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Enhancing Low Temperature Combustion Through the Application of Alcohol Blends

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Abstract

Future road transportation requires innovative propulsion technologies to address the environmental issues associated with internal combustion engines. Low temperature combustion (LTC) is a new, highly investigated technology capable of simultaneously reducing nitrogen oxide and particulate matter emissions. However, the low combustion temperature in LTC can impair oxidation, limiting its effectiveness under various operating conditions. This paper aims to investigate the effects of oxygenates, particularly alcohols, on LTC to mitigate oxidation difficulties. To demonstrate the effects of alcohols, modulated kinetics (MK) type LTC was achieved in an unmodified diesel engine by applying high rates of low-pressure exhaust gas recirculation at three different loads at 1250 rpm. The combustion and emission characteristics of the engine were evaluated during MK operation using a diesel reference fuel, a diesel-alcohol blend with 30% ethanol, and another diesel-alcohol blend with 30% 2-ethylhexanol. Both alcohols reduced particulate matter emissions and enabled a higher LTC operating range. It was concluded that introducing oxygenated fuels could be advantageous when commercial vehicles utilizing LTC become prevalent, as new combustion technologies necessitate fuels with specific characteristics for optimal performance.

Keywords

Low Temperature Combustion, Modulated Kinetics, Oxygenated Fuels, Alcohols

1. Introduction

Heavy-duty diesel engines are widely applied in many sectors of mobility, such as maritime or road transport. Despite the apparent environmental issues of this technology, there are no other competitive alternatives due to their low costs, high reliability, and well-built infrastructure. Instead of searching for entirely different alternative technologies, the investigation of other supplementary technologies could provide a faster solution to environmental concerns. The two main problems are the air pollution resulting from the high nitrogen oxide (NO_x) and particulate matter (PM) emissions of diesel engines and the greenhouse gas production from fossil fuels. Low temperature combustion (LTC) is a new combustion technology that focuses on the problem of air pollution since it enables a better NO_x-PM trade-off (Singh and Agarwal, 2012). This technique utilizes a homogeneous lean charge that is autoignited in the presence of high amount of residual gases (Krishnamoorthi et al., 2019). The autoignited homogeneous charge burns with a rapid volumetric combustion, but the slowing effects of residual gases keep the pressure gradients in a feasible range (Agarwal et al., 2017). The high heat capacity of the recirculated exhaust gases lowers the combustion temperature; thus, the generation of NO_x through the Zeldovich mechanism is reduced (Zeldovich, 1946). Besides NO_x reduction, PM emission is also reduced due to the mixture homogeneity, which impedes soot formation. Although the technology provides many benefits, it also raises many issues (Singh and Agarwal, 2018). The pressure gradients at higher loads can rise to unacceptable levels, and the mixture can become too lean at lower loads,

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resulting in high cyclic variations or even misfires. Thus, the operating range of LTC has lower and upper bounds. The low temperature can also lead to oxidation issues that worsen the emission characteristics of the engine.

There are many different approaches to realize LTC, and each of them creates a compromise between the technique's benefits and demerits. Duan et al. (2021) completed a detailed review of the homogeneous charge compression ignition (HCCI) type LTC technology, which is one of the most investigated methods. Controlling combustion is a challenging task since the compression ignition of a perfectly homogeneous charge cannot be controlled using the usual direct methods. They concluded that techniques that apply stratification in the combustion chamber can lead to better LTC operation.

Li et al. (2017) wrote a review on the reactivity controlled compression ignition (RCCI). RCCI is a technology that applies a dual fuel strategy to create stratified reactivity in the combustion chamber. They concluded that this method could help control combustion. However, the main benefit is the enlarged LTC operating range; since the stratification allows slower combustion, thus higher loads become feasible. Lawler et al. (2017) and Rahimi Boldaji et al. (2018) investigated thermally stratified compression ignition (TSCI), which is another similar approach. Thermal stratification is achieved by water injection, and the operating range can be extended similarly. Moreover, the water injection can retard the combustion since the water cools the charge. Therefore, the control of combustion becomes easier. However, these techniques require additional expensive systems on the engine.

