Evaluating OMEx combustion towards stoichiometric conditions in a compression ignition engine

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Abstract

Low energy density fuels combined with low temperature combustion modes have demonstrated a great contribution to engine-out NOx and soot reduction. Additionally, synthetic fuels have become an important way of reaching carbon neutral utilization of hydrocarbon-based fuels and internal combustion engines. Specifically, poly-oxymethylene dimethyl ethers (OMEx) have demonstrated great advantages in combination with conventional fuels with higher energy content to compensate that aspect to reduce NOx emissions below the EU VI homologation normative while maintaining ultra-low soot emissions with a great benefit in CO_2 emissions in a well-to-wheel basis. Nonetheless, the properties of this fuel in single-fuel combustion strategies are not thoroughly investigated in the literature. The objective of this work is to investigate the capabilities of OMEx fuel under conventional combustion modes compared to those of conventional diesel combustion. To do this, an experimental characterization under stoichiometric combustion has been carried out to evaluate the impact on engine hardware demand and total emissions. Additionally, a brief exploration under leaner conditions is performed. The results obtained from this work point out that, even under ultra-high EGR rates to reach high fuel-to-air ratios, OMEx fuel can emit ultra-low soot and NOx emissions with more than 90% reduction compared to diesel on engine out emissions. Under stoichiometric conditions, a significant increase appears on CO, UHC due to excessive usage of EGR and equivalent fuel consumption is penalized from 15% to 40% depending on the operating condition, but under slightly leaner conditions, a region where equivalent fuel consumption is improved with respect to CDC appears, and the four main pollutants investigated are almost EU VI compliant, exposing a very high potential for this fuel.

Keywords

OMEx; synthetic fuels; engine-out emissions; EURO VI;

1. Introduction

The current demanding regulations and the even more restrictive normative that will be imposed in the incoming years have put the internal combustion engines (ICE) in a critical situation [1]. For a vehicle using an ICE as its propulsive plant, they must ensure ultra-low emission levels of species that are harmful to the human health [2], like nitrogen oxides (NOx), carbon monoxide (CO), soot and unburned hydrocarbons (UHC), and additionally contribute to reducing the environmental impact by reducing their emissions of greenhouse effect gases [3], like the carbon dioxide (CO_2) and water vapor (H_2O).

The first type of pollutants is consequence of an incomplete combustion process of the fuel associated to imperfections during mixing and combustion process, which can be mitigated by improving the injection strategies and combustion modes, while the second group of emissions results from the complete oxidation process of the fuel and can only be lowered by reducing the total amount of fuel used if the same chemical composition is maintained [4]. As a result, the final objective is to produce and engine that can maintain very high combustion efficiency and thermal efficiency when obtaining energy from the burned fuel.

The current solution adopted by the manufacturers is to increase the thermal efficiency of the engine to reduce the fuel consumption while maintaining reasonable levels of emissions and then reduce the total emissions to values below the regulation limits by means of an aftertreatment system (ATS) [5]. The ATS has to be able to deal with different species, each one with different requirements for their reduction. Normally, an ATS for conventional diesel engines includes an oxidizer catalyst (DOC) for reducing the CO and UHC emissions that originate from incomplete combustion reactions, a selective catalytic reducer (SCR) for reducing the NOx emissions, and a particulate filter (DPF) for treating the soot emissions [5]. As a result of this strategy based on ATS for emissions reduction, with more restrictive emission limits the ATS becomes more complex and expensive. For the current NOx emissions targets, some manufacturers have need to move to a dual-SCR strategy and even propose to move to a three-SCR architecture on the ATS [6-8]. This tendency only increases the manufacturing and operating costs of the ATS, especially with the SCR that consumes urea as a reactive agent for NOx reduction [9, 10].

The scientific community has put a great amount of effort in devising a way to reduce emissions from its source, the combustion process. For this purpose, several low temperature combustion (LTC) modes have been conceptualized and put into practice to evaluate their respective benefits and drawbacks compared to conventional diesel combustion (CDC) [11, 12]. In general, the LTC modes have brought great benefits in terms of reduced NOx emissions and improved thermal efficiency. Further development of the LTC strategies can allow to reach engine-out NOx emissions below the current normative levels and bring the possibility of removing the SCR from the ATS, reducing considerably the associated costs [10].

To reach such low levels of NOx emissions, the LTC strategies are combined with different strategies like ultra-high EGR (Exhaust Gas Recirculation) rates [13, 14] or alternative fuels [15, 16] with lower energy density to reduce the in-cylinder peak temperatures, one of the main drivers in the NOx production mechanism. Complementary to this, the use of alternative fuels with a very high oxygen content and no carbon-carbon bonds provides the possibility of eradicating the soot emissions [17, 18]. Specifically, the poly-oxymethylene dimethyl ether (OMEx) has demonstrated to provide zero-soot results when applied in dual-fuel systems with very high EGR rates and still be able to ensure a good combustion rate with its higher reactivity compared to diesel and reduced NOx emissions as a combined consequence of the high EGR rates and reduced lower heating values (LHV) [19, 20]. As a drawback, the use of such strategies produces a decrement on the reactivity of the fuel mixture and lower local temperatures that can end up in high CO and UHC emissions that do not have enough energy and time to complete their oxidation [21, 22]. Nonetheless, if the penalty in CO and UHC is not excessive, it can be manageable by means of alterations in the ATS [23].

As the literature shows, the use of oxygenated synthetic fuels like OMEx brings significant benefits for reducing the complexity and costs of the ATS as it allows to reduce the relevance of the SCR and the DPF or even remove them if the emissions are lower than the normative limits [19, 21]. On the other hand, the potential increase of CO and UHC could be managed by means of different strategies and devices depending on the exhaust gases composition. In this sense, two main streams are differentiated: stoichiometric combustion and diluted combustion. The first case is a solution normally used in spark ignition engines that work under stoichiometric conditions consuming most of the oxygen during the combustion process [24], which normally results in balanced emissions between NOx, CO and UHC. In this case, a three-way catalyst (TWC) is the preferred option to reduce the three contaminants simultaneously [25]. The second option is typical of diesel engines and it is used together with high air boosting conditions to improve the fuel consumption, but this can lead to very high emissions of NOx and unbalanced emissions of CO and UHC depending on the operating condition.

In this case, the NOx emissions are treated separately and CO and UHC are treated with a Diesel Oxidizer Catalyst (DOC) [26].

In previous applications of OMEx in dual-fuel systems or in fuel blends, the fuel consumption was not highly penalized as there was a second fuel with higher energy density to compensate for the lower LHV of OMEx [20, 21]. However, when considering an application using OMEx as single fuel this cannot be solved and the total fuel consumption is significantly increased, meaning that the total CO_2 emissions are also proportionally increased. In a tank-to-wheel (TtW) analysis, there is no benefit in this application, and other alternatives like vehicle electrification [27-29] or fuel decarbonization [30] would be necessary. Nonetheless, if the OMEx production process is considered and the CO_2 emissions are analysed on a well-to-tank (WtT) basis, there is huge difference as OMEx is synthesized using CO_2 coming from the atmosphere with techniques like direct air capture (DAC) [31, 32]. If this factor is included, synthetic fuels formed through clean production paths can highly contribute to achieve the CO_2 reduction targets imposed for the next future. According to production data provided by the fuel supplier, the Well-to-Wheel (WtW) CO_2 emissions can be reduced between 80% to 90% with respect to commercial diesel or gasoline depending on the energy pool and production path.

Considering all the benefits and drawbacks of using OMEx as single fuel in an ICE, this work aims to evaluate the potential of OMEx and its suitability with conventional ATS systems in terms of emissions. For that, pure OMEx combustion is evaluated in a single-cylinder compression ignition engine under stoichiometric conditions with the objective of evaluating the suitability of using a cheap and easy-to-implement TWC as the sole ATS for an OMEx-fuelled ICE.

2. Materials and Methodology

2.1. Engine characteristics

The experimental evaluation has been carried out on a D5K engine from Volvo, a production four-cylinder engine dedicated to medium-duty transportation vehicles, and the main features of the stock engine can be found in Table 1. For this study, the stock engine has been modified into a single-cylinder engine by disabling three of the four cylinders and removing the turbocharging and injection system to be replaced by external devices that provide greater flexibility when defining the boundary conditions that are desired for the operating condition.

Table 1. Stock engine characteristics.

