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Combustion, Ecological, and Energetic Indicators for Mixtures of Hydrotreated Vegetable Oil (HVO) with Duck Fat Applied as Fuel in a Compression Ignition Engine

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Abstract: The aim of the present study was to investigate the effects of the application of hydrotreated vegetable oil (HVO) mixed with pure duck fat (F100) as fuel, replacing the conventional fossil diesel fuel (D100). The tests were performed using a four-stroke direct injection CI engine diesel engine. Six fuel samples were used: D100, HVO100, F100, as well as three HVO–fat mixtures F25, F50, and F75. To further study the main characteristics of fuel combustion, the AVL BOOST software (Burn program) was applied. The results of experimental studies showed that with the addition of pure fat to HVO, the ignition delay phase increased with an increase in the amount of heat released during the premix combustion phase and the pressure and temperature rise in the cylinder increased; however, the mentioned parameters were not higher as compared to diesel fuel. It was found that as the concentration of fat in the HVO–fat mixtures increases, the viscosity and density increases, while LHV was decreased, which thereby increases brake specific fuel consumption and slightly decreases brake thermal efficiency in comparison to diesel fuel. A decrease of CO_2, HC, NO_x emissions, and smoke was established for all HVO–fat mixtures as compared to diesel fuel at all loads; however; under low loads, CO emissions increased.

Keywords: combustion; fuel; emissions; engine

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1. Introduction

The lack of components and raw materials mined in Ukraine and Russia, as well as international sanctions, are only part of the war-related crises that the automotive industry has experienced.

The rapid decline in hydrocarbon reserves and the constant rise in prices for them require large-scale development of renewable energy sources [1–3]. Moreover, an important reason stimulating the transition to alternative energy sources are the problems of global climate change, which will reduce the impact on the environment of harmful factors, improve the ecology of our planet, as well as implement the recommendations written in the "Paris Convention on Climate Change", which entered into action on 4 November 2016 [4,5].

The current situation calls for regulation of the biofuels sector in 2023 with regard to the possibilities and obligations for the use of biocomponents in fuels. The aim is to contain further increases in fuel prices, to stabilize the situation involving the national fuel and biofuel markets, and to increase the state's fuel safety.

The EU biofuel policy aims to promote and encourage the development of biofuels, such as biodiesel, bioethanol, and biomass [6,7]. The Energy Union strategy, entitled "Clean energy for all Europeans" published in 2016, highlighted the further measures to reduce CO_2 emissions by up to 40% by 2030 and have net zero by 2050 [8,9].

As a result of environmental policies, many automotive alliances and partnerships have emerged to work together on large-scale biofuel projects. For example, FCA teamed up with Tesla and Honda, Mazda with Toyota, and Ford with Volvo and Polestar [10]. Since 1990 emissions of CO_2 in Europe have reduced by about 24% [11].

The European Union is the leader in the use of diesel biocomponents, the region accounts for 41% of the world demand for diesel biocomponents, which is 15.9 million tons, or about 7.4% of the volume of diesel fuel consumption in the EU. The vast majority of biocomponents used in the EU—about 85.5% (13.6 million tons)—are FAME (fatty acid methyl esters), the remaining 14.5% (2.3 million tons) are HVO. Of this volume, 11.6 million tons of FAME are produced directly in the EU countries and 2.7 Mt of HVO [12]. The HVO system enables the industrial application of the hydrogenation of rapeseed oil, used cooking oil (UCO), or a mixture of both. The final product may be used as an additive to diesel or jet fuel.

Experts predict that this figure will be 70% by 2030. Thus, the environmental and economic indicators for numerous countries, for instance Poland, Slovakia, Malta, Bulgaria, and Estonia, will be even more vulnerable to the impact of the transport industry [13].

The recently adopted European Climate Law raises the EU's 2030 vehicle emissions target from 40% to a minimum of 55% and introduces a legislative commitment to carbon neutrality by 2050, which, in turn, should help reduce emissions of CO_2 in the volume of about 420 million tons per year [13].

Today, most experts [14–19] agree that an important factor for the creation and use of innovative fuels for diesel engines is the availability of extensive raw materials for the production of alternative motor fuels. The energy features of the presented sources of raw materials, similar to mineral fuels, make it possible to use the latter as motor fuels [20].

The balance of the combination of rational prices for raw materials and measures to regulate social and environmental risks is of particular importance [21].

Hydrogenated vegetable oil (HVO) was introduced in 2005 when it was derived exclusively from palm oil [22]. Free of aromatics, oxygen, and sulfur, hydrogenated vegetable oil has a high cetane number, resulting in reduced NO_x emissions, improved stability in storage, and low temperature properties, making it suitable for almost all diesel engines [23,24]. The main limiting factor in the industrial producing of biodiesel is the cost of vegetable oil. The purchase of oilseeds, transportation, storage, and extraction of oil are the main items of expenditure related with the production of biodiesel. The production of fuel from plants takes up agricultural land, while more pesticides, herbicides, and fertilizers are used for higher yields, making it impossible to continue growing any other plants suitable for food on this area [25].

At the same time, intensive animal husbandry and subsequent processing of raw meat leads to the accumulation of a significant amount of fat-containing raw materials and waste [17,26–28]. This resource can be used to further solve energy problems for the production of biofuel.

Biodiesel can be exploited as pure (B100) or mixed with diesel fuel at any combination in most diesel engines. Generally, the use of such fuel does not require modification of the vehicle's engine [29–31].

Analysis of recent studies and publications suggests that numerous research on alternative fuels for diesel engines focuses more heavily on blending ratios with diesel [32–35], but there is little research evaluating the use of clean duck fat fuels as oxygenated fuels in combination with HVO.

Thus, in the opinion of the authors of this work, it is also important to study the potential of the presented samples of mixtures for further assessment of the main criteria of fuel quality during operating in a diesel engine.

According to most research [18,32,35–39], when biodiesel is burned, the greenhouse effect does not increase; it decreases the content of hydrocarbons, soot, and carbon monoxide exhaust gases. Biodiesel does not contain carcinogenic substances, such as polycyclic aromatic hydrocarbons and especially benzopyrene, with comparison to fossil fuel [40].

Some of the important indicators of engine efficiency are the parameters of the fuel used, in particular: density and kinematic viscosity [18,41,42]. In this paper, [43] noted that biodiesel extracted from duck fat has favorable properties of density, kinematic viscosity, and also, lower heating value compared to diesel fuel.

Animal fat as a fuel component can be widely used due to its cheapness (because it is obtained as a by-product of meat processing) and availability (every country has a meat processing industry). Pure lard is filtered before use, its preparation is carried out (heating to a uniform consistency and repeated filtering) [44]. When choosing the proportions of fat mixtures with traditional fuels, their physicochemical properties must be taken into account [45]. Depending on the type of fat, it is necessary to select measures to prevent it from solidifying in fuel mixtures (chemical stabilizers are used, additional heating, and constant mixing) [46].

The combustion parameters of chicken fat are different compared to traditional diesel fuel, such as a lower rate of heat release, which is determined by prolonged reactions at low temperatures [47]. To improve them, additional hydrogen can be added to fuel containing chicken fat—a better energetic (increased BTE) and ecological effect (decrease in sharpness, CO, and UHC emissions) is achieved [48].

The peculiarity of the high viscosity of the biodiesels is that it tends to negatively affect the loss of engine power. Due a high viscosity, large droplets and a short jet are formed; therefore, it takes more time for the fuel to evaporate, the ignition delay phase increases, incomplete combustion occurs, carbon deposits form, and fuel consumption increases [49]. Poor sprinkling, in turn, leads to clogging of the nozzle and fuel pump, which directly affect the increase in toxic emissions, such as CO, CO_2, and SO_x [50,51]. Besides, the straight using of pure vegetable oil causes the formation of injector sediments, a result of which gives rise to higher exhaust gases [52].

As known, density is one of the key characteristics of petroleum products for diesel engines. The density is determined by the parameters of the fuel itself. The higher the fractional composition, the more difficult the processes of evaporation and atomization of fuel in the injectors become [53].

Hoekman et al. [54] indicated that due to the oxygen content of biofuels, it has a lower content of energy (MJ/kg) than diesel fuel.

It should be noted that biodiesels have a higher cetane number than diesel fuel, which indicates a good ignition rate of the fuel [26,55].

A large number of studies have been carried out to study the consequence on the performance of a diesel engine of biodiesel based on various animal fats [38,56–58].

Şen et al. [38] used chicken fat for the making of biodiesel. In a pilot study, it was noted that the use of biodiesel blends led to a reduce in emissions CO, CO_2, HC, and smokiness, but slightly increased the torque values and indicators NO_x. Raman et al. [49] also found that CO emissions from biodiesel blends are lower than those of a diesel engine, but CO values are higher at low loads. One of the possible reasons is the presence of a rich fuel mixture at higher loads.

In this research [56], the authors investigated duck fat oil used in a single cylinder Kirloskar TV-1 diesel engine. The results have shown that emissions of CO and HC were increased. Opposite results were for CO_2 and NO_x, which was reduced compared to diesel fuel.

