Performance, Combustion and Emissions of a Diesel Engine Operated with Reformed EGR. Comparison of Diesel and GTL Fuelling

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ABSTRACT

In this work, the effects of a standard ultra low sulphur diesel (ULSD) fuel and a new, ultra-clean synthetic GTL (gas-to-liquid) fuel on the performance, combustion and emissions of a single cylinder, direct injection, diesel engine were studied under different operating conditions with addition of simulated reformer product gas, referred to as reformed EGR (REGR). For this purpose various levels of REGR of two different compositions were tested. Tests with standard EGR were also carried out for comparison. Experiments were performed at four steady state operating conditions and the brake thermal efficiency, combustion process and engine emission data are presented and discussed. In general, GTL fuel resulted in a higher brake thermal efficiency compared to ULSD but the differences depended on the engine condition and EGR/REGR level and composition. The combustion pattern was significantly modified when the REGR level was increased. Although the extent of the effects of REGR on emissions depended on the engine load, it can be generally concluded that an optimal combination of GTL and REGR significantly improved both NOx and smoke emissions. In some cases, NOx and smoke emission reductions of 75% and 60%, respectively, were achieved compared to operation with ULSD without REGR. This offers a great potential for engine manufacturers to meet the requirements of future emission regulations.

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1. INTRODUCTION

In order to meet the stringent requirements of the upcoming automotive emissions regulations, engine manufacturers have been exploring various techniques such as new modes of combustion, Exhaust Gas Recirculation –EGR, aftertreatment and use of hydrogen produced by fuel reforming as a combustion improver. For diesel engines, these techniques are mainly focused on the reduction of both nitrogen oxides (NOx) and particulate matter (PM) emissions. EGR has been extensively used as a successful method of reducing NOx emissions [1-3], but it results in a well-reported increase in the fuel consumption and increased smoke and PM emissions [3,4], as the air admitted into the engine is partially substituted by exhaust gases.

In order to overcome the drawback of EGR, the technique of using hydrogen-rich gas, referred to as reformed EGR (REGR), has been proposed and tested recently [4-6], even in multi-cylinder engines [7,8]. REGR has been proved to be effective in reducing both smoke and NOx emissions, thus noticeably improving the smoke-NOx trade-off trend. REGR may be generated on-board in a fuel reformer, by direct interaction of hydrocarbon fuels and exhaust gas over a catalyst. In this way a H_2/CO rich gas is produced that is then fed into the engine inlet manifold, consequently resulting in a reduction of the required amount of the in-cylinder diesel injected fuel [5,9]. The CO_2 content of the REGR reduces the combustion temperatures and helps to control NOx emissions (similarly to standard EGR).

With the use of reformate (REGR) gas in addition to the main liquid engine fuel, the engine operates as a dual fuelled engine. With addition of high REGR levels the engine operates in Partially Premixed Charge Compression Ignition (PPCCI) mode which is broadly considered as an Homogeneous Charge Compression Ignition (HCCI) type of combustion. Engines operating in this mode have been demonstrated to have very low PM and NOx emissions, while they are capable of reaching high efficiencies compared to spark ignition (SI) engines [10-12]. In a dual fuelled engine, the ignition of the premixed gaseous fuel (REGR) and air mixture and thus the combustion phasing can be controlled by the injection of the high cetane liquid diesel fuel [9]. Besides the emissions benefits of the application of the exhaust gas fuel reforming for on-board hydrogen production, this technique can also provide solutions to problems related to H_2 utilization (i.e. storage, distribution) in internal combustion engines.

Pollutant regulations are not a matter of concern only for engine manufacturers but they also require invite an important effort by the fuel industry in order to provide environmentally friendly fuels. These fuels will help to achieve reduced emissions and improve the performance of new engine and aftertreatment technologies (e.g. REGR technique, SCR catalysts for reduction of NOx, diesel particulate filters). Such fuels include biodiesel fuels (i.e. transesterified oil), which strongly reduce CO_2, CO, THC and PM emissions in diesel engines [13-15], and more importantly new synthetic, ultra-clean diesel fuels produced by Fischer-Tropsch processes [5,16,17]. The latter are improved quality fuels with an extremely high cetane number, and are virtually free of sulphur and aromatic hydrocarbons. The raw material can either be natural gas (the final liquid fuel is GTL, gas-to-liquid), coal (CTL, coal-to-liquid) or residual biomass (BTL, biomass-to-liquid,). GTL is already produced commercially and Diesel fuels blended with GTL are available in several European Countries.

The aim of the present work is to perform a comparative study of the effect of two liquid fuels (ultra-low sulphur diesel fuel and GTL fuel) combined with three types of gas recirculation (standard EGR and two different REGR compositions) on the performance, combustion process and emissions of a single-cylinder diesel engine. The EGR or REGR levels were varied from 0 to 30% in order to examine the effects on the PM and NOx emissions and engine performance. It has been previously reported that engine operation with high cetane number fuels (such as GTL) is usually more tolerant to EGR as the combustion efficiency is not limited by the smoke emissions [4]. However, the effect of GTL in conjunction with REGR on the engine operation has to be studied, and the advantages, if any, should be identified. Although the authors have published a number of papers regarding engine operation with REGR mainly with standard diesel fuels [18-20], the different properties of GTL are expected to influence differently the partially premixed combustion patterns and the engine performance and emissions.

2. EXPERIMENTAL SETUP

The experiments were carried out on a Lister-Petter TR1 engine. The engine is a 773 cm^3, naturally aspirated, air-cooled, single-cylinder direct injection diesel engine. An electric dynamometer with a motor and a load cell was coupled to the engine and used to load and motor the engine. The nominal injection timing was 22 ºCA (crank angle) degrees BTDC (before top dead centre), and it was kept constant in all the tests. The full engine test rig has been described in detail in previous publications [4,21].

The EGR flow was controlled manually by a valve and the EGR level was determined volumetrically as the percentage reduction in volume flow rate of air at a fixed engine operating point. A KISTLER 6125B pressure transducer (1% measurement accuracy), mounted flush at the cylinder head and connected via a KISTLER 5011 charge amplifier to a National Instruments data acquisition board, was used to record the cylinder pressure. The crankshaft position was measured using a digital shaft encoder. The test rig included other standard engine instrumentation such as thermocouples to measure oil, air, inlet manifold and exhaust temperatures and pressure gauges mounted at relevant points. Normal engine test bed safety features were also included. Atmospheric conditions (humidity, temperature, pressure) were monitored during the tests.

Data acquisition and combustion analysis were carried out using an in-house developed LabVIEW based software. Output from the analysis of 200 consecutive engine cycles included peak engine cylinder pressure, values of indicated mean effective pressure (IMEP), percentage coefficient of variation (% COV) of IMEP, average values and percentage COV of peak cylinder pressures, Rate of Heat Release (ROHR) and other standard combustion parameters. The COVs of IMEP and peak cylinder pressure were used as criteria for combustion stability (cyclic variability). In all tests presented here the COVs were below 2%.

An AVL Digas4000 analyser was used to measure NO_x, CO, and CO_2, by NDIR (nondispersive infrared gas analysis), and oxygen concentrations in the exhaust (electrochemical method). The accuracy of the Digas4000 analyser is 1ppm for NO_x and 0.01% for CO, O_2 and CO_2. Smoke was measured using a Bosch smoke meter with accuracy of 0.1%.

