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Content of Selected Compounds in the Exhaust Gas of a Naturally Aspirated CI Engine Fueled with Diesel–Tire Pyrolysis Oil Blend

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Abstract: This paper presents the results of naturally aspirated compression ignition (CI) internal combustion engine (ICE) bench tests of fuels in the form of a blend of diesel oil with recycled oil (RF) in the form of tire pyrolysis oil (TPO) as an admixture with the content of pyrolytic oil with the blend being 10% m/m (D90+RF10). The results relate to reference conditions in which the engine is fed with pure diesel oil (D100). The experiment included the evaluation of engine performance and the determination of the content of selected substances in the exhaust gas for brake-set engine loads equal to 5 Nm, 10 Nm, 15 Nm, and 20 Nm. For each load, engine operating parameters and emissions of selected exhaust components were recorded at preset speeds in the range of 1400–2400 rpm for each engine load. The hourly fuel consumption and exhaust gas temperature were determined. The contents of CO_2, CO, and HC in the exhaust gas were measured. The consumption of D90+RF10 increased by 56%, and CO_2 emissions were 21.7% higher at low loads. The addition of sulfur-containing pyrolytic oil as an admixture to diesel oil resulted in SO_x emissions. The results show the suitability of pyrolytic oil and the possibility of using it as an admixture to fossil fuels. In order to meet SO_x emission levels in land-based installations and for vehicle propulsion, it is necessary to desulfurize fuel or desulfurize deSO_x exhaust gas systems. The CO and HC emission levels in the exhaust gases from the engine powered by the D90+RF10 fuel meet current requirements for motor vehicle exhaust composition.

Keywords: diesel oil; recycled oil; tire pyrolytic oil; fuel blends; engine performance; CO_2 emission; CO emission; HC emission; hydrocarbons

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1. Introduction

Continuing pressure to reduce emissions of harmful compounds and growing interest in sustainable energy development are prompting researchers to look for alternative fuels. One of these alternative fuels is fuel derived from waste properly selected and prepared for processing. Wastes that can be used as raw materials for the production of alternative RF fuels are as follows: polymer plastics, wood, textiles, and tires [1]. Among these, used tires are a particularly promising source of raw material due to their high calorific value and constant availability, as tire production continues to increase. This type of oil has the potential to replace traditional fuels in a variety of industries, such as the construction, energy, heating, and petrochemical industries. Its use falls in line with the idea of a closed-loop sustainable economy, which translates into meeting environmental requirements (e.g., reducing waste in landfills, recovering recyclable materials, and reducing greenhouse gas emissions) [2]. It is estimated that about 35 million tires are produced annually in Poland, which presents both a challenge and an opportunity (Figure 1).

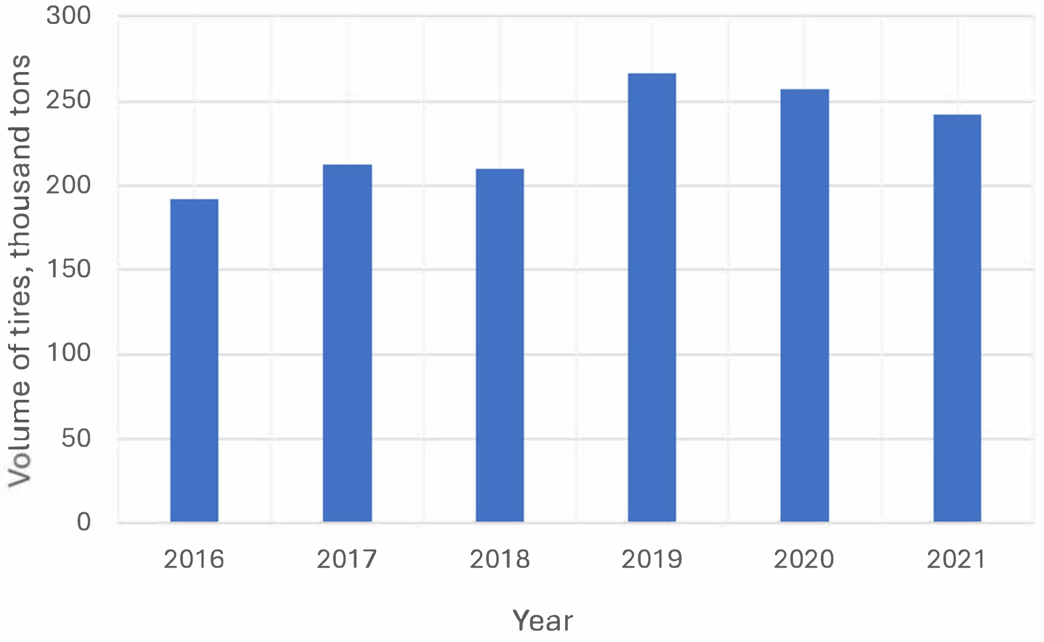

Figure 1. Mass of tires produced in Poland between 2017 and 2021 (own compilation based on ref. [3]).

According to Polish legislation, 75% of tires placed on the market in the previous year are subject to recycling obligations. According to data from the Central Statistical Office, the level of recovery of waste tires in 2021 was 68.1%, of which 38.2% was recycled (Figure 2). The fact that more tires are being recycled than produced in Poland is due to the significant share of imported tires in the overall population of recycled tires.

Car tires are a particularly profitable waste material due to the following:

- High energy values. Their calorific value is 30 to 35 MJ/kg, which is comparable to coal [4,5].
- Constant availability. With the ever-increasing number of vehicles, tires are becoming an increasingly common waste product [6,7].

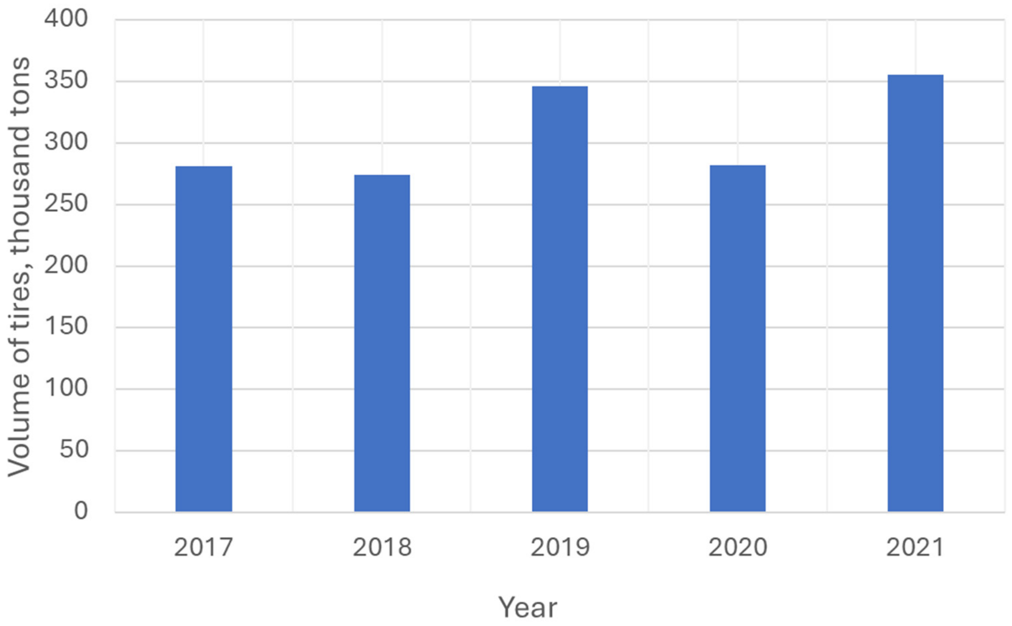

Figure 2. Mass of tires recycled in Poland between 2016 and 2021 (own compilation based on ref. [3]).

Technologies such as pyrolysis make it possible to convert waste into fuels that can be used as an alternative or admixture to diesel oil. Pyrolysis is a process that decomposes waste materials, such as tires, at high temperatures and without oxygen, converting them into usable substances [8–10]. The resulting oil contains a blend of hydrocarbons with different boiling points, which affects its varying chemical and physical properties. The process of pyrolysis of used tires reduces landfill waste and greenhouse gas emissions associated with burning them in the open atmosphere [11–13]. As demonstrated in previous works [14–19], there is great potential for using pyrolysis oil from used tires as an alternative fuel or as an admixture to normative fuels. Blends of pyrolysis oil and normative fuel (B7) show synergistic effects that favorably influence their use as alternative fuels. Earlier works [18,20,21] show that blends containing up to 30% pyrolytic oil are stable and do not require modifications of the engine design. Hybrid blends consisting of 10% pyrolysis oil, 20% biodiesel, and 70% diesel have a higher heating value and better lubricating properties compared with conventional diesel, which reduces engine wear [22,23]. Toxic compounds emitted during the combustion of fuels with post-pyrolysis admixtures in compression-ignition engines can become a problem. However, as Prajapati et al. showed in their work [24], blending pyrolytic oil with normative fuel can reduce CO and HC emissions. Various purification methods, such as desulfurization or vacuum distillation, can be used to reduce the contents of various impurities in pyrolytic oil [14,25,26].