Goga et al. [59] used a fuel mixture in their experiment (10% rice bran oil and 90% diesel) and it was found that hydrocarbon emissions are decreased when biodiesel was used as opposed to diesel fuel, which may indicate a shorter ignition delay phase due to a higher cetane number of the biodiesel mixture. Furthermore, it should be said that a shorter ignition delay phase contributes to a more complete combustion of the fuel; consequently, there is less hydrocarbon emission. Other authors [33] also obtained similar results of a decrease in the emission of HC.

Results obtained from experiment with edible sunflower oil and non-edible Karanj oil indicated longer ignition, which consecutively caused an increase in pressure in a cylinder and higher CO and NO_x emissions, while in contrast, demonstrated lower BSFC in comparison to diesel fuel [52].

Additionally, diesel fuel is composed of alkines, cycloalkine, and aromatic hydrocarbons, which, in turn, also increase the formation of smoke.

In this research [23], the effect of pure chicken fat and various mixtures of fat and diesel in the ratio of 70/30, 50/50, and 30/70 was studied. An increase was noted in emissions of CO and CO_2 for mixtures with pure fat. Reduced emissions of NO_x during low engine loads for mixtures due to larger droplets of fuel, which caused a decrease in temperature, was also observed.

The authors [60] point out that high NO_x emissions from biodiesel mixtures may result from the high oxygen content of biodiesel. Barrios et al. have the same opinion [61].

Several publications [36,62] indicate that NO_x emissions are influenced by fuel density. NO_x emissions are also dependent on engine load and rpm, injection timing, and ignition delay [63,64].

Many studies have found that the use of biofuels in a diesel engine improves environmental performance, but at the same time increases BSFC [33,35,36,49,60,62,65,66].

Emiroğlu et al. [42] studied turkey fat as the main raw material for biodiesel in blends. It was found that the mixtures had at all loads with an engine speed from 1600 rpm to 2400 rpm, higher specific fuel consumption (BSFC) values and, at the same time, lower brake thermal efficiency (BTE) values compared to diesel fuel. Rao et al. [67] have similar conclusions. They pointed out that as the percentage of chicken fat biodiesel increased, exhaust temperatures, CO emissions, and BTE declined, while BSFC and NO_x increased. In [68], biodiesel based on chicken fat (B) was blended with diesel fuel (D) in specific blending percent: B20D80, B30D70, B40D60, and B50D50. It was indicated that the lower the engine power, the higher the fat content in the mixture, which is associated with a low calorific value.

Selvan, V.A.M. has made a major contribution to the development of knowledge about the use of fats for energy purposes [69–73]. His experimental studies have shown that chicken fat and egg shell are suitable as catalysts for the production of biodiesel. In addition, he was able to demonstrate that the physicochemical properties of the biodiesel produced from chicken oil comply with the ASTM D 6751 standard. In his scientific studies, Selvan, V.A.M. has shown that skin fat is an excellent source of energy.

Mikulski et al. [33] conducted experimental work on a four-stroke Common Rail diesel engine investigating pork fat methyl esters. It was noted that increasing the methyl ester in the blend increased the BSFC. This was due to the low calorific value of the tested mixtures, and also indicated a shorter ignition delay phase of the fuel. At the same time, an increase in BTE values was observed with an increase in the amount of biodiesel, on average, by 1.6%, 4.8%, and 7.8% for B25, B50, and B75, respectively. The same results are consistent with the solution indicated by Abed et al. [74] and Jayaprabakar et al. [75]. Consequently, the higher fuel consumption of biodiesel fuel contributes to improved fuel combustion due to oxygen enrichment, which also affects the performance of higher exhaust gas temperatures. Analysis of some publications recommends the use of biodiesel blends containing no more than 20% fuel based on renewable sources to minimize losses in engine performance [16,58].

The European Union's climate policy aims at climate neutrality. One way to achieve this is to reduce emissions of harmful gases (including greenhouse gases) from transport as much as possible. A large proportion of vehicle manufacturers selling their products in Europe have declared that they will not sell combustion vehicles between 2030 and 2040.

Electromobility is being developed and promoted in many countries of the European Union. However, there is no way to remove all of the combustion vehicles (approx. 2.5 to 3 billion). This applies to both passenger and truck transport. In the case of heavy vehicles, the problem is even greater. Currently, diesel tractors are responsible for international traffic. They travel thousands of kilometers to transport between states. In this case, electromobility is not yet equipped for these major challenges. On the one hand, there are vehicles that do not yet have sufficient range, and on the other, there is the infrastructure.

Hydrotreated vegetable oil (HVO) could be a solution. This is fuel derived from waste from the food industry, i.e., in reality from residues of vegetables, fruit, and fat products (even animal origin).

Preliminary studies have shown that its benefits include reduced carbon dioxide emissions (between 50% and 90%, depending on the purity) and the absence of sulfur compounds. A 2011 study by VTT of Finland found that older cars can emit up to 30% less carbon dioxide. HVO100 is a pure hydrogenated vegetable oil without the addition of fossil fuels. HVO can also be mixed with conventional diesel in different proportions, e.g., HVO30, HVO50, etc. For new vehicles, HVO reduces CO_2 emissions by about 90%.

In the case of HVO, emissions cannot be avoided during production. This process still requires oil extraction and processing.

Leading truck manufacturers support the spread of the HVO. Compliance with the standards for its entire fleet has been announced by the DAF and has been declared for several years by Scania, MAN, Volvo, Mercedes, Renault, and Iveco. In particular, owners of Euro 5 and Euro 6 compliant lorries will be able to use the new biodiesel, i.e., practically the entire Polish fleet serving international transport as well as most local vehicles. After verification, the HVO mixtures can also refuel Euro 3 and 4 vehicles.

Volkswagen announced that from July 2021 diesel vehicles can be operated with pure HVO. In addition, the group estimates that the share of this fuel will reach up to 30 percent of the energy mix needed for transportation within a decade.

The reduction of pollutant concentrations during the combustion process and the ability of the HVO to act as a substitute fuel for most compression ignition engines makes it worthwhile to develop. Hydro-refined vegetable oil is not emission-free and consumes a fairly large amount of energy, but it is produced from waste that would have to be disposed of anyway.

The main aim of this research is to evaluate the energy and ecological benefits obtained with blends containing HVO and pure fat, as opposed to diesel fuel.

2. Methods and Materials

The study of engine performance indicators using HVO and fat fuel mixtures was carried out by means of experimental and numerical analysis. In the course of the experimental analysis, energy and ecological indicators were determined and the pressure in the cylinder was measured. Analysis of the combustion process was performed with the help of the BURN subroutine of the AVL BOOST program. Summarizing conclusions are presented based on the indicators of experimental and numerical analysis (Figure 1). The algorithms for controlling combustion engines require a considerable amount of time and cost. Engine manufacturers and research centers are increasingly using advanced tools to simulate engine operation. These tests allow a significant reduction in the analysis time and a reduction in the costs of engine design and development. AVL BOOST is a multi-level computing system with the possibility of real-time operation to simulate variable engine conditions. The calculation program simulates engine operation over time using current and constant zero-dimensional and quasi-dimensional components of the model.

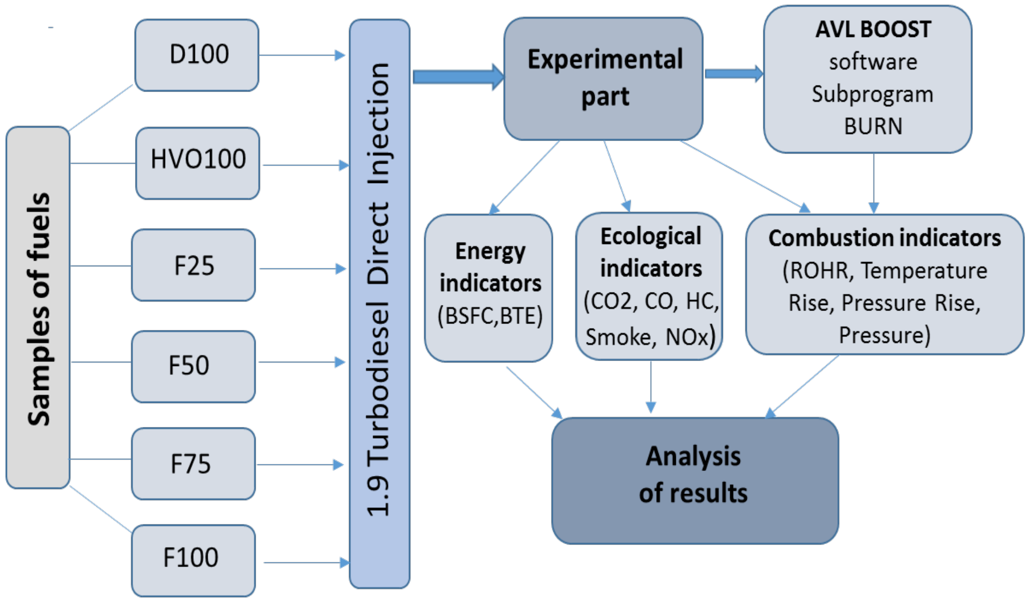

Figure 1. Nomenclature of research.

2.1. Fuel Preparation

The main properties of fuel samples for a CI engine were examined in accordance with fuel standards in the European Union. In the EU, there are two standards for diesel fuel: standard EN 590 for mineral diesel fuel, to which it is allowed to add up to 5% fatty acid methyl esters, and the standard EN 14214—fatty acid methyl esters applying for diesel engines.