3. TESTING CONDITIONS AND FUELS

The experimental tests presented in this paper were carried out at two different engine speeds, 1200 and 1500 rpm. For each speed, two loads were tested, 25% (low load) and 50% (medium load), defined as the percentage of the maximum engine torque (when operated with ULSD fuel) at each speed. The four engine operation conditions chosen are part of the 13-Mode European Stationary Cycle.

As earlier mentioned, two different liquid fuels were tested, one ultra-low sulphur diesel (ULSD) and one synthetic, ultra-clean GTL fuel. GTL fuel was produced in a low-temperature Fischer-

Tropsch (LTFT) process., which is a more efficient route to diesel fuels since it maximises the amount of final products in the middle distillate range. High Temperature Fischer Tropsch (HTFT) by contrast produces a product slate containing a variety of gasoline blending components as well as a middle distillate stream that is much higher in aromatics ... Since the products produced by different manufacturers using LTFT are likely to be similar, the GTL fuel tested here can be considered as a representative sample of the future GTL production. The main physical and chemical properties of the fuels are shown in Table 1.

Table 1. *Fuel properties*

	Method	ULSD fuel	GTL fuel
Cetane number	**ASTM D613**	53.9	79
Density at 15ºC (kg/m^3)	**ASTM D4052**	827.1	784.6
Viscosity at 40ºC (cSt)	**ASTM D 445**	2.467	3.497
50% distillation (ºC)	**ASTM D86**	264	295.2
90% distillation (ºC)	**ASTM D86**	329	342.1
LHV (MJ/kg)		42.7	43.9
Sulphur (mg/kg)	**ASTM D2622**	46	<10
Aromatics (wt %)		24.4	0.3
C (wt %)		86.5	85
H (wt %)		13.5	15
H/C ratio		1.88	2.10

For each liquid fuel and engine operating condition, tests were performed with standard EGR and with two different compositions of reformed REGR, using ratios of 0, 10, 20 and 30%. The REGR was simulated by mixing the standard EGR with bottled pure H_2 and CO. The flow of these gases was chosen so that the compositions of the final REGR were 25% H_2 – 0% CO – 75% EGR in one case, and 15% H_2 – 10% CO -75% EGR in the other case. In this way the effect of REGR obtained under different reforming conditions could be studied. The REGR compositions were selected on the basis of diesel exhaust gas-assisted fuel reforming results that have been published previously [22,23]. The 15% H_2 – 10% CO composition corresponds to the situation where the exothermic water gas shift reaction (i.e. $CO + H_2 \rightarrow CO_2 + H_2O$) is not significantly promoted. As this reaction is an exothermic one ($\Delta H<0$), the calorific value of the 15% H_2 – 10% CO REGR is higher than that of the 25% H_2 – 0% CO REGR.

It has been proved [5] that, under real exhaust gas fuel reforming conditions, GTL fuels be reformed with higher process efficiencies, and the H_2 production can be improved compared to that of diesel fuels due to the absence of aromatic compounds and the increased H/C ratio. However, the concentrations of H_2 and CO in this study were selected to be the same for both fuels (ULSD diesel fuel and GTL fuel) in order to study the effect of these fuels under the same engine and premixed combustion conditions.

4. RESULTS

4.1. Brake thermal efficiency and liquid fuel replacement

The liquid fuel replacement is defined here as the reduction on a percentage basis, of the liquid fuel mass flow (ULSD or GTL fuel) injected in the engine compared to the 0% (R)EGR operating condition. Both the brake thermal efficiency and the liquid fuel (ULSD or GTL) replacement are shown in Figure 1 for the four tested engine operating conditions (1200 and 1500 rpm, at low and medium load). In the brake thermal efficiency calculation, the energy content of both the liquid and the gaseous (if any) fuels has been taken into account.

As expected, the brake thermal efficiency was higher in the case of the two medium-load conditions compared to low load operation (since less fuel, on a relative basis, is needed to cover the mechanical losses of the engine when the engine load is increased). The liquid fuel replacement showed an increasing linear trend when the REGR percentage (and so the amount of gaseous fuels in the engine inlet manifold) was increased.

Several conclusions can be drawn about the combined effect of the liquid fuel and the type of (R)EGR on the engine performance. In general, the high cetane number, better quality GTL fuel (dotted lines) combustion improved the engine brake thermal efficiency compared to diesel fuel (solid lines). This was more evident at the low-load operating conditions (Figure 1, left graphs), where the liquid fuel replacement was higher when the engine was fuelled with GTL fuel. The improved thermal efficiency when using GTL fuel is a consequence of its higher cetane number and different hydrocarbon composition, which prompted several changes in the combustion phasing (lower peak of heat release, etc.) as further discussed in Subsection 4.2. In the view of the energy saving and efficient energy use considerations that are becoming increasingly important, this improved brake thermal efficiency with synthetic fuels constitutes a noticeable advantage. Moreover, the higher brake thermal efficiency gives a wider range of opportunities for the engine manufacturers to meet the upcoming pollutant regulations and aftertreatment system requirements by modifying the injection parameters.

Regardless of the engine speed and load, when the engine was fuelled with ULSD fuel and the EGR percentage was increased, the brake thermal efficiency was slightly but continuously decreased. In contrast to ULSD, in the case of GTL fuelling the engine brake thermal efficiency was not affected as notably when EGR was introduced. Thus, it can be confirmed that higher EGR ratios may be used with GTL fuels to further reduce NOx emissions without a significant penalty on the engine efficiency.

When testing both REGR compositions at the two low-load engine operating conditions (Figure 1, left graphs), the brake thermal efficiency was significantly reduced by increasing the REGR level, with the reduction in efficiency being less significant in the case of GTL fuelling. In the case of an actual GTL fuelled engine-reformer system, the thermal efficiency can be further improved since higher calorific value reformate (H_2 and CO) will be produced as explained in the Introduction section. Consistently, at these low-load engine conditions the liquid fuel replacement (mass basis) was higher with GTL fuel. However, at the medium-load operation conditions the thermal efficiency increased as the REGR level was increased. In general, GTL gave the higher efficiency values also at these conditions.

The opposite trends of the engine brake thermal efficiency seen at low and at medium-load engine conditions can be explained by two competing effects. First, the faster gaseous fuels combustion, mainly due to higher level of premixing, that can occur spontaneously near the top dead centre (as discussed in Section 4.2 and shown in Figures 2-5), and thus result in improved brake thermal efficiency compared to diesel combustion by reducing the compression work and increasing the expansion work. Second, at low load and low in-cylinder temperatures the gaseous fuels (H_2 and CO) can not be efficiently oxidised and part of them is emitted with the exhaust gases, hence decreasing the engine thermal efficiency. It can be concluded that, at low-load conditions, the second effect (negative effect) overshadows the first one (positive effect), because the in-cylinder temperature is relatively low and a larger amount of gaseous fuel is not combusted and escapes with the exhaust gases. This was confirmed by the CO and H_2 emissions, which in general were higher for the low-load condition compared to medium-load (as presented later in the paper). Once again, these results show that the combination of synthetic fuels with the REGR technique is a promising alternative for engine manufacturers to fulfil future requirements.