Despite its potential, the use of pyrolysis oil from used tires is not without its challenges. The chemical composition of such oil can be highly variable, which can affect its usefulness as a stable fuel. In addition, emissions from combustion processes with pyrolytic oil as an admixture must be further investigated to meet emission standards. With further research, production of pyrolysis oils will enable the widespread use of waste tires and other polymer plastics, which may be attractive from the point of view of a closed-loop economy [27–29]. The challenge remains to be optimizing pyrolysis processes and developing purification technologies that would make the resulting oil a more viable and stable alternative fuel to meet the standards required by the transportation industry [30–32]. Sources [18,33–36] have conducted partial investigations—focusing on selected exhaust gas components—regarding the impact of fuels blended with tire pyrolysis oil (TPO) on emission composition. These studies indicate that the TPO–diesel blend results in increased fuel consumption at low loads, attributed to its lower cetane number and higher non-volatile content. A source [37] examined the effects of TPO–diesel mixtures on fuel consumption and emissions in a diesel engine, also reporting that the inclusion of TPO leads to elevated fuel consumption under low load conditions. In contrast, studies [35,36] investigated TPO fuel blends in combination with combustion-enhancing additives, which fall outside the scope of the current research. Additionally, these studies did not assess naturally aspirated engines and did not provide comparisons with applicable legal emission standards.

Pyrolysis oil offers a number of environmental and technological advantages. Its widespread use, however, requires further research into the properties of fuel blends, purification processes, and environmental impacts with a particular focus on reducing emissions of harmful exhaust compounds during combustion in compression-ignition engines.

On the other hand, exhaust gases emitted by internal combustion engines are a significant source of environmental pollution, negatively affecting air quality and human health. In an era of increasing environmental awareness and tightening legal requirements, special attention is being paid to reducing emissions of harmful exhaust compounds. The introduction of admixtures to fuel, such as pyrolytic oil obtained from recycled tires, can affect the amount and nature of emissions of these compounds, which is important from the point of view of ecology and compliance with current exhaust emission standards [38,39]. Studies [37,40,41] confirm the reduced combustion temperature for TPO blends due to the lower cetane number and the cooling effect of evaporation of water and heavier fractions. The lowered temperature may affect reducing NOx emissions, which relates to thermal conditions in the combustion chamber.

Therefore, emissions are strongly dependent on the sulfury content of the fuel—and this is much higher in TPO than in conventional diesel (D100), resulting in a marked increase in SO_2 emissions [17,42,43].

Sources [40,44,45] indicate lower CO_2 in TPO–diesel blends, while others, e.g., [13], indicate higher CO_2 emissions with a higher proportion of TPO. In the work of Jakubowski et al. [46], the emission of CO_2 increased with the rise in engine load. The differences between the mixtures of diesel oil and TPO decreased as the load increased. Sources [40,42,47] confirm that CO emissions are higher for TPO especially at high loads due to poorer combustion and lower lambda ratio. Carbon monoxide (CO) emissions, in studies by [36], showed that carbon monoxide (CO) emissions rise with increasing engine load and with a higher proportion of TPO in the fuel mixture. The increased CO emission is attributed to a less efficient combustion process.

Several studies [34,35,47–49] confirm that TPO causes an increase in HC emissions, especially at low combustion rates and low ignition temperatures. The higher HC emissions are due to long-chain hydrocarbons and the difficulty in burning them completely.

In order to reduce the negative impact of exhaust emissions on the environment and public health, the European Union has introduced emission standards for internal combustion engines. The regulations in force include, among others, the following:

- Euro 6 standards [50,51]: Applied to road vehicles and are being systematically tightened. Euro 6d-Temp introduced in 2017 [50] establishes stricter emission requirements compared with the Euro 6 standard (2007) [51].
- Euro 7 [52]: This forthcoming standard, currently anticipated for implementation in 2029 [53], aims to further tighten emission regulations. Euro 7 is expected to encompass a broader range of pollutants, including nitrogen oxide (NOx) limits set at 60 mg/km, applicable to both petrol and diesel vehicles. Additionally, it will extend the compliance period for vehicles from 5 years or 100,000 km to 10 years or 200,000 km.

- Stage V [54]: European emission standard limiting nitrogen oxide emissions and particulate matter content in exhaust gases from engines for non-road machinery and vehicles [55].
- Directive 2009/30/EC [56]: Regulates the quality of motor fuels, limiting, among other things, the permissible sulfur content of diesel oil, which has a direct impact on SO_x emissions.

The addition of pyrolysis oil to fuel can affect emissions of particular compounds, especially in the context of nitric oxides and particulate matter (PM). Therefore, it is important to determine whether its use allows it to meet European emission standards and what changes in the composition of the exhaust gas it causes compared with conventional diesel oil.

The process for assessing the value of each of these compounds has been formalized and is extensively outlined in various international standards. It is crucial to recognize that, given the numerous standards and types of equipment available for measurements, it is important to clarify the methodology used for a specific measurement. This ensures that results from different researchers can be effectively compared.

Emission limits for harmful exhaust compounds during combustion in compression-ignition engines, such as carbon oxides (COs), hydrocarbons (HCs), and carbon dioxide (CO_2), have been set by Polish and EU laws to limit their negative impact on the environment and public health. These regulations include the Regulation of the Minister of Economy of 30 April 2014 [57], which specifies in detail the requirements for limiting the emission of gaseous and particulate pollutants by internal combustion engines in Poland; European Union directives (such as Directive 2005/55/EC [58] on the approximation of the laws of the Member States relating to internal combustion engines for land transport vehicles); and Regulation (EU) 2016/1628 [59] of the European Parliament and the Council establishing requirements for emission limits for gaseous and particulate pollutants and type approval for internal combustion engines intended for non-road mobile machinery.

Sulfur dioxide (SO_2) emissions are primarily controlled indirectly through fuel quality standards, like the maximum sulfur content allowed in diesel (e.g., 10 ppm in Europe per EN 590 [60]). While not directly limited during vehicle inspections, CO_2 emissions are regulated at the manufacturer level under climate policies, as they are considered a global pollutant. The novelty of this study lies in its focus on a naturally aspirated compression-ignition engine and in the direct comparison of measured exhaust emissions—specifically CO and HC—with the emission limits currently specified in Polish legal regulations [57].

There is a current trend among fuel producers to reduce the use of fossil fuels by increasing the share of biocomponents (such as fatty acid methyl esters (FAME), (bio)methanol, and (bio)ethanol) and synthetic fuels (electro-fuels or e-fuels). In the EU, fuels for land-based applications currently contain up to 10% m/m bioalcohols in gasoline and up to 7% m/m FAME in diesel oil. The blending of these components is on the rise, and it is highly likely that the biocomponent content in diesel oil will reach 10% m/m or more in the future. For this reason, we attempted to use tire pyrolysis oil (TPO) as an admixture to diesel oil at a mass share of 10%. With the above in mind, the authors undertake in this article an experiment to study the effect of a fuel consisting of D100 diesel oil with the addition of 10% m/m oil obtained from tire pyrolysis (RF) on the change in engine performance (i.e., hourly fuel consumption and exhaust gas temperature) and to determine the content of CO_2, CO, HC and SO_x in the exhaust gas for brake-set engine loads equal over the entire engine load range. Unlike other studies that focus solely on the chemical composition of blends with TPO, we have examined engine performance and exhaust emissions over a broad range of conditions. We conducted an extensive comparison of D90+RF10 and D100 fuels in the 1400 to 2400 rpm speed range. The aim of this article is to assess the impact of pyrolysis oil on engine performance and exhaust emissions, and to evaluate its compliance with EU exhaust emission standards and marine fuel regulations.

2. Materials and Methods

2.1. General Objectives

This experiment involved the evaluation of engine performance and the carbon content of the exhaust gas when the engine was supplied with the tested fuels. The fuel flows into the fuel injection system by gravity from a tank located above the engine. For each brake-fixed load and set engine speed, engine performance parameters were recorded. The characteristics of hourly fuel consumption and exhaust gas temperature were drawn.

For each engine load torque value, the average values of carbon dioxide CO_2, carbon monoxide CO, and hydrocarbon HC in the exhaust gas were determined. In addition, hourly and specific emissions of sulfur oxides related to SO_2 were calculated.

Each measurement was carried out after the mechanical loads had stabilized and the engine was in a stabilized thermal state. Measurement of the parameters was carried out over a period of 10 s with a sampling frequency of 10 ms. In the case of measurements of exhaust gas components, as the values of component content at extreme engine speeds showed little change in the investigated speed range for a given engine torque load, the experiment used averaged values of each component obtained for a given engine load.

During the experiment, selected parameters were recorded for preset loads of 5 Nm, 10 Nm, 15 Nm, and 20 Nm, respectively, with preset speeds of 1400 rpm, 1700 rpm, 2000 rpm, and 2400 rpm. The selected parameters cover the entire operating field of the engine; i.e., they refer to a torque load equal to about 25%, 50%, 75%, and 100% of the rated value, respectively, and for the rated speed range. The measurements were made under the following conditions: ambient temperature of 24.4 °C, barometric pressure of 1002 hPa, and relative humidity of the air around the engine of 31.7%.