Characteristic	Value
Engine Type	4 stroke, Direct Injection diesel engine
Number of cylinders [-]	4 in-line
Number of valves [-]	4 per cylinder
Total displaced volume [cm^3]	5100
Stroke [mm]	135
Bore [mm]	110
Compression ratio [-]	17.5:1
Rated Power [kW]	177 kW @ 2200 rpm
Rated Torque [N·m]	900 N·m @ 1200-1600 rpm

2.2. Test cell description

The engine has been mounted on an AVL-APA 404 asynchronous dynamometer that governs the engine speed and is commanded from its own software platform AVL PUMA Open. As the stock air management system has been removed, the boosting is delivered by an externally driven screw compressor that can boost up to 3.7 bar. An air dryer is mounted after the compressor to remove the ambient humidity and a set heat exchanger and heating resistance are mounted in the circuit to control independently the intake temperature. To ensure the actual mass flow of fresh air, a volumetric air flow meter G-100 RVG from Elster is mounted in the intake circuit. Two settling chambers are used to remove undesired pressure waves coming from actuators and other devices mounted at the intake and outlet circuits. To control the back pressure at the exhaust manifold, an actuated valve is placed between the EGR circuit and the exhaust settling chamber. In the EGR circuit there is another set of heat exchanger plus flow heater mounted to control the EGR temperature and an EGR valve to better control the EGR flows and be able to emulate realistic operating conditions. External and independent coolant circuits were employed for the EGR and oil conditioning for greater operability of the test cell. Nonetheless, to avoid unrealistically cooling engine conditions, the oil and coolant temperature were maintained at temperature values representative of the stock engine. All these devices are controlled from the AVL PUMA platform, where different temperatures and pressures registered at relevant locations of the test cell are registered too and serve as inputs for the controllers of the auxiliary systems.

Regarding the injection system, a common rail injection system is used to deliver the desired injection pressure to the in-cylinder injector. The fuel pump used for this project was an external Bosch CP3 fuel pump that allowed to reach rail pressures up to 2500 bar. The fuel temperature was conditioned on a AVL 753C and the fuel mass flow was measured with a AVL 735S [33]. The injection settings like rail pressure, injection timing and energizing time were set using a driven engine controller to have full access to the injection parameters through the ECU (Engine Control Unit).

For the emissions characterization and EGR rate measurements, a five-gas analyser HORIBA MEXA-ONE-D1-EGR was used to account for the NOx, CO, UHC, CO_2 and O_2 [34]. A heated line is included to avoid formation of condensates that can damage the equipment or affect the measurement accuracy. Additionally, an AVL 415S smoke meter was used to measure the smoke emissions and convert them into soot mass emissions in accordance to the methodology provided by the manufacturer [35].

Finally, the in-cylinder pressure was obtained by means of a piezoelectric transducer. This signal is processed online by INDICOM to provide with instantaneous reports of indicated magnitudes related to the energy liberation that takes place inside the combustion chamber, and this information is used for optimizing the injection settings and have a better control over the combustion process [36]. INDICOM provides this information with an increment of 0.2 CAD (crank angle degree) using as reference the crank position provided by the AVL 364 encoder.

The layout of the test cell with all the mentioned devices and relevant locations where the temperature and pressure are registered are shown in Figure 1, and a summary of the models and accuracy of the different measuring devices is included in Table 2.

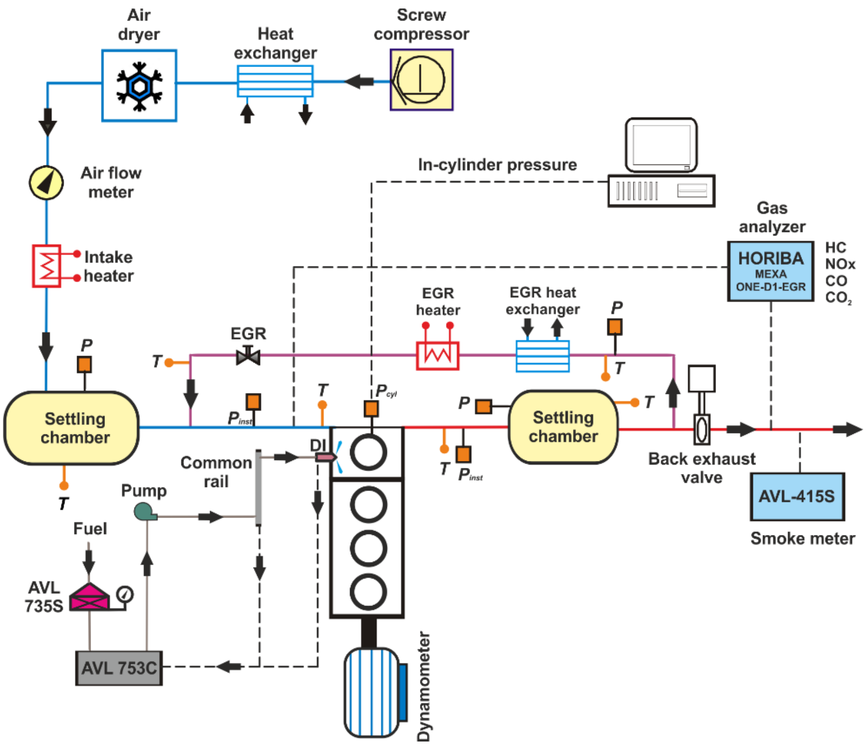


Figure 1. Test cell layout.

Table 2. Accuracy of the measuring devices used in the test cell.

Variable Measured	Device	Manufacturer / Model	Accuracy
In-cylinder pressure	Piezoelectric transducer	Kistler / 6125C	± 1.25 bar
Pressure	Piezoresistive transducer	Kistler / 4045A10	± 25 mbar
Temperature	Thermocouple	TC direct / K type	± 2.5 ºC
Crank angle, engine speed	Encoder	AVL / 364	± 0.02 CAD
NOx, CO, UHC, O_2, CO_2, EGR	Gas Analyzer	HORIBA/MEXA-ONE-D1-EGR	± 4%
Smoke	Smoke meter	AVL / 415S	± 0.025 FSN
Fuel mass flow	Fuel flow meter	AVL / 735S	± 0.12%
Air mass flow	Air flow meter	Elster / RVG G100	± 0.1%

2.3. Injector and fuel properties

Low energy density fuels suffer from increased fuel mass consumption as it requires higher mass to have the same energy input. This also means that the injection durations must be significantly increased compared to conventional fuels when using the same injector. Anticipating this effect when using OMEx, it was decided to use an injector with higher flow rate capacity to not reach excessively long injection durations that cannot be managed by the ECU limitations, the properties of which can be found in Table 3. This injector was used during all the experimental evaluation, including the reference performance with diesel and the calibration using OMEx. For a reference on the differences between both fuels in terms of relevant physical properties and combustion properties, Table 4 includes a summary of the most relevant properties. Note that the OMEx used in this study is a mixture of different poly-oxymethylene dimethyl ethers mainly ranging between OME_3 and OME_5 (OME mix 3-5).

Table 3. Injector properties.

Injector property	Value
Actuation Type [-]	Solenoid
Steady flow rate @ 100 bar [cm^3/min]	2200
Included spray angle [°]	140
Number of holes [-]	6
Hole diameter [μm]	244
Maximum injection pressure [bar]	2500

Table 4. Summary of fuel characteristics.

	EN 590 diesel	OMEx
Lower heating value [MJ/kg]	42.44	19.21
Density [kg/m^3] (15 °C)	842	1067
Viscosity [mm^2/s] (40 °C)	2.93	1.18

Cetane number [-]	55.7	72.9
Carbon content [% m/m]	86.2	43.6
Hydrogen content [% m/m]	13.8	8.82
Oxygen content [% m/m]	0	47.1
Vapor pressure [hPa] (T=40 °C)	1-10	32
Stoichiometric Air-to-Fuel ratio [-]	14.5:1	5.85:1

2.4. Testing methodology

Eight operating points from the engine map have been chosen as representative of the complete engine operation based on previous vehicle simulations under different driving scenarios [21]: 10% and 25% engine load at 1200 rpm, 20% load at 1500 rpm and 10%, 25%, 50%, 75% and 100% engine load at 1800 rpm. These eight operating points, represented in Figure 2, have been evaluated first with diesel using the injection settings from the original engine calibration. These points serve as a reference of the real performance of the engine even if the injector has been replaced by one with higher flow rate capacity than the stock one. For the OMEx combustion optimization under stoichiometric conditions, it was decided to use a simple injection strategy with a single injection as this allows to have a first insight on the performance of the concept with a good trade-off between testing time and results.