For HVO, we applied the recommendation of Neste Renewable Diesel, in that hydrotreated vegetable oil contains paraffinic hydrocarbons, and cannot be equivalent to the requirements of EN 14214, which was proposed solely for fatty acid methyl esters, that is, FAME. Nonetheless, HVO is close to standard EN 590, not including density.

Biodiesel concentrations studied, include mixing, was carried out in the following proportions. Blends of hydrotreated vegetable oil (HVO100) and pure duck fat (F100) mixed in the ratio of F25, F50, and F75 by volume. The comparison of physical and chemical properties of various fuels are given in Table 1.

Table 1. Physicochemical properties of the analyzed fuels.

Fuels	Density (kg/m^3) at 15°	Viscosity (mm^2/s) at 40°	Sulfur Content (mg/kg)	Water Content (mg/kg)	Total Contamination (mg/kg)	Cetane Number	Hydrogen %	Carbon %	Oxygen%	C/H%	LHV (MJ/kg)
Allowed value in accordance with quality standard EN 590											
	820–845	2–4.5	≤10	≤200	≤24	≥51					
D100	823.00	3.5	7.25	85	20	45	0.130	0.870	0.000	6.69	42.70
Allowed value in accordance with quality standard EN 14214											
	860–900	3.5–5	≤10	≤500	≤24	≥51					
F25	800	4.7	4.52	690	43.27	72.04	0.146	0.827	0.027	5.64	42.40
F50	831	9.8	4.87	770	-	67.19	0.141	0.804	0.055	5.70	40.70
F75	867	18.8	5.21	925	-	62.34	0.136	0.782	0.082	5.77	39.00
F100	908	34.8	5.31	1450	-	57.49	0.130	0.760	0.110	5.85	37.30
Allowed value in accordance with the booklet information on Neste Renewable Diesel for HVO											
	770–790	2–4	≤5	≤200	≤10	>70					
HVO100	776.00	2.9	4.16	20	5.52	76.89	0.152	0.848	0.000	5.58	43.70

Physicochemical properties of biodiesel made from animal fats or vegetable oils, in particular, viscosity, density, heat of combustion, cetane number, etc., differ from those for diesel fuel. It can be noted that the fuel mixtures presented are within the normal range. To ensure proper viscosity, duck fat fuel was heated to 40–50 °C.

Thus, the above analysis of the physicochemical properties of hydrotreated vegetable oil and its mixtures with pure duck fat indicates the possibility of using most of them to power diesel engines, despite the weighted fractional composition of fat; hence, with increased viscosity. However, these differences in the properties of pure fat and mixtures based on them from the properties of diesel fuel can lead to a deterioration in the quality of fuel atomization and mixture formation [68]. Therefore, it is preferable to use low fat hydrotreated vegetable oil in diesel engines; the less the viscosity of the fuel, the easier the fuel supply and its atomization (Table 1).

2.2. Test Bench, Measuring Instruments, and Data Processing

Specifications of the engine used in the experiment are given in Table 2. During the experimental part, the engine was taken at fixed speed n = 2000 rpm, the engine brake torque (MB) was presented in 30 Nm, 60 Nm, 90 Nm, and 120 Nm, which meant the brake mean effective pressure (BMEP) was 0.2 MPa, 0.4 MPa, 0.6 MPa and 0.8 MPa.

Table 2. Specifications of the engine used in the experiment.

Specification	Parameter
Engine	1.9 Turbodiesel Direct Injection
Number of cylinders	4
Compression ratio	19.5
Stroke	95.5 mm
Bore	79.5 mm
Maximum power output	66 kW at 4000 rpm
Maximum torque	182 Nm at 2000–2500 rpm

The tests were carried out at the stand used in the direct injection of the CI engine equipped with the electronic control unit. For measuring the composition of exhaust gases CO, HC, NO_x, smoke, and CO_2, the instrument AVL DiCom 4000 was applied, with precision of the result of 0.01% for CO, and for HC and NO_x, respectively, 1 ppm, and smoke 0.01 m^{-1}, and 0.1% for CO_2. The consumption of the tested fuel samples was carried out by weighing them on an electronic balance, CK-5000, with precision of 1.0 g. Therefore, an air meter was used to measure the air flow BOSCH HFM 5, with an accuracy of 2%. Pressure sensor Delta OHM HD 2304.0 measured the pressure of the turbocharger, with an accuracy of 0.0002 MPa. The temperature was measured using a thermoelectric converter, with an accuracy of 1.5 C (Figure 2).

In order to ensure uniformity of results and to avoid random errors, each test point was repeated 5 times. Such repeatability showed that during the test the recording of the results was done only when the smooth operation of the engine was established.

During the experimental tests, the CO concentration was measured, the accuracy of the measurement was 0.01%. At low engine load (BMEP = 0.2 MPa) and the engine running on HVO fuel, the CO concentration was 0.01%, with F100 fuel the CO concentration was close to 0.03%. When the engine was running at a load of BMEP = 0.8 MPa, the CO concentration of all fuels was the same—0.01%. The pollutant concentration was recalculated into a specific emission g/kWh and the obtained results correlate with the experimental data.

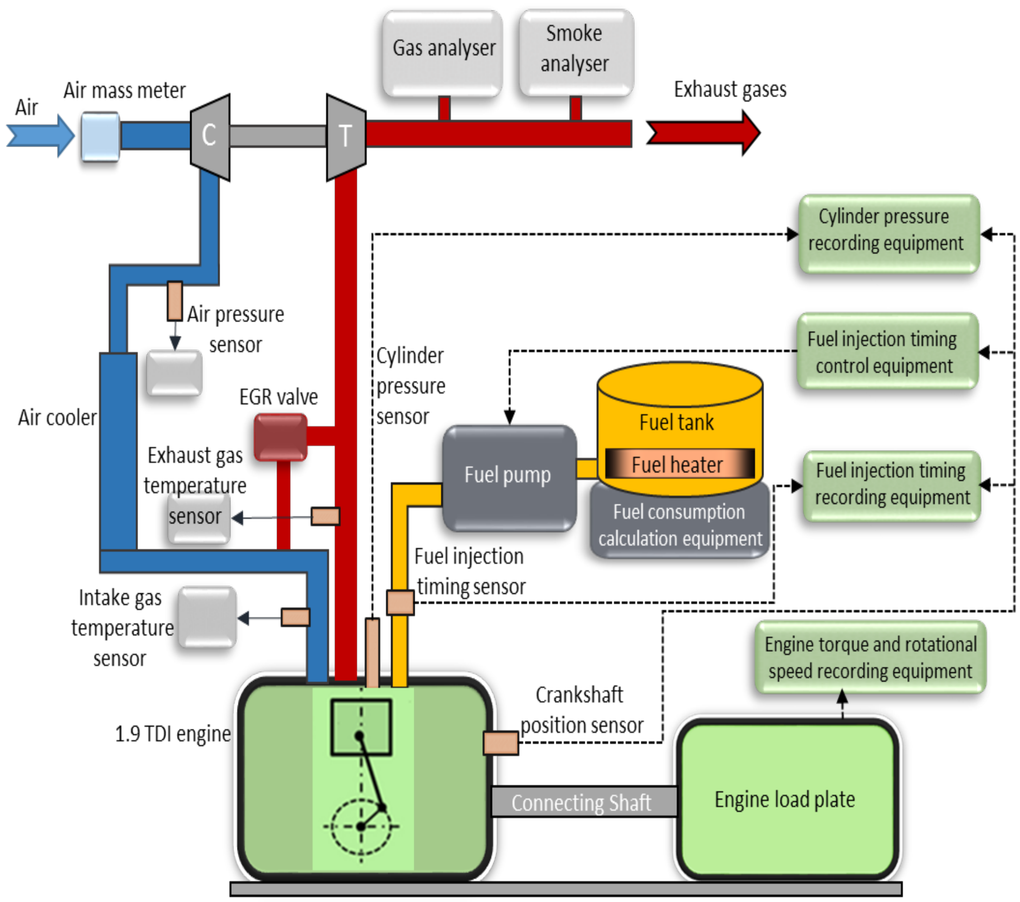

Figure 2. Schematic internal combustion engine testing equipment.

The piston position at the top dead center (TDC) was determined by an optical crankshaft position sensor, A58M-F, with signal repeatability of 0.176 CAD. To convert the signals from the pressure and crankshaft position sensors, the device AVL DiTEST DPM 800 was used. A quartz piezoelectric sensor was used to measure the gas pressure in the cylinder. AVL GH13P had a sensitivity of 15.84 ± 0.09 pC/bar. LabView Real software recorded the engine pressure (100 cycles). Registration of the start of fuel injection was noted by the equipment VAG-COM. The fuel injection timing control equipment controlled the fuel injection process.

During the tests, each point was repeated 5 times after the engine had stabilized. Standard error statistical evaluation was used:

$$\mathrm{u}\left(\bar{\mathrm{x}}\right) = \mathrm{u}(\mathrm{x})/\sqrt{\mathrm{n}} \tag{1}$$

where, the number of repetitions, in the case, was equal to 5.

