energies

MDPI

Article

Effects of Chemical Compositions and Cetane Number of Fischer–Tropsch Fuels on Diesel Engine Performance

Haoyu Yuan [1], Takuma Tsukuda [1], Yurui Yang [1], Gen Shibata [2,*], Yoshimitsu Kobashi [2] and Hideyuki Ogawa [2]

[1] Division of Energy and Environmental Systems, Graduate School of Engineering, Hokkaido University, Sapporo 060-8628, Japan; haoyu.yuan@elms.hokudai.ac.jp (H.Y.); tsukuda.takuma.w1@elms.hokudai.ac.jp (T.T.); yangyurui@eis.hokudai.ac.jp (Y.Y.)
[2] Division of Mechanical and Aerospace Engineering, Faculty of Engineering, Hokkaido University, Sapporo 060-8628, Japan; kobashi@eng.hokudai.ac.jp (Y.K.); h-ogawa@eng.hokudai.ac.jp (H.O.)
* Correspondence: g-shibata@eng.hokudai.ac.jp

Abstract: Fischer–Tropsch synthetic (FT) fuels are expected to be an ideal alternative for diesel fuel to achieve higher thermal efficiency and reduction in exhaust emissions because of their characteristics of being aromatic-free, sulfur-free, and high cetane number. In this study, the effects of chemical compositions and cetane number of FT fuels on diesel engine performance were investigated by using a commercial GTL (Gas-to-Liquids) diesel fuel synthesized by the FT method and blended paraffinic hydrocarbon fuels made to simulate FT fuels with different chemical compositions and cetane numbers. At first, a commercial diesel fuel (JIS No.2) and GTL were examined by varying the intake oxygen concentrations with cooled EGR. Compared with diesel fuel, GTL shows shorter premixed combustion, smaller heat release peak, and longer diffusion combustion duration at both high and medium conditions due to the higher cetane number. Further, by using the GTL, a limited improvement in thermal efficiency and exhaust emission reduction of NOx have been obtained, but no significant reduction in the smoke emissions is achieved, even though FT fuels have been considered smokeless due to their aromatic-free characteristics. Next, three types of paraffinic hydrocarbon fuels with cetane numbers of 78, 57, and 38 were blended as simulated FT fuels and were examined under the same experimental apparatus and operation conditions. For the low cetane number simulated FT fuel (cetane number 38 fuel), the results show that the ignition delay and premixing period are significantly longer at low intake oxygen concentration conditions, meaning that the premixing of low cetane number fuel is more sufficient than other fuels, especially under the high EGR rate conditions, resulting in fewer smoke emissions. Furthermore, with CN38 fuel, an excellent indicated thermal efficiency was obtained at the high load condition. To summarize the results, the low cetane number FT fuel shows a potential to achieve higher thermal efficiency and reduction in exhaust emissions on commercial diesel engines with EGR.

Keywords: e-fuel; Fischer–Tropsch synthetic fuel; diesel engine; thermal efficiency; exhaust emission; paraffinic hydrocarbon fuel

check for updates

Citation: Yuan, H.; Tsukuda, T.; Yang, Y.; Shibata, G.; Kobashi, Y.; Ogawa, H. Effects of Chemical Compositions and Cetane Number of Fischer–Tropsch Fuels on Diesel Engine Performance. *Energies* **2022**, *15*, 4047. https://doi.org/10.3390/en15114047

Academic Editor: Karol F. Abramek

Received: 30 April 2022
Accepted: 27 May 2022
Published: 31 May 2022

1. Introduction

Diesel engines, which have high thermal efficiency and power performance, have been considered an attractive solution to suppress carbon dioxide (CO_2) emissions. However, with the increasingly strict emission regulation around the world [1–3], the simultaneous reductions in nitrogen oxide (NOx) and particulate matter (PM) emissions are still serious issues for diesel engines because of the trade-off relationship between NOx and PM emissions [4,5]. To reduce both NOx and PM emissions, reformed exhaust gas recirculation (REGR) [5–7], aftertreatment technologies such as diesel particulate filters (DPF) [8,9], and selective catalytic reduction (SCR) catalysts [10,11] have been studied and applied for diesel engines [12].

Synthetic fuels, called E-fuels, which are generated from renewable electricity in a synthetic process [13] consuming carbon dioxide and water, have been considered carbon-neutral [14].

Among these, the Fischer–Tropsch synthetic (FT) fuels are expected to be an ideal alternative to replace the fossil diesel fuels due to their similar properties, such as viscosity, lubricity, cold flow properties, flash temperatures, and boiling temperature, to diesel fuels [15]. Recently, many studies have been conducted on the application of FT fuels or FT-diesel blended fuel to diesel engines. The combustion of Ultra-low Sulfur Diesel (ULSD), GTL, and a ULSD-GTL blend (50/50 by volume) was studied by Abu-Jrai et al. [5]. The GTL and ULSD-GTL are effective for the NOx reduction, improvement of thermal efficiency, and reduced smoke emissions by optimizing the fuel injection timing. Schaberg et al. [16] investigated the exhaust emission performance and combustion properties with neat and blended GTL diesel fuel based on a Mercedes Benz 2.2 L passenger car diesel engine. Vehicle emission tests showed that GTL fuel results in reductions in HC and CO emissions of greater than 90%, while smoke is reduced by 30%, and NOx remains approximately unchanged. Engine bench tests showed 30–60% reductions in soot, and up to 10% of NOx reductions with the GTL diesel fuel, depending on the operating point. Different studies have shown that FT diesel fuels can be used with no loss of efficiency and/or reductions in exhaust emissions in diesel engines [17–21]. Furthermore, it has been reported that depending on the synthesis processes and operating conditions, the fuel compositions, such as the iso-paraffin to n-paraffin ratio and cetane numbers of the synthesized FT fuel, are also different [22–26]. However, few studies have considered the effect of compositions and properties (such as cetane number) of FT fuels on engine performance or exhaust emissions. Kitano and Sakata [4] investigated the effects of distillation characteristics and cetane number of experimental GTL test fuels on direct injection (DI) diesel combustion. With lower distillation test fuels, the smoke and PM emissions reduce with the increase in cetane numbers. However, the experiments were limited to high cetane number fuels of 71.5–85, and the effects of FT fuels with lower cetane numbers have not been considered.

In this paper, the effects of the chemical compositions and cetane numbers of FT fuels on diesel engine performance were investigated in an experimental diesel engine with low-pressure cooled EGR by using a commercial GTL (Gas-to-Liquids) diesel fuel synthesized by FT processes and blended paraffinic hydrocarbon fuels made to simulate FT fuels with different chemical compositions and cetane numbers in a relatively wider range of variables.

2. Experimental Apparatus and Procedures

A single-cylinder, water-cooled, direct-injection diesel engine (stroke volume 654 cm^3, compression ratio 16.8) with a common-rail fuel injection system and a solenoid injector (Denso G4S) was used in all experiments, and the injection pressure can be achieved up to 200 MPa. The intake system of the experimental engine has an externally driven supercharger equipped with an intercooler and a low-pressure loop EGR system, and the intake air temperature and pressure can be changed independently.

Table 1 shows the engine specification, and Figure 1 shows a schematic diagram of the experimental apparatus.

Table 1. Engine specifications.

Engine Name	Kubota V2607-DI-E3B
Number of cylinders	1
Type	Water Cooling, Direct injection, Common-rail system
Bore × Stroke	87 mm × 110 mm
Compression ratio	16.8
Displacement	654 cm^3
Intake valve Open/Close	−14° ATDC/−140° ATDC
Exhaust valve Open/Close	130° ATDC/14° ATDC
Combustion chamber	Re-entrant type
Injection type	Denso G4S solenoid type

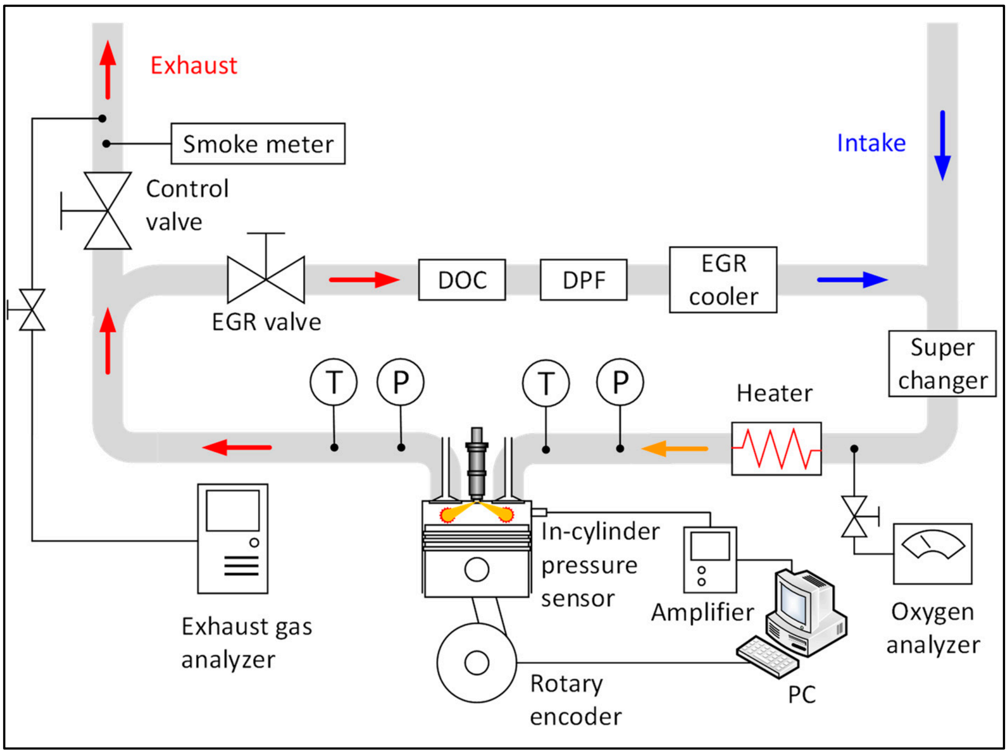


Figure 1. Experimental apparatus.