For the definition of the cylinder boundary conditions, some hypotheses were applied based on relevant literature. First is that the low AF_{st} (stoichiometric air-to-fuel ratio) of OMEx makes necessary to significantly reduce the amount of fresh air as stoichiometric conditions would be reached [37, 38]. For this reason, the fresh air density was decreased using the intake flow heater to reach a consistent intake temperature of 80 °C in all the engine map [39]. The air mass flow reduction will also diminish the power output, so it was decided to reach a compromise and loose some benefit from heating the intake by boosting the engine. To have consistent and realistic boundary conditions, the same boosting map used for the results with diesel was used as it is representative of the real conditions of the stock engine turbocharger. Also, as the OMEx energy density is lower than that of diesel, the injection pressures where consistently higher than for diesel to reduce the injection durations, maintaining the coherence of the original map with an increasing injection pressure with the engine load [40, 41]. Finally, stoichiometric conditions were achieved by increasing the EGR fraction to further displace the fresh air. The injection duration and timing were optimized looking for the minimum specific fuel consumption to then evaluate the impact on the engine-out emissions. In any case, the mechanical limitations of the engine were respected and the limitations of 190 bar of maximum in-cylinder pressure and 15 bar/CAD of maximum in-cylinder pressure gradient were imposed as limitations of the calibration strategy.

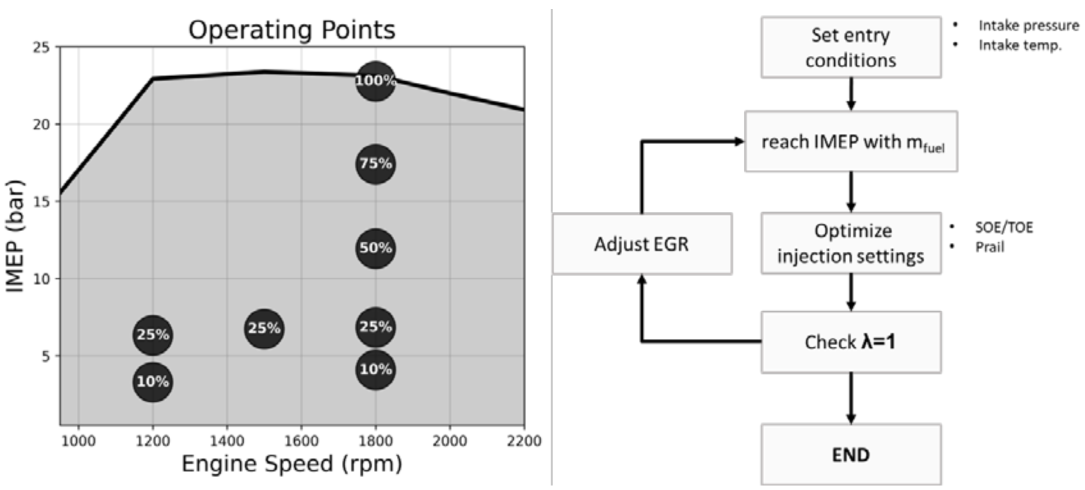


Figure 2. Summary of the testing methodology.

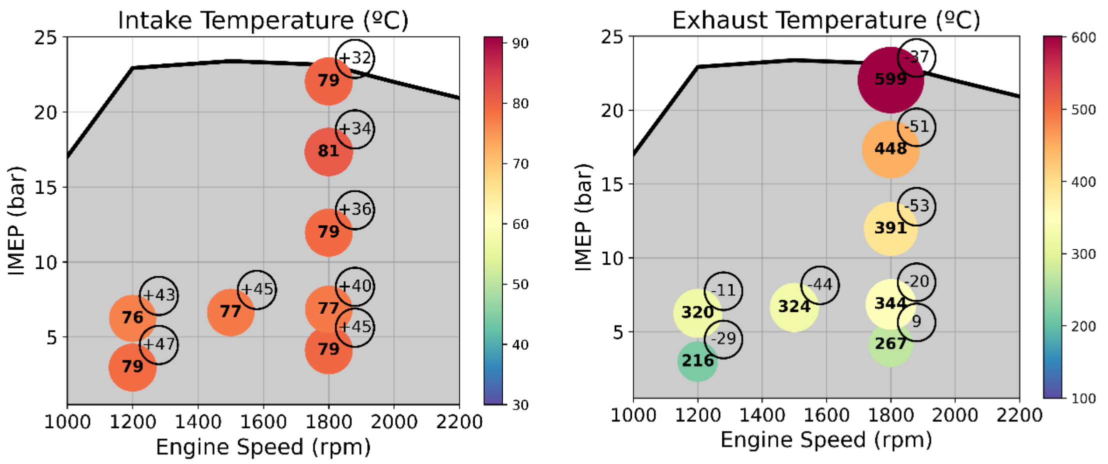
For a reliable data acquisition strategy, emission measurements from the five-gas analyser were averaged during a period of 40 seconds after a stationary operating condition was achieved to remove the possible noise and scattering on the output. The variable sampling smoke meter was set to perform three consecutive measurements that were averaged afterwards. For the in-cylinder measurements, INDICOM was set to record 100 cycles that were then averaged to minimize the effect of the possible cycle-to-cycle variation and the coefficient of variation of the IMEP provided by INDICOM during the test has to be lower than 3% to consider the operating condition as stable. Together with this measurement, INDICOM also provided with combustion parameters on an indicated analysis. For a more detailed thermodynamic analysis of the results, these results were post-processed using the in-house code CALMEC [42]. This software uses 0D models to include thermodynamic phenomena like heat transfer and obtain effective burning rates and a more detailed analysis of the combustion process.

3. Results and discussion

3.1. Boundary conditions

Promoting a stoichiometric combustion of a fuel with low AF_{st} and low energy density has certain implications that must be discussed. The first difference that can be noticed is the increased intake temperature that has been almost doubled in all the engine map, as shown in Figure 3a. Depending on the application, having such an increase in the intake temperature may seem to be unrealistic for the requirements of the flow heater, but it has to be noticed that the boundary conditions for diesel results belong to a turbocharged and intercooled engine. The hotter intake requirements for the OMEx points could be easily achieved by implementing a less demanding thermal management strategy for the intercooler and the EGR circuit. Additionally, the increased EGR rates will also contribute to increase the intake temperature as there will be a higher mass fraction of hot gases in the intake mixture.

Contrary to what could be expected, the exhaust temperature, included in Figure 3b, is not increased with respect to the reference, but it is reduced up to 53 °C depending on the operating condition. This is a consequence of several factors like having a more advanced combustion phasing, higher EGR rates that acts as a heat sink during all the combustion process due to its higher specific heat and its non-reactivity that acts as a quenching factor, and finally, the reduced energy density of OMEx plays a great role in produced lower peak and local temperatures within the combustion chamber. Even if this trait of oxygenated fuels will be beneficial for NOx reduction, the fact that for this combustion strategy the EGR has been increased and the in-cylinder temperatures have been reduced will reduce the reactivity of the mixture and the CO and UHC emissions will be increased. Considering that the DOC will play a more important role on the ATS, the operational requirement of having temperatures above 200ºC - 230ºC at the inlet of the DOC for a reasonable conversion efficiency [26], reducing the exhaust temperature is going in the opposite direction, especially considering that the expansion at the turbine (as it is not mounted in the test facility) is not being considered.



(a) (b)

Figure 3. Intake (a) and exhaust (b) temperatures for OMEx results (colored balls) and their difference with CDC reference (black bordered balls).

The other important change on the cylinder boundary conditions is the EGR fraction needed to reach stoichiometry on a turbocharged diesel engine. As can be seen in Figure 4, the EGR rates have been increased from 40% to 50% depending on the operating point. From the feasibility point of view of this requirement for the engine, these EGR rates are excessively high, but considering that fresh air density has been reduced significantly, it can be displaced easier and such an increase in EGR could be doable with proper turbo-matching. Nonetheless, from the applicability point of view, having such high EGR rates with high intake temperature will drastically reduce the volumetric efficiency of the engine and penalize the power output or fuel consumption in addition to the reduced reactivity and lower outlet temperature for the DOC and the possibility of having unbalance emissions. These implications will be analysed in more detail in the following sections.

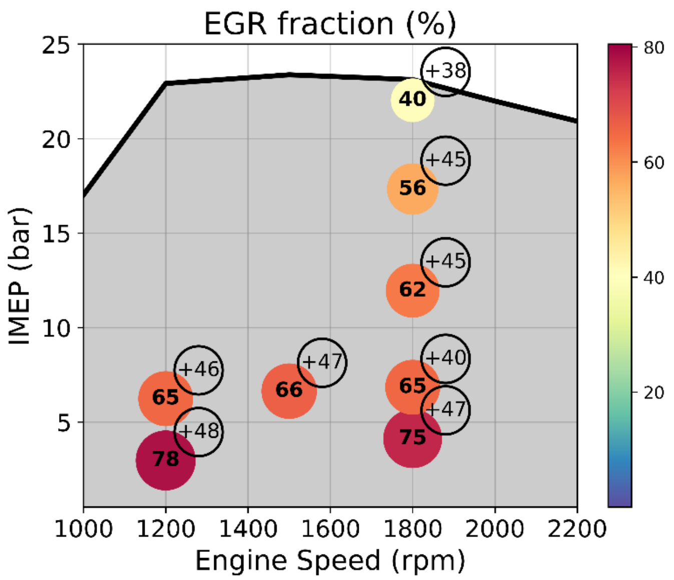


Figure 4. EGR rate for OMEx results and its difference with CDC reference.