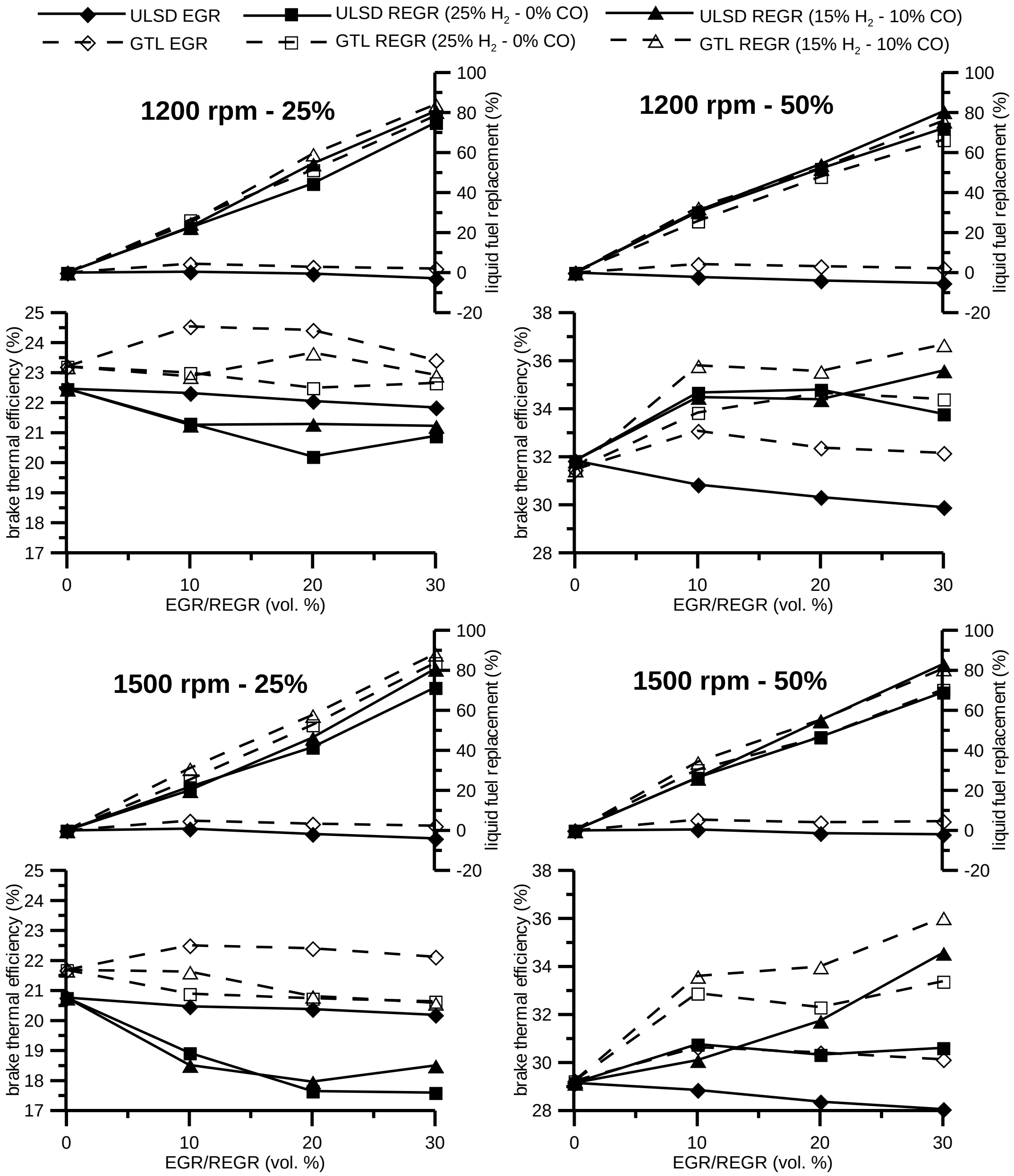

Figure 1. *Brake thermal efficiency and liquid fuel replacement.*

Among the two compositions of the REGR tested, the one with 15% H_2 - 10% CO, which is easier to obtain in a real reforming system, usually results in higher brake thermal efficiencies and reduced amounts of in-cylinder injected liquid fuel. This is due to i) improved CO oxidation in the combustion chamber compared to H_2, and ii) higher net calorific value of the 15% H_2 - 10% CO REGR, which is more than 7% higher compared to the 25% H_2 - 0% CO REGR.

4.2. Combustion Analysis

The in-cylinder pressure and rate of heat release (ROHR) are presented in Figures 2-5. To reduce the number of graphs and avoid showing repeatedly similar trends, only results for four combinations of engine speed-load conditions and fuels, one in each figure, are shown. Nevertheless, the comments provided for these selected conditions can be extended to all the tested combinations of engine conditions and fuels. Besides, the main combustion parameters (maximum pressure, maximum rate of pressure rise, etc.) are in fact shown in following figures for all the fuels and engine operating conditions.

From Figures 2-5, it can be seen that the combustion patterns for both ULSD and GTL were not significantly affected by the application of EGR (top-left figures). There was only a small delay in the start of combustion (retarded combustion) as the EGR percentage was increased.

In general, for all the engine conditions the use of REGR (both tested compositions) instead of standard EGR shifted the premixed combustion process to a later stage and most of the energy during that combustion phase was released over a longer period of time, especially in the case of engine operation with 30% REGR. For the low-load conditions (Figures 2, 4 and 5), the event of the peak pressure was shifted towards the expansion stroke as the REGR percentage was increased. The duration of the combustion process with REGR was shorter at medium load (Figure 3) compared to low load (Figure 2). Although the start of combustion was practically the same for all the REGR levels in the case of low-load operation at 1200 rpm (Figure 2), it was retarded with increasing REGR at 1500 rpm low load conditions (Figure 4). The main effect of the high-cetane GTL fuel (Figure 5) compared to the ULSD fuel (Figure 2) on the combustion patterns was the reduction of the first heat release peak, which corresponds to the combustion of the injected liquid fuel.