Table 2 shows the main parameters of the different elements of the experimental apparatus. The in-cylinder pressure signal was obtained with a piezoelectric transducer (KISTLER 6056A). The intake oxygen concentration was measured with a paramagnetic oxygen analyzer (Shimadzu POT-101), a Bosch smoke meter (ZEXEL DSM-20AN), and an exhaust gas analyzer (Best-SOKKi BEX-5100D) were used for exhaust analysis, including the NOx, THC, CO, and smoke emissions.

Table 2. Information of measurement instruments.

Variable	Device	Manufacturer/Model	Capability/Accuracy
In-cylinder pressure	Piezoelectric transducer	KISTLER 6056A	0~25 MPa/±0.5% (200 ± 50 °C)
Intake oxygen concentration	Paramagnetic oxygen analyzer	Shimadzu POT-101	0~25 Vol.% O_2/±3.0% F.S.
Crank angle, engine speed	Incremental encoder	Tamagawa TS5015	3600 C/T/1 μs
NOx emissions	CLD NO/NOx analyzer	Best-SOKKi BEX-5100D	0~5000 ppm/±1.0% F.S.
CO emissions	NDIR gas analyzer	Best-SOKKi BEX-5100D	0~12 Vol.%/±1.0% F.S.
THC emissions	Flame ionization analyzer	Best-SOKKi BEX-5100D	0~20,000 ppmC/±1.0% F.S.
Smoke emissions	Bosch smoke meter	ZEXEL DSM-20AN	0~100% in Bosch/±3.0% F.S.

In this study, the experiments were conducted under the following two conditions.

(1) Experiment 1: Engine is run on injection of GTL and diesel fuels at the different load conditions varying the intake oxygen concentration by cooled EGR to investigate the performance differences of thermal efficiency and exhaust emissions between GTL and diesel fuels. Table 2 shows the experimental conditions.
(2) Experiment 2: Engine is run on injection of GTL and three types of simulated FT fuels, which were blended by paraffin-based organic solvents at the same load conditions as Experiment 1 to investigate the effects of chemical compositions and cetane number of FT fuels on diesel engine performance. Table 3 shows the experimental conditions.

Table 3. Operating conditions for Experiment 1.

	High Load	Medium Load
Engine load	IMEP ≈ 0.9 MPa	IMEP ≈ 0.6 MPa
Test fuel	GTL, JIS No. 2 diesel fuel	
Engine speed	1600 rpm	
Intake temperature	30 °C	
Intake pressure	140 kPa	120 kPa
Fuel injection pressure	180 MPa	
Ignition timing	Single-injection, TDC w/injection timing	
Intake Oxygen Concentration	21, 14, 12%	
Coolant temperature	80 °C	

In the experiments, the load and intake oxygen concentration conditions in the experiments were selected by a pre-experiment, as shown in Appendix A. The ignition timing was defined as the timing of the derivative of the heat release rate $\frac{d^2Q}{d\theta^2}$ when it exceeded 10 J/°CA^2, and the fuel injection timing was adjusted to the start of ignition near the top dead center (TDC) for all conditions. Tables 3 and 4 show the experimental conditions.

Table 4. Operating conditions for Experiment 2.

	High Load	Medium Load
Engine load	IMEP ≈ 0.9 MPa	IMEP ≈ 0.6 MPa
Test fuel	GTL, paraffinic hydrocarbon fuels	
Engine speed	1600 rpm	
Intake temperature	30 °C	
Intake pressure	140 kPa	120 kPa
Fuel injection pressure	180 MPa	
Ignition timing	Single-injection, TDC w/injection timing	
Intake Oxygen Concentration	21, 14, 12%	
Coolant temperature	80 °C	

The hydrocarbon composition of test fuels was investigated by a GC-MS analyzer. The instrument information and analysis conditions are shown in Table 5.

Table 5. Instrument information and conditions of GC-MS analysis.

MS Instrument	JMS-T100GCV	GC Instrument	Agilent 7890A
Ionization method	FI	Column	Agilent VF5-20 min-0.2 µL
Acquired *m/z* Range	20 ~ 800	Career Gas	He
Ion source temp.	70 °C	Flow	1.4 mL/min
		Inlet temp.	250 °C
		Oven temp. Control	50 °C (1.5 min) 20 °C/min-300 °C 5 °C/min-330 °C

The results with GTL and ordinary diesel fuel (JIS No.2) are shown in Figures 2 and 3. The analysis results show that the carbon numbers of both fuels are mainly concentrated around 12 to 20. For diesel fuel, as shown in Figure 2, the multiple peaks (▲) with regular intervals are paraffins (CnH2n + 2). However, a variable number of lower peaks can be seen near these peaks because olefins, aromatics, and their isomers are intricately overlapping. On the other hand, for GTL, the analysis results show that there are fewer components other than paraffins in the fuel compositions, as shown in Figure 3. Since the fuel aromatics significantly affect smoke emissions [27], GTL is generally considered a low smoke fuel for diesel engines.

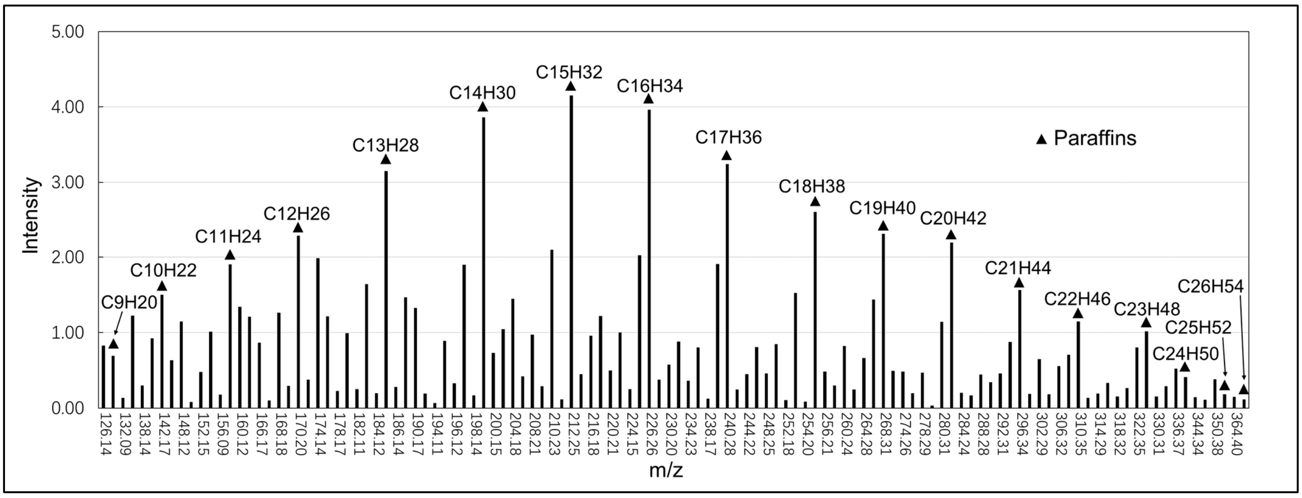


Figure 2. GC-MS analysis results for diesel fuel.

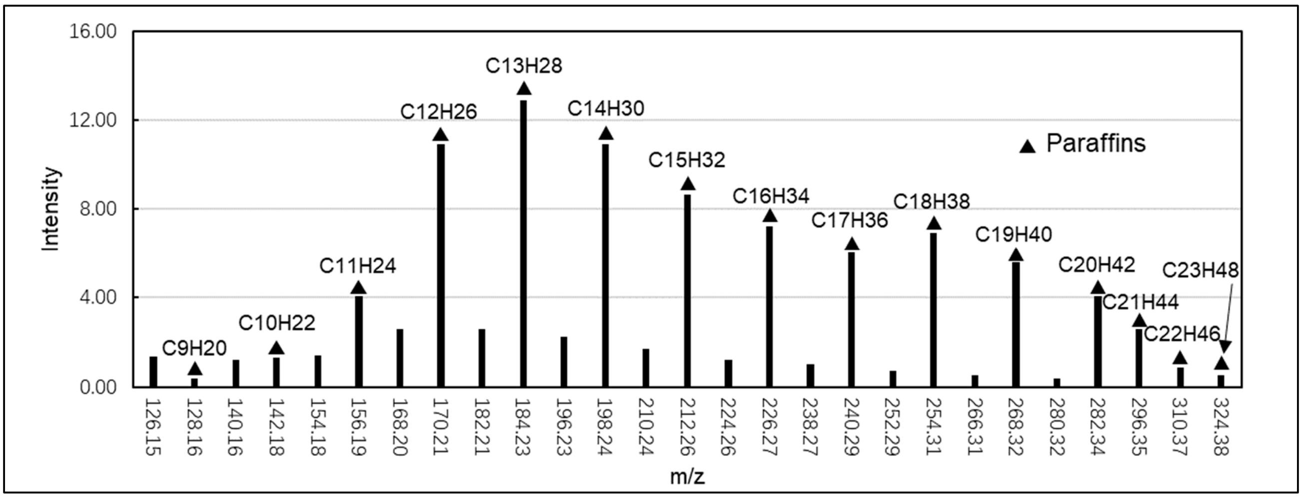


Figure 3. GC-MS analysis results for GTL.

