SIMULTANEOUS PARTICULATE MATTER AND NITROGEN OXIDE EMISSION REDUCTION THROUGH ENHANCED CHARGE HOMOGENIZATION IN DIESEL ENGINES

by

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In the presented study, low temperature combustion was established with a direct injection of diesel fuel being a representative of high reactivity fuels and tire pyrolysis oil being a representative of low reactivity fuels. Tire pyrolysis oil was tested as a potential waste derived fuel for low temperature combustion, as it features diesel-like physical properties and lower cetane number compared to diesel fuel. The goal of this study was determination of suitable injection strategies and exhaust gas re-circulation rates to explore potentials of both fuels in reducing emissions in low temperature combustion modes. It was demonstrated that relatively small changes in the engine control strategy possess the potential to significantly improve NO_x/particulate matter trade-off with minor effect on engine efficiency. In addition, low temperature combustion was for the first time successfully demonstrated with tire pyrolysis oil fuel, however, it was shown that lower reactivity of the fuel is by itself not sufficient to improve NO_x /soot trade-off compared to the diesel fuel as entire spectra of fuel properties play an important role in improving NO_x /soot trade-off. This study thus establishes relations between different engine control strategies, intake manifold pressure and exhaust gas re-circulation rate on engine thermodynamic parameters and engine-out emissions while utilizing innovative waste derived fuel that have not yet been analysed in similar combustion concepts.

Key words: *compression ignition engine, low temperature combustion, partially premixed combustion, tire pyrolysis oil, engine control, combustion parameters, emissions*

Introduction

Compression ignition (CI) engines with heterogeneous charge (Diesel engines) are widespread both in transport as well as in stationary systems for generation of the electricity because of their higher efficiency in comparison to the spark ignition engines. However, Diesel engines are characterized by high concentrations of particulate matter (PM) and NO_x emissions due to the combustion of heterogeneous charge. To comply with stricter emission limits, use of complex exhaust after treatment systems and/or the introduction of advanced combustion strategies is required. Complex exhaust after treatment systems cause an increase in weight, complexity and price of the vehicle. Therefore, the advanced combustion concepts

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which possess the potential for reducing the emissions of pollutants while maintaining or even increasing the indicated engine efficiency are being intensively researched.

The development is focused on the low temperature combustion (LTC) concepts, as the low local temperature prevents local formation of high NO_x concentrations, with a high level of charge homogenization, which is crucial for achieving low emissions of PM [1]. The LTC concepts can be considered as an efficient measure to simultaneously reduce NO_x and PM emissions [2], while plausible control of the combustion process also ensures maintaining high engine efficiencies of LTC concepts [3]. Single fuel combustion concepts that rely on a higher level or even full mixture homogenisation spread from homogenous charge CI (HCCI) featuring fully homogeneous mixture to the partially premixed combustion (PPC) featuring partially stratified mixture. Some references, *e. g.* [4], position between the HCCI and PPC concepts in addition also a premixed charge CI (PCCI) concept, which should feature higher level of charge homogenisation than PPC and lower than HCCI. Unlike, other references, *e. g.* [5], equate PPC concept with PCCI concept and thus it can be concluded that a common consensus on naming of partially premixed mixture combustion concepts is not yet reached. Therefore, in this paper PPC notation will be used to denote partially premixed mixture combustion concepts.

The PPC is a promising approach to increase robustness of the combustion process over the HCCI [6], while achieving low pollutant emissions. In order to achieve PPC through higher level of charge homogenisation, few techniques that include early fuel injection [7], increase of swirl rates [8], increase of fuel injection pressures [9], very high exhaust gas recirculation (EGR) rates [10], increase of the EGR cooler efficiency [11], decrease of engine compression ratios [10], and increase of utilized fuel octane number were investigated. In the studies, focused on analyses of an increase in fuel octane number on main thermodynamic parameters and emissions with standard gasoline fuel [12], n-butanol diesel blends [9] and ethanol [13] were utilized. In combination with commercial gasoline, Kalghatgi *et al.* [14] managed to achieve simultaneous very low NO_x and smoke emissions in operating point at nearly 16 bar IMEP.

In addition to lowering emissions of internal combustion engines at preserved engine efficiency, the search for alternative sources of energy to power internal combustion engines continues because of gradual depletion of fossil oil reserves. Furthermore, growing problem of disposal of slowly degradable waste, among which car tires represent a big portion, makes waste-to-fuel technologies a logical step towards the alternative fuels. Several conversion processes have been developed to transform solid waste disposals into liquid fuels which have similar physical characteristics to conventional automotive fuels and could be therefore used in the conventional engines with small adaptations of the engine control. Various types of pyrolysis are widely used for producing the fuels. One of the waste derived fuels that can be of interest for the low temperature combustion concepts is tire pyrolysis oil (TPO), which features diesel-like fuel physical properties that allow for its direct injection at high pressures without additives. However, TPO features lower cetane number, therefore in the past its use in engines was enabled through mixing of the TPO with the diesel fuel (D2) [15] or cetane improvers [16], or increasing compression ratio [17] or increasing air intake temperature to at least 145 °C [18]. In the previous studies, it was demonstrated that pure TPO can be utilized at high loads with 1 injection [19] or at mid- to high-loads with addition of pilot injection (PI) [20]. Furthermore, it was demonstrated that operating range can be extended to low-loads with addition of EGR and tailored injection strategy [21]. In this study, the TPO was thus tested as a potential fuel for the LTC as decreased cetane number compared to

D2 allows for achieving higher level of charge homogenization. High octane number fuels were found to be superior for PPC as they could lead to extended engine operation region [7].