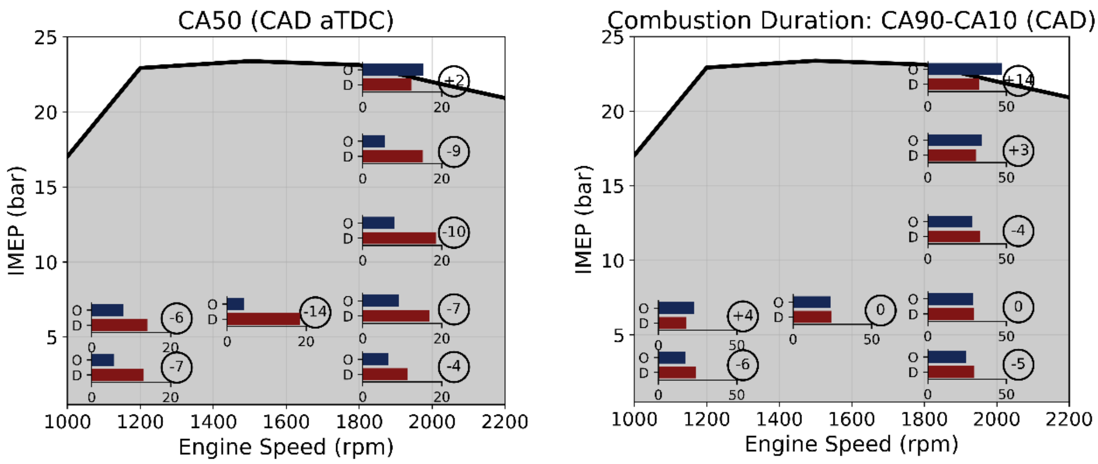
Regarding the intake and exhaust pressures to control EGR and boosting, the intake pressure followed the turbocharger conditions from the reference in all the cases except for the full load condition. To achieve stoichiometric conditions by means of EGR, the exhaust pressure was tuned by commanding the exhaust back pressure and leaving fully open the EGR valve. It is important to remark that the changes in the exhaust back pressure were not greater than 0.1 bar, and this could be interpreted as an indicator of the feasibility to obtain a turbocharger design that could reach such high EGR rates. Finally, regarding the injection pressure, it was observed that increasing the injection pressure with optimum combustion phasing resulted in greater pressure gradients, so the same injection pressure was used for both fuels except for the full load condition.

A comment on the limitations found to reach the full load condition should be made. As it was observed that maximum power output could not be achieved using the designated strategy, the injection pressure was increased to the maximum capacity of the system, 2500 bar, to increase the amount of fuel injected. Then, the injection duration was increased to 4 ms, the maximum injection duration allowed by the ECU per injection. Finally, a pilot injection was included, and its duration was increased together with the boost pressure, that was increased by 0.15 bar with respect to the reference value for that operating point. As it can be seen, to reach such condition, the injection system capacity and boosting capacity are pushed to the limit to achieve the desired power output, but the final setting may result in an unrealistic application. This clearly states the main limitation of the concept to reach high power rates.

3.2. Combustion analysis

The changes in the calibration strategy combined to the modifications of the boundary conditions have a direct impact on the burning rate and other combustion properties. The first indicator of a change in the combustion control is the CA50 (crank angle for which 50% of the energy has been released, represented in Figure 5a). In the case of OMEx, the injection timing is optimized to reach the best specific fuel consumption and not from an emissions control strategy standpoint, as in the case of the diesel reference. For this reason, the injection timings are advanced, and the combustion takes place near the TDC. This can be observed in the CA50, that takes values around 4 to 8 CAD aTDC. For the results with diesel, the CA50 takes place around 15 to 20 CAD aTDC as the purpose of the calibration is to reduce the peak temperatures and have a certain control over the NOx emissions to have acceptable levels that can be treated on the ATS that would be equipped with an SCR. Despite the change in the objectives of both calibrations, a similar trend can be observed in the distribution of the combustion phasing along the engine map with a certain offset. Considering the fact that the diesel reference is an already optimized calibration, it is valid to assume that the single-injection strategy with OMEx is enough to have a consistent engine calibration with acceptable results and is valid for further comparisons. Nonetheless, an exception to this trend of having more advanced combustion with OMEx appears at full load conditions. This change in the trend appears as a consequence of the limitations of the concept and the hardware, as the injection system is pushed to the limit in terms of injection duration and rail pressure to achieve the targeted power output regardless of the combustion or emissions performance.

Differences can be also found is the burning rate, evaluated through the CA10 to CA90 difference to avoid distorted trends as a consequence of the signal noise and that can be consulted in Figure 5b. In general, OMEx results in a very similar or even shorter combustion duration than diesel. Considering the significantly increased EGR rate, the higher reactivity of OMEx combined to the higher intake temperature is enough to compensate for the almost doubled total mass of fuel that must be burned due to its LHV, which is less than half of that of Diesel. In this sense, it is possible to obtain a faster combustion despite the increase in the fuel flow. Again, the outlier at full load condition is not considered when analysing these trends as it is the result of a hardware limitation.



(a) (b)

Figure 5. Comparison of combustion phasing (a) and combustion duration (b) for OMEx results and the Diesel reference.

Initially, by considering that the combustion phasing is advanced, and the combustion duration has been kept to similar values, the direct consequence of having the end of combustion displaced towards the TDC may lead to think that less combustion inhomogeneities may appear and the soot emissions and the penalty in UHC and CO associated to combustion at cooler stages of the expansion stroke may be reduced. Contrary to this, the increased EGR has the opposite effect, leading to less oxygenated regions that are easily saturated with the long fuel injections, rapidly consuming the oxygen available and leading to an increase of combustion imperfections. To evaluate the compromise between these two effects, the combustion efficiency obtained from the post-processing based on exhaust composition is analysed in Figure 6. It is observed in Figure 6 that combustion efficiency, which usually has values greater than 99% for conventional fuels, in the case of OMEx has suffered an important penalty, going down to 87% in the worst case [43]. This means that the remaining fraction is the fraction of fuel that has not been fully oxidized, therefore, a significant penalty in fuel consumption is expected as not the energy available in the fuel is being profited during the work extraction. From this, it can be concluded that the excessive EGR rates lead to an unacceptable combustion performance that is not suitable for a real application and needs significant improvements.

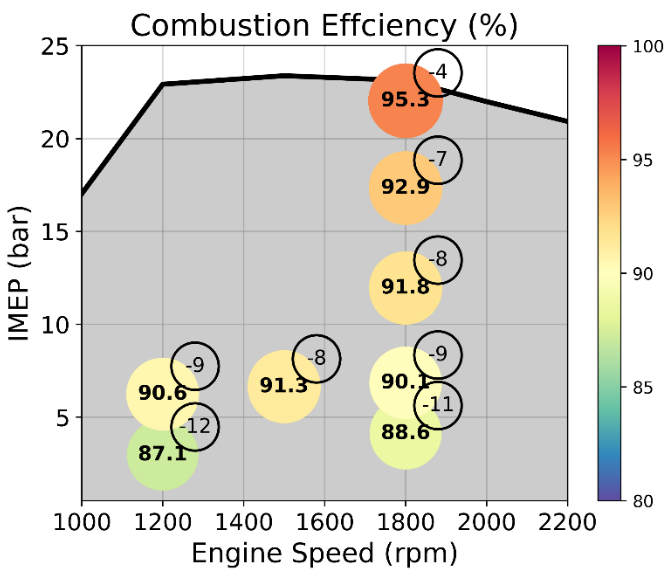


Figure 6. Combustion efficiency for OMEx results and its difference with CDC reference.

All these effects are clearly observed when analysing the rate of heat release (RoHR) at different operating points. Comparing the RoHR at 50% load and 1800 rpm for both fuels (Figure 7a), several observations can be extracted. The main difference is obviously the advance in the injection strategy for the case with OMEx, but despite this, both heat release curves follow a very similar shape with an initial portion of fuel that is premixed and burns rapidly (the first peak) that is then followed by a diffusive combustion. In general, the capacity of OMEx to produce high peaks is limited compared to that of diesel and this can be observed in the local peaks that are always lower even if the total mass injected is significantly higher. This results in a lower efficiency when extracting energy from the combustion to convert it into effective work [44]. Also, the combustion duration for OMEx is slightly shorter given its enhanced reactivity. It can be said that for this operating condition, OMEx is able to operate on a very similar manner compared to diesel and the calibration strategies may not be very different apart from the total mass flows required.

