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Article

Effects of Propanol on the Performance and Emissions of a Dual-Fuel Industrial Diesel Engine

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Abstract: The search for alternative fuels that can limit the use of traditional fossil fuels to power internal combustion engines is one of the main tasks faced by both the modern automotive industry and the modern energy industry. This paper presents experimental tests of a compression ignition engine, in which the conventional fuel, i.e., diesel, was partially replaced with propyl alcohol, i.e., a renewable biofuel. Studies on the co-combustion of diesel fuel with propanol were carried out, in which the energy share of alcohol varied from 0 to 65%. The research showed that an increase in the proportion of propanol, up to 30%, resulted in a significant increase in the rate of heat release and the rate of pressure increase in the cylinder of a compression-ignition engine. Increasing the alcohol content to 65% resulted in an increase in the ignition delay time and significantly shortened the duration of combustion. During the combustion of diesel fuel with a 50% propanol share, the engine was characterized by maximum efficiency, higher than diesel fuel combustion by 5.5%. The addition of propanol caused a slight deterioration of the combustion stability determined by the coefficient of variation for IMEP. The study of engine exhaust emissions has shown that the combustion of diesel fuel with a small proportion of propanol, up to 30%, causes an increase in nitrogen oxide emissions, while up to 50% contributes to a decrease in HC emissions. The increased share of alcohol contributed to a significant decrease in the emissions of both carbon monoxide and carbon dioxide, and caused a significant reduction in the concentration of soot in the exhaust of the compression-ignition engine.

Keywords: propanol; dual-fuel; diesel engine; emission

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1. Introduction

Compression ignition internal combustion engines are used in transport and heavy construction machinery and are a source of propulsion for generators due to their high durability, high power, and relatively low fuel consumption [1]. These engines combust mixtures with a large excess of air (lean mixtures) and thus they have lower emissions of CO and THC compared to spark ignition engines [2]. A significant limitation of these engines is their soot emission [3]. For this reason, alternative combustion systems and alternative fuels are used. Another two important factors prompting the use of alternative fuels are the constantly growing oil prices and the instability of the fuel market. The diversification of fuel sources is very important for industries to ensure energy stability [4]. Biofuels [5] are an alternative fuel to fossil fuels, and alcohols are a large group of biofuels. They are renewable fuels because they can be produced from biomass [6]. Additionally, alcohol-based fuels contain oxygen in their molecular structure, and thus can reduce the emission of some exhaust components, such as soot [7]. Alcohol-based fuels cannot be a substitute for diesel or biodiesel due to their self-ignition limitations. They are characterized by a low value of the cetane number, which adversely affects the self-ignition of these fuels, and which during combustion may result in knock combustion. Another disadvantage is the poor lubricating properties of alcohols, which contribute to faster wear of the engine injection elements [8]. Another disadvantage of alcohols is their lower calorific value in relation to diesel, which requires larger doses supplied to the engine to ensure sufficiently high engine power [9]. Piston engines are powered by both lower alcohols, such as methanol and ethanol, and higher alcohols, such as butanol or propanol [10]. Higher alcohols have properties similar to diesel fuel. This applies to both their relatively high calorific value and their cetane number or density [6]. Moreover, alcohols are characterized by a higher value of the heat of vaporization compared to diesel fuel. One of the interesting alcoholic fuels is propanol, which has better properties than methanol or ethanol. Currently, alcohols are viewed as an oxygen enriched additive that can be co-combusted with diesel fuel/biodiesel to intensify the combustion process in a compression ignition engine. Alcohols can be used as an additive to diesel fuel, but there are difficulties with the miscibility of both fuels whereby phase separation can occur [11]. To create a stable mixture, various types of stabilizers, such as n-pentanol and tetrahydrofuran, are used [12,13]. As shown by the results of extensive research, the alcohol content in the mixture with diesel fuel is limited to about 20% by volume [14]. Alcohols mix better with biodiesel and are closer to each other in terms of their molecular structure [15]. The technology devoid of these drawbacks is the dual-fuel engine, where the co-combusted fuels are delivered separately. Alcoholic fuel is fed to the intake manifold during the cylinder intake stroke (PFI—Port Fuel Injection), and diesel or biodiesel is fed directly to the combustion chamber to initiate combustion [16]. A dual fuel system is one of the most effective techniques for using alternative fuels to power the industrial engine. This technology allows for almost any share of fuels supplying the engine depending on its load or resources [17]. The share of alcohol in the combustion process significantly affects both the course of the combustion process, its phases, and the emission of exhaust gases. The alcohol that is fuel injected into the intake manifold, due to the high value of the heat of vaporization, causes the decrease in the temperature of fresh charge before the combustion is initiated with a dose of diesel fuel. This contributes to an increase in ignition delay along with an increase in the share of alcohol fuel [18]. The increase in ignition delay causes combustion to occur more rapidly, with a large increase in pressure, which causes an increase in temperature in the combustion chamber. The combustion takes place over a shorter time, which may contribute to an increase in an industrial engine's efficiency [19]. The objective of the paper [20] was to investigate the thermal performance, exhaust emissions, and combustion process of a small-displacement stationary compression ignition dual-fuel engine using fumigated ethanol. It was found that the addition of ethanol in a CI engine increased the rate of heat release, peak pressure, and thermal efficiency. Cycle-by-cycle variations were minimal with the diesel fuel. Engine cycle variations presented by the higher value of COV of IMEP were evidently related to various ethanol flow rates.

