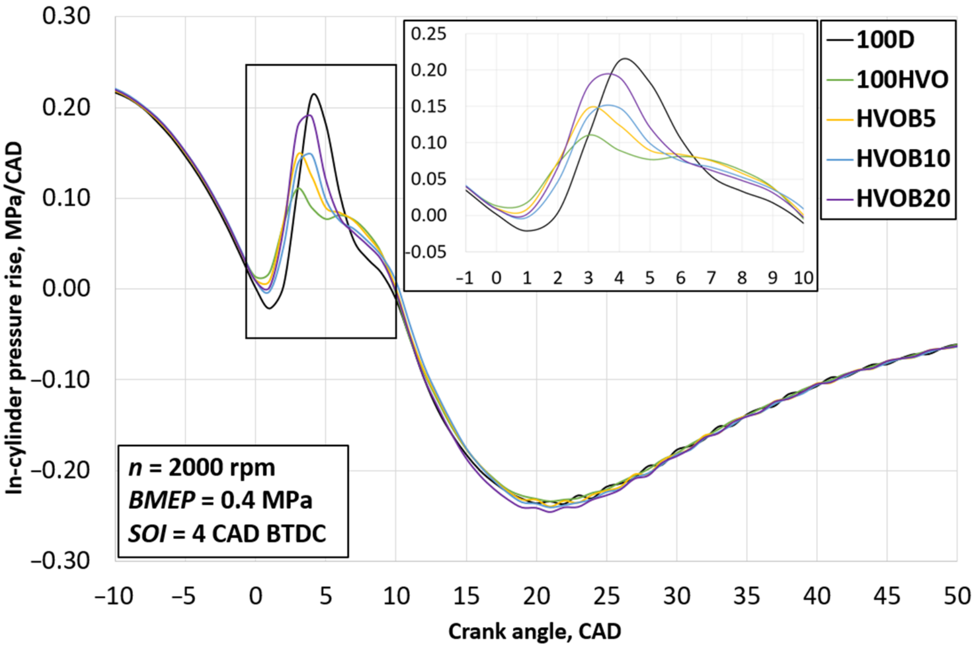


Figure 7. Pressure rise in-cylinder depending on fuel composition.

Figure 8 illustrates the in-cylinder pressure graph. When using conventional diesel (D100), the highest in-cylinder combustion pressure was ~7.68 MPa. When using HVO100, the maximum combustion pressure decreased to ~7.59 MPa. When increasing biobutanol concentration in HVO, the maximum combustion pressure of HVOB20 fuel blend increased to ~7.78 MPa (~1.3% more compared with conventional diesel). When using diesel, the highest combustion pressure was reached at ~9 CAD ATDC, and when using HVO and its blends with biobutanol it was 1 CAD later.

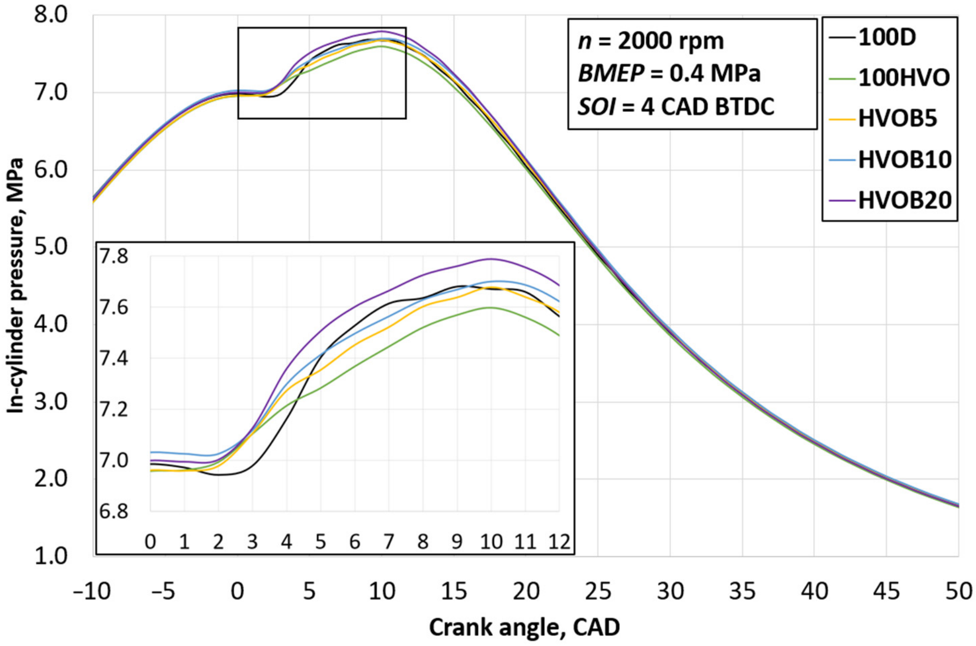
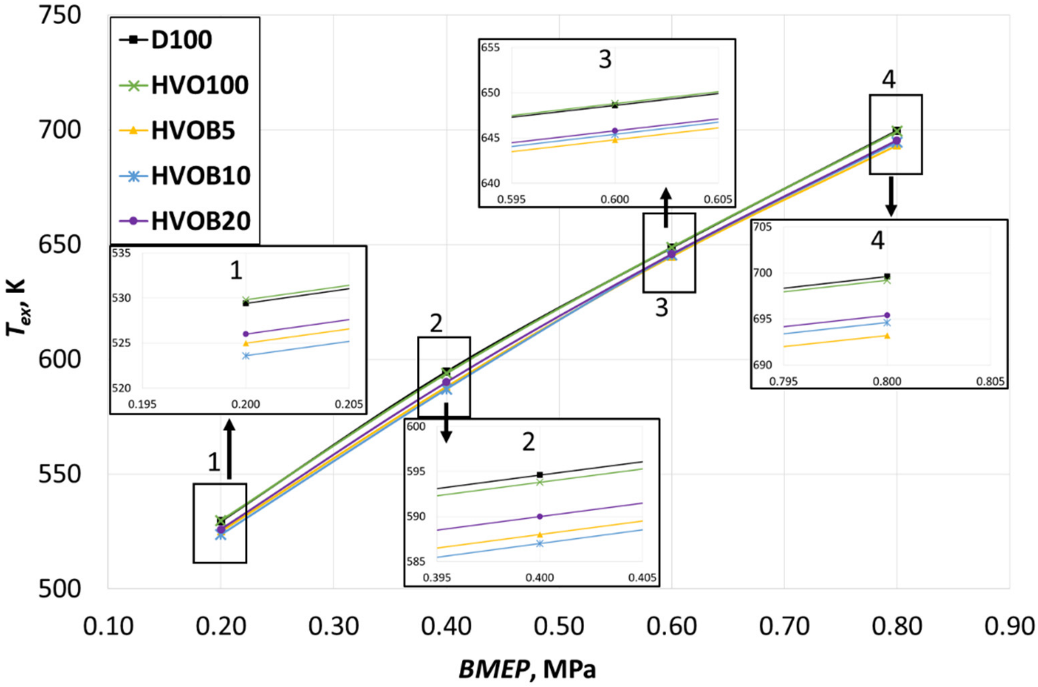


Figure 8. In-cylinder pressure depending on fuel composition.

Figure 9 presents the dependence of the temperature of emissions on the engine load measured in the experimental research. The temperature of emissions of D100 and HVO100 fuels was observed to be almost the same at changing engine loads (*BMEP* = 0.2 MPa; 0.4 MPa, 0.6 MPa, and 0.8 MPa). Increasing the biobutanol concentration in HVO from 5% to 20% decreased the temperature of exhaust emissions in the range of 0.5% to 1.5%. Exhaust temperature depends on LHV value—with decreasing LHV, exhaust temperature also decreases (to supply the same amount of fuel in the cylinders per cycle) [61]. Having added biobutanol to HVO in the research, the value of LHV decreased compared with HVO100 (Tables 1 and 2); however, more fuel was supplied (Figure 11) because the engine generated equal power. Having performed similar fuel tests, Yilmaz et al. concluded that blends of biodiesel and n-butanol rendered lower exhaust gas temperatures because of lower density of n-butanol and cetane number compared with diesel or biodiesel. Moreover, n-butanol mixed into fuel blends increases the oxygen content of the fuel, which improves and speeds up the combustion process, which lowers the exhaust gas temperature [63]. This is confirmed by ROHR (Figure 4), which shows that by increasing the concentration of biobutanol in the mixture, energy is released more intensively during the premixed combustion phase and that the amount of energy released decreases during the controlled combustion phase and later controlled combustion phase.

Figure 10 illustrates the dependence of the turbocharger pressure on engine load. Turbocharger pressure of D100 and HVO blends with biobutanol (HVOB5, HVOB10, and HVOB20) increased or decreased by no more than 0.5% at the designated engine loads. When using HVO fuel, this indicator increased and was about 1% higher in all engine modes compared with D100. The trend of a change in the turbocharger pressure was found to be similar to that of BTE of the engine (Figure 13), while values of brake thermal efficiency of HVOB5, HVOB10, and HVOB20 were determined to be similar to those of D100. The value of brake thermal efficiency of HVO100 was about 0.5% higher compared with conventional diesel. Energy efficiency of the engine running on HVOB5, HVOB10, and HVOB20 blends and the amount of energy emitted to the exhaust and cooling system was similar to that of D100.



