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Operational Issues of Using Replacement Fuels to Power Internal Combustion Engines

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Abstract: The classification of engine fuels was systematised in the present study. The basic evaluation criterion included the type of raw material used for the production of motor fuel and the prevalence of its usage. There was a reason for the purposefulness of searching for new kinds of engine fuels not only for the sake of environmental protection but also for the rational use of natural resources. The concept of substitute fuels was methodically presented. The criteria for the qualification of substitute fuels for internal combustion engines were systematised. Using the example of fuels produced from bio-oils, tests were carried out to assess the prospects of considering bio-oil fuels as substitute ones for self-ignition engines. Accordingly, an analysis was, inter alia, conducted on the fuel combustion process in the cylinder of a test self-ignition engine. Based on the results obtained, the thesis was formulated that rapeseed methyl ester (RME) fuel can be considered a substitute fuel for modern self-ignition engines. There are no significant differences between the physicochemical properties between DF diesel fuel and B100 fuel apart from a significantly higher oxygen mass content in B100. The torque of an internal combustion engine is regularly higher for diesel fuel. The use of B100 fuel enables a measurable reduction in pollutant emissions. The working factor pressure in the cylinder is slightly lower when the engine is powered by B100. The relative heat release rate for B100 is slightly lower compared to DF diesel.

Keywords: conventional and nonconventional fuels; substitute fuels; engine combustion process analysis

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1. Introduction

In the modern world, the consumption of combustion engine fuels has become a global problem. As a general rule, the consumption of energy carriers is a source of pollution for the environment, causes the depletion of natural resources and contributes significantly to the intensification of sociopolitical tensions due to the availability of required resources.

Hence, a growing interest in expanding the possibilities for the obtainable energy carriers applicable in the energy conversion system has been observed. The need for new solutions is mainly due to the issues related to the energy security of the states and their structures as well as environmental protection, thus, human well-being. Consequently, these issues concern sustainable development at a global level.

In light of the methodical subject of the present study, relevant definitions are provided below.

Energy carriers are substances, phenomena, objects or devices that can be used to satisfy human energy needs. Fuels are energy carriers that make it possible to obtain energy through combustion. Combustion is an exothermic redox chemical reaction, as a result of which, the rate of heat release causes electromagnetic radiation of the reaction products with a frequency in the range of visible radiation with an intensity considered to be the luminous efficacy of radiation. In addition, a given fuel is a reducing agent (reductant) in the combustion reaction with an oxidizing agent (oxidant) that is primarily oxygen contained in the air (some heat engines, e.g., rocket engines, also use other substances as oxidants). Therefore, calling hydrogen “a fuel” for the fuel cell is not justified—it is an energy carrier but not a fuel.

In light of the prevalence of their use to date, motor fuels can be classified into

- Conventional,
- Nonconventional.

Conventional motor fuels are assumed to be those for which internal combustion engines are adapted as standard by the manufacturers. Accordingly, these are hydrocarbon fuels derived from the processing of crude oil: motor gasoline and diesel fuels. Nonconventional fuels are other fuels used to power internal combustion engines, both hydrocarbon and nonhydrocarbon ones derived from the processing of crude oil and other mineral resources, including those derived from the processing of biological resources as well as the so-called synthetic fuels.

There is a wide variety of available fuels for powering internal combustion engines.

The basic nonconventional gaseous hydrocarbon fuels (Traditionally, some unconventional fuels are named after raw materials for their production. In reality, they are fuels made from, e.g., petroleum gas, natural gas and biogas and processed, and above all, they are cleaned of impurities and composed with multifunctional additives.) are as follows [1–14]:

- A mixture of liquefied petroleum gases (mainly propane and butane)—LPG—stored at ambient temperature and pressure ($0.3 \div 0.5$) MPa;
- Liquefied natural gas (mainly methane)—LNG—stored at -162 °C and at atmospheric pressure;
- Compressed natural gas (mainly methane)—CNG—stored at ambient temperature and at pressure ($16 \div 25$) MPa;
- Biogas fuel;
- Biogas fuel purified to natural gas standard, the so-called biomethane.

As nonhydrocarbon nonconventional fuels, there are usually considered:

- Hydrogen—H_2;
- Alcohols:
  - Methanol—CH_3OH;
  - Ethanol—CH_3CH_2OH;
  - Higher alcohols, e.g., butyl alcohols—C_4H_9OH: n-butanol, sec-butanol, isobutanol and tert-butyl alcohol.

For nonconventional fuels, there are requirements in terms of the operation of internal combustion engines. The basic requirements include [3,14–16]:

- Safety of use;
- Physicochemical stability;
- Compliance with requirements related to physicochemical properties;
- Fulfilment of other functions indispensable in engine operation by ensuring appropriate physical and chemical properties, e.g., anticorrosive, antiwear, washing, with effects on the course of combustion processes, etc.;
- Reducing emissions of substances particularly harmful to the environment, inter alia, by:
  - Reducing contents of cyclic organic compounds;
  - Reducing contents of impurities and additives contributing to the emission of substances particularly harmful to the environment, among others: lead and sulphur compounds.

For environmental reasons, fuels are required [3,14–16] to:

- Ensure that engines are as efficient as possible overall with the purpose of protecting natural resources and reducing global emissions from fuel combustion—which translates into the use of fuels with the highest possible calorific value;
- Enable a reduction in the emissions of substances that are particularly harmful to the environment; this translates into minimising the proportion of pollutants and additives in fuels that contribute to the emission of substances harmful to the environment; this also calls for the renewability of fuels to make possible carbon circulation on a small timescale;
- Keep with safety requirements for the use of means of transportation and engines; in this respect, the biodegradability of fuels is also called for;
- Ensure sufficient durability of engines—reducing the generation of wear and tear products as well as waste products due to the operation of means of transportation;
- Be produced and distributed so that the environment is impacted possibly the least.
- An important criterion for the classification of fuels in terms of fossil carbon emissions is the division into [1,3,7,8,14,16,17]:
- Nonrenewable (fossil) fuels;
- Renewable fuels.

Nonrenewable nonconventional fuels are hydrocarbon fuels derived from the processing of raw materials of fossil origin. In contrast, nonconventional renewable fuels are derived from the processing of biological substrates. Biodegradable products, waste or residues of biological origin from industry, forestry and agriculture, including fisheries and aquaculture, as well as industrial and municipal wastes, are used to produce bio-based fuels. Their use makes it possible to safeguard natural resources.

In work [18], there the potential of tyre pyrolysis oil to power diesel engines was also presented. Work [19] discusses the combustion and characteristics of particulate matter morphology in a compression ignition diesel engine.

Article [20] describes the properties of components of residual marine fuels (RMF).