For full load condition (Figure 7b), OMEx does not operate in a normal way and several conclusions can be obtained from it. First thing to observe is that the peak values of RoHR do not differ much between 50% load and full load. This is the first limitation imposed by the reduced LHV of OMEx. Independently on the fuel mass injected, the EGR rates used or the combustion phasing, there is a very restrictive limit on the energy that can be transferred effectively to the crankshaft. Even if a pilot injection is added, as in this case, the fuel burns rapidly and does not contribute to the premixed phase of the spray combustion, resulting in split combustion stages that do not produce a smooth burning rate as in the first case. Then there is the impact of total injection duration. Even with a greater injection pressure (2500 bar for OMEx and 1900 bar for diesel), it is observed how a constant burning rate appears after the most energetic combustion stage. This is caused by a constant inflow and fuel burning that are stabilized. It is observed that the fuel is being injected during more than 30 CAD and, as more advanced is the expansion stroke, the lower power is obtained from the fuel injected at that late stage. As it can be expected, this prolongated fuel injection results in very long combustion duration that makes very difficult to properly match the combustion phasing, which reduces the fuel economy significantly. In addition to this, the exhaust temperatures are increased up to 600^{o}C, which is near the usual safety limit of a conventional turbine.

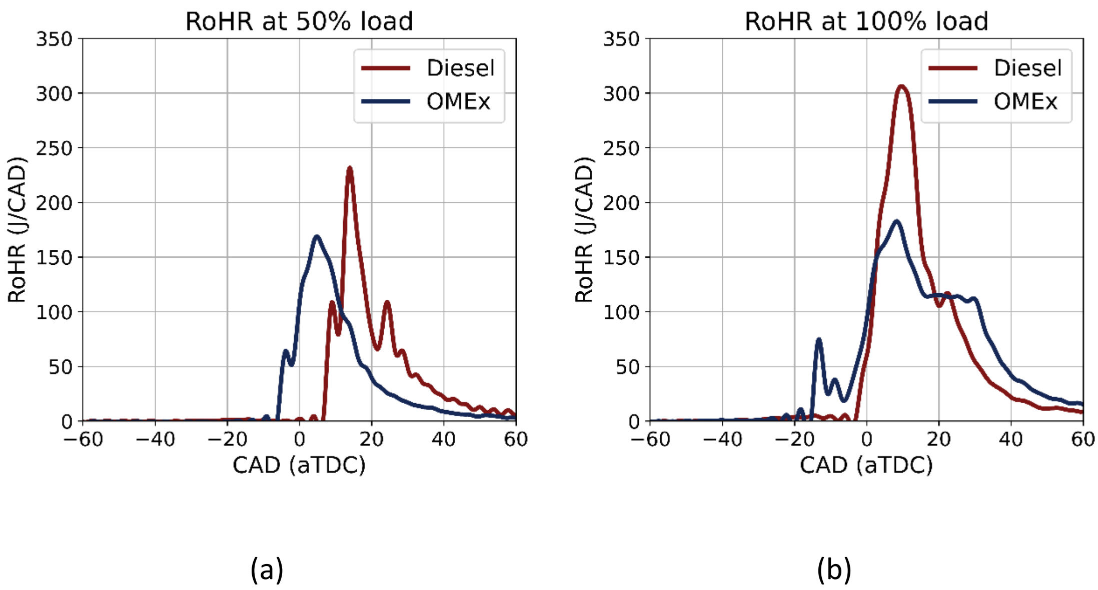


Figure 7. Comparison of rates of heat release for OMEx and diesel at 50% load (a) and full load (b) operating points at 1800 rpm.

From this analysis, it is possible to conclude that there is a power limit up to which a high-reactivity fuel with low LHV like OMEx can operate in a similar way to a conventional diesel, independently of other restrictions imposed by EGR strategies or hardware limitations. In case that a conventional engine architecture is used with a low LHV fuel, a certain de-rating of its maximum power output is expected to maintain smooth operation and coherent strategies with assumable engine performance in terms of fuel consumption.

3.3. Fuel consumption and engine-out emissions

Previous sections showed that the boundary conditions and combustion strategy modifications followed in order to reach stoichiometric operation utilizing OMEx have a detrimental effect in terms of fuel consumption. In this section, the indicated specific fuel consumption (ISFC) of OMEx under λ=1 is represented in equivalent terms and it is represented in Figure 8. This equivalent ISFC accounts for the total ISFC scaled by the energy density ratio of OMEx and diesel as expressed in Eq. 1 to have a more representative comparison in terms of energy utilization efficiency and equivalent diesel fuel consumption.

$$ISFC_{eq} = ISFC \cdot \frac{LHV_{OMEx}}{LHV_{Diesel}} \left[\frac{g}{kWh}\right] \qquad \text{Eq. 1}$$

The added effect of combustion worsening coming from the high EGR rates and reduced in-cylinder trapped mass leads to a total penalty on engine performance in terms of $ISFC_{eq}$ that varies from 15% at high load to almost 40% at lower loads. It can be observed that the trends in this penalty are very similar to that of the increment in the EGR rates, so it reasonable to assume that this parameter is the one with the highest relevance of fuel economy as it may be the main cause for increasing the combustion imperfections and limited RoHR peaks. From these results, the final fuel consumption on a real application would be much higher than that of conventional diesel engines, with a significant increase in re-fuelling costs and an unavoidable reduction of the vehicle autonomy, therefore the application of this concept may not be interesting for road vehicles. Nonetheless, it may still hold certain attractive for off-road applications.

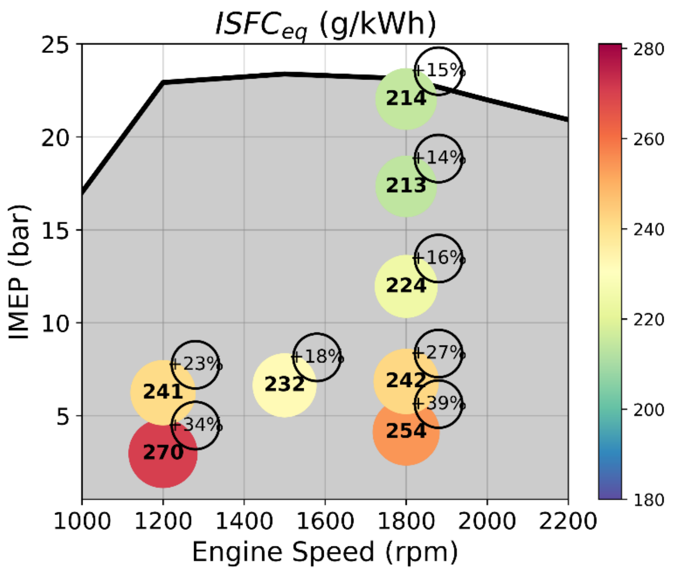


Figure 8. Equivalent BSFC for OMEx results and its difference with CDC reference.

To finish with the evaluation of this combustion concept, the engine-out emissions of most relevant controlled species: NOx, soot, UHC and CO are shown in Figure 9. In the figure, the red circles denote the operating condition that fulfils the EU VI limit for the corresponding specie. In general trends, the concept performs exceptionally well for NOx and soot emissions, while greatly penalizes the UHC and CO emissions.

The NOx emissions are practically removed up to 50% load, for 75% load there is a small increase, but still insignificant, and then at full load there are greater NOx emissions that go beyond the EU VI limit, but still, it greatly reduces NOx emissions compared to diesel. To explain this, it is necessary to consider that the two main factors affecting NOx production in this case are local hot spots with high temperature and the residence time at that high temperature. As can be deduced from the analysis of the combustion process, the RoHR peak limit also limits the maximum temperatures contributing to the NOx reduction. This, combined with the enormous amounts of EGR that act as a heat sink and slows down the reactivity of the mixture, can reach virtually-zero NOx emissions. For 75% and 100% load, the phenomenon of constant heat release due to a long diffusive flame creates a hot region that is maintained during a significant amount of time, allowing for the progressive formation of NOx emissions. Given this scenario, it can be concluded that the SCR of the ATS could be removed as almost no NOx is being produced, and the only point that emits above the regulation limit is a point that is scarcely used during normal driving conditions and it would be possible to easily fulfil during a homologation cycle.

In the case of soot emissions, OMEx is able to maintain ultra-low emissions in every operating condition, reaching less than a tenth of the limit. The molecular structure of OMEx with no carbon-to-carbon bonds allows to avoid the creation of soot precursors like polycyclic aromatics and produce a significant improvement in this aspect. In other applications like dual-fuel combustion, OMEx has produced virtually zero soot emissions, and the small presence of soot measurements in this case may be the result of having a slightly rich mixture due to uncertainties in the definition of stoichiometric conditions. Nonetheless, it is important to remark that the measuring device employed for this study may have a certain under reporting when working with oxygenated fuels [45, 46].