As a consequence, other researchers investigated simpler methods. These methods usually reduce the degree of homogeneity to gain more control over the combustion and extend the operating range. Hoang (2020) investigated premixed charge compression ignition (PCCI), which uses a premixed charge instead of a homogeneous charge. He pointed out that creating a premixed charge with the early direct injection can lead to increased wall impingement. Thus, a narrow cone angle injector is required to aim the fuel spray on the piston bowl. Lee and Huh (2014) created a premixed charge with a different approach. They applied normal injection timings and extremely high rates of cooled exhaust gas recirculation (EGR) along with high swirl in the combustion chamber. This caused a prolonged ignition delay, and the fuel had time to form a premixed charge with the air, resulting in LTC. This technique is called modulated kinetics (MK), and in our previous research we also studied it. In our latest work (Virt and Zöldy, 2024a), we concluded that the MK is the best type of LTC if no engine modification is possible. However, we experienced a highly limited operating range due to the extremely high EGR rates and the relatively short time available for mixing.

The LTC can be an excellent approach to solve the environmental problems of internal combustion engines. However there is another promising technology: the oxygenated e-fuels. E-fuels are carbon-neutral synthetic fuels produced by utilizing renewable energy and sustainable feedstocks. The feedstock can be waste-based biomass that does not lead to direct or indirect land use changes, carbon dioxide captured directly from the air, and green hydrogen generated with renewable energy (Wicke et al., 2012). Usually, syngas is created from these feedstocks, and properly engineered e-fuels are generated through catalytic processes. A typical example is the Fischer–Tropsch process, which can produce excellent fuel alternatives (Pastor et al., 2020). Due to the renewable feedstocks, carbon neutrality is guaranteed by the carbon cycle (Prentice et al., 2001). Besides carbon neutrality, the reduction of air pollution is also substantial. The application of oxygenates is a widely investigated solution that can reduce PM emissions by aiding the oxidation of local inhomogeneities. A good example is oxymethylene ether (OME), an e-fuel with extremely high oxygen concentration.

Liu et al. (2022) published a review on the effects of OME. They concluded that OME is able to reduce PM emissions significantly. Among other aspects, high oxygen concentration is key since the generated solid particles can be oxidized more easily during combustion. This also leads to a better NO_x-PM compromise; thus, higher EGR rates can be applied to reduce NO_x emission. The oxygen can also accelerate combustion, leading to increased brake thermal efficiency (BTE). Although, the high oxygen concentration of a fuel may lead to disadvantages as well. The lower heating value becomes even lower as the oxygen concentration increases (Pélerin et al. 2020); therefore, bigger fuel tanks and longer injections or increased rail pressure may be necessary. Polarity might be another challenge, since oxygen can make molecules polar, thus conventional sealing materials in the fuel system may be incompatible with the fuel. The effects of oxygen are usually similar for other oxygenates as well. There are several widely investigated oxygenates, usually ethers such as diethyl ether (Agarwal and Chandra, 2022), or alcohols, such as methanol (Hasan et al., 2021). We also conducted multiple studies with oxygenates. We investigated diesel-OME blends and concluded that OME can highly reduce PM emissions However, fuel characteristics have to be improved to meet the requirements of EN590 (Virt and Arnold, 2022). Later, we introduced n-decanol to the diesel-OME blends, and the fuel characteristics were successfully improved (Virt and Zöldy, 2024b). The material compatibility aspects were also considered, since engine safety is a key factor during engine dyno tests. Based on our material compatibility assessments, we defined precautions to ensure the safe testing of polar fuels (Virt and Zöldy, 2024c).

