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Realisation of Low Temperature Combustion in an Unmodified Diesel Engine

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Abstract

Heavy-duty diesel engines are an essential part of road transportation. Since viable alternatives are not expected in the short and medium term, the problematic emission characteristics of compression ignition engines must be addressed. Low-temperature combustion (LTC) is an alternative combustion method for compression ignition engines that allows low particulate matter and nitrogen oxide emissions while improving efficiency. To overcome the difficulties of market introduction, the realisation of such alternative combustion methods should come with marginal engine modifications. Thus, this work investigates a possible realisation of LTC in an unmodified diesel engine. LTC methods were studied with and without injection strategy modifications to provide sufficient recommendations for other researchers. It was concluded that techniques requiring early direct injection, such as homogeneous charge compression ignition (HCCI), necessitate a narrow cone angle injector to reduce wall impingement. It was also determined that modulated kinetics (MK) type LTC can be easily achieved by applying a conventional injection strategy and high amounts of cooled exhaust gas recirculation. The realised MK combustion resulted in an enhanced NO_x-PM trade-off and a lower peak pressure rise rate than normal operation.

Keywords

Low-temperature combustion, Modulated Kinetics, Homogeneous Charge Compression Ignition, Low-Pressure Exhaust Gas Recirculation

1. Introduction

Among the many concerns about future mobility, the environmental aspects of road transport are one of the most significant (*Zöldy, 2009*). As a reaction to global challenges, the European Union (EU) set many ambitious goals for the European Green Deal (*Fetting, 2020*). Until 2050, the EU aims to become climate neutral; thus, many policies, such as the new 95 g/km CO_2 emission limit, were formulated. Moreover, the Ambient Air Quality Directive (*EP, 2008*) aims to achieve zero air pollution by 2050. Regarding road vehicles, the new Euro 7 norm (*EP, 2023*) is essential to achieving this goal. Electrification is the most discussed topic from the wide variety of alternative technologies. Due to its many advantages, it can be a proper solution for passenger cars; however, there are some transportation sectors where this technology cannot be applied (*Koller et al., 2022*). Besides the slow charging time and the lack of infrastructure, the main problem with batteries is their low energy density. The latest EU forecasts expect 500 Wh/kg batteries by 2030 (*Edström, 2020*). This equals 1.8 MJ/kg of energy density, much higher than current vehicle batteries' energy densities. However, liquid hydrocarbons have lower heating values (LHVs), well above 40 MJ/kg (*Manuel and Chivanga Barros, 2023*). Thus, this significant difference prevents the use of batteries in applications that require high energy density on-board energy storage. Heavy-duty vehicles for road transport are among these critical applications. Thus, alternatives have to be identified.

One of the most promising alternatives for heavy-duty vehicles is the application of carbon-neutral advanced fuels (*Tóth et al., 2020*). By applying these, the well-to-wheel CO_2 emission can be minimised (*Virt et al., 2022*). Advanced fuels can also positively affect pollutant emissions; however, additional engine improvements are necessary to reduce air pollution further in internal combustion engines (*Zöldy, 2007; Zöldy and Vass, 2018*). The most critical emissions from heavy-duty

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diesel engines are nitrogen oxides (NO_x) and particulate matter (PM). NO_x is mainly generated through the Zeldovich mechanism (*Zeldovich, 1946*) due to the high oxygen concentration and temperature during combustion. The PM emission can be attributed to the inhomogeneity of the fuel mixture. Solid combustion products are formed in local rich zones, and soot is formed through agglomeration (*Heywood, 1988*). The simultaneous reduction of these compounds is impossible in conventional diesel engines due to a trade-off between them.