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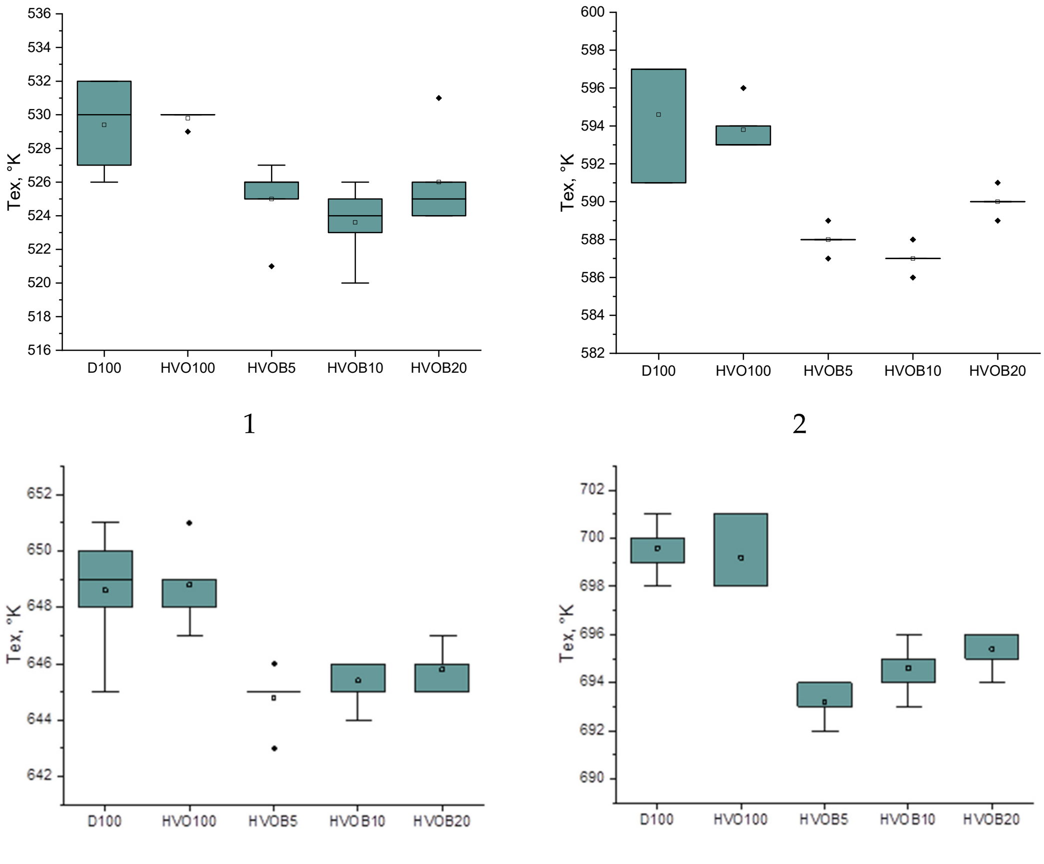

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(**b**)

Figure 9. Dependence of exhaust temperature on fuel composition and engine load: (**a**) summary of results; (**b**) accuracy and errors of measurements.

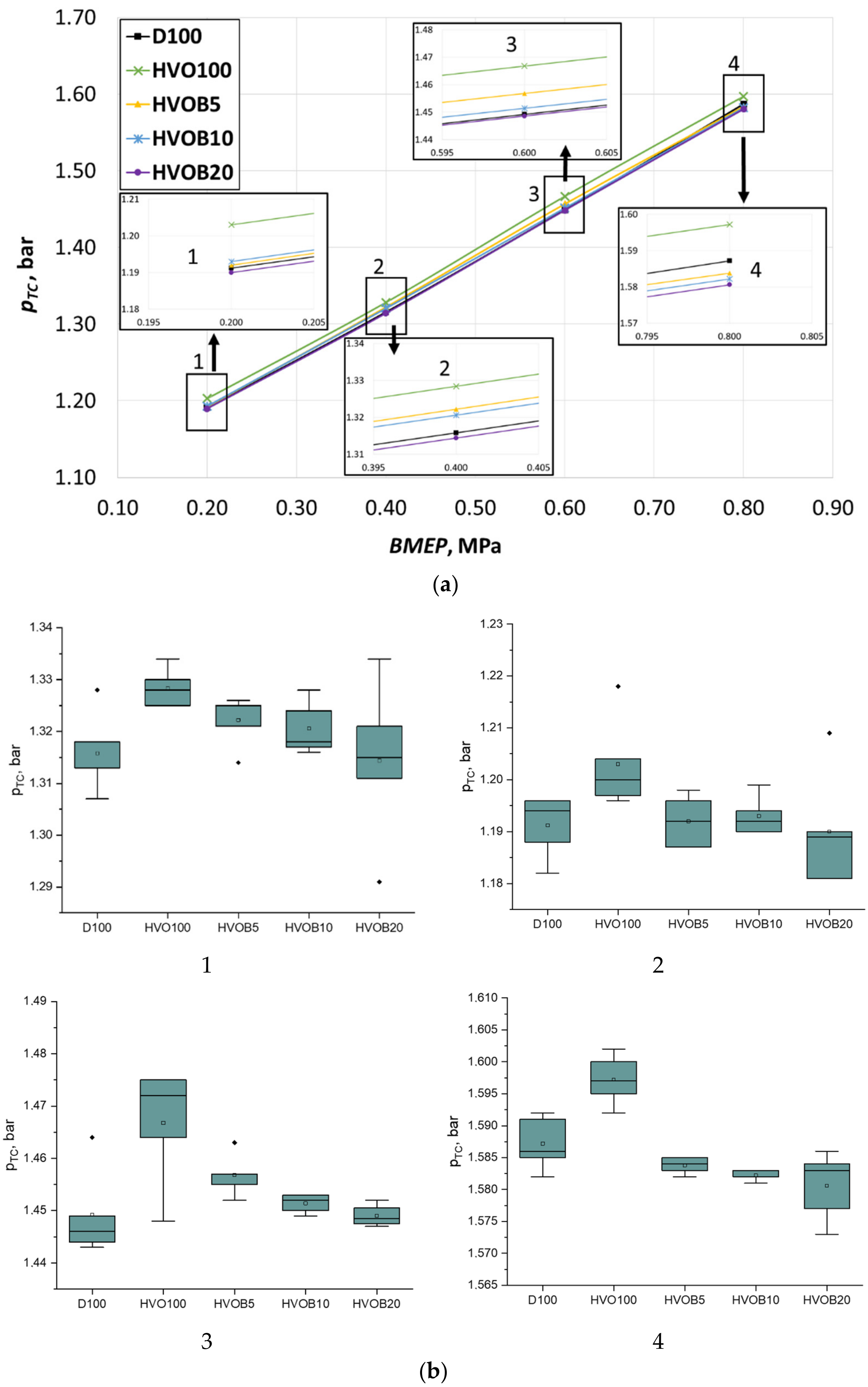


Figure 10. Dependence of turbocharger pressure on fuel composition and engine load: (**a**) summary of results; (**b**) accuracy and errors of measurements.

3.2. Energy Indicators

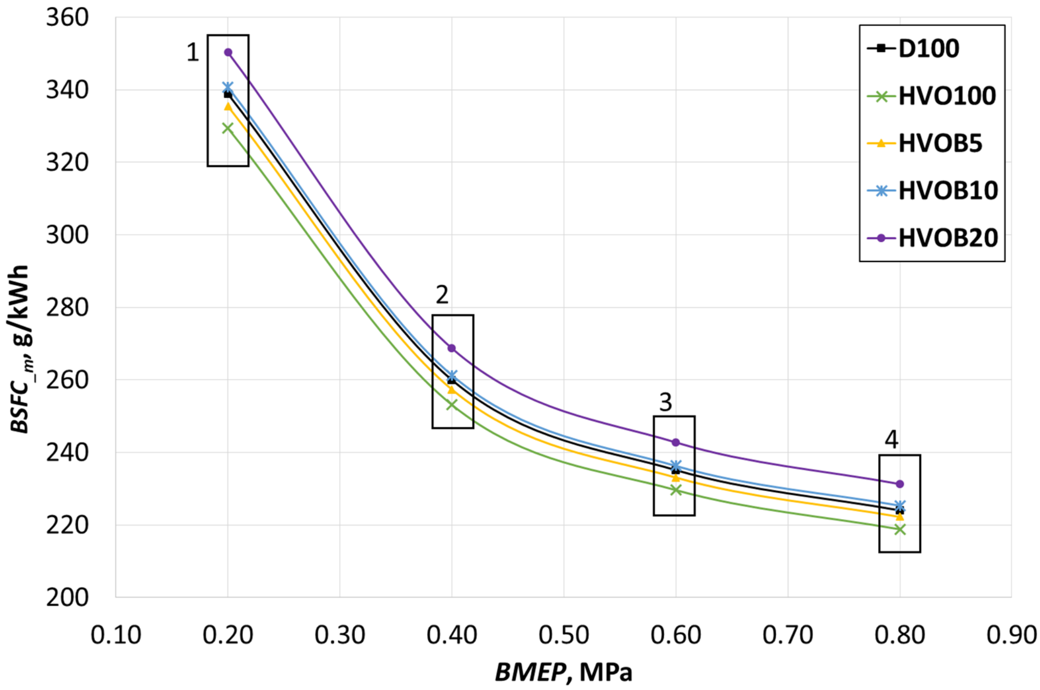
Figure 11 illustrates the dependence of brake specific fuel mass consumption on fuel composition ($BSFC_{\_m}$) and the engine load. The conducted research determined the brake specific fuel mass consumption (*BSFC* by mass) of the compression ignition engine and revealed that at different engine loads, comparative HVO100 consumption in terms of mass was about 2.3–2.8% lower compared with D100, while consumption of HVOB5 *BSFC* was lower by 0.8–1% compared with D100. The results of the fuel study (Tables 1 and 2) revealed that compared with conventional diesel, the density of HVO100 was 7.5% lower, but its lower heating value (LHV) was 2.3% higher than that of D100. The assessment of HVOB5 fuel density revealed that its density was 7.0% lower and that the lower heating value (*LHV*) was 1% higher compared with that of D100. Higher *LHV* resulted in lower values of *BSFC* by mass. However, it was also observed that when increasing the concentration of biobutanol in HVO (from 10% to 20%), *BSFC* by mass also started increasing: HVOB10 by 0.5–0.6% and HVOB20 by 3.2–3.4% compared with D100. According to the obtained fuel study results (Tables 1 and 2), HVOB10 density was 6.5% lower compared with conventional diesel, and lower heating value (*LHV*) was 0.3% lower than that of D100. The analysis of HVOB20 fuel blend revealed that its density was 6.0% lower, and that *LHV* was 2.8% lower compared with that of D100.