Considering the effects of LTC and oxygenated e-fuels, it can be assumed that the two technologies can supplement each other well. Both techniques can improve the NO_x-PM trade-off. Thus, even better emission characteristics can be expected. The LTC has oxidation problems due to the lean mixture and the high EGR rates. Oxygenates can help the oxidation locally; thus, better LTC may be achieved. The LTC's positive effects on PM emission can also permit the use of less oxygen in the fuel to achieve the same PM emission levels as normal operation, thus enabling the application of fuels with higher energy density. In addition, both LTC and oxygenated fuels can improve brake thermal efficiency (BTE), which may lead to more economical engine operation. The assumed advantages are significant, so the effects of oxygenates on LTC must be studied. Therefore, this work applies two different alcohols, ethanol and 2-ethylhexanol (2-EH), as oxygenates. Ethanol is a simple alcohol with two carbon atoms. It can be produced as an e-fuel and has a high oxygen concentration; thus, it is a promising material. However, the cetane number of this molecule is too low; therefore, it cannot be mixed into diesel at high concentrations (Zöldy, 2007). 2-EH is a branched alcohol with eight carbon atoms. Due to the longer chain length, it has a higher cetane number, but the blending is still limited. Compared to ethanol, the application of 2-EH as a fuel component is really underinvestigated. However, there exist some studies (Wojcieszyk et al., 2023; Preuß et al. 2021; Munch and Zhang, 2016) that applied 2-EH successfully.

This paper analyses the effects of oxygenates on LTC by blending B7 diesel with 30% ethanol and 30% 2-EH, respectively. The combustion and emissions are investigated at 1250 rpm at 25, 50, and 75 Nm. MK type LTC was achieved by applying high rates of cooled low-pressure exhaust gas recirculation (LP-EGR). The test fuels and the measurement methods are described in Section 2. Section 3 presents and analyses the results in the studied steady-state conditions. The engine's performance is investigated during MK operation with and without alcohol blending. Besides the NO_x and PM emissions, the heat release rates (HRRs), combustion timings, combustion durations, and peak pressure rise rates are presented.

2. Materials and Methods

2.1. Test Fuels

The blends investigated in this work consist of three components: commercial B7 diesel, ethanol, and 2-ethylhexanol. The ethanol's purity is 98.46 vol%, and the remaining volume is mostly ethyl tertiary butyl ether. The 2-EH's purity is over 99 vol%. Two diesel-alcohol blends were formed, each with 30 vol% alcohol concentration. The blend with ethanol is abbreviated with ETA30, and the blend with 2-EH is abbreviated with EHX30. Table 1 presents the properties of the blends and the blending components. The properties of B7 were measured in our previous study (Virt and Zöldy, 2024b). The properties of alcohols are given in the literature (Yanowitz et al., 2014) and the GESTIS Substance Database. The blend properties were calculated with commonly used mixing rules. These are simple linear mixing rules, except for the viscosity that was calculated by the Arrhenius mixing rule (Nour et al., 2022).

Table 1 Properties of the test fuels and blending components

Property	B7	Ethanol	2-EH	ETA30	EHX30
Cetane number [-]	52.7	8.0	23.5	39.9	44.0
Lower heating value [MJ/kg]	45.55	26.7	37.6	40.2	43.2
Density [kg/m^3]	844	790	830	829	840
Kinematic viscosity [mm^2/s]	2.780	1.047	11.810	2.071	4.290
Oxygen concentration [wt%]	1.00	34.73	12.29	10.01	3.71

2.2. Experimental Apparatus and Calculations

The experiment utilized a Cummins ISBe 170 30 turbocharged medium-duty commercial diesel engine, which had been employed in several previous studies (Nyerges and Zöldy, 2023; Virt and Nyerges, 2023; Nyerges and Zöldy, 2020). This engine was equipped with a common-rail injection system, an intercooler, and both high-pressure (HP) and low-pressure (LP) EGR systems, and it was mounted on an engine dynamometer. Temperature and pressure were measured at the intake side both before and after the compressor, as well as after the intercooler. On the exhaust side, readings were taken before

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and after the turbine and at the exhaust outlet. Fuel consumption was measured using an AI 2000 gravimetric device. Table 2 presents the engine's main parameters.