Regarding UHC and CO emissions, the effect of the recirculated gas is the main cause. The great amount of EGR rates imply that pockets with almost no oxygen presence may appear in the cylinder, inhibiting the hydrocarbons oxidation. Additionally, the low in-cylinder temperatures also reduce the reactivity of said oxidation reactions and contribute to increase the amount of fuel that is not fully utilized. As can be seen in Figure 9c, the amount of UHC is increased between 10 and 70 times compared to conventional diesel operation, but it is necessary to remark that CDC usually produces very low levels of these emissions. Of course, such great amounts of UHC do not fulfil EU VI regulations and would require the utilization of an ATS system capable of completing the oxidation reactions. It is interesting to note that the UHC emissions levels are relatively similar to those of other LTC concepts, and it has been previously demonstrated that conventional DOCs are able to deal with such high emissions [21, 23]. Nonetheless, it is important to mention that unburned hydrocarbons produced by oxygenated fuels can contain aldehydes, ketones and other species that cannot be reduced by conventional DOC [47] and dedicated evaluations would be necessary to select or design an appropriate aftertreatment device considering the specific speciation of UHC coming from OMEx.

To explain the CO emissions increase, the effect of high EGR rates is combined with the excessively long injection times, producing large regions with very rich concentrations that rapidly consume all the oxygen available. The reduction of CO to CO_2 has one of the longer characteristic times, therefore, by the time this reaction would take place, there is no oxygen available for it within the spray structure, specially at late stages if the injection process. This leads to an unacceptable level of CO emissions that are increased up to 600 times.

Considering the final balance of emissions with almost no NOx and soot, high UHC and unacceptable CO emissions, the impact on a conventional ATS system is significant. The SCR for NOx reduction and the particulate filter can be removed as the engine-out emissions do fulfil the EU VI regulation. In the case of UHC, a conventional DOC could do the work with adequate resizing and catalyst material composition. Nonetheless, when considering CO, there is no possibility to use any conventional system to reduce it to acceptable levels. A TWC could not be used as there is no adequate balance between NOx, UHC and CO, and a DOC cannot be considered as there is not sufficient oxygen at the exhaust given the combustion strategy utilized. The only conclusion on this side is that there is no conventional ATS capable of dealing with such high emissions of CO and HC simultaneously without a significant stage of development. Added to this, the 30% of penalty in the equivalent fuel consumption makes this concept not viable for its implementation in a real application.

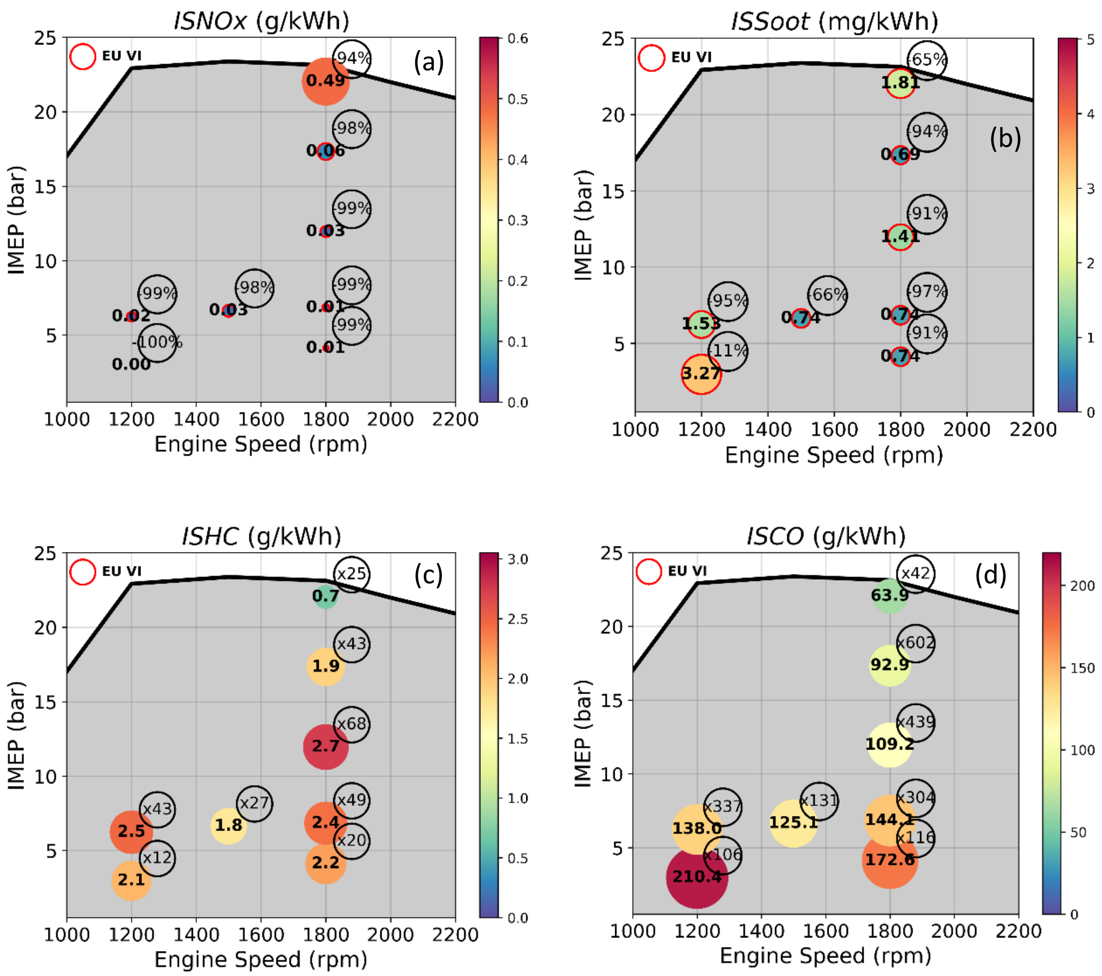


Figure 9. Emissions of NOx (a), soot (b), unburned hydrocarbons (c) and CO (d) from OMEx results and their difference with diesel reference.

4. Global lambda sweep study

At this stage, it is clear that the concept of reaching stoichiometric combustion with an oxygenated fuel with low LHV is not a viable option for commercial applications. It was thought that even with such high EGR rates, the maximum power output would not be that difficult to reach and that NOx emissions would not decrease so much.

Considering the current scenario, with an excessive amount of EGR, OMEx is still able to have almost zero NOx and soot emissions and there seems to have room for lowering the EGR rates towards mixture conditions of $\lambda>1$ and have a more diesel-like operation while maintaining certain benefits. The authors decided to perform a preliminary re-evaluation of how OMEx performs under other conditions of dilution to decide if there is any interesting direction for the application of OMEx as a single-fuel in an ICE.

This study consisted of a lambda sweep at two operating conditions: 1800 rpm at 25% and 75% engine load. The results shown in Figure 10 depict the evolution of regulated emissions normalized with the EU VI limits (when lower than 1, it fulfils EU VI), equivalent fuel consumption and EGR requirements when moving towards leaner conditions.

It is observed how the reduction of EGR utilization produces a rapid decrease in UHC as temperatures and oxygen availability are slightly increased. As the combustion goes leaner, CO emissions are also reduced below accepted limits while NOx start to go over the regulation limit. At the same time, engine performance is improved, and energy utilization efficiency can even surpass that of conventional diesel operation having lower equivalent fuel consumption. At every condition, soot remains virtually null. These trends are maintained for both engine loads, and the most interesting finding is that in both cases there is a region in a narrow gap of λ for which all emissions are very near to be EU VI compliant and engine efficiency is slightly better than that of diesel. In this region, the EGR levels are still high compared to conventional strategies, but they remain below 50%, which is a more reasonable demand for the air management system.

The authors think that a detailed calibration around this region with more complex multi-injection strategies has a great potential to reach results that can fulfil the EU VI regulation in engine-out basis, not requiring any ATS while increasing engine thermal efficiency at the same time. As a next step, the authors consider carrying out this detailed calibration and report the viability of extending these trends to all the engine operating map.