The objective of the current study was to investigate potentials to improve NO_x/soot trade-off of the ICE while preserving as high level of engine efficiency as possible and relatively low level of CO and total hydrocarbon (THC) emissions. This was achieved by higher level of charge homogenisation through longer ignition delay periods, which resulted in LTC concepts. Design space was explored by targeted variations of the injection strategy, boost pressure, EGR rates and temperatures as well as engine loads. The study establishes relations between engine thermodynamic parameters and engine-out emissions. Furthermore, besides a well-established D2, TPO was utilized as innovative waste derived fuel that have not yet been analysed in LTC combustion concepts.

Fuel properties

The TPO used in this study was produced with the method of vacuum pyrolysis which has the potential to produce a low sulphur fuel with reasonably high yield from waste vehicle tires [22]. Pyrolysis process was performed between 600 °C and 700 °C and the retention time was 60 minutes. In this study, fractions between 190 °C and 350 °C were used.

The main properties of the TPO and D2 that were analysed with standard methods are presented in tab. 1. Utilized commercial D2 complies with the specifications of the SIST EN-590 standard. The TPO features significantly higher sulphur content compared to D2, which restricts its use in road vehicles. To overcome this issue, the sulphur content in the fuel can be reduced or the exhaust gases can be desulfurized as described in [19].

Another important difference between the TPO and the D2 arises from significantly lower cetane number of the TPO, which is reflected in its lower reactivity. This property could be beneficial in case of LTC since longer ignition delay leads to higher level of charge homogenization. It seems generally accepted that the cetane number of TPO is certainly below 30 [17]. On the other hand conventional D2 has much higher cetane number of at least 51, as set in the European standard SIST EN-590 [23]. Difference between D2 and TPO cetane number was confirmed by the calculated value of cetane index, tab. 1, which may be used to estimate the cetane number of the fuel [24], when the traditional cetane number cannot be directly measured. Although there is discrepancy between cetane number and calculated cetane index, it can be concluded that TPO features lower reactivity compared to D2.

Table 1. Main properties of D2 and TPO

Property\Fuel	D2	TPO
Density [kgL^{-1}]	0.83	0.92
LHV on mass basis [$MJkg^{-1}$]	42.95	42.7
Aromatic content [$\%mm^{-1}$]	26.0	39.3
Viscosity [mm^2s^{-1}]	2.54 at 40 °C	3.22 at 20 °C
S [$\%mm^{-1}$]	<0.001 [23]	0.96
H/C ratio [–]	0.149	0.112-0.140
Calculated cetane index *	53.2	28.6

* Following SIST EN ISO 4264

Experimental set-up

Experimental set-up is based on a PSA 4-cylinder, 4 stroke, turbocharged 1.6 litre Diesel engine (PSA DV6 ATED4) featuring characteristics presented in [21]. One of the cylinders was thermodynamically separated along with entire gas path and fuel supply system as presented in the experimental scheme in fig. 1. Full control system for its operation was developed, while other three cylinders were controlled by original electronic control unit. To achieve the desired conditions in the intake manifold (IM) of this particular cylinder, the IM for selected cylinder was physically separated and the intake air was externally supplied with compressed air from laboratory high pressure compressed air distribution system using pressure regulator. This was combined with external EGR system, fig. 1. The overall proportion of EGR was measured through the O_2 content in the IM by electrochemical sensor and regulated by an exhaust backpressure valve.

Engine was coupled with eddy-current dynamometer (Zollner B-350AC), controlled by real-time control system (Kristel, Seibt & CO ADAC). Pressure was indicated every 0.1 °CA with piezo-electric pressure transducer (AVL GH14D) in combination with charge amplifier (AVL MICROIFEM). External clock for data acquisition and injection control system was obtained with an optical crank angle encoder (Kistler 2613B).

Fuel supply was divided into two separate common rail systems, among which one was used for one separated cylinder and another for other three cylinders. The D2 mass-flow was measured with gravimetric fuel meter (AVL 730) and TPO flow (Micro Motion ELITE CMFS) as well as air mass-flow (Micro Motion F025) were measured with Coriolis flow meters.