The fuel properties of GTL and diesel fuel used in the experiment are shown in Table 6.

Table 6. Properties of GTL and JIS No. 2 diesel fuel.

		JIS No. 2 Diesel Fuel	GTL
Density (15 °C)		0.8211 g/cm^3	0.779 g/cm^3
Cetane number		58.7	68.4
Lower heating value		42.87 MJ/kg	44.08 MJ/kg
Compositions	Paraffins	81.5 vol.%	99.7 vol.%
	Aromatics	18.5 vol.%	0.3 vol.%

To simulate FT fuels with different chemical compositions and cetane numbers, two types of paraffin-based organic solvents, Solvent G-71 and Solvent G, were used for blending. Solvent G-71 is composed of only normal paraffins with carbon numbers 11 and 12, and Solvent G is totally composed of iso-paraffins with carbon number 12. To investigate the effects of chemical compositions and cetane number of FT fuels within a wide range of variations, the following paraffinic hydrocarbon fuels were used in the experiments.

- Cetane number 78 fuel (CN78, 100 vol.% G-71): The highest cetane number that can be obtained by blending.
- Cetane number 57 fuel (CN57, a mixture of 62.5 vol.% G-71 and 37.5 vol.% G): The cetane number is close to the ordinary diesel fuel (JIS No. 2).
- Cetane number 38 fuel (CN38, a mixture of 35 vol.% G-71 and 65 vol.% G): The cetane number is close to the lower limit of the ASTM D975 standard (Cetane number ≥ 40).

The fuel properties are shown in Table 7.

Table 7. Properties of paraffinic hydrocarbon fuels.

		CN 78	CN 56	CN38
Solvent G-71 ratio		100 vol.%	62.5 vol.%	35 vol.%
Density (15 °C)		0.75 g/cm^3	0.75 g/cm^3	0.75 g/cm^3
Cetane number		78.1	56.5	38.3
Lower heating value		43.95 MJ/kg	43.95 MJ/kg	43.95 MJ/kg
Compositions	N-paraffin	100 vol.%	62.5 vol.%	35 vol.%
	Iso-paraffin	0 vol.%	37.5 vol.%	65 vol.%

To describe the combustion characteristics, the crank angles at 10%, 50%, and 90% completion of heat release ATDC are defined as CA10, CA50, and CA90, and further define the duration from CA10 to CA90 as the combustion duration (CA10–CA90), as shown in Figure 4. On the other hand, the period from the fuel injection timing to the ignition timing is defined as the ignition delay, and the period from the end timing of fuel injection to the ignition timing is defined as the premixing period. If the premixing period shows a negative valve, it means that ignition occurred before the end timing of fuel injection.

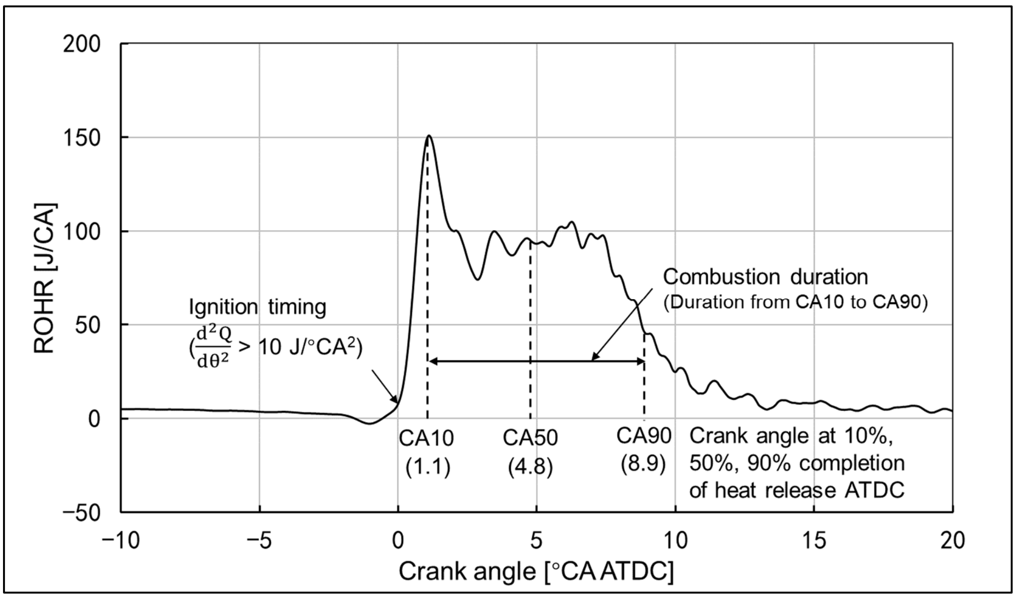


Figure 4. Definition of CA10, CA50, CA90, and the combustion duration.

The thermal efficiency-related parameters were evaluated with the energy balance analysis. The energy balance during one cycle is described in Equation (1).

$$\eta_i = \eta_u - \phi_{ex} - \phi_p - \phi_{other} \quad (1)$$

η_i: The indicated thermal efficiency calculated with the fuel consumption per cycle and the in-cylinder pressure.

η_u: The combustion efficiency calculated from the carbon monoxide (CO) and total hydrocarbon (THC) concentrations in the exhaust gas.

ϕ_{ex}: The exhaust loss fraction calculated from the change in enthalpy between the exhaust and intake gases considering the change in the specific heat with the temperature and gas compositions.

ϕ_p: The pumping loss fraction calculated with the in-cylinder pressure during the exhaust and intake strokes.

ϕ_{other}: The other loss fractions, calculated from Equation (1), include the cooling loss as the main component and also the unburned fuel diluted into the lubricant oil.

Since the injection timing is set to be not far from the TDC, the fuel diluted into the lubricant oil is negligible in this experiment, and ϕ_{other} is considered to be the cooling loss, ϕ_w, which is finally calculated from Equation (1) as $\phi_w = \eta_i - \eta_u - \phi_{ex}$.

3. Experimental Results and Discussion

3.1. Combustion Characteristic of GTL (Gas-to-Liquids) Fuel

Figure 5 shows the in-cylinder pressure, rate of heat release (ROHR), and injector energizing signal for the GTL and the commercial diesel fuel at the high (IMEP ≈ 0.9 MPa) and medium (IMEP ≈ 0.6 MPa) load conditions with varying intake oxygen concentration by cooled EGR. At the high load condition (IMEP ≈ 0.9 MPa), as shown in Figure 5a, both fuels presented typical heat release patterns of diesel combustion at all intake oxygen concentration conditions, where the diffusion combustion continued after a rapid heat release caused by the premixed combustion. The duration of diffusion combustions gradually decreased with the decrease of intake oxygen concentration due to injection timing advances. At the medium load condition (IMEP ≈ 0.6 MPa), as shown in Figure 5b, the duration of the diffusion combustion for both fuels shortened with the decreasing intake oxygen concentration. This was especially true at the 12% intake oxygen concentration, showing typical heat release patterns of premixed combustion for both fuels. For all load conditions, the peak of heat release of GTL was smaller, but the duration of diffusion combustion was longer than diesel fuel at all intake oxygen concentration conditions. This is because the premixing of GTL is less sufficient due to the shorter ignition delay under the injection condition where ignition started near the TDC for both fuels.

Figure 6 shows the ignition delay, premixing period, CA50, and combustion duration at the same condition as in Figure 5. Since GTL has a higher cetane number, the ignition delay and premixing period of GTL are both shorter than with diesel fuel. Especially at the medium load condition, the premixing period of diesel fuel is almost zero at 12% intake oxygen concentration, as shown in Figure 6b, but for the GTL, the ignition occurs during the injection period at about −1 °CA at the same intake oxygen concentration condition. This means the premixing is insufficient in combustion; even the GTL showed a heat release pattern of premixed combustion at 12% intake oxygen concentration in Figure 5b. At the high load condition (Figure 6a), for both fuels, the combustion duration increased, and CA50 was delayed with the decrease in intake oxygen concentration. This is due to the afterburn, which becomes longer, and the extended premixing period resulting in higher heat release of premixed combustion at low intake oxygen concentration conditions (14% and 12%), as shown in Figure 5a. Compared with the GTL, diesel fuel showed an advanced CA50 and a shorter combustion duration due to the advances in the injection timing at the high load condition (Figure 6a). However, at the medium load condition (Figure 6b), the differences in CA50 and combustion duration between both fuels were not as remarkable as the decreases in intake oxygen concentration. This is due to the typical heat release patterns of premixed combustion shown at 14% and 12% intake oxygen concentrations for both fuels in Figure 5b. At this condition, only slight or no diffusion combustion occurred after premixed combustion, resulting in no difference in CA50 and combustion duration for the two fuels.

Figure 7 shows the energy balances at the same conditions as in Figure 5. For both fuels, the cooling losses show a trade-off relation to the exhaust losses and gradually reduce with decreases of the intake oxygen concentration by cooled EGR. However, due to the deterioration in combustion efficiency at 12% intake oxygen concentration, the thermal efficiency reached the maximum at 14% intake oxygen concentration for both fuels. At the high load condition (Figure 7a), the cooling losses of GTL are slightly lower at 21% and 14% intake oxygen concentrations, causing 1.2% and 0.7% improvement in the indicated thermal efficiency. At the 12% intake oxygen concentration, although the cooling losses and exhaust losses of GTL and diesel fuel are basically the same, as the combustion deterioration of diesel fuel is more severe, there is still a 0.7% improvement in the indicated thermal efficiency by the GTL fuel. At the medium load condition (Figure 7b), the heat balance of GTL shows a 1.0% reduction in cooling loss at 21% intake oxygen concentration, causing a 0.8% improvement in the indicated thermal efficiency similar to the high load condition. However, for the intake oxygen concentrations at 14% and 12%, there were no notable differences in cooling loss and thermal efficiency for both fuels. The reason could be the effect of the difference in the distillation characteristics of GTL and diesel fuel; this effect was less significant under the fully premixed combustion condition, such as with 14% and 12% intake oxygen concentration at the medium load condition.