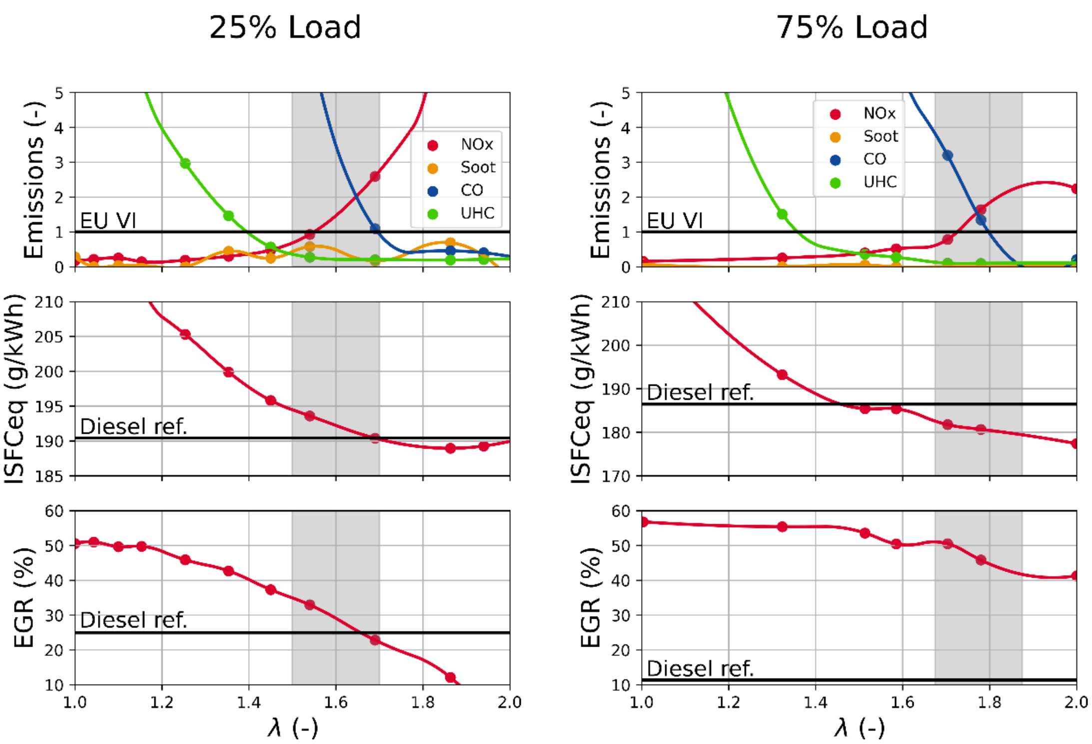


Figure 10. Effect of global lambda on OMEx combustion.

5. Conclusions

This work explores the concept of utilizing an oxygenated fuel with low LHV like OMEx in a turbocharged compression ignition engine under stoichiometric conditions as a low-emission architecture to evaluate the impact of the fuel properties on the engine performance. For this, a preliminary calibration for best fuel consumption is obtained with OMEx and compared against a conventional diesel calibration. From this study it was possible to obtain the following conclusions:

- Excessively high EGR rates of almost 80% are required to maintain stoichiometric conditions, and this has a huge impact on combustion efficiency and engine performance in terms of equivalent specific fuel consumption reaching a penalty of 34% compared to that of diesel.
- Peak heat release is limited by the LHV of the fuel and allows to maintain low in-cylinder temperatures that contribute to significantly reduce NOx emissions. This property combined with the high EGR rates permits to almost erase NOx emissions in most of the engine map ranging from 95% to 100% reduction.
- The limitation imposed by the reduced LHV of the fuel cannot be easily overcome by increasing injection pressure to reduce injection times, establishing a power limit up to which normal combustion strategies can be maintained.
- Oxygenated fuels with no carbon-to-carbon bonds in their molecular structure like OMEx are able to maintain almost-zero soot operation in all the engine operational range.
- Due to the low temperatures and high EGR fraction, UHC and CO emissions are greatly increased. For UHC, the values are typical of other LTC, but for CO, the increase of up to 600 times is too high and associated to extended local regions with very rich fuel concentrations.

- No suitable ATS based on conventional components can be established as a preferred option to deal with these emissions levels, which together with the significant penalty in fuel consumption make this concept not attractive for real applications.

Based on these conclusions, the authors performed a brief exploration of other combustion strategies under leaner stoichiometric ratios and found out that there is a region of lambda at which OMEx combustion can fulfil almost all controlled species on engine-out measurements with a more efficient usage of the energy content in the fuel compared to conventional diesel engines. Due to the interesting properties found, the authors have proposed as next steps of this OMEx combustion evaluation to perform a detailed calibration to evaluate the complete potential of this combustion strategy.

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7. References

[1] Reitz RD, Ogawa H, Payri R, Fansler T, Kokjohn S, Moriyoshi Y, et al. IJER editorial: The future of the internal combustion engine. Int Journal of Engine Research 2020; 21:3–10. https://doi.org/10.1177/1468087419877990.

[2] European Parliament and Council. Commission Regulation (EU) No 582/2011. Official Journal of the European Union 2011:1–168.

[3] EU. Regulation (EU) 2019/1242 of the European Parliament and of the Council of 20 June 2019 Setting CO2 emission performance standards for new heavy-duty vehicles and amending Regulations (EC) No 595/2009 and (EU) 2018/956 of the European Parliament. Official Journal of the European Union 2019; L 198:202–40.

[4] Reşitoglu I.A., Altinişik K., Keskin A. The pollutant emissions from diesel-engine vehicles and exhaust aftertreatment systems. Clean Technology Environmental Policy 2015;17:15–27. https://doi.org/10.1007/s10098-014-0793-9.

[5] Wade J, Farrauto RJ. Controlling emissions of pollutants in urban areas. Metropolitan Sustainability: Understanding Improving the Urban Environment 2012:260–91. https://doi.org/10.1533/9780857096463.3.260.

[6] Helbing C, K¨ohne M, Kassel T, Wietholt B, Krause A, Lohre L, et al. Volkswagen's TDI-engines for EURO 6d – clean efficiency for modern mobility. 41st Internationales Wiener Motorensymposium. 2020.

[7] Daimler, n.d. Changeover to new emissions standard: New Mercedes-Benz passenger cars comply with the EURO 6d-TEMP standard as a minimum. Retrieved November 09, 2020, from https://www.daimler.com/innovation/diesel/nox-reduction.html.

[8] Demuynck J, Favre C, Bosteels D, Bunar F, Spitta J, Kuhrt A, 2019, Diesel Vehicle with Ultra-Low NOx Emissions on the Road. SAE Technical Papers, 2019 September. https://doi.org/10.4271/2019-24-0145.

[9] Ou L, Cai H, Seong HJ, Longman DE, Dunn JB, Storey JME, et al. Co-optimization of Heavy-Duty Fuels and Engines: Cost Benefit Analysis and Implications.

Environmental Science and Technology 2019; 53:12904–13. https://doi.org/10.1021/acs.est.9b03690.

[10] Dallmann T, Posada F, Bandivadekar A. Costs of Emission Reduction Technologies for Diesel Engines Used in Non-Road Vehicles and Equipment. International Council on Clean Transportation 2018:1–26.

[11] Krishnamoorthi M, Malayalamurthi R, He Z, Kandasamy S. A review on low temperature combustion engines: Performance, combustion and emission characteristics. Renewable and Sustainable Energy Reviews 2019; 116:109404. https://doi.org/10.1016/j.rser.2019.109404.

[12] Duraisamy G, Rangasamy M, Ramasankaran AP. Statistical and experimental investigation of single fuel reactivity controlled compression ignition combustion on a non-road diesel engine. Energy Conversion and Management 2019; 199:112025. https://doi.org/10.1016/j.enconman.2019.112025.

[13] Liang J, Zhang Q, Chen Z, Zheng Z. The effects of EGR rates and ternary blends of biodiesel/n-pentanol/diesel on the combustion and emission characteristics of a CRDI diesel engine. Fuel 2021; 286:119297. https://doi.org/10.1016/j.fuel.2020.119297.

[14] Pathak SK, Nayyar A, Goel V. Optimization of EGR effects on performance and emission parameters of a dual fuel (Diesel + CNG) CI engine: An experimental investigation. Fuel 2021; 291:120183. https://doi.org/10.1016/j.fuel.2021.120183.

[15] Kalghatgi G, Levinsky H, Colket M. Future transportation fuels. Progress in Energy and Combustion Science 2018; 69:103–5. https://doi.org/10.1016/j.pecs.2018.06.003.

[16] Martins M, Perin A, Prante G, Pinto D, Dalla Nora M, Machado PRM. HCCI of wet ethanol on dedicated cylinder of a diesel engine using exhaust heat recovery. SAE Technical Paper 2018. https://doi.org/10.4271/2018-36-0191.

[17] Park W, Park S, Reitz RD, Kurtz E. The effect of oxygenated fuel properties on diesel spray combustion and soot formation. Combustion and Flame 2017; 180:276–83. https://doi.org/10.1016/j.combustflame.2016.02.026.

[18] Wei J, Zeng Y, Pan M, Zhuang Y, Qiu L, Zhou T, et al. Morphology analysis of soot particles from a modern diesel engine fueled with different types of oxygenated fuels. Fuel 2020; 267:117248. https://doi.org/10.1016/j.fuel.2020.117248.

[19] García A, Monsalve-Serrano J, Villalta D, Guzmán-Mendoza M. Methanol and OMEx as fuel candidates to fulfill the potential EURO VII emissions regulation under dual-mode dual-fuel combustion. Fuel 2021; 287. https://doi.org/10.1016/j.fuel.2020.119548.