2.2. Engine Test Stand

The experimental part of the research was carried out on a dynamometer stand installed in the laboratory at the Faculty of Mechanical and Power Engineering of the Koszalin University of Technology. A schematic diagram of the stand is shown in Figure 3, whereas its view is presented in Figure 4. The essential element of this stand is a single-cylinder, undercharged Yanmar TF70 compression-ignition engine (1) loaded with a dynamic water brake (2) with a load capacity of 0–35 Nm. Other components of the system are a fuel tank (3), a fuel consumption meter (4), a Horiba Mexa exhaust gas composition analyzer (5), and a computer with ParmDataLab control and measurement software (6).

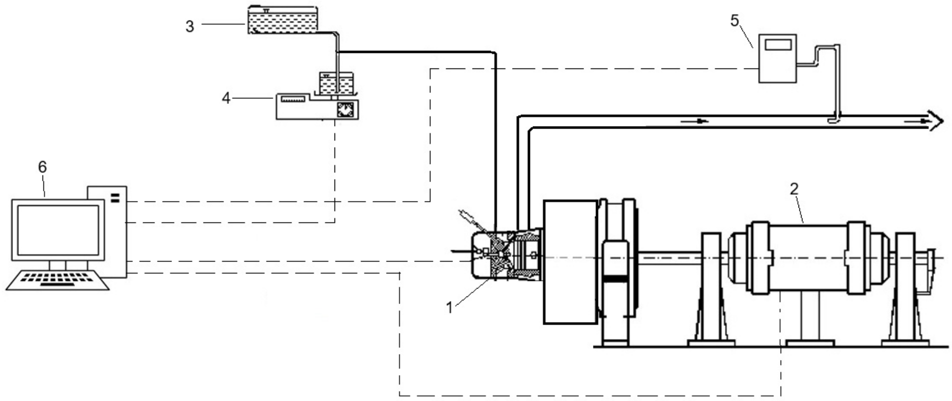

Figure 3. Diagram of the test stand with a Yanmar TF70 engine (description in the text).

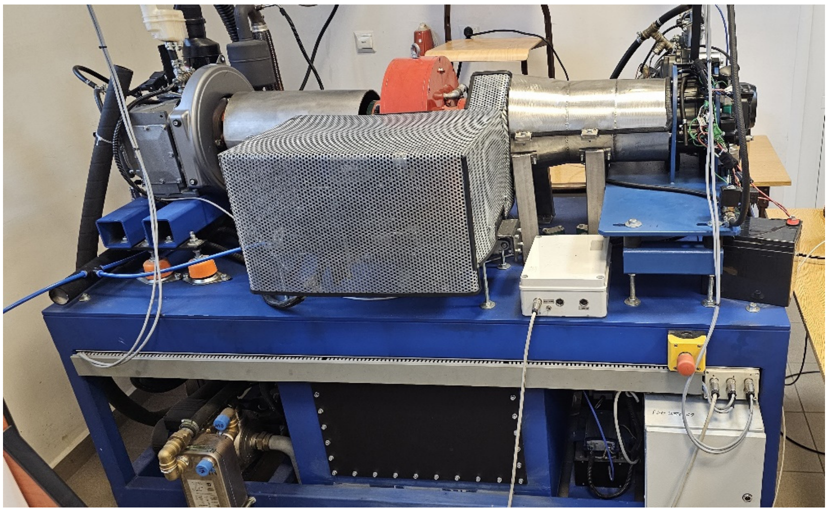

Figure 4. View of the test stand used.

The bench allows for the conduction of a cause-and-effect analysis, including determining the effect of preset changes in operating conditions (i.e., load, preset speed, and type of fuel) on combustion, engine efficiency, and exhaust gas composition and making it possible to assess the nature of the effect of these changes.

The manufacturer's declared nominal parameters of the Yanmar TF70 engine are shown in Table 1.

Table 1. Yanmar TF70 engine characteristics [61].

Parameter	Value/Description	Parameter	Value/Description
Injection timing	17 °BTDC	Dimensions length	607.5 mm
Cylinder bore	78 mm	width	311.5 mm
Piston stroke	80 mm	height	469.0 mm
Displacement	0.382 dm^3	Net weight	67.5 kg
Rated continuous output @ 2400 rpm	4.5 kW		
Rated output at 1 h @ 2400 rpm	5.2 kW	Lubrication Cooling	circulating pressurized liquid, forced
Maximum torque @ 1800 rpm	24.33 Nm		
Compression ratio	18.1		
Specific fuel oil consumption	237.93 g/kWh		

The experiment was supported by ParmDataLab's software, a dedicated and comprehensive data analysis system that allows for real-time plotting of the engine's indicator diagram, determination of the system's heat balance during operation, measurement of key engine performance parameters, and analysis of exhaust gas composition.

2.3. Characteristics of Fuels Used in the Experiment

The tests were carried out for an engine fueled by pure D100 diesel oil with no added fatty acid methyl esters (FAMEs) as the reference fuel and a blend of D100 diesel oil at 90% m/m with RF pyrolytic oil at 10% m/m. The blend containing 10% RF was prepared in accordance with EU Directive 2009/28/EC, which aims to ensure a 10% share of renewable energy (in this case, RF) in fuels used for transport [20,62]. The basic properties of the fuels tested and their compositions are shown in Table 2.

Table 2. Basic properties of the fuels used in the experiment.

Parameter	Unit	Measurement Standard	Diesel Oil (D100)	Diesel Oil and Recycled Oil Blend (D90+RF10)
Density @ 15 °C, ρ_{15}	kg/m^3	ISO 12185:2024 [63]	836.4	846.5
Kinematic viscosity @ 40 °C, ν_{40}	mm^2/s	ISO 3104:2023 [64]	2.728	2.791
Kinematic viscosity @ 100 °C, ν_{100}	mm^2/s	ISO 3104:2023 [64]	1.173	1.198
Lower heat value W	MJ/kg	PN-C-04062:2018-05 [65]	45.46	46.68
Flash point temperature t_{FP}	°C	ISO 2719:2016 [66]	64	59
Derived cetane number DCN	–	ASTM D7668(2017) [67]	54.35	50.40
Water content C_w	% m/m	ISO 12937:2005 [68]	0.0020	0.0035
Sulfur content C_S	% m/m	ISO 8754:2003 [69]	0.000	0.102
Coke residue (with 10% distillation residue) X_{CR}	% m/m	ISO 10370:2014-12 [70]	0.015	0.054
X_A incineration residue	% m/m	ISO 6245:2008 [71]	0.004	0.032
Elemental composition	ppm	ASTM D6595-17 [72]		
Fe			0.0	0.0
Cr			1.1	0.3
Pb			7.3	4.6
Cu			0.0	0.0
Sn			7.4	21.0
Al			2.5	0.0
Ni			7.6	7.9
Ag			0.5	0.0
Si			27.0	13.4
B			1.0	0.6
Mg			0.0	0.4
Ba			0.0	0.0
P			0.0	0.0
Zn			9.5	2.5
Mo			1.3	2.1
Ti			1.7	0.0
V			0.0	0.0

To provide a more complete representation of the engine operating conditions, distillation curves for the fuels used in the experiment were prepared and are shown in Figure 5. The D90+RF10 fuel exhibits higher distillation temperatures, indicating a greater content of hydrocarbons with longer carbon chains.

The mixtures were prepared in mass proportions to maintain consistency in composition, as the volume depends on temperature, and temperature variability differs for various fuels. The authors based the development of this blend on their previous research presented in [20,62].