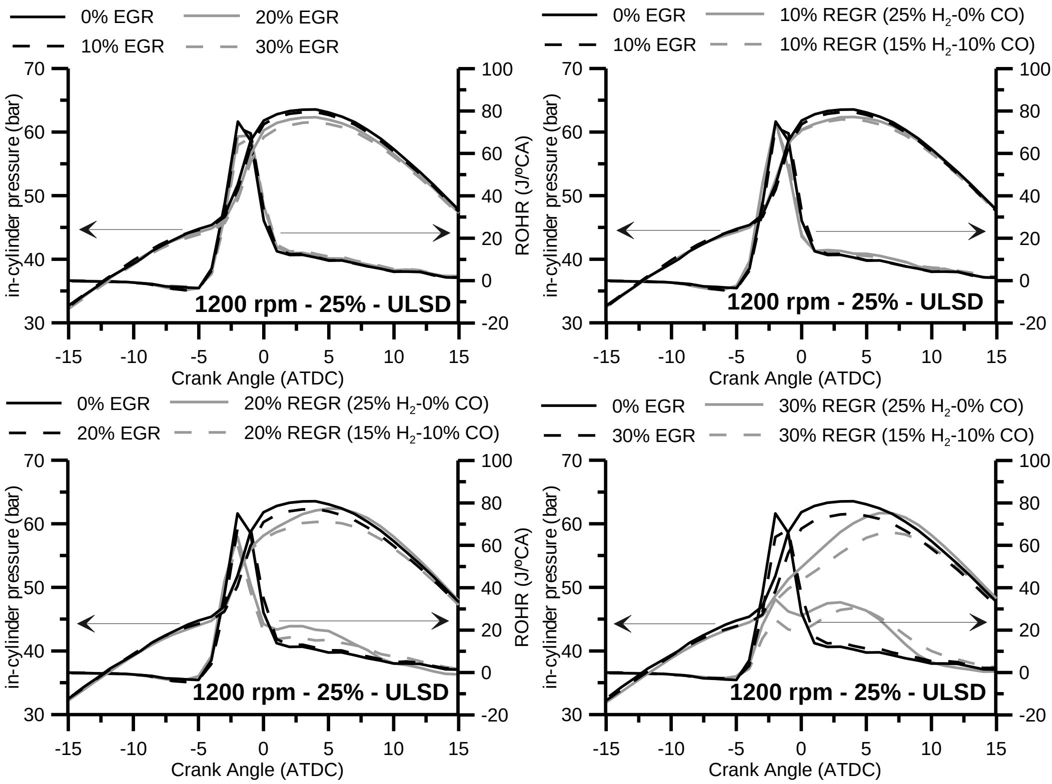

Figure 2. *In-cylinder pressure and rate of heat release (ROHR), ULSD fuel.*

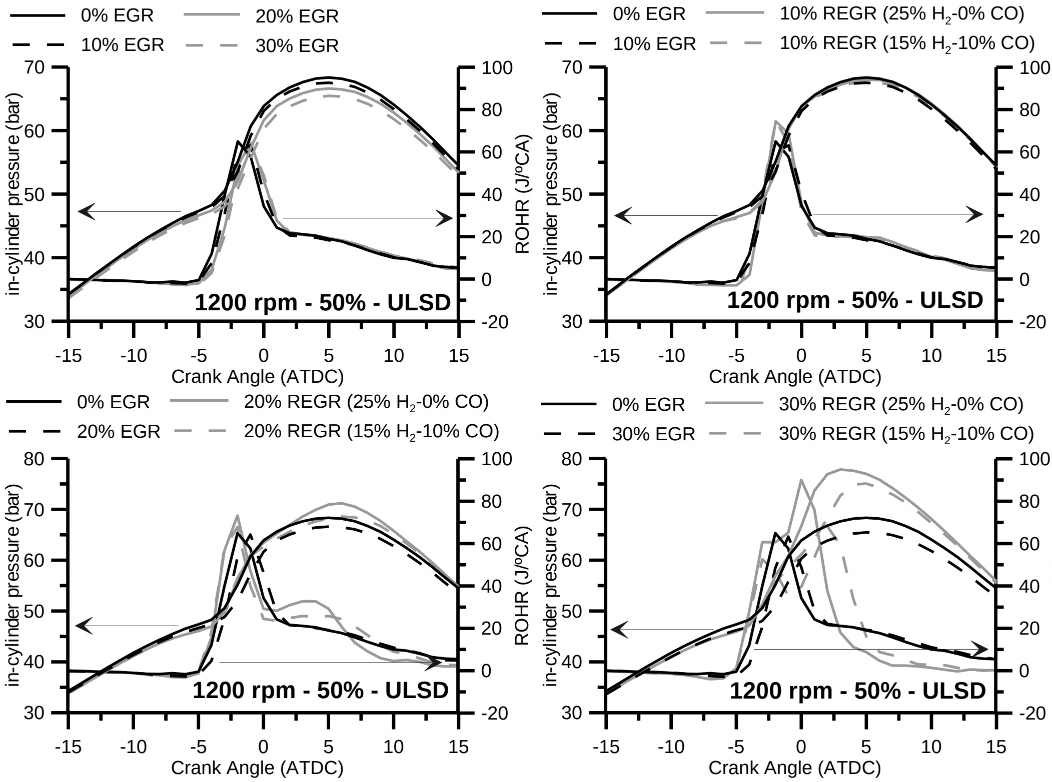

Figure 3. *In-cylinder pressure and rate of heat release (ROHR), ULSD fuel.*

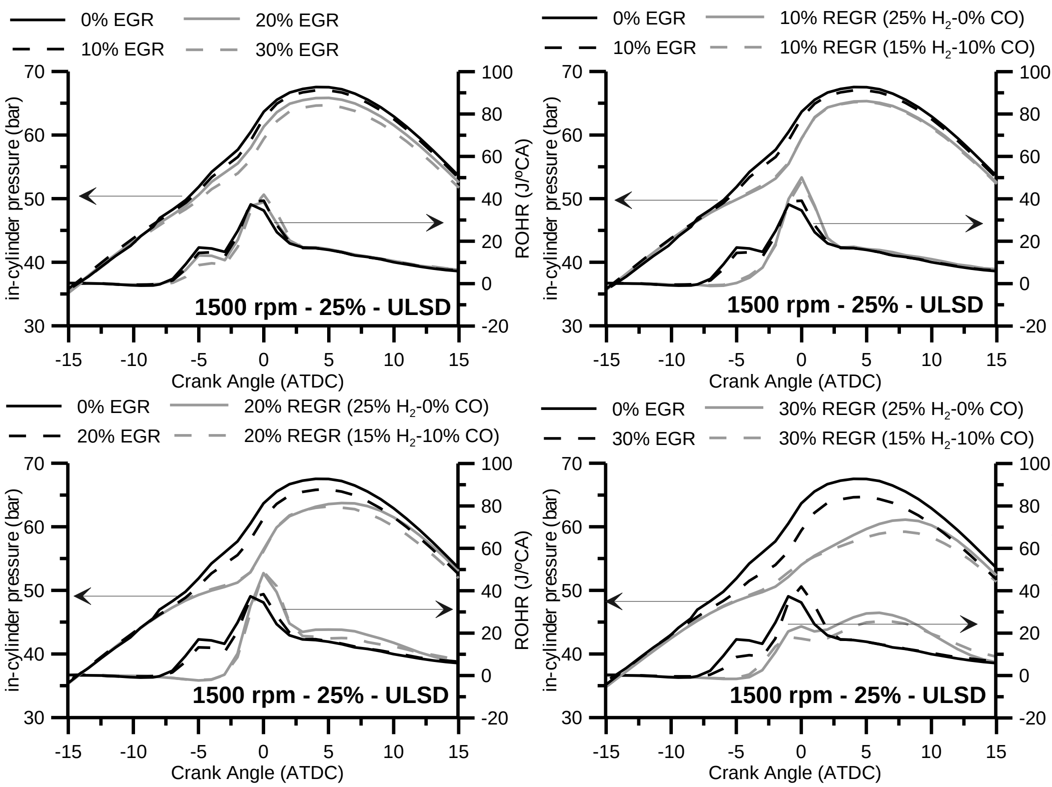

Figure 4. *In-cylinder pressure and rate of heat release (ROHR), ULSD fuel.*

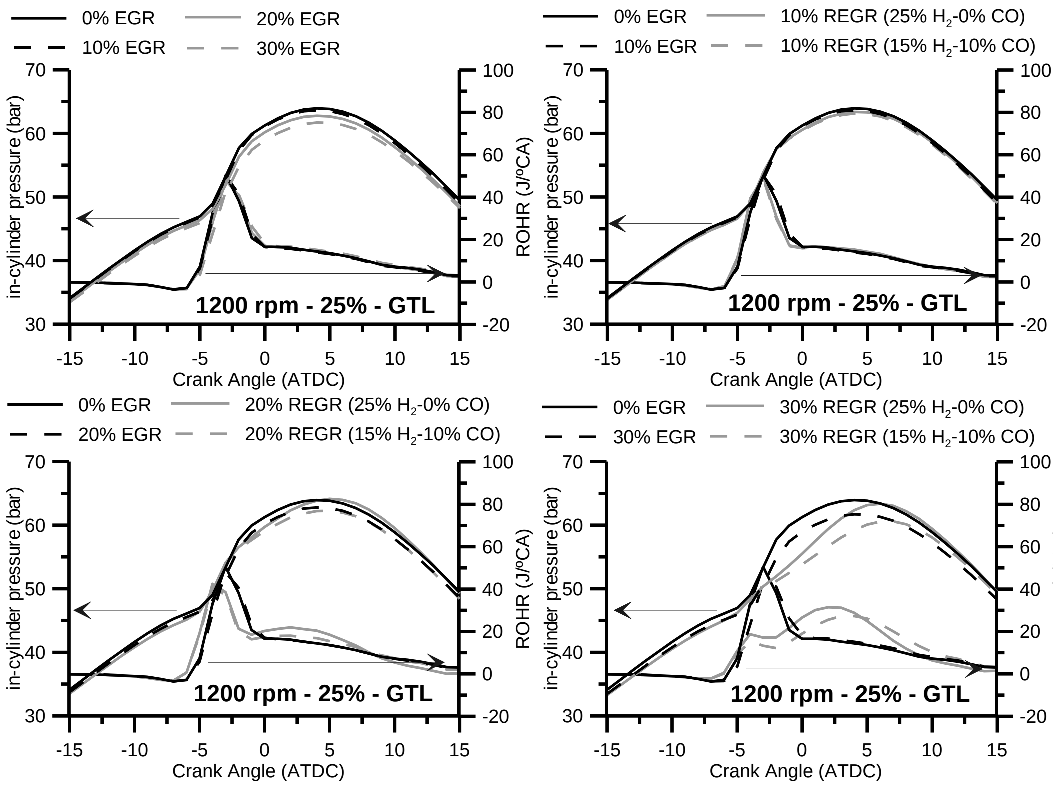

Figure 5. *In-cylinder pressure and rate of heat release (ROHR), GTL fuel.*

Further combustion analysis in terms of maximum in-cylinder pressure, maximum rate of pressure rise (mROPR), maximum rate of heat release (mROHR) and combustion duration in terms of ºCA for mass fraction burnt between 5% to 60% given as '5-60% ºCA' is shown in Figures 6-7. The parameter '5-60% ºCA' is defined here as the elapsed crank angle from the moment at which 5% of the total fuel (liquid fuel plus gaseous fuel if any) has been burnt to the moment at which 60% of the total fuel is burnt. This parameter has been introduced in order to quantify the duration of the first part of the combustion process, which was seen in Figure 2-5 to increase with the use of high REGR levels.

It is directly observed that standard EGR, regardless of its percentage, did not significantly modify the combustion parameters shown in Figures 6, which however did depend strongly on the REGR level. The trends of the maximum pressure and mROPR with REGR level were not the same for all the tested engine conditions and fuels and are discussed in the following paragraphs.

