Characterization of Partially Premixed Combustion With Ethanol: EGR Sweeps, Low and Maximum Loads

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Exhaust gas recirculation (EGR) sweeps were performed on ethanol partially premixed combustion (PPC) to show different emission and efficiency trends as compared with diesel PPC. The sweeps showed that when the EGR rate is increased, the efficiency does not diminish, HC trace is flat, and CO is low even with 45% of EGR. NO_x exponentially decreases by increasing EGR while soot levels are nearly zero throughout the sweep. The EGR sweeps underlined that at high EGR levels, the pressure rise rate is a concern. To overcome this problem and keep high efficiency and low emissions, a sweep in the timing of the pilot injection and pilot-main ratio was done at ~16.5 bars gross IMEP. It was found that with a pilot-main ratio of 50:50, and by placing the pilot at −60 with 42% of EGR, NO_x and soot are below EURO VI levels; the indicated efficiency is 47% and the maximum pressure rise rate is below 10 bar/CAD. Low load conditions were examined as well. It was found that by placing the start of injection at −35 top dead center, the efficiency is maximized, on the other hand, when the injection is at −25, the emissions are minimized, and the efficiency is only 1.64% lower than its optimum value. The idle test also showed that a certain amount of EGR is needed in order to minimize the pressure rise rate. [DOI: 10.1115/1.4000291]

1 Introduction

Partially premixed combustion is a hybrid combustion concept between HCCI and diffusion combustion; fuel and air mix before ignition, but before the start of the combustion, the mixture distribution is not homogeneous. PPC targets are the ones of achieving a contemporary reduction of soot and NO_x as in HCCI, and control the combustion phasing by means of the position of the main injection as in classical diesel combustion. To accomplish the goal of a contemporary reduction of soot and NO_x, the ignition delay has to be long enough to create a fairly homogeneous mixture prior to ignition. There are many ways to accomplish this goal: inject the fuel very early, decrease the compression ratio, use a large amount of EGR, and decrease the cetane number of the fuels [1–8]. From a NO_x, soot point of view, these strategies were properly working, on the other hand, the engine efficiency was penalized most of the time, and CO and HC were reaching very high values. Toyota successfully implemented diesel PPC to production, but unfortunately, the operative window of this strategy was limited at half load and roughly 2750 rpm [8]. In order to separate the end of injection with the start of combustion even at high loads, in 2006, Kalghatgi [9,10] proposed to inject gasoline in a compression ignition engine. The results were remarkable because he was able to run the engine at 13 bars IMEP, and with 25% of EGR, achieved 0.4 g/kWh of NO_x, 0.9% AVL smoke opacity, and 174 g/kWh fuel consumption. To accomplish roughly the same goal with diesel, Andersson et al. [7] showed that 80% of EGR were needed, and unfortunately, the fuel consumption was 285 g/kWh.

Following the path traced by Kalghatgi [9,10], the authors performed similar experiments but with higher compression ratio, in order to improve further the engine efficiency [11]. From an emissions point of view, the results were amazing, but unfortunately, the engine efficiency was penalized. The reason was lying in the high pressure oscillations after combustion, which were enhancing the heat flux, thus reducing the thermal efficiency. To overcome this problem (and the acoustic noise as well), the authors proposed a new injection strategy [12]. The strategy consisted of injecting 50% of the fuel in the pilot at −60 top dead center (TDC), and to trigger the combustion by means of the stratification level created by the main injection, EGR were also used. At 16 bars IMEP, the results were very low NO_x, high efficiency, but unfortunately, soot were in the range of 5FSN because of the low injection pressure and low swirl.

The aim of this paper is to perform a sweep in the start of injection of the pilot and pilot-main ratio at high load, in order to demonstrate the previous founding. Low load conditions were also tested. A start of injection (SOI) sweep was performed in order to understand the most convenient stratification level that maximize the efficiency and minimize the emissions. Two EGR sweeps were presented for understanding how emissions and efficiencies are behaving when high octane number (ON) fuels are used in PPC combustion. The fuel used in these experiments was ethanol, even though it is known that, for a series of issues, this fuel will never be put on the market, the authors decided to use it for showing that the most suitable fuel for this combustion concept has to be oxygenated e.g., a blend of ethanol and gasoline.

2 Experimental Apparatus

2.1 Engine. The experiments were made on a single cylinder diesel Scania engine, D12, and its main geometrical properties are found in Table 1. The cylinder head was flat and the piston used was a shallow bowl type. The engine was boosted by using compressed air from an external air line; the inlet pressure was adjusted by using a waste gate valve. A heater (supplied by Leister) placed before the inlet manifold was used for heating up the air at the desired inlet temperature. The engine was coupled to a dyno, which could absorb only 15 bars BMEP.

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Table 1 Geometric properties of the engine

Displaced volume	1966 cc
Stroke	154 mm
Bore	127.5 mm
Connecting rod	255 mm
Compression ratio	15:1
Swirl ratio	2.9

2.2 Injection System.

2.2 Injection System. The fuel was injected by using a first prototype Bosch injection system from 2000. The injector had eight holes with a diameter of 0.18 mm, 120 deg umbrella angle. The rail pressure was kept constant at 1600 bars during all the experiments; the current control system allowed a maximum of two injections per cycle. The fuel flow was measured by using a gravity scale, and each operative point was sampled for 2 min.