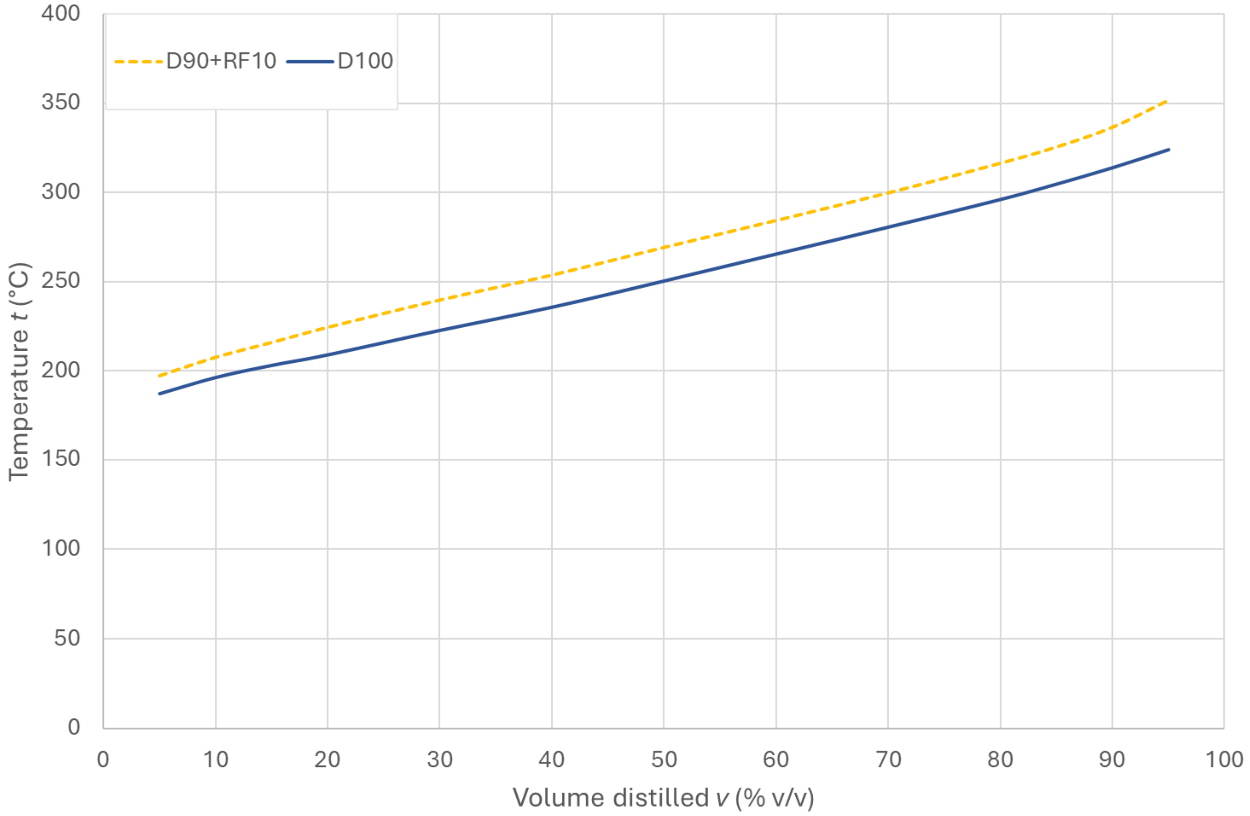

Figure 5. Distillation characteristics of fuels used.

3. Results and Discussion

3.1. Fuel Consumption

Figure 6 shows the recorded characteristics of hourly mass fuel consumption. For all the recorded measurements, the fuel consumption of the engine fueled with D90+RF10 fuel was higher than that of the engine fueled with D100 fuel.

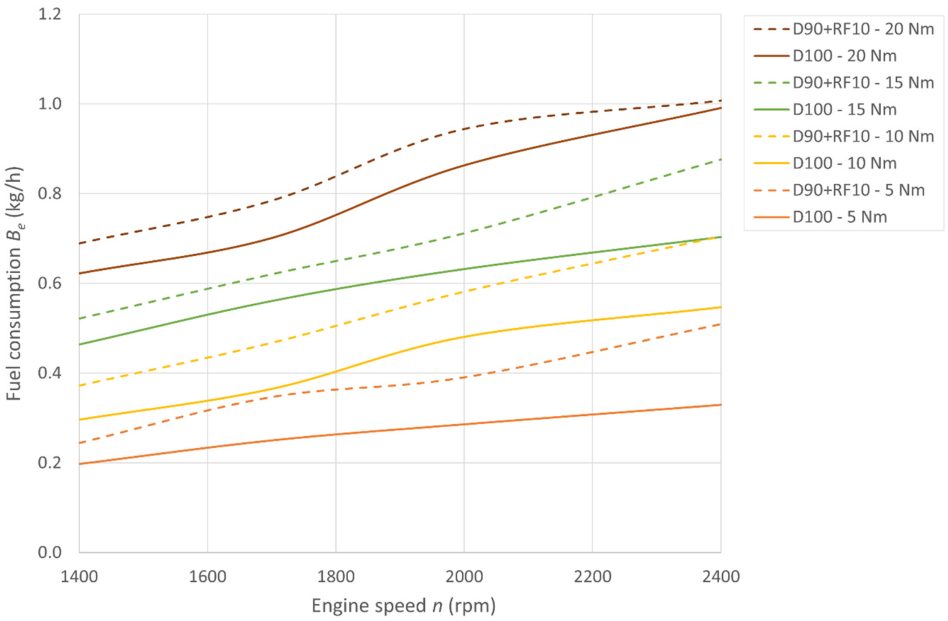

Figure 6. Speed characteristics of hourly mass engine fuel consumption for the tested partial loads.

For partial loads, the largest differences in fuel consumption values occurred at a maximum speed of 2400 rpm and amounted to about 0.18 kg/h, which is a relatively large value, bearing in mind that, for an engine torque load of 5 Nm and a speed of 2400 rpm, the fuel consumption of D100 was 0.32 kg/h, so the increase in fuel consumption when switching to fueling with pyrolytic oil was 56%.

Table 3 presents the values of measurement uncertainty for fuel consumption B_e at a confidence level of 95%. For fuel D100, the highest uncertainty values (0.069 at 5 Nm and 0.108 at 10 Nm) occur at an engine speed of 2000 rpm, indicating lower measurement stability. In contrast, for fuel D90+RF10, the lowest uncertainty (0.006 at 20 Nm) is observed at an engine speed of 2400 rpm, confirming higher measurement reliability in this range.

Table 3. Results of measurement uncertainties for fuel consumption B_e.

Fuel	**Torque *T* (Nm)**	**Engine Speed (rpm)**			
		1400	**1600**	**2000**	**2400**
D100	5	0.032	0.022	0.069	0.053
	10	0.016	0.092	0.108	0.030
	15	0.014	0.015	0.034	0.012
	20	0.006	0.037	0.017	0.013
D90 +RF10	5	0.114	0.039	0.062	0.017
	10	0.081	0.018	0.017	0.017
	15	0.029	0.042	0.034	0.027
	20	0.015	0.012	0.010	0.006

With increasing engine load, the differences in fuel consumption values for the engine fueled by each of the tested fuels decreased. At a maximum load of 20 Nm and a rotational speed of 2400 rpm, the difference in fuel consumption was 0.01 kg/h, so with respect to the D100 fuel consumption of 0.99 kg/h occurring under these conditions, this is an increase equal to 1%.

The lower hourly fuel consumption of the engine powered by the C90+RF10 fuel compared with the D100 fuel can be attributed to the higher calorific value of the fuel mixture. Additionally, the difference in fuel consumption is likely the result of a synergistic effect of various factors. The authors hypothesize that, in this case, it is due to the lower cetane number of the D90+RF10 fuel and its higher content of water and non-combustible components.

To obtain a more complete picture of the fuel's impact on engine performance, the brake-specific fuel consumption (BSFC) was calculated based on the hourly fuel consumption and the known engine power output. Subsequently, using the measured calorific values of the fuels, the engine efficiency was determined. The engine efficiency for each load across the entire range of engine speeds is presented in Figure 7.

The results presented in Figure 7 indicate an increase in efficiency with rising load, which corresponds to the engine operating closer to its nominal conditions. For all tested load levels, the highest efficiency is achieved in the range of 1800–2400 rpm. These observations stem from the fact that the engine's operating point moves closer to the point of optimal performance. At the same time, the efficiency of the engine running on D100 fuel is higher than that of the engine powered by D90+RF10, which is due to more favorable combustion conditions. This is further confirmed by the combustion temperature analysis presented later in the article, showing that higher combustion temperatures are achieved with the D100 fuel.

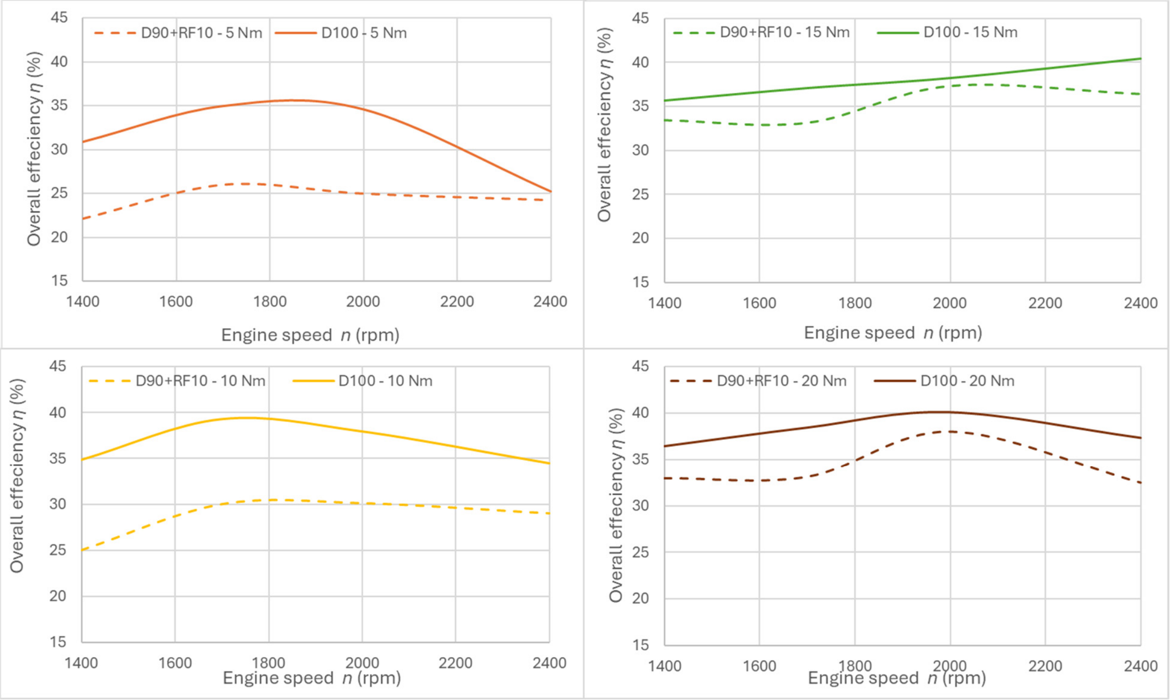

Figure 7. The engine efficiency for each load across the entire range of engine speeds.