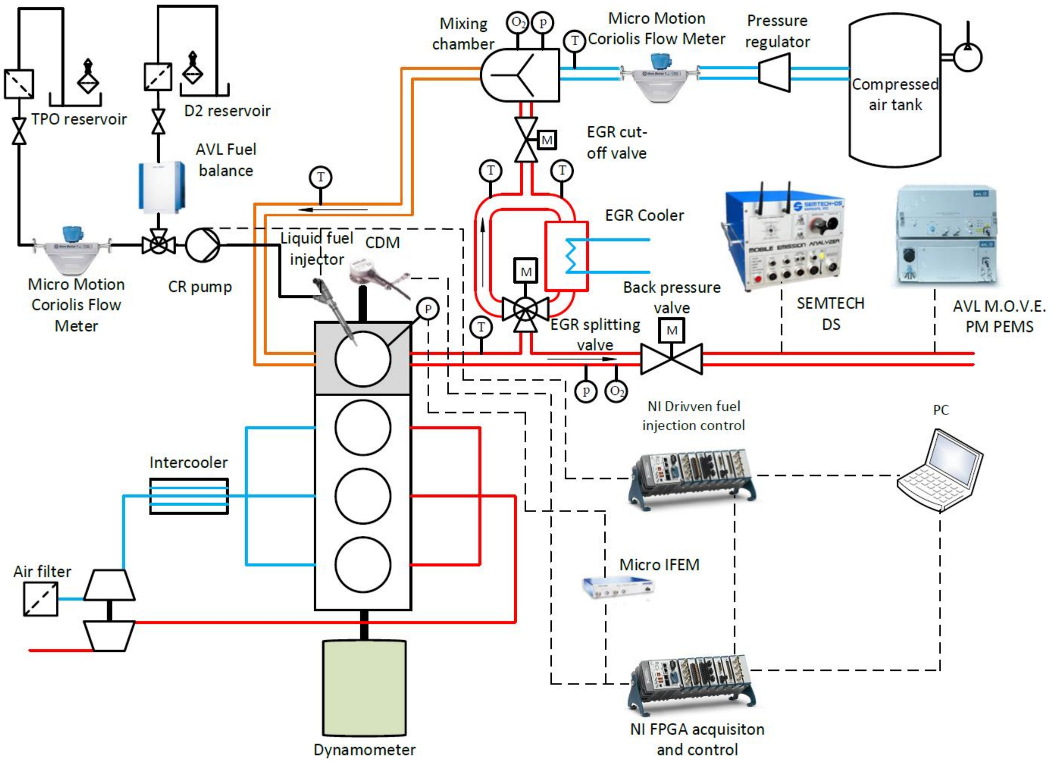


Figure 1. Scheme of the experimental system

Data acquisition and injection control for the indicated cylinder was based on reconfigurable input/output embedded system (National Instruments cRIO 9039). In the LabView based software running on PC, user set injection parameters, which were sent to the injection control system (National Instruments, Drivven system). It controlled energizing characteristics of the injectors as well as operation of common rail high pressure pump. Exhaust gaseous emissions were measured with portable exhaust gas analyser (Sensors Semtech-DS), which incorporates flame ionization detector for detection of THC, non-dispersive infrared analyser for detection of CO and chemiluminescent detector for detection NO_x emissions. The exhaust

PM emissions were measured with a portable exhaust gas analyser AVL M. O. V. E. The PM using AVL MSS method. Due to high share of sulphur in the TPO which can potentially damage measuring equipment, in the TPO operating mode, soot was measured instead of PM. Soot emissions were measured with the light scattering method (AVL Dismoke 4000).

Test procedure

The experiments were performed at 2,000 rpm while varying start of energizing (SOE) and energizing durations as well as the EGR rates for the separated cylinder. The analysed operating case was selected on the basis of preliminary screening, where the goal was to achieve LTC with both fuels at all loads.

In the first operating mode only one separate injection of high reactivity fuel (D2) was used, tab. 2, to reduce the experimental space. The SOE for main injection (MI) was kept the same as in the original equipment manufacturer (OEM) mode while energizing duration for MI was selected in a way to achieve 4 bar IMEP. The IM pressure was increased compared to OEM control strategy to 2.25 bar to support achieving higher level of charge homogenization. This operating mode was further benchmarked with IM pressure, p_{IM}, of the OEM control strategy being 1.19 bar. In the second operating mode injections strategy was similar to first operating mode while ED and rail pressure (RP) were increased to achieve 8 bar IMEP. In the first two operating modes EGR was cooled due to high reactivity of the D2 fuel.

Table 2. Operating modes with corresponding engine operating parameters and combustion strategies

	PI1		PI2		MI		RP	O_2
Operating mode	SOE [°CA]	ED [°CA]	SOE [°CA]	ED [°CA]	SOE [°CA]	ED [°CA]	bar	%
D2, 4 bar IMEP, 1 inj.	–	–	–	–	−13	3.6	700	10.2-20.5
D2, 8 bar IMEP, 1 inj.	–	–	–	–	−13	4.2	1,000	10.6-17.8
TPO, 3 bar IMEP, 3 inj.	−45	1.2	−32	1.26	−17	2.58	700	15.7-20.3

In the case of the low reactivity fuel (TPO), which was utilized in the third operating mode, two PI were used. Two additional fuel injection pulses were added to allow for achieving higher level of charge homogenisation. The IMEP was reduced to 3 bar, since at higher loads, operation was unstable. The variety of investigated cases is presented in tab. 2, where in each operating mode, multiple EGR rate variation were done resulting in O_2 concentration variation in the IM. Due to low reactivity of the TPO, EGR was only partially cooled and increase in charge temperature can be noticed with increase of EGR rate.

In-cylinder pressure measurements were performed over 100 consecutive cycles in every operating point and afterwards averaged in order to eliminate cycle-to-cycle variations due to signal noise, whereas Chauvenet's criterion [25] was taken into account to eliminate the points with significant deviation. Furthermore, to acquire representative average pressure trace without high pressure oscillations, averaged pressure trace was filtered by applying low-pass FIR filter [26]. Filtered pressure trace was used as input data for calculation of thermodynamic parameters. Emissions and other engine operating parameters were measured continuously at sampling frequency of 1 Hz.

Results and discussion

In the following section, thermodynamic and emission results for the operating modes, listed in tab. 2 will be presented and analyzed in order to explain influences of various combustion concepts and fuel properties on engine performance, combustion phenomena and exhaust emissions. In each operating mode from tab. 2 the effect of varying EGR rate will be presented.