2.3 Fuel. The fuel used was ethanol (99.5% by volume), its lower heating value was 29 (MJ/kg) while its RON 107 (−).

3 Experiments

A summary of the three experiments is reported below. More detailed information can be found in Sec. 4.

1. Two EGR sweeps were done at two different fuel rates: 16.28 and 14.39 fuel MEP (this quantity is defined as the fuel energy per cycle normalized with the displacement volume). The engine speed was 1100 rpm, and CA50 was kept constant by adjusting the SOI; single injection was employed. For a given sweep, the inlet pressure was held constant, while the inlet temperature was adjusted to keep a stable combustion.
2. *Low load analysis*. A SOI sweep was done at constant fuelling rate: 4.58 bar fuel MEP. The start of injection was varied between −45 TDC and −10 TDC. The inlet temperature was held constant at 423 K, and the engine was running naturally aspirated at 800 rpm. The sweep was done at two different EGR rates: 0% and 28%.
3. *High load analysis*. A SOI pilot and pilot-main ratio sweeps were performed at constant fuel MEP of 35.67 bars. The start of the pilot injection was varied as follows: −80 TDC, −60 TDC, −50 TDC, and −40 TDC. For each SOI, the pilot-main ratios tested were: 75–25, 62.5–37.5, 50–50, and 25–75. The engine speed was 1100 rpm, and CA50 was kept constant by adjusting the start of the main injection. 42% of EGR was used, the inlet temperature was kept constant at 323 K, and the absolute inlet pressure was 2.38 bars.

4 Results

4.1 EGR Sweep. In this first test, two EGR sweeps were performed at two different fuelling rates: 16.28 bars and 14.39 bars fuel MEP. The running conditions were the following: 1100 rpm, 1.90 bar abs inlet pressure, 430 K inlet temperature, and 8.22 TDC CA50 for the higher fuelling rate. While in the second case: 1100 rpm, 1.52 bar abs inlet pressure (This value and the above one were chosen in order to have $\lambda \sim 2.2$ without EGR. By doing so when λ is close to stoichiometric, there are enough EGR to have low NO_x values), 400 K inlet temperature, and 6.81 TDC CA50. During both sweeps, when λ was roughly below 1.3, the inlet temperature had to be slightly increased in order to have a stable combustion.

In order to keep the EGR rate as only a variable, the injection strategy was kept constant. Single injection was employed and not the one proposed by the authors in Ref. [12], which allowed smooth running of PPC combustion with high ON fuels; without EGR, the proposed injection strategy would have led to very early ignition. The gross IMEP traces as a function of EGR are presented in Fig. 1; a slight increase in IMEP is observed when the EGR rate increases. As shown by Fig. 1, the increase is due to the faster increase in thermal efficiency over the small decrease in combustion efficiency.

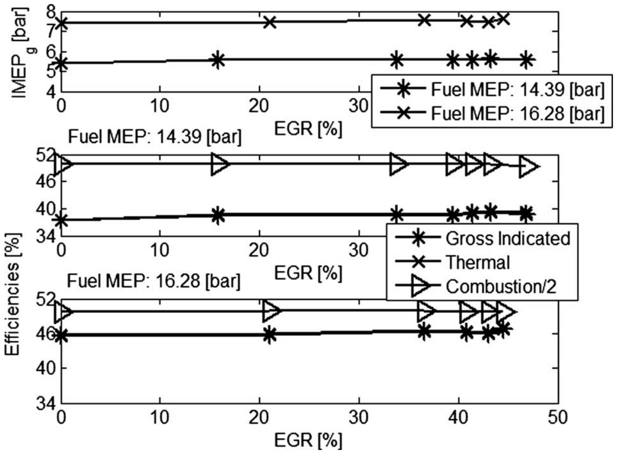

Fig. 1 Gross IMEP, combustion, thermal, and gross indicated efficiency as a function of EGR at 14.39 bars fuel MEP and 16.28 bars fuel MEP

The analysis of the burning rate profile, see Fig. 2, indicates that by increasing the EGR rate, the typology of combustion moves from partially diffusion controlled to totally kinetically controlled combustion. Kinetically controlled combustion is faster than the diffusion counterpart. This situation results in a faster decrease in exhaust losses as compared with the minor increase in heat transfer and a negligible increment in conversion losses, see Fig. 3.

The emission level variations with the EGR rate are presented in Fig. 4. As expected, by increasing the EGR rate, NO_x decreases, CO increases, soot barely shows any variation, and HC has a tendency to decrease. In terms of soot, ethanol does not show high values because of its molecular structure, on the other hand, low values of NO_x appears with more than 40% of EGR. When EGR spans between 40% and 47%, very low CO, HC, soot, and NO_x can be simultaneously achieved.

Figure 5 shows the NO_x-soot tradeoff during the two EGR sweeps. With a moderate amount of EGR, ethanol PPC is able to be within the estimated values of EURO VI legislation.