3.2. Exhaust Gas Temperature

The exhaust gas temperature was used as a comparative indicator indirectly representing the conditions of the combustion course in the engine cylinder. The differences in exhaust gas temperature for a given load when the engine is fueled with D100 fuel and D90+RF10 fuel under fixed and unchanged external conditions show the change in the combustion course resulting from the type of fuel used. A comparison of the average, minimum, and maximum exhaust gas temperatures for each of the analyzed engine loads at 2400 rpm for both fuels is presented in Figure 8.

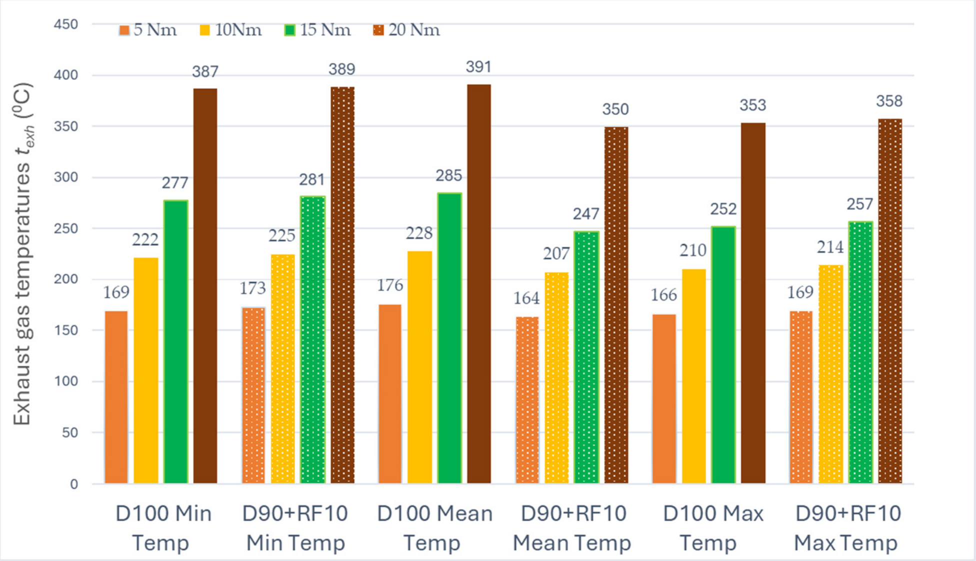

Figure 8. Comparison of exhaust gas temperatures for different engine loads at 2400 rpm powered by D100 and D90+RF10 fuel.

In all the cases analyzed, the maximum and minimum exhaust gas temperatures for the tested loads were higher for the engine fueled with D100. In contrast, the mean exhaust gas temperatures showed the opposite trend, which is presumably due to the individual combustion conditions at each of the tested load points. The physical rationale behind the changes shown in Figure 8 is based on the multiple factors. The complex nature of these changes is likely the result of the synergistic interaction of multiple factors, including the higher water content and lower cetane number of the D90+RF10 fuel, as well as its higher calorific value.

Table 4 presents the values of measurement uncertainty for exhaust gas temperatures t_{exh} at a confidence level of 95%. For fuel D100, the highest uncertainty values (5.569 at 15 Nm and 4.184 at 10 Nm) occur at an engine speed of 2000 rpm, indicating lower measurement stability. The lowest uncertainty (1.994 at 20 Nm) is observed at an engine speed of 2400 rpm, confirming higher measurement reliability in this range.

Table 4. Results of measurement uncertainties of exhaust gas temperatures t_{exh}.

Fuel	**Torque *T* (Nm)**	**Engine Speed (rpm)**			
		1400	**1600**	**2000**	**2400**
D100	5	2.671	3.100	4.378	4.534
	10	3.215	3.526	4.184	4.388
	15	3.843	3.660	5.569	2.679
	20	3.099	1.943	2.105	1.994
D90 +RF10	5	2.200	3.475	3.035	4.562
	10	3.286	3.502	3.109	5.698
	15	3.702	9.292	2.067	5.184
	20	1.715	1.904	2.737	11.125

Water, by removing heat from the combustion chamber, contributes to lowering the combustion temperature and, thus, the temperature of the exhaust gas flowing out of the cylinder. The lower cetane number, in turn, is associated with an increase in the ignition delay and a reduction in the maximum combustion pressure and, thus, the maximum combustion temperature and, ultimately, the exhaust gas temperature. Hence, the results show a beneficial effect, in terms of potential NO_x emissions, on the addition of pyrolytic oil to the fuel, resulting in a reduction in the combustion temperature [73]. However, an accurate assessment of this effect requires further detailed studies using a suitable exhaust gas analyzer capable of measuring NO_x content.

3.3. SO_x Emissions in Exhaust Gas

The sulfur in the fuel is burned to form sulfur dioxide SO_2, a small portion of which is converted into sulfur trioxide SO_3 when it contacts the catalytic agents. These two oxides present in the exhaust gas are collectively designated as SO_x. The level of SO_x in the exhaust gas of an engine not equipped with a scrubber in the exhaust system is, therefore, a direct result of the sulfur content of the fuel. Based on the measured mass consumption of fuel, the known molar mass of SO_2, and the known sulfur content of the fuel, the maximum and average sulfur oxide emissions relating to pure SO_2 were calculated. In turn, the hourly SO_2 emission relating to the power developed by the engine enables the calculation of specific emissions. The hourly and specific SO_2 emissions obtained during the experiment at 2400 rpm are shown in Figures 9 and 10, respectively.

Since D100 fuel does not contain sulfur, an engine powered by this fuel does not emit sulfur oxides. On the other hand, for an engine fueled with D90+RF10 fuel, hourly SO_2 emissions increase as the amount of exhaust gas emitted grows, while specific emission decreases with an increase in engine load to a value below 0.5 g/kWh, after which the specific emission level stabilizes and holds steady.

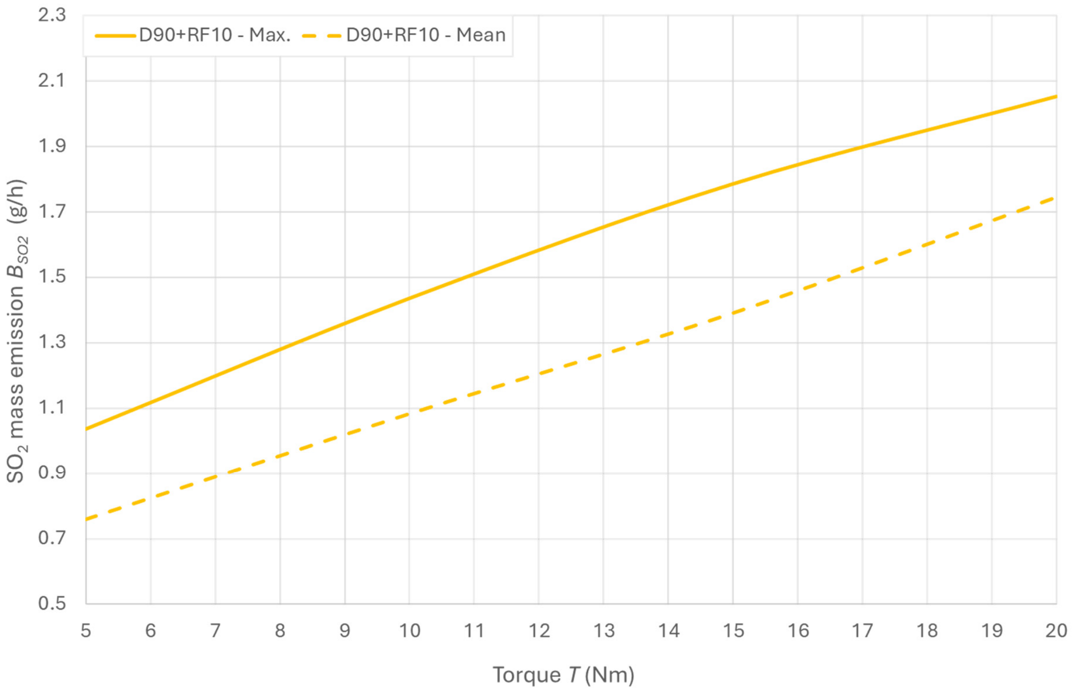

Figure 9. Calculated hourly B_{SO_2} at 2400 rpm emissions in the exhaust gas.