Renewable fuels are mainly based on [1,3,5–9,14,16,17,21–30]:

- Alcohols (methanol, ethanol, propyl alcohols, butyl alcohols and others);
- Higher carboxylic acids (vegetable oils) and their derivatives (primarily esters)—rapeseed methyl esters (RME, RŐME—German lang.: Rapsölmethylester), soybean oil methyl esters (SBME), sunflower oil methyl esters (SME, German lang.: Sonnenblumenmethylester), palm oil methyl esters (PME, PŐME—German lang.: Palmölmethylester) and coconut methyl esters (CME);
- Biogas—derived from the process of anaerobic decomposition of organic compounds.

Currently, the following uses of nonconventional fuels are commonly accepted:

- Addition of ethanol to gasoline up to 5% V/V (V/V—volume fraction);
- Addition of vegetable oil methyl esters to diesel fuel up to 7% V/V;
- Fuel B100—vegetable oil methyl esters;
- Fuel B20—20% V/V vegetable oil methyl esters blended with diesel;
- Liquefied petroleum gas;
- Natural gas, biomethane and biogas fuel.

For normative reasons, gasoline and diesel fuels with an ethanol content of no more than 5% V/V and 7% V/V, respectively, are not included in the biofuel category and, therefore, are classified as conventional fuels.

The use of gaseous fuels to power internal combustion engines in vehicles and machinery requires structural modernisation of engines and their power systems. In the case of the use of fuels based on natural gas and biogas, the thoroughgoing modernisation of engine design is required. The use of gaseous fuels also necessitates the modernisation of engine control algorithms [31].

The use of fuels mixed with ethanol requires thorough structural changes to internal combustion engines [1,9,10,16]. In the case of spark-ignition engines, there is a group of so-called flexi-fuel engines, i.e., 'flexible' in terms of the fuels used [1,9]. These fuels can be

E85 fuel, a gasoline mixture containing (70 ÷ 85)% V/V ethanol mixed with water 95% V/V, gasoline and a mixture of gasoline and E85 fuel. Self-ignition engines running on ethanol fuels are Scania engines powered with E95 fuel (also called ED95) [11,13]. E95 fuel contains 92.2% m/m (m/m—mass share) ethanol/water mixture with 95% V/V alcohol and an ignition activator (the so-called ignition improver) at 5% m/m, as well as methyl tert-butyl ether (MTBE) and isobutanol at 2.8% m/m [11,13]. Numerous companies producing self-ignition engines allow the use of B100 and B20 fuels. Consequently, fuels based on bio-oil esters are usually considered substitutes for diesel fuels used to power self-ignition engines, although many study results indicate that the use of fuels of this kind may lead to changes in engine performance [3–6,14–16].

The aim of the present study was to assess to what extent it was reasonable to consider B100 fuel based on rapeseed oil methyl esters (RME) as a substitute for diesel fuel. The assessment was made on the basis of the results of empirical tests presented in this paper and carried out on a test engine powered with diesel or B100 fuel—a type adapted for summer use. The tests focused on the performance characteristics of the engine and, in particular, on the processes describing fuel combustion processes in the engine cylinders. The assessment was supported by the knowledge provided in the literature on the subject.

2. Criteria for Qualification of Substitute Fuels for Internal Combustion Engines

The search for nonconventional fuels in relation to traditional petroleum-derived fuels principally used for powering internal combustion engines has been dictated by both environmental and economic considerations. Among the ecological considerations, first and foremost, there are not only emissions of pollutants harmful to health, but also—from the perspective of fuels from renewable sources—emissions of fossil carbon dioxide, taking into account climate change programmes aimed at emissions reduction. Both environmental and economic considerations include the search for fuels not derived from fossil sources in efforts to protect natural resources. The economic and social aspect is the activation of communities and hitherto neglected areas to produce raw materials for nonconventional fuels.

The use of nonconventional fuels usually requires modifications to engines adapted to run on those that are conventional.

The modifications deliberated are related not only to the design, materials and technology of engine parts and systems but also to the engine's power systems, which constitute structural components of engine-driven equipment [31].

Regulatory changes are related to the autonomous control algorithms of the engine processes [31]. These changes mainly concern fuel dosage. In spark-ignition engines, it is usually necessary to modify the control algorithm of the ignition advance angle, and in self-ignition engines, the injection advance angle and time characteristics ('Characteristics' regards not only dependencies (as is generally understood) but also values—zero-dimensional (otherwise: point)—characteristics.) of the power supply system. In both spark-ignition and self-ignition engines, there can be considered a modification of the control algorithms for the exhaust gas recirculation ratio, engine boost pressure, valve timing and lift, intake system parameters and thermal state of the engine.

The use of substitute fuels does not require modification of engines originally adapted to run on conventional fuels.

There are several basic criteria for evaluating nonconventional fuels in terms of meeting the requirements for substitute fuels. These criteria can be broadly classified as follows [3,5,6,14,16,17]:

- Criteria based on the evaluation of the physicochemical properties related to the use of fuels for engine running;
- Criteria based on the evaluation of the processes occurring in the internal combustion engines powered by the evaluated fuels;
- Criteria based on the evaluation of the performance characteristics of the internal combustion engines powered by the evaluated fuels.

The first criterion mainly concerns the properties that determine the processes occurring in the engine. Among the criterion values related to the assessment of physicochemical properties, the following can be mentioned first and foremost: elemental composition and, related to it, calorific value and the stoichiometric factor. In terms of fuel atomisation quality, the important roles are played by fuel viscosity, density and surface tension. The viscosity and other parameters that characterise fuel tribological properties, such as propensity to affect engine structural and operating materials, have a significant impact on the wear of engine components and, consequently, on their durability and reliability, as well as on service characteristics. Amongst fuel physicochemical properties, fuel stability is important for organisational reasons.

The processes occurring in internal combustion engines that determine their operating characteristics are mainly those related to the power supply and fuel combustion in the cylinders [32]. This mainly concerns engine operational characteristics. Moreover, the tribological processes, which take place in the engines and are determined by fuel physicochemical properties, belong to the group of processes that determine engine performance.

Among the criteria based on the evaluation of the performance properties of internal combustion engines, there are firstly operational properties mainly in terms of characteristics related to energy, economics and ecological issues [3,5,6,14,17].

Energy characteristics are pronounced by an engine's capacity to perform work. Thus, effective engine power is the measure that most generally characterises this feature. Surely, the aspects characterising the ability to do work can also include torque and usable RPM range, and the brake means effective pressure. In automotive applications, the maximum speed of a vehicle can be included in this group of characteristics. The energy properties are also characterised by the dynamic properties of the engines and the equipment they drive. In the case of automotive engines, a relevant parameter is, for example, the time needed by a vehicle to accelerate to a certain speed.

