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Article

Improvement of Fusel Oil Features and Effect of Its Use in Different Compression Ratios for an SI Engine on Performance and Emission

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Abstract: In this study, the effects of the use of improved fusel oil on engine performance and on exhaust emissions in a spark-ignition engine were investigated experimentally in consideration of the water, gum, and moisture content at high compression ratios according to TS EN 228 standards. In the study, a four-stroke, single-cylinder, air-cooled, spark plug ignition engine with an 8/1 compression ratio was used at three different compression ratios (8/1, 8.5/1, 9.12/1). Experiments were performed for six different ratios of fuel blends (F0, F10, F20, F30, F40, and F50) at a constant speed and different loads. The data obtained from the experiments were compared with the original operating parameters of the engine while using gasoline. According to the test results, the optimal engine performance was at a 9.12/1 compression ratio and with a F30 fuel blend. With the increase from an 8/1 to 9.12/1 compression ratio for the F30 fuel blend, the overall efficiency increased by 6.91%, and the specific fuel consumption decreased by 2.35%. The effect of the optimum fusel blend on the emissions was also examined and CO emissions were reduced by 36.82%, HC emissions were reduced by 23.07%, and NO_x emissions were reduced by 15.42%, while CO_2 emissions were increased by 13.88%.

Keywords: fusel oil; SI engine; compressions ratio; engine performance; emission; removal of gum and water content

1. Introduction

Due to the increasing energy demand in the world and the fact that the petroleum fuels used in motor vehicles will not be able to meet the needs in the near future, recently, many studies have been carried out on alternative energy sources and the development of existing systems [1].

In addition to fossil fuels, alternative fuels are used in internal combustion engines. Fusel oil can be used as an alternative fuel in internal combustion engines due to the amount of alcohol it contains. As alternative fuels are advantageous over fossil fuels, due to the lower exhaust emissions, and because they are renewable and can be produced from waste materials, they are more economical. Alcohols can be used in engines as standalone fuel or as gasoline–alcohol blends [1]. Alcohols may have a cooling effect on the fresh mixture due to their lower thermal values and higher vaporization temperatures, which may result in an increased volumetric efficiency of the engine [2–4]. Since alcohols are higher in octane number than gasoline, the engine can operate at higher compression ratios, which in turn can improve engine efficiency and reduce fuel consumption [5–8].

Fusel oil is a distillation by-product from ethyl alcohol fermentation [9]. Normal and branched chain monohydric alcohols with lower carbon atoms (2–5 carbon atoms) are the only natural sources of fusel oil [9–11]. Fusel oil may be colorless, yellow, brown, or green, depending on the type of substance used in fermentation; it has a very sharp, unpleasant, and irritating odor [12]. In addition, fuel oil is contained at the rates of 0.1% to 0.7% in sugar beet molasses residue. The composition and quantity of fusel oil varies depending on the type of carbon source used in the process of alcohol production by fermentation and the methods of preparation and the resolution of the fusel oil from the fermentation mixture [9,12].

In some studies on fusel oil, the effects of fusel oil–gasoline blends on engine characteristics were investigated by reducing the amount of H_2O in fusel oil for internal combustion engines [13–15]. The effect of fusel oil on the combustion and performance of the engine was investigated by improving the calorific value by decreasing the moisture content, and the moisture content was found to have negatively affected the combustion [16,17]. In order to determine the optimal fusel oil–gasoline blend, engine performance and emission values were investigated using the response surface technique (RSM) by operating the engine at a specific load [18–20]. The effects of fusel oil on combustion, specifically before and after the removal of moisture content, were examined comparatively and analyzed statistically [21,22]. In other studies on fusel oil, the effects of fusel–gasoline blends on engine performance and emissions were also investigated [8,23–26].

The utilization of waste fusel oil as an alternative fuel source over gasoline is important in terms of preventing environmental pollution and for the economic use of natural resources. Literature reviews have revealed that there were no studies on the use of fusel oil in internal combustion engines at different compression ratios [16,18,23,27–29]. This study fills a gap in the literature as it uses the waste fusel oil, a by-product obtained from the ethanol production processes of sugar production plants, as an alternative energy source to unleaded gasoline, a petroleum-based fuel, in a spark plug ignition engine [30,31]. Different physical and chemical characteristics of waste fusel oil and water as well as the gum and moisture ratios were analyzed according to the standard methods and were then accorded to the standards [32]. In addition, the ratio of an optimal fuel mixture at constant speed and the different operating loads at different compression ratios was determined, and their effects on engine performance and exhaust emissions were investigated.

2. Materials and Methods

2.1. Test Fuel Improvement

The fusel oil used in the experiments was supplied by Eskişehir Sugar Plant and Konya Sugar Plant, both of which produce ethyl alcohol with a 99.5% purity according to the TS 1810 standard. Molasses fusel, which is an oily, yellow to brown liquid, was used in the study. The H_2O content was found to be 240 mg/kg, and the distillation analysis showed a flash point of 39.5 °C. The test results by TUBITAK MRC to the physical and chemical composition properties of the fusel oil sample used as an alternative fuel in this study are shown in Table 1.

Table 1. Composition of fusel oil blend.

Amyl Alcohol	Chemical Formula	Molecular Weight (g/mol)	Density (g/cm^3)	Boiling Point (°C)	Melting Point (°C)	Volume (%)	Viscosity (cp)	Specific Heat (J/Kg °K)
2-Methyl 1-Butanol	$C_5H_{12}O$	88.148	0.815	129	−70	0.22	4	2386.5
4-Methylpe 2-Penthanol	$C_6H_{14}O$	102	0.8079	131.8	−90	0.27	-	-
i-amyl alcohol (3-Methyll 1-Butanol)	$C_5H_{12}O$	88	0.809	132	−117.2	62.29	3.86	2239.9
n-Hexanol (1-Hexyl Alcohol)	$C_6H_{14}O$	102	0.8186	157.2	−51.6	0.51	-	-
n-Heptanol (1-Heptil Alcohol)	$C_7H_{16}O$	116	0.824	175	−34.6	0.08	-	-
i-Butanol	$C_4H_{10}O$	74	0.805	108	−108	8.71	3.5	2470.2
n-Butanol	$C_4H_{10}O$	74	0.81	117	−79.9	0.12	2.6	2876.3
n-Propanol	C_3H_8O	60	0.804	97.2	−127	0.738	2.256	2470.2
i-Propanol	C_3H_8O	60	0.789	82.5	−85.8	8.06	2.1	2763.3
Ethanol	C_2H_6O	46	0.789	78	−112	11.09	1.41	2847.1
Water	H_2O	18	1	100	0	10.3	1	4186.8

2.2. Preparation of a Proper Fuel Blend

The amount of H_2O contained in fusel oil as a factory waste has adverse effects on engine performance and combustion [15]. Even though olefins increase the octane number in gasoline, the unstable olefins formed during cracking cause the formation of gum when they come into contact with air to oxidize. Figure 1 shows the amount of gum in the fusel–gasoline blend. The amount of gum and H_2O in the fusel oil prevents a homogeneous blend with gasoline [19]. In order to provide an alternative fuel, the amount of gum must be reduced, and it must be refined to reduce the water content. For this purpose, the fusel oil, having been subjected to a series of processes, was made available for use in engine tests.

