

Investigation of the Combustion Characteristics with Focus on Partially Premixed Combustion in a Heavy Duty Engine

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ABSTRACT

Partially Premixed Combustion (PPC) has shown its potential by combining high combustion controllability with emission characteristics that are close to those of an HCCI engine. In order to get PPC the ignition delay needs to be long enough for the fuel and air to mix prior to combustion. This can be achieved by injecting the fuel sufficiently early while running with high EGR.

In order to find out where and how PPC occurs a map that shows the changes in combustion characteristics with injection timing and EGR was created. The combustion characteristics were studied in a six cylinder heavy duty engine where the Start of Injection (SOI) was swept from early to late injection over a wide range of EGR levels. The emissions were monitored during the sweeps and in the most promising regions, with low emissions and high efficiency, additional changes in injection pressure and engine speed were applied to get a more versatile picture of the combustion.

INTRODUCTION

Partially Premixed Combustion is a combustion strategy in the region between diffusion combustion and Homogeneous Charge Compression Ignition (HCCI) meaning that the fuel and air mixes before combustion but the charge is not homogeneous. The interest in PPC has increased in recent years due to its capability to achieve low emissions while having control of the combustion phasing which is one of the major issues when using the HCCI combustion strategy to

obtain low emissions.

The higher controllability is caused by the connection between the combustion timing and the injection timing. In traditional diesel combustion the fuel is injected close to TDC with a short ignition delay and it is fairly easy to get the desired combustion timing. However, a short ignition delay does not permit extensive fuel/air mixing which in turn may lead to high levels of PM. Hence it is of interest to extend the ignition delay without losing too much of the controllability.

There are many ways of increasing the ignition delay. It can be done by injecting the fuel very early as in [1, 7, 8], with a lower cetane fuel as in [1, 5] or with lower compression ratio as in [11] etc. In this study the ignition delay was made longer by running the engine on high EGR levels and advance or retard the start of injection compared to conventional injection timing. These strategies cover the "Model Kinetics" combustion proposed in [2] and early injection concepts presented in [4, 6, 9, 10] among others. By diluting the mixture with EGR the combustion temperature decreases which reduces NO_x formation. It is therefore possible to combine low PM and NO_x emissions with these concepts. However, too high EGR rates lead to high CO and HC emissions as well as low efficiency.

The intention of this paper is to show the changes in combustion characteristics with injection timing and EGR. In particular it is investigated how the heat release is affected. The investigation focused on changes in mixing period, in this work defined as the difference between the end of injection and the

crank angle of 10% heat released, but other parameters were also considered and together they created a map that shows the development from diffusion combustion to partially premixed combustion.

The EGR level was changed from 0 to 50% and even higher in some cases. The emissions and efficiencies were monitored during these sweeps and then studied to find the most promising regions where the study was intensified and additional changes in injection pressure and engine speed were made to get a more versatile and graduated picture of the changes in combustion. Due to the magnitude of the emission maps, a part of this work is dedicated to analyze the emission data and compare the outcome with previous studies in the field.

In the last part of this paper the dynamics between the fuel injection and the combustion was studied by means of step response analysis where the dynamic effects that changes in the injection duration and pressure have on the combustion parameters were considered. The underlying relations that affect the combustion behaviour were discussed in an effort to understand and explain the combustion dynamics from a physical perspective. Finally, the connection between the combustion related parameters and emissions and efficiency were investigated with the purpose of telling which of the parameters that are suitable as controlled outputs in a closed loop system.

The result from these experiments constitutes the foundation for control oriented system identification of different PPC regions which in turn will be the basis for closed loop control in future work.

EXPERIMENTAL

EXPERIMENTAL SETUP The engine that was used in these experiments was a 12 litre, six cylinder, Volvo diesel engine. Table 1 shows the engine specifications. The engine was equipped with Delphi E3 unit injectors where the injection pressure, start of injection and injection duration could be changed from cycle to cycle when needed. The E3 injector has injection pressure capability up to 2500bar. The limit is determined by several factors including the fuel cam rate and cam phasing relative to the engine. The design of camshaft used for these tests allowed the cam phasing to be set for maximum pressure capability at injection timings after 20 BTDC. The engine had a cooled long route EGR system and a Variable Geometry Turbine (VGT) that made it possible to adjust the boost pressure. The fuel that was used in the experiments was Swedish Class 1 diesel fuel with cetane number 51.