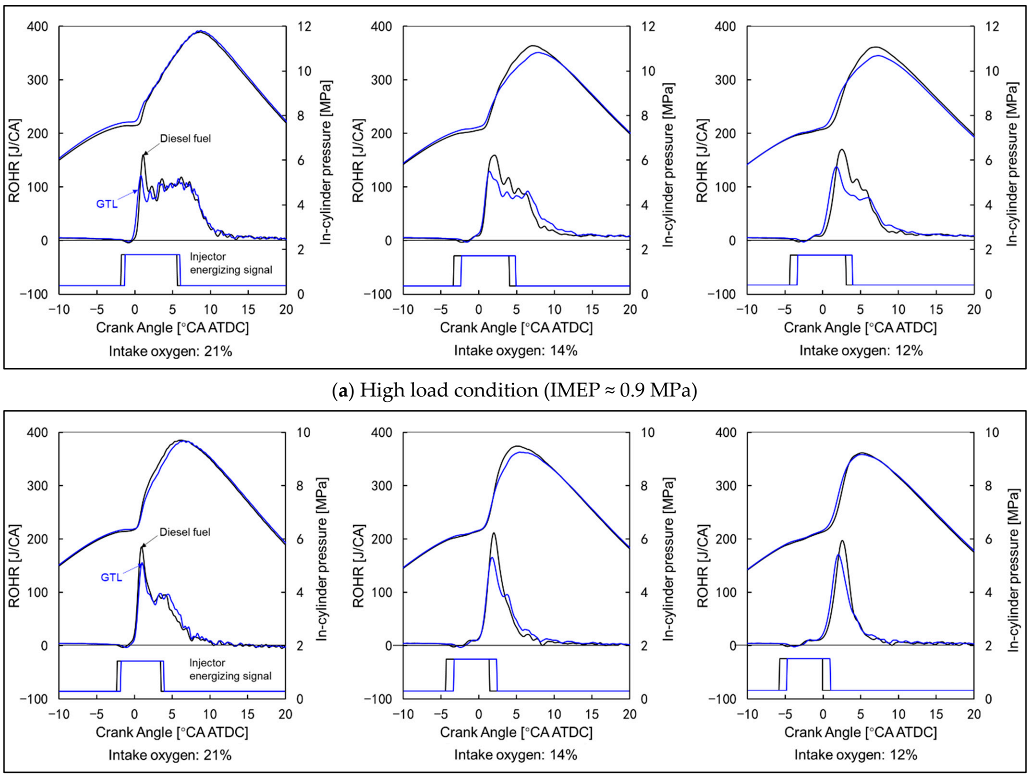
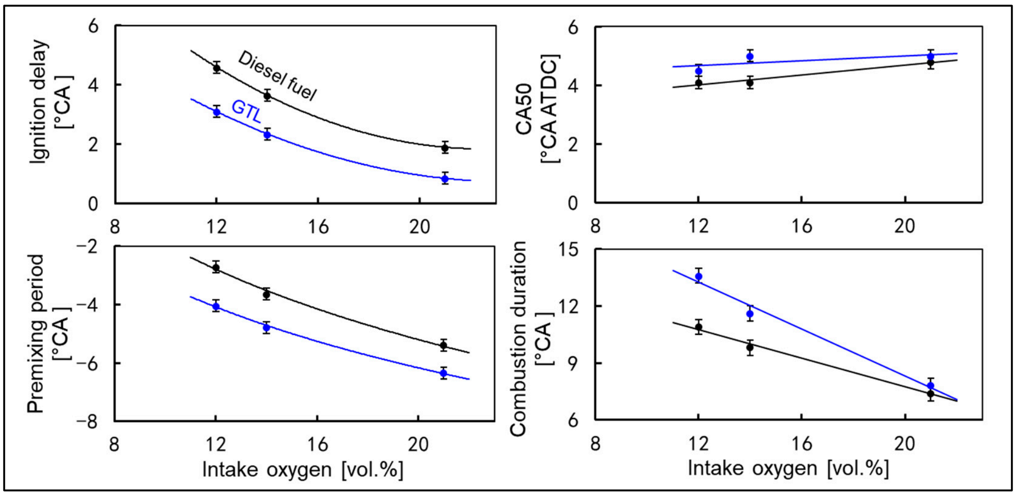
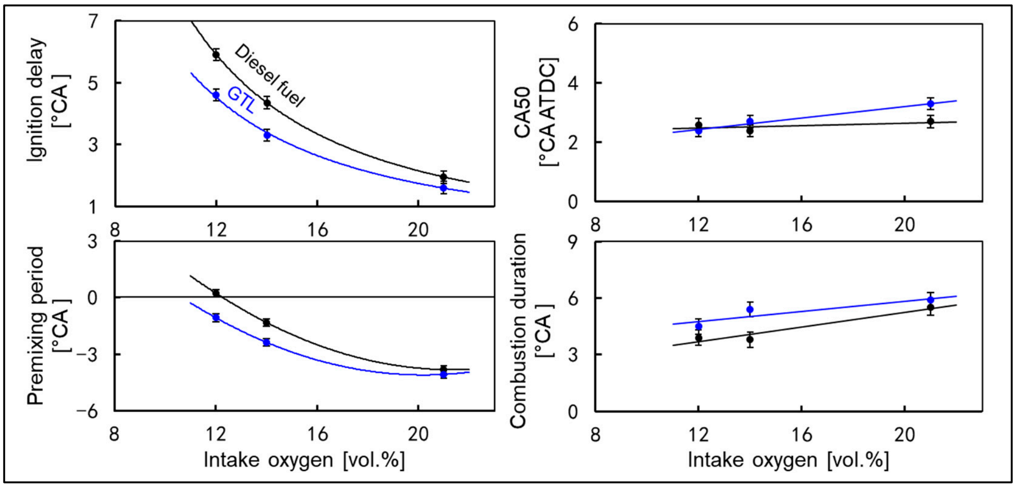


Figure 5. In-cylinder pressure, rate of heat release (ROHR), and injector energizing signal for GTL and diesel fuel.

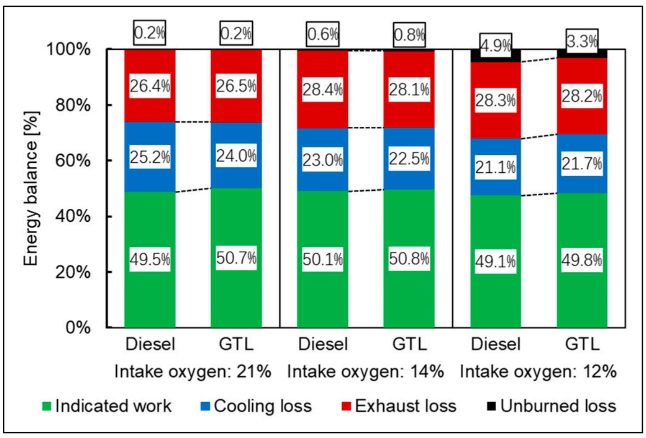


(**a**) High load condition (IMEP = 0.9 MPa)

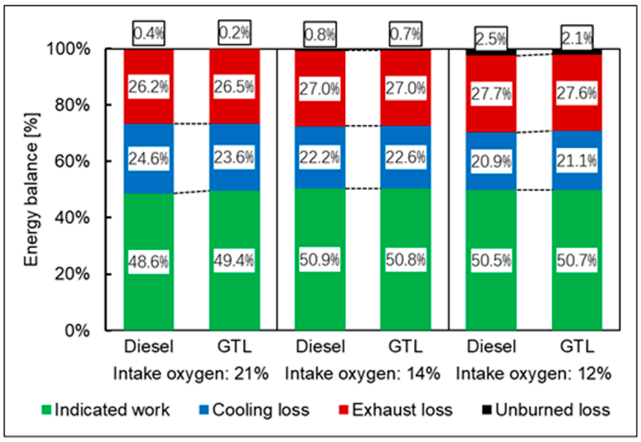


(**b**) Medium load condition (IMEP ≈ 0.6 MPa)

Figure 6. Ignition delay, premixing period, CA50, and combustion duration for GTL and diesel fuel.