The D2, 4 bar IMEP, 1 injection

As stated in [27], it is relatively demanding to realize very high premixed rates of the reactive D2 while preserving low PM emissions. To achieve very high charge premixed rates, p_{IM} was increased to 2.25 bar, as this allows for achieving higher level of charge homogenization due to enhanced spray atomization. Furthermore, PI was omitted to prevent auto-ignition of the fuel injected during PI before the end of injection of the fuel injected in the MI. Combination of presented measures allows for achieving LTC with potential of improving NO_x/PM trade-off at sufficiently high EGR rates. It is discernible from fig. 2(a) that increasing EGR first advanced combustion and thus resulted in increased maximum in-cylinder pressures with increasing EGR rate up to the oxygen concentration of 16.6%, whereas an opposite trend is observed for higher EGR rates. This can be explained by fig. 2(b), which indicates that ignition delay is shortened and premixed peak becomes more pronounced when reducing oxygen concentration from 19.1 to 16.6%. With further reduction of oxygen concentration to 12.9% ignition delay is prolonged, whereas premixed peak further grows, still indicating a conventional diesel like rate of heat release (ROHR) shape. Further decrease of oxygen concentration is characterized by prolonged ignition delay period and omission of premixed peaks, which in combination with high in-cylinder pressures indicates higher level of charge homogenisation. It is important to observe that premixed ROHR peak also decreased with the prolonged ignition delay period at lower oxygen concentrations, which indicates lower reaction rate and thus LTC combustion.

Results measured at p_{IM} of 2.25 bar were further benchmarked against one operating point with lower p_{IM} (1.19 bar), which was set to similar value of p_{IM} as in the OEM control strategy at the analysed IMEP. In this operating point oxygen concentration was 16.7%, which is also similar to the OEM control strategy. It is discernible from figs. 2(c) and 2(d) that lower p_{IM} expectedly resulted in lower in-cylinder pressure. Despite that, decreased p_{IM} that adversely affects spray breakup and spray atomisation leads in combination with slightly lower in-cylinder temperature to longer ignition delay period compared to the operating points at higher value of p_{IM}. As a consequence of relatively high oxygen concentration and less intense mixture homogenisation, the shape of ROHR at p_{IM} of 1.19 bar differs significantly to the one at p_{IM} of 2.25 bar by featuring a pronounced premixed ROHR peak characteristic for conventional CI operation.

Exhaust emissions of conventional CI engines have been traditionally limited by a NO_x/PM trade-off, where within a certain technology level one emission type can be decreased at the expense of increasing the other one. Decreasing trend of NO_x with increasing EGR rate is expected and is noticeable in all cases, as increased EGR rates lower the overall oxygen concentration thereby reducing reaction rates and reducing local temperatures. When comparing NO_x emissions at different p_{IM} and the same oxygen concentration, it can be concluded that lower p_{IM} results in more intense ROHR in the premixed phase, which consequently leads to higher local temperatures yielding higher NO_x emissions. It is also expected that PM emissions are increasing with increasing EGR rates at lower levels of EGR rates, since lower oxygen concentration promote PM formation and relatively low in-cylinder temperatures in combination with lower oxygen concentration prevent their subsequent oxidation. An important aspect of introducing LTC arises from the fact that higher level of charge ho-

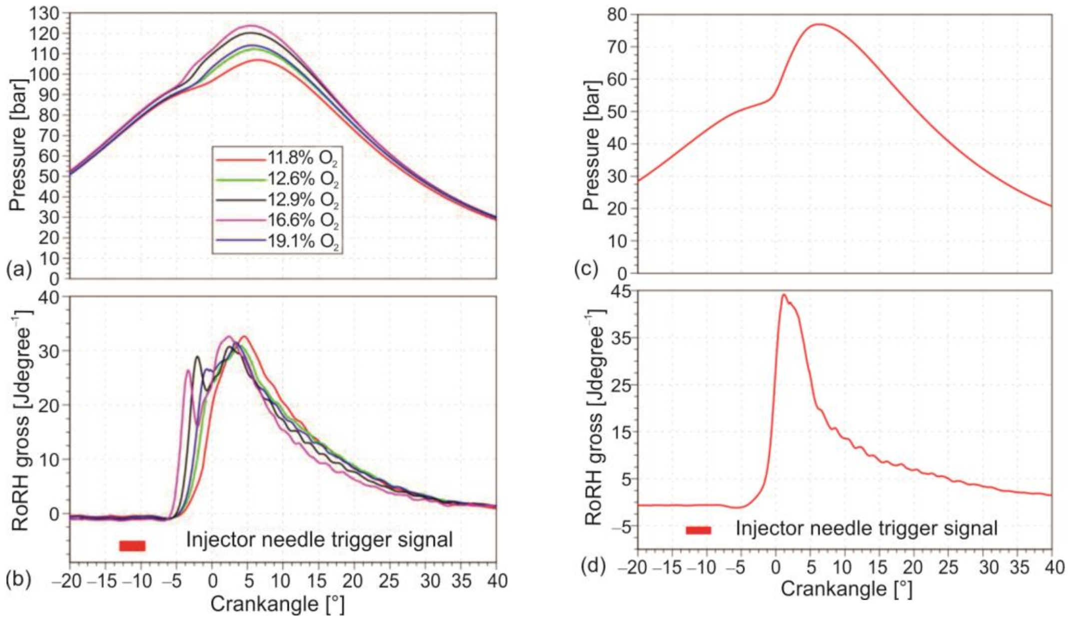


Figure 2. Pressure traces (a), (c) and ROHR (b), (d) of the D2 for the first operating mode, listed in tab. 2 with higher – 2.25 bar (a), (b) and lower – 1.19 bar (c) and p_{IM} (d)
(*for color image see journal web site*)

mogenisation allows for simultaneous reduction of NO_x and PM emissions, which can – due to the NO_x kinetics – be achieved only at high ERG rates. It is thus crucial to achieve sufficiently high level of charge homogenization to hinder PM formation. Figure 3 demonstrates that a sharp drop in PM emissions was achieved at oxygen concentration below 12%, thus confirming simultaneous reduction of NO_x and PM emissions and reaching LTC.