Low-temperature combustion (LTC) can overcome this issue with a new combustion technology that lowers combustion temperature (*Agarwal et al., 2017*). LTC applies a homogeneous lean mixture, high residual gas, and compression ignition to improve engine characteristics (*Krishnamoorthi et al., 2019*). The lean homogeneous mixture ensures low PM emission, while the high heat capacity of residual gases results in lower combustion temperature, lowering NO_x emission. The compression ignition provides high brake thermal efficiency. In addition, an LTC engine is also quality-controlled; thus, the lack of a throttle valve reduces engine losses (*Singh et al., 2018*). The low exhaust gas temperature also contributes to higher efficiency since the heat loss is reduced—the autoignition of the homogeneous charge results in volumetric combustion. However, the residual gases slow the combustion; thus, the peak pressure rise rate (dp_{max}) can be kept in an acceptable range. The amount of residual gas can be increased by applying internal or external exhaust gas recirculation (EGR). Usually, external EGR is preferable since the recirculated exhaust gases can be cooled down before reintroduction (*Nyerges and Zöldy, 2020*).

The advantages of the previously described LTC process make this technology promising for commercial diesel engines. However, some serious demerits make its application challenging. First, the low temperature can be problematic since it may lead to incomplete combustion. Therefore, LTC engines can have higher CO and HC emissions. Other unregulated emissions, such as formaldehyde or polyaromatic hydrocarbons (PAHs), can also increase.

Moreover, the lower exhaust gas temperature reduces the efficiency of conventional catalytic converters; therefore, new after-treatment systems may be necessary. The harder cold start of LTC engines can further increase these emissions. Besides low temperatures, the compression ignition of the homogeneous charge generates challenges. Since the homogeneous mixture is autoignited, the start of combustion (SoC) can only be controlled through indirect parameters, making combustion control difficult. The EGR sufficiently slows the reaction kinetics; however, the homogeneous charge still results in a rapid heat release, and the duration of combustion (DoC) is short. This short DoC leads to worsening oxidation due to the shorter combustion times. Also, rapid ignition means that higher loads must be avoided because the pressure rise rate can be unacceptably high. This limits the operating range of the engine. To prevent high-pressure rise rates, extremely lean mixtures are used. For low loads, the mixture can be so lean that cyclic variations increase or even misfire can occur. Thus, the operating range has a lower limit. Finally, applying homogeneous mixtures can also lead to severe wall wetting if early direct injection (DI) is used to formulate the charge. This increases emissions, decreases efficiency, and leads to oil dilution.

Several different LTC technologies are described in the literature. Homogeneous charge compression ignition (HCCI) is one of the most commonly investigated methods (*Duan et al., 2021*). It achieves LTC by following the exact principles described previously. Therefore, it provides good engine behaviour in a specific operating range but exhibits all the described disadvantages outside of this range. Many other LTC techniques exist to solve the problems in a wider operating range. These do not follow the LTC principles precisely; thus, they achieve a compromise between the benefits of LTC and the increased operating range. This paper focuses on unmodified engines; therefore, LTC methods without specific modifications must be identified. Some technologies require extreme modifications, such as reactivity-controlled compression ignition (RCCI) that slows combustion by stratifying mixture reactivity with a dual fuel system (*Elkelawy et al., 2022*).

Another example is thermally stratified compression ignition (TSCI), which achieves thermal stratification through direct water injection (*Rahimi Boldaji et al., 2018*). These complex modifications may lead to good combustion characteristics, although smaller changes can also be enough. Mixture homogeneity is one of the factors that creates the most benefits and demerits. Thus, a compromise can be achieved by reducing homogeneity. Premixed charge compression ignition (PCCI) and partially premixed compression ignition (PPCI) are examples of this approach (Hoang, 2020). They apply an injection strategy that provides enough time for a premixed charge, so the homogeneity is higher compared to normal operation; however, the charge is not as homogeneous as in the case of HCCI. Modulated kinetics (MK) also follows this approach (*Lee and Huh, 2014*). Still, it can be considered an extreme example since it applies injection timings similar to conventional

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diesel engines or even later timings in some cases. Extremely high EGR rates can achieve the premixed charge to prolong the ignition delay (ID) so much that the fuel has time to mix with the air. Some essential factors can help achieve good MK combustion. The EGR has to be cooled, and the combustion chamber's geometry should provide a high swirl for proper mixing. However, MK is only suitable for low loads, as high amounts of fuel cannot be properly mixed.