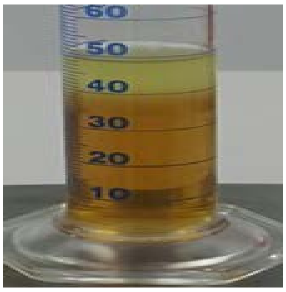

Figure 1. Gum amount in the fusel–gasoline blend.

Distillation efficiency of fusel oil was found to be 96.5% at the final boiling point, 139.9 °C. The amount of gum present is at the limit determined by TS EN 228, which is a maximum of 5 mg/100 mL. In the mixture of a fusel–gasoline fuel blend (10% fusel + 90% gasoline), this value was found to be 26.6 mg/100 mL, which was reduced to 13.4 mg/100 mL using a gum solver and to 0.8 mg/100 mL using a molecular sieve Z4-01 (2.5–5 mm) moisture scavenger, and was refined of H_2O approximately by 96.9%. The reduction in gum and H_2O was observed on a GC/MS chromatography mass spectroscopy device. The fuel blend was accorded to TS EN 228 standards, and a homogeneous fuel blend was obtained. Removal of water content from fusel oil leads to a distillation of alcohols in lower temperatures but does not cause a significant change in the amount of alcohol [24]. Figure 2 shows the Sieve Z4-01 (2.5–5 mm) moisture scavenger and the improved fusel–gasoline blends.

Figure 2. Sieve Z4-01 (2.5–5 mm) moisture scavenger and improved fusel–gasoline blends.

2.3. Experiment Fuels

Five blends of unleaded gasoline–fusel oil were prepared, and their characteristics are shown in Table 2.

Table 2. Fuel blends and characteristics.

Blend.	Composition	Density (g/m^3)	Lower Calorific Value (KJ/kg)	Engine Octane Number	Research Octane Number	Freezing Point (°C)
F0	0% fusel oil 100% unleaded gasoline	721.79	43,580	86.51	96.33	−53
F10	10% fusel oil 90% unleaded gasoline	726.03	42,449.60	87.08	97.80	>50
F20	20% fusel oil 80% unleaded gasoline	735.13	41,319.20	87.12	97.84	>50
F30	30% fusel oil 70% unleaded gasoline	750.55	40,188.81	87.17	98.30	>50
F40	40% fusel oil 60% unleaded gasoline	758.54	39,058.41	88.50	98.34	>50
F50	50% fusel oil 50% unleaded gasoline	764.83	37,928.02	89.30	98.38	>50
F100	100% fusel oil 0% unleaded gasoline	852.1	32,276.04	103.61	106.82	>50

2.4. Increase of Compression Rate for the Test Engine

In the experiments, three different cylinder heads of the spark-ignition engine used were removed from the grounding plates and grinded, and the compression ratio was altered. Cylinder heads were grinded at ateliers of Mercedes Benz (Hadımköy, Istanbul-Turkey) through measurements. Figure 3 shows the grinding operations; 0.40 and 0.80 mm of sawdust were removed from the cylinder heads. In order to calculate the compression ratios, the volumetric capacity of the cylinder was measured.

Figure 3. Grinding of cylinder head.

The geometric compression ratio, defined as the ratio of the cylinder volume (V_1) at initial compression to the end-compression volume (V_2), is shown in Equation (1), where Vh is the piston displacement (swept) volume and Vc is clearance volume.

$$\varepsilon = \frac{V_1}{V_2} = \frac{V_h + V_c}{V_c} = 1 + \frac{V_h}{V_c} \quad (1)$$

In the actual engine, the compression does not start at bottom dead center (BDC) but after the intake valve is closed. Therefore, the compression ratio (ε_g) of the actual motor can be expressed as in Equation (2). V_k is the volume that the piston covers until the valves close after BDC. Table 3 shows the altered compression ratios.

$$\varepsilon_g = \frac{(V_h - V_k) + V_c}{V_c} \tag{2}$$

Table 3. Altered compression rates.

Volumetric Values	ε
Unmodified engine	8
Cylinder head grinded by 0.40 mm	8.50
Cylinder head grinded by 0.80 mm	9.12

2.5. Experiment Procedure

In the experiments, a Honda HK 550 MS, which is a four-stroke, single cylinder, carburetted, and spark-ignition generator, was used. The technical specifications of the generator and the engine of the generator used in the experiments are given in Table 4.

Table 4. Technical specifications of the test engine.

Specifications	
Model	Honda GX390
Type	4-stroke, overhead cam, single cylinder
Compression ratio	8.0:1
Cooling system	Forced-air cooling
Piston displacement (cm^3) (Bore × Stroke) (mm)	389 (86.0 × 64.0)
Net power (SAE 1349)	11.8/11.7 HP (8.7 kW) @ 3600 rpm
Net torque (SAE 1349)	2.70 kg/m (26.5 N/m) @ 2500 rpm
Power Generator Specifications	
Model	Honda HK 550 M/MS
Max. output	55 kW
Voltage	230 V
Phase	Single-phase
Frequency	50
Power factor	13.0 @ 3600
AC circuit breaker	Yes

A Bilsa MOD 2210 WINXP-K exhaust gas analyzer was used in the experiments to measure the CO, HC, CO_2, and NO_x emissions, and lambda (λ) values. The precisions are shown in Table 5.

Table 5. Measurement ranges of the exhaust gas analyzer.

Parameters	Limits	Precision
CO	0–10.0 vol.%	0.001%
CO_2	0–20.0 vol.%	0.001%
HC	0–10.000 vol. ppm	1 ppm
O_2	0–10 vol.%	0.01%
NO_x	0–5000	1 ppm
Lambda	0.5–2.00	0.001
RPM	0–9990 rpm	10 rpm
Lambda	0.5–2.00	0.001

The experimental setup is shown in Figure 4. In order to measure fuel consumption, an Ender SWOCK YP20002 electronic scale that can measure up to 2 kg with a precision of 0.01 g was used. A Delta SW 305 digital chronometer was used to determine the fuel consumption per unit time. A K/pt100 type thermocouple was used to measure the exhaust gas temperature. The PCE-FOT 10 brand digital instrument was used to measure the engine oil temperature. The numerical data from the sensors were read from the motor and monitored on the test computer. Since the lower thermal value of fusel oil is lower than that of gasoline, the main nozzle on the carburettor was widened to adjust to $\lambda = 1$. The nozzle cross-section was adjusted to $\lambda = 1$ in all experiments by means of the conical-tipped fuel adjustment screw. The air excess coefficient was monitored on the computer during the experiments. Six 1000 W halogen projector lamps were used to load the fixed speed generator at different operating loads for dynamometer purposes.