Ecological criteria describing, e.g., pollutant and noise emissions or a fuel's predisposition to biodegrade, are also important from the perspective of utility aims [3,5,6,14,17].

The parameters, such as durability and reliability, as well as service requirements are related to the operational properties of internal combustion engines.

3. Assessment of Bio-Oil Ester-Based Fuels in Terms of Possibilities to Be Qualified as Substitute Fuels for Internal Combustion Engines

The empirical tests were carried out with the use of the AVL single cylinder test bed [33], the AVL 5402 single-cylinder self-ignition test engine [34], a set of exhaust gas analysers and the apparatus for controlling the entire system operation. AVL PUMA [2] and AVL CONCERTO [35] software were used for data collection and analysis.

The basic data on the AVL 5402 engine are presented in Table 1.

Table 1. Basic information on the AVL 5402 engine.

Number of Cylinders	1
Cylinder diameter	85.01 mm
Piston stroke	90.00 mm
Displacement	511.00 cm^3
Combustion system	Self-ignition
Timing	Four-valve
Compression ratio	17.0 ÷ 17.5
Engine power system	Direct injection, single injector, tray system (Common Rail)
Maximum net power, nonsupercharged	6 kW
Maximum net power, supercharged	16 kW
Rated speed	4200 min^{-1}
Injection pressure	180 MPa

Thanks to the use of specially designed head gaskets, the AVL 5402 engine is capable of changing compression ratios. Specific openings in the engine head allow for the insertion of cameras into the combustion chamber and for the observation of the fuel mixture burning. The engine is equipped with an exhaust gas recirculation system and sensors to measure, inter alia, the combustion chamber pressure and exhaust gas temperature. The engine's fuel supply algorithm can be modified through the injection apparatus installed and the included software.

The AVL single cylinder test bed is equipped with the electrorotor brake AVL DP80 (water-cooled) for load setting as well as an electric motor that allows the engine to be started and driven. There also are mounted pumps and heat exchangers to ensure the circulation of the cooling liquid and motor oil as well as to maintain their temperature.

This study focused on speed characteristics of the basic properties of the engine fuelled with:

- Classic diesel ORLEN VERVA ON BIO (quality certificate no. 14BMK/A/2502)—labelling: DF;
- RME biofuel—with summer additive Bioagra Oil (quality certificate no. 74/E/2014)—labelling: B100.
- Under the study framework, there were determined speed characteristics of basic parameters characterising engine properties:
- Energy-related: torque and effective engine power;
- Economy-related, in light of fuel consumption: mass fuel consumption rate;
- Ecology-related, in light of pollutant emissions: concentrations of substances harmful to the health, contained in exhaust gases: volumetric concentration of carbon monoxide, the volumetric concentration of hydrocarbons, the volumetric concentration of nitrogen oxides and the mass concentration of particulate matter;
- Mass air flow rate;
- Air volume flow rate;
- Exhaust gas mass flow rate;
- Exhaust gas volume flow rate;
- Exhaust gas temperature.

The speed characteristics of the engine were determined for the rotation speed $(1200 \div 3600)$ min^{-1}.

At each operating point of the engine, the engine was signposted. The pressure of the working medium in the cylinder was recorded with a resolution of 0.1 degree of crankshaft rotation.

Table 2 presents the physical and chemical characteristics of the tested fuels consistent with the quality certificates issued by the producers. Fuel properties are presented on the basis of fuel specifications provided by manufacturers. The properties of the supplied fuels meet the requirements applicable to the presented work.

Table 2. Physical and chemical characteristics of fuels.

Characteristics	Unit	DF	B100	Δ	β
Density	kg/m^3	832.5	880.0	47.5	0.057
Calorific value	MJ/kg	43	38	−5	−0.116
Cetane number		55.6	57.3	1.7	0.031
Kinematic viscosity at 40 °C	mm^2/s	2.87	4.50	1.630	0.568
Elemental composition of the fuel					
Carbon content by mass	% m/m	0.837	0.772	−0.065	−0.077
Hydrogen content of fuel, mass fraction	% m/m	0.149	0.120	−0.029	−0.197
Oxygen content of fuel, mass fraction	% m/m	0.014	0.108	0.094	6.676
Sulphur content of fuel, mass fraction	ppm	7.5	3.0	−4.5	−0.600
Turbidity temperature	°C	−9	−10	1	
Temperature of fuel filter plugging	°C	−28	−15	13	
Fuel ignition temperature	°C	65	101	36	

The table also shows the difference Δ and the relative difference β between the values of the physical characteristics of B100 fuel compared to DF fuel.

$$\Delta[X] = X_{B100} - X_{DF} \tag{1}$$

$$\beta[X] = \frac{\Delta[X]}{X_{DF}} = \frac{X_{B100} - X_{DF}}{X_{DF}} \tag{2}$$

where:

X_{B100}—physical characteristic of fuel B100;

X_{DF}—physical characteristic of diesel fuel DF.

The relative difference was not determined for temperatures, as they have no physical interpretation for the value zero—in contrast to other fuel characteristics analysed.

The physical and chemical properties of fuels are influenced by their elemental composition—Figure 1.

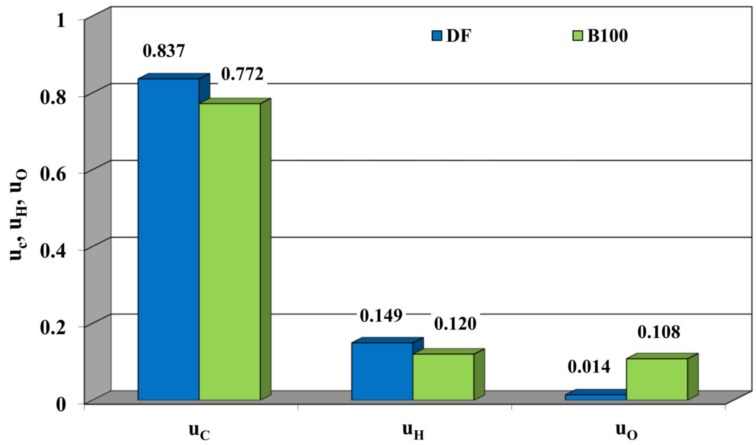

Figure 1. Elemental composition of the fuels tested.

The proportion of oxygen in diesel fuel DF is a result of the normative addition of bio-oil esters, yet it amounts only to 1.4%. In the case of B100 fuel, the oxygen proportion is 10.8%, which affects the fuel calorific value (for diesel fuel—11.6% higher).

The density of B100 fuel is 5.7% higher than that of diesel. This has a bearing on the amount of fuel delivered to the engine cylinder, as volumetric dosing is used in self-ignition engine supply systems. It follows that when using B100, more fuel is supplied to the cylinder, meaning that there is a richer combustible mixture overall.