In the paper by Paul et al. [21] regarding the investigation of blend combustion, the authors presented the results of the investigation of the diesel-ethanol combustion process in the diesel engine. The experimental work was conducted on a single-cylinder, 4 stroke, water-cooled, naturally aspirated, and stationary DI engine that can produce a maximum brake power of 3.6 kW at 1500 rpm. The ethanol percentage was increased from 5% to 20% with a step of 5%, with a reduction of the diesel oil's participation. Paul et al. stated that a blend with 15% ethanol showed the best engine performance characteristics, with a 21.17% increase in thermal brake efficiency and 4.61% decrease in BSEC at full load. The combustion analysis also revealed an increase in the cylinder pressure and the heat release rate indicating an improvement in combustion conditions for the blend, as mentioned earlier. The blend also showed a substantial improvement in THC and CO emissions with a slight increase in NO_x emission. The exergy analysis showed a 25.64% increase in exergetic efficiency. Zhao et al. [22] presented the results of the assessment of combustion in an industrial engine powered by a mixture of diesel and propanol. They also found that the alcohol content increases the ignition delay time and shortens the duration of combustion. They also achieved a significant reduction in soot emissions but an increase in NO_x emissions compared to an engine powered by diesel fuel alone.

Study [23] investigated the effect of the fuel premixing ratio, direct fuel injection timings, and engine compression ratio on the soot particle emissions in the nano-size range from a non-road compression ignition engine. Experiments were conducted on a modified dual fuel single-cylinder engine at 1500 rpm. Methanol fuel premixing was found to have higher cyclic variations than gasoline premixing in the dual-fuel engine.

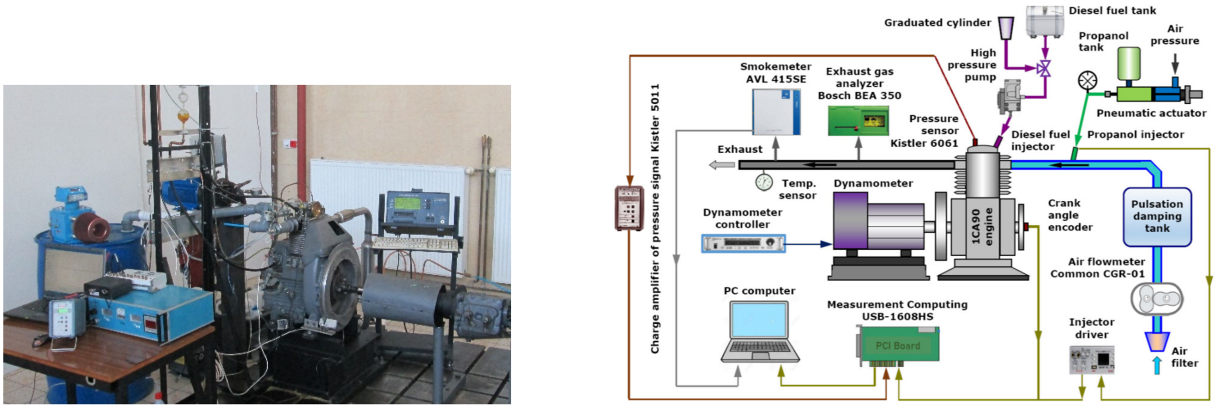
Muthaiyan et al. [24] investigated the combustion of propanol mixtures with diesel fuel in a stationary compression ignition engine with alcohol volume fractions of 10, 15, 20, and 25%. Combustion parameters such as cylinder pressure, ignition delay, heat release rate, and pressure increase rate were analyzed. The engine performance and emission characteristics were also tested. Propanol-diesel blends showed more prolonged ignition delay, higher heat release rates, and increased pressure. The engine's thermal efficiency decreased slightly with the combustion of the mixtures. Propanol-diesel blends significantly reduced CO, NO_x, and soot emissions.

Experimental research on the co-combustion of n-butanol with a mixture of pyrolysis oil and diesel fuel (TDF) was carried out by Karagöz [25]. The experiment demonstrated that using high doses of TDF in a fuel mixture causes a significant increase in NO_x, CO, and HC emissions. However, by adding n-butanol (up to 15%), the emission of these components can be reduced. For mixtures of TDF with alcohol, a reduction in the specific fuel consumption (BSFC) was achieved. Due to the high proportion of n-butanol in the mixture with TDF, the engine's thermal efficiency (BTE) was improved. It was found that a mixture of n-butanol, diesel fuel, and pyrolysis oil can be used in an industrial compression-ignition engine without the need to modify it, improving its performance and emissions. In paper [26], the authors presented the results of the impact of propanol as an additive to diesel fuel on an agricultural engine's performance. Propanol reduced the smoke emissions of rapeseed oil but increased NO_x, total hydrocarbons (THC), and CO emissions significantly. A drop in peak pressure and a slight increase in ignition delay were observed with increasing the propanol content in the diesel fuel. A propanol fraction in a blend causes improvement in the engine's performance due to the higher percentage of premixed combustion as a result of the low cetane number of propanol.

Most studies on the co-combustion of propanol with other fuels in a compression-ignition engine refer to fuel mixtures. The technology of the dual-fuel engine, the concept for which is very similar to the RCCI (Reactivity Controlled Compression Ignition) engine, which is considered to be a technology significantly contributing to the reduction of exhaust emissions. This paper presents the results of the evaluation of the combustion process in an industrial compression-ignition test engine with a dual-fuel system where propanol and diesel were used.

2. Experimental Setup

The research on the co-combustion of diesel fuel with propyl alcohol was carried out on a compression-ignition engine (Andoria 1CA90, Poland), air-cooled, equipped with an additional fuel supply system, and an apparatus allowing for operation in the dual-fuel system (dual-fuel engine). Diesel fuel was supplied to the engine by an original direct injection system, while propanol was supplied with an additional injector to the intake manifold (PFI). The test engine was a single-cylinder engine with a displacement of 573 cm^3 and a cylinder bore and a stroke of 90 mm. The rotational speed of the engine was 1500 rpm. The compression ratio was 17:1. The start of the injection was 20° CA bTDC. The rated power of the engine was 7 kW. The tests included indicating the engine, that is, recording changes in pressure in the engine cylinder and measuring its exhaust emissions. During the experiment, a piezoelectric pressure sensor (Kistler 6061) was placed in the combustion chamber. A crankshaft rotation angle marker (encoder) was installed on the engine crankshaft. A charge amplifier (Kistler 5011) and a digital data acquisition system with an A/D card (Measurement Computing USB-1608HS) were used. Figure 1 shows a diagram of the test stand for testing a dual-fuel engine powered by diesel and propyl alcohol, while Table 1 shows the technical data of the test engine.