From Figures 6-7, it can be depicted that in most of the cases, the combustion of GTL fuel (dotted lines) showed lower in-cylinder pressure, lower mROPR and lower mROHR than the ULSD fuel combustion. This is a consequence of the high cetane number of GTL, which reduces the amount of fuel that is burnt during the premixed phase of the combustion process. The parameter 5-60% ºCA was not clearly affected by the fuel tested, except in the case of the lowest speed and low-load operating condition (Figure 7, top-left), where GTL fuelling resulted in a sharp increase of the duration of the first part of the combustion process compared to ULSD. GTL fuels are usually matched to the same boiling range of conventional refinery diesels, as such their carbon chain length distributions are similar. However, because they are exclusively paraffins then their viscosity bucks the normal density-viscosity trend for fuels. So in spite of low density, they tend to have viscosities close to conventional diesel. All these changes in combustion phasing resulted in a higher efficiency when the engine was fuelled with GTL instead of ULSD fuel (as shown in Subsection 4.1 and Figure 1).

For all the engine operating conditions and fuels tested, none of the four combustion parameters plotted in Figures 6 and 7 was significantly affected when the percentage of standard EGR was increased. The maximum pressure was only slightly reduced with increased EGR levels.

On the contrary, the REGR percentage strongly affected the combustion parameters as shown in both Figures 6 and 7. At low load, the maximum in-cylinder pressure and the mROPR were slightly decreased with REGR (Figure 6, left graphs), while the opposite trend, i.e. increase of both these parameters with REGR, was mostly found at medium load (Figure 6, right graphs). This indicates that when the injected liquid fuel is ignited at low load, the low temperature and pressure conditions in the chamber are not enough to oxidise the gaseous fuels, which are burnt later.