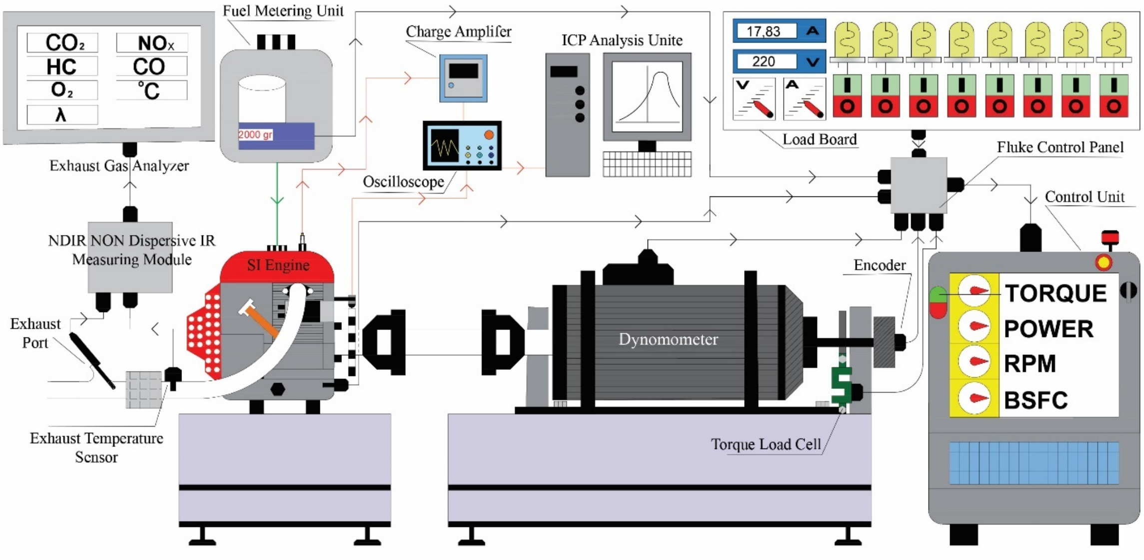

Figure 4. An overview of the experimental setup.

A system consisting of a piezoelectric pressure transducer, inductive pick-up, charge amplifier, oscilloscope, and personal computer (PC) was set up to measure the in-cylinder pressure of the test engine. To collect data for the in-cylinder pressure, a Kistler model 611C piezoelectric transducer mounted on the spark plug was used, where the in-cylinder pressure values were transferred to a Rigol digital oscilloscope (DS2202E) via a Kistler model 5018A charge amplifier and recorded on a PC. The data regarding the crank angles and the position of the top dead center were transmitted to an oscilloscope via an inductive pick-up.

Before starting the data collection for the experimental tests, the engine was operated until it reached the operating temperature. Engine tests were conducted at constant speed using six different volumetric fuel blends (F0, F10, F20, F30, F40, and F50) at the original cylinder head (CR = 8:1); the overall efficiency at 1000–6000 W load ranges, specific fuel consumption, in-cylinder pressure data, and the CO, HC, CO_2, and NO_x exhaust emission values were examined. As a result, an optimal fuel blend and the most efficient operation range were determined at different compression ratios (8.5/1–9.12/1).

3. Findings and Discussion

3.1. Brake Thermal Efficiency and In-Cylinder Pressure at Different Compression Ratios

Brake thermal efficiency is the ratio of the useful mechanical power obtained from the engine to the energy released by the fuel consumed per unit time [33]. Since the octane numbers of alcohols are higher than those of gasoline, they can work without knocking at high compression rates. This, as it increases the combustion efficiency and, thus, the end-compression temperature and pressure, can provide a higher overall efficiency than does the gasoline [34].

The most important parameters having an effect on engine efficiency are the physical and chemical characteristics and the compression ratio of the fuel used [6,34,35]. Figure 5 shows the brake thermal efficiency graph based on a CR of 8/1 engine load. At an 8/1 compression ratio, we found that for all loads, the brake thermal efficiency for the F10, F20, and F30 fuel blends, when compared to that of the F0 fuel, increased by an average of 1.41%, 2.77%, and 4.29% respectively, whereas for the F40 and F50 fuel blends, it decreased by an average of 5.33% and 10.54%, respectively. The abundance of oxygen content in the molecular structure of alcohols in the fusel oil and the higher octane number in comparison to gasoline improved combustion and increased efficiency. For higher rates of fusel oil in fuel blends, as the H_2O content increases, the temperature inside the cylinder and the efficiency decrease. This shows that the H_2O content of fusel oil decreases efficiency, as shown in some studies in the literature [18,27,36,37]. Awad et al. [13] conducted an RSM analysis to examine the effect of different H_2O content of fusel oil–gasoline blends on engine performance. It was stated that fusel oil with water content within fusel oil–gasoline blends, whether water is reduced or not, has a significant effect on the brake thermal efficiency (BTE) engine load.

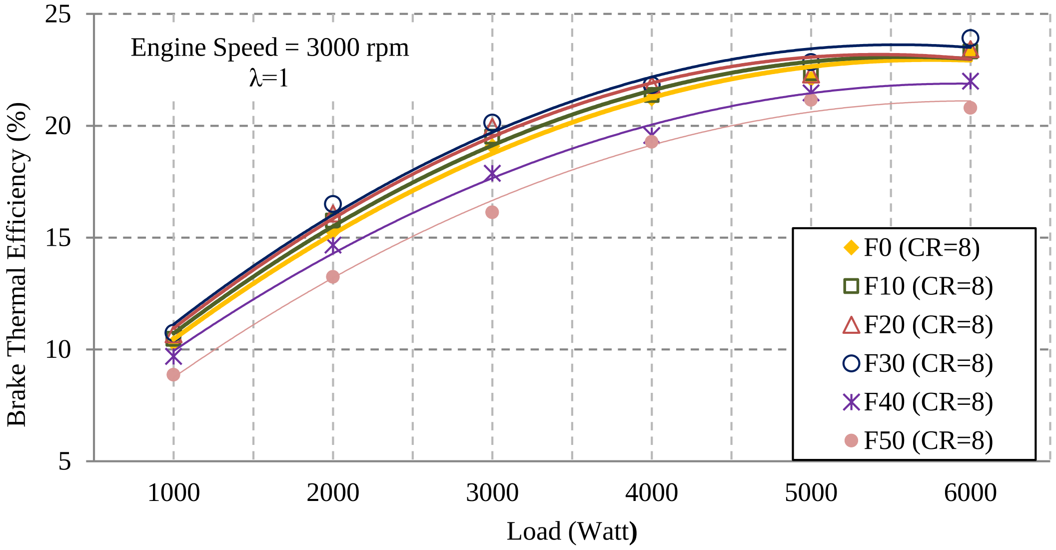

Figure 5. Overall efficiency graph based on an engine load at a cylinder head (CR) of 8:1.