(**a**) (**b**)

Figure 1. Andoria 1CA90 engine on a test stand (**a**) and schematic arrangement of the engine test stand, instrumentation, and data logging system (**b**).

Table 1. Main technical specifications of the test engine.

Item	
Engine model	Andoria 1CA90
Type of engine	Stationary, four stroke
Type of ignition	Compression ignition
Rated speed (rpm)	1500
Engine rated power @1500 rpm (kW)	7
Technique of cooling	Air cooled
Intake system	Naturally aspirates
Bore/stroke (mm)	90/90
Displacement (cc)	573
No. of cylinders	1
Injection system	Direct injection
Compression ratio	17
Start of injection (SoI) (deg bTDC)	20

The engine's emissions were measured using a five-gas exhaust gas analyzer (Bosch BEA 350) [27]. Concentrations of NO, HC, CO, and CO_2 were recorded. Soot concentration was recorded with use of an opacimeter (AVL Smoke meter 415SE) [28]. The method of measuring HC, CO, and CO_2 emissions was the technology of nondispersive infrared (NDIR) spectrometry, while the measurement of NO emissions was based on electrochemical sensors. The smoke opacity of the exhaust gases was measured using the filter paper method on the FSN scale (Filter Smoke Number) (according to ISO 10054), which enables the mapping of the soot concentration in mg/m^3. Details of the equipment used can be found in Table 2.

Table 2. The main instruments and equipment of the test.

Equipment Name	Type	Precision
In-cylinder pressure sensor	Kistler 6061 SN 298131	±0.5% FS, range: 0–25 MPa
Charge amplifier	Kistler 5011	±3% FS, range for 10 V FS: ±10 ... ±999,000 pC
Data acquisition module	Measurement Computing USB-1608HS	16 bits resolution, sampling frequency 20 kHz
Emission equipment	Bosch BEA 350 AVL Smokemeter 415SE	CO: ±0.06% vol., HC: ±12 ppm vol., CO_2: ±0.5% vol., NO: ±25 ppm vol. Soot: $\sigma \leq \pm 0.005$ FSN + 3%, range 0–10 FSN

2.1. Methodology

The experiments conducted on the engine consisted mainly of its indication, during which the pressure in the cylinder was measured and recorded as a function of the crank angle. The pressure courses made it possible to determine the most important parameters of the combustion process, i.e., peak pressure (p_{max}) and pressure increase rate (PPR), normalized heat released (Q_{norm}) and heat release rate (HRR), ignition delay (ID) and combustion time (CD), as well as thermal efficiency of the engine (ITE). Based on the uniqueness of pressure changes in several hundred successive cycles, the stability of the test engine operation was analyzed by determining the COV_{IMEP} coefficient. The engine tests also included measurements of the concentrations of undesirable engine exhaust components such as nitrogen oxides (NO_x), hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), and soot. As part of the research, the engine operation was analyzed depending on the proportion of propanol co-combusted with diesel fuel. The share of energy input in the alcohol fuel was 15% (21% by volume) (DP15), 30% (39% by volume) (DP30), 50% (58% by volume) (DP50), and 65% (72% by volume) (DP65) of the total energy delivered in the fuel to the engine. The tests were carried out at constant and maximum engine load, after achieving its thermal stabilization. The test results were compared with the tests of the engine powered by diesel (D100) as the reference fuel.

The injection system on this test engine did not allow the injection start angle to be changed. This work concerns the use of alternative fuels in stationary industrial engines. Many such engines are used to drive machines and devices in our environment. One of the main ideas was to show how the engine behaves and its properties when powered by dual fuel.

2.2. Fuels Characteristics

The fuels used in the research are diesel ($C_{14}H_{30}$) and propyl alcohol (C_3H_7OH). Selected properties of fuels are presented in Table 3. Diesel is a typical fuel commonly used to power automotive diesel engines, compliant with the EN 590 standard, and offered at petrol stations in European countries. It is a mixture of liquid hydrocarbons and is obtained in the distillation processes of crude oil. In the case of diesel fuels, the most important parameter is the cetane number, which determines the susceptibility of a given type of fuel to spontaneous combustion. The standards define the minimum cetane number of diesel fuels sold, guaranteeing proper engine operation, at about 51. Propanol is an organic compound from the group of alcohols with three carbon atoms in the molecule, and it is colorless and has the properties of a flammable liquid. It is characterized by excellent disinfecting, cleaning, and degreasing properties. It is chemically neutral to plastics. It can be obtained by catalytic oxidation of propane. Propanol (propyl alcohol) is much less toxic and less volatile than, for example, methanol. It can be used as fuel in spark ignition engines without major modernization. The calorific value (LHV) of propanol slightly exceeds 30 MJ/kg and is approx. 25% lower than that of gasoline or diesel. Propanol has a high-octane number of about 118, but due to its high production cost, it is not commonly used to power spark ignition engines. Similar to other alcohols, it is an oxygenated fuel and contains 26.6% oxygen. The alcoholic fuel, which is propanol, is characterized by a low cetane number, a lower value of the stoichiometric air to fuel ratio, a higher value of the heat of vaporization and the temperature of self-ignition, and a lower energy density, compared to diesel and gasoline. The low cetane number makes it impossible to use propanol as an independent fuel in compression ignition engines.

Table 3. Fuel specifications [29–31].