This work aims to achieve LTC in an unmodified commercial diesel engine to provide recommendations and best practices for researchers to achieve LTC operation more easily. The case study investigated the possible realisation of LTC with and without injection strategy modification. The LTC is achieved by applying cooled low-pressure EGR.

2. Materials and Methods

2.1. Experimental Apparatus

The experiment was conducted on a Cummins ISBe 170 30 turbocharged, medium-duty commercial diesel engine, which had been used in numerous previous studies (*Nyerges and Zöldy, 2023; Virt et al., 2023; Virt et al., 2024*). This engine features a common-rail injection system, an intercooler, and a high-pressure (HP) and low-pressure (LP) EGR system. For the experiment, the engine was mounted on an engine dynamometer. Temperature and pressure readings were taken at the intake side both before and after the compressor, as well as after the intercooler. On the exhaust side, measurements were taken before and after the turbine and at the exhaust outlet. Fuel consumption was recorded using an AI 2000 gravimetric device.

Table 1. 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

The HP- and LP-EGR valves and the exhaust brakes adjusted the EGR rate. Only the LP EGR valve and an exhaust brake were utilised during the measurements. The valves were controlled via CAN communication using a dSpace MicroAutoBox DS1401/1505/1506, and sensor data were also transmitted via CAN. Combustion analysis was conducted using an AVL indicating system. Cylinder pressure was measured with an AVL GH13P piezoelectric sensor connected to the glow plug seat with a linearity of ±0.3% FSO. The crankshaft position was determined with an AVL 365C crank angle encoder with 0.1°CA resolution. The indicating data were processed with an AVL 612 Indi-Smart, an 8-channel multipurpose indicating device with charge amplifiers for the piezoelectric sensors. AVL IndiCom was used to process the combustion data, and an additional Matlab/Simulink model was used to record emission and fuel consumption data. Oxygen and NOx concentrations were measured with a UniNOx-Sensor with an accuracy of 10 ppm. Exhaust gas opacity was assessed using an AVL 439 opacimeter with 0.1% sensitivity. Emissions were not treated with catalysts or a diesel particulate filter.

The injection could be modified in all cylinders. A dSpace RapidPro Power Unit with two PS-DINJ 2/1 modules drove the injectors. A dSpace MicroAutobox DS1401/1505/1506 controlled the start of the injection, while an Arduino UNO Rev3 controlled the duration of the injections. The desired engine speed could be set with a potentiometer, and a PID controller running on the Arduino set the necessary dose.

2.2. Calculation methods

Several parameters have to be calculated. Some parameters are based on the engine's normal power:

$$P_{norm} = P_{eff} \cdot \frac{p_0 - \phi_0 \cdot p_{g0}}{p_{amb} - \phi_{amb} \cdot p_{g,amb}} \cdot \sqrt{\frac{t_{amb}+273}{t_0+273}}, \quad (1)$$

where P_{eff} is the effective power, p_{amb}, t_{amb}, ϕ_{amb} are the ambient pressure, temperature and humidity, p_0, t_0, ϕ_0 are the pressure, temperature and humidity under normal conditions, and p_g is the vapour pressure of water. The first calculated parameter is the brake-specific fuel consumption (BSFC) that is required to calculate brake thermal efficiency (BTE) later:

$$BSFC = \frac{\dot{m}_{fuel}}{P_{norm}}, \quad (2)$$

where $\dot{m}_{fuel}$ is the fuel mass flow. Then, the BTE can be derived:

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$$BTE = \frac{1}{BSFC \cdot LHV}, \quad (3)$$

where LHV is the lower heating value of the mixture.