Figure 6 shows the in-cylinder pressure graph of six different fuel blends (F0, F10, F20, F30, F40, F50) at a CR of 8:1. The vaporization temperature of fusel oil is higher than that of gasoline. The increase in the internal combustion pressure (ICP) ratio, the decreased H_2O content of the fusel oil, the higher octane number of fusel oil in comparison to gasoline and fusel oil's oxygen content improved the combustion. The review of graph showed that the ICP of F30 fuel increased by the fusel ratio in the fuel blend, and it was found to be 33.02 bars.

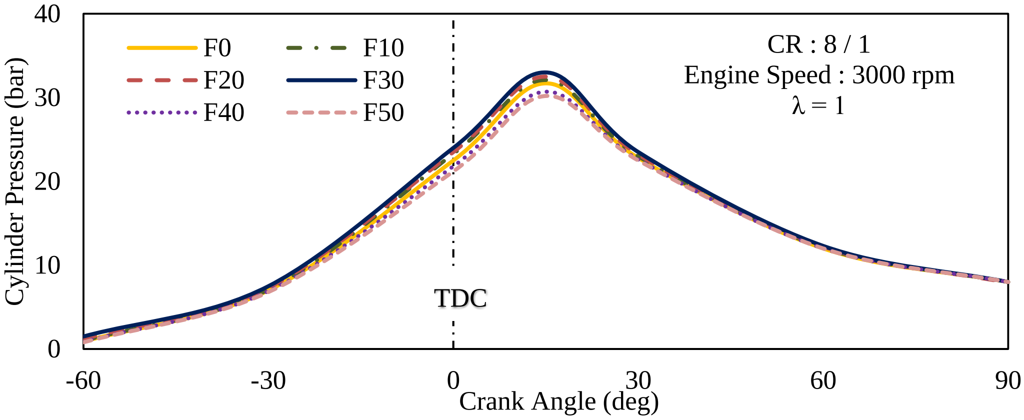

Figure 6. In-cylinder pressure graph at a CR of 8:1.

The overall efficiency increased in parallel with the increase in the amount of load. According to the experimental results, among the blends tested, the F30 fuel has the highest overall efficiency. Figure 7 shows the overall efficiency changes at all loads studied with the F30 fuel blend at three different compression ratios. When the compression ratio was increased from 8:1 to 8.5:1 and then to 9.12:1 for all the loads tested using the F30 fuel blend, on average, there was an increase by 4.29%, 8.07%, and 17.20%, respectively. It was found that the overall efficiency of the F30 fuel blend at the compression ratio of 9.12 was the highest. An increase in the cylinder temperature due to the increase in compression ratio and the compression of the air–fuel mixture in a smaller area resulted in a better combustion and evaporation of the high-octane fusel oil. This result is similar to some studies in the literature [38,39].

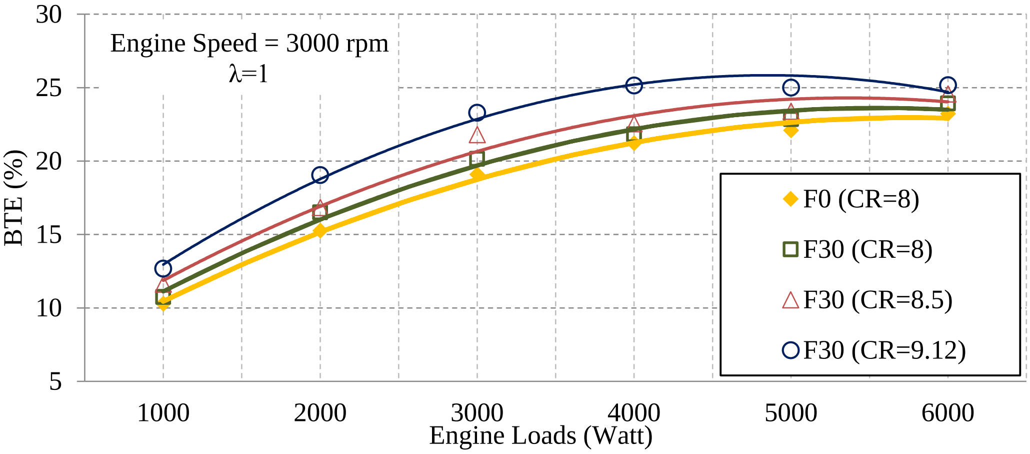

Figure 7. Overall efficiency graph for F0 and the F30 blend at different compression ratios.

The in-cylinder pressures of the F30 and F0 fuels at a compression ratio of 8.5:1 and 9.12:1 are given in Figure 8. In Figure 8A, at a CR of 8.5:1, the maximum pressure of the fuel F30 after the initiation of combustion cycle was measured to be 40.62 bars with a 6.8% increase in pressure in comparison to the F0 fuel. In Figure 8B, at a CR of 9.12:1, the maximum pressure of the fuel F30 after the initiation of the combustion cycle was measured to be 51.98 bars with a 6.12% increase in pressure in comparison to the fuel F0.

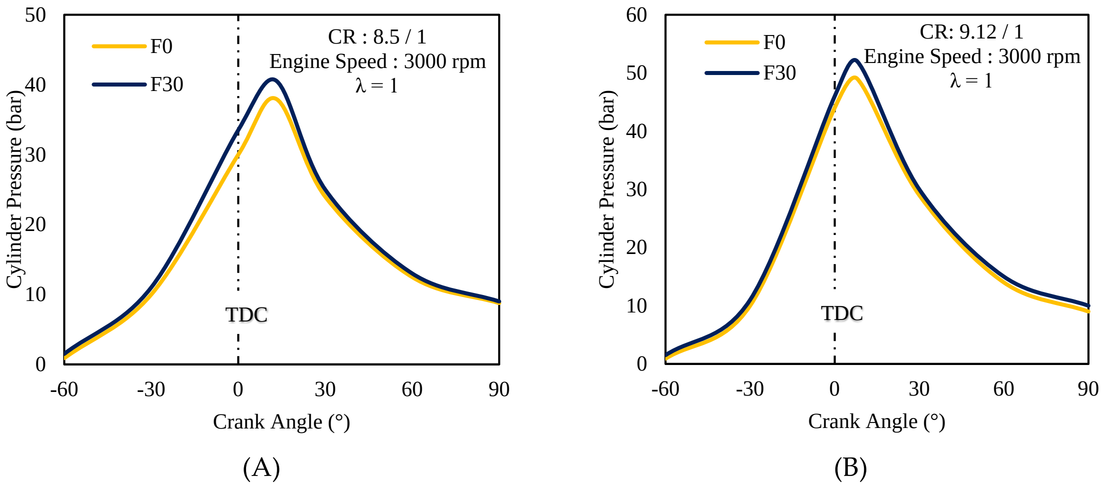

Figure 8. In-cylinder pressure by CRs at a CR of (**A**) 8.5:1 and (**B**) 9.12:1.