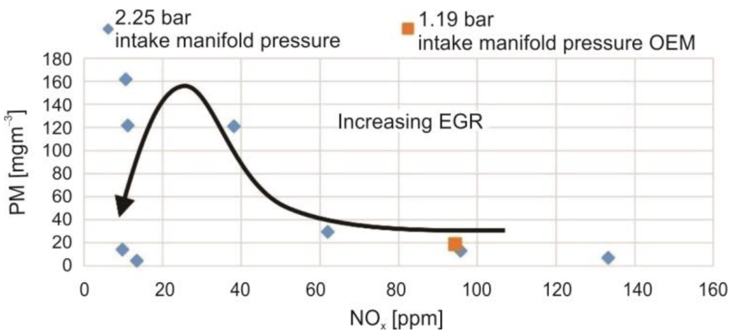
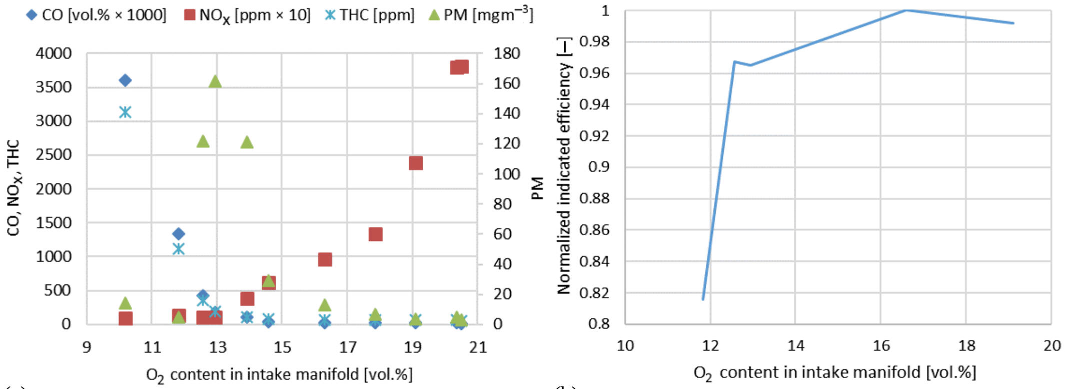


Figure 3. The NO_x/PM trade-off of the D2 for the first operating mode, listed in tab. 2

The CO emissions are normally relatively low for diffusion combustion in CI engines at high air-fuel ratios, which is discernible also in our case as presented in fig. 4(a). At lower EGR rates, CO emissions are increasing only insignificantly with increasing EGR rates as combination of sufficiently high oxygen concentration and local temperatures allows for high conversion efficiency of CO to CO_2. Unlike, pronounced increase in CO emissions is observed below oxygen concentrations of 13% due to lower overall air-fuel ratios (lower oxygen content), whereas in addition, at high EGR rates local temperatures are decreased reducing conversion efficiency of CO to CO_2. At p_{IM} of the OEM control strategy, CO emissions are slightly higher because lower degree of charge homogenization also results in increased time needed for mixing fuel with oxygen, which consequently yields reduced carbon oxidation. The THC emissions follow similar trend as CO emissions, with the main difference of CO emissions featuring more pronounced increase with increased EGR ratio, fig. 4(a). This trend can be reasoned by lower oxygen content and lower local temperatures that reduce conversion rate of CO, *e.g.* [28]. Again, sharp increase in THC emissions can be noticed at approximately 13% oxygen content, fig. 4(a).

Normalized indicated efficiency, fig. 4(b), features a mixed trend characterized by a very moderate increase followed by first a moderate and then a significant decrease with increasing EGR rate. Initial increase in normalized indicated efficiency, up to approx. 16% oxygen concentration, is mainly due to centring ROHR around the TDC in a way to increase the area in the *p-V* diagram in this period. Afterwards, normalized indicated efficiency decreases only moderately with increased EGR rates up to oxygen concentration of 12.6%, which is mainly related to slightly delayed combustion due to lower reaction rates. Higher EGR rates are characterized by a significant drop in normalized indicated efficiency being related to a combined effect of delayed combustion and incomplete combustion indicated by high CO and THC emissions. This is confirmed also through lower in-cylinder pressures, fig. 2(a).

These results indicate that significant simultaneous reduction of NO_x and PM emissions can be realized at the expense of reduced normalized indicated efficiency of the engine, which calls for very efficient engine control to efficiently balance between reduction of NO_x and PM emissions while preserving as high engine efficiency as possible.



(a) (b)

Figure 4. Exhaust gaseous emissions with PM (a) and normalized indicated efficiency of the D2 for the first operating mode (b), listed in tab. 2

The D2, 8 bar IMEP, 1 injection

High load operating mode was performed at 8 bar IMEP by using a 1 fuel injection, while p_{IM} was again 2.25 bar. It is discernible from fig. 5b that decrease of the premixed peak with decreasing oxygen concentration is similar to the 1 injection and 4 bar IMEP operating mode. It is discernible from fig. 5 that ignition delay is prolonged in all cases with the reduction of oxygen concentration. At higher oxygen concentrations (17.7 and 16.0%), premixed peaks can still be observed whereas further decrease of oxygen concentration is characterized by omission of premixed peaks, which indicates higher level of charge homogenisation.