Huang et al. obtained similar research results when assessing *BSFC*, when *BSFC* by mass values increased in 70% conventional diesel and 30% n-butanol fuel blends. This can be explained by lower density of n-butanol and lower cetane number compared with diesel [64]. Xiao et al. conclude that in blends of biodiesel and n-butanol (adding up to 30% of n-butanol by mass), *BSFC* results are higher than those of conventional diesel because of a lower calorific value of biodiesel and n-butanol [65]. In the analysed case, the cetane number in biobutanol was 2.5 times lower than that of conventional diesel and 4 times lower than that of HVO (Table 1), while the cetane number of fuel mixtures HVOB10 and HVOB20 was lower than that of D100 (Table 2).

Dependence of brake specific fuel volume consumption ($BSFC_{\_V}$) and the engine load is presented in Figure 12. The results presented in this figure look absolutely different compared with Figure 11; however, the assessment of *LHV* in terms of volume (MJ/l), which are presented in Tables 1 and 2, revealed that these values (MJ/l) have tended to decrease: HVO100 about 5%, HVOB5 6%, HVOB10 7%, and HVOB20 9% lower compared with conventional diesel. Figure 12 illustrates this trend. Decreasing *LHV* value (MJ/l) in fuels or their blends leads to increasing brake specific fuel volume consumption. The greatest difference in $BSFC_{\_V}$ was observed using HVOB20, where an increase was consistent at different engine loads: 9% compared with D100.

Another analysed energy indicator parameter was brake thermal efficiency—*BTE* (Figure 13). The comparison of HVO100 and D100 fuels at different loads revealed an increase in BTE of 0.1–0.6%. With increasing biobutanol concentration in HVO (from 5% to 20%), BTE value starts decreasing compared with D100: HVOB5 0.1–0.2%, HVOB10 0.2–0.3%, and HVOB20 0.3–0.4%. A decrease in BTE with blends with HVO and biobutanol was minor (1% difference in *BTE* was not achieved compared with D100). The obtained research results allow concluding that biobutanol additive of up to 20% by volume in HVO does not have any material impact on energy efficiency of the combustion process.

A decrease in *LHV* of fuel blends can be explained by the fact that the addition of n-butanol allows reducing fuel viscosity, improving injection and providing more oxygen in the combustion cylinder to improve chemical energy of fuel by turning it into useful engine work [66]. Studies conducted by other researchers rendered different results. Pan et al. used blends of biodiesel and 2-butanol in a CI engine in their research and discovered that *BTE* decreased at low engine loads but increased by about 7.08% at high engine loads [57].



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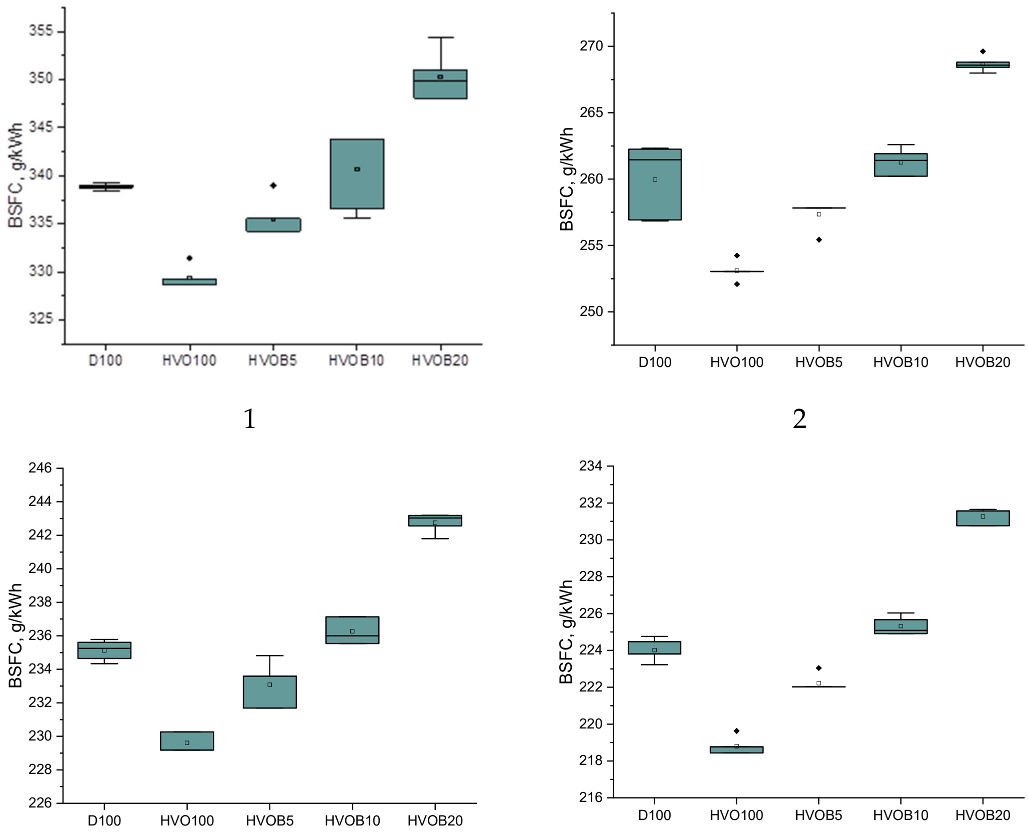

1 2

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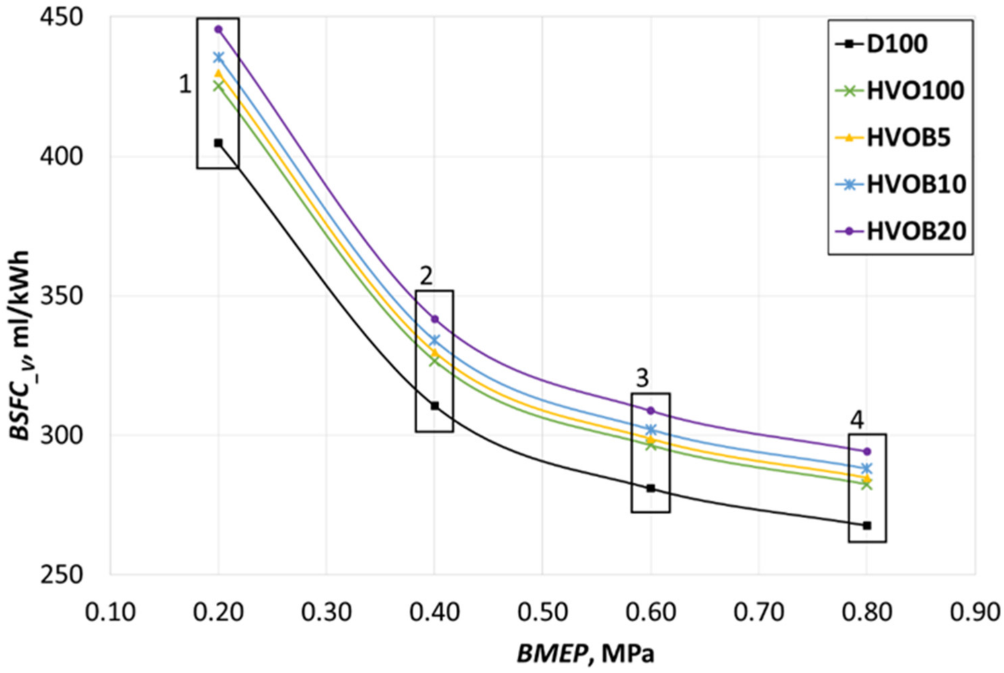
Figure 11. Dependence of BSFC by mass on fuel composition and the engine load: (**a**) summary of results; (**b**) accuracy and errors of measurements.