As compared to diesel fuel, the cetane number is slightly higher for B100 fuel—a relative difference of 3.1%.

There is a big difference in the kinematic viscosity of the fuels tested—B100 kinematic viscosity is over 56% greater. This is one of the most problematic issues when considering B100 fuel as a substitute for diesel DF since operational problems may occur when B100 is used, especially at engine cold start. The viscosity–temperature characteristics of bio-oil esters are operationally unfavourable, as bio-oil ester viscosity increases significantly at low temperatures. This is confirmed by cold filter plugging at certain temperatures due to fuel components.

In the case of B100 fuel, the ignition temperature is significantly higher when compared to DF diesel, which is important for fire safety.

Figure 2 shows the external speed characteristics of the torque.

The torque value for B100 fuel is clearly lower compared to that of diesel, which is mainly due to B100′s lower calorific value (regardless of its higher density). The average absolute value of the relative torque difference in the rotation speed domain is 5.6%.

Figure 3 shows the external speed characteristics of the overall efficiency.

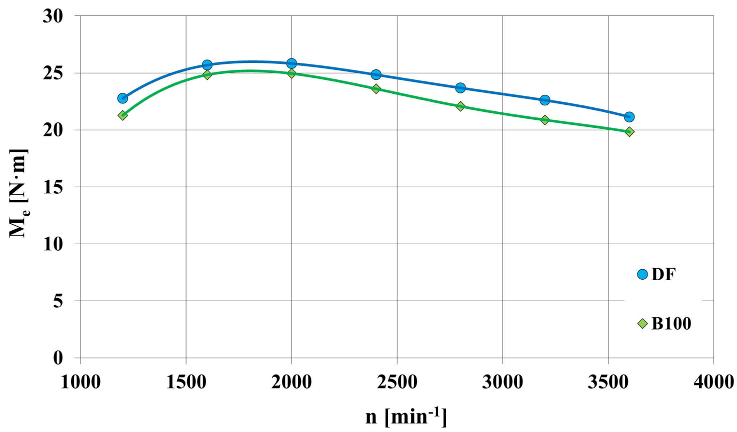

Figure 2. External speed characteristics of the torque-M_e in the rotation speed domain-n for an engine fuelled with DF diesel or B100 fuel.

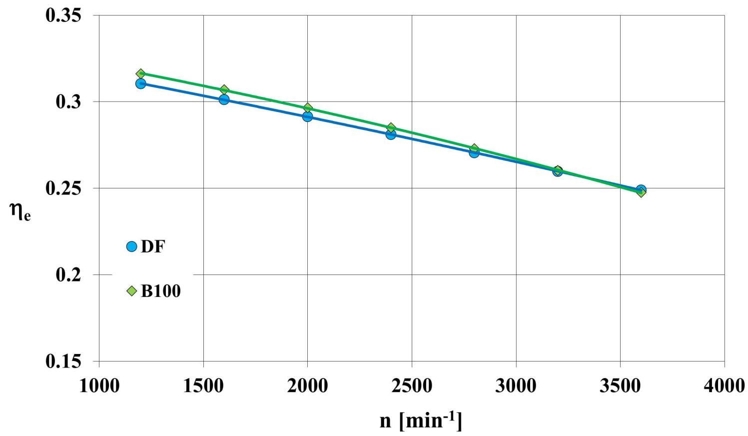

Figure 3. External speed characteristics of the overall efficiency-η_e in the rotation speed domain-n for an engine fuelled with DF diesel or B100 fuel.

The overall efficiency is slightly higher in the case of B100 fuel. The average absolute value of the relative difference in the speed domain is about 1%.

Figure 4 shows the external speed characteristics of the temperature of exhaust gas.

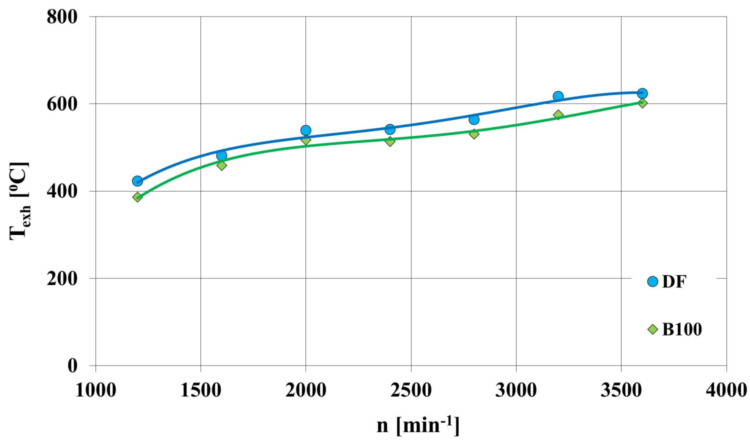

Figure 4. External speed characteristics of the temperature of exhaust gas -T_{exh} in the rotation speed domain-n for the engine powered with fuels DF diesel or B100.

A regularly lower exhaust gas temperature is apparent for B100 fuel, which is mainly due to its lower calorific value and poorer combustible mixture. In the rotation speed domain, this difference is on average approximately 30 K.

Figures 5–8 show the external speed characteristics of the specific brake emission of pollutants.

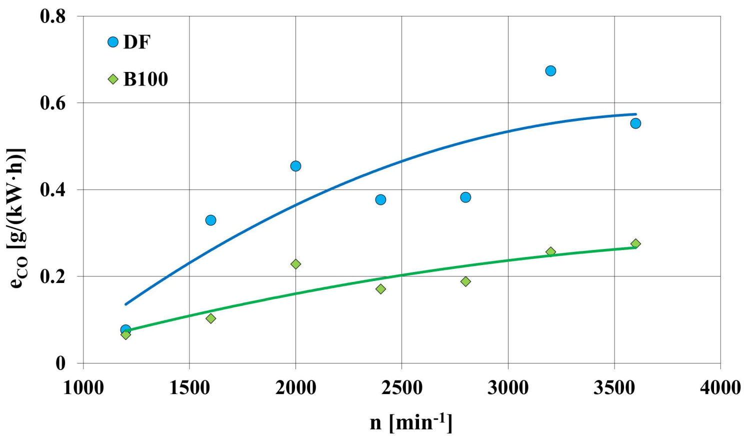

Figure 5. External speed characteristics of the specific brake emission of carbon monoxide-e_{CO} in the rotation speed domain-n for the engine powered with fuels DF diesel or B100.