	Unit	**Diesel**	**Propanol**
Molecular formula		$C_{14}H_{30}$	C_3H_7OH
Molecular weight	kg/kmol	198	60.065
Cetane number	-	51	12
Research octane number	-	15–25	118
Boiling point	K	453–643	370.1
Liquid density	kg/m^3	840	815
Lower heating value	MJ/kg	42.5	30.6
Heat of evaporation	kJ/kg	243	728
Autoignition temperature	K	503	623
Stoichiometric air–fuel ratio	-	14.6	10.35
Viscosity (at 25 °C)	mPa·s	2.419	1.959
Carbon content	%	85	60.0
Hydrogen content	%	15	13.4
Oxygen content	%	0	26.6

The engine tests were carried out at a constant load, presented as a constant value of mean indicated pressure (IMEP = 0.75 MPa). The use of propyl alcohol, a fuel with a lower calorific value compared to diesel, resulted in an increase in the total mass of fuels supplied to the engine per one power cycle along with an increase in alcohol content. Figure 2a shows the change in the total fuel dose and the change in mass fractions of co-combusted fuels. Propyl alcohol, as an oxygenated fuel, introduced additional oxygen and hydrogen to the engine cylinder. Thus, both the carbon to oxygen (C/O) ratios and the carbon to hydrogen (C/H) ratios were changed. The relationship between elemental carbon, oxygen, and hydrogen in the combusted fuel has a significant impact on the exhaust emissions of a reciprocating engine. Figure 2b shows the masses of individual fuel components (carbon, hydrogen, and oxygen) burned in a dual-fuel engine, as well as the relationships between carbon and hydrogen and between carbon and oxygen.

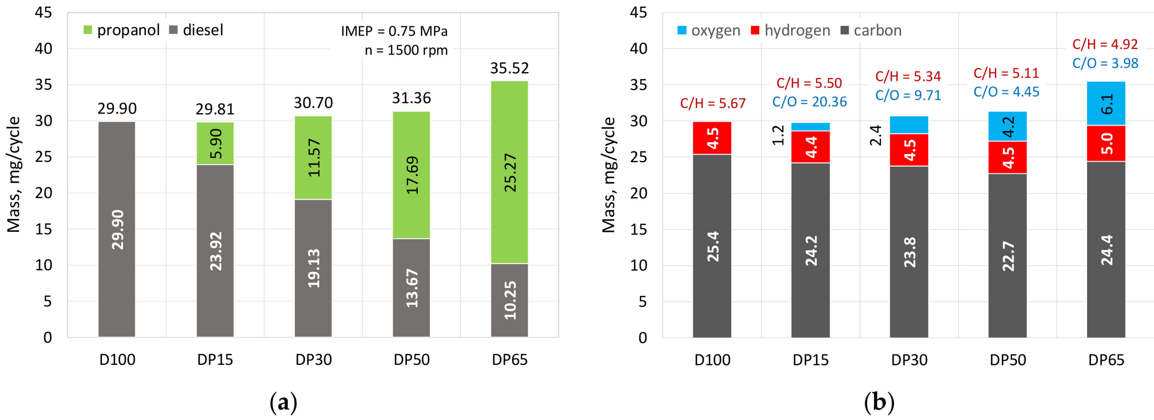


Figure 2. Mass of propanol and diesel fuel (**a**) and mass of carbon, hydrogen, and oxygen (**b**) in a dose of fuel supplied for one cycle of engine.

3. Results and Discussion

As a part of the research, an analysis of the impact of propanol's energetic share on the combustion process and exhaust emissions of a compression-ignition combustion engine was carried out. The analysis of the combustion process was carried out based on an indicator diagram, which is a basic and good source of information about the engine combustion process. The combustion process was analyzed based on the average course of 200 consecutive engine operation cycles.

3.1. Combustion Characteristics

Combustion in a dual-fuel engine differs from that in a conventional single fuel engine. In a conventional compression-ignition engine, the flame front forms around the jet of injected fuel. The successively formed fuel–air mixture is burned, and the intensity of this combustion is determined by the physical and chemical side of this complex process. In a dual-fuel engine, a stream of fuel is injected directly into a combustion chamber filled with a mixture of another fuel and air. The flame front may also spread towards areas filled with a homogeneous combustible mixture. Figure 3 shows the pressure courses and the corresponding heat release rates for the analyzed energy shares of propanol.

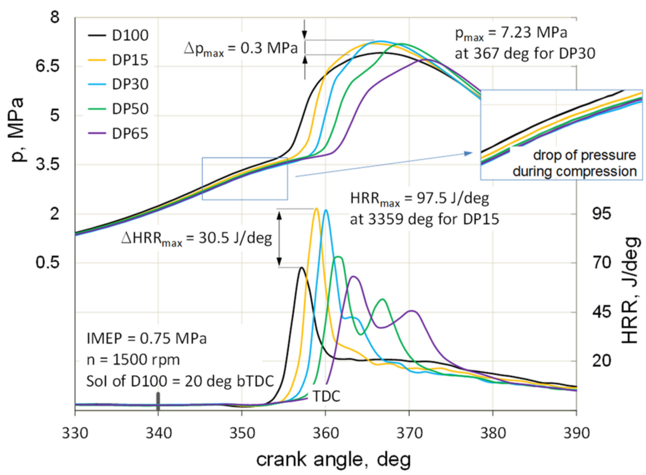


Figure 3. In-cylinder pressure (p) and heat release rate (HRR) characteristics for dual-fuel engine fueled by diesel and propanol with alcohol content from 0 to 65%.

As with most PFI powered engines, the vaporization of fuel during the intake stroke and compression reduces the charge pressure before ignition. Lower pressure also means a lower temperature value, which especially affects the initial combustion phase. Along with the increase in the energy share of propanol, its volume share increases even more, due to the lower LHV value compared to diesel, and this increases the cooling effect of the fresh charge. Along with the increase in the propanol share, up to its 50% share, the maximum pressure value (p_{max}) increased in relation to the value obtained for the reference fuel. The greatest difference in p_{max} was obtained for 30% propanol content, and it was 0.3 MPa. The propanol fraction shifted the p_{max} value to later CA values after TDC. The maximum acceptable 65% propanol content caused a drop in the p_{max} value to a value slightly lower than that obtained for the diesel engine.

When analyzing the heat release rate, it was found that up to 30% propanol share, there was a significant increase in the kinetic combustion phase; for 15% propanol the HRR increased by over 30 J/deg compared to diesel fuel supply. A different trace of combustion was noticed for the proportion from 50% of propanol, where two characteristic peaks are visible on the HRR curve. It can be stated here that the combustion process takes place in two stages. The second stage of combustion takes place clearly later than the first.