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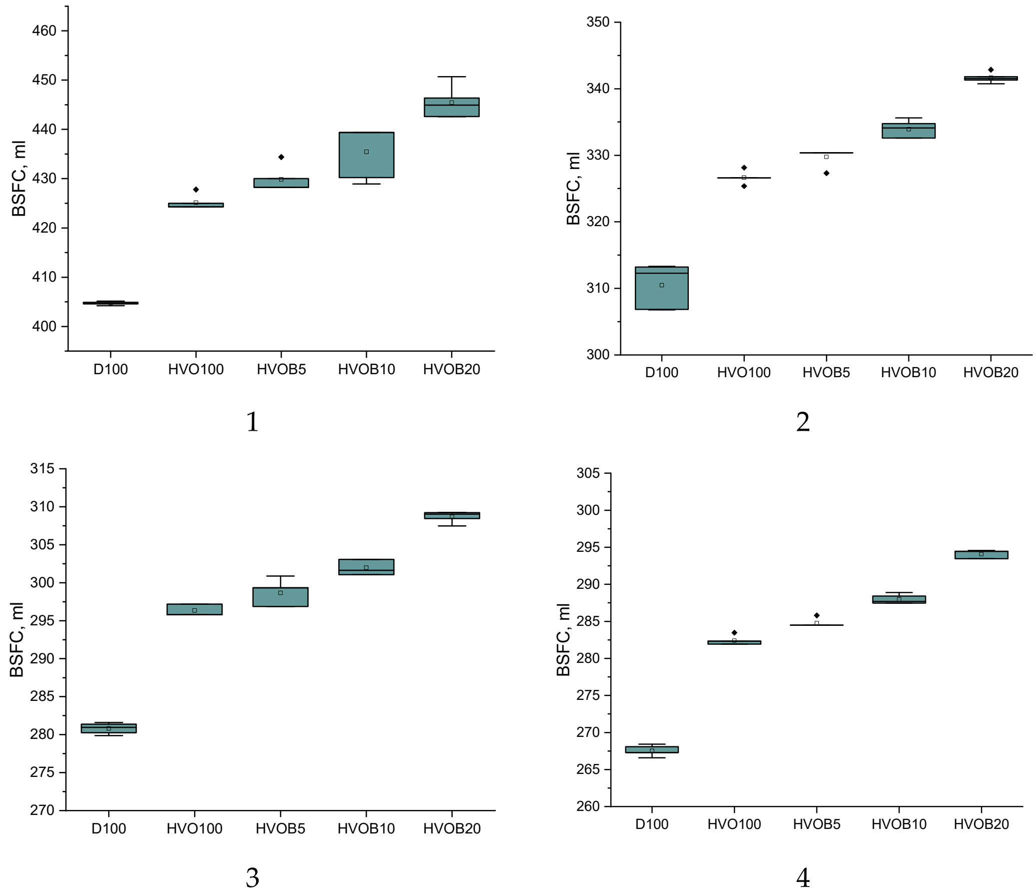

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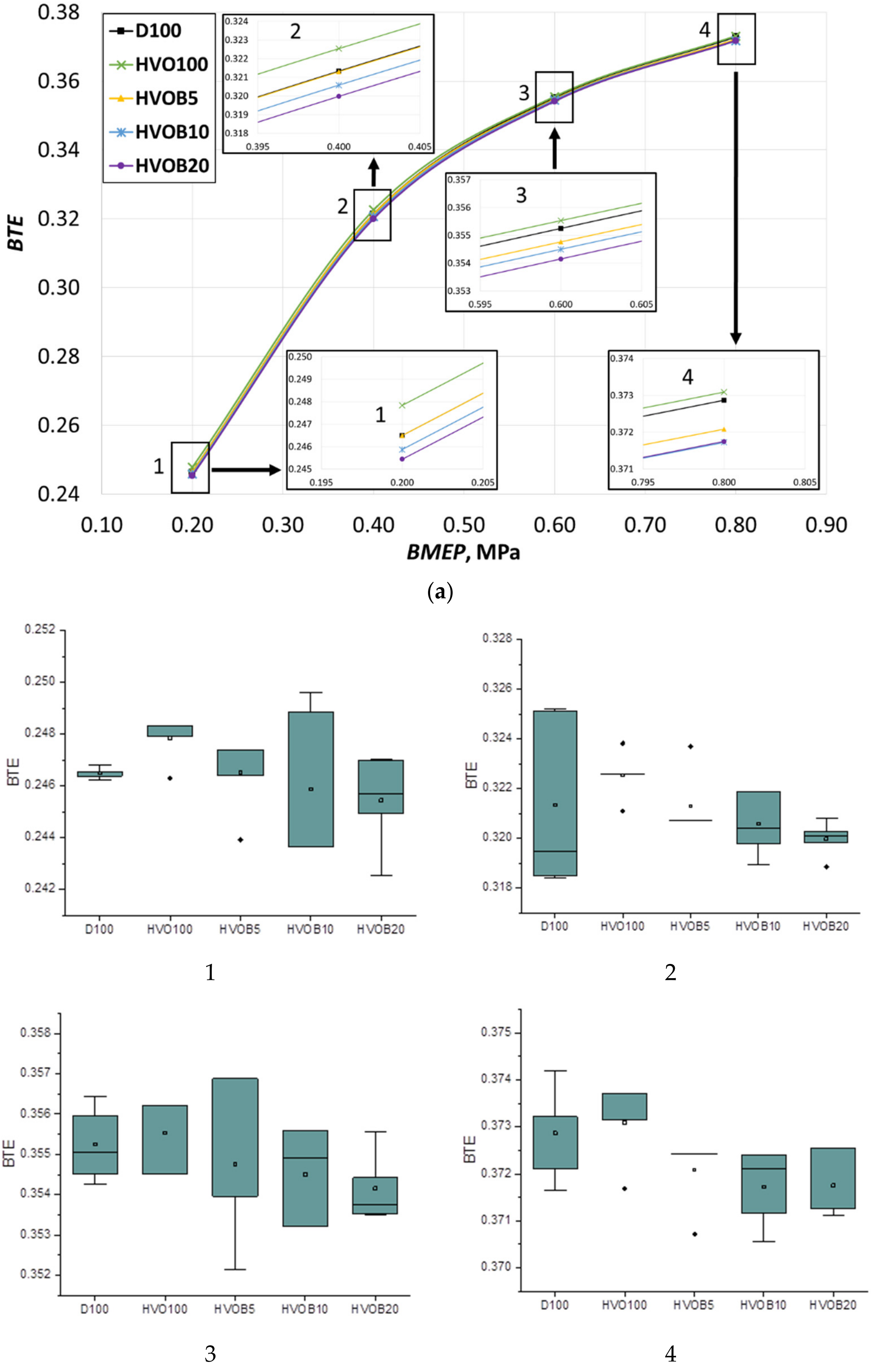
Figure 12. Dependence of BSFC by volume on fuel composition and the engine load: (**a**) summary of results; (**b**) accuracy and errors of measurements.



(**a**)

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Figure 13. Dependence of brake thermal efficiency on fuel composition and the engine load: (**a**) summary of results; (**b**) accuracy and errors of measurements.

3.3. Environmental Indicators

One of the key environmental indicators found during the research was carbon dioxide (CO_2) content in the exhaust gas. Carbon dioxide is an environmental parameter emitted in complete combustion process when oxygen for a complete combustion process is enough. CO_2 content can also increase with increasing content of carbon in fuel molecules [67]. The substitution of conventional diesel by HVO100 reduces CO_2 emissions by 3.5–6.7% (Figure 14). The use of HVO and biobutanol fuel blends (with biobutanol concentration of 5–20%) did not result in any material changes in CO_2 emissions; CO_2 values of fuel blends were close to HVO100: 3.3–6.8%. The assessment of the obtained CO_2 research results allows stating that biobutanol additive of up to 20% by volume in HVO does not have any significant impact on CO_2 emissions.

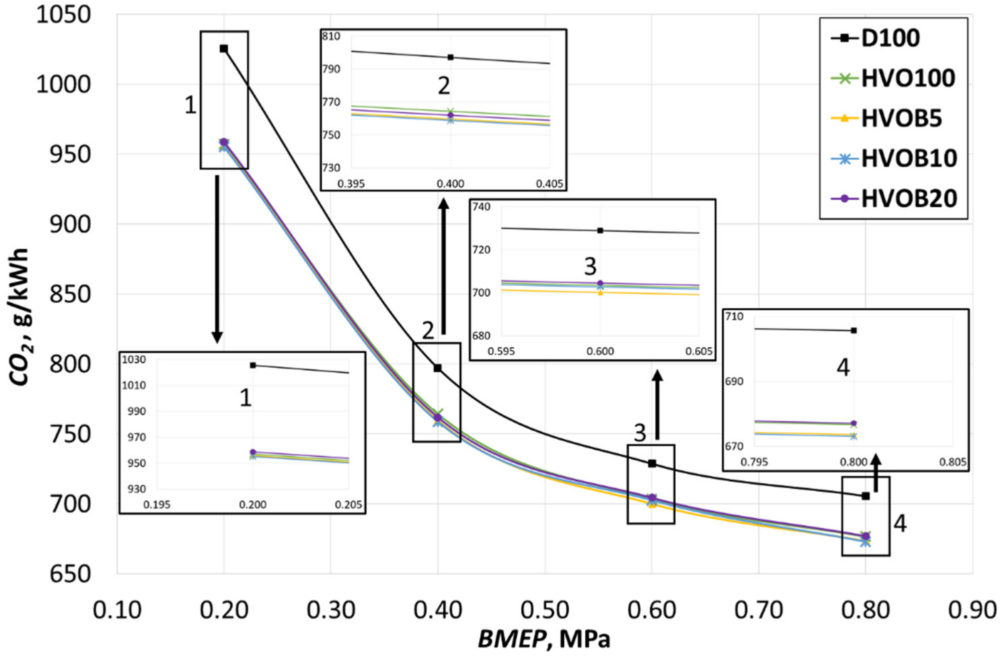
Bandbafha et al. explained a reduction in carbon dioxide compared with conventional diesel. They say that biodiesel has a lower elemental carbon to hydrogen ratio (C/H) than conventional diesel, so CO_2 emissions from air combustion will be lower than those of diesel [61].