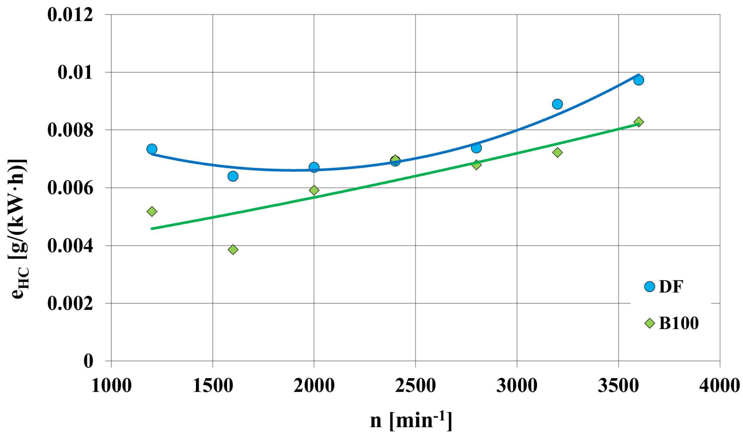

Figure 6. External speed characteristics of the specific brake emission of hydrocarbons e_{HC} in the rotation speed domain-n for the engine powered with fuels DF diesel or B100.

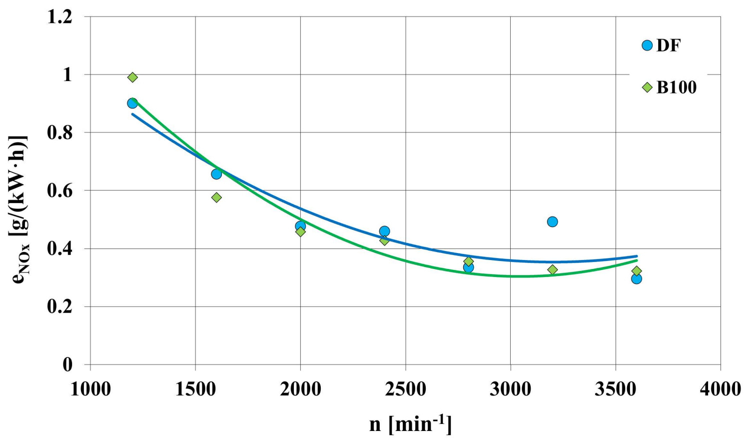

Figure 7. External speed characteristics of the specific brake emission of nitrogen oxides-e_{NOx} in the rotation speed domain-n for the engine powered with fuels DF diesel or B100.

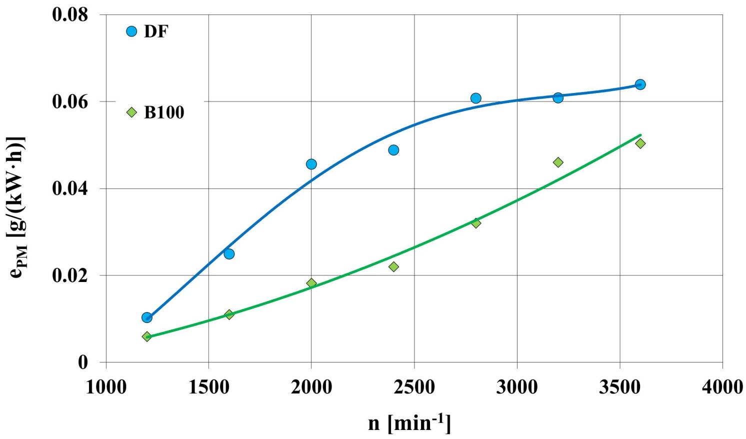

Figure 8. External speed characteristics of the specific brake emission of particulate matter-e_{PM} in the rotation speed domain-n for the engine powered with fuels DF diesel or B100.

Some irregularity in the characteristics tested is apparent, being particularly high for carbon monoxide. It is therefore advisable to compare the average values in the speed domain of the specific brake emissions—Figures 9–12.

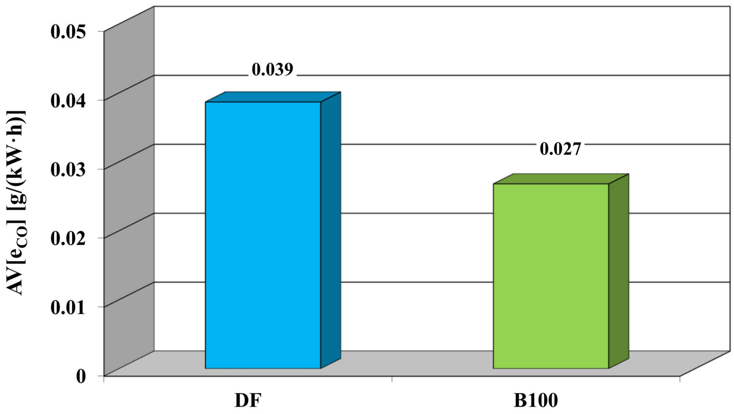

Figure 9. Average value—AV in the speed domain of the specific brake emissions of carbon monoxide—e_{CO} for the engine powered with fuels DF diesel or B100.

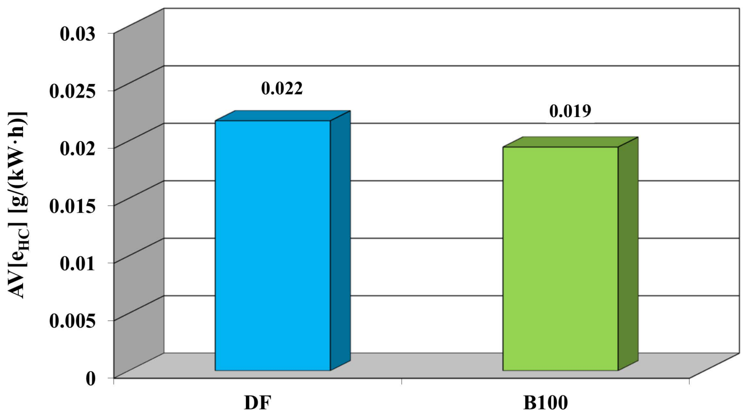

Figure 10. Average value—AV in the speed domain of the specific brake emissions of hydrocarbons e_{HC} for the engine powered with fuels DF diesel or B100.

For all pollutants, there is a significant reduction in specific pollutant emissions. The relative difference in the specific brake emissions is observed for carbon monoxide—31%, hydrocarbons—14%, oxides of nitrogen—9% and particulate matter—28%.