3.2. Brake Specific Fuel Consumption

Specific fuel consumption is the value that shows how much of the chemical energy of the fuel used in the engine to produce heat is converted to power in the crankshaft [40]. In other words, specific fuel consumption refers to the amount of fuel consumed per unit power. Specific fuel consumption decreased as the engine load and the CR increased. When the specific fuel consumption of F30 fuel for all engine loads at 8:1 compression ratio increased to 8.5:1 and then to 9.12:1, the specific fuel consumption increased by an average of 3.56% and decreased by an average of 1.27% and 9.08%, respectively, in comparison to the F0 fuel. This is shown in Figure 9. Since CR increases engine efficiency and power, specific fuel consumption decreases with a CR increase. The lower thermal value of fusel oil is lower than that of gasoline. The lower thermal value of fusel oil increased the fuel consumption in order to generate the same power at a CR of 8:1. This is similar to some studies in the literature [39,41].

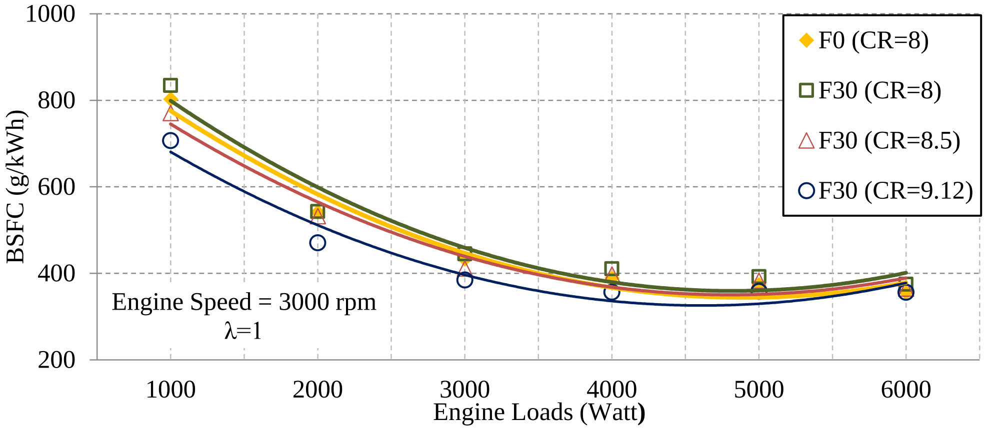

Figure 9. Specific fuel consumption for F0 and the F30 blend at different compression ratios.

3.3. Effect of Fusel Blends on the Amount of Carbon Monoxide Emissions at Different Compression Ratios

CO emissions occur in the cases of incomplete combustion and insufficient oxygen in the cylinder to achieve a full combustion in the rich air/fuel mixtures when there is not enough time for combustion in the cylinder [41]. The CO emission concentration depends largely on the engine operating condition and the air/fuel ratio. Figure 10 shows the CO emission changes based on the compression ratios of the F30 fuel at all engine loads and at constant speed. For all the engine loads for the F30 fuel blend, in comparison to the F0 fuel, the volumetric CO emission values decreased by 20.88% at CR 8:1, 40.02% at CR 8.5:1, and 49.81% at CR 9:1. This is similar in some studies in the literature [7,26,42,43]. As the CR increases, the chemical reactions increase, and CO emissions may decrease as combustion temperature increases.

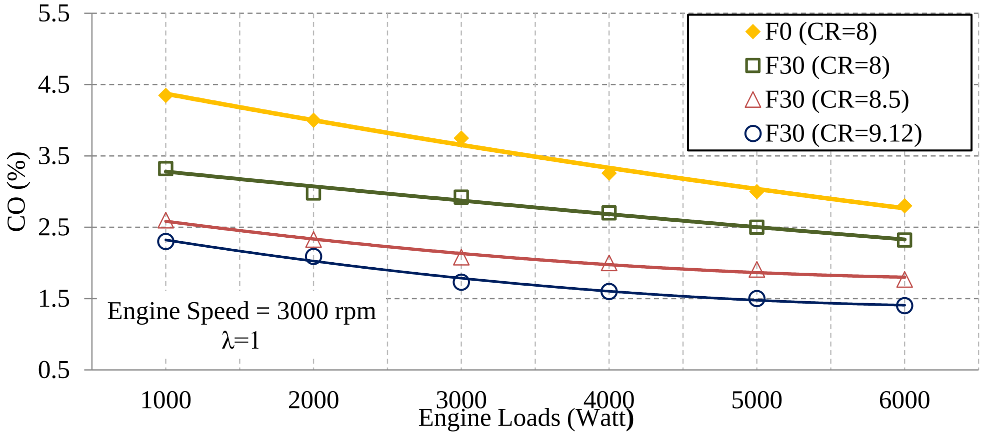

Figure 10. CO graph for F0 and F30 at different compression ratios.

3.4. *Effect of Fusel Blends on the Amount of Hydrocarbon Emissions at Different Compression Ratios*

Hydrocarbon (HC) emission occurs in the case of incomplete combustion due to lack of air and oxygen in the cylinder [41,43]. HC emission is the fuel that is exhausted unburned. HC emission changes for the F30 fuel are shown in Figure 11. Turbulence in the cylinder increases due to the increase in engine load. Since the turbulence near the exhaust duct enables post-exhaust oxidation, HC emissions decrease as the load increases. The F30 fuel used in the experiments showed a decrease in HC emission values due to increased engine loads. For all the engine loads for the F30 blend, in comparison to the F0 fuel, the HC emissions at CRs of 8:1, 8.5:1, and 9.12:1 decreased by an average of 30.19%, 45.38%, and 52.07%, respectively. The highest HC emission was at a CR of 8:1, and the lowest HC emission was at a CR of 9.12:1. This is similar to some studies in the literature [41].