Figure 15 presents the results of the study of carbon monoxide (CO). The obtained results revealed a significant difference in CO at BMEP of 0.2–0.6 MPa when comparing HVO100, HVO, and biobutanol fuel blends with D100. Having increased the engine load (BMEP 0.8 MPa), CO values became the same. The HVO100 CO value at BMEP 0.2 MPa was 50% lower, and at BMEP 0.6 MPa it was 6% lower compared with D100. An increase of biobutanol concentration in HVO (from 5% to 20%) led to a decrease in CO value at BMEP 0.2 MPa: HVOB5 was 51%, and HVOB20 was 51%, compared with D100. Having increased engine load to BMEP 0.4 MPa, CO values of HVO100, HVOB5, HVOB10, and HVOB20 became the same. With the engine running at BMEP 0.8 MPa, CO values of all fuels used and their blends were the same. CO emissions are affected by different engine operating conditions. The engine load has been proven to have a significant effect on CO emissions. Higher load values are associated with reduced CO emissions [68]. The cylinder temperature was also experimentally proven to increase when moving from low to high loads, which allows for a better combustion and thus reduces CO emissions [69].

Studies of physicochemical properties of fuels (Table 1) revealed the ratio of masses of carbon and hydrogen C/H was 6.25, fuel HVO100 was 5.47 (12.5% lower), and HVOB20 was 5.36 (14.2% lower). CO reduction in the use of pure HVO and blends of HVO with biobutanol can be explained by a lower C/H ratio. Researchers Bandbafha et al. concluded that CO emissions decreased using biodiesel due to a lower carbon-to-hydrogen ratio compared with diesel. CO can also decrease due to a higher oxygen content in the fuel mixture [26].

The composition of fuel and fuel blends (Tables 1 and 2) allowed determining that stoichiometric air–fuel ratio (AFR) for D100 was 14.79 kg, HVO100 was 15.18 kg (2.6% more), and HVOB20 was 14.38 kg (2.8% less). Having added biobutanol and castor oil in HVO, air-to-fuel ratio decreased. The said reduction of AFR was due to oxygen (O_2) content in biobutanol and castor oil (O_2).

The use of HVO100 and blends of HVO and biobutanol led to a gradual decrease in smoke (Figure 16). The obtained research results revealed that HVO100 smoke value was 22–33% lower compared with D100, while smoke values of HVO and biobutanol blends had a tendency to decrease: HVOB5 from 39% to 45%, HVOB10 from 45% to 55%, and HVOB20 from 50% to 64%, compared with conventional diesel. Researchers Imdadulas and others used n-butanol and biodiesel mixtures at different proportions and observed a decrease in smoke compared with conventional diesel [35]. Additionally, researchers Imtenan et al. confirmed that oxygen contained in alcohols, such as n-butanol, used in combination with biodiesel reduces smoke emissions [69].



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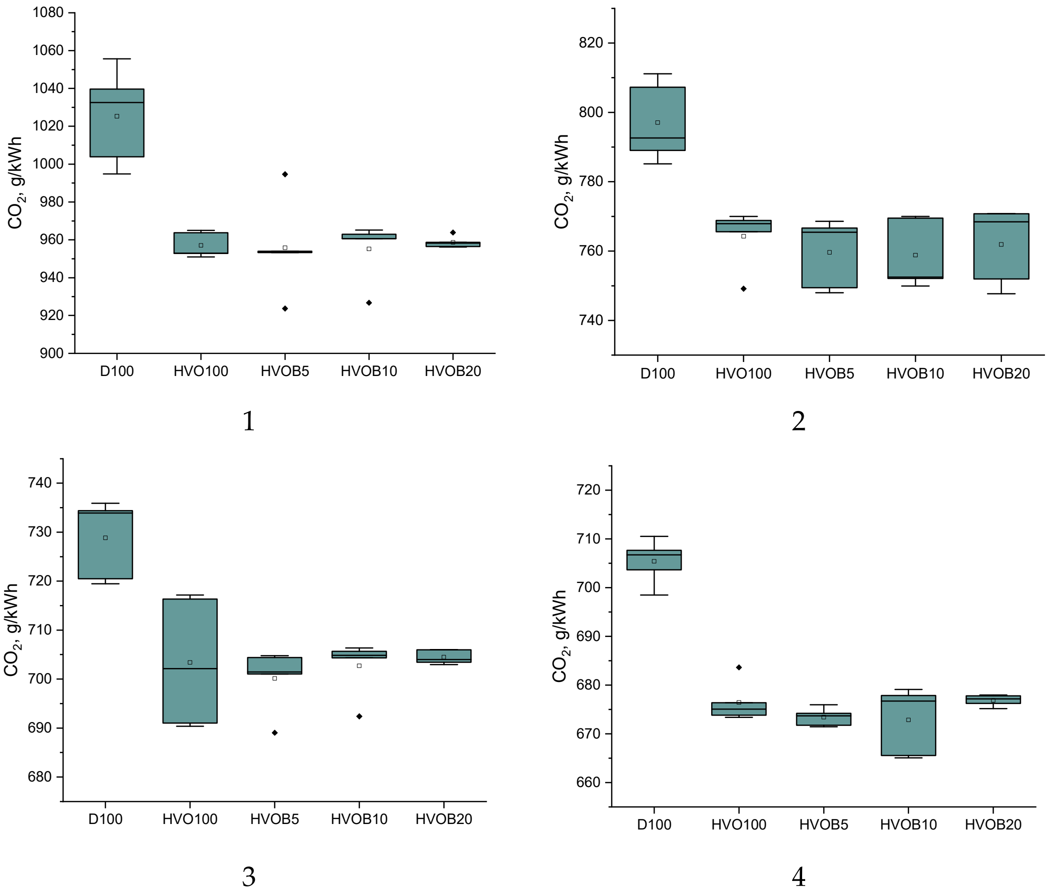

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Figure 14. Dependence of CO_2 emissions on fuel composition and engine load: (**a**) summary of results; (**b**) accuracy and errors of measurements.