Decreasing trend of NO_x with increasing EGR rate is also noticeable at this higher IMEP operating mode, fig. 6, as EGR lowers the overall oxygen concentration and lowers reaction rates, which results in decreased local temperatures. Likewise, in the lower IMEP operating mode, PM emissions are increasing with increasing EGR rates at lower EGR rates, due to combination of lower oxygen concentration and lower in-cylinder temperatures. Sharp drop in PM emissions was again achieved at higher EGR rates, however transition to low PM and NO_x operation was realized at lower oxygen concentration (11%) compared to the lower IMEP operating mode.

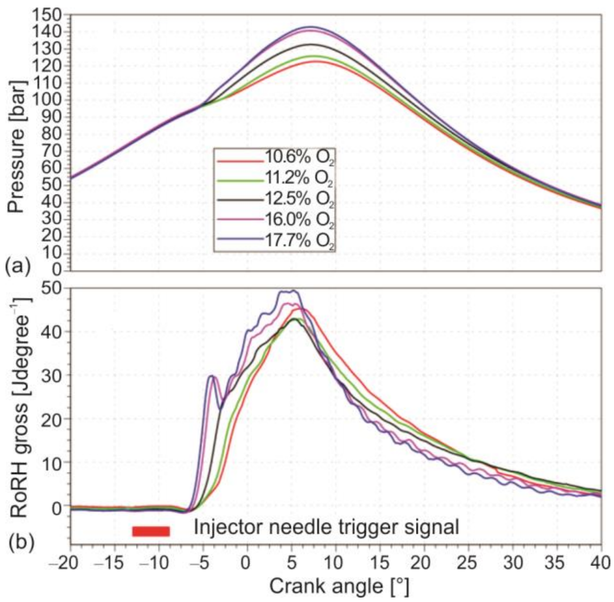


Figure 5. Pressure traces (a) and ROHR of the D2 for the second operating mode (b), listed in tab. 2
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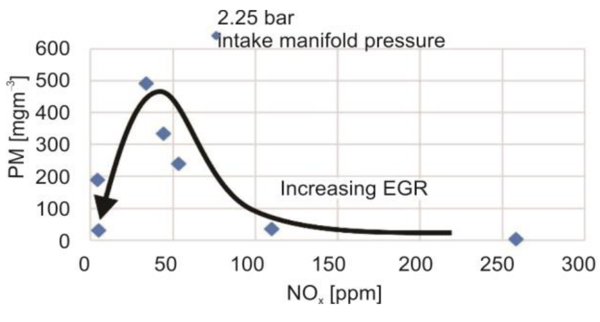
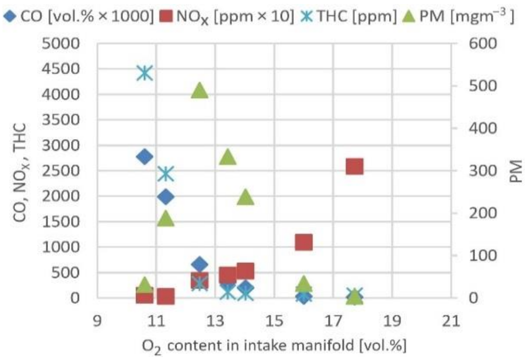


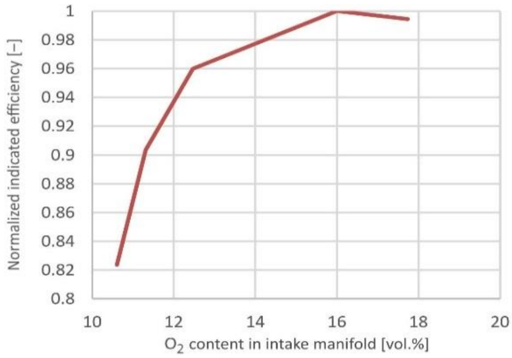
Figure 6. The NO_x/PM trade-off of the D2 for the second operating mode, listed in tab. 2

Expectedly, CO emissions, presented in fig. 7(a), are again increasing with EGR ratio, while transition to low PM operation was achieved at higher CO emission levels compared to the lower IMEP operating mode. This can mainly be associated with the fact that increased fuel concentration at lean conditions needs to be counteracted with higher EGR rate to allow for sufficient level of change homogenisation, which reduces overall air-fuel ratio and thus increases CO emissions. The THC emissions again follow similar trend as CO emissions, with initial insignificant and subsequently more pronounced increase with increased EGR ratio, fig. 7(a). Similar to lower load, sharp increase in CO and THC emissions can be noticed at around 13% oxygen content, fig. 7(a).

Normalized indicated efficiency again slightly increases up to approximately 16% oxygen concentration, fig. 7(b), since ignition delay is not yet notably affected by the reduced O_2 content, the effect of increased in-cylinder temperature due to higher EGR rate prevails over the change in combustion profile. Afterwards, normalized indicated efficiency decreases only moderately with increased EGR rates up to oxygen concentration of 12.6%, which is mainly related to slightly delayed combustion due to lower reaction rates. Higher EGR rates are again characterized by a significant drop in normalized indicated efficiency being related to a combined effect of delayed combustion and incomplete combustion indicated by high CO and THC emissions, which is confirmed also through lower in-cylinder pressures, fig. 5(a). Since transition to low NO_x/PM was demonstrated at 11% oxygen content, where CO and THC emissions, fig. 7(a), are relatively high and indicated engine efficiency is relatively low, it can be concluded that LTC operation with single fuel injections is more meaningful at lower loads.