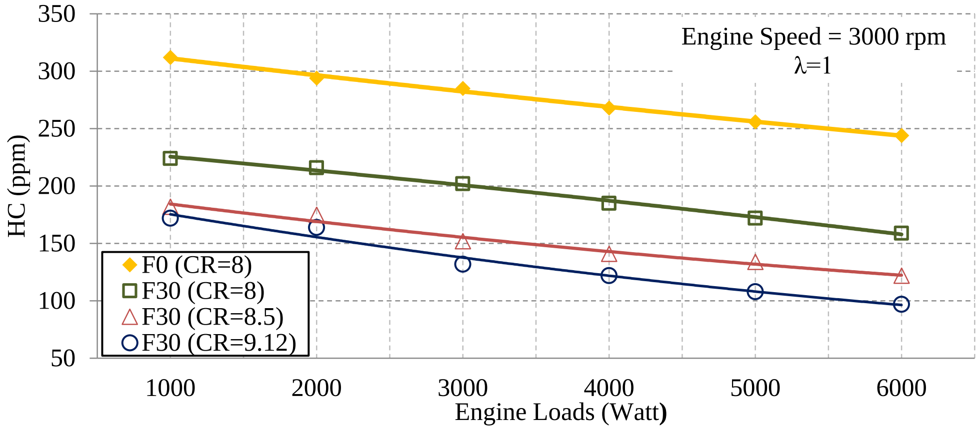

Figure 11. Hydrocarbon (HC) graph for F0 and the F30 blend at different compression ratios.

3.5. *Effect of Fusel Blends on the Amount of Carbon Dioxide Emissions at Different Compression Ratios*

Carbon dioxide (CO_2) is an end combustion product of any fuel containing a carbon molecule in its structure. In gasoline engines, the emission of carbon dioxide is related to the complete combustion of the fuel and occurs due to the high combustion temperature. The presence of sufficient oxygen (O_2) for complete combustion increases the amount of carbon dioxide (CO_2) emissions. Since fusel oil contains oxygen, the hydroxyl radical OH (one of the major oxidizing agents) converts carbon monoxide to carbon dioxide with the presence of sufficient oxygen O_2. Figure 12 shows the variation of CO_2 emissions at different compression rates and at all loads. For all engine loads for the F30 blend, in comparison to the F0 fuel, the volumetric CO_2 emissions increased by an average of 12.56% at CR 8:1, by 17.65% at CR 8.5:1, and by 24.99% at CR 9.16:1. The abundance of O_2 content in fusel oil improved the combustion. This shows similarities with some studies in the literature, where alcohol fuels reduce the amount of CO_2 due to the high O_2 content [41].

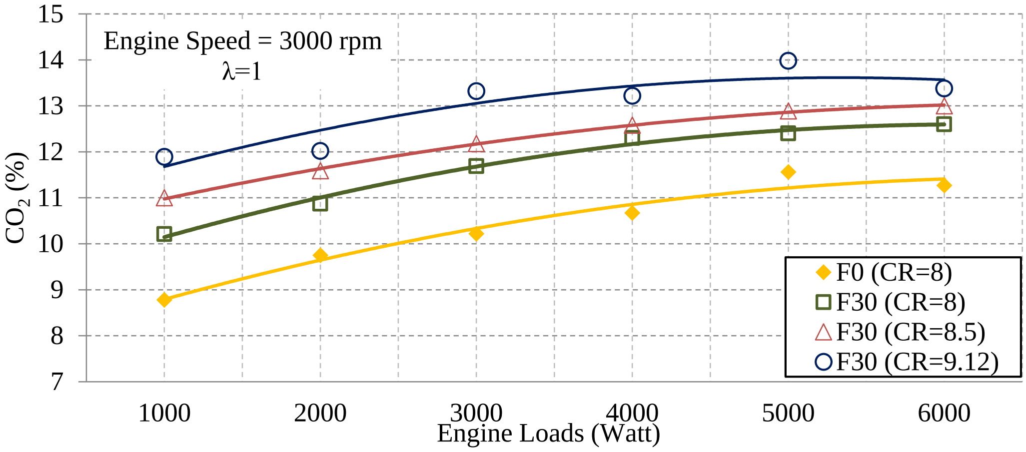

Figure 12. CO_2 graph for F0 and F30 at different compression ratios.

3.6. *Effect of Fusel Blends on the Amount of Nitrogen Oxides Emissions at Different Compression Ratios*

NO_x is an exhaust emission product due to cylinder temperatures. NO_x emissions are particularly noticeable at temperatures above 1500 °C [19]. The second most important parameter having effect on NO_x formation is the oxygen concentration in the cylinder [13]. Figure 13 shows the NO_x graph for the different compression ratios of F0 and the F30 blend. For all engine loads tested with the F30 blend in comparison to F0, NO_x emission decreased by an average of 58.23%, 39.88%, and 15.42% at CRs of 8:1, 8.5:1, and 9.12:1, respectively. As CR increases, NO_x emissions increase as the combustion temperature increases. The reason why NO_x emission is lower for fusel oil at different compression ratios compared to that of gasoline is due to the lower thermal value and alcohol and H_2O content of fusel oil. This situation is similar to some studies in the literature [6,41,44].

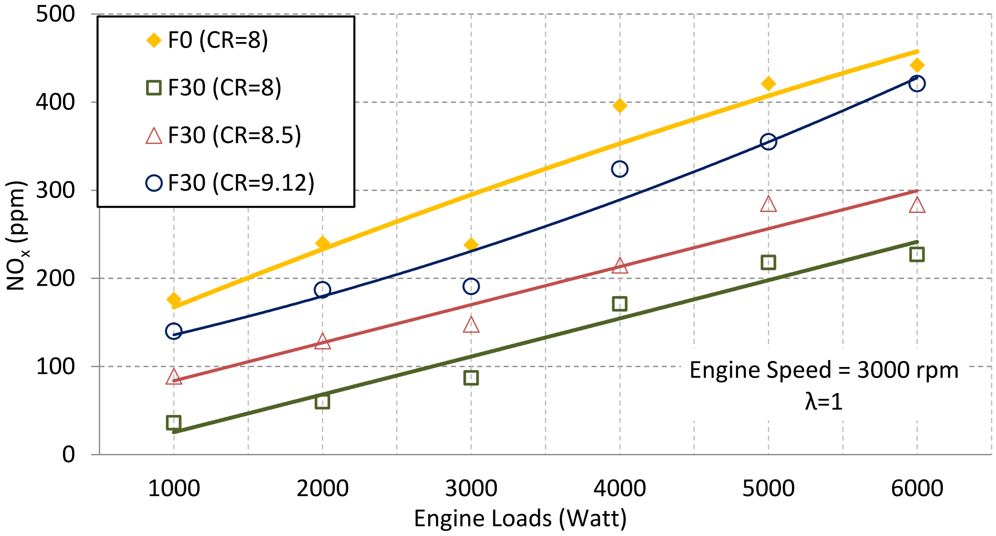

Figure 13. NO_x graph for F0 and F30 at different compression ratios.

4. Results

The conversion of waste fusel oil into an alternative fuel source to gasoline is important in terms of preventing environmental pollution and the economic use of natural resources. In this study, water and gum content of fusel–gasoline blends were improved upon; the optimal fuel blend was determined, and the effect of increasing compression ratio was investigated. The test was carried out in a single cylinder, four-stroke, SI engine at different working loads, at $\lambda = 1$, and at different compression ratios. The CO, HC, CO_2, and NO_x values were measured as BTE, brake specific fuel consumptions (BSFC), ICP, and the emission values of the improved fusel oil.