Figure 4 shows the courses of the peak pressure rise (PPR) for the analyzed cases. For compression-ignition piston engines, the limit value of PPR is 1 MPa/deg, which is accompanied by the so-called hard work of the engine [32]. The highest recorded increase in PPR was obtained for the 15% proportion of propanol and was higher by 0.25 MPa/deg, in relation to the engine fueled with the reference fuel. From 50% of propanol share, the maximum PPR value did not exceed the value obtained for the engine fueled with diesel.

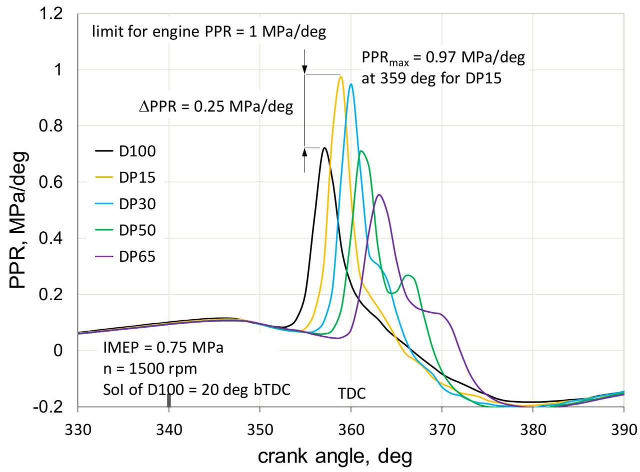


Figure 4. Peak pressure rise (PPR) characteristics for dual-fuel engine fueled by diesel and propanol with an alcohol content from 0 to 65%.

The evaluation of the combustion process was carried out based on the analysis of the heat release. The following combustion stages are assessed: the ignition delay time (ID), the angle of 50% heat release (CA50), and the duration of combustion (CD) (Figure 5). The ignition delay time is defined as the period from the start of the fuel injection to the release of 10% of the heat. The value of the ignition delay depends on the chemical properties of the fuel (the so-called chemical retardation), such as its propensity for self-ignition, molecular structure, or the heat of vaporization, and on the physical side (the so-called physical retardation), i.e., the parameters of the injected fuel stream, charge turbulence, and turbulence in the combustion chamber of the engine. The ignition delay period must be included in the engine control algorithm for optimal operation. The 50% (CA50) heat release angle is important for optimization reasons and its value should be within 7–10 deg after TDC. The duration of combustion (CD) is the period from the 10% heat release angle to the 90% heat release angle. The duration of combustion is reflected in the efficiency of the engine: the longer the combustion takes, the greater heat losses can be expected across the system boundaries. On the other hand, if the combustion process is very fast, it is accompanied by large pressure increases, which are an undesirable phenomena in a combustion engine.

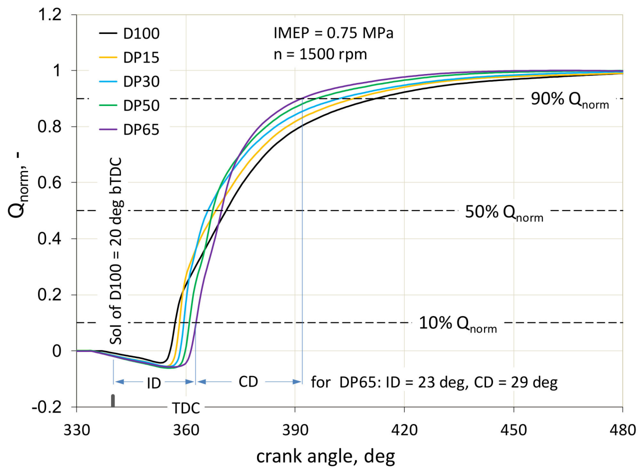


Figure 5. Normalized heat release (Q_{norm}) characteristics for dual-fuel engine fueled by diesel and propanol with alcohol content from 0 to 65%.

Figure 6 shows the influence of propanol content on the values of the characteristic combustion stages. The presented values are the obtained differences in relation to a conventional engine powered by diesel. The increased proportion of propanol in the process of co-combustion with diesel fuel increases the ignition delay time. The highest value of Δ(ID), 6 deg, was obtained for the highest proportion of propanol (DP65), because in this case the share of fuel with the high heat of vaporization and low cetane number (CN) value was the highest, which significantly influences the ignition delay time. A dose of diesel fuel is injected into a propanol-air mixture that fills the cylinder at a temperature lower than in a conventional engine, where the air itself is compressed. In a dual-fuel engine, on the one hand, the high value of the heat of vaporization adversely affects the ignition initiation, because it lowers the initial temperature, on the other hand, the share of oxygen in the alcohol molecular structure promotes the combustion process. It turns out that in the initial stage of combustion, the dominant role is played by the influence of alcohol on the charge temperature before ignition, and in the second, the essential stage of combustion, the share of oxygen in the molecular structure accelerates this process. By analyzing the influence of propanol on combustion duration (CD), it was found that it significantly contributed to its shortening. For the highest proportion of propanol (DP65), the combustion duration was shortened by as much as 26 deg compared to the engine fueled with the reference fuel. The reduction of the combustion duration also influenced the value of the 50% heat release angle. The CA50 angle was close to TDC. The greatest effect of propanol on the CA50 angle was recorded for the DP30 and the difference was 5 deg.

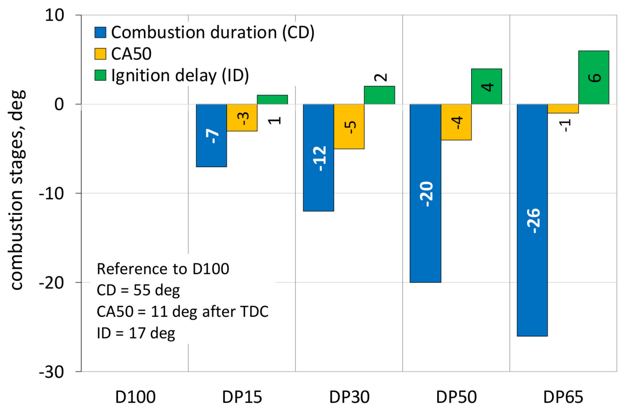


Figure 6. The stages of ID, CA50 and CD combustion.