The combustion-related parameters are calculated from the cylinder pressure. The combustion temperature is derived from the ideal gas law. Note that this simple assumption is only enough to compare the trends of the investigated combustions. The heat release rate (HRR) is calculated from the First Law of Thermodynamics (*Heywood, 1988*):

$$\frac{dQ_b}{d_\phi} = \frac{\kappa p}{\kappa - 1} \cdot \frac{dV}{d_\phi} + \frac{V}{\kappa - 1} \cdot \frac{dp}{d\phi} - \frac{dQ_w}{d_\phi}, \quad (4)$$

where Q_b is released heat, κ is the adiabatic gas constant of air, p is the pressure in the combustion chamber, V is the volume of the combustion chamber, Q_w is the heat loss, and ϕ is the crank angle. The heat loss was neglected during our calculations. The start of combustion (SoC) is the crank angle where 5% of the heat is released. The 90% heat release marks the end of combustion. The duration of combustion (DoC) is the difference between the two previous crank angle values.

3. Results and Discussion

3.1. LTC with Modified Injection Strategy

First, the possibility of LTC realisation is investigated with a modified injection strategy. HCCI, PCCI, and PPCI require earlier DI to achieve higher degrees of homogeneity and a high EGR rate. The main difference between these technologies is the degree of homogeneity. HCCI has near-perfect homogeneity, while PPCI only applies a partially premixed charge. The homogeneity can be controlled with injection timing. Thus, single injections with six different start of injection (SoI) values between 300 and 350 °CA were investigated. The EGR is another crucial factor in LTC. The LP-EGR of our test system can be cooled; thus, it was preferred over the HP-EGR system. Based on our previous experiences, intake oxygen concentrations were kept between 13% and 14% with the LP-EGR and an exhaust brake. The investigated operating point was selected to be 1250 rpm with 50 Nm. This provides low load conditions, thus making the realisation of LTC easier.

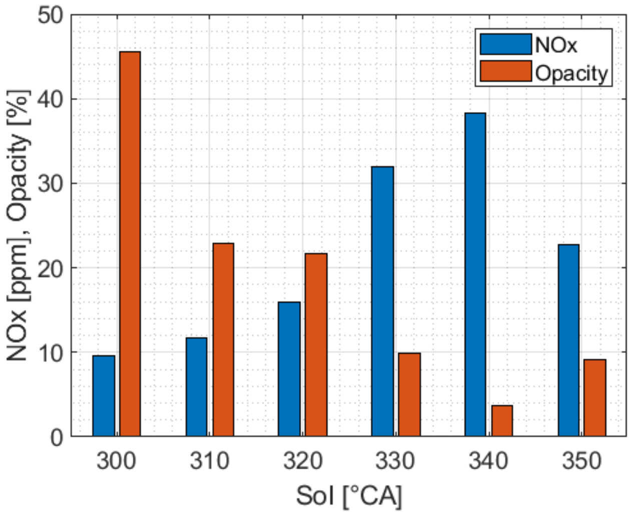

Figure 1. NO_x emission and opacity at different injection timings.

The main goal of LTC is to improve the NO_x–PM trade-off. Therefore, Figure 1 presents NO_x emission and exhaust opacity at different injection timings. As expected, NO_x emission is low in all cases due to the high amount of EGR used. By changing the SoI, a relatively small change of around 30 ppm occurred. This may be attributed to the change in combustion temperature. It is also discernible that the trade-off is present between NO_x and soot generation. At the latter injections, the opacity is lower, while the values for NO_x emission are higher.