The EGR rate was adjusted using the LP-EGR valves along with an exhaust brake. The control of the valves was managed through CAN communication with a dSpace MicroAutoBox DS1401/1505/1506, and the sensor data were transmitted via CAN as well. Combustion analysis was carried out using an AVL indicating system. Cylinder pressure was monitored using an AVL GH13P piezoelectric sensor with a ±0.3% FSO linearity, mounted in the glow plug seat. The crankshaft position was tracked using an AVL 365C crank angle encoder with a resolution of 0.1°CA. The data from the indicating system were processed with an AVL 612 Indi-Smart, an 8-channel device with charge amplifiers for the piezoelectric sensors. AVL IndiCom software was employed to process combustion data, while emission and fuel consumption data were recorded using a Matlab/Simulink model. Oxygen and NO_x levels were measured with a Continental UniNOx-Sensor, accurate to 10 ppm. Exhaust gas opacity was measured with an AVL 439 opacimeter, with a sensitivity of 0.1%. No catalytic converters or diesel particulate filters were used to treat the emissions.

Table 2 Cummins ISBe 170 30 main parameters

Displacement	3922 cm^3
Bore	102 mm
Stroke	120 mm
Compression Ratio	17.3
Rated Effective Power	125 kW

Regarding the calculation methods, we applied the same methods as in our previous article, since the current work is the continuation of that study (Virt and Zöldy, 2024a). The parameters related to combustion are calculated from the cylinder pressure, including the heat release rates that are determined based on the First Law of Thermodynamics (Heywood, 1988). The start of combustion (SoC) is determined by the crank angle at which 5% of the total heat is released. The point at which 90% of the heat is released marks the end of combustion. The duration of combustion (DoC) is calculated as the interval between these two crank angle positions.

3. Results and discussion

3.1. Emissions

The engine was operated based on the findings of our previous experiments (Virt and Zöldy, 2024a). By using the LP-EGR valve and the exhaust brake, 9.5% oxygen concentration was achieved at the intake side, while the engine speed was 1250 rpm and the torque was 25, 50, and 75 Nm. Regarding emissions, the exhaust opacity and NO_x concentration were measured. Since the EGR rate was extremely high, the NO_x emission was nearly zero for all the investigated loads. The sensor recorded NO_x concentrations between 1 and 10 ppm, but these values are lower than the sensor's specified accuracy.

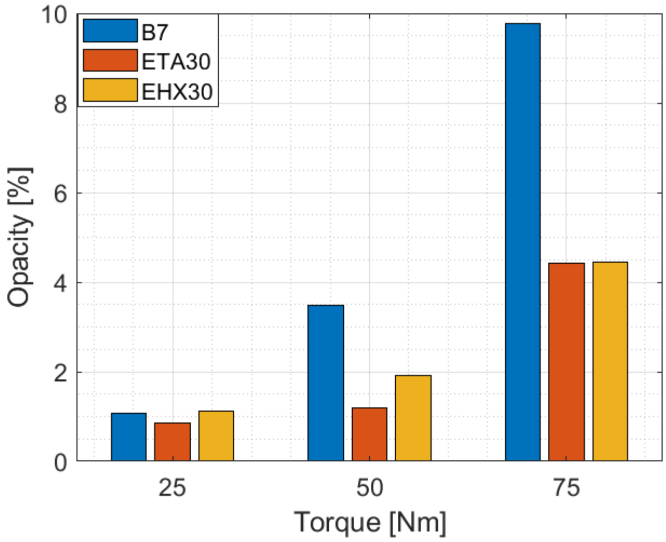

Figure 1. The opacity of the investigated fuels at 1250 rpm with different loads during MK operation

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Figure 1 provides the results of the exhaust opacity measurement. The diesel reference fuel shows a significant increase in sooting, since the dose starts to be too large to properly mix with the air during the ignition delay. This increased heterogeneity leads to increased soot formation, while the oxidation of the generated soot is hindered by the reduced temperature and oxygen concentration caused by the high EGR rate. In the case of oxygenates, oxygen is present in the fuel itself, thus the oxidation of the generated solid particles is easier. It is evident that both diesel-alcohol blends reduced exhaust opacity. The ETA30 blend has three times higher oxygen concentration than the EXH30 blend. Despite this, the ETA30 does not reduce the opacity to a much higher extent than the EHX30.