3.2. Performance Characteristics

When assessing the combustion process in a reciprocating engine, refer to the engine's performance. One of the main indicators is engine efficiency, which determines the engine's ability to convert the chemical energy contained in the fuel to the work obtained on the engine's crankshaft. Figure 7 shows the efficiency gains of the dual-fueled engine ΔITE compared to the reference fuel-fed engine. It was found that the dual-fuel engine was more efficient than the conventional engine for the entire range of propanol content. The highest value of the increase in efficiency ΔITE was recorded for the 50% proportion of propanol (DP50) and it amounted to 1.94%. Up to a 50% propanol share, a gradual increase in efficiency was achieved; after exceeding this share, the efficiency decreased but was still higher than for the engine powered with diesel. Figure 7 also shows the influence of propanol share on the specific energy consumption SEC. The nature of the changes in this parameter of the engine performance evaluation is consistent with the changes in ITE. For an engine powered by diesel alone, the SEC was 10.27 MJ/kWh. The lowest specific energy consumption was recorded for the DP50 power supply, and it was 9.69 MJ/kWh.

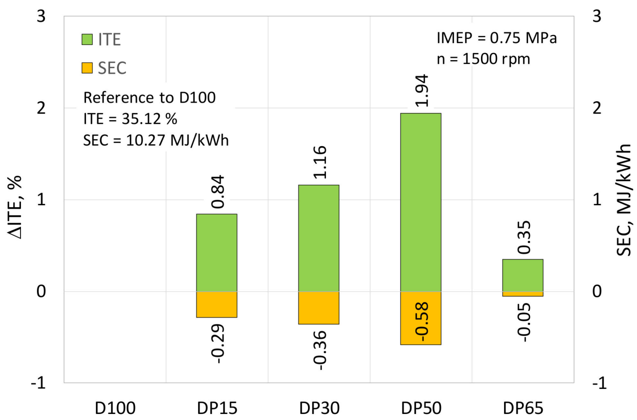


Figure 7. Thermal efficiency (ITE) and specific energy consumption (SEC) of a dual-fuel engine fueled by diesel and propanol with alcohol content from 0 to 65%.

An internal combustion engine is a cyclic machine in which each of the individual work cycles is practically different. For the quality of the engine's work, it is recommended that this uniqueness be as low as possible. The basic assessment of the operating stability of a piston engine is based on the COV_{IMEP} index. According to the literature, the limit value for piston engines used to drive machines and devices should not exceed 5% [32]. Figure 8 shows the influence of propanol content on the nature of the changes in the COV_{IMEP} uniqueness index. For the engine powered by diesel alone, the value of the COV_{IMEP} uniqueness index was 3.33%. The share of propanol in the combustion process in the engine increased the COV_{IMEP} value by nearly 2%, and for a share of 15 to 50%. For the entire range of propanol shares, an increase in the uniqueness of the IMEP value was recorded. The main reason for this is propanol's properties: it has worst self-ignition ability, which is the most important in the initial phase of flame front propagation. Small differences in the pre-combustion stage then translate into differences in the main stage of the combustion process. Other authors show a similar nature of COV_{IMEP} changes with the participation of alcoholic fuels [33,34].

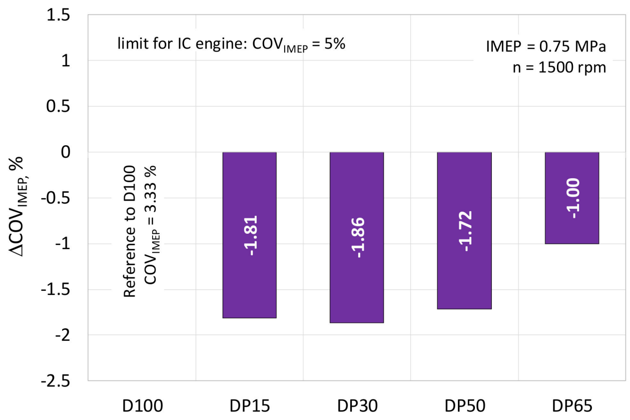


Figure 8. Uniqueness of IMEP.

3.3. Emission Characteristics

The emission of toxic and harmful compounds resulting from the combustion of hydrocarbon fuel is one of the most important indicators of the operation of a modern internal combustion engine. The main undesirable components of exhaust gases are nitrogen oxides (NO_x), hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), and soot. Currently, research is conducted around the world to reduce the exhaust emissions from a reciprocating engine. Research consisting in design changes, the use of new technologies and materials, and the improvement of control systems contribute to the improvement of efficiency, the reduction of fuel consumption, and indirectly positively influence exhaust emissions. Another effective method for reducing piston engine exhaust emissions is the use of renewable fuels that are alternatives to diesel and gasoline. As part of this work, the emission of an engine co-combusting diesel with propyl alcohol was tested, with the energy share of alcohol from 0 to 65%.