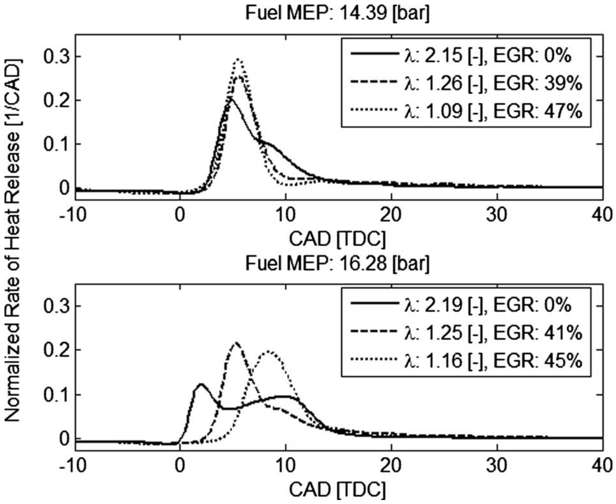

Fig. 2 Burning rate profile at low, medium, and high EGR rate at 14.39 bars fuel MEP and 16.28 bars fuel MEP

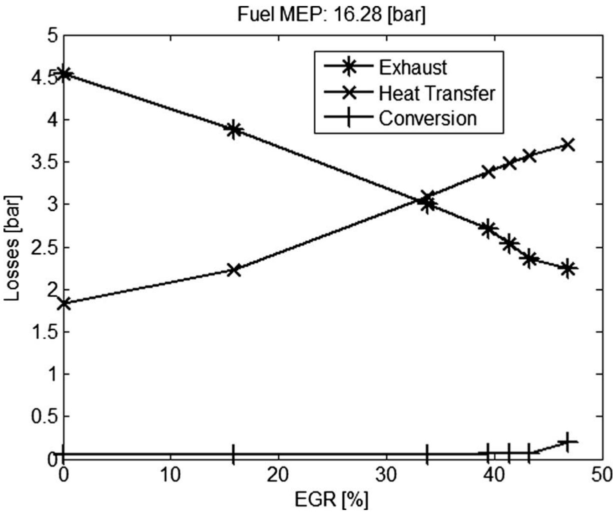

Fig. 3 Exhaust, heat transfer, and conversion losses as a function of λ and EGR at 16.28 bars fuel MEP

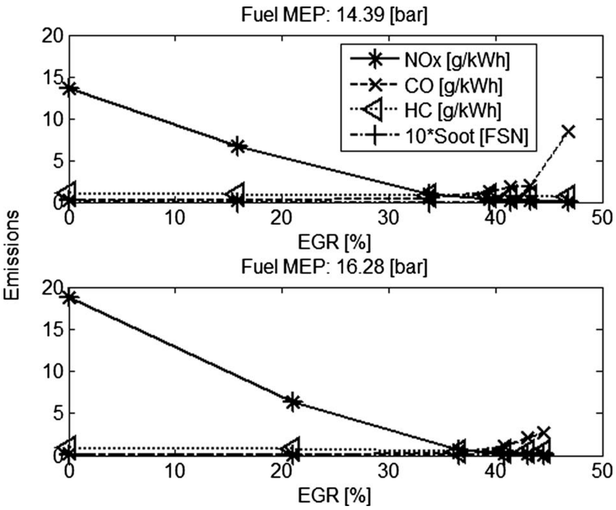

Fig. 4 NO_x, CO, HC, and soot as a function of EGR at 14.39 bars fuel MEP and 16.28 bar fuel MEP

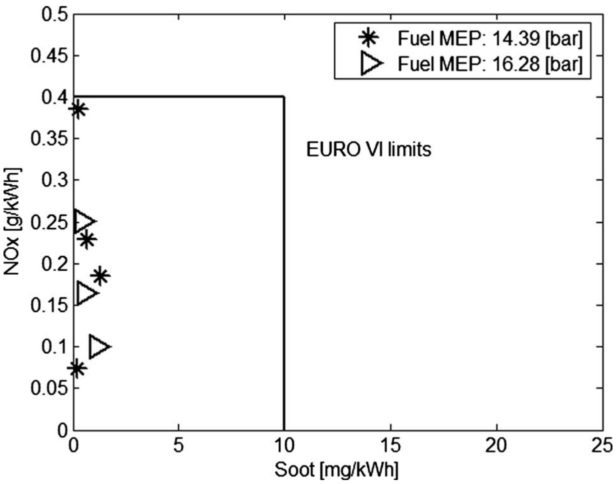

Fig. 5 NO_x-soot tradeoff during the EGR sweep

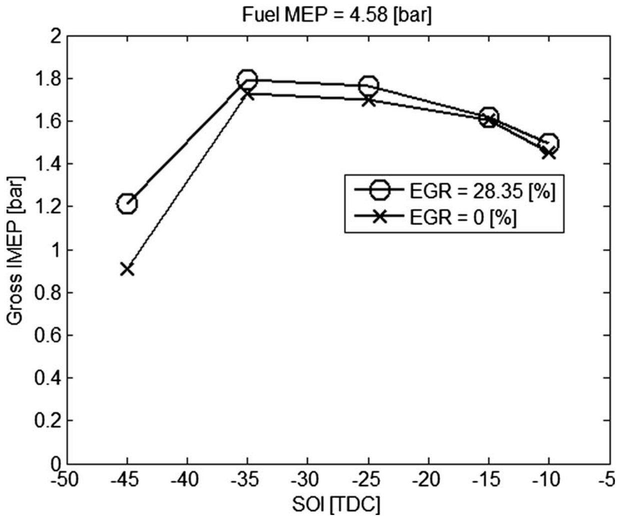

Fig. 6 IMEP gross as a function of the SOI at two different EGR rates

4.2 Low Load: SOI Sweep. A start of injection sweep was performed at a very low load condition in order to understand:

1. the temperature requirement; and
2. the most appropriate SOI for maximizing the efficiencies and having low emissions.