(a)



(b)

Figure 7. Exhaust gaseous emissions with PM (a) and normalized indicated efficiency of the D2 for the second operating mode (b), listed in tab. 2

The TPO, 3 bar IMEP, 3 injections

In this section, TPO was used as a representative of low reactivity fuel. Since it was already demonstrated [29] that at least one PI is required for successful utilization of the TPO fuel, in this case two PI were introduced for the TPO after initial scanning of the operational space to allow for achieving higher level of mixture homogenisation and reduction of the fuel amount injected during the MI. Due to its lower reactivity, fuel injection parameters in the case of the TPO were further advanced compared to the D2 cases to achieve higher degree of charge homogenisation and allows to demonstrate LTC operation. Engine operating parameters are presented in tab. 2.

Expectedly, TPO features long ignition delays for low EGR rates, which is mainly driven by its low reactivity and low in-cylinder temperatures [20]. After the ignition, TPO burns much more intensively compared to the D2, fig. 8(b), which is consistent with previous analyses [19]. This is also in-line with the fundamental studies presented in [30], where it was shown that for lower initial temperatures that are associated with longer ignition delay periods more fuel burns in the auto-ignition regime, whereas higher initial temperatures favour shorter ignition delay periods and hence flame propagating as well as flame enclosing combustion regimes.

Thus unlike the reports in [31], where it was shown that a diesel like combustion can be attained in modern turbocharged and intercooled engine by introducing two pilot injections and appropriate amount of EGR, ROHR of the TPO in fig. 8 significantly differ from the diesel-like combustion. This can be reasoned by the fact that in the present study fuel injected during the PI did not ignite prior to the SOE of the MI to achieve a higher level of charge homogenisation, whereas in [31] ignition of the fuel injected during PI was one of the main measures to achieve a diesel like combustion.

This finding clearly indicates that application of a lower reactivity fuel and higher level of mixture homogenisation while applying a slightly modified diesel injection strategy can

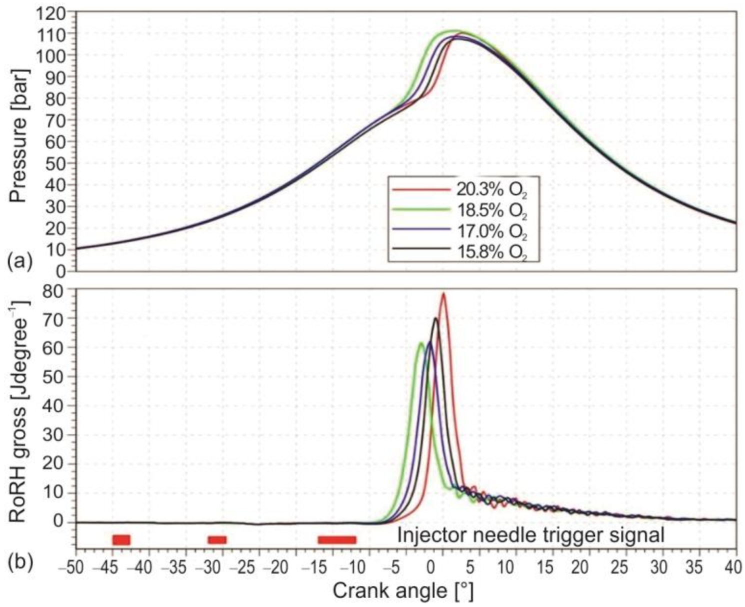


Figure 8. Pressure traces (a) and ROHR of the TPO for the third operating mode (b), listed in tab. 2 (*for color image see journal web site*)

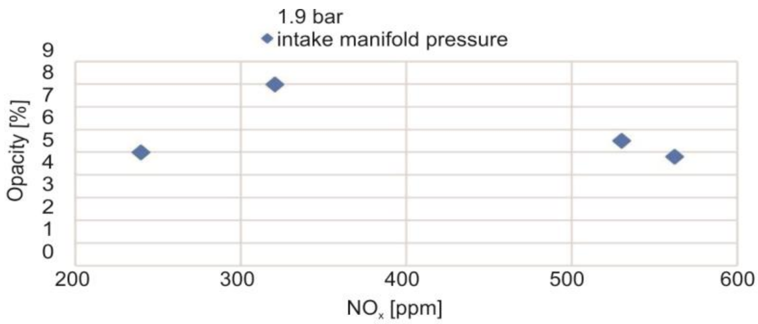


Figure 9. The NO_x/soot trade-off of the TPO for the third operating case, listed in tab. 2

lead to intense ROHR, which was also observed by other groups [13]. This can pose mechanical challenges on the engine and can also have adverse effects on NO_x emissions as can be seen in fig. 9.