3.3.1. Nitrogen Oxides

Among the most toxic components of an internal combustion engine's exhaust gases are nitrogen oxides (NO_x). They primarily have a negative impact on human health, but are also responsible for environmental changes, including the formation of the so-called photochemical smog or acid rain. Nitrogen oxides are compounds composed almost entirely of nitrogen oxide (NO), which is formed by the chemical reaction of nitrogen and oxygen in the combustion process in the engine cylinder. NO_x also include other nitrogen compounds together with oxygen, such as NO_2, N_2O_3, and others, formed outside the cylinder, primarily in the exhaust system. The necessary conditions for the formation of nitrogen oxide in the cylinder are a high temperature and the presence of excess oxygen. Compression ignition engines operating mainly on very lean mixtures can generate significant amounts of NO_x. In a diesel engine, the combustion phase of the pre-prepared mixture (kinetic phase) takes place at a high temperature, associated with a high rate of heat release, which favors the formation of nitrogen oxides. Figure 9 shows the NO emission changes of a dual-fuel diesel and propanol engine with respect to the emissions determined for the reference fuel engine (D100). It is clear that the combustion of diesel fuel with a small proportion of propanol, up to 30%, causes an increase in nitrogen oxide emissions, caused by an increase in the maximum temperature in the cylinder, resulting from a significant increase in the rate of heat release. Moreover, the formation of NO was favored by the additional active oxygen supplied with the alcoholic fuel. For DP30, compared to D100, the NO concentration increased by 292 ppm (38%). As a result of the combustion of diesel with 50% propanol (DP50), compared to the combustion of diesel fuel (D100) alone, a slight decrease in NO emissions by 14 ppm (2%) was recorded. Correspondingly, for DP65, this decrease was more pronounced and reached a value of 135 ppm (17.5%) lower than for diesel. The reduction in the concentration of nitrogen oxides resulted mainly from the reduction of the heat release rate and the lowering of the maximum temperature in the engine cylinder.

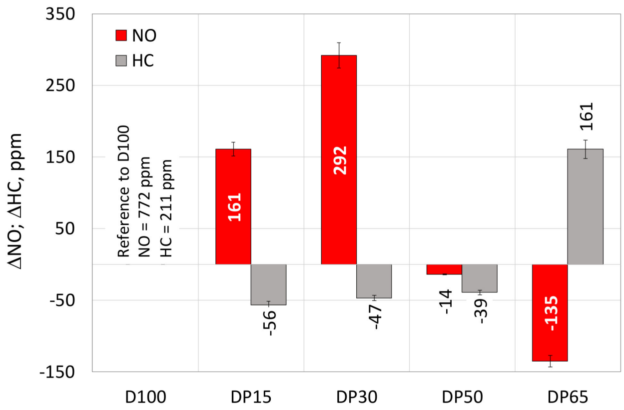


Figure 9. Emission of NO and HC for dual-fuel engine fueled by diesel and propanol.

3.3.2. Hydrocarbons

Unburned hydrocarbons are the product of the incomplete combustion of the fuel in the engine cylinder where not all the fuel particles are involved in the oxidation reaction with limited contact with oxygen. Increased HC emissions are favored by local oxygen deficiencies in the combustion chamber during the combustion of a rich mixture. The places where the accumulated fuel may remain unoxidized are the piston ring gaps and the boundary layer zones. Hydrocarbons are also formed in large amounts when a very lean mixture is burned, due to the prolonged oxidation process caused by the slow combustion rate. Figure 9 shows the changes in the concentration of hydrocarbons in the exhaust gas of the test engine powered by diesel and propanol, compared to the engine powered by D100. It is evident that the co-combustion of diesel fuel with propanol, up to 50%, contributed to the decrease in HC emissions. For DP15, DP30, and DP50, the decrease was 56 ppm (26.5%), 47 (22.3%) ppm, and 39 ppm (18.5%), respectively. The increase in alcohol content caused increasing amounts of fuel injected into the intake manifold, where it formed a homogeneous alcohol-air mixture, and then delivered it to the cylinder during the intake stroke. In this case, the amount of diesel directly injected into the cylinder decreased, which no longer accumulated as much in the gaps and on the walls of the combustion chamber, and had a limited possibility of creating fuel-rich zones. This led to a reduction in the number of hydrocarbons produced in the test engine cylinder. In addition, supplying the cylinder with alcohol fuel delayed auto-ignition, extending the time to create a homogeneous mixture in the engine cylinder. It also reduced the fuel-rich areas that emit unburned hydrocarbons. A sharp increase in HC concentration in the exhaust gas was recorded for the highest alcohol content (DP65), which amounted to 161 ppm (76.3%). It was caused by a decrease in combustion temperature and heat release rate in the engine cylinder due to a significant ignition delay.

3.3.3. Carbon Monoxide

Carbon monoxide is produced at high temperatures in the fuel-rich zones of the combustion chamber. The formation of CO in an internal combustion engine is favored by a mixture that is too rich, generating the formation of local fuel-rich zones; a low combustion temperature leading to a slower reaction rate, even in zones with high excess air; as well as a low level of turbulence and low mixture turbulence. Figure 10 shows changes in the carbon monoxide emission of the engine powered by diesel and propanol in relation to the engine powered by D100. The figure shows that increasing the propyl alcohol content in the mixture combusted in a compression-ignition engine causes a decrease in the carbon monoxide content in the exhaust gas. This fact is due to two factors. First, the additional oxygen provided in the alcohol fuel has a positive effect on achieving complete combustion, and thus improves the oxidation of CO to CO_2, reducing the concentration of CO. Secondly, as the amount of alcohol is increased, the amount of carbon in the combustible mixture is reduced, and therefore the possibility of forming its compounds, including CO, is also limited. For DP65, compared to D100, there was a decrease in CO concentration by 1.3%.

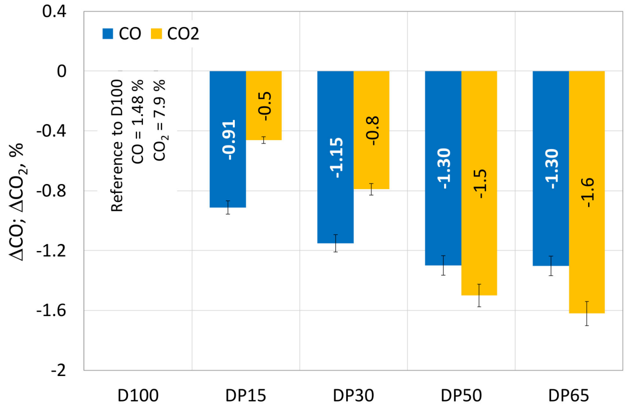


Figure 10. Emission of CO and CO_2 for dual-fuel engine fueled by diesel and propanol.