The engine was running at 800 rpm, naturally aspirated, inlet temperature set at 423 K, and fuel MEP at 4.58 bars. This fuel flow resulted in the IMEP values shown in Fig. 6. Some of those values are higher than idle conditions (roughly 1.5 bar IMEP), but with the common rail used in the experiments, it was impossible to further decrease the fuel amount per cycle.

The sweep was performed with two different EGR rates: 0% and 28.35%, which, respectively, correspond to a relative excess of air λ of 4.55 and 3.26. Exhaust gasses were recirculated in order to decrease the pressure rise rate, thus, the further increase in engine acoustic noise in EGR was not possible without increasing the already high inlet temperature, see Fig. 7.

The three efficiencies are shown in Fig. 8; relatively high values were achieved. The stratification level created by injecting the fuel between −35 TDC and −15 TDC was able to result in high

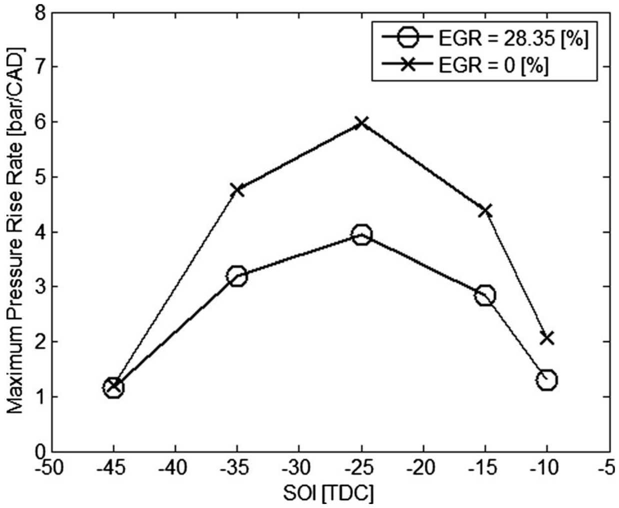

Fig. 7 Pressure rise rate as a function of the SOI at two different EGR rates

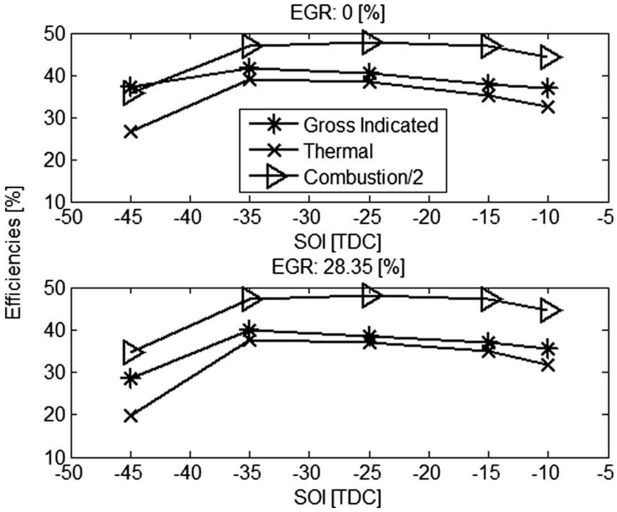

Fig. 8 Indicated, thermal, and combustion efficiencies as a function of the SOI at 0% and 28.35% EGR

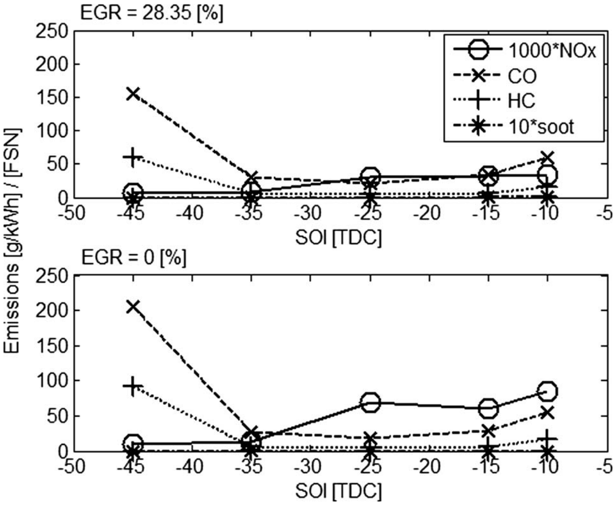

Fig. 10 NO_x, CO, HC versus SOI at 0% and 28.35% EGR

values (relatively to the load) of combustion efficiency. Outside this range, this parameter starts to significantly decrease. The thermal and gross indicated efficiencies have a maximum at −35 TDC. If the SOI is advanced, both parameters slowly decrease, on the other hand, if the SOI is retarded, the decrement is faster.

