Towards Identifying Flame Patterns in Multiple Injection Schemes on a Single Cylinder Optical Diesel Engine

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1 Introduction – Concept

Engine development is nowadays focused on optimising thermal efficiency by incorporating alternative technological concepts and fuels, also accounting for the global dependence on fossil feedstock, which will maintain its share in combustion technologies, at least for the foreseeable future [1].The target is to cover the increased demand for high performance and comfort levels, while simultaneously address stringent vehicular exhaust emission norms. These novel combustion modes diverge from conventional flames which are collectively characterized by high temperatures, significant heat losses, sooty behavior, and go towards regimes characterized by high mixing, low temperatures and controlled heat release rates. In particular, the optimization of Diesel engines is vital since they dominate road-based transportations [2]. Modern diesel engines exploit technologies such as common-rail systems, complex fuel injection control strategies, exhaust gas recirculation and exhaust gas after-treatment schemes [3], to meet the emission limitations while maintaining high thermal efficiency and specific power output. Consequently, low temperature combustion models, such as Homogeneous or Partially-Premixed Charge Compression Ignition (HCCI or PCCI) arise [4-7].

HCCI operation at low loads is difficult to achieve because of inability to autoignite very lean mixtures, while, at high loads, high pressure rise rate may potentially cause very high noise and possible damage to the engine. PCCI combustion constitutes an attractive, since the partially premixed mixtures allow autoignition at low and high loads with high efficiency and lower NO_x and particulate matter (PM). However, relatively high emissions of hydrocarbons (HC) and carbon monoxide (CO) may be present combined with increased noise levels, a fact that is tackled through a variety of fuel types and combustion phasing control strategies [8-12]. Contrary to conventional diesel combustion comprising both kinetically- and mixing- controlled phases, partially premixed combustion constrains the diffusion phase which is largely responsible for soot formation. As a result, the focus is shifting on autoignition kinetics which are, in turn, affected by the local charge composition (equivalence ratio) and reactants temperature and pressure histories. Evidently, EGR, apart from reducing NO_x [13], is a promising alternative for controlling such engine combustion modes. However, a major issue is to overcome the fact that the start of combustion is not an independent variable and may vary to an unacceptable extent [14]. This may be treated by complex injection schemes and excessive EGR levels, hence prolonging ignition delay [15], resulting in greater premixing and in turn lower smoke due to either shorter formation time, or through enhancing soot oxidation [16].

Multi-injection strategies are rapidly transforming diesel combustion into a series of low temperature, stratified charge, premixed combustion events, where NO_x formation is avoided due to lower temperatures and soot formation is avoided as the mixture gets more fuel-lean. Soot exhaust emissions are in turn reduced by lowering the local equivalence ratio and re-oxidation of formed soot [17-18]. In addition, many injection strategies incorporate post-injection schemes aiming at reducing engine-out emissions of unburned hydrocarbons. By injecting small amounts of fuel soon after the end of the main injection, fuel-lean mixtures near the injector that suffer incomplete combustion can be enriched with post-injection fuel and burned to completion [19]. Moreover, late injection may be also used for particulate filter regeneration [20]. Such schemes have attracted considerable research focus so as to accurately describe the in-cylinder processes associated to fuel post-injection in diesel engine especially operated at Low Temperature Combustion [21-23].

The present work expands acknowledged operating conditions and attempts to visualise this behaviour in the previously characterized single cylinder Ricardo Hydra engine [24]. Measurements are performed in the latter apparatus with respect to various post- injection timings and amounts. The multiple pilot and main injection events are kept constant and correspond to partially premixed combustion modes, facilitating the systematic assessment of post-injections effect on in-cylinder pressure and heat release as well as various flame characteristics. The results reveal important differences despite minor differences on in-cylinder pressure. It is shown that the effect of the injected amount is less important than its timing especially, as the post-injection is closer to the main event.