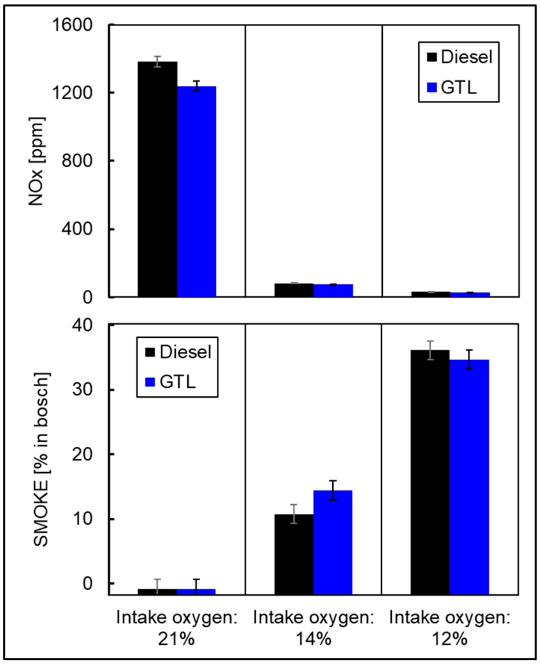
(**a**) High load condition (IMEP ≈ 0.9 MPa)



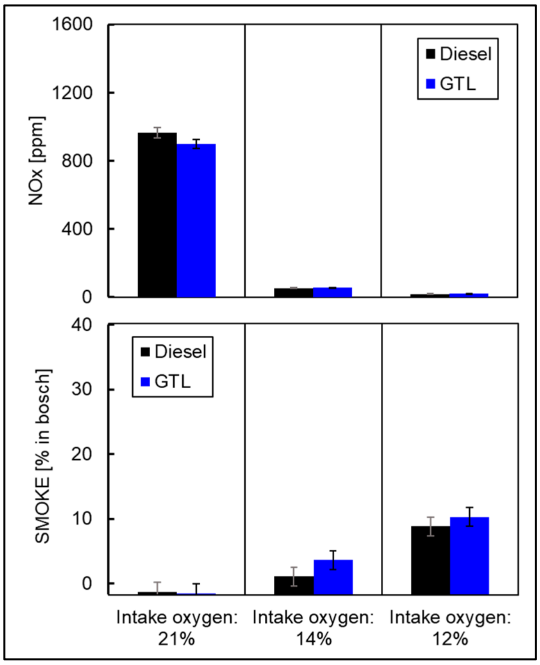
(**b**) Medium load condition (IMEP ≈ 0.6 MPa)

Figure 7. Energy balances for GTL and diesel fuel.

Figure 8 shows the NOx and smoke emissions in the exhaust under the same conditions as Figure 5. The base value of the Bosch smoke meter (DSM-20AN: ZEXEL) is −3.5%, thus negative value is obtained when there is no smoke or/and smoke emission is very low. For both fuels, NOx emissions decreased dramatically with the decreases in intake oxygen concentration and showed an extremely low emission level at the highest thermal efficiency at 14% or less intake oxygen concentration at the medium and high load conditions. Further, smoke emissions displayed a trade-off relationship to the NOx emissions, which showed a higher value at 12% intake oxygen concentration. At the high load condition (Figure 8a), the GTL NOx emissions were slightly lower than diesel fuel; this is consistent with the trend of differences in CA50 for GTL and diesel, as shown in Figure 6a, showing the potential correlation between combustion phase and NOx emissions.



(**a**) High load condition (IMEP ≈ 0.9 MPa)



(**b**) Medium load condition (IMEP ≈ 0.6 MPa)

Figure 8. The exhaust emissions of NOx and smoke for GTL and diesel fuel.

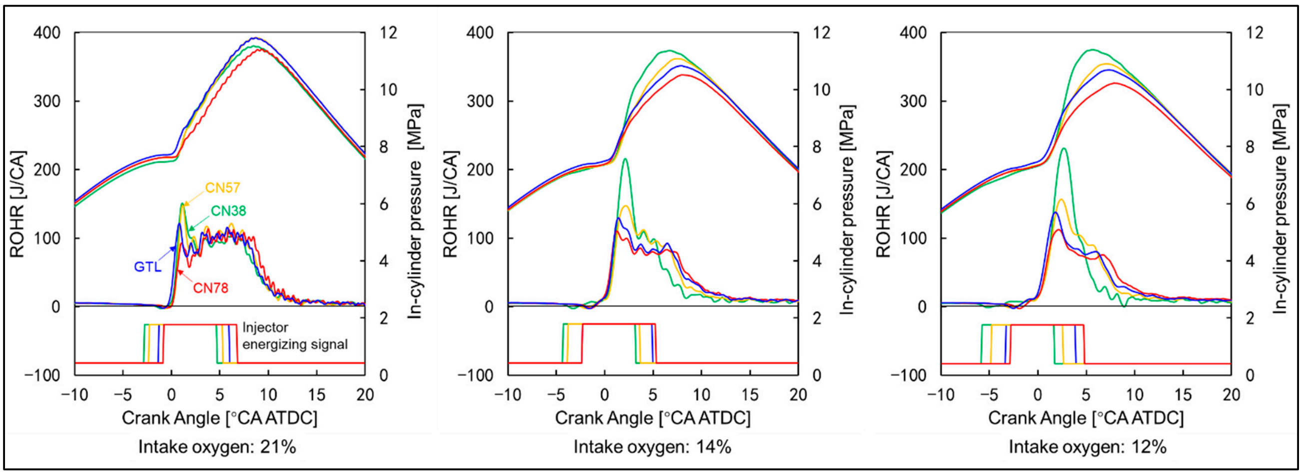
Although the FT fuel has been considered a smokeless fuel due to its aromatic-free characteristics, a limited reduction in the smoke emission was observed at 12% intake oxygen concentration. The reason is mainly the lower density and higher cetane number for GTL compared to diesel fuel, as shown in Table 6, resulting in shorter premixed combustion and longer diffusion combustion. At the medium load condition (Figure 8b), both NOx and smoke emissions were lower overall compared to the high load condition. Compared to diesel fuel, the NOx emissions of GTL were slightly lower, but the smoke emissions increased at all intake oxygen concentrations.

In this section, by using a commercial GTL (Gas-to-Liquids) synthetic FT fuel and a conventional diesel engine, the effect on thermal efficiency and exhaust emissions was observed. The results show that the use of GTL can achieve the effects of thermal efficiency improvement and emission reduction at specific load or intake oxygen concentration conditions. Although the effects are limited, FT fuels are still potential for conventional diesel engines due to their characteristics of zero sulfur and zero aromatics. Considering the fuel compositions of FT fuels could be selected by different synthesis processes, in the next section, the effects of the chemical compositions and cetane number of FT fuels on diesel engine performance are investigated with GTL and additionally blended paraffinic hydrocarbon fuels.

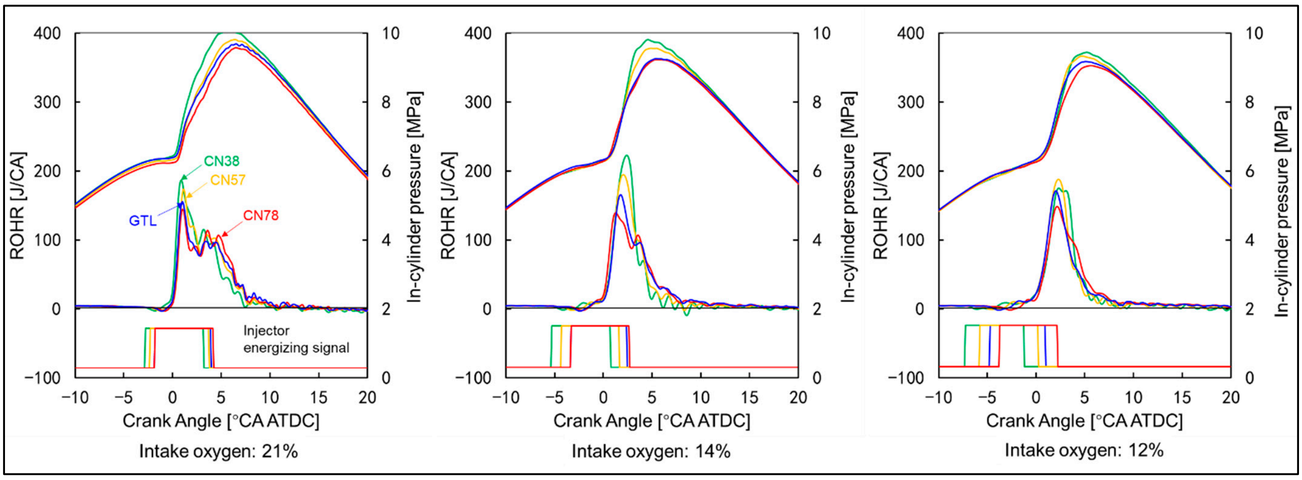
3.2. Effects of the Chemical Compositions and Cetane Number of Fischer–Tropsch Fuels on Diesel Combustion Characteristics

In this section, three types of paraffinic hydrocarbon fuels with different cetane numbers (CN78, CN57, and CN38; additional to that investigated above) are used to investigate the effects of the chemical compositions and cetane number on diesel combustion characteristics of Fischer–Tropsch fuels.

Figure 9 shows the in-cylinder pressure, rate of heat release (ROHR), and injector energizing signal for GTL (CN68) and the paraffinic hydrocarbons fuels (CN78, CN57, CN38) at the high (IMEP ≈ 0.9 MPa) and medium (IMEP ≈ 0.6 MPa) load conditions with varying intake oxygen concentrations by cooled EGR. At the high load condition in Figure 9a, all fuels showed typical heat release patterns for diesel combustion at all intake oxygen concentration conditions. Advancing the injection timing resulted in a relatively shorter duration of diffusion combustion for fuels with lower cetane number. Further, the heat release peak of premixed combustion was higher for low cetane fuels, especially for CN38 fuel, which was more significant at low intake oxygen concentration conditions (12% and 14%). At the medium load condition in Figure 9b, GTL, CN38, and CN57 fuels showed heat release patterns of premixed combustion at 12% intake oxygen concentration; however, a slight heat released by the diffusion combustion was seen for CN78 fuel.