Table 1: Engine specifications

Operated cylinders	6
Displaced Volume	2000 cm ³
Bore	131 mm
Stroke	150 mm
Connecting Rod Length	260 mm
Number of Valves	4
Compression Ratio	18.5:1
Fuel Supply	DI

All cylinders were equipped with Kistler 7061B pressure transducers. The rocker arm at cylinder one was equipped with a force transducer which signal was used to calculate the injection pressure. The cylinder and injection pressure signals were sampled every 0.2 CAD by a Microstar DAP 5400a/627 data acquisition card while additional pressures and temperatures were sampled by a data logger working at a slow sampling frequency. Pressure data was transferred from the AD card to a control program. When a new pressure curve was available in the control program, a simplified rate of heat release calculation was performed based on the apparent heat release rate with a fixed ratio of specific heats [12].

In this paper the brake efficiency consists of four sub-efficiencies. Combustion efficiency is the ratio between the heat released and the energy in the fuel. Thermodynamic efficiency is the ratio between the mechanical work at the piston and the heat released. Gas exchange efficiency is the ratio between IMEPn and IMEPg. Mechanical efficiency is the ratio between BMEP and IMEPn.

METHOD The experiments were carried out at low and medium speed at 25% of the maximum load at conventional diesel operation. The lower speed is 1200 rpm and the medium speed is 1450 rpm. These operating points are referred to as A25 and B25 respectively. The load was tuned in conventional diesel mode without EGR where the inlet pressure was set to 1.3 Bar since it gave good brake efficiency and allowed the engine to run lean up to 60% EGR. The amount of fuel injected each cycle was kept constant by using a fixed injection duration and injection pressure in order to let SOI be the only injection parameter varied in the sweeps. This resulted in a slightly lower load at high EGR due to lower efficiency.

SOI was swept between -20 to 4 CAD ATDC. On lower EGR levels it was not possible to inject the fuel earlier than -12 CAD ATDC due to violation of $dP/dCAD_{max}$ constraints. The latest SOI tested was at 4 CAD ATDC which is on the combustion stability border for higher EGR levels with this setup.

RESULTS AT A25

EMISSIONS Figure 1 shows how the emissions vary with injection timing and EGR at 1200 rpm with 25% load corresponding to a BMEP of 5 bar. The PM level, which was calculated from opacimeter measurements, becomes an issue at higher EGR levels and at 50 % EGR PM emissions are very high which is a similar trend to that reported in [4]. The increase of PM is probably due to a temperature reduction in combination with a lower λ that follows an EGR raise when the intake pressure is constant. The SOI dependency is connected to changes in mixing period. A long mixing period reduces PM formation.

The NO_x formation was very high for the region with low EGR, especially for advanced injection timings. This trend can also be seen in [1] where NO_x increases with an advanced SOI due to higher combustion temperatures until the injection is early enough to achieve a lean mixture with high homogeneity.

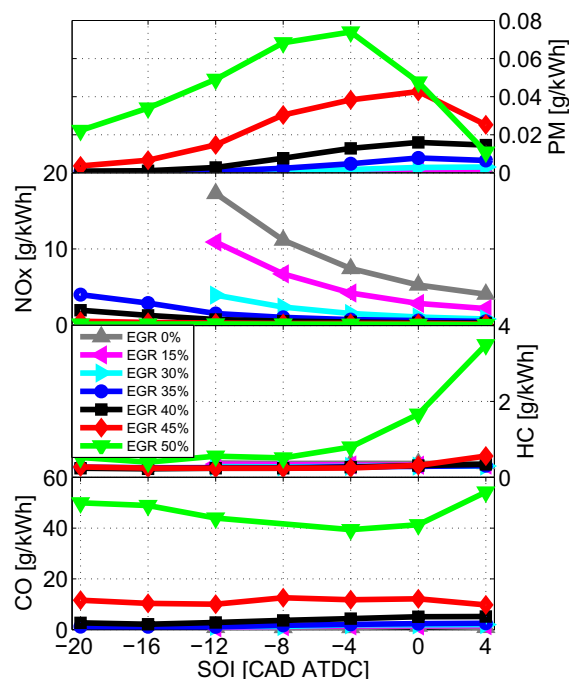


Figure 1: Emissions vs. SOI for different EGR levels

The development for HC and CO emissions is also studied. The level of HC is low and fairly constant at EGR rates up to 45 % but increases dramatically for late injection at 50 % EGR. This behaviour can also be seen in [2] where the "Model Kinetics" combustion concept shows high HC emissions under similar circumstances. CO on the other hand does not seem to be a function of SOI. However, the EGR level dependency is clear. CO is high for EGR levels above 40 %