The analysis of the heat transfer, exhaust, and emission losses reveals why the increasing amount of EGR increases the efficiency and IMEP. 28.35% of recirculated exhaust gasses does not have any effect on the emission losses, see Fig. 9, on the other hand, heat transfer and exhaust losses are affected. In the higher EGR case, heat transfer losses are higher while the exhaust ones are lower. On the other hand, with 0% EGR, the situation is the opposite, see Fig. 9. By increasing the EGR rate, it is clear that the decrease in exhaust losses is faster than the increase in heat transfer, thus resulting in higher efficiency and IMEP. In the high EGR case, lower exhaust losses might be due to the faster combustion ($CD_{90-10} \sim 10$ versus 11.5 CAD), while the increase in heat transfer can be thought to be the combined effect of faster combustion (higher temperature) and longer ignition delay (the hot areas of the combustion are closer to the walls).

Figure 10 shows CO, NO_x, HC, and soot emissions as a function of the SOI at two different EGR rates. In both cases, because of the high dilution of the mixture and low combustion rate, NO_x levels are very low; in case of soot, the long ignition delay (thus, higher homogeneity when the combustion starts) combined with the molecular structure of ethanol resulted in nearly zero emissions. HC and CO are displaying relatively low values when the SOI spans from −35 TDC to −15 TDC. Both emissions have a minimum at −25 TDC. The 0% EGR case shows slightly lower values: 19 versus 23 g/kWh and 5.01 versus 5.15 g/kWh for CO and HC, respectively.

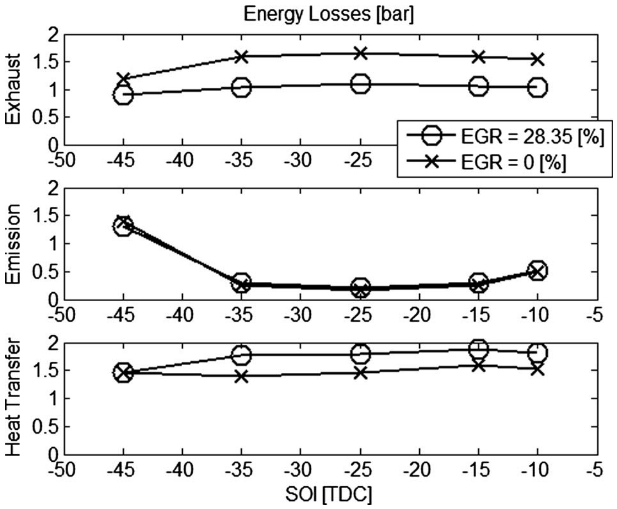

Fig. 9 Exhaust, emission, and heat transfer losses as a function of the SOI and EGR rate (the three losses were normalized with the displacement volume to facilitate the comparison with IMEP and fuel MEP)

4.3 High Load: SOI_p and Pilot-Main Ratio Sweeps. A previous paper written by the authors has shown that high load PPC employing high ON fuels can give low emissions and low fuel consumption by adopting an unconventional injection strategy [12]. The strategy consisted in injecting 52% of the total fuel in the pilot at −60 TDC, add a certain amount of EGR in order to avoid reactions during the compression stroke, and then inject the remaining fuel at TDC; the stratification created by the second injection triggers the combustion, the phasing is controlled by adjusting the start of the main injection.

In this paragraph, a sweep in the start of injection of the pilot and pilot-main ratio has been done in order to prove the validity of the previous founding. The engine was running at 1100 rpm, 323 K inlet temperature, 2.38 bars absolute pressure, 42% of EGR (λ: 1.27 (−)), 12.75 CAD CA50, and 35.67 bars fuel MEP.

Figure 11 shows the variation in IMEP gross during the sweep. High values are obtained when the pilot ratio does not exceed 50% and the SOI_p lies between −80 TDC and −50 TDC. The analysis of HC and CO, see Fig. 12, suggests that if the pilot ratio is higher than 50%, partial quenching of the mixture might occur in the squish region; a proof might come from the high values of unburned hydrocarbons (UHC) and low values of CO when the pilot exceeds 50%.

Figure 13 displays NO_x and soot emissions. Low NO_x can be found when the pilot ratio is between 62.5% and 50%. There is almost any dependence with the position of the SOI_p. Higher NO_x is obtained by reducing the pilot amount. With more fuel in the main, the combustion is mainly diffusion controlled, which leads to a higher NO_x production rate in the rich burning zones. In terms of soot, ethanol shows low values, and as previously stated, this is due to its molecular structure [13]. An increase in soot production can be seen when the SOI_p is set at −50 TDC; this founding is almost independent from the pilot ratio. The authors believe that at this specific crank angle, the spray is hitting the squish area of the piston, thus resulting in pyrolysis phenomena on the piston surface.