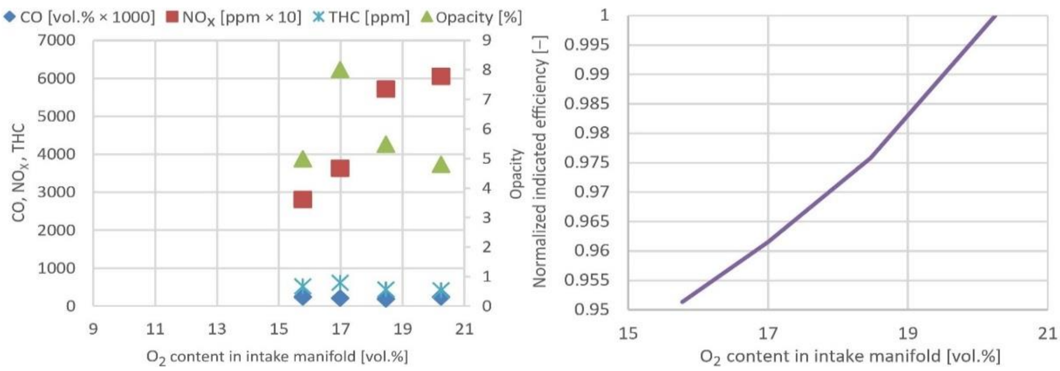
Unlike for the D2, the TPO is characterized by advanced ROHR for increased EGR rate, fig. 8(b), as for the less reactive TPO impact of higher in-cylinder temperature prevails over the impact of lower oxygen concentration at low EGR rates. This effect is then reversed towards high EGR rates as increase in in-cylinder temperature is not very pronounced and oxygen concentration is further lowered being a prevailing effect. In addition, it needs to be noted that TPO was operated only at relatively high oxygen concentrations (higher to those characterized by simultaneous decrease of PM and NO_x in D2 operation) since operation at higher EGR rates became unstable with low reactivity fuel.

In general, TPO also features expected trend of reduced NO_x emissions with increasing EGR rate. However, it can be clearly seen from fig. 9 that TPO is characterized by higher NO_x emission levels at similar EGR rates compared to the D2 combustion, which can mainly be associated with very intense ROHR and thus high local in-cylinder temperatures. Although, some references, *e. g.* [13], report reduced NO_x emissions despite significantly more intense ROHR of low reactivity fuels, similar trend of increasing NO_x emissions with more intense ROHR was already observed in one of the previous studies [19].

Due to higher NO_x and soot emissions in similar operating conditions TPO features worse NO_x/soot trade-off compared to both D2 combustion modes, fig. 3. This result thus clearly communicates that combination of higher level of homogenisation and lower reactivity fuel does not necessarily lead to improved NO_x/soot trade-off and that fuel properties play an important role in its optimisation. Soot emissions are normally higher for the TPO, since the TPO is more prone to soot formation than D2 as elaborated in [21].

Figure 10(a) shows that CO emissions of the TPO are significantly lower compared to D2 in all analysed operating points. Overall lower CO levels can be attributed to more homogeneous mixture due to delayed ignition of both PI and higher in-cylinder temperatures due to higher ROHR, while CO emissions are still increasing with increased EGR rate, similar to D2 operating modes, which can be attributed to lower overall air-fuel ratios (lower oxygen content). Similar trend is observed also for THC emissions, fig. 10(a).

Figure 10(b) shows that normalized indicated efficiency of the engine while utilizing the TPO increased with increasing EGR rate. However, it needs to be recalled that TPO was operated only at relatively high oxygen concentrations, since operation at higher EGR rates became unstable with low reactivity fuel.



(a) (b)

Figure 10. Exhaust gaseous emissions with opacity (a) and normalized indicated efficiency of the TPO for the third operating mode (b), listed in tab. 2

Conclusions

The paper presents the analysis of combustion properties and engine-out emissions in various LTC operating regimes with the D2 and the TPO in a modern CI engine. An LTC regime was established by adapting injection strategy including number of injections and tailoring EGR rates thus applying changes in the engine control that can be realized on a conventional CI engine. The TPO was selected as an innovative representative of lower reactivity fuels featuring diesel-like physical properties and lower cetane number, compared to D2. The LTC operation was successfully demonstrated with the TPO fuel. The innovative contribution of the presented study can be recognised in investigations of potentials to improve NO_x/soot trade-off with increasing p_{IM} and minimized changes in engine control strategy.

Combustion parameters and engine-out emissions analysis revealed the following.

- It is possible to achieve transition to low NO_x/soot operation at wide range of engine loads at high EGR rates.
- Low NO_x/PM operation in LTC operating mode featuring high level of charge homogenisation is always associated with increased CO and THC emissions and thus lower engine efficiency.
- For D2 fuel improved NO_x/PM trade-off can be realized for higher IM pressures.
- Low NO_x/PM operation of the D2 fuel at high loads can be realized at reduced oxygen concentration and is thus characterized by higher CO and THC emissions and significant drop in indicated efficiency.
- For D2 and lower engine loads, it is possible to achieve higher level of charge homogenization by using only 1 injection. This LTC operating strategy is characterized by reduced CO and THC emissions at similar oxygen concertation and NO_x/PM trade-off.
- Lower reactivity of the fuel, as of the TPO, is by itself not sufficient to improve NO_x/soot trade-off compared to the D2 as entire spectra of fuel properties play an important role in improving NO_x/soot trade-off.

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Acronyms

CA – crank angle
CI – compression ignition
D2 – commercial diesel fuel
EGR – exhaust gas recirculation
HCCI – homogeneous charge compression ignition
IM – intake manifold
IMEP – indicated mean effective pressure
LHV – lower heating value
LTC – low temperature combustion
MI – main injection
OEM – original equipment manufacturer
PCCI – premixed-charge compression ignition
PI – pilot injection
PM – particulate matter
PPC – partially premixed combustion
ROHR– rate of heat release
RP – rail pressure
SOE – start-of-energizing
THC – total hydrocarbons
TPO – tire pyrolysis oil

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