due to low combustion temperature which affects the chemistry and an equivalence ratio close to stoichiometric with locally rich regions.

The critical area in terms of PM emissions is seen in Figure 2. The level curves corresponding to emission legislations show that early injection is to prefer in order to keep PM at a low level at these EGR rates. The peninsula shape can be recognized as a combination of the smoke formation development in [4] when sweeping EGR and the smoke formation development that [5] shows when sweeping SOI at 60% EGR. In the region between 35-50 % EGR NO_x emis-

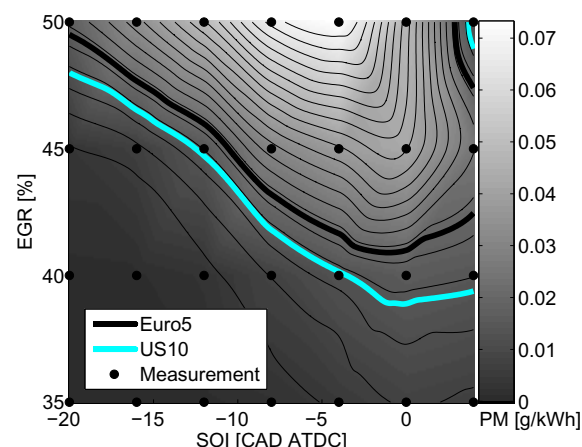


Figure 2: PM emissions in the critical region with level curves at Euro5 and US10 Emission Standards

sions reach lower levels. When studying Figure 3 it can be seen that even the very stringent US10 emission standard is fulfilled in a window with high EGR levels, preferably with late injection. The major reason for the decrease in NO_x is the decrease in combustion temperature.

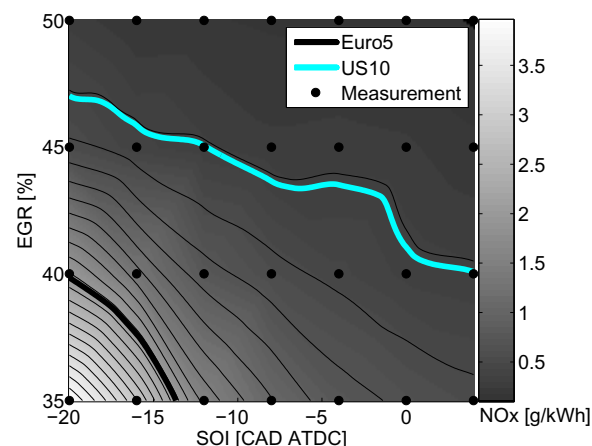


Figure 3: NO_x emissions in the critical region with level curves at Euro5 and US10 Emission Standards

EFFICIENCIES The different efficiencies can be studied in Figure 4. The combustion efficiency is fairly constant and SOI independent up to 40 % EGR where it starts to decrease. The increase in HC emissions for late injection timings at 50 % EGR that was shown earlier can be observed as a decrease in combustion efficiency all though this decrease was expected to be larger. The most noticeable change in thermodynamic efficiency is that the maximum tends to be found for earlier injection timings when increasing EGR. This is due to a longer ignition delay that follows a higher EGR ratio where MBT timing is achieved for earlier SOI.