[20] Benajes J, García A, Monsalve-Serrano J, Sari R. Clean and efficient dual-fuel combustion using OMEx as high reactivity fuel: Comparison to diesel-gasoline calibration. Energy Conversion and Management 2020; 216:112953. https://doi.org/10.1016/j.enconman.2020.112953.

[21] Macián V, Monsalve-Serrano J, Villalta D, Fogué-Robles Á. Extending the potential of the dual-mode dual-fuel combustion towards the prospective EURO VII emissions limits using gasoline and OMEx. Energy Conversion and Management 2021; 233. https://doi.org/10.1016/j.enconman.2021.113927.

[22] Singh AP, Kumar V, Agarwal AK. Evaluation of comparative engine combustion, performance and emission characteristics of low temperature combustion (PCCI

and RCCI) modes. Applied Energy 2020; 278:115644. https://doi.org/10.1016/j.apenergy.2020.115644.

[23] Benajes J, García A, Monsalve-Serrano J, Lago Sari R. Experimental investigation on the efficiency of a diesel oxidation catalyst in a medium-duty multi-cylinder RCCI engine. Energy Conversion and Management 2018; 176:1–10. https://doi.org/10.1016/j.enconman.2018.09.016.

[24] Melaika M, Herbillon G, Dahlander P. Spark ignition engine performance, standard emissions and particulates using GDI, PFI-CNG and DI-CNG systems. Fuel 2021;293:120454. https://doi.org/10.1016/j.fuel.2021.120454.

[25] Santos H, Costa M. Evaluation of the conversion efficiency of ceramic and metallic three-way catalytic converters. Energy Conversion and Management 2008; 49:291–300. https://doi.org/10.1016/j.enconman.2007.06.008.

[26] García A, Monsalve-Serrano J, Villalta D, Lago Sari R. Performance of a conventional diesel aftertreatment system used in a medium-duty multi-cylinder dual-mode dual-fuel engine. Energy Conversion and Management 2019; 184:327–37. https://doi.org/10.1016/j.enconman.2019.01.069.

[27] García A, Monsalve-Serrano J, Martinez-Boggio S, Gaillard P, Poussin O, Amer AA. Dual fuel combustion and hybrid electric powertrains as potential solution to achieve 2025 emissions targets in medium duty trucks sector. Energy Conversion and Management 2020; 224:113320. https://doi.org/10.1016/j.enconman.2020.113320.

[28] Luján JM, García A, Monsalve-Serrano J, Martínez-Boggio S. Effectiveness of hybrid powertrains to reduce the fuel consumption and NOx emissions of a Euro 6d-temp diesel engine under real-life driving conditions. Energy Conversion and

Management 2019; 199:111987. https://doi.org/10.1016/j.enconman.2019.111987.

[29] Benajes J, García A, Monsalve-Serrano J, Martínez-Boggio S. Optimization of the parallel and mild hybrid vehicle platforms operating under conventional and advanced combustion modes. Energy Conversion and Management 2019; 190:73–90. https://doi.org/10.1016/j.enconman.2019.04.010.

[30] Desantes JM, Molina S, Novella R, Lopez-Juarez M. Comparative global warming impact and NOX emissions of conventional and hydrogen automotive propulsion systems. Energy Conversion and Management 2020; 221:113137. https://doi.org/10.1016/j.enconman.2020.113137.

[31] Benajes J, García A, Monsalve-Serrano J, Martínez-Boggio S. Potential of using OMEx as substitute of diesel in the dual-fuel combustion mode to reduce the global CO2 emissions. Transportation Engineering 2020; 1:100001. https://doi.org/10.1016/j.treng.2020.01.001.

[32] García A, Monsalve-Serrano J, Villalta D, Lago Sari R, Gordillo Zavaleta V, Gaillard P. Potential of e-Fischer Tropsch diesel and oxymethyl-ether (OMEx) as fuels for the dual-mode dual-fuel concept. Applied Energy 2019; 253:113622. https://doi.org/10.1016/j.apenergy.2019.113622.

[33] Avl fuel mass flow meter and fuel temperature control. https://www.avl.com/-/avl-fuel-mass-flow-meter-and-fuel-temperature-control. Accessed in March 2021.

[34] Systems EM, 2019, Emission Measurement Systems - HORIBA. 1–3. https://www.horiba.com/en_en/products/by-segment/automotive-test-systems/emissions-measurement-systems/. Accessed in March 2021.

[35] AVL, 2005, Smoke Value Measurements with the Filter-Paper-Method (Issue June).

[36] IndiCom Indicating Software AVL. https://www.avl.com/-/indicom-indicating-software. Accessed in March 2021.

[37] Barro C, Parravicini M, Boulouchos K. Neat polyoxymethylene dimethyl ether in a diesel engine; part 1: Detailed combustion analysis. Fuel 2019; 256:115892. https://doi.org/10.1016/j.fuel.2019.115892.

[38] Barro C, Parravicini M, Boulouchos K, Liati A. Neat polyoxymethylene dimethyl ether in a diesel engine; part 2: Exhaust emission analysis. Fuel 2018; 234:1414–21. https://doi.org/10.1016/j.fuel.2018.07.108.

[39] Benajes J, Novella R, Pastor JM, Hernández-López A, Kokjohn S. Computational optimization of a combustion system for a stoichiometric DME fueled compression ignition engine. Fuel 2018; 223:20–31. https://doi.org/10.1016/j.fuel.2018.03.022.

[40] Yang S, Lee C. Exhaust gas characteristics according to the injection conditions in diesel and DME engines. Applied Sciences (Switzerland) 2019; 9. https://doi.org/10.3390/app9040647.

[41] García A, Monsalve-Serrano J, José Sanchís E, Fogué-Robles Á. Exploration of suitable injector configuration for dual-mode dual-fuel engine with diesel and OMEx as high reactivity fuels. Fuel 2020; 280:118670. https://doi.org/10.1016/j.fuel.2020.118670.

[42] Payri Francisco, Olmeda Pablo, Martin Jaime, Carreño Ricardo. A New tool to perform global energy balances in DI diesel engines. SAE Int J Engines 2014; 7(1):43–59. https://doi.org/10.4271/2014-01-0665.

[43] Divekar PS, Chen X, Tjong J, Zheng M. Energy efficiency impact of EGR on organizing clean combustion in diesel engines. Energy Conversion and Management 2016; 112:369–81. https://doi.org/10.1016/j.enconman.2016.01.042.

[44] Caton JA. Combustion phasing for maximum efficiency for conventional and high efficiency engines. Energy Conversion and Management 2014; 77:564–76. https://doi.org/10.1016/j.enconman.2013.09.060.

[45] Han J, Wang S, Maria Vittori R, Somers LMT. Experimental study of the combustion and emission characteristics of oxygenated fuels on a heavy-duty diesel engine. Fuel 2020; 268:117219. https://doi.org/10.1016/j.fuel.2020.117219.

[46] Härtl M, Seidenspinner P, Jacob E, Wachtmeister G. Oxygenate screening on a heavy-duty diesel engine and emission characteristics of highly oxygenated oxymethylene ether fuel OME1. Fuel 2015; 153:328–35. https://doi.org/10.1016/j.fuel.2015.03.012.

[47] Magnusson R, Nilsson C. The influence of oxygenated fuels on emissions of aldehydes and ketones from a two-stroke spark ignition engine. Fuel 2011;90:1145–54. https://doi.org/10.1016/j.fuel.2010.10.026.

Abbreviations

AFst: Stoichiometric Air-to-fuel ratio

ATS: Aftertreatment System

CA50: Crank Angle at which 50% of fuel mass has been burned

CDC: Conventional Diesel Combustion

CO: Carbon Monoxide

CO_2: Carbon Dioxide

DAC: Direct Air Capture

DOC: Diesel Oxidation Catalyst

DPF: Diesel Particulate Filter

ECU: Engine Control Unit

EGR: Exhaust Gas Recirculation

EU VI: EURO VI regulation for engine homologation

H_2O: water vapor

ICE: Internal Combustion Engine

ISCO: Indicated Specific CO emissions

ISFC: Indicated Specific Fuel Consumption

ISFCeq: Equivalent Indicated Specific Fuel Consumption

ISHC: Indicated Specific UHC emissions

ISNOx: Indicated Specific NOx emissions

ISSoot: Indicated Specific Soot emissions

LTC: Low Temperature Combustion

NOx: Nitrogen Oxides

OME: Poly-oxymethylene Dimethyl Ether

OMEx: Poly-oxymethylene Dimethyl Ether mixture

RoHR: Rate of Heat release

SCR: Selective Catalytic Reducer

TtW: Tank-to-Wheel

TWC: Three-Way Catalyst

UHC: Unburned Hydrocarbons

WtT: Well-to-Tank

WtW: Well-to-Wheel