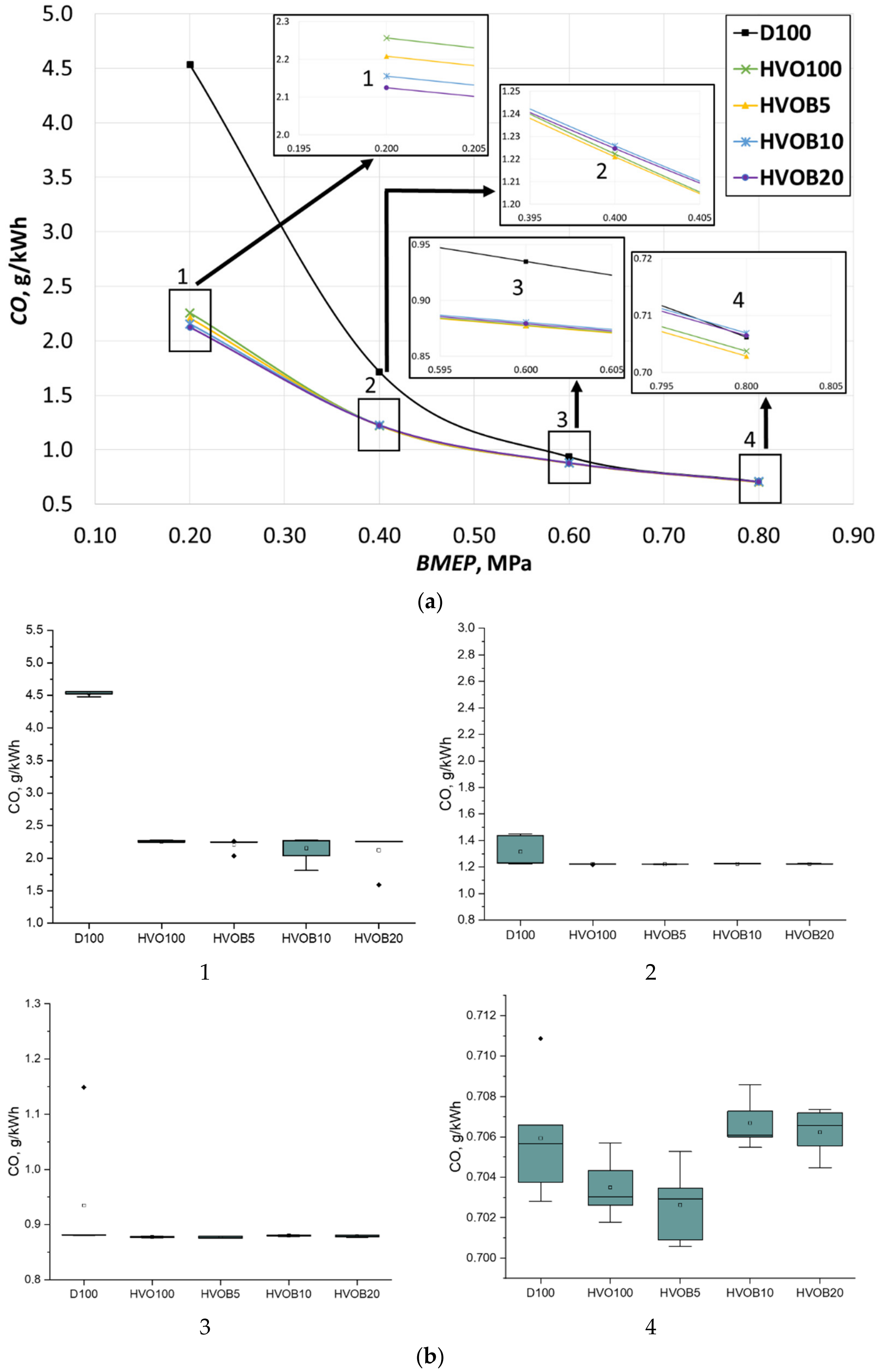
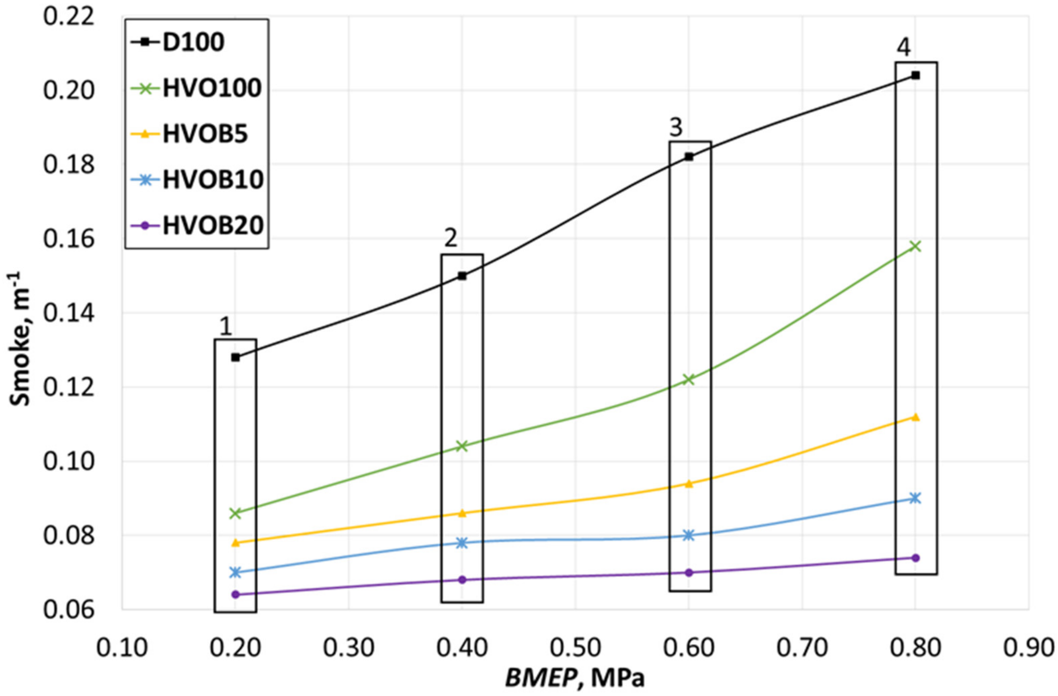


Figure 15. Dependence of CO emissions on fuel composition and engine load: (**a**) summary of results; (**b**) accuracy and errors of measurements.



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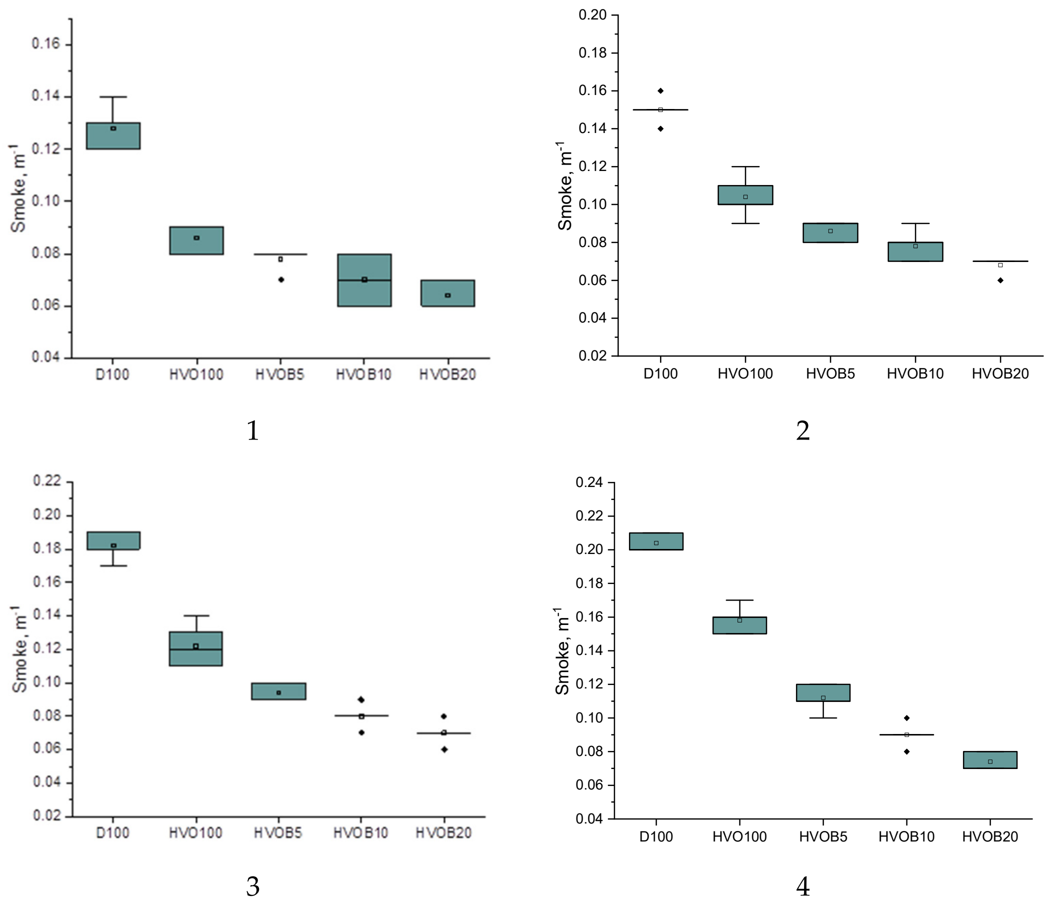

(**b**)

Figure 16. Dependence of smoke on fuel composition and the engine load: (**a**) summary of results; (**b**) accuracy and errors of measurements.

In a compression ignition engine, the air intake system operates with excess air, resulting in unburnt hydrocarbons (HC) and thus low emission concentrations [70]. Figure 17 shows the results of studies of unburnt hydrocarbon (HC) at different engine loads. The obtained results revealed that the concentration of HVO100 is 36–43% lower depending on the engine load compared with conventional diesel. However, having added biobutanol to HVO, HC concentration increased steadily depending on biobutanol concentration. With biobutanol concentration of 5% (HVOB5) it was 28–34%, while adding biobutanol 10% (HVOB10) HC concentration it was 6–8% lower compared with D100. However, increasing the concentration of biobutanol in HVO fuel to 20% resulted in a higher concentration of unburned hydrocarbons than in conventional diesel: 12–39%.

Hosseinzadeh et al. explained the increase in HC concentration having added biobutanol. Studies revealed that adding alcohol in biodiesel resulted in lower HC emissions. HC emissions also decreased mixing in biodiesel 15% and 20% of n-butanol compared with biodiesel without alcohols. This was due to increased oxygen content in the fuel. On the other hand, the addition of alcohols resulted in an increase in the diameter of fuel droplets, which in turn led to an increase in the ignition delay, which can increase HC formation during combustion. The use of alcohols as additives in biodiesel needs to be assessed comprehensively [26].

HC emissions can also be associated with a lower fuel viscosity. Farayedhi et al. say that lower viscosity fuels create smaller droplets in the injection process. These smaller fuel droplets reach the cylinder walls due to a weaker mixing of fuel and air mixture near the walls, which causes a quenching effect, thus increasing the emission of unburned fuel (HC) [71].