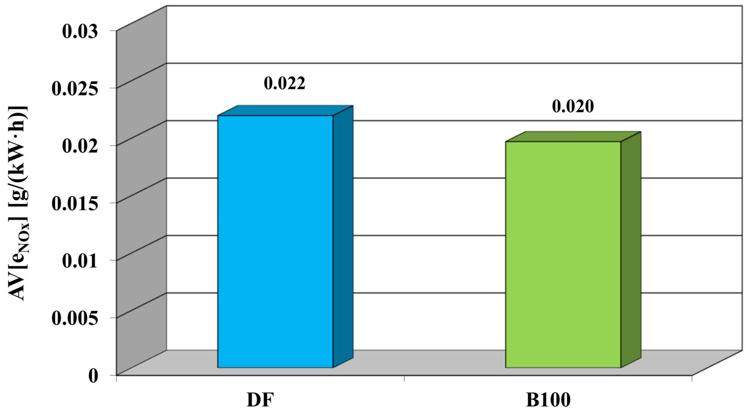

Figure 11. Average value—AV in the speed domain of the specific brake emissions of nitrogen oxides—e_{NOx} for the engine powered with fuels DF diesel or B100.

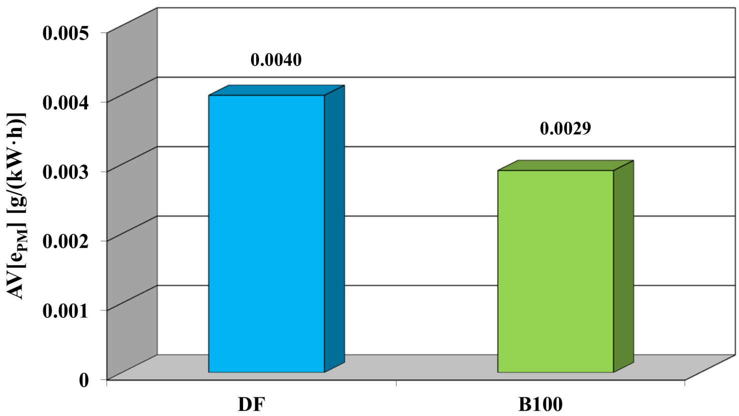

Figure 12. Average value—AV in the speed domain of the specific brake emission of particulate matter—e_{PM} the engine powered with fuels DF diesel or B100.

The engine indexing results are presented for operating points at rotation speeds of 1600 min^{-1} and 3600 min^{-1} for a crankshaft rotation angle in the range ($-30 \div 90$) degrees.

The results of the in-cylinder working medium pressure measurements were processed using a second-degree Savitzky–Golay filter [21] to reduce the contribution of high-frequency noise in the signals.

The working factor pressure process in the cylinder is shown in Figures 13 and 14.

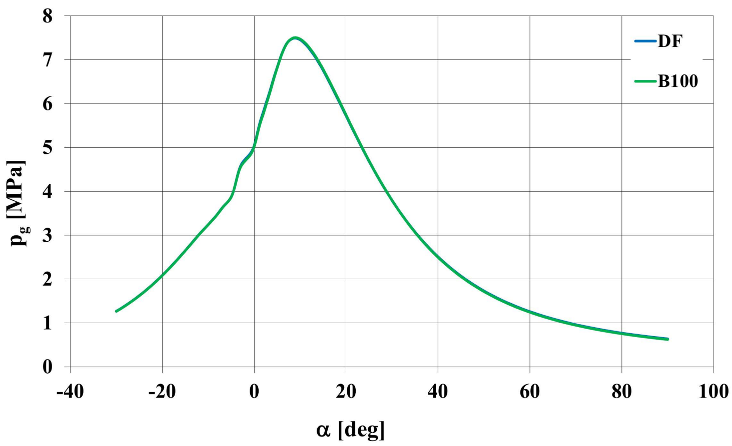

Figure 13. Process in the pressure of the working factor in the cylinder-p_g in the domain of the crankshaft rotation angle-α at the rotation speed of 1600 min^{-1} for the engine powered with fuels DF diesel or B100.

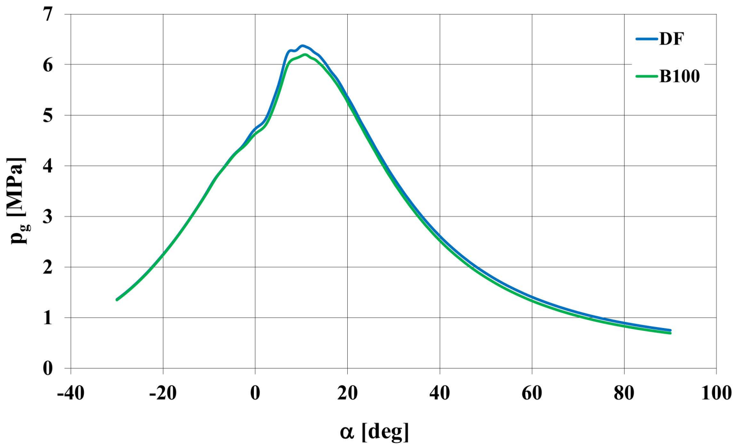

Figure 14. Process in the pressure of the working factor in the cylinder-p_g in the domain of the crankshaft rotation angle-α at the rotation speed of 3600 min-1 for the engine powered with fuels DF diesel or B100.

For the rotation speed of 1600 min^{-1}, there is practically no difference observed in the indexing graph. The pressure is faintly lower for B100 fuel. The average of the absolute value of the relative difference of the pressure of the working factor in the cylinder in the crankshaft angle domain is 0.69%. For the rotation speed, a slight difference is visible. Smaller values for fuel B100 are obtained (the mean value of the absolute value of the relative difference of the pressure of the working factor in the cylinder in the crankshaft angle domain is 3.33%).

Figures 15 and 16 show the process of the derivative of the working factor pressure in the cylinder against the angle of the crankshaft rotation. This is the measure of the so-called hardness of engine operation—the dynamic load on the piston–crank system [31].

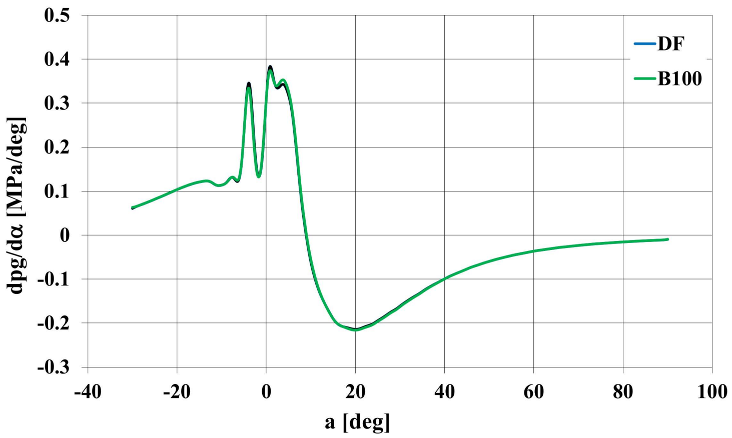

Figure 15. Process of the derivative of the pressure of the working factor in the cylinder-p_g against the angle of rotation of the crankshaft-$dp_g/d\alpha$ in the domain of the angle of rotation of the crankshaft-at the rotation speed of 1600 min^{-1} for the engine powered with fuels DF diesel or B100.