3.2. Combustion

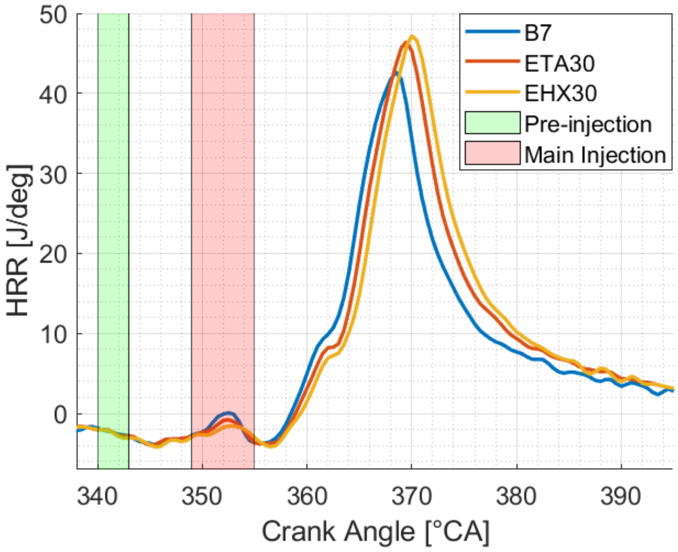

Figure 2. Heat release rates of the investigated fuels at 1250 rpm and 25 Nm during MK operation

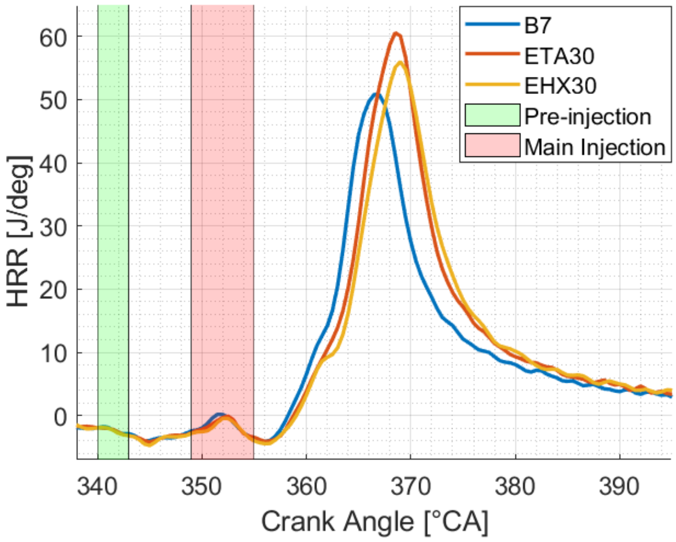

Figure 3. Heat release rates of the investigated fuels at 1250 rpm and 50 Nm during MK operation

Figures 2, 3, and 4 present the heat release rates of the blends at the three investigated loads. The injection strategy was similar in all cases, regardless of the load. The pre-injection happened between 340 and 343°CA, and the main injection was performed between 349 and 355°CA. For higher loads, the higher dose was ensured by the increased injection pressure (around 25 bar increment for each load). The behavior of the fuels is similar for all loads. The heat dissipation of both the pre-and main injection can be observed on the curves. Around 352°CA, a low temperature heat release (LTHR) phase is visible. This is a typical phenomenon of LTC heat release rates when the fuel contains diesel. Here, the combustion has not started yet, but some low activation energy reactions are taking place. The combustion begins after the top dead center (TDC). A brake around 362°CA can be observed. This may be a sign that after the first short period of the combustion, the less homogeneous parts of the charge are burning. Regarding the differences between the fuels, it is evident that the combustion of alcohol blends starts slower. This can be attributed to the low cetane number of the alcohols. Despite the lower cetane number of ethanol, the combustion of EHX30 is somewhat slower than that of ETA30. This may be attributed to the much higher viscosity of 2-EH that leads to worsening spray atomization. The peak heat release rate is higher in the case of the alcohol blends. This can be the effect of the higher oxygen concentration. Interestingly, the DoC does not change much. In our previous research with oxygenates, we experienced that the combustion is much shorter when oxygenates are applied (Virt and Arnold, 2022; Virt and Zöldy, 2024b). In these studies, conventional diesel combustion was applied, which had a premixed and a diffusion phase. The fuel’s oxygen likely has the most significant accelerating effect during the diffusion phase because it facilitates oxidation in locally rich zones. However, since MK combustion and other LTC techniques are lacking the diffusion phase, the oxygen content of the fuel may not lead to DoC reduction.