Combustion temperature and oxygen unused during combustion have the greatest impact on the formation of nitrogen oxides (NO_X). In experimental studies, NO_X emissions were the highest in D100 and the lowest in HVO100 (Figure 18). Increasing biobutanol concentration in HVO fuel leads to a steady decrease in NO_X emissions at all engine load modes compared with D100. The comparison of NO_X emissions of HVO100 and D100 revealed that having substituted the fuel with HVO100, NO_X emissions decreased by 17–20% (Figure 18). The decrease in NO_X emissions can be explained by lower ROHR intensity (Figure 4) and a smaller temperature rise (Figure 5). Vojtisek et al., having conducted similar studies, also state that NO_X emissions were similar when comparing HVO with n-butanol and i-butanol blends with pure HVO, but in both cases they were lower than that of pure diesel [39].

Mixtures of HVO and biobutanol used in the study contain oxygen (Table 2). When increasing the volume of biobutanol, oxygen concentration increases as well. The comparison of NO_X emissions in HVO and biobutanol blends with D100 revealed that NO_x emissions increased when increasing the biobutanol volume from 5% to 20% in HVO fuels. In HVOB5, NO_X emissions decreased by 16–18% compared with D100, in HVOB10 by 14–17%, and in HVOB20 by 13–14%. Addition of oxygen to the fuel also demonstrated conflicting results. Having conducted research with biodiesel and n-butanol (with n-butanol accounting for 30% in the volume of biodiesel), Prabu et al. state that NO_X emissions decreased compared with diesels without alcohols. This phenomenon can be justified by a decrease in the combustion temperature [72]. However, results of research conducted by Imdadulas et al. [35] revealed that using oxygen additives, such as n-butanol in biodiesel, rendered an opposite effect, with no reduction in NO_X emissions. These conclusions were justified by the fact that alcohols used as an additive in biodiesel reduced the cetane number.

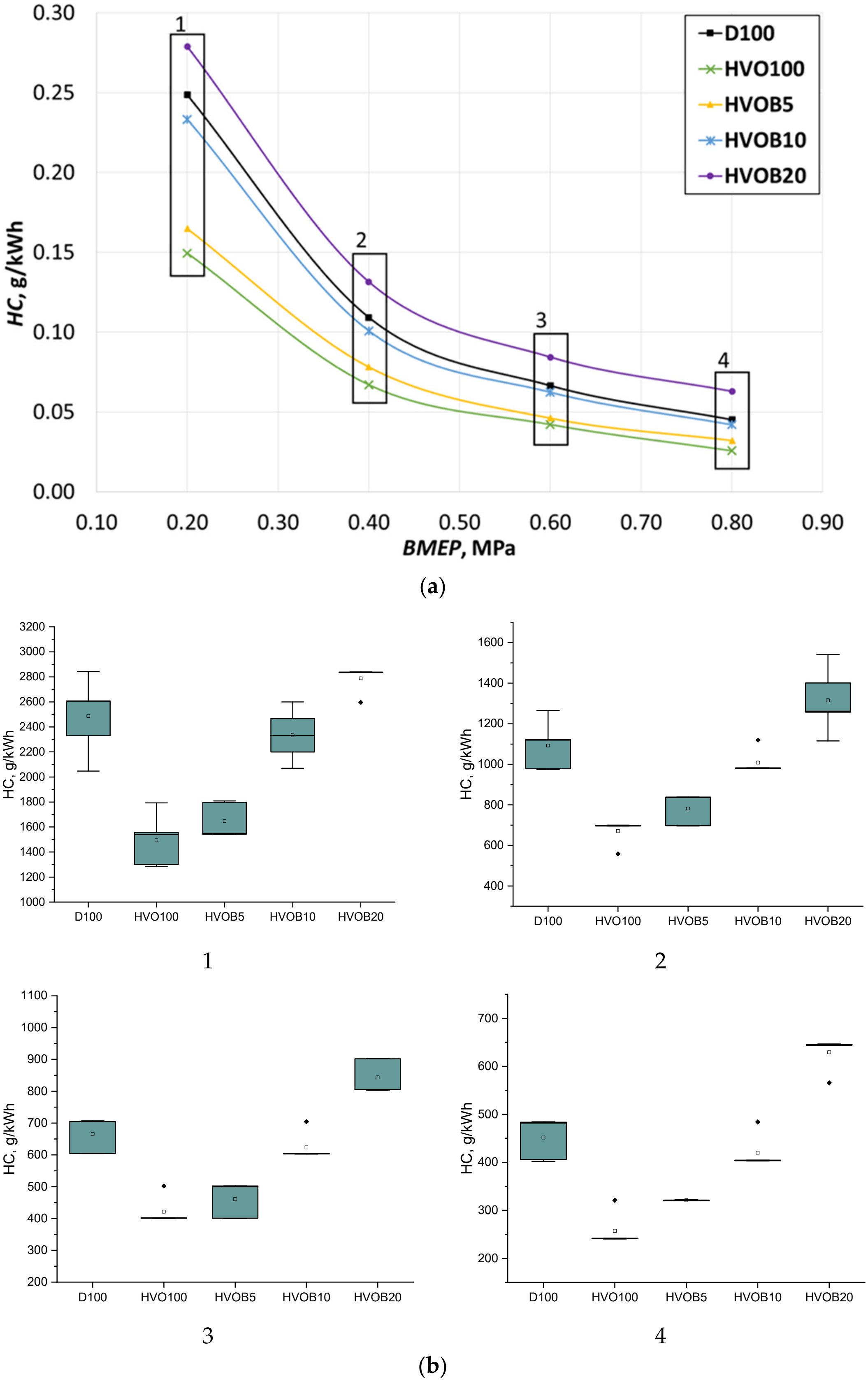

Figure 17. Dependence of HC emission on fuel composition and the engine load: (**a**) summary of results; (**b**) accuracy and errors of measurements.

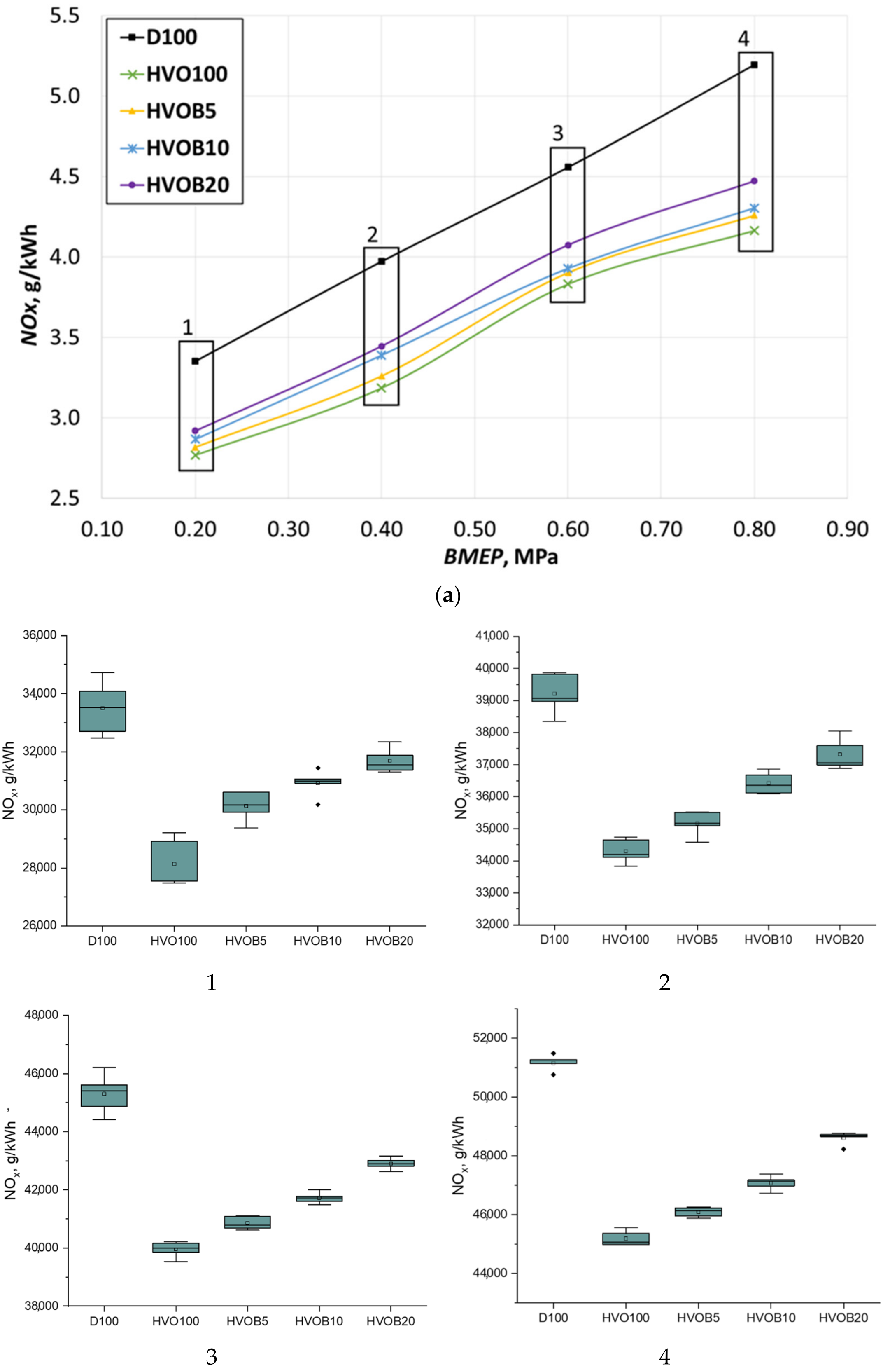

Figure 18. Dependence of NO_X emission on fuel composition and the engine load: (**a**) summary of results; (**b**) accuracy and errors of measurements.