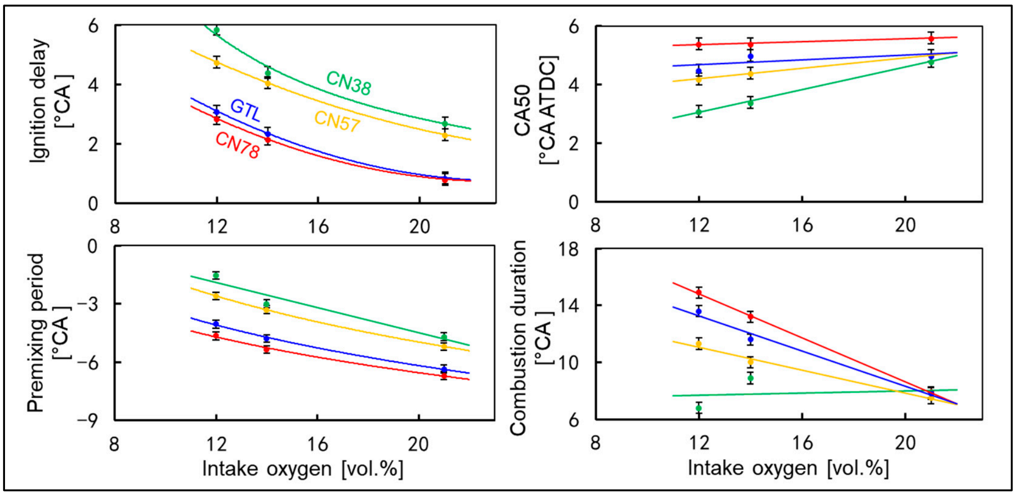
(**a**) High load condition (IMEP ≈ 0.9 MPa)



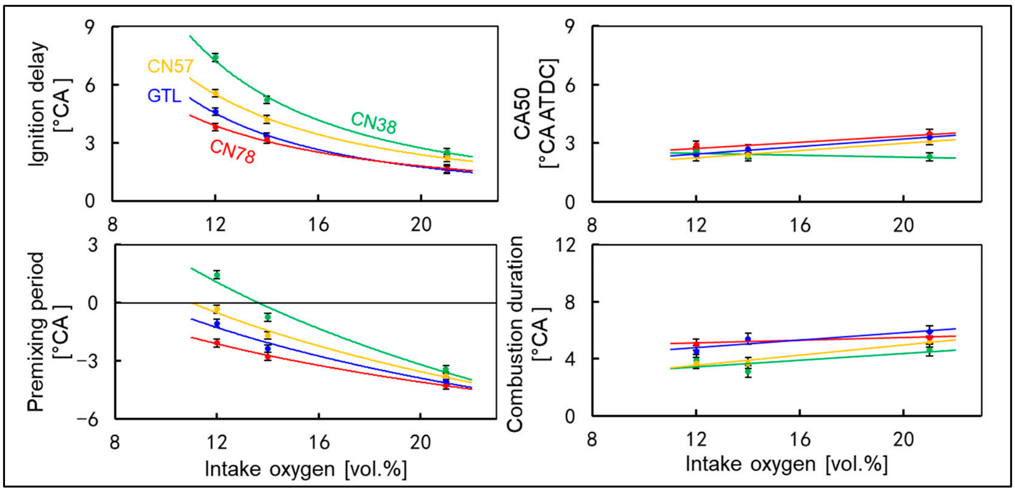
(**b**) Medium load condition (IMEP ≈ 0.6 MPa)

Figure 9. In-cylinder pressure, rate of heat release (ROHR), and injector energizing signal for GTL and CN78, CN57, CN38 paraffinic hydrocarbon fuels.

Figure 10 shows the ignition delay, premixing period, CA50, and combustion duration under the same conditions as in Figure 9. For all load conditions, the ignition delay and premixing period were shorter with higher cetane number, especially at the low intake oxygen concentrations (14% and 12%). At the medium load condition (Figure 10b), at 12% intake oxygen concentration, the premixing period was about 1.45 °CA for CN38 fuel. This shows that premixing progressed sufficiently at the timing of ignition for CN38 fuel. For GTL and CN57 fuel, although the heat release patterns of premixed combustion are shown at 12% intake oxygen concentration in Figure 9b, the ignition occurred during the injection period at about −1 °CA for GTL and almost zero for CN57 fuel, suggesting that premixing of GTL and CN57 fuel are still insufficient in this condition. At the high load condition (Figure 10a), except for CN38 fuel, the combustion duration of other fuels increased with the decrease in intake oxygen concentration due to the extension of afterburn at low intake oxygen concentrations (14% and 12%), as shown in Figure 9a. For CN38 fuel, due to the heat release pattern of premixed combustion, as shown at 12% intake oxygen concentration in Figure 9a, the combustion duration of CN38 at 12% intake oxygen concentration was shorter than that at 21% intake oxygen concentration. The CA50 for all fuels advanced with the decrease in the intake oxygen concentration and cetane number. At the medium load condition, as shown in Figure 10b, the differences in CA50 and combustion duration between fuels were not remarkable, which is similar to the experimental results for GTL and diesel fuel in the previous section.



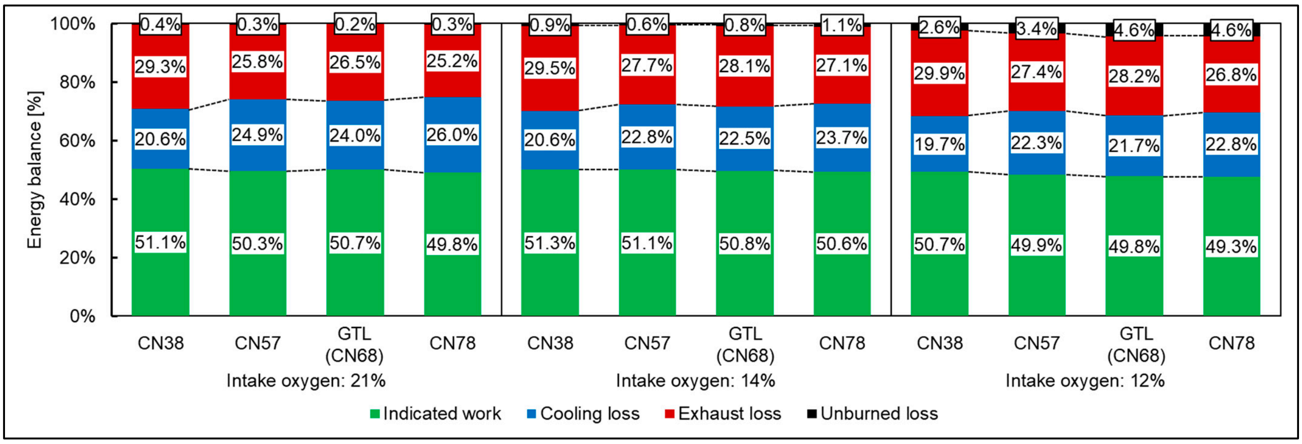
(**a**) High load condition (IMEP ≈ 0.9 MPa)



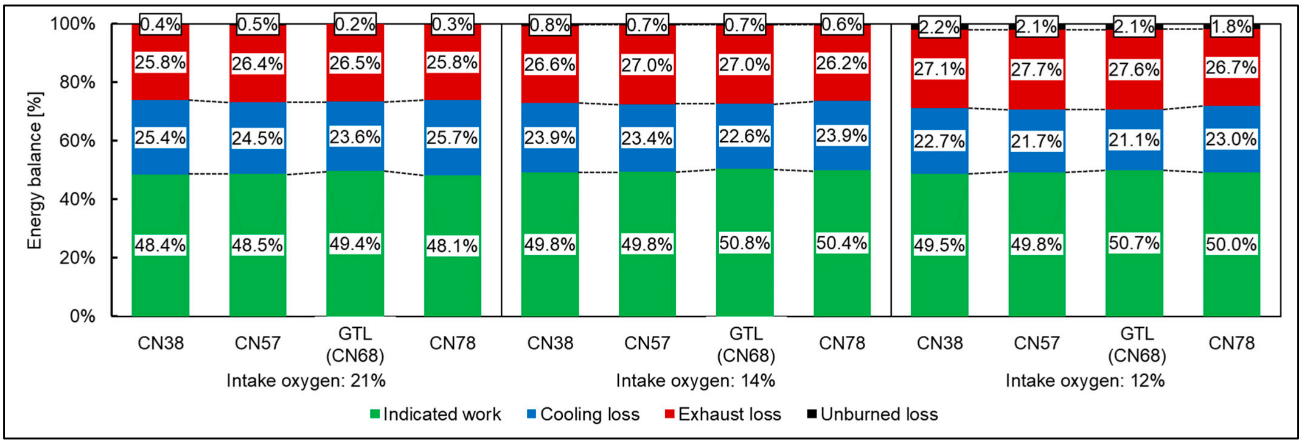
(**b**) Medium load condition (IMEP ≈ 0.6 MPa)

Figure 10. Ignition delay, premixing period, CA50, and combustion duration for GTL and CN78, CN57, CN38 paraffinic hydrocarbon fuels.

Figure 11 presents the energy balances at the same condition as in Figure 9. Similar to the experimental results of diesel fuel, all fuels showed the highest indicated thermal efficiency at the 14% intake oxygen concentration, and the deterioration in combustion efficiency could be observed at 12% intake oxygen concentration. At the high load condition (Figure 11a), the cooling losses reduced significantly with the decrease in cetane number. Even exhaust losses increased as the cooling losses reduced, and the indicated thermal efficiency still showed an increasing trend with the decrease in cetane number. Especially for the CN38 fuel, the indicated thermal efficiency was excellent at all intake oxygen concentrations. Compared with CN78, there are 1.4%, 0.7%, and 1.3% increases in indicated thermal efficiency at the 21%, 14%, and 12% intake oxygen concentrations, respectively. The reason might be that the cooling losses are reduced by shorter combustion duration and a decrease in cetane number, as shown in Figure 10a. However, at the medium load condition (Figure 11b), the difference in cooling loss between fuels is smaller than the high load condition. One possible reason could be that the difference in combustion duration of the fuels is insignificant at the medium load conditions, as shown in Figure 10b.