Conversely, earlier injections lead to slightly lower NO_x emissions and much higher opacity. LTC should not produce higher opacity for early SoIs due to the higher homogeneity. Thus, this is a clear sign of increased wall wetting. Our test engine has regular injectors because the aim is to achieve LTC without applying any hardware modifications. According to the literature, this result was expected since narrow cone angle injectors must be applied to avoid high levels of wall impingement. Another sign of extreme wall wetting is the increased fuel consumption. The engine required 1.0 g/s of fuel

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to maintain the operating point with 350°CA SoI, while the consumption increased to 1.6 g/s when 300°CA SoI was applied. Overall, it can be concluded that LTC with early DI cannot be realised without narrow cone angle injectors.

3.2. LTC with Conventional Injection Strategy

LTC may be achieved without the modification of the injection strategy. The previously described MK combustion can theoretically be achieved by applying extremely high rates of cooled EGR. However, the geometry of the combustion chamber can also be critical since a high swirl is required for proper mixing. A previous experiment investigated four dual-loop EGR modes on this test engine (Nyerges and Zöldy, 2023). The study examined the effects of the different EGR valves and exhaust brakes. The experiments found that LP-EGR can lead to a drop in NO_x and PM emissions. This suggests that LTC might have happened in that experiment. Based on the findings, the combustion and emission of the engine is investigated at 1250 rpm and 50 Nm. The EGR rate is increased with the LP-EGR valve and an exhaust brake to reproduce and analyse the phenomenon in detail.

Figure 2 presents the measured NO_x emission and exhaust opacity regarding the intake oxygen concentration. The engine exhibits normal EGR behaviour up to an oxygen concentration of 12%. Increasing the EGR ratio (decreasing oxygen levels) causes the NOx emission to drop and the opacity to rise due to the trade-off. However, the engine behaviour changes if oxygen intake is below 12%. The NO_x continues to drop, but now the opacity also decreases. Around 9.5% of the intake oxygen levels are high, and the opacity is not much higher than in the case of normal operation without EGR, while the NO_x emission is nearly eliminated. This is a much better compromise between the emissions than the original. Thus, it can be assumed that MK combustion was achieved when the intake of oxygen levels reached 9.5%.

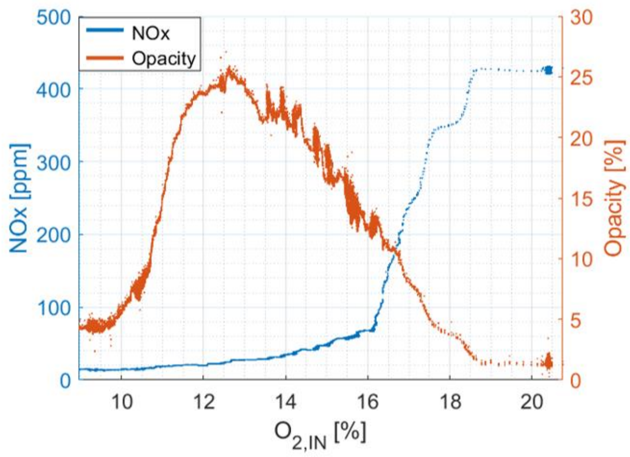

Figure 2. NO_x emission and opacity with conventional injection strategy and increasing LP-EGR levels.

Now, further analysis of this possible MK combustion is necessary. Figure 3 demonstrates the heat release rates in normal operation (without EGR) and MK operation. The MK was achieved at 1250 rpm and 50 Nm by increasing the LP-EGR levels with the LP-EGR valve and the exhaust brake until the intake oxygen dropped to 9.5%. The engine ECU applied a pre-injection between 339 and 342 °CA and a main injection between 348 and 354 °CA in normal and MK operations. It is discernible that normal operation involves conventional diesel combustion. After the pre-injection, a small heat drop occurs due to the fuel's heat dissipation. Then, around the start of the main injection, the combustion also starts with a short premixed phase, where the dose of pre-injection burns mainly. The ignition delay between the start of the main injection and SoC is small; therefore, the main dose burns in the slow diffusion phase. The MK operation mode exhibits an entirely different behaviour. First, the combustion is highly delayed by the EGR. This prolonged the ignition delay so much that the main dose could achieve premixed conditions. Therefore, the heat release rate is nearly symmetrical. The symmetrical shape signifies LTC combustion (*Agarwal et al., 2017*). Before SoC, a small heat release peak can also be observed. This is the low-temperature heat release (LTHR) or cool flame phase. The ignition has not started yet; only reactions with small activation energy have occurred. This is another typical sign of diesel fuel's LTC combustion. A separate mixing-controlled diffusion phase cannot be identified in the diagram. The final slower combustion part can be attributed to the remaining