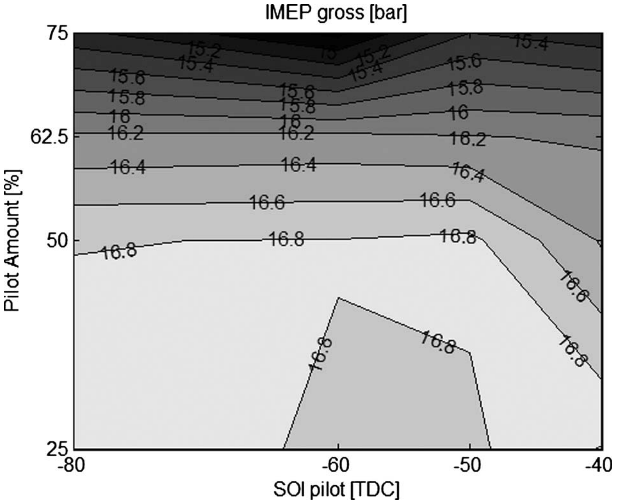

Fig. 11 IMEP gross as a function of SOI_p and pilot-main ratio

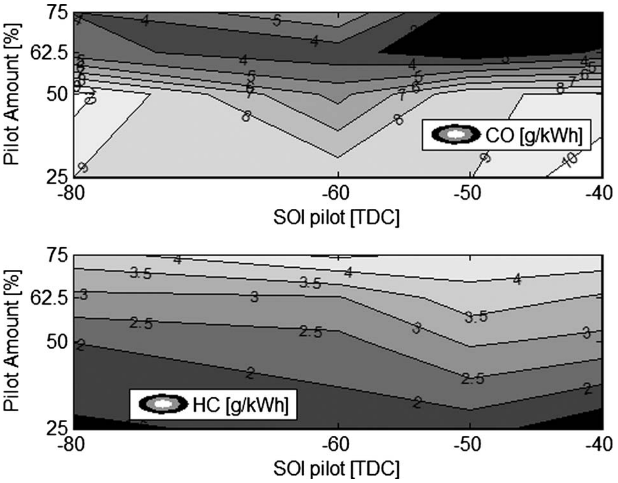

Fig. 12 Gross indicated specific CO and HC as a function of SOI_p and pilot-main ratio

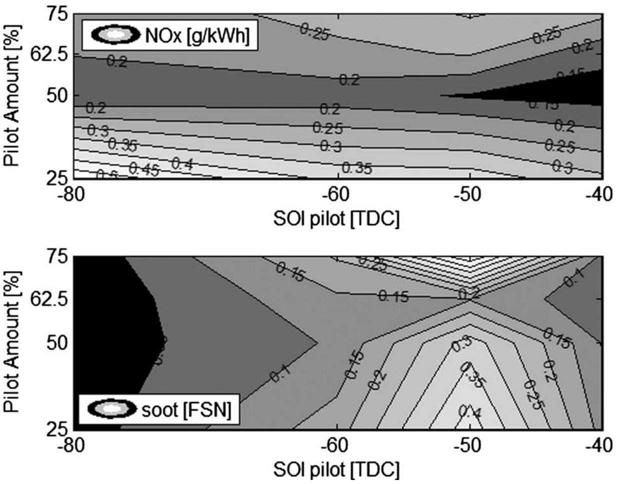

Fig. 13 Gross indicated specific NO_x and soot as a function of SOI_p and pilot-main ratio

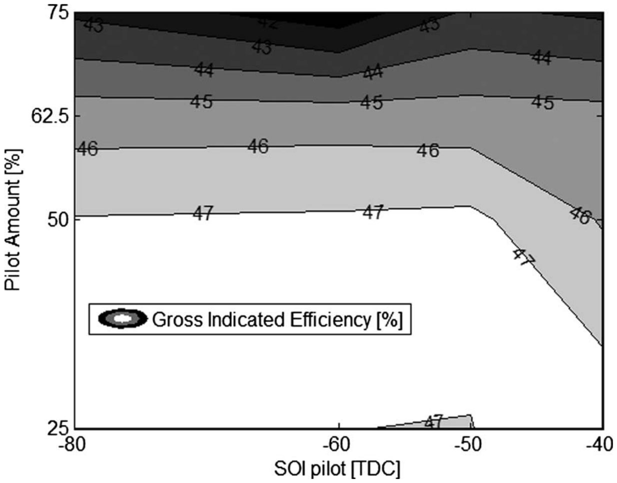

Fig. 14 Gross indicated efficiency a function of SOI_p and pilot-main ratio

In the gross indicated, thermal and combustion efficiencies are presented in Figs. 14 and 15. As argued for the IMEP plot, high indicated efficiency is achieved with a pilot ratio below 62.5% and SOI_p between −80 TDC and −50 TDC. Gross indicated efficiency higher than 47% was obtained; this result was possible because of a combination of high thermal efficiency and high combustion efficiency. Despite the relatively low λ, 1.27, the combustion efficiency is still high (in the worst case 97.4 %); this was possible because ethanol molecule already contains O_2, thus, the combustion is not penalized by air utilization issues as in the case of diesel PPC. Because of the high combustion efficiency, as shown in Fig. 15, CO emissions are not high when λ is low; in the worst case, their value is ~ 10 g/kWh.