3.3.4. Carbon Dioxide

Apart from methane, carbon dioxide is one of the gaseous compounds that dominate the greenhouse effect, increasing the average temperature on Earth, among other things. Carbon dioxide is a product of the complete combustion of fuel, which fully oxidizes CO and is produced in both the spark-ignition engine and the diesel engine cylinder. Figure 10 shows the changes in CO_2 emissions of a dual-fuel engine powered by diesel and propanol, compared to the reference fuel engine. It is evident that increasing the amount of propanol, up to 65%, co-combusted with diesel fuel in a compression-ignition engine results in a reduction of CO_2 emissions. For the DP65, compared to the D100, there was a decrease of 1.6%, or about 20%. The reason for the reduced carbon dioxide emissions is primarily a reduction in the amount of elemental carbon supplied with the fuel to the engine cylinder.

3.3.5. Soot

Soot is a carbon compound with adsorbed products of incomplete combustion of hydrocarbon fuel. The mixing-controlled combustion phase (diffusion phase), which is dominant in a diesel engine, plays a major role in the soot formation process. The soot content in the cylinder changes during combustion and expansion until the exhaust valve opens. In the diffusion combustion phase, throughout the period of heat release, the concentration of soot increases. After the heat release is complete, with the availability of oxygen, the soot particles are burnt off until the exhaust valve is opened. The burnout of soot is favored by intensive swirling of the charge in the cylinder, caused, among others, by high engine speed.

Figure 11 shows the changes in the soot emissions of the test engine, in which diesel fuel was co-combusted with propanol, in relation to the emissions of the engine combusting only diesel. It is evident that even a small addition of alcohol caused a significant reduction in the soot concentration in the exhaust of a compression-ignition engine. For DP15, compared to D100, a decrease in the concentration of soot was achieved by 854 mg/m^3, i.e., by 76%. The highest, almost complete, reduction of soot was recorded for DP65, and it was 1114 mg/m^3, i.e., 99%. The reason for the decrease in the soot concentration in the exhaust gas of a dual-fuel engine powered by diesel and propanol was the increasing oxygen content in the fuel, which limited the formation of oxidant-poor areas. The decrease in soot concentration in the exhaust gas is also caused by the decrease in the amount of elemental carbon supplied to the engine cylinder with the increase in the alcohol fuel content.

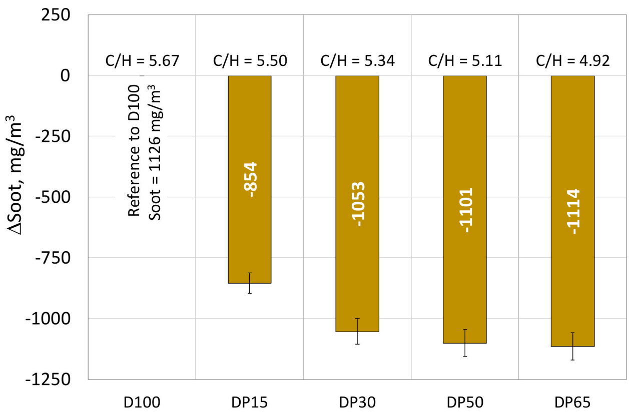


Figure 11. Soot emission for dual-fuel engine fueled by diesel and propanol.

4. Conclusions

The paper presents experimental studies of a dual-fuel compression-ignition engine powered by diesel and propyl alcohol. The engine allowed for the co-combustion of conventional hydrocarbon fuel with biofuel, the energy share of which was up to 65%. The combustion process in the cylinder and the engine exhaust emissions were analyzed. Based on the research results, it can be concluded that:

- with an increase in the proportion of propanol, the value of the maximum pressure (p_{max}) increases to its 50% share in relation to the value obtained for the reference fuel; the highest difference in p_{max} is for 30% propanol and it was 0.3 MPa;
- analyzing the courses of the heat release rate and the peak pressure rate, it can be seen that up to 30% propanol share, there is a clear increase in HRR and PPR, by approximately 30 J/deg and 0.25 MPa/deg, respectively, compared to the diesel fuel supply;
- an increase in the proportion of propanol in the process of co-combustion with diesel fuel causes an increase in the ignition delay time; significantly reduces the combustion duration (CD);
- the highest ITE was recorded for a 50% proportion of propanol, compared to D100 it was higher by 1.95%,
- the proportion of propanol in the combustion process in a compression ignition engine increases the COV_{IMEP} value by nearly 2%, for a share of 15 to 50%, which proves a slightly deteriorated stability of the engine operation;
- the combustion of diesel fuel with propanol, up to 30%, causes an increase in nitrogen oxide emissions, for DP30 compared to D100 there was an increase by 292 ppm,
- the co-combustion of diesel with propanol, up to 50%, contributes to a decrease in HC emissions, for DP15, DP30 and DP50 the decrease was respectively 56 ppm (26.5%), 47 (22.3%) ppm and 39 ppm (18.5%);
- the addition of alcohol in the fuel-air mixture supplied to a compression-ignition engine results in a significant reduction of the soot concentration in the exhaust of this engine; the highest, almost complete reduction was recorded for DP65, which was 1114 mg/m^3.

It turns out that powering the engine in a dual-fuel system, even with such an old design, gives positive results. Having a modern injection system opens up several interesting possibilities, such as the optimization of the engine thermal cycle according to the CA50 angle, the influence of the pilot dose, or a more advanced distribution of the diesel fuel stream. A modern injection system will most likely minimize the amount that initiates combustion.

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Nomenclature

p	pressure
CA	crank angle
TDC	top dead center
p_{max}	peak pressure
IMEP	indicated mean effective pressure
PPR	pressure increase rate
COV_{IMEP}	coefficient of variation of the indicated mean effective pressure
Q_{norm}	normalized heat released
HRR	heat release rate
SoI	start of injection
ID	ignition delay
CD	combustion duration
CA50	50% heat release
ITE	thermal efficiency of the engine
SEC	specific energy consumption
NO_x	nitrogen oxides
THC	total hydrocarbons
CO	carbon monoxide
CO_2	carbon dioxide
O	oxygen
C	carbon
H	hydrogen
RCCI	reactivity controlled compression ignition
PFI	port fuel injection
LHV	lower heating value
CN	cetane number

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