Further, the errors were evaluated according to the sources [76,77] in the calculation and expanded uncertainly $U_{0.99}$.

The error values are shown in Table 3.

Table 3. The error values.

Parameter	Standard Uncertainly u	Expanded Uncertainly $U_{0.99}$
ROHR, J/CAD	0.003657	0.025
Temperature rise K/deg	0.002987	0.017
Pressure rise in cylinder, MPa/deg	0.005987	0.036
Pressure in cylinder, MPa	0.005745	0.034
CO_2, g/kWh	0.000301	0.007
CO, g/kWh	0.000258	0.006
HC, g/kWh	0.006987	0.041
Smoke, m^{-1}	0.000249	0.005
NO_x, g/kWh	0.007459	0.052
BSFC, g/kWh	0.005221	0.032
BTE	0.003698	0.025

2.3. Analysis of Experimental Results with the Use of AVL Boost Software

The fuel combustion processes were further studied by means of the software AVL Boost. AVL Boost is a software that includes of a pre-processing program for the starting data and description of the engine that will be represented as a model. Thereafter, the system applications form the mathematical equations and algorithmic program with a illustrative user interface, and inspect and calculate the processes that will be needed in the analysis and modeling. The software AVL BOOST's subprogram BURN uses the experimental data: cylinder pressure, as well as fuel and air consumption, properties of tested fuel samples, etc. By means of the subprogram BURN, the start of combustion (SOC), combustion duration (CD), and shape parameter (m) was determined. Furthermore, the rate of heat release (ROHR), temperature, and pressure rise in the cylinder were observed.

3. Results and Discussion

3.1. Indicators of Combustion

The combustion process is affected by both the structure and size of fuel droplets, the difference in the molecular structure of fuel hydrocarbons, the types of hydrocarbon compounds, and the types of chemical intermolecular bonds [78]. These characteristics of the fuel supplied for combustion have a significant effect on the qualitative and quantitative characteristics of the combustion process, and on the oxidation reactions of hydrocarbon compounds in the combustion zone [53].

The start of combustion (SOC) and ignition delay (ID) for various fuels at engine load BMEP = 0.8 MPa are shown in Figure 3. From the analysis of the experimental data, it can be found that SOI = 7 CAD bTDC for all fuels. The ignition delay phase for different fuels increases in the following order: HVO100, F25, F50, F75, F100, and D100. The shorter ignition delay phase of biofuel mixtures compared to diesel is explained by its higher cetane number [79]. Moreover, Sivalakshmi et al. [80] explained that low molecular weight gaseous compounds degraded from biodiesel during injection into an engine cylinder at high temperatures can ignite earlier; thereby reducing ignition delay phase and accelerating the onset of biofuel combustion.

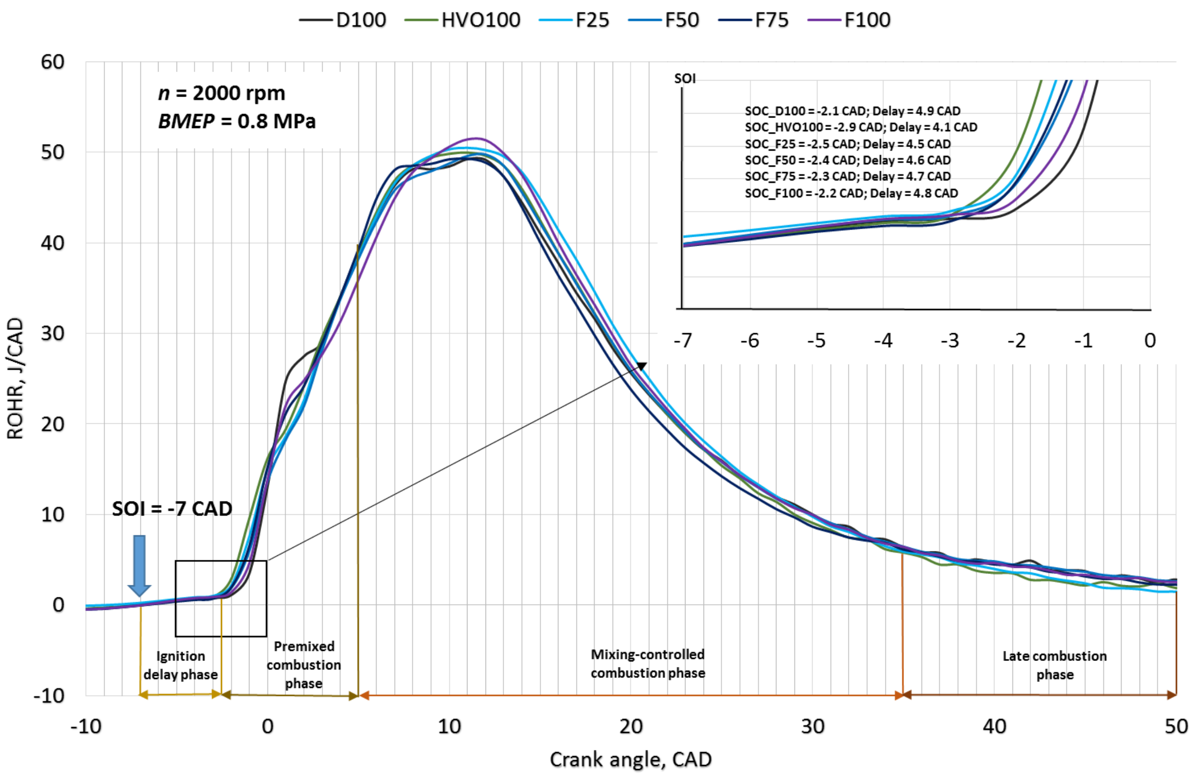

Figure 3. Dependence of the rate of heat release in the cylinder using different fuels.

At high engine load (BMEP = 0.8 MPa), the amount of fuel consumed increases in the order of HVO100, D100, F25, F50, F75, and F100 due to the lower calorific value of the mixtures compared to diesel (Table 1). An increase in the mass of injected fuel occurs, which leads to an increase temperature rise in the combustion chamber (Figure 4). Adding more fat to the HVO increases the mass of fuel injected, which leads to a delay in ignition, which is associated with a large consumption of heat for the evaporation of fuel droplets.

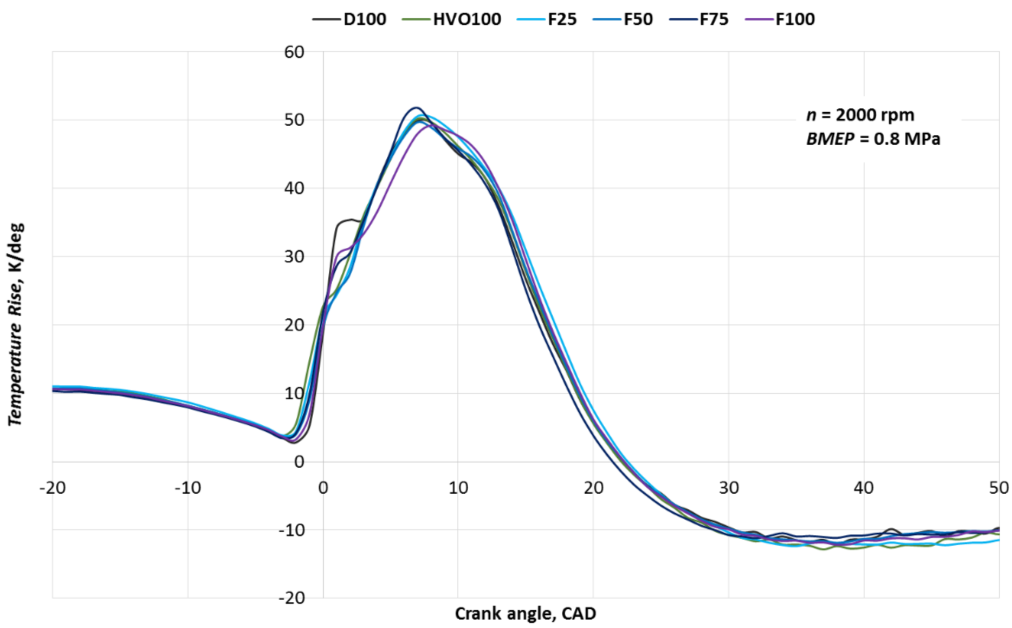

Figure 4. Dependence of the temperature rise in the cylinder using different fuels.

Furthermore, in having a shorter ignition delay, less fuel for the samples of fuel is burned in the premix mode and more during the mixing-controlled combustion phase. A decrease in the ignition delay phase for HVO, in comparison to mineral fuel, will lead to a reduced part of fuel that burns during the flash period (premixed combustion phase), and accordingly, the proportion of fuel burned in the time period of diffusion combustion will increase (mixing-controlled combustion phase).

One of the important factors causing such differences in the combustion process is the viscosity of the fuels. Table 1 shows that the viscosity of HVO is 20% less than the diesel fuel. The addition of duck fat to the fuel mixture causes a significant increase in the fuel viscosity and the ignition delay. Thus, the correlation between the viscosity of the fuel and the ignition delay phase is visible.