Gum and H_2O content of fusel oil was reduced by 0.8 mg/100 ml, and a homogenous fuel blend was obtained. The presence of oxygen in the fusel oil and the higher octane number of it, in comparison to gasoline, increased the combustion efficiency of the improved fusel oil fuel blend. For all engine loads, F30 was found to be the ideal fuel blend with a BTE increase by 4.29% and with a maximum pressure value of 33.2 bars for ICP at a CR of 8:1.

Increasing the compression ratio increased the post-combustion pressure and temperature. F0 and the F30 fuel blend were compared at all loads and with different compression ratios. BTE improved by 17.20%, and ICP increased by 52.1% for the improved fusel oil blend at a CR of 9.12:1. BSFC was found to be the most efficient compression ratio by a reduction of 9.08%. Due to the higher latent vaporization heat and abundant oxygen content of the improved fusel oil, for the ideal blend, namely, F30, the CO, HC, and NO_x decreased by 49.81%, 52.07%, and 15.42% respectively, whereas CO_2 increased by 24.99% at a CR of 9.12:1.

Fusel oil cannot be blended homogeneously due to the gum and H_2O content in it; this not only causes knocking by worsening the combustion in the engine, but it also causes corrosion by leaving soot residue in the cylinder and intake valve. Experiment results show that waste fusel oil, obtained as a by-product, can be used as an alternative fuel to a certain extent in the gasoline engines after a series of processes.

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References

1. Balki, M.K.; Sayin, C.; Canakci, M. The effect of different alcohol fuels on the performance, emission and combustion characteristics of a gasoline engine. *Fuel* **2014**, *115*, 901–906. [CrossRef]
2. Bayraktar, H. Experimental and theoretical investigation of using gasoline–ethanol blends in spark-ignition engines. *Renew. Energy* **2005**, *30*, 1733–1747. [CrossRef]
3. Canakci, M.; Ozsezen, A.N.; Alptekin, E.; Eyidogan, M. Impact of alcohol–gasoline fuel blends on the exhaust emission of an SI engine. *Renew. Energy* **2013**, *52*, 111–117. [CrossRef]
4. Ozsezen, A.N.; Canakci, M. Performance and combustion characteristics of alcohol–gasoline blends at wide-open throttle. *Energy* **2011**, *36*, 2747–2752. [CrossRef]

5. Eyidogan, M.; Ozsezen, A.N.; Canakci, M.; Turkcan, A. Impact of alcohol–gasoline fuel blends on the performance and combustion characteristics of an SI engine. *Fuel* **2010**, *89*, 2713–2720. [CrossRef]
6. Balki, M.K.; Sayin, C. The effect of compression ratio on the performance, emissions and combustion of an SI (spark ignition) engine fueled with pure ethanol, methanol and unleaded gasoline. *Energy* **2014**, *71*, 194–201. [CrossRef]
7. Sayin, C.; Balki, M.K. Effect of compression ratio on the emission, performance and combustion characteristics of a gasoline engine fueled with iso-butanol/gasoline blends. *Energy* **2015**, *82*, 550–555. [CrossRef]
8. Abdalla, A.N.; Awad, O.I.; Tao, H.; Ibrahim, T.K.; Mamat, R.; Hammid, A.T. Performance and emissions of gasoline blended with fusel oil that a potential using as an octane enhancer. *Energy Sources Part A Recover. Util. Environ. Eff.* **2019**, *41*, 931–947. [CrossRef]
9. Suslick, K. *Kirk-Othmer Encyclopedia of Chemical Technology*; John Wiley & Sons: New York, NY, USA, 1998; Volume 26.
10. Gülten, A.; Yavaş, F. *Effect of Wind Speed on Optimum Insulation Thickness for Energy Saving in Elazığ*; IATS17: Elazığ, Turkey, 2017.
11. Erdoğan, S.; Balki, M.K.; Aydın, S.; Sayin, C. The best fuel selection with hybrid multiple-criteria decision making approaches in a CI engine fueled with their blends and pure biodiesels produced from different sources. *Renew. Energy* **2019**, *134*, 653–668. [CrossRef]
12. Welsh, F.W.; Williams, R.E. Lipase mediated production of flavor and fragrance esters from fusel oil. *J. Food Sci.* **1989**, *54*, 1565–1568. [CrossRef]
13. Awad, O.I.; Mamat, R.; Ibrahim, T.K.; Kettner, M.; Kadirgama, K.; Leman, A.; Saiful, A. Effects of fusel oil water content reduction on fuel properties, performance and emissions of SI engine fueled with gasoline-fusel oil blends. *Renew. Energy* **2018**, *118*, 858–869. [CrossRef]
14. Abdalla, A.N.; Ali, O.M.; Awad, O.I.; Tao, H. Wavelet analysis of an SI engine cycle-to-cycle variations fuelled with the blending of gasoline-fusel oil at a various water content. *Energy Convers. Manag.* **2019**, *183*, 746–752. [CrossRef]
15. Awad, O.I.; Mamat, R.; Ibrahim, T.K.; Ali, O.M.; Kadirgama, K.; Leman, A. Performance and combustion characteristics of an SI engine fueled with fusel oil-gasoline at different water content. *Appl. Therm. Eng.* **2017**, *123*, 1374–1385. [CrossRef]
16. Awad, O.I.; Mamat, R.; Ibrahim, T.K.; Hagos, F.Y.; Noor, M.; Yusri, I.; Leman, A. Calorific value enhancement of fusel oil by moisture removal and its effect on the performance and combustion of a spark ignition engine. *Energy Convers. Manag* **2017**, *137*, 86–96. [CrossRef]
17. Uslu, S.; Celik, M. Experimental investigation of the effects of diethyl ether-diesel fuel blends on engine parameters in a low power diesel engine. *Int. J. Eng. Sci. Res. Technol.* **2018**, *7*, 1–13.
18. Ardebili, S.M.S.; Solmaz, H.; Mostafaei, M. Optimization of fusel oil–Gasoline blend ratio to enhance the performance and reduce emissions. *Appl. Therm. Eng.* **2019**, *148*, 1334–1345. [CrossRef]
19. Abdalla, A.N.; Tao, H.; Bagaber, S.A.; Ali, O.M.; Kamil, M.; Ma, X.; Awad, O.I. Prediction of emissions and performance of a gasoline engine running with fusel oil–gasoline blends using response surface methodology. *Fuel* **2019**, *253*, 1–14. [CrossRef]
20. Awad, O.I.; Mamat, R.; Ali, O.M.; Azmi, W.; Kadirgama, K.; Yusri, I.; Leman, A.; Yusaf, T. Response surface methodology (RSM) based multi-objective optimization of fusel oil-gasoline blends at different water content in SI engine. *Energy Convers. Manag.* **2017**, *150*, 222–241. [CrossRef]
21. Awad, O.I.; Ali, O.M.; Hammid, A.T.; Mamat, R. Impact of fusel oil moisture reduction on the fuel properties and combustion characteristics of SI engine fueled with gasoline-fusel oil blends. *Renew. Energy* **2018**, *123*, 79–91. [CrossRef]
22. Li, Y.; Ning, Z.; Lee, C.-f.F.; Lee, T.H.; Yan, J. Performance and Regulated/Unregulated Emission Evaluation of a Spark Ignition Engine Fueled with Acetone–Butanol–Ethanol and Gasoline Blends. *Energies* **2018**, *11*, 1121. [CrossRef]
23. Rosdia, S.; Mamata, R.; Azri, A.; Sudhakar, K.; Yusri, I. Evaluation of properties on performance and emission to turbocharged SI engine using fusel oil blend with gasoline. In Proceedings of the IOP Conference Series: Materials Science and Engineering, Beijing, China, 19–22 August 2019; Volume 469, p. 012113.
24. Şimşek, S.; Özdalyan, B.; Saygın, H. Improvement of the Properties of Sugar Factory Fusel Oil Waste and Investigation of its Effect on the Performance and Emissions of Spark Ignition Engine. *Bioresources* **2019**, *14*, 440–452.