The gas exchange efficiency deteriorates with an increased EGR ratio due to a higher exhaust back pressure that is needed to raise the EGR level. It is also seen that the mechanical efficiency deteriorates which follows directly from the reduction in IMEP. The result is that brake efficiency deteriorates with in-

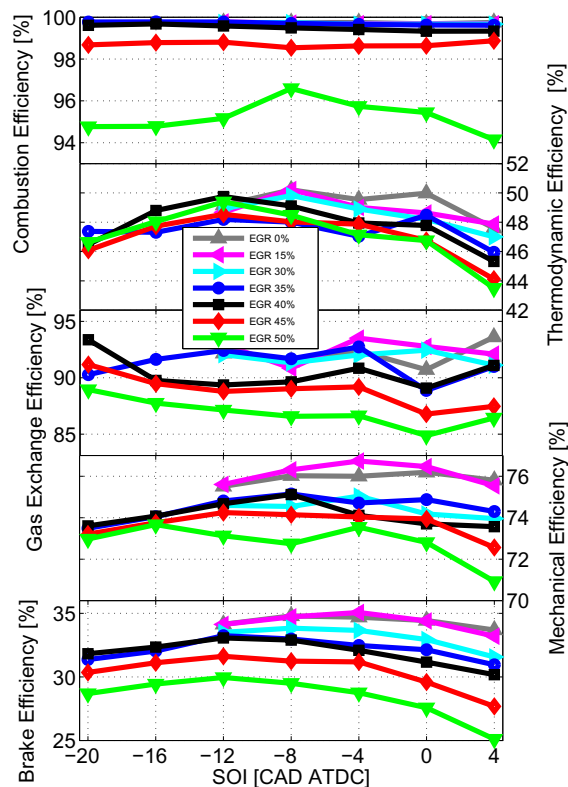


Figure 4: Efficiencies vs. SOI for different EGR rates

creasing EGR, a behaviour which is very distinct for EGR levels over 40 %. The lowest efficiency is found for high EGR levels with late injection timing. This result is similar to that reported in [5] for this type of combustion.

COMBUSTION CHARACTERISTICS Figure 5 shows the Mixing Period (MP) defined as the distance between end of injection and start of combustion ($MP=CA_{10}-EOI$), similar definitions can be found in [3, 5, 6] among others. The black level curve shows where this period is zero. The region with a positive mixing period is considered a Partially Premixed Combustion region. The Heat Release Rates (HRR) for different operating points are shown in the lower part of the figure. The typical shape of a premixed combustion can be seen for the point at 50% EGR with start of injection at -20 CAD ATDC. There is also a large part of premixed combustion at 35% EGR all though some diffusion combustion occurs. The difference in combustion timing is very clear while the maximum in HRR is approximately the same for early injection PPC at 35% and 50% EGR. In both cases low temperature reactions occur but they are more pronounced in the case with high EGR.

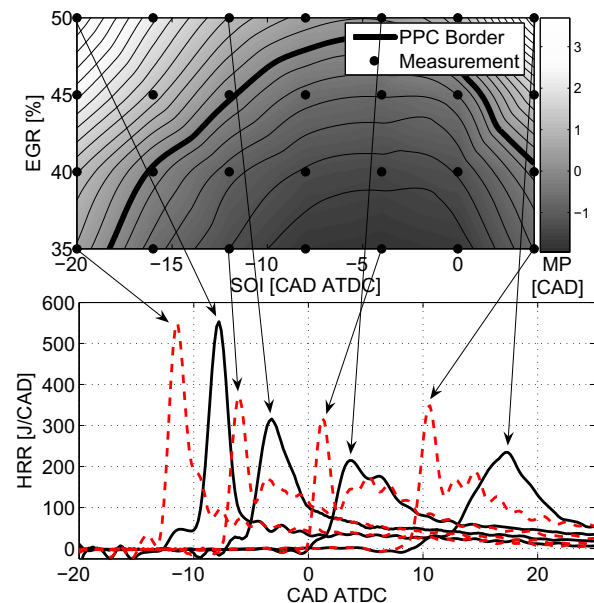


Figure 5: Mixing period and the corresponding HRR at A25 with 1000 bar injection pressure

In the other end of the spectrum the late injection at 50% EGR results in a MK combustion event described in [2, 3]. This also involves a low temperature reaction as with the early injection PPC. When looking at points in the SOI interval [-12,0] the conventional diesel HRR can be observed for 35% EGR where as the same interval shows borderline PPC combustion for the 50 % EGR test corresponding to the high smoke experiments in [4]. It is also observed that the combustion duration increases with a retarded injection.