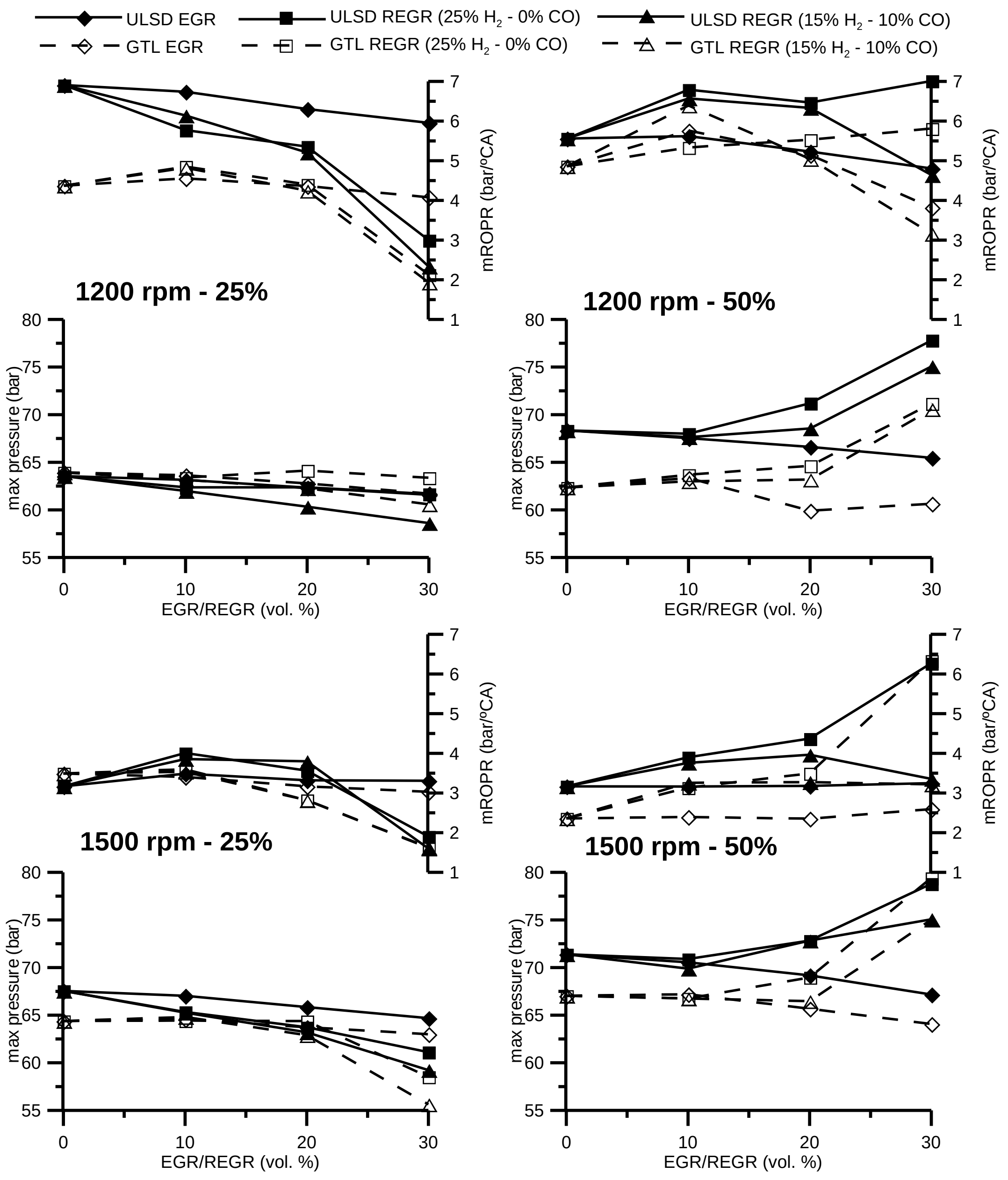

Figure 6. *Maximum in-cylinder pressure and maximum rate of pressure rise (mROPR).*

Hence the maximum pressure reached and the pressure gradient was reduced at low load with increasing addition of REGR. Consistently with this explanation, the mROHR was also reduced at low load while the 5-60% ºCA was increased, as the REGR percentage was increased (Figure 7). Moreover, the use of 30% REGR at medium load prompted a more efficient combustion of the gaseous fuels, thus resulting in a sharp increase of the maximum in-cylinder pressure (and the mROPR and mROHR), which is consistent with the decrease of the 5-60% ºCA parameter.

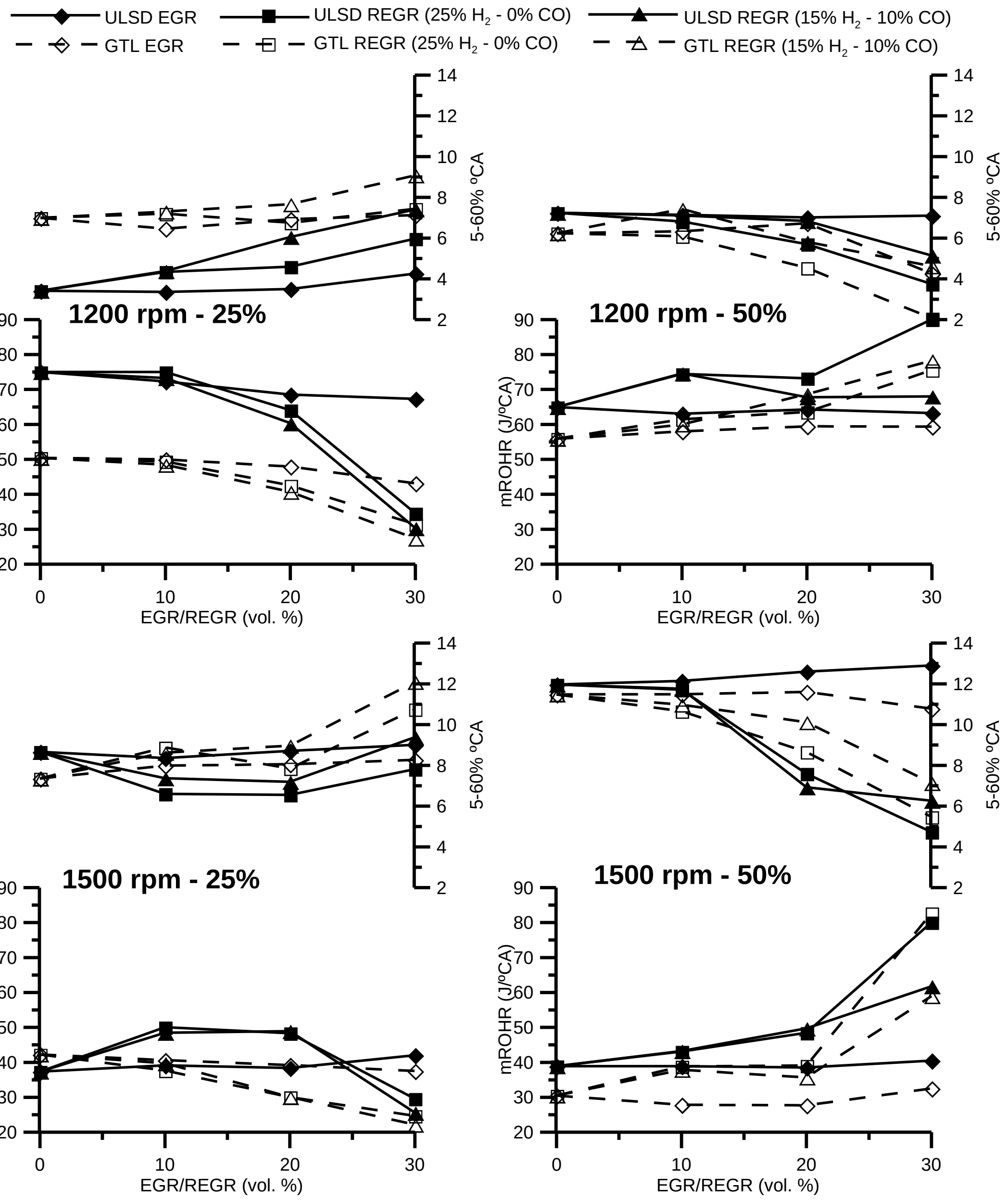

Figure 7. *Maximum rate of heat release (mROHR) and 5-60% ºCA.*

The two different tested compositions of REGR showed very similar trends, although some differences can be observed if the absolute values of the combustion parameters are compared. In general, the 25% H_2 - 0% CO REGR was found to result in higher maximum in-cylinder pressure, higher mROPR and higher mROHR (although those were small differences), while the 5-60% ºCA parameter was lower. This can be attributed to the higher H_2 oxidation rates compared to those of the H_2/CO mixture, and to the larger amount of liquid fuel injected in the case of 25% H_2 - 0% CO REGR as the net calorific value of this type of REGR is lower compared to 15% H_2 - 10% CO.