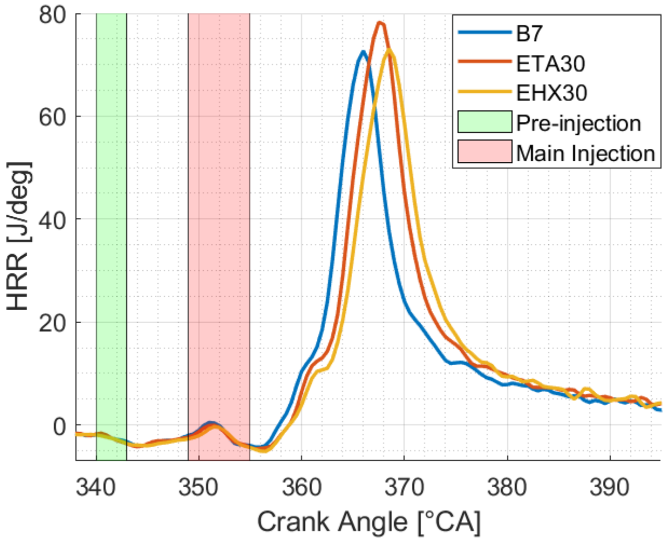

Figure 4. Heat release rates of the investigated fuels at 1250 rpm and 75 Nm during MK operation

Figure 5 demonstrates the start of combustion for the different loads, and Figure 6 presents the center of heat release (CoHR). The values support the previous observations. The SoC is retarded by the low cetane number of the alcohols and the high viscosity of 2-EH. Since the injection strategy is unmodified, the ignition delay changes similarly to the SoC. The change of ID is small, only around 1-2°CA, thus the alcohols does not prolong it so much that a significantly better mixing could be achieved by it. The CoHR results are similar to the SoC results since the DoC did not change that much. The MK combustion leads to a late CoHR that can reduce the BTE compared to normal diesel combustion because work loss can arise due to the late heat release.

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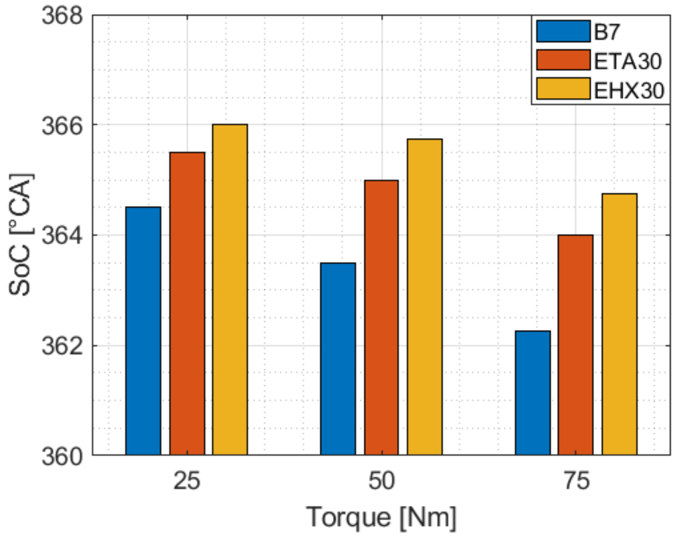

Figure 5. Start of combustion of the investigated fuels at 1250 rpm at different loads during MK operation

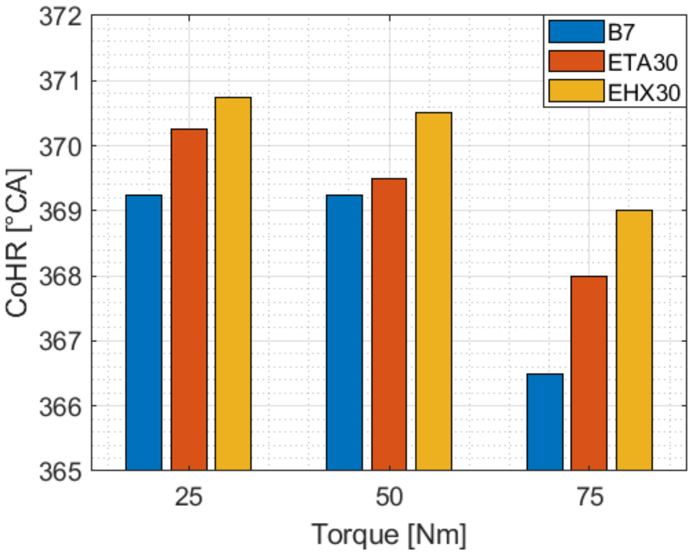

Figure 6. Center of heat release of the investigated fuels at 1250 rpm at different loads during MK operation