Due to the absence of a flue gas desulfurization (deSOx) system in the experimental setup, the physical explanation for the observed changes shown in Figures 9 and 10 can be attributed to the fact that the hourly SO_2 emission level depends on the sulfur content in the fuel and is directly proportional to the hourly fuel consumption. In contrast, the specific SO_2 emission is directly proportional to the hourly mass emission of SO_2 and inversely proportional to the engine power output.

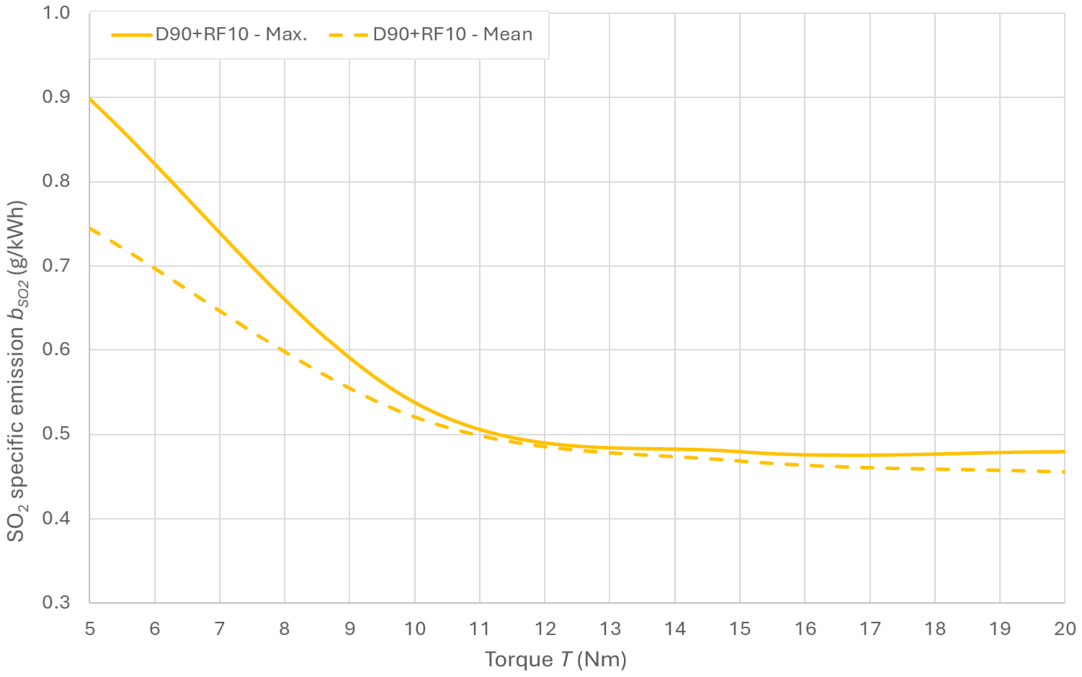

Figure 10. Specific emission of b_{SO_2} at 2400 rpm in the exhaust gas.

Table 5 presents the values of measurement uncertainty for a specific emission of B_{SO_2} and b_{SO_2} in the exhaust gas at a confidence level of 95%. The uncertainty B_{SO_2} remains relatively low across the entire range of torque values, at 0.008 for both 10 Nm and 20 Nm.

In contrast, the uncertainty b_{SO_2} is higher at all torque levels, reaching its maximum value of 0.153 at 15 Nm. The SO_2 content in the exhaust gases does not comply with current European standards, which set a maximum sulfur content in fuel of 0.0105% m/m. It exceeds the allowable limit of 0.00001% m/m (10 mg/kg) [74]. For this reason, the TPO used as an additive to diesel fuel should undergo desulfurization.

Table 5. Results of measurement uncertainties of a specific emission of B_{SO_2} and b_{SO_2} in the exhaust gas.

Torque T (Nm)	Uncertainty $u(B_{SO_2})$	Uncertainty $u(b_{SO_2})$
5	0.072	0.111
10	0.008	0.146

3.4. CO_2 Emissions in the Exhaust Gas

The average carbon dioxide (CO_2) content of the exhaust gas for an engine fueled by each of the tested fuels at the given assumed loads at 2400 rpm is presented in the form of load characteristics in Figure 11.

The nature of changes in CO_2 content for D100 fuel and D90+RF10 fuel is similar. The value of the CO_2 level increases with a growing load, which is a result of the increase in fuel consumption with the increase in power developed. The CO_2 emission level for D100 fuel in the studied load range increases from ~2.7% v/v to ~9.0% v/v and, for D90+RF10 fuel, from ~3.2% v/v to ~9.0% v/v. In the load range studied, the slightly changed maximum percentage difference in exhaust CO_2 emissions occurs at loads of 5–15 Nm and, relative to the emission level for D100 fuel, does not exceed 0.6% and drops to ~0.6% at a full load of 20 Nm. The physical rationale behind the changes shown in Figure 11 is based on the fact that the CO_2 emission level is directly proportional to the hourly fuel consumption.

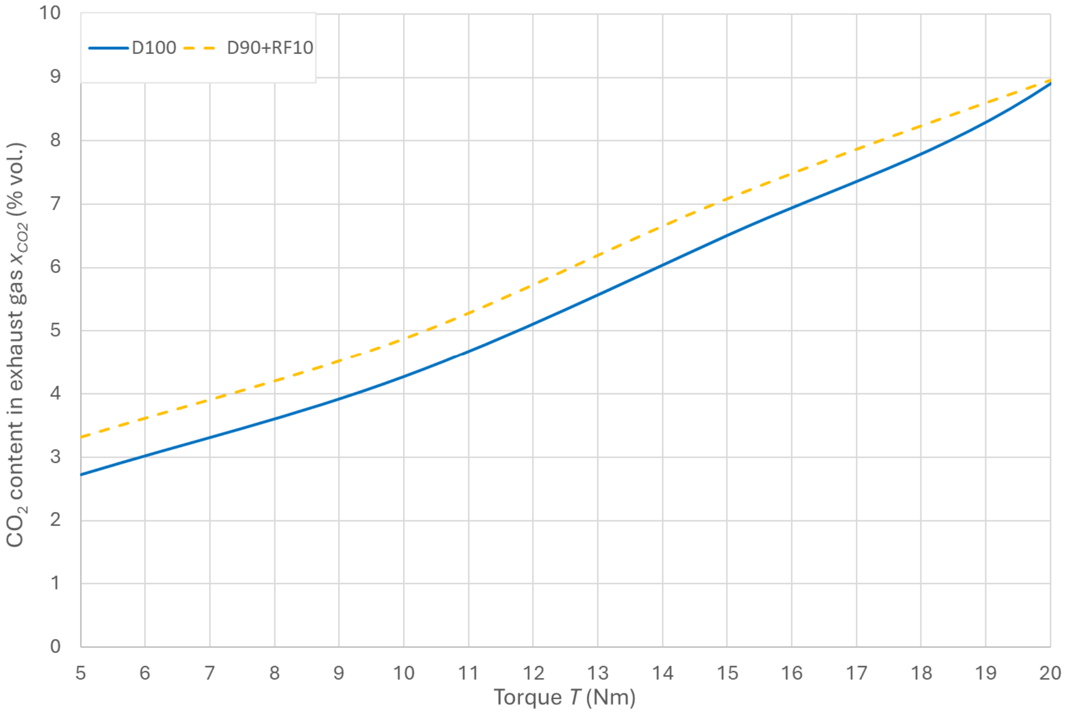

Figure 11. Average CO_2 content at 2400 rpm in the exhaust gas.

Table 6 presents the values of measurement uncertainty for CO_2 content in the exhaust gas at a confidence level of 95%. For D100 fuel, the uncertainties are stable at 5 Nm (0.190) and 10 Nm (0.190), indicating high measurement repeatability. At 15 Nm, the uncertainty increases to 0.230, while the lowest value (0.120) occurs at 20 Nm, confirming improved measurement stability. In the case of D90+RF10 fuel, the uncertainties are varied: at 5 Nm, they are 0.200; at 10 Nm, they rise to 0.790; at 15 Nm, they are 0.250; and at 20 Nm, they reach 0.260, indicating higher measurement variability compared with D100.

Table 6. Results of measurement uncertainties of a specific emission of CO_2 content in the exhaust gas.

Fuel	Torque T (Nm)	Uncertainty $u(x_{CO2})$
D100	5	2.671
	10	3.215
	15	3.843
	20	3.099
D90 +RF10	5	2.200
	10	3.286
	15	3.702
	20	1.715

3.5. CO Emissions in the Exhaust Gas

The average CO monoxide content in the exhaust gas for an engine fueled by each of the tested fuels at the given assumed loads at 2400 rpm is presented in the form of load characteristics in Figure 12.