4. Conclusions

Experimental studies and numerical analysis of the combustion process of pure conventional diesel (D100), hydrotreated vegetable oil (HVO100), and hydrotreated vegetable oil and biobutanol mixtures (HVOB5, HVOB10, and HVOB20) with different engine loads have resulted in the following conclusions:

1. Comparing fuels HVOB5, HVOB10, and HVOB20 with D100, LHV (MJ/l) values decrease by ~5.85%, 6.81%, and 8.75%, respectively. When using hydrotreated vegetable oil and biobutanol mixtures, due to the oxygen in the biobutanol, the other stoichiometric AFR parameter was: HVOB5 ~1.28% higher compared with D100 (HVO100 stoichiometric AFR parameter was ~2.64% higher compared with D100, so in this case HVOB5 fuel mixture is stoichiometric and AFR is ~1.32% higher compared with HVO100), and HVOB10 and HVOB20 are lower (0.14% and 2.77%) compared with D100.), and HVOB10 ~0.14% and HVOB20 ~2.77% lower compared with D100.
2. The ignition delay phase duration of the mentioned fuels and their mixtures at the brake mean effective pressure value of 0.4 MPa was different: D100 ~4.7 CAD ATDC, HVO100 ~3.7 CAD ATDC (which is 1 CAD less compared with D100), HVOB5, HVOB10, and HVOB20 ~3.9 CAD ATDC (which is 0.8 CAD less compared with the D100). Comparing the maximum ROHR at premixed combustion phase, value D100 at 5 CAD ATDC-35.0 J/CAD with hydrotreated vegetable oil (HVO), the maximum ROHR value at 3 CAD ATDC was 21.5 J/CAD lower (reduction ~39%). The maximum ROHR at 4 CAD ATDC value was reduced by adding 5%, 10%, and 20% of HVO addative in the premixed combustion phase respectively, compared with pure diesel by ~28%, ~21%, and ~10%. Comparing the maximum ROHR value at controlled combustion phase using D100 32.4 J/CAD at 10 CAD ATDC with HVO-34 J/CAD at 9 CAD ATDC was an increase in HVOB5 ~5.9% at 9 CAD ATDC, an increase in increase ~4.9%). The HVOB10 at 10 CAD ATDC and HVOB20 increases of ~6.8% and ~5.4% compared with D100 at 9 CAD ATDC. Comparing the maximum ROHR at controlled combustion value phase using D100 32.4 J/CAD at 10 CAD ATDC with HVO-34 J/CAD at 9 CAD ATDC was increased ~4.9%. The ROHR value of controlled combustion phase when biobutanol was added to HVO was an increases using the fuel mixtures HVOB5 ~5.9% at 9 CAD ATDC, HVOB10 ~6.8% at 10 CAD ATDC and HVOB20 ~5.4% at 9 CAD ATDC compared with D100.
3. As the concentration of biobutanol in HVO fuel increases, the temperature rise in premix combustion phase difference decreases and approaches the value of D100 fuel. The maximum temperature rise value was reached with D100 ~53° K/CAD, at 4 CAD ATDC). Using HVO100, the maximum fuel temperature rise is reduced by ~22% at 8 CAD ATDC compared with conventional diesel. Decreases respectively: HVOB5 ~24% 8 CAD ATDC, HVOB10 ~19% 4 CAD ATDC, and HVOB20 ~4% at 4 CAD ATDC. The same trend of the results was obtained according to the in-cylinder pressure rise indicator. As the concentration of biobutanol in HVO fuel increases, the pressure rise increases, but the value does not reach higher than D100: the maximum in-cylinder pressure rise during the premix combustion phase was achieved using pure diesel ~0.21 MPa/CAD. HVO100 fuel premix combustion phase pressure rise is reduced by ~48%. HVOB5 ~30%, HVOB10 ~30%, HVOB20 ~11%.
4. Regarding brake specific fuel mass consumption on fuel composition (BSFC_m) and the engine load, at different engine loads, the HVO100′s relative fuel mass consumption by mass is less than 2.3–2.8% compared with D100, and the value of the fuel mixture HVOB5 BSFC by mass is less than 0.8–1% compared with D100. However, the density of HVO100 is 7.5% lower compared with conventional diesel, but the lower heating value (LHV) is 2.3% higher than that of D100, and when evaluating the HVOB5 fuel mixture, the density is 7.0% lower, and the lower heating value (LHV) is 1% higher compared with the D100. The higher LHV value results in lower BSFC by mass values. Additionally, with increasing biobutanol concentration in HVO fuel (from 10% to 20%), BSFC by mass starts to increase: HVOB10 by 0.5–0.6% and

HVOB20 by 3.2–3.4% increase compared with D100. The density of HVOB10 is 6.5% lower compared with conventional diesel, and the lower heating value (LHV) is 0.3% lower than D100; the density of HVOB20 fuel mixture is 6.0% lower, and the LHV value is 2.8% lower compared with D100. Estimation of brake specific consumption by volume gave different results, but there is a dependence on LHV by volume (MJ/l). As the value of LHV by volume (MJ/l) decreased in fuels and their mixtures, the brake specific fuel volume consumption increased: HVO100 about 5%, HVOB5 6%, HVOB10 7%, HVOB20 9% less compared with D100.

5. Based on the results of the research, it can be stated that biobutanol, as an additive up to 20% by volume, in HVO fuels does not significantly affect the energy efficiency of the combustion process. The increase in BTE was 0.1–0.6% at different loads comparing HVO100 and D100. As the concentration of biobutanol in HVO fuel increases (from 5% to 20%), the BTE values decrease compared with D100: HVOB5 by 0.1–0.2%, HVOB10 by 0.2–0.3%, and HVOB20 by 0.3–0.4%. The reduction in BTE with HVO and biobutanol fuel blends is small (no 1% BTE difference compared with D100 is achieved).
6. In terms of ecological parameters, biobutanol as an additive up to 20% by volume in HVO fuels does not have a significant effect on CO_2 emissions. Replacing HVO100 with D100 reduced CO_2 emissions by 3.5–6.7%. Using mixtures of HVO and biobutanol fuels (5% to 20% biobutanol concentration), CO_2 concentration does not decrease, although the C/H ratio decreases because the BTE effect was not positive. Due to its oxygen, biobutanol reduces CO emissions at low loads and lower combustion temperatures. However, throughout the load range, HC concentrations increase due to the change in fuel droplets due to biobutanol.
7. Replacing diesel D100 with H100 fuel reduces the smoke at various loads by 22–33%; increasing the biobutanol concentration reduces the smoke by 50–64%. The main influence is the decreasing C/H ratio and the increasing oxygen concentration in the fuel. Compared with D100, H100 reduces NOx emissions in the entire load range by 17–20%, as the higher cetane number reduces the intensity of ROHR and the combustion temperature. The addition of biobutanol to HVO fuel increases NOx emissions by up to 20% (decreases the cetane number of the fuel mixture, increases oxygen concentration, and this increases ROHR intensity and combustion temperature), but nitrogen oxide emissions remain 13–14% lower compared with pure diesel.
8. Replacing pure diesel with a mixture of 100% renewable fuel (hydrotreated vegetable oil and biobutanol up to 20%) can significantly improve the engine's environmental performance without compromising energy efficiency. However, additional studies are needed to assess the effect of fuel on engine reliability and reliability.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

BMEP	Brake mean effective pressure (bar)
$BSFC_{\_m}$	Brake specific fuel mass consumption (g/kWh)
$BSFC_{\_V}$	Brake specific fuel volume consumption (mL/kWh)
BTE	Brake thermal efficiency
LHV	Lower heating value (MJ/kg)
ROHR	Rate of heat release (J/CAD)
M_B	Brake torque (Nm)
m/m	Mass ratio
n	Rotational speed of the crankshaft (rpm)
v/*v*	Volumetric ratio

Abbreviations

ATDC	After top dead centre
BTDC	Before top dead centre
BTL	Biomass to liquid fuel
B5	5% biodiesel, 95% diesel
B20	20% biodiesel, 80% diesel
B25	25% biodiesel, 75% diesel
B50	50% biodiesel, 50% diesel
B75	75% biodiesel, 25% diesel
B100	100% biodiesel
CAD	Crank angle degree
C/H	Carbon/hydrogen ratio
CI	Compression ignition
CO	Carbon monoxide
CO_2	Carbon dioxide
D100	100% conventional diesel fuel
ECU	Electronic control unit
EGR	Exhaust gas recirculation
EGT	Exhaust gas temperature
ES	European Union
HC	Hydrocarbons
HVO	Hydrotreated vegetable oil
HVOB5	95% hydrotreated vegetable oil, 5% biobutanol
HVOB10	90% hydrotreated vegetable oil, 10% biobutanol
HVOB20	80% hydrotreated vegetable oil, 20% biobutanol
HVO100	100% hydrotreated vegetable oil
NO_X	Nitrogen oxides
O_2	Oxygen
PM	Particulate matter
RME	Rapeseed methyl ester
SOC	Start of combustion
SOI	Start of injection
TDI	Turbocharged direct injection

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