4.3. Emissions

NOx emissions and smoke shown as Bosch Smoke Number (BSN) are plotted in Figure 8 by means of the widely used trade-off representation. Each NOx–smoke trade-off line in this figure corresponds to one type of recirculation (i.e. EGR or REGR), and only the 0% and 30% levels have been labelled in order to allow identification of the trends observed with variation of the (R)EGR percentage.

Although the trends recorded for the combustion of GTL and ULSD with EGR or REGR were similar, the absolute values differed. In the case of standard EGR, regardless of its percentage and engine operation conditions, GTL fuel (dotted lines) generally resulted in a shift of the BSN-NOx trade-off curves to lower values compared to ULSD (Figure 8). The significantly lower NOx emissions recorded in the case of GTL combustion compared to ULSD are mainly due to the GTL combustion characteristics discussed earlier (i.e. reduced in-cylinder peak pressure, Figure 6).

At low load conditions (Figure 8, left graphs), the addition of standard EGR, as expected, resulted in decreased NOx emissions but strongly increased smoke (negative slope trade-off curves). However with addition of REGR both NOx and smoke emissions were decreased (positive slope curves), hence resulting in a more favourable trend. This pattern occurred with both GTL and ULSD fuel. The measured NOx reduction did not vary linearly with the REGR percentage. NOx emissions were reduced substantially with a modest addition of 10% REGR, while increase of the REGR level to 20 and 30% resulted in further but less pronounced NOx reductions.

For the medium-load engine operation with 10% REGR, both NOx and smoke emissions were decreased respect to 0% REGR. However, higher REGR percentages than 10% resulted in an additional decrease in smoke, as a consequence of the higher contribution of the soot-free, premixed combustion, but with a strong penalty in NOx emissions, because the peak pressure and temperature were considerably increased (as it was described in the previous subsection). Thinking of a future application of REGR in vehicles, it may be reasonably assumed that the injection parameters (such as start of injection, injection rate, multiple injections) can be optimised in order to control both NOx emissions and smoke at high REGR levels. This possibility was not explored in this work, but it offers a great potential for future studies.

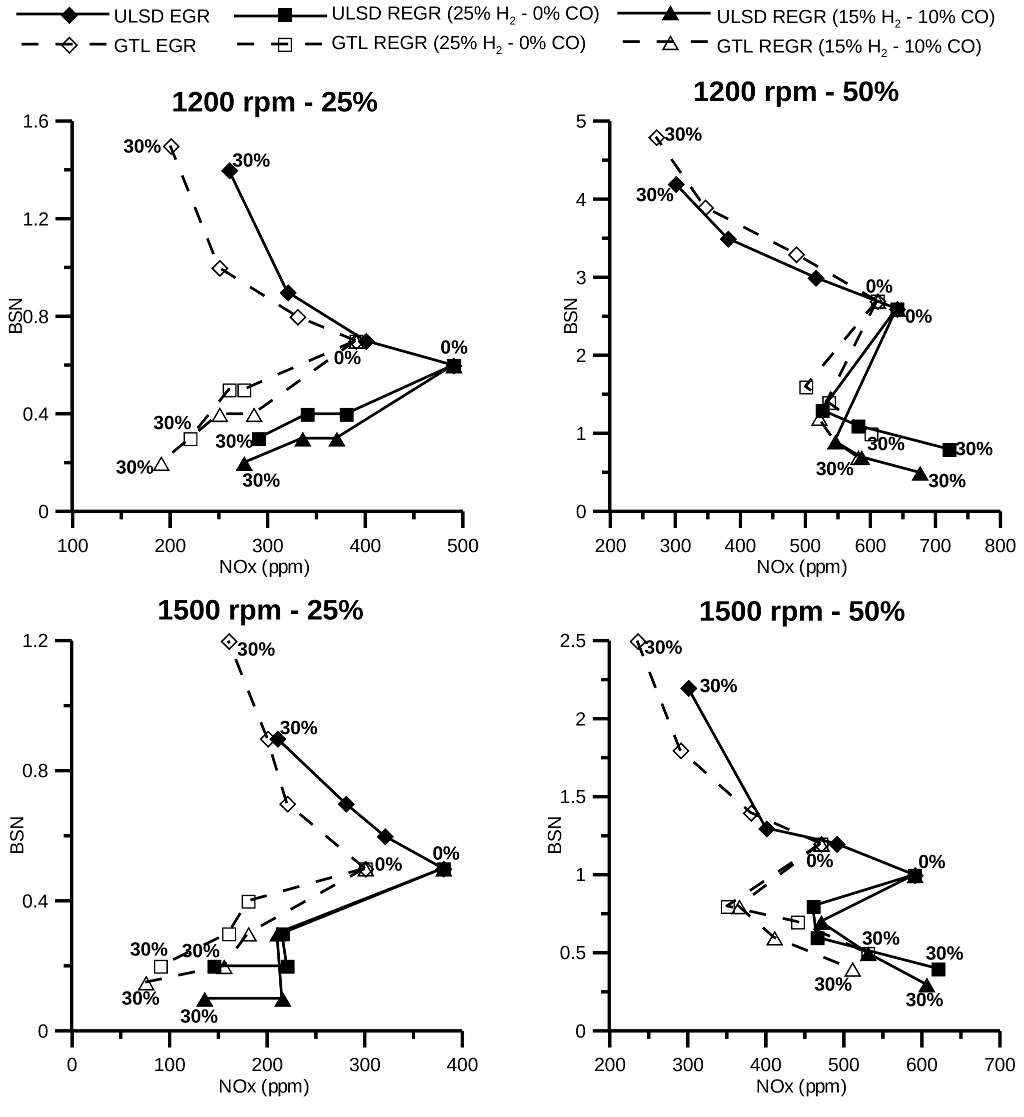

__Figure 8.__ Trade-off NOx and Bosch Smoke Number (BSN).

As a result of the combination of GTL fuelling and REGR addition (with an adequate REGR percentage depending on the engine load condition, as discussed above), more favourable NOx-smoke trade-off curves were achieved compared to ULSD fuelling. In the cases of both low-load operating conditions (Figure 8, left graphs, 30% REGR combined with GTL resulted in a simultaneous decrease of NOx and smoke emissions of approximately 75% and 60%, respectively, compared to the case ULSD fuelling and 0% REGR. For the medium-load conditions and 10% REGR, those reductions were around 40% and 30%, respectively.

The two tested compositions of REGR had similar effects on the NOx and smoke emissions and their trade-off. The NOx reduction was a consequence of the lower maximum in-cylinder pressure, as presented in Section 4.2, while the smoke number reduction was due to the lower amount of liquid fuel injected (i.e. larger fraction of the gaseous fuel combustion, which is a premixed-type combustion without generation of soot).