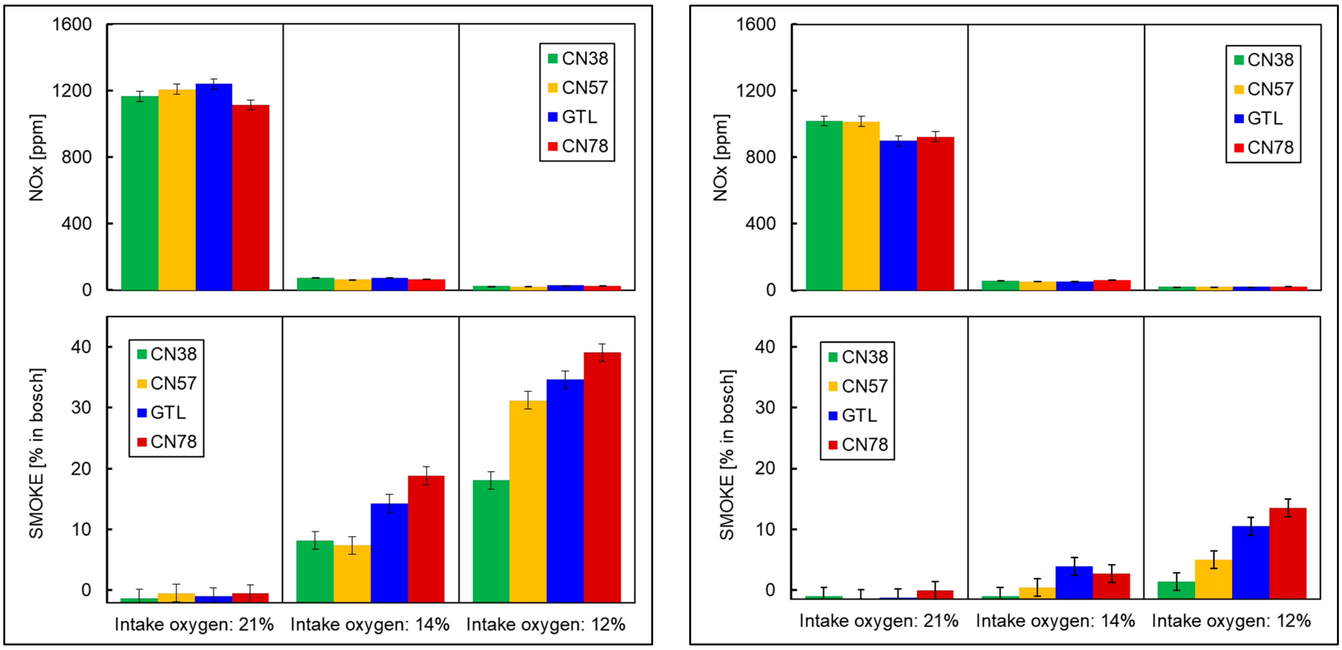
(**a**) High load condition (IMEP ≈ 0.9 MPa)



(**b**) Medium load condition (IMEP ≈ 0.6 MPa)

Figure 11. Energy balances for GTL and CN78, CN57, CN38 paraffinic hydrocarbon fuels.

Figure 12 shows the exhaust emissions of NOx and smoke under the same conditions as in Figure 9. Because the premixing period is longer for lower cetane number fuels, as shown in Figure 10, the reduction in smoke emissions can be obtained under both high and medium conditions. Especially for CN38 fuel, the smokeless combustion can be achieved over a wide range of intake oxygen concentrations at the medium load condition, as shown in Figure 12b. Even at the high load condition, the smoke emissions of CN38 fuel were the lowest of all fuels (Figure 12a). While the exhaust emission of NOx for all fuels reached an extremely low level at 14% and 12% intake oxygen concentration, high thermal efficiency and reductions of smoke and NOx emissions can be achieved by EGR with low cetane number simulated FT fuel (CN38 fuel).



(**a**) High load condition (IMEP ≈ 0.9 MPa) (**b**) Medium load condition (IMEP ≈ 0.6 MPa)

Figure 12. The exhaust emissions of NOx and smoke for GTL and CN78, CN57, CN38 paraffinic hydrocarbon fuels.

4. Conclusions

In this paper, the effects of the chemical compositions and cetane numbers of Fischer–Tropsch fuels on diesel engine performance were investigated by using diesel fuel, GTL (Gas-to-Liquids) diesel fuel, and blended paraffinic hydrocarbon fuels as simulated FT fuels in an experimental diesel engine with low-pressure cooled EGR under the same operating conditions and ignition timing. The conclusions may be summarized as follows:

1. The combustion of GTL showed a shorter premixed combustion, smaller heat release peak, and longer diffusion combustion duration at both high and medium conditions with respect to conventional petroleum diesel fuel due to the higher cetane number, ignition delay, and premixing period of GTL. At the high load condition, GTL presented a delayed CA50 and shorter combustion duration, but for the medium load condition, the differences between fuels were not remarkable.
2. At the high load condition (IMEP ≈ 0.9 MPa), compared to diesel fuel, the indicated thermal efficiency of GTL was improved by 1.2%, 0.7%, and 0.7% at 21%, 14%, and 12% intake oxygen concentrations, respectively. At the medium load condition (IMEP ≈ 0.6 MPa), a 0.8% improvement in the thermal efficiency was shown at 21% intake oxygen concentration.
3. The GTL showed a slight reduction in the NOx emissions over diesel fuel at both medium and high load conditions. However, no significant reduction in the smoke emissions was achieved due to shorter premixed combustion and longer diffusion combustion, even though FT fuel has been considered a smokeless fuel due to its aromatic-free characteristics.
4. With a low cetane number simulated FT fuel (CN 38 fuel), the ignition delay and premixing period were longer, and a significantly higher heat release peak of premixed combustion was shown at low intake oxygen concentration conditions (12% and 14%) under the high load condition. At the medium load condition, CN38 fuel exhibited a premixing period of about 1.45 °CA (Ignition occurred at 1.45 °CA after the end timing of fuel injection), and a heat release pattern of premixed combustion was shown at 12% intake oxygen concentration. This indicates that with the low cetane FT

fuel, the premixing of fuel can be progressed more sufficiently under high EGR rate conditions, resulting in fewer smoke emissions.

5. At the high load condition, the cooling losses were reduced significantly with the decrease in cetane number, causing the indicated thermal efficiency improvement with the decrease in cetane number. For CN38 fuel, there were 1.4%, 0.7%, and 1.3% increases in indicated thermal efficiency over the CN 78 fuel at the 21%, 14%, and 12% intake oxygen concentrations, respectively. However, at the medium load condition, the difference in the cooling loss and indicated thermal efficiency between fuels was not remarkable.
6. By using a lower cetane number fuel, there are reductions in smoke emissions under both high and medium conditions. Especially for CN38 fuel, smokeless combustion can be achieved over a wide range of intake oxygen concentrations at the medium load condition. Even at the high load condition, the smoke emissions of CN38 fuel were the lowest of all fuels.

In summary, the experimental results present a potential to achieve higher thermal efficiency and reduction in exhaust emissions on commercial diesel engines with EGR by the low cetane number FT fuel.

Author Contributions: Conceptualization, H.Y., T.T., G.S. and H.O.; Data curation, H.Y., T.T. and Y.Y.; Supervision, G.S., Y.K. and H.O.; Writing—original draft, H.Y.; Writing—review & editing, H.Y. and G.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research is one of the projects promoted by the New Energy and Industrial Technology Development Organization (NEDO) and Japan Petroleum Energy Center (JPEC) and was financially supported.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We would like to thank everyone involved.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

To improve the experimental efficiency as much as possible, the operating conditions of experiments in this study were selected by a pre-experiment. The experimental conditions of the pre-experiment were as follows.

Figure A1 shows the indicated thermal efficiency, combustion efficiency, NOx, and smoke emissions for the pre-experiment at conditions as shown in Table A1. Under the low load condition (IMEP $\approx$ 0.3 MPa), when the intake oxygen concentration exceeds 14%, since the maximum pressure rise rate (MPRR) is over 1.5 MPa/°CA, considering the safety of the experiment, data were not taken. Under the high (IMEP $\approx$ 0.9 MPa) and medium (IMEP $\approx$ 0.6 MPa) load conditions, the thermal efficiency showed slight increases with the decrease of the intake oxygen concentration and reached the maximum at around 14% intake oxygen concentration. For the intake oxygen concentration below 14% to 11%, the combustion efficiency reduced sharply, leading to thermal efficiency deterioration. At the intake oxygen concentration of 14% or less, the NOx emissions are suppressed to a relatively low level (less than 100 ppm) for all load conditions, but the smoke emissions are increased significantly with the decrease of intake oxygen concentration for both high and medium load conditions.

Table A1. Operating conditions for pre-experiment.