As can be seen from the data presented in Figure 3, for HVO the first ROHR peak corresponding to the premixed combustion phase is about 20–25% lower than for diesel fuel, and this peak is reached 1 degree earlier. This regularity can be explained by a reduced ignition delay phase, and consequently, by a smaller amount of fuel that enters the diesel cylinder during this period of time. The addition of duck fat to the fuel causes an increase in the ignition delay phase and an increase in the intensity of the combustion process during the premixed combustion phase.

The regularity described above causes a reduction in the proportion of fuel that burns out over the ignition delay phase, and consequently, an increase in the proportion of fuel that burns during the mixing-controlled combustion phase with an increase in the concentration of animal fat in the fuel mixture. This is clearly seen from the data presented in Figure 3—the maximum ROHR level in the "mixing-controlled combustion phase" (Crank angle 11–12 CAD) for pure diesel fuel is the smallest of all the presented samples. With an increase in the concentration of fat (duck fat) in the fuel mixture, an increase in the level of the maximum ROHR in the "mixing-controlled combustion phase" is observed. For F100 fuel, the maximum ROHR level during the mixing-controlled combustion phase is the highest, which confirms the described tendency.

As the percentage of fat in the mixtures increased, the ignition delay phase increased; thereby increasing the peak rate of heat release. A longer ignition delay phase was observed with the F100 mixture than with HVO and other mixtures.

It was found that the ignition delay phase for pure HVO and mixtures with pure fat is lower in contrast to diesel fuel. A possible explanation is the higher cetane number for pure HVO [81]. The higher the amount of cetanes, the shorter the ignition time. The amount of cetanes increases with the length of the unbranched carbon chain. Therefore, the lower the content of "harmful" aromatic hydrocarbons in the fuel, the higher the cetane number will be [82].

During the combustion phase, including a premix at 2 CAD, the rate of heat release for HVO is ~21% less than for D100. It should also be noted that the ignition delay phase also depends on the viscosity and density of the test mixture samples. Since HVO has a lower viscosity than diesel, this, in turn, contributes to better mixing in the premix phase. Furthermore, due to the fact that the HVO has a chain with paraffinic hydrocarbon which decomposes and evaporates faster, this contributes to a more intensive mixing with the ambient air in comparison with diesel fuel. The fat increases the viscosity of the mixture with HVO, and increases in the ignition delay phase and ROHR in the premix combustion phase approaches that of diesel. The variance between the heat release rate in 1 CAD for F25 is ~24%, F50 is ~26%, F75 is ~14%, and F100 is ~10% compared to fossil fuel.

Examining the mixing-controlled combustion phase the maximum rate of heat release for D100 (at 10–12 CAD) was ~1.2% less than for HVO100 (at 11 CAD). Furthermore, comparing mixtures with pure fat, we observed that for F100 the maximum heat release is ~4.5% higher compared to fossil fuel; for F25, F50, and F75 the results were ~2.5%, 0.7%, and 0.8%.

In Figure 4, the maximum temperature rise at the premixed combustion phase observed for diesel fuel was 1–2 CAD—34 K/deg. When the temperature rise for D and for HVO was compared, it was found that diesel fuel had a higher rate at ~26% as compared to HVO. The HVO mixtures with pure fat and the premixed combustion phase temperature rise show a related trend as compared to fossil fuel. For F25, F50, F75, and F100, they were smaller than that for diesel: ~28%, ~27%, ~16%, and ~12%, respectively. This effect may be due to the higher viscosity, later start of combustion, longer fuel injection, higher injection pressure, and velocity along with lower heating value. The intense combustion in the premix phase that influences the formation of NO_x should also be noted. Thus, the rate of formation of nitrogen oxide for mineral fuel will be higher compared to other mixtures.

In Figure 5, it was found when testing diesel fuel the pressure rise at 2 CAD (premixed combustion phase) was higher ~28% compared with HVO. Similar results were obtained for other blends. For F25, F50, F75, and F100 they were accordingly, ~20%, ~34%, ~26%, and ~14% less compared to diesel fuel. The pressure rise correlates with ROHR and the temperature rise in the cylinder. During the mixing-controlled combustion phase, the minimum pressure rise fixed using pure fat F100. This was due to the decreased fuel injection rate due to the high viscosity.

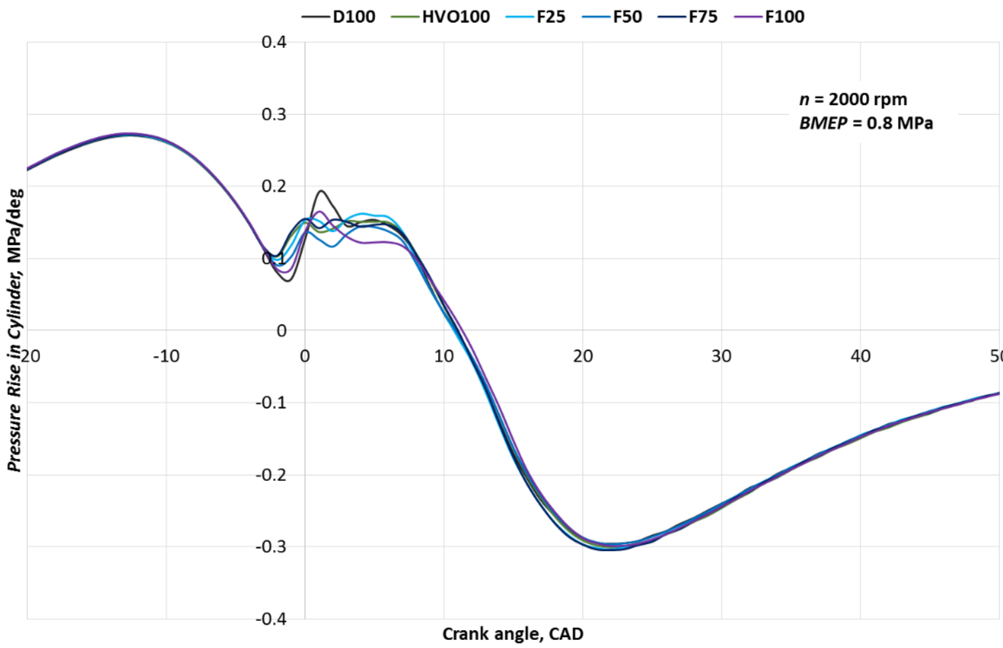

Figure 5. Dependence of the pressure rise in the cylinder using different fuels.

Peak pressure varies little, but pressure at the end of compression and start of combustion is higher with added fat (Figure 6). This means that the burning of fat is longer. The longer combustion duration was determined due to the higher consumption (lower LHV), the longer injection duration, which was further increased by the higher fuel viscosity. Exhaust gas flow energy became higher and this increased the turbocharger pressure. However, longer combustion duration of fat reduced the BTE.

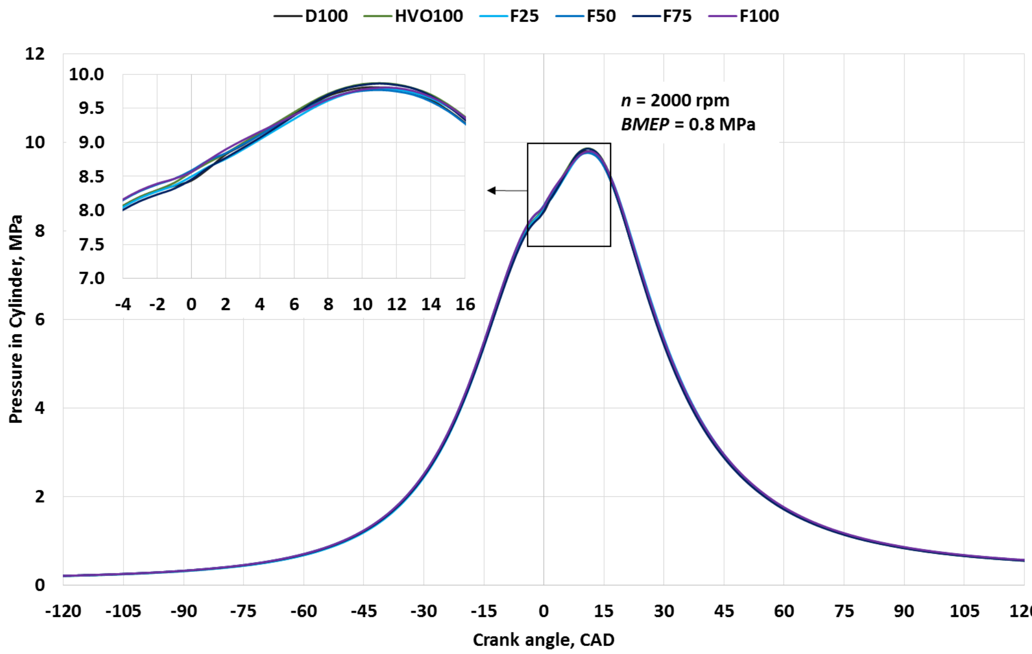

Figure 6. Dependence of the pressure in the cylinder using different fuels.

Figure 6 shows the pressure in the cylinder when BMEP = 0.8 MPa. We do not see any significant pressure differences because, for all fuel mixtures, the start of the fuel injection is the same (SOI = 7 BTDC), there is no very significant difference in fuel properties, and the engine load is the same. However, after performing the analysis of the combustion process (using these pressures), we see more pronounced differences in the various combustion indicators (Figures 3–5) when the studied fuel mixtures are used.