The last point to be discussed is the maximum pressure rise rate, which is one of the main issues from a customer's point of view. The maximum pressure rise rate is presented in Fig. 16. Considering the load (~ 16.5 bars gross IMEP), the area in which this parameter is below the threshold value of 15 bars/CAD, is pretty broad. This was possible by the stratification created by partially overlapping the end of the main injection with the start of combustion (SOC); see the ignition delay in Fig. 16.

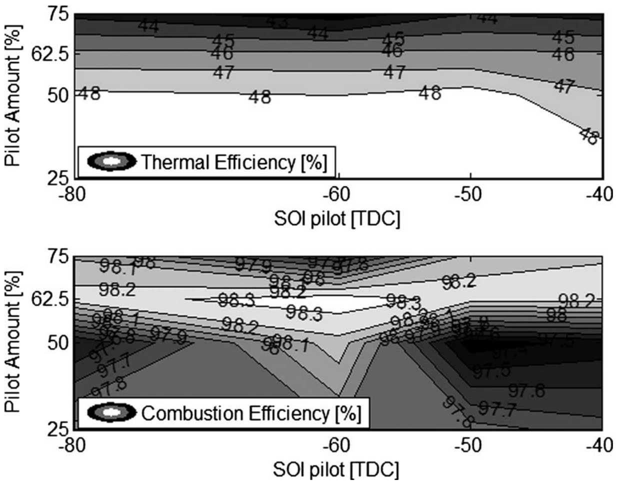

Fig. 15 Thermal and combustion efficiencies a function of SOI_p and pilot-main ratio

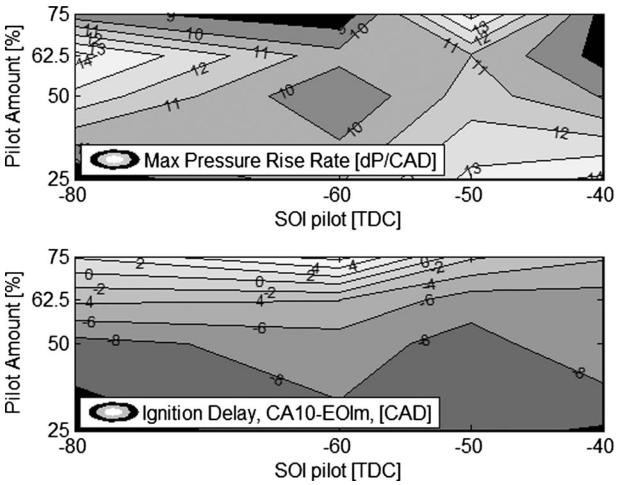

Fig. 16 Maximum pressure rise rate and ignition delay as a function of SOI$_p$ and pilot-main ratio

5 Discussion

The EGR sweep has underlined that PPC combustion with ethanol has the capability of achieving low NO_x and low soot (below 0.4 g/kWh and 0.02 FSN, respectively), and efficiencies above 40%; this is achievable if combustion takes place using 40–47% of EGR, and with λ between 1.15 and 1.25. Within this EGR and λ ranges, CO emissions are still within an acceptable range; a maximum value of 8 g/kWh was found. Those relatively low values of CO were possible because the combustion efficiency is still above 97% when the cylinder is filled with more than 43% of EGR; this is not possible with classical diesel PPC, e.g., Ref. [7]. The reason, which contributed to keep the combustion efficiency at high levels with a lot of EGR, is the fact that ethanol molecule contains 36% in mass of O_2, which means that fuel-oxygen mixing issues are less severe with PPC ethanol because part of the oxidizer is already present in the fuel. The main issue underlined by these EGR sweeps was the high pressure rise rate. When EGR is increased, because the combustion becomes more kinetically controlled, maximum pressure rise rates up to 20 (bar/CAD) are experienced as in classical high load HCCI or as shown by the gasoline PPC engine concept proposed by Kalghatgi [9,10]. In order to solve this issue, double injection is a solution. In a previous work, the authors proposed a new injection strategy in order to properly run PPC combustion with gasoline, and achieve low emissions, high efficiency, and low pressure rise rate [12]. As described in Sec. 4.3, at high load, the strategy consisted in injecting 52% of the total fuel in the pilot, add EGR in order to avoid early ignition, and trigger the combustion through the stratification created by the main injection. By doing so, the compression ratio can be still kept as the one in classical CI engines, and preignition of the pilot can be avoided with EGR. In this way, it is possible to run PPC at high loads to keep the expansion ratio high, and then because of the high compression ratio at medium and low loads, it is not necessary to excessively increase the inlet temperature, thus decreasing the volumetric efficiency. When diesel fuel is used, it is impossible to run the engine in the whole operating range in PPC mode, basically because at high loads, the ignition delay is too short to allow a low stratified mixture prior to ignition. Diesel PPC combustion proposed by Toyota and Nissan, and UNIBUS and MK, respectively, are able to run PPC up to roughly half load, keeping the classical diesel compression ratio [8,14]. By lowering the compression ratio and increasing the EGR rate up to 80%, low NO_x and soot can be achieved at 15 bars BMEP with diesel PPC, but the main penalty resulted in poor efficiency, high CO and HC, and bad utilization of the combustion volume (only 20% of the cylinder is used) [7]. The third section in the paragraph of Sec. 4.3 wanted to prove that even for ethanol, the injection strategy developed for PPC gasoline works; in order to do that, a sweep was done in SOI$_p$ and pilot-main ratio. In order to find the optimized injection strategy, the following boundaries were assumed: $NO_x < 0.17$ g/kWh, maximum pressure rise rate <12 bars/CAD, indicated gross efficiency $>45\%$, and soot as low as possible; the optimized point is presented in Table 2.