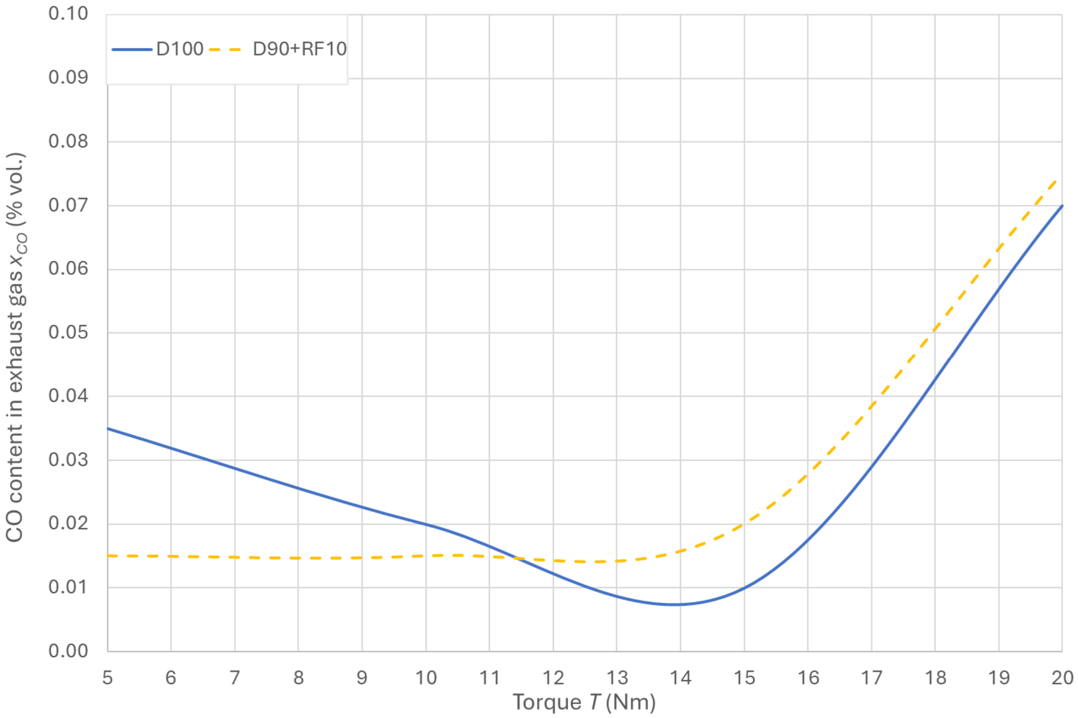

Figure 12. Average CO content in the exhaust gas as a function of torque at 2400 rpm.

The nature of changes in CO content for D100 fuel and D90+RF10 fuel is similar over much of the analyzed load range. The value of the CO level initially decreases for the D100 fuel or remains constant for the D90+RF10 fuel, after which it begins to increase for both fuels, which is a result of the increase in fuel consumption with the growth in power developed and the increase in the engine's need for air, which is drawn into the cylinder directly from the cylinder environment. Thus, this is the effect of the lack of supercharging in the test engine used. It does, however, provide an idea of the trend of changes occurring in self-aspirated (naturally aspirated) engines.

The CO emission level for D100 fuel over the load range studied increases from 0.010% v/v to 0.070% v/v and, for D90+RF10 fuel, from 0.015% v/v to 0.075% v/v. Thus, the maximum difference in CO levels for the tested fuels does not exceed 0.005% v/v. In the studied load range, the maximum percentage difference in CO emission levels in the exhaust gas occurs at a load of 15 Nm, at which the CO emission level for D90+RF10 fuel is 0.02% v/v relative to the emission level for D100 fuel of 0.01% v/v. It can also be observed that, for loads below ~11.5 Nm, the CO emission level of the D100 fuel is higher than that of the D90+RF10 fuel, while at loads >11.5 Nm, the CO emission level of the D100 fuel engine is lower than that of the D90+RF10 fuel engine. With an increase in load in the load range of 14–20 Nm, a decrease in the difference between the CO emission level of the D100-fueled engine and that of the D90+RF10-fueled engine is observed. The difference at 20 Nm is ~7.1% relative to the level for D100, while at other loads, it is below 9.0% and decreases to ~0.7% for full loads equal to 20 Nm.

The physical basis for CO formation presented in Figure 12 stems directly from the quality of the combustion process. Specifically, as the oxygen content increases (i.e., with a higher air–fuel equivalence ratio), the likelihood of the formation of regions with incomplete combustion in the combustion chamber is minimized, reducing the chance that the carbon in the fuel oxidizes to CO instead of CO_2. Initially, due to increased engine efficiency, CO levels remain relatively low. However, at medium to high loads, CO emissions increase, which can be attributed to the fact that the tested engine is naturally aspirated. As a result, proper mixture quality is achieved solely through precise throttle adjustment and fuel dose control. In contrast, turbocharged engines—thanks to the action of the intake air compressor—can maintain higher air excess ratios, which contributes to lower CO emission levels in the exhaust gases.

Table 7 presents the values of measurement uncertainty for *CO* content in the exhaust gas at a confidence level of 95%. For D100 fuel, the uncertainties are low at 5 Nm (0.005) and 10 Nm (0.010), confirming high measurement repeatability. At 15 Nm, the uncertainty is 0.001, indicating very high stability, while at 20 Nm, it increases to 0.050, reflecting greater variability. For D90 + RF10 fuel, the uncertainties are low at 5 Nm (0.005) and 10 Nm (0.005), confirming good repeatability. At 15 Nm, the uncertainty is 0.010, which is higher than that for D100 but still acceptable. At 20 Nm, the uncertainty rises to 0.055, indicating increased variability compared with D100.

Table 7. Results of measurement uncertainties of a specific emission of *CO* content in the exhaust gas.

Fuel	Torque T (Nm)	Uncertainty $u(x_{CO})$
D100	5	0.005
	10	0.010
	15	0.001
	20	0.050
D90 +RF10	5	0.005
	10	0.005
	15	0.010
	20	0.055

In accordance with Polish emission standards [57], for vehicles registered after 1 May 2004, the maximum allowable carbon monoxide (CO) concentration in exhaust gases is 4.5% v/v for motorcycles and 0.3% v/v for other motor vehicles at idle and 0.2% v/v at engine speeds between 2000 and 3000 rpm. The maximum CO emission measured for the D90+RF10 fuel blend did not exceed 0.075% v/v, remaining well below the regulatory limit.

3.6. Hydrocarbon Emissions in the Exhaust Gas

The average content of HC hydrocarbons in the exhaust gas for an engine fueled by each of the tested fuels at the given assumed loads at 2400 rpm is presented in the form of load characteristics in Figure 13.

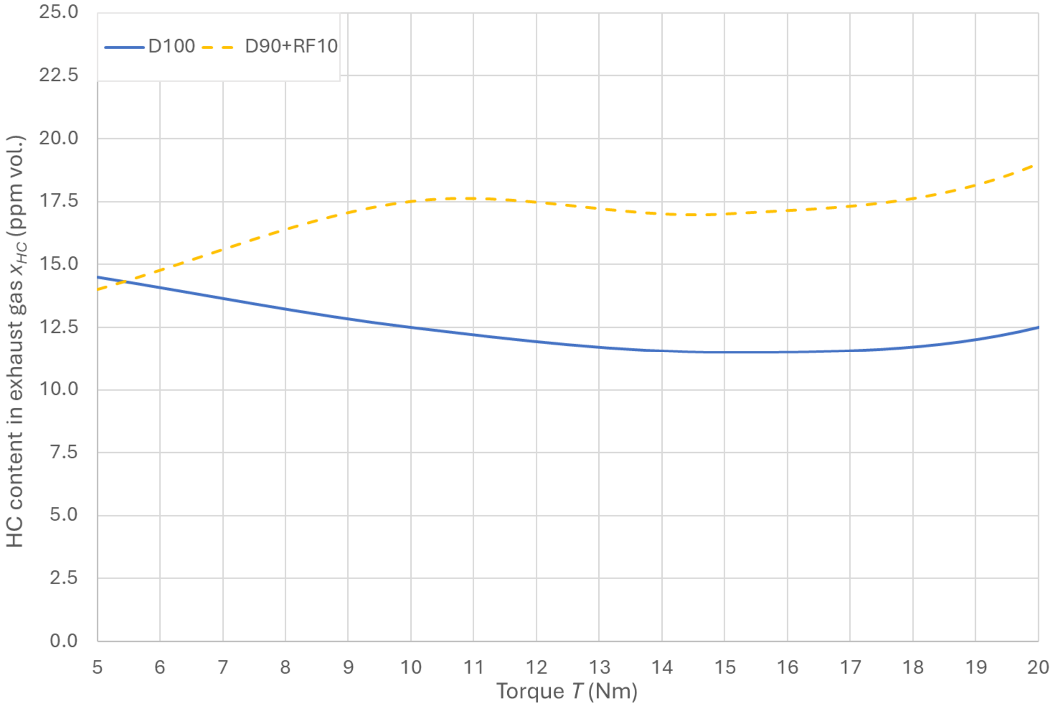

Figure 13. Average HC content in the exhaust gas as a function of torque at 2400 rpm.