As in the case of the working factor pressure and also in the case of the factor pressure derivative with respect to the angle of rotation of the crankshaft, the value for B100 fuel is on average slightly lower. For the rotation speed of 1600 min^{-1}, the mean value of the absolute value of the relative difference of the derivative of the working factor pressure in the cylinder with respect to the angle of rotation of the crankshaft in the field of the angle of rotation of the crankshaft is 1.45%, while for the rotation speed of 3600 min^{-1}, it is 4.51%.

The test of heat release in the engine cylinder was also carried out on the basis of the recorded working factor pressure process. AVL's CONCERTO™ software [35] was used for this purpose. Figures 17 and 18 show the heat release rate in relation to piston displacement (In the determination of the rate of unit heat release with respect to piston displacement—$\delta q/d\alpha$, the symbol "δ" denotes the linear Pfaff differential form as opposed to the symbol "$d\alpha$" denoting a complete differential. This is because the infinitesimal heat gain is not a complete differential but a Pfaff form, as heat is a thermodynamic function of the process and not a thermodynamic function of the state [32]).

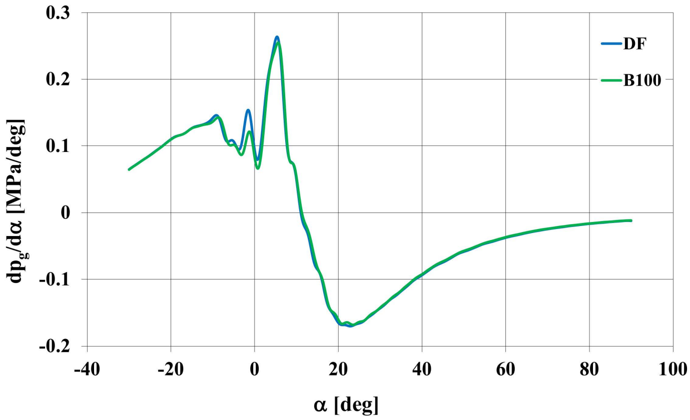

Figure 16. Process of the derivative of the pressure of the working factor in the cylinder-p_g against the angle of rotation of the crankshaft-$dp_g/d\alpha$ in the domain of the angle of rotation of the crankshaft-at the rotation speed of 3600 min^{-1} for the engine powered with fuels DF diesel or B100.

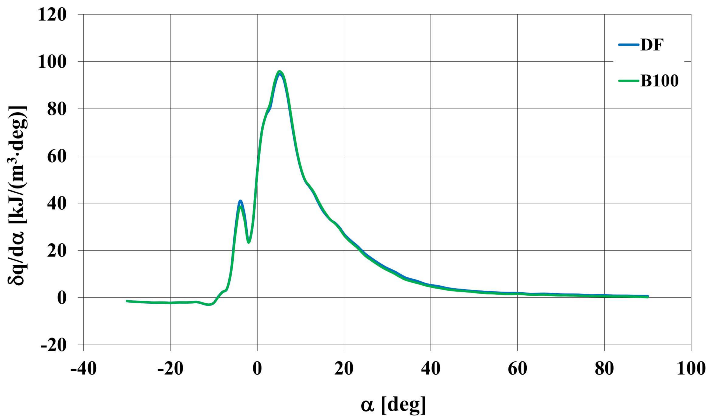

Figure 17. Process of the rate of unit heat release in relation to piston displacement-$\delta q/d\alpha$ in the domain of crankshaft rotation angle-at the rotation speed of 1600 min^{-1} for the engine powered with fuels DF diesel or B100.

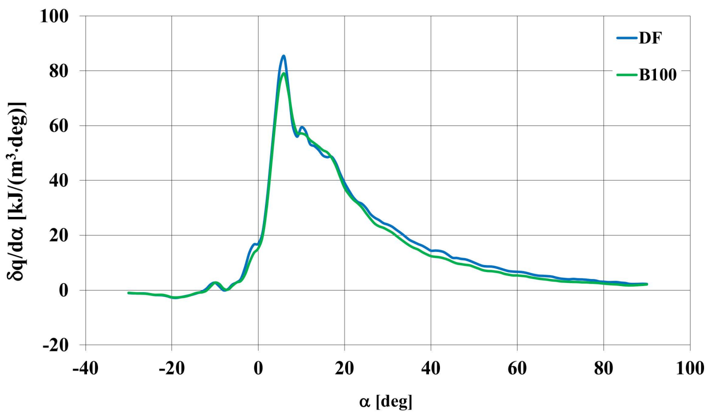

Figure 18. Process of the rate of unit heat release in relation to piston displacement-$\delta q/d\alpha$ in the domain of crankshaft rotation angle-at the rotation speed of 3600 min^{-1} for the engine powered with fuels DF diesel or B100.

On average, the relative heat release rate for B100 fuel is slightly lower. At a rotation speed of 1600 min^{-1}, the difference is practically imperceptible. The average value of the absolute difference in the relative heat release rates is 3.26%, whereas at the rotation speed of 3600 min^{-1}, it is 8.22%.

The temperature process of the working factor in the cylinder was also determined—Figures 19 and 20.

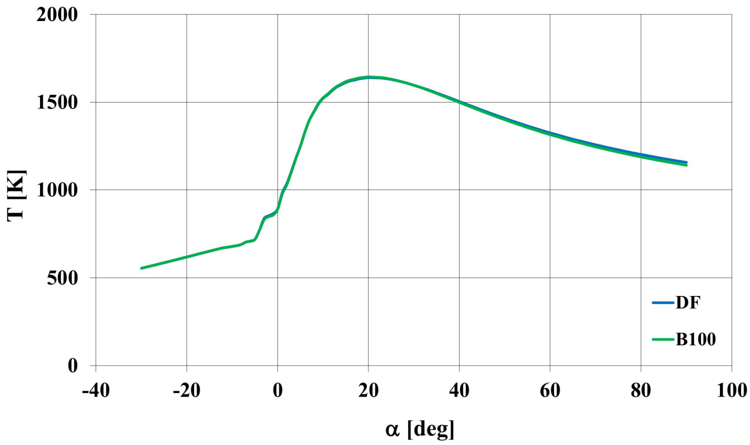

Figure 19. Process of the working factor temperature in the cylinder-T in the domain of the angle of rotation of the crankshaft-α at the rotation speed of 1600 min^{-1} for the engine powered with fuels DF diesel or B100.