Higher maximum cylinder pressures were observed when the engine was running on diesel. This resulted in the longest ignition delay phase, maximum ROHR, temperature rise, and pressure rise in the premixed combustion phase. The maximum cylinder pressure was slightly reduced with the use of HVO and fat mixtures.

3.2. Ecological Indicators

3.2.1. Emissions of Carbon Dioxide (CO_2)

Specific CO_2 emissions, that are shown Figure 7, decrease for all samples of fuel with growth in the load. The BMEP = 0.8 MPa for HVO emissions of carbon dioxide were ~4.6% lower compared with fossil fuel. Furthermore, a decrease in CO_2 for F25 and F50 ~ 3.2% and 1.7% appropriately, was established. For F75 and F100, the CO_2 emissions were on average ~0.9% and ~2.1% higher compared with fossil fuel. The higher rates of CO_2 in the mixtures are because of the higher carbon and oxygen content of the examined fuels in comparison with mineral fuel and due to higher fuel consumption.

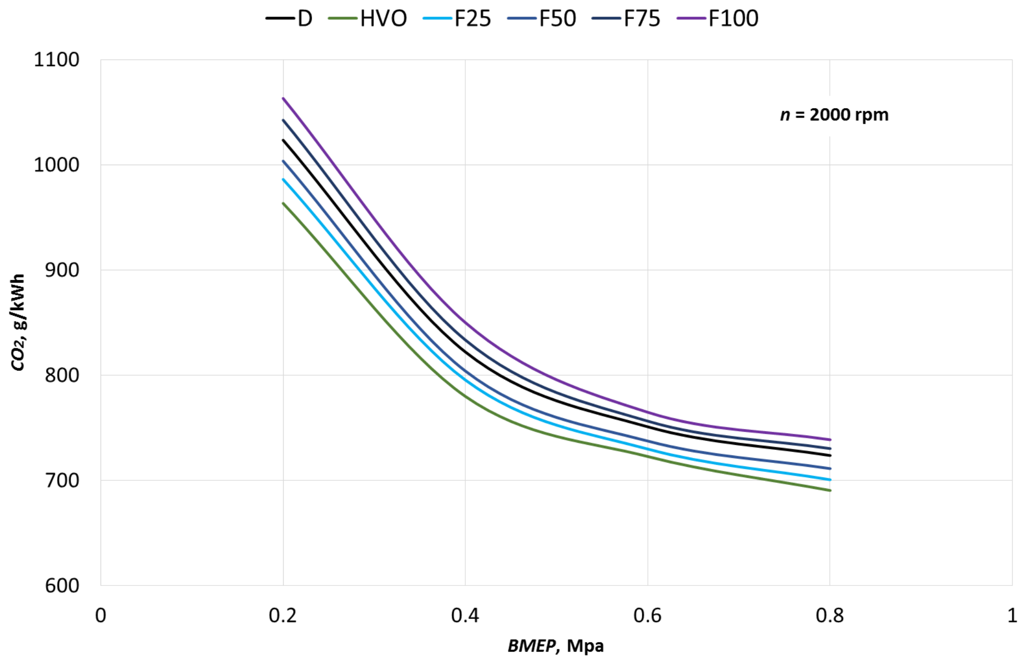

Figure 7. Dependence of carbon dioxide emissions on the load using different fuels.

Additionally, in the time of testing, it was found that blends that have a smaller ratio of C/H contribute the most to CO_2 reduction (Table 1). HVO, in turn, has a smaller ratio of C/H (5.7%), which allows for the reduction of CO_2 for this fuel sample compared to the mixtures and fossil fuel. With decreasing emissions of CO_2 less fuel consumption was noted. Perhaps the lack of air in the mixture of F25 and F50 slows down the combustion process, and thus reduces the production of CO_2 compared to D100, F75, and F100. The rate of the combustion process has little effect on the level of CO_2 formation. Several factors prevail: specific fuel consumption and specific carbon content in the fuel.

The level of specific CO_2 emissions of diesel exhaust gases for different fuels (Figure 7) at the same load is directly proportional to the specific fuel consumption and is directly proportional to the percentage of carbon in the fuel. It can be seen from Table 1 that with an increase in the concentration of fat (duck fat) in the fuel mixture, the percentage of carbon in the fuel decreases, but at the same time, the lower specific heat of combustion of the fuel also decreases, which causes an increase in specific fuel consumption. That is, the influence of the above factors on the level of CO_2 emissions with exhaust gases is opposite. Consequently, the final effect of fuel on the level of CO_2 emissions from the exhaust gases is determined by which of the two factors will dominate over the other.

So, for F75 and F100 fuels, an increase in the specific fuel consumption by an average of 12–18%, respectively, is the dominant factor over a 7–9% decrease in the specific carbon content in the fuel. As a consequence, there is an increase in specific CO_2 emissions for F75 and F100 fuels in comparison to diesel fuel throughout the entire range of engine operating loads. For HVO, F25, and F50 fuels, a decrease of 7%, 5%, and 3%, respectively, of the carbon content in the fuel is the dominant factor over the change in the average specific fuel consumption. As a consequence, for these fuels, a decrease in the specific CO_2 emission is observed over the entire load range.

3.2.2. Emissions of Carbon Monoxide (CO)

Since the fuel is split into CO at the time of the combustion process and then oxidized to carbon dioxide, the amount of CO tends to reduce with the growing temperature. The presence of hydrogen-containing substances, such as hydrogen, accelerates this process [83]. Moreover, pure fat blends are oxygenated fuel and the extra oxygen molecule helps the fuel burn better, which helps lower CO emissions.

With an increase in the concentration of fat (duck fat) in the mixture, the viscosity of the fuel increases, and also the specific net calorific value decreases (Table 1). A decrease in the specific net calorific value causes an increase in the cycle fuel supply. Both of these factors cause an increase in the maximum fuel injection pressure, and that can decrease the average diameter of fuel droplets in the cylinder and improve the distribution of fuel to the periphery of the combustion chamber. In turn, a decrease in the average diameter of fuel droplets has a positive effect on the completeness of fuel combustion, and an improvement in the distribution of fuel droplets to the periphery of the combustion chamber contributes to the elimination of zones with low local oxygen deficiency, which also reduces the formation of CO. However, with a significant increase in fuel viscosity, this effect of reducing CO emissions may not be achieved and pollutant emissions may increase.

Thus, at low load (BMEP = 0.2 MPa), the CO emission of F100 is ~160% higher compared to fossil diesel fuel (Figure 8). This indicates incomplete burning of fuel that consists of pure fat. A low cycle rate results in a low pressure, which, in turn, causes the formation of large droplets of high density and viscosity fuel, which burn much worse. The same trend was noticed for all HVO and fat blends. By increasing the load to BMEP = 0.4 MPa, the maximum difference of emissions for F100 and diesel fuel was ~63%. By increasing the load to BMEP = 0.6 MPa and BMEP = 0.8 MPa, the CO emissions of all fuel mixtures became similar.

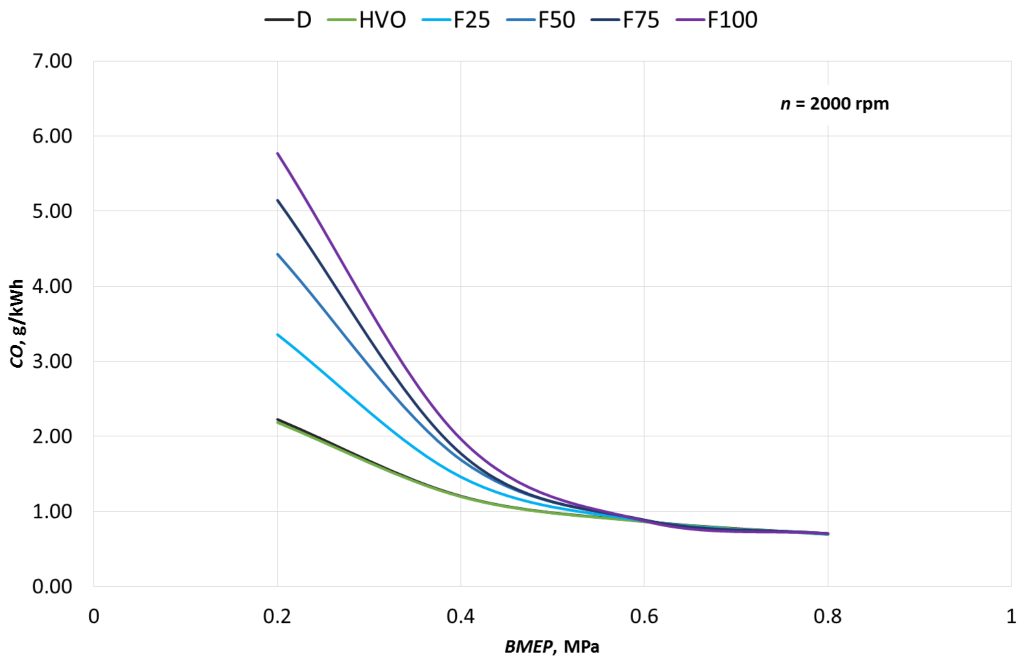

Figure 8. Dependence of carbon monoxide emissions on the load using different fuels.