	High Load	Medium Load	Low Load
Engine load	IMEP ≈ 0.9 MPa	IMEP ≈ 0.6 MPa	IMEP ≈ 0.3 MPa
Test fuel		JIS No. 2 diesel fuel	
Engine speed		1600 rpm	
Intake temperature		30 °C	
Intake pressure	140 kPa	120 kPa	101 kPa
Fuel injection pressure		180 MPa	
Ignition timing		Single-injection, TDC w/injection timing	
Intake oxygen concentration		21, 18, 16, 14, 12, 11%	
Coolant temperature		80 °C	

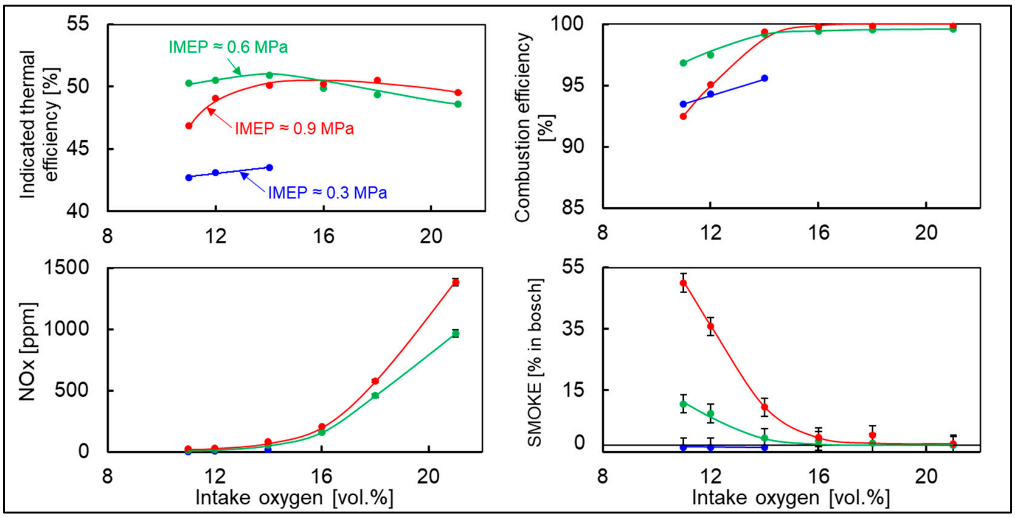


Figure A1. Indicated thermal efficiency, combustion efficiency, NOx, and smoke emissions for pre-experiment.

Considering that under the low load condition (IMEP ≈ 0.3 MPa), the experimental data may not be fully taken, and the NOx and smoke emissions are both maintained at a low level, respectively, it is difficult to reflect the difference between fuels. Therefore, in this study, the high load condition (IMEP ≈ 0.9 MPa) and medium load condition (IMEP ≈ 0.9 MPa) were selected as the operating conditions. For the intake oxygen concentration, referring to the results of the pre-experiment, the operating conditions were selected as follows.

- 21%: The intake oxygen concentration condition without EGR.
- 14%: The NOx emissions are suppressed to a low level, while the smoke emissions are relevantly lower, it is expected to achieve smokeless and low NOx combustion by FT fuels.
- 12%: The smoke emissions are relatively high, which can be used to compare the effect of FT fuels in smoke emission reduction.

References

1. European Vehicle Emissions Standards—Euro 7 for Cars, Vans, Lorries and Buses. Available online: https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12313-European-vehicle-emissions-standards-Euro-7-for-cars-vans-lorries-and-buses_en (accessed on 20 May 2022).
2. Motor Vehicle Exhaust Emission Standards. Available online: https://www.env.go.jp/en/air/aq/mv/table_290628.pdf (accessed on 20 May 2022).
3. Regulations for Emissions from Vehicles and Engines. Available online: https://www.epa.gov/regulations-emissions-vehicles-and-engines (accessed on 20 May 2022).
4. Kitano, K.; Sakata, I.; Clark, R. Effects of GTL fuel properties on DI diesel combustion. *SAE Trans.* **2005**, *114*, 1415–1425.

5. Abu-Jrai, A.; Tsolakis, A.; Theinnoi, K.; Cracknell, R.; Megaritis, A.; Wyszynski, M.L.; Golunski, S.E. Effect of gas-to-liquid diesel fuels on combustion characteristics, engine emissions, and exhaust gas fuel reforming. Comparative study. *Energy Fuels* **2006**, *20*, 2377–2384. [CrossRef]
6. Tsolakis, A.; Megaritis, A.; Yap, D.; Abu-Jrai, A. *Combustion Characteristics and Exhaust Gas Emissions of a Diesel Engine Supplied with Reformed EGR*; No. 2005-01-2087; SAE Technical Paper; SAE International: Warrendale, PA, USA, 2005.
7. Abu-Jrai, A.; Rodríguez-Fernández, J.; Tsolakis, A.; Megaritis, A.; Theinnoi, K.; Cracknell, R.F.; Clark, R.H. Performance, combustion and emissions of a diesel engine operated with reformed EGR. Comparison of diesel and GTL fuelling. *Fuel* **2009**, *88*, 1031–1041. [CrossRef]
8. Allansson, R.; Blakeman, P.G.; Cooper, B.J.; Hess, H.; Silcock, P.J.; Walker, A.P. Optimising the low temperature performance and regeneration efficiency of the continuously regenerating diesel particulate filter (CR-DPF) system. In Proceedings of the SAE 2002 World Congress & Exhibition, Detroit, MI, USA, 7–9 May 2002.
9. Boehman, A.L.; Song, J.; Alam, M. Impact of biodiesel blending on diesel soot and the regeneration of particulate filters. *Energy Fuels* **2005**, *19*, 1857–1864. [CrossRef]
10. Houel, V.; Millington, P.; Pollington, S.; Poulston, S.; Rajaram, R.R.; Tsolakis, A. Chemical deactivation of Ag/Al_2O_3 by sulphur for the selective reduction of NOx using hydrocarbons. *Catal. Today* **2006**, *114*, 334–339. [CrossRef]
11. Fickel, D.W. *Investigating the High-Temperature Chemistry of Zeolites: Dehydrogenation of Zeolites and Ammonia-SCR of Copper Exchanged Small-Pore Zeolites*; University of Delaware: Newark, Delaware, 2010.
12. Gill, S.S.; Tsolakis, A.; Dearn, K.D.; Rodríguez-Fernández, J. Combustion characteristics and emissions of Fischer–Tropsch diesel fuels in IC engines. *Prog. Energy Combust. Sci.* **2011**, *37*, 503–523. [CrossRef]
13. Siegemund, S.; Trommler, M.; Kolb, O.; Zinnecker, V.; Schmidt, P.; Weindorf, W. *E-Fuels Study. The Potential of Electricity-Based Fuels for Low-Emission Transport in the EU, Dtsch*; Energie-Agentur GmbH: Berlin, Germany, 2017.
14. Choi, Y.H.; Jang, Y.J.; Park, H.; Kim, W.Y.; Lee, Y.H.; Choi, S.H.; Lee, J.S. Carbon dioxide Fischer-Tropsch synthesis: A new path to carbon-neutral fuels. *Appl. Catal. B Environ.* **2017**, *202*, 605–610. [CrossRef]
15. Pastor, J.V.; García, A.; Micó, C.; Lewiski, F. An optical investigation of Fischer-Tropsch diesel and Oxymethylene dimethyl ether impact on combustion process for CI engines. *Appl. Energy* **2020**, *260*, 114238. [CrossRef]
16. Schaberg, P.; Botha, J.; Schnell, M.; Hermann, H.O.; Pelz, N.; Maly, R. Emissions performance of GTL diesel fuel and blends with optimized engine calibrations. *SAE Trans.* **2005**, *114*, 1074–1087.
17. Kook, S.; Pickett, L.M. Liquid length and vapor penetration of conventional, Fischer-Tropsch, coal-derived, and surrogate fuel sprays at high-temperature and high-pressure ambient conditions. *Fuel* **2012**, *93*, 539–548. [CrossRef]
18. Rimkus, A.; Žaglinskis, J.; Rapalis, P.; Skačkauskas, P. Research on the combustion, energy and emission parameters of diesel fuel and a biomass-to-liquid (BTL) fuel blend in a compression-ignition engine. *Energy Convers. Manag.* **2015**, *106*, 1109–1117. [CrossRef]
19. Schemme, S.; Samsun, R.C.; Peters, R.; Stolten, D. Power-to-fuel as a key to sustainable transport systems—An analysis of diesel fuels produced from CO2 and renewable electricity. *Fuel* **2017**, *205*, 198–221. [CrossRef]
20. Lapuerta, M.; Armas, O.; Hernández, J.J.; Tsolakis, A. Potential for reducing emissions in a diesel engine by fuelling with conventional biodiesel and Fischer-Tropsch diesel. *Fuel* **2010**, *89*, 3106–3113. [CrossRef]
21. Jiao, Y.; Liu, R.; Zhang, Z.; Yang, C.; Zhou, G.; Dong, S.; Liu, W. Comparison of combustion and emission characteristics of a diesel engine fueled with diesel and methanol- Fischer-Tropsch diesel-biodiesel-diesel blends at various altitudes. *Fuel* **2019**, *243*, 52–59. [CrossRef]
22. Leckel, D. Diesel production from Fischer−Tropsch: The past, the present, and new concepts. *Energy Fuels* **2009**, *23*, 2342–2358. [CrossRef]
23. Dry, M.E. High quality diesel via the Fischer–Tropsch process—A review. *J. Chem. Technol. Biotechnol. Int. Res. Process. Environ. Clean Technol.* **2002**, *77*, 43–50. [CrossRef]
24. Leckel, D. Low-pressure hydrocracking of coal-derived Fischer−Tropsch waxes to diesel. *Energy Fuels* **2007**, *21*, 1425–1431. [CrossRef]
25. Leckel, D.; Liwanga-Ehumbu, M. Diesel-selective hydrocracking of an iron-based Fischer−Tropsch wax fraction (C15−C45) using a MoO_3-modified noble metal catalyst. *Energy Fuels* **2006**, *20*, 2330–2336. [CrossRef]
26. Li, X.; Luo, M.; Asami, K. Direct synthesis of middle iso-paraffins from synthesis gas on hybrid catalysts. *Catal. Today* **2004**, *89*, 439–446. [CrossRef]
27. Spreen, K.B.; Ullman, T.L.; Mason, R.L. Effects of cetane number, aromatics, and oxygenates on emissions from a 1994 heavy-duty diesel engine with exhaust catalyst. *SAE Trans.* **1995**, *104*, 238–254.