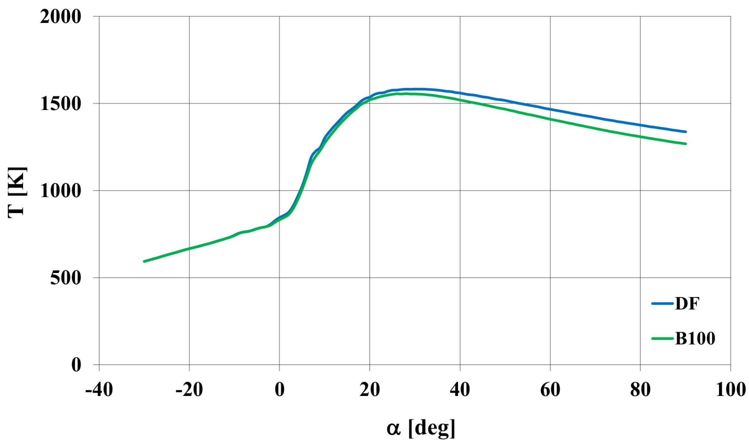

Figure 20. Process of the working factor temperature in the cylinder-T in the domain of the angle of rotation of the crankshaft-α at the rotation speed of 3600 min^{-1} for the engine powered with fuels DF diesel or B100.

The temperature of the working factor in the cylinder is on average slightly lower for B100 fuel. For the rotation speed of 1600 min^{-1}, the difference is practically imperceptible. The average value of the absolute value of the difference in the temperature of the working factor in the cylinder is 6 K, whereas for the rotation speed of 3600 min^{-1}, it is 32 K.

On the basis of the results of the combustion process analysis, the parameters of the process were also determined, including the start angle of combustion and the angle of autoignition delay, as well as the maximum values of the working factor pressure and temperature, heat release rates and corresponding crankshaft rotation angles. Then again, these results do not show much difference for the fuels tested.

4. Conclusions

The results of the study allow for the following conclusions:

1. For the majority of physical characteristics, there are no substantial differences between the physicochemical properties of DF diesel fuel and B100 fuel apart from a significantly higher oxygen mass content in B100—almost eight times as compared to DF diesel—and a considerably higher kinematic viscosity of B100—almost 1.6 times higher. The density of B100 is higher by almost 6%. The calorific value of B100 is lower by more than 11%. Regardless of the higher density, this results in a reduction of the heat input. Among the advantageous properties of B100, the cetane number higher by almost two should be noted. In addition, the comparably greater viscosity of B100 results in cold filter plugging at a higher temperature by 13 °C compared to that for DF diesel fuel. The viscosity of B100 and its low-temperature properties differ considerably from those of diesel.
2. The torque of the internal combustion engine was regularly higher for diesel fuel. The average value of the absolute value of the relative torque difference in the speed domain was 5.6%. The torque decrease observed in the case when the engine was powered by B100 fuel was mostly due to the lower calorific value of this fuel (apart from its higher density), resulting in a reduction in the mass fuel application rate. The effective engine power was reduced to the same extent. On the other hand, however, these are not important aspects of engine operation.
3. In the case of overall efficiency, there is a regular trend towards a higher value for B100 fuel. The difference is not large; the average value of the relative difference in the speed domain is about 1%. This is not a value of considerable importance for engine performance characteristics.
4. The use of B100 enables a measurable reduction in pollutant emissions. The relative difference in the specific brake emission is 31% for carbon monoxide, 14% for hydrocarbons, 9% for nitrogen oxides and 28% for particulate matter. These are the results important for engine characteristics in relation to emissions of pollutants that are harmful to the health of living beings. The reduction in emissions of carbon monoxide, hydrocarbons and particulate matter is primarily due to a higher mass proportion of oxygen in the fuel molecule. The molecular proximity of oxygen and, above all, of carbon promotes more complete and total combustion, as the reactivity of hydrogen to oxygen is much higher than that of carbon. In addition, there is a lower mass content of sulphur in B100 fuel—3 ppm versus 7.5 ppm for DF diesel. This factor also promotes a reduction in the intensity of particulate matter formation.
5. The working factor pressure in the cylinder was slightly lower when the engine was powered by B100. The average value of the absolute value of the relative difference in working factor pressure in the cylinder in the crankshaft angle domain ranges between (0.5 ÷ 3.5)%.
6. The hardness of engine operation was also lower when the engine was powered by B100. The average value of the absolute value of the relative difference of the derivative of the working factor pressure in the cylinder in relation to the crankshaft rotation angle in the crankshaft rotation angle domain is (1.5 ÷ 4.5)%.
7. The relative heat release rate for B100 was slightly lower compared to DF diesel. The average value of the absolute difference in the relative heat release rate ranges between (3 ÷ 8.5)%.

In relation to the similarity criteria considered and applied in the present study for the analysis of the investigated combustion processes, considerable similarities in the evaluated characteristics of the tested DF diesel and B100 fuels were observed. This relationship exists despite the differences in the values of the aspects characterising the physicochemical properties of the fuels, particularly in terms of the calorific value and viscosity.

To sum up the presented considerations, it may be concluded that slight differences in the evaluated functional properties of the internal combustion engine powered with diesel fuel or that based on rapeseed oil methyl esters justify the postulation that—based on the results of the study carried out—rapeseed oil methyl esters with summer additive may be considered a substitute fuel for diesel oil, taking into account the similarity criteria used in this study. This opinion has been confirmed by the data contained in the literature on the subject, in particular, that with regard to the operating properties of engines powered by rapeseed oil methyl ester-based fuels, such as engine reliability and component wear.

This article shows that treating the results of the analysis of the combustion process can be an effective way of qualifying unconventional fuels as substitute fuels. In a situation of care for the preservation of natural resources and the tendency to use renewable raw materials, the results of the research are very important for economic, ecological and social reasons.

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List of Acronyms and Symbols

AV - Average Value Operator
B100 - rapeseed oil methyl ester fuel
c_{CO} - volumetric concentration of carbon monoxide
c_{HC} - volumetric concentration of hydrocarbons
c_{NOx} - volumetric concentration of nitrogen oxides
c_{PM} - mass concentration of particulate matter
DF - diesel fuel
M_e - torque
n - rotation speed
q - unit heat
RME - rapeseed oil methyl ester
T_{exh} - exhaust gas temperature
T_g - temperature of the working factor
u_C - carbon content of fuel, mass fraction
u_H - hydrogen content of fuel, mass fraction
u_O - oxygen content of fuel, mass fraction
Δ - difference
α - angle of crankshaft rotation
β - relative difference
δ - Pfaff form
$\delta q/d\alpha$ - unit heat release rate
η_e - overall efficiency

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