3.2.3. Emissions of Hydrocarbons (HC)

As can be seen from the Figure 9, at all loads the mixtures have lower HC values, unlike mineral fuel, and for HVO this indicator is the smallest. The high-rise cetane number of HVO, and thus of blends with HVO, reduces hydrocarbon exhaust gases in comparison to diesel fuel [84]. That is due to the low content of aromatic compounds in the fuel mixtures. Furthermore, it should be noted that the fuel mixture with duck fat contains some oxygen in the structure, so it improves the fuel combustion process, and HC emissions will be reduced when using these blends with a percentage of pure fat.

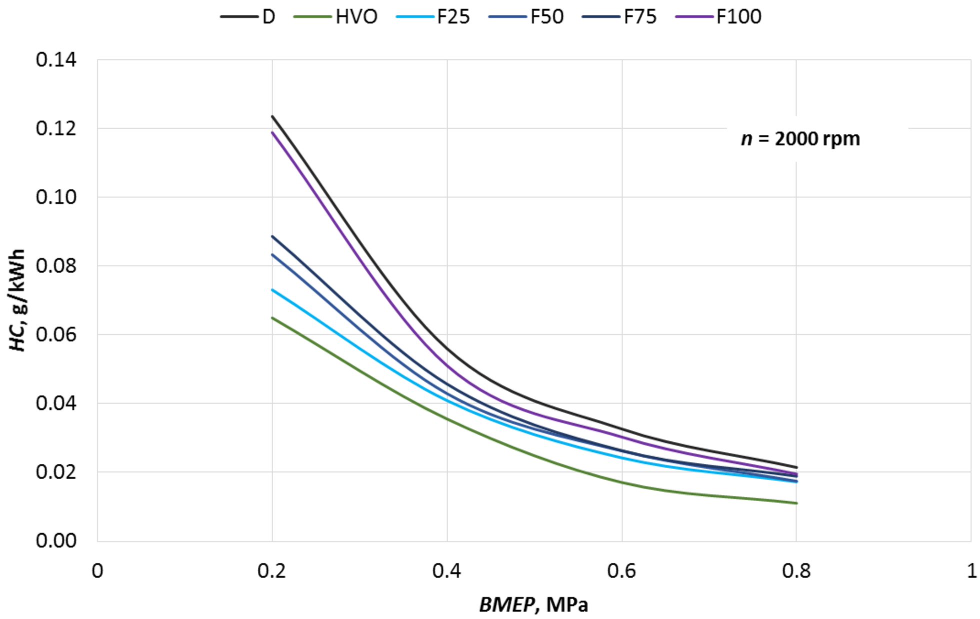

Figure 9. Dependence of hydrocarbon emissions on the load using different fuels.

For example, F100 for BMEP = 0.2 MPa has ~4% less HC emissions than D, while HVO has ~ 47% less, opposite with diesel fuel. At higher loads, a similar trend was determined for all fuel samples. On average, the HC values for the combinations F25, F50, F75, and F100 were lower, opposite to fossil diesel fuel, respectively, ~28%, ~23%, ~19%, and ~7%. HC emissions from HVO fuel at higher engine loads are ~45% lower compared to diesel. This can be explained by the above-discussed influence of fuel on the quality of the atomization and combustion processes. In case the fuel has a lower cetane number, it takes longer to start, which causes higher HC emissions [85].

3.2.4. Smoke

Smoke is generated by partial combustion of the fuel. The HVO smoke levels that we see in the graph (Figure 10) are reduced by an average of ~18% compared to diesel. This can be explained by the fact that the C/H ratio in HVO in its composition was 17% less (Table 1), and also does not have such components as sulfur, aromatic hydrocarbons, and other mineral impurities in its chemical composition, which form the formation of soot [86]. As discussed earlier, testing mixtures with duck fat (Table 1) contains some oxygen in its molecule, which improves combustion. Blends of HVO and pure fat have lower values in comparison with diesel fuel. The average values for all tested loads were: for F25~51%, F50~54%, F75~56%, and F100~59%. The decrease in smoke emission for the mixtures can be explained by the high mass oxygen content and the lower C/H ratio (Table 1). The presence of excess oxygen in mixtures with pure fat leads to better combustion and results in less smoke generation under all engine load conditions.

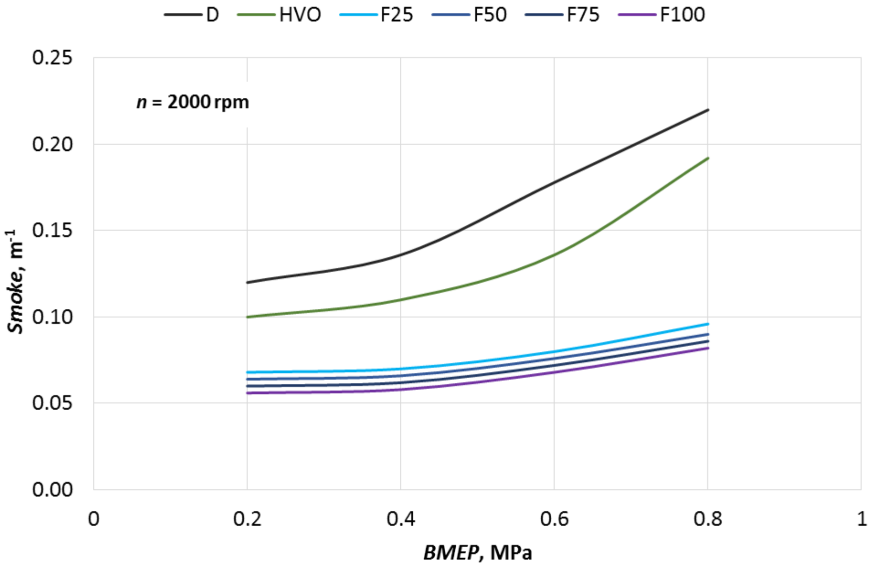

Figure 10. Dependence of smoke emissions on the load using different fuels.

3.2.5. Emissions of Nitrogen Oxide (NO_x)

Figure 11 shows increasing NO_x emissions with increasing loads for all testing fuels. This was due to the higher combustion temperature. D100 has the highest NO_x emissions. Furthermore, the variation between D100 and HVO100 to various loads on average is ~18%, and between D100 and F100, ~5%. At a higher load (BMEP = 0.8 MPa), the NO_x emissions were reduced for HVO~17.6%, F25~9.1%, F50~7.2%, F75~5.4%, and F100~3%, than for D100. This means that NO_x emissions from conventional diesel are highest in all cases. Nitrogen oxide emissions are lowest with HVO, which has the highest CN count of all samples. The ambiguous impact on nitrogen oxide emissions may depend on the cumulative effects of ignition delay, fuel injection quantity, and injection quantity distribution between the pilot and main injection [62]. Ignition quality is often influenced by cetane number; therefore, a high CN value indicates a short ignition delay, which means less fuel energy (ROHR) in the premix stage, and therefore, lower NO_x emissions.

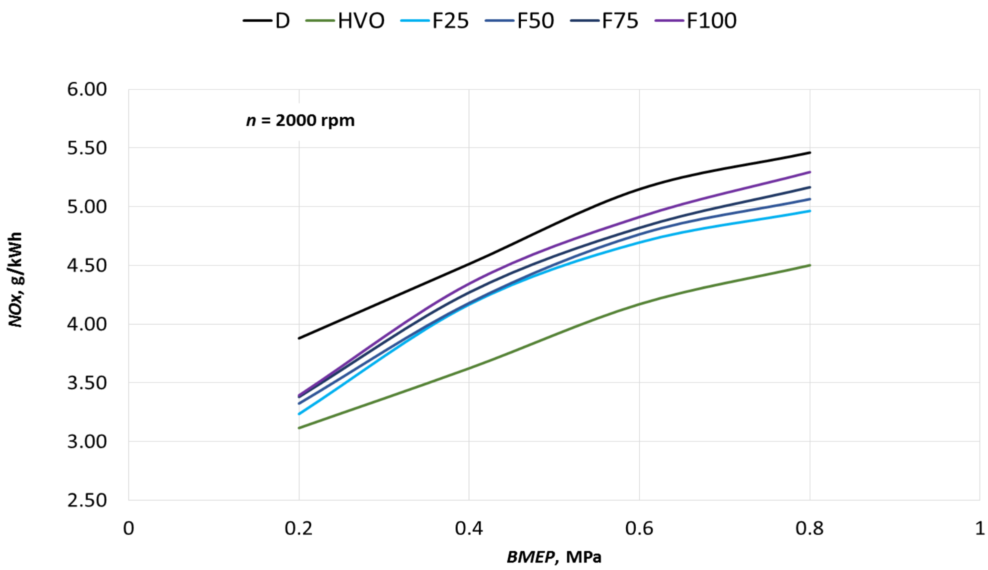

Figure 11. Dependence of nitrogen oxide emissions on the load using different fuels.

It can be assumed that the emissions grow for HVO–fat mixtures is related to the presence of oxygen molecules in the fuel. The increase of NO_x emissions can also be explained by an increase in the iodine value. The amount of iodine is related to the cetane number, and the density and compressibility of fuel samples [87]. Thus, the experimental pure fat mixtures improve the oxidation of the fuel during combustion, leading to a higher local temperature, and therefore, a rise in nitrogen oxide emissions.