Table 2 Best setting for ethanol PPC at 16.81 bars gross IMEP

Pilot	50	(%)
Main	50	(%)
SOI$_p$	−60	(TDC)
$\eta_{\text{ind gross}}$	47.13	(%)
NO_x	0.17	(g/kWh)
Soot	0.0080	(g/kWh)
CO	5.65	(g/kWh)
HC	2.34	(g/kWh)
dP	9.95	(bar/CAD)

Assuming the efficiency of the exhaust, the catalyst is in the range of 95% for CO and HC, and estimating that the EURO VI emission limits are: 0.01 g/kWh, 0.4 g/kWh, 0.16 g/kWh, and 4 g/kWh, respectively, for soot, NO_x, HC and CO, and ethanol PPC at high load is always within the limits.

At high load, ethanol was proved to be a good fuel for PPC combustion. The issue is represented by low load conditions since due to its ON, it requires high inlet temperature to achieve autoignition. It was found that with 423 K as inlet temperature, reliable low load operations can be achieved when the SOI spans from −35 TDC to −15 TDC. The peak of indicated efficiency is achieved at −35 TDC, 39.10%, while the combustion one is above 93% in the previously mentioned range of SOI. In terms of emissions, the problem is constituted by HC and CO. Because of the low combustion temperature, their values are high; for the same reason, NO_x is negligible, and because of the long ignition delay, thus, low stratified combustion, soot does not constitute a concern. The minimum CO and HC were found at −25 TDC, where the indicated efficiency is 1.64% lower than the best setting. In Sec. 4.2, it was underlined that smooth operation can be achieved by adding some EGR, 28.35%. In the optimum point, the emissions of NO_x, soot, CO, and HC were, respectively, 0.03 (g/kWh) below detectable levels, 21.73 (g/kWh), and 4.9 (g/kWh). Assuming again an efficiency of the exhaust catalyst of 95%, all the emissions are within EURO VI, except HC, which is 35% higher than the desired value; an efficiency of at least 97.5% is required.

6 Conclusions

Two EGR sweeps, high and low loads tests were ran on ethanol PPC.

The EGR sweeps showed the following.

1. Low NO_x, soot, CO, and HC can be achieved when the EGR rate lies between 40–47% and λ between 1.15 and 1.25.
2. HC levels slightly decrease when the EGR rate increases.
3. In the λ and EGR ranges previously mentioned, high gross indicated efficiency is achieved, thanks to the fact that the combustion efficiency does not drop when λ is close to stoichiometric.
4. The use of single injection resulted in too high pressure rise rate.

The SOI sweep at idle demonstrates the following.

1. A different optimum SOI exists in order to maximize the gross indicated efficiency and minimize CO and HC.
2. When CO and HC are minimized, the efficiency is only 1.64% lower.
3. NO_x and soot levels are negligible at this load.

4. All the emissions are within EURO VI if it is assumed as a catalyst efficiency for CO and HC of 95% and 97.5%, respectively.
5. The mixture needs to be diluted with a certain amount of EGR in order to smooth the combustion, low pressure rise rate.

The SOI$_p$ and pilot-main ratio showed the following.

1. An optimum SOI$_p$ and pilot-main ratio exist in order to minimize the emissions and maximize the efficiency. In this point, the pilot injection has to be placed at -60 TDC, while the pilot-main ratio was found to be 50:50.
2. By running ethanol PPC, with the optimum settings, NO$_x$ and soot are below EURO VI legislation without using an exhaust aftertreatment system.
3. HC and CO are within EURO VI if an exhaust catalyst with at least 95% of efficiency is used.
4. The engine was proved to be highly efficient. In the optimum point, the gross indicated efficiency was higher than 47%. This was possible, thanks to high thermal efficiency and to the fact that the combustion efficiency does not deteriorate when the cylinder is filled with more than 40% of EGR.

The research has also underlined that the fuel of the future, for this type of combustion process, has to be constituted by a fraction of ethanol (or some other appropriate oxygenate); this is because of the following.

1. The combustion efficiency can be kept above 97%, even when a much EGR are introduced.
2. Oxygenates enable to have high thermal efficiency, which, when combined with high combustion efficiency, result in low specific fuel consumption.
3. The use of some oxygenate, e.g., ethanol, is able to reduce soot production because some of the reactions, which lead to soot formation, are skipped.

Acknowledgment

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Nomenclature

BMEP = brake mean effective pressure
CO = carbon monoxide
EGR = exhaust gas recirculation
HC = hydrocarbon
IMEP = indicated mean effective pressure
λ = relative excess of air
NO$_x$ = nitrogen monoxide and dioxide
ON = octane number
PPC = partially premixed combustion
SACI = spark assisted compression ignition
SOC = start of combustion
SOI = start of injection
SOI$_p$ = start of pilot injection
TDC = top dead center
UHC = unburned hydrocarbon

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