25. Calam, A.; Solmaz, H.; Uyumaz, A.; Polat, S.; Yilmaz, E.; Içingür, Y. Investigation of usability of the fusel oil in a single cylinder spark ignition engine. *J. Energy Inst.* **2015**, *88*, 258–265. [CrossRef]
26. Uslu, S.; Celik, M.B. Performance and Exhaust Emission Prediction of a SI Engine Fueled with I-amyl Alcohol-Gasoline Blends: An ANN Coupled RSM Based Optimization. *Fuel* **2020**, *265*, 116922. [CrossRef]
27. Calam, A.; İçingür, Y.; Solmaz, H.; Yamık, H. A comparison of engine performance and the emission of fusel oil and gasoline mixtures at different ignition timings. *Int. J. Green Energy* **2015**, *12*, 767–772. [CrossRef]
28. Papagiannakis, R.G.; Rakopoulos, D.C.; Rakopoulos, C.D. Theoretical study of the effects of spark timing on the performance and emissions of a light-duty spark ignited engine running under either gasoline or ethanol or butanol fuel operating modes. *Energies* **2017**, *10*, 1198. [CrossRef]
29. Uslu, S.; Celik, M.B. Prediction of engine emissions and performance with artificial neural networks in a single cylinder diesel engine using diethyl ether. *Eng. Sci. Technol. Int. J.* **2018**, *21*, 1194–1201. [CrossRef]
30. Şimşek, S. Effects of biodiesel obtained from Canola, sefflower oils and waste oils on the engine performance and exhaust emissions. *Fuel* **2020**, *265*, 117026. [CrossRef]
31. Şimşek, S.; Uslu, S. Determination of a diesel engine operating parameters powered with canola, safflower and waste vegetable oil based biodiesel combination using response surface methodology (RSM). *Fuel* **2020**, *270*, 117496. [CrossRef]
32. Şimşek, S.; Özdalyan, B. Improvements to the Composition of Fusel Oil and Analysis of the Effects of Fusel Oil–Gasoline Blends on a Spark-Ignited (SI) Engine's Performance and Emissions. *Energies* **2018**, *11*, 625. [CrossRef]
33. Yusoff, M.N.A.M.; Zulkifli, N.W.M.; Masjuki, H.H.; Harith, M.H.; Syahir, A.Z.; Khuong, L.S.; Zaharin, M.S.M.; Alabdulkarem, A. Comparative assessment of ethanol and isobutanol addition in gasoline on engine performance and exhaust emissions. *J. Clean. Prod.* **2018**, *190*, 483–495. [CrossRef]
34. Mourad, M.; Mahmoud, K. Investigation into SI engine performance characteristics and emissions fuelled with ethanol/butanol-gasoline blends. *Renew. Energy* **2019**, *143*, 762–771. [CrossRef]
35. Hasan, A.O.; Al-Rawashdeh, H.; Al-Muhtaseb, A.a.H.; Abu-jrai, A.; Ahmad, R.; Zeaiter, J. Impact of changing combustion chamber geometry on emissions, and combustion characteristics of a single cylinder SI (spark ignition) engine fueled with ethanol/gasoline blends. *Fuel* **2018**, *231*, 197–203. [CrossRef]
36. Solmaz, H. Combustion, performance and emission characteristics of fusel oil in a spark ignition engine. *Fuel Process. Technol.* **2015**, *133*, 20–28. [CrossRef]
37. Karaosmanoğlu, F.; Işiğigür, A.; Aksoy, H.A. Methanol-unleaded gasoline blends containing fusel oil fraction as spark ignition engine fuel. *Energy Sources* **1997**, *19*, 567–577. [CrossRef]
38. Thomas, R.; Sreesankaran, M.; Jaidi, J.; Paul, D.M.; Manjunath, P. Experimental evaluation of the effect of compression ratio on performance and emission of SI engine fuelled with gasoline and n-butanol blend at different loads. *Perspect. Sci.* **2016**, *8*, 743–746. [CrossRef]
39. Çelik, M.B.; Özdalyan, B.; Alkan, F. The use of pure methanol as fuel at high compression ratio in a single cylinder gasoline engine. *Fuel* **2011**, *90*, 1591–1598. [CrossRef]
40. Yusri, I.M.; Mamat, R.; Najafi, G.; Razman, A.; Awad, O.I.; Azmi, W.H.; Ishak, W.F.W.; Shaiful, A.I.M. Alcohol based automotive fuels from first four alcohol family in compression and spark ignition engine: A review on engine performance and exhaust emissions. *Renew. Sustain. Energy Rev.* **2017**, *77*, 169–181. [CrossRef]
41. Celik, M.B. Experimental determination of suitable ethanol–gasoline blend rate at high compression ratio for gasoline engine. *Appl. Therm. Eng.* **2008**, *28*, 396–404. [CrossRef]
42. Elfasakhany, A.; Mahrous, A.-F. Performance and emissions assessment of n-butanol–methanol–gasoline blends as a fuel in spark-ignition engines. *Alex. Eng. J.* **2016**, *55*, 3015–3024. [CrossRef]
43. Yücesu, H.S.; Topgül, T.; Çinar, C.; Okur, M. Effect of ethanol–gasoline blends on engine performance and exhaust emissions in different compression ratios. *Appl. Therm. Eng.* **2006**, *26*, 2272–2278. [CrossRef]
44. Ghazikhani, M.; Hatami, M.; Safari, B.; Ganji, D.D. Experimental investigation of performance improving and emissions reducing in a two stroke SI engine by using ethanol additives. *Propuls. Power Res.* **2013**, *2*, 276–283. [CrossRef]