3.3. Energy Indicators

As presented in Figure 12, the brake specific fuel consumption (BSFC, g/kWh) for all duck fat blends at high loads was higher compared with pure diesel. However, the BSFC for HVO was lower by ~2.4% in comparison with pure diesel. It was noted that with an increase in the percent of pure fat in the samples, the fuel consumption rose for F100 ~ 17.7% in comparison to diesel fuel. When comparing fossil diesel fuel and other HVO mixtures with pure fat, an increase in BSFC for F25 ~ 1.6%, F50 ~ 6.8%, and F75 ~ 11.8% was noted. On condition that the calorific value of fat has a low value, then to maintain a constant speed at a certain load, the engine needs, accordingly, more fuel, and hence, we have an increased consumption of fuel [88]. One of the reasons that may influence the increase in BSFC with a percentage of pure fat is associated with a higher density compared to fossil fuels [89].

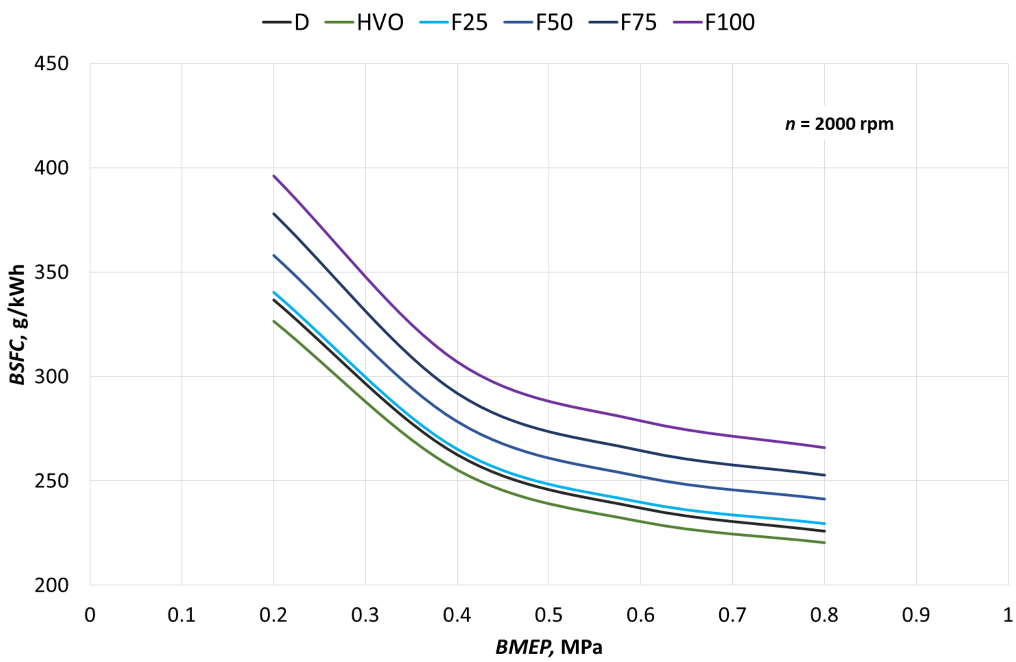

Figure 12. Dependence of BSFC, g/kWh on the load using different fuels.

Figure 13 presents that, for all samples of fuel, BTE was increased with increasing load, due to a rise in the ratio of indicated power and internal mechanical losses of the engine. With an increase in the load, the quality of the processes of mixture formation and fuel combustion improves as the combustion temperature rises [90], which also determines the above-described dependence of the BTE on the engine load.

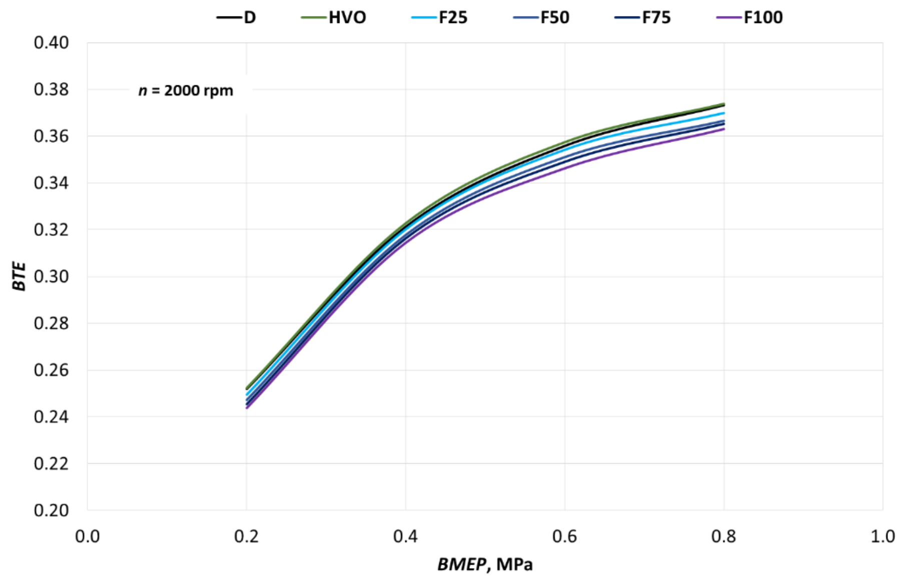

Figure 13. Dependence of BTE on the load using different fuels.

Figure 13 shows the highest BTE for HVO, followed by mineral diesel fuels. The contrast between these samples of fuels was ~0.14%, which is directly related to LHV and the combustion process. A total of 1 kg of HVO fuel has ~2.4% more energy and HVO cyclic fuel mass is ~2.4% less compared to diesel. HVO fuels have shorter injection duration and shorter combustion duration. Lower cooling and exhaust heat losses increase the BTE of HVO in comparison to diesel fuel.

There is a clear trend in Figure 13 that as the pure fat in the blends increases, the BTE tends to decrease. At loads of BMEP = 0.8 MPa for F100 it was found that a reduction of BTE was on average ~2.7%, compared to diesel fuel. Brake thermal efficiency depends on how efficient the combustion is. The amount of oxygen in the fuel with the duck fat additive increases, this reduces the LHV and requires longer fuel injection duration. The BTE tends to decrease, since poor atomization is important due to the high viscosity of fat. With longer combustion duration, more energy of fuel is transferred to the cooling system and to the exhaust, which reduces the BTE. Higher amounts of oxygen, which accelerates combustion, have a smaller effect here.

4. Conclusions

On the basis of the studies carried out, it can be concluded that:

1. The HVO compared to diesel fuel has ~1 CAD shorter ignition delay, ~20% lower ROHR during the premixed combustion phase, and slightly higher ROHR during the mixing-controlled combustion phase. The addition of pure fat to the mixtures increased the ignition delay phase compared to HVO, causing a shorter period of the premixed combustion phase and increasing ROHR at same time, but did not reach the level of diesel;
2. CO_2 emissions at all engine loads were reduced for HVO ~ 7% for F25 and F50 mixtures approximately by 3–5%, except F75 and F100, which were ~1.2% and ~2.8% higher than diesel fuel. This is mainly due to the specific fuel consumption and C/H ratio in fuels, as well as the efficiency of the mixing and combustion processes;
3. CO emission at a low load for F100 increased by 160–60% compared to diesel fuel. The reason for this is a low fuel pressure, which, in turn, causes the formation of large droplets of high density and viscosity fuel, which burn much worse. Increasing the engine load significantly reduces the CO emissions of pure fat. HC emissions for HVO100, F25, F50, F75, and F100 were lower, opposite to fossil diesel fuel, respectively, ~45%, ~28%, ~23%, ~19%, and ~7%. This is explained by the simpler molecular

structure of HVO and better injection and combustion properties. The fat changes the quality of the injection and the combustion deteriorates, especially at low loads;

4. Smoke values, on average, decreased by 18% for HVO and 51%, 54%, 56%, and 59% for F25, F50, F75, and F100 compared to diesel fuel. The decrease in smoke emission for the mixtures can be explained by the high mass oxygen content in duck fat and the lower C/H ratio in HVO. Due to the fat additive, the worst fuel injection did not increase the smoke;
5. The maximum difference of NO_x emissions was observed between D and HVO and amounted to ~18%. By increasing to F100 emission of NO_x, it remained 6% lower compared to diesel. It can be assumed that the maximum temperature rise during the combustion of diesel fuel is higher; therefore, the level of formation of nitrogen oxides for diesel is higher. Due to the worst fat injection, the maximum combustion temperature was lower compared to diesel;
6. BSFC of pure HVO fuel was ~2.4% lower compared to conventional diesel due to 2.4% higher LHV. HVO fuel mixtures with a duck fat additive can only be used after heating them to 40–50 °C. With an increase in the concentration of fat to 100% in the HVO–fat mixtures, a proportional increase in the BSFC was observed on average up to 17.5% in comparison with conventional fossil diesel fuel due to the ~13% lower calorific value of the fat and slightly (2–3%) lower BTE for fat containing mixtures, due to their higher viscosity, and accordingly, poor atomization and combustion compared to diesel fuel.

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