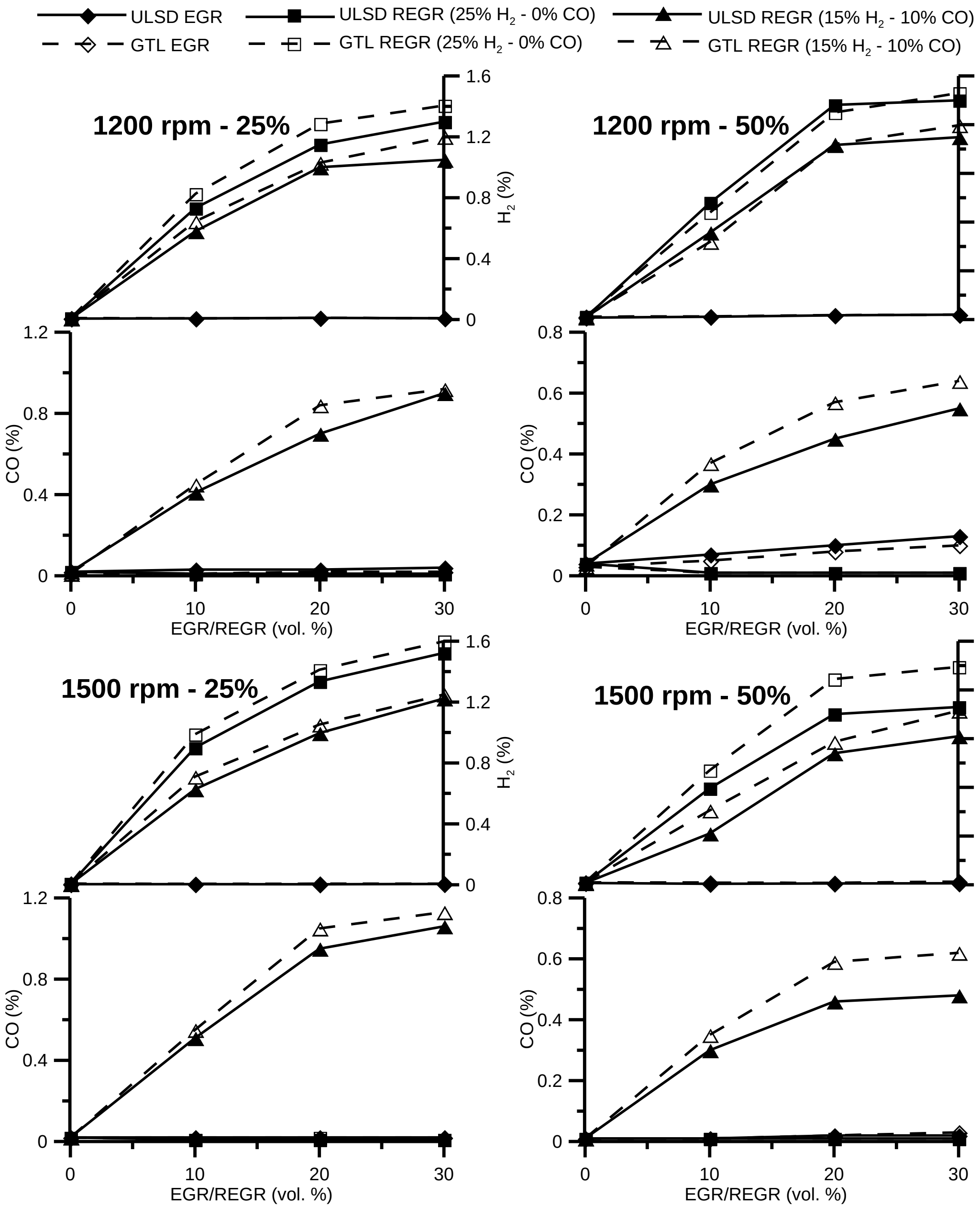

Figure 9. *Carbon monoxide and hydrogen emissions.*

Finally, carbon monoxide and un-combusted hydrogen emissions are presented in Figure 9. In general, CO emissions were higher with GTL compared to ULSD fuel. In the cases of standard EGR and 25% H_2 – 0% CO REGR, the CO concentration in the exhaust gases was very low (as it is typical for diesel engines). Increasing the standard EGR percentage resulted in a small increase in CO emissions, while the substitution of EGR by 25% H_2 – 0% CO REGR resulted in a reduction of the (already low) CO emission levels. These trends were more pronounced in the case of the lowest speed, medium-load operating condition (Figure 9, top-right). On the other hand when 25% H_2 – 15% CO REGR was introduced, the CO emissions were much higher as a result of the incomplete CO oxidation. When REGR of this composition was used, the CO emissions were decreased with increased engine load.

Rather similar trends to those of CO emissions were observed for the hydrogen emissions. As expected, among the two tested REGR compositions, the one with the highest hydrogen content was found to result in higher hydrogen concentrations in the exhaust gas. Increase of the engine load resulted in a more efficient H_2 combustion due to the higher in-cylinder temperature which promoted the hydrogen combustion, thus reducing the emissions of this compound.

The high CO and H_2 emissions appear to be an effect of REGR addition resulting in an increase of the harmful nature of the engine exhaust gases. However, this may not be such an undesirable effect as it first appears since it should be noted that both compounds have been reported to affect positively the activity of some catalysts used for NOx reduction in automotive SCR (selective catalytic reduction) devices [24]. In this way, the combined use of synthetic fuels, fuel reformers and SCR devices may result in further decreases of NOx emissions without increased concentrations of CO and H_2 in the exhaust gas. This promising research line has already been planned and is currently being explored by the authors.

5. CONCLUSIONS

A comprehensive work has been carried out in order to compare GTL and ULSD fuels in terms of combustion pattern, performance and emissions in a single cylinder diesel engine operated under dual fuelling conditions. For this, two different compositions of simulated reformed EGR (REGR), apart from the standard EGR, were tested. The main conclusions may be summarized as follows:

- Especially at low load, the GTL fuel was found to result in higher brake thermal efficiency than ULSD fuel. As a consequence, when REGR was used liquid fuel replacement was higher in the case of GTL fuel compared to ULSD. Engine manufacturers can take advantage of the improvement in efficiency when the engine is fuelled with GTL fuel to further reduce pollutant emissions.
- The effect of REGR on the brake thermal efficiency was load-dependant. At low load, the efficiency was decreased with increasing REGR ratio, and it was found that this was due to incomplete combustion of the gaseous fuels. On the contrary, at high load the higher flame

velocity of hydrogen and the increase in the expansion work resulted in increases of the brake thermal efficiency as the REGR level was increased.

- The high cetane number of the GTL fuel resulted in less pronounced premixed combustion phase. Thus, the maximum in-cylinder pressure and the maximum rate of heat release were lower. Consistently, the NOx emissions with GTL were reduced compared to those of ULSD fuel.
- The addition of REGR strongly affected the combustion pattern. At medium load, where the combustion temperature was relatively high, the use of 30% REGR resulted in more efficient gaseous fuels combustion, and a sharp increase of the maximum in-cylinder pressure and maximum rate of heat release were recorded.
- REGR affected significantly the NOx and smoke emissions. At low load, the higher the REGR level, the higher the decrease of both NOx and smoke emissions. At high load both emissions were reduced with 10% REGR while higher REGR percentages resulted in an additional decrease in smoke but with a penalty in NOx emissions. Different injection parameters can be tested in order to improve this trade-off.
- The combination of GTL and REGR showed the most spectacular results in terms of exhaust emissions. At low load, GTL fuelling combined with 30% REGR resulted in a decrease of approximately 60% smoke and 75% NOx emissions compared to ULSD fuelling with 0% REGR. At high load, GTL combined with 10% REGR resulted in a decrease of around 40% of both smoke and NOx emissions. The composition of REGR did not show a very significant effect, but slightly better results were achieved with the 15% H_2 – 10% CO REGR composition.

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