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reactions with slow reaction kinetics. Despite the autoignition of the premixed charge, the DoC is relatively long due to the high EGR rate; thus, the mechanical load of the engine is expected to be low.

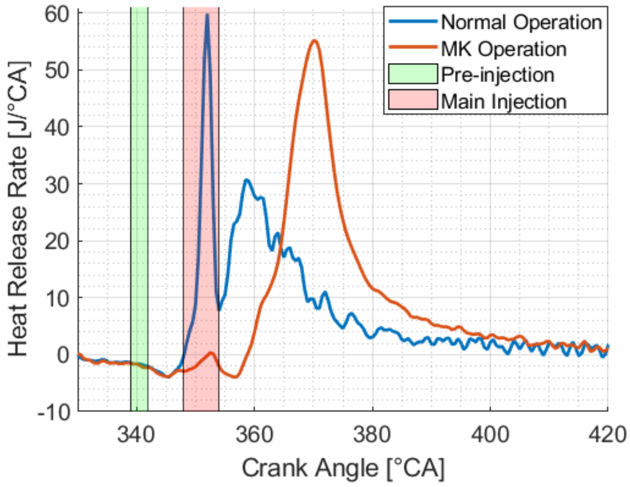

Figure 3. Heat release rates of normal and MK operation modes at 1250 rpm and 50 Nm.

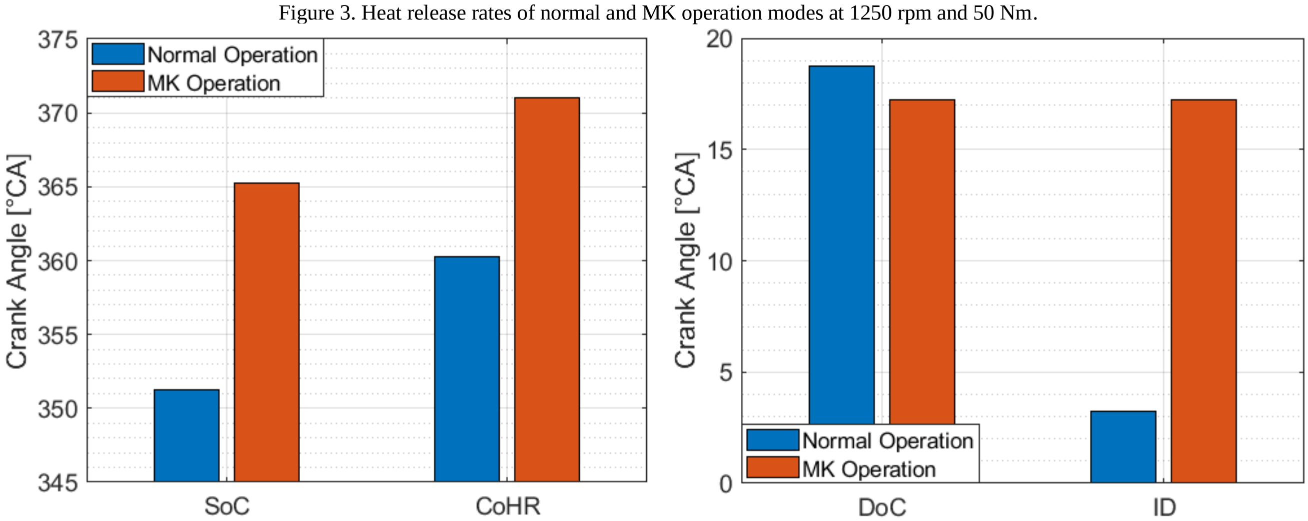

Figure 4. SoC, CoHR, DoC, and ID of normal and MK operation modes at 1250 rpm and 50 Nm.