When the engine is fed with each of the tested fuels, the change in the level of HC emissions in the exhaust gas shows relatively low variability. For the load range analyzed, the HC content in the exhaust of the engine fueled with D100 fuel varied from 14.5 ppm v/v at a load of 5 Nm, which decreased to 11.5 ppm v/v at a load of 15 Nm, then increasing slightly to 12.5 ppm v/v at a load of 20 Nm. On the other hand, for the engine fueled with D90+RF10 in the load range of 5–10 Nm, HC emissions increased from 14 ppm v/v to 17.5 ppm v/v, then showed fluctuating values in the range of 17.5 ppm v/v to 19 ppm v/v in the load range of 10–20 Nm. It can be concluded that, for each engine power case, the variation of HC levels in the exhaust gas was at a relatively fixed level, indicating good combustion processes in the engine. In addition, the higher values of HC emissions for the engine fueled with pyrolytic oil admixture relative to pure D100 fuel indicate the higher amount of long-chain hydrocarbons in the RF100 fuel used as an admixture relative to the D100 fuel.

Table 8 presents the values of measurement uncertainty for *HC* content in the exhaust gas at a confidence level of 95%. For D100 fuel, the uncertainties are 0.500 at all torque levels (5 Nm, 10 Nm, 15 Nm, and 20 Nm), confirming the high repeatability and stability of the measurements. In the case of D90+RF10 fuel, the uncertainties are significantly higher and varied: 1.000 at 5 Nm, 1.500 at 10 Nm, and 1.000 at both 15 Nm and 20 Nm, indicating greater variability in the measurements compared with D100.

Table 8. Results of measurement uncertainties of a specific emission of *HC* content in the exhaust gas.

Fuel	Torque T (Nm)	Uncertainty $u(x_{HC})$
D100	5	0.500
	10	0.500
	15	0.500
	20	0.500
D90 +RF10	5	1.000
	10	1.500
	15	1.000
	20	1.000

From a physical standpoint, the nature of the changes in CH emission levels shown in Figure 13 can be explained similarly to the changes in CO emission levels. The presence of hydrocarbons (HCs) in the exhaust is a result of incomplete combustion. Naturally, CH emission levels also depend on the length of the hydrocarbon chains in the fuel components used to power the engine. In the case of the tested fuels, this suggests a more complex chemical structure of the hydrocarbons that make up the TPO used as an admixture in the D90+RF10 fuel blend. From a physical standpoint, the nature of the changes in CH emission levels shown in Figure 13 can be explained similarly to the changes in CO emission levels. The presence of hydrocarbons (HCs) in the exhaust is a result of incomplete combustion. Naturally, CH emission levels also depend on the length of the hydrocarbon chains in the fuel components used to power the engine. In the case of the tested fuels, this suggests a more complex chemical structure of the hydrocarbons that make up the TPO used as an admixture in the D90+RF10 fuel blend.

According to Polish standards [57], the hydrocarbon (HC) level in exhaust gases is not subject to testing for vehicles registered after 1 May 2004. However, for older vehicles registered between 1 July 1995 and 30 April 2004, the permissible HC emission level must be below 100 ppm v/v. Our test results showed that the maximum HC emission for the D90+RF10 fuel blend was 19 ppm at a load of 20 Nm, thus meeting the specified standards.

4. Conclusions

The conducted research showed the possibility of using pyrolysis oil as a possible admixture to diesel oil, especially in marine applications as the fuel used in the experiment meets current international standards for sulfur content. This study compared the effects of the fuels, pure diesel oil (D100), and a blend of diesel oil with 10% pyrolytic oil admixture (D90+RF10) on the exhaust emissions produced by their combustion in a Yanmar TF70 internal combustion research engine.

The difference in fuel consumption occurred at 2400 rpm and was 0.18 kg/h. This translates into a 56% increase in D90+RF10 fuel consumption at low loads. At higher loads, the value decreased, reaching 0.01 kg/h (1%) at maximum load.

The maximum and minimum exhaust gas temperatures at the tested loads were higher for the engine fueled with D100. In contrast, the mean exhaust gas temperatures showed the opposite trend, likely due to varying combustion conditions at each load point. The complex nature of these changes is probably the result of the synergistic interaction of several factors, including the higher water content and lower cetane number of the D90+RF10 fuel, as well as its higher calorific value. The lower cetane number and higher water content contribute to delayed ignition and reduced combustion temperatures [37,40,41].

D100 fuel is a standard fuel (according to ISO EN 590) and has no sulfur oxide emissions. For D90+RF10 fuel, SO_2 emissions increased in proportion to fuel consumption. The sulfur emission level in D90+RF10 fuel does not comply with European standards, and this fuel should undergo desulfurization. However, the specific emission value decreased with increasing load and stabilized at 0.5 g/kWh, indicating that the fuel combustion efficiency increased with a growing load.

In terms of CO_2 emissions, the D90+RF10 fuel showed higher CO_2 levels compared with the D100 fuel, with a maximum difference of 21.7% at the lowest load. At the maximum load, the difference decreased to 0.7%. Carbon monoxide (CO) emissions showed similar trends for both fuels, with D100 being higher at low load ranges and D90+RF10 at higher loads. The differences between the fuels decreased as the load increased. The maximum difference between emissions was 0.005% v/v.

In the case of hydrocarbon (HC) emissions, the D90+RF10 fuel showed higher values throughout the test range, which may be due to the presence of longer-chain hydrocarbons in the pyrolytic oil. Emissions of the HC content for D90+RF10 fuel had a range of 14–19 ppm v/v, while for D100 fuel, the values ranged from 11.5 to 14.5 ppm v/v. Elevated HC emissions may indicate incomplete combustion of pyrolytic fuel components. The D90+RF10 fuel blend demonstrated significantly lower CO and HC emissions than the limits set by Polish standards, with maximum values of 0.075% v/v (limit: 0.3% at idle, 0.2% at 2000–3000 rpm).

The conducted studies indicate the possibility of wider use of post-recycled oils as admixtures to standard fuels. However, this may be associated with higher fuel consumption and increased emissions of toxic exhaust compounds produced during their combustion. It may have a negative impact on the ability to meet environmental standards and increase the market's hostility to the use of such admixtures. This necessitates further work on optimizing the composition of the fuel blend and its production processes. Future research will focus on the further refinement of the blend composition and the long-term evaluation of the impact of pyrolysis oil on the performance and wear of internal combustion engines, especially in terms of their durability and energy efficiency. The D90+RF10 fuel blend demonstrated significantly lower CO and HC emissions than the limits set by Polish standards, with maximum values of 0.075% v/v (limit: 0.3% at idle, 0.2% at 2000–3000 rpm) for CO and 19 ppm (limit: 100 ppm) for HC.

The conducted study reveals promising possibilities for using pyrolysis oil (TPO) as a diesel oil admixture. However, several critical areas require further investigation. First, it is essential to carry out long-term endurance testing of internal combustion engines to evaluate the effects of TPO blends on engine wear, stability, and energy efficiency over extended periods. Another important research direction is the optimization of fuel blend composition, exploring various TPO concentrations (e.g., 5%, 15%, 20%) and their impact on fuel efficiency, emissions, and engine performance. Furthermore, it is necessary to examine the variability of TPO properties resulting from different feedstocks and pyrolysis methods. Comparative studies of TPO types could help determine the most suitable oil for specific engine types or applications. Moreover, research should include an evaluation of compliance with marine emission standards, such as those set out in MARPOL Annex VI, particularly given the suggested maritime use of such fuels. Finally, studying the impact of environmental and operational conditions, including temperature, humidity, and extended engine load cycles, will be critical for the practical implementation and reliable field performance of TPO-blended fuels.

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T.P. and P.B.; supervision: L.C.; project administration: L.C.; funding acquisition: L.C. and W.K. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

ASTM	US-based international standards organization
BTDC	angle before the top dead center
B_{SO2}	mass SO_2 emission
b_{SO2}	specific SO_2 emission
CO	carbon monoxide
CO_2	carbon dioxide
C_S	sulfur content in the fuels under study
C_w	water content in the fuels under study
D100	pure diesel oil without FAME admixtures
D90+RF10	fuel with 90% m/m of D100 diesel and 10% m/m of pyrolytic oil (RF)
$deSO_x$	flue gas desulfurization system
FAME	fatty acid methyl ester
HC	general hydrocarbon designation
ISO	International Organization for Standardization
NO	nitric oxide
NO_2	nitrogen dioxide
NO_x	generic determination of NO and NO_2 nitrogen oxides
RF	recycled fuel
SO_2	sulfur dioxide
SO_3	sulfur trioxide
SO_x	general designation for sulfur oxides SO_2 and SO_3
TPO	tire pyrolytic oil
u	uncertainty
W	lower heat value
X_A	incineration residue
x_{CO}	measured CO emission
x_{CO2}	measured CO_2 emission
X_{CR}	coking residue with 10% distillation residue
x_{HC}	measured HC emission
X_S	total sediment by hot filtration
ν_{100}	kinematic viscosity at a reference temperature of 100 °C
ν_{40}	kinematic viscosity at a reference temperature of 40 °C
ρ_{15}	density at a reference temperature of 15 °C

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