Figure 7 outlines the peak pressure rise rate at the different loads. In the case of commercial diesel engines, this value should not exceed 6 bar/°CA to avoid mechanical damage (Yin et al., 2021). The high EGR rate usually leads to slower combustion, although the homogeneous charge of LTC can increase the pressure rise rate. All the values remain well below the given limit and the alcohols tend to reduce the pressure rise rate compared to neat B7 diesel. This may be the effect of the retarded SoC.

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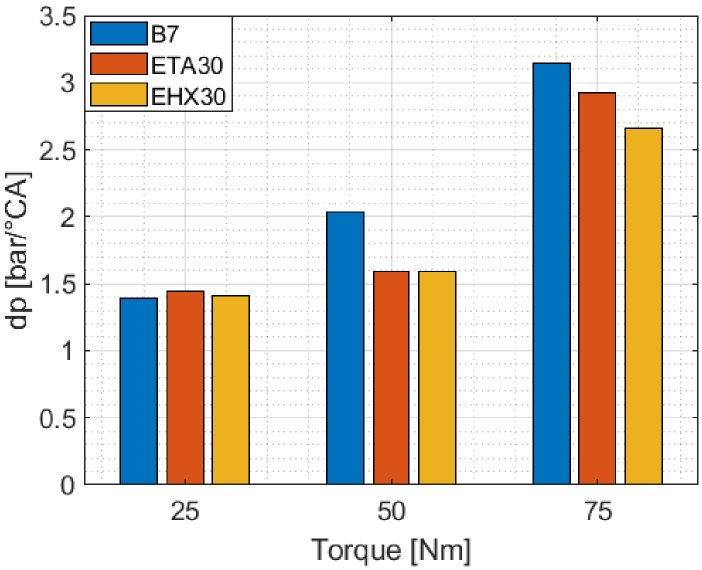

Figure 7. Peak pressure rise rates of the investigated fuels at 1250 rpm at different loads during MK operation

4. Conclusion

This work demonstrated the possibilities of enhancing low temperature combustion by using oxygenated fuels. MK type LTC was realized under three different steady state conditions, and diesel-alcohol blends with ethanol and 2-EH were investigated. It was concluded that these alcohols could improve the LTC. The MK operation has an upper bound for engine load, since high fuel doses cannot mix with air properly during the prolonged ignition delay. The oxygen helped the oxidation and reduced exhaust opacity; thus, this upper bound could be elevated. In contrast to conventional diesel combustion, the DoC did not become notably shorter by adding oxygen to the fuel. In the case of normal engine operation, the oxygen's accelerating effect mainly influences the diffusion phase. This phase is not present in the case of LTC; thus, the combustion is not accelerated that much. This is an advantage, since the rate of pressure rise is a critical parameter for LTC, and increased combustion speed would lead to higher pressure gradients. The investigated blends have relatively low cetane numbers. For MK operation, this can be beneficial, since the ignition delay can be prolonged further. Consequently. higher fuel doses could be used due to the increased mixing time. In conclusion, it was demonstrated that new combustion technologies require new fuel characteristics in order to achieve better operation. The alcohols can be beneficial for LTC due to their high oxygen concentration and lower cetane number. Future investigations should study the effects of even higher oxygen concentrations, for example by applying oxymethylene ether. Moreover, blends with higher alcohol ratios should also be investigated to examine the MK operation with lower cetane numbers. The MK type LTC does not require any engine modification, but it is an inadequate LTC technology due to the highly limited operating conditions. The effects of oxygenates should also be investigated by applying other LTC technologies, such as HCCI or PCCI.

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