The SoC and the centre of heat release (CoHR) are important combustion parameters that affect brake thermal efficiency. Figure 4 presents these values for normal and MK operation modes. In normal operation, the combustion starts shortly after the main injection, while in the case of MK mode, it starts after the top dead centre (TDC). The reason for the delay is the high amount of cooled LP-EGR. The CoHR is also retarded due to the latter SoC. The BTE is the highest when the CoHR is close to TDC. Therefore, the normal operation's CoHR is good, but the MK's late CoHR may lead to loss of work since the charge has less time to produce work during the power stroke. This can reduce BTE.

The DoC and the ID are important combustion parameters that affect combustion quality. Figure 4 also presents these values for the two operation modes. A shorter DoC can lead to higher BTE, while it can also increase the pressure rise rate. During LTC, the autoignition of the homogeneous charge provides a hazard for the engine due to the rapid combustion. The slowing effect of the residual gases makes the LTC feasible. Comparing the DoC of the MK combustion with the normal one, it can be observed that only a small drop arose due to the homogeneity. The EGR rate was extremely high; thus, the combustion could be prolonged well. The other effect of EGR is the delay of SoC. The ID from the start of the main injection increased by 14°CA, which is a significant change. This longer ID provides sufficient time for the fuel of the main dose to form a premixed charge with the air.

Peak pressure rise rate, brake thermal efficiency, and peak combustion temperature are important parameters for properly evaluating MK combustion. These are summarised in Table 2. Despite the decrease in DoC, MK's peak pressure rise rate is much smaller than normal. During normal operation, this peak occurs during the premixed phase, characterised by short but

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rapid combustion. In the case of MK combustion, the whole charge is premixed, but the EGR slows reaction kinetics. Therefore, the rate of pressure rise becomes small.

Regarding the BTE, it can be noted that the low engine load led to small efficiencies. However, the MK exhibits an even smaller BTE. The main reason for this drop can be the retarded CoHR that resulted in loss of work. The estimated peak combustion temperature is also low due to the low load. The applied high levels of EGR decreased this temperature by nearly 100 K. This can contribute to smaller NOx emissions.

Table 2. Peak pressure rise rate, brake thermal efficiency, and peak combustion temperature at the operation modes

	Normal operation	MK operation
dp_{max} [%]	5.82	1.48
BTE [%]	19.96	16.35
T_{max} [K]	1482.8	1381.7

Overall, the investigation proved that LTC could happen by applying extremely high rates of cooled LP-EGR. The method provides similarities to the MK combustion technology described in the literature. Thus, it can be concluded that the observed phenomenon is an MK-type LTC.

4. Conclusion

This paper investigated the possibility of realising LTC in an unmodified commercial diesel engine. Two approaches were studied: LTC with and without injection strategy modification. The LP-EGR was utilised for all cases because it can be cooled better. It was found that forming a homogeneous mixture with early direct injection is impossible due to the increasing wall wetting. According to the literature, this problem can be solved by applying a narrow cone angle injector. Without injection strategy modification, the realisation of MK-type LTC was possible. The applied high LP-EGR rates resulted in a prolonged ignition delay, making forming a premixed charge possible. This enabled low soot generation, while the high EGR rate provided low NO_x emission; thus, the NO_x-PM trade-off could be enhanced. However, the brake thermal efficiency decreased by around 3.5% due to the retarded centre of heat release that led to the loss of work. It can be concluded that the MK may be a possible solution to improve the emission values of commercial diesel engines, although other techniques, such as applying oxygenated e-fuel, could be an excellent supplementary solution.

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