2 Experimental Apparatus

The experimental campaign utilized Ricardo Hydra single cylinder engine sharing the same head with a metal I4, EURO-V, Ford Puma diesel engine (2.2 L, 114 kW), with common rail (Siemens PRC 2.5 and Continental K10-14) 8 hole injectors (350 Flow 153 CA). The engine has been recently modified to incorporate hydraulic systems for effortless assembly and access to the combustion chamber. Previous work focused on parameterizing the effect of the pre-injection pressure and timing on spray and flame characteristics via Laser Induce Incandescence measurements [24]. In-cylinder pressure trace monitoring and analysis was realized through in-house codes. The camera system consisted of a Photron Fastcam APX-RS high-speed CMOS camera controlled by LaVision HighSpeed Controller, equipped with a 50 mm (1:1.8) Nikkon lens. The camera was driven at a frequency of 20000 Hz which corresponds approximately to 3 images per CAD for 1200 rpm. The images (exposure time: 50 μs) were recorded with 720x526 pixel resolution over 10 cycles, with 100 images per cycle. The optical filter for CH chemiluminescence was a 430 nm bandpass filter (FWHM 20 nm, T_{max}=45%) whereas chemiluminescence of C_2 was detected with a an optical bandpass filter at 514 nm (FWHM 30 nm, T_{max}=54%). Additional proper orthogonal decomposition (POD) analysis was realized so as to identify major flame patterns. POD analysis was also essential for analysing chemiluminescence images. In particular, CH and C_2 line-of-sight, high speed chemiluminescence measurements have been performed as they hold an eminent role on flame characteristics. The short-lived CH^* radicals mainly include C_2 and C_2H as precursor species and are formed within a narrow reaction zone of high temperature gradients (indication of the flame front), hence regarded within the context of the current campaign as an indication of the mixture reactivity. On the other hand, CH_2 and C_3 species play a prominent role on the formation of the excited C_2 species, which become more intense on the locally fuel-rich pockets formed. Therefore, C_2 chemiluminescence images can provide information about fuel-rich zones, predominately originated from premixed areas of the flame [25].

3 Results and Discussion

The work examines the effect on late injection on the lifted, partially premixed, turbulent diffusion flame created by imposing a triple pre-injection strategy and several post-injections, as presented in Table 1. The results presented here on correspond to engine speed at 1200 rpm, intake air temperature 60 ^{o}C and injection pressure at 25 MPa. The IMEP was kept at 2.5 bar. Obviously this is not the valid for the base case considered (less fuel amount injected hence IMEP value approx. 2 bar) although it can be anticipated that since post-injection reduces the overall efficiency, such a comparison is of essence for practical purposes. Evidently, the initial stage of ignition is virtually the same for all studied cases. The analysis is performed through flame luminosity, CH and C_2 chemiluminescence as well as via in-cylinder pressure analysis. The flame natural luminosity (Fig. 1) along with the respective in-cylinder pressure and heat release rates (Fig. 2) are shown in below.

Table 1. Cases considered. Base Case follows the same injection events without any post-injection

Case	Pre injection(s) (CAD)	Pre injection(s) (mg/cycle)	Main injection (CAD)	Main injection (mg/cycle)	Post injection (CAD)	Post injection (mg/cycle)
A	-14.7/-8.1	1.68/1.59	-5.6	5	5	1
B	-14.7/-8.1	1.68/1.60	-5.6	5	5	2
C	-14.7/-8.1	1.68/1.61	-5.6	5	0	2
D	-14.7/-8.1	1.68/1.62	-5.6	5	10	2

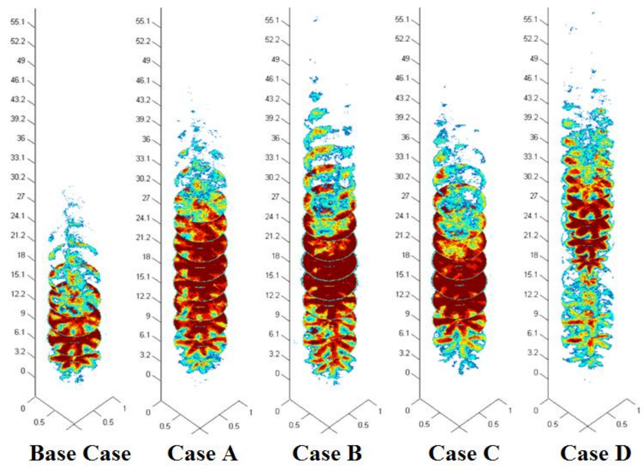

Figure 1. Flame natural luminosity profiles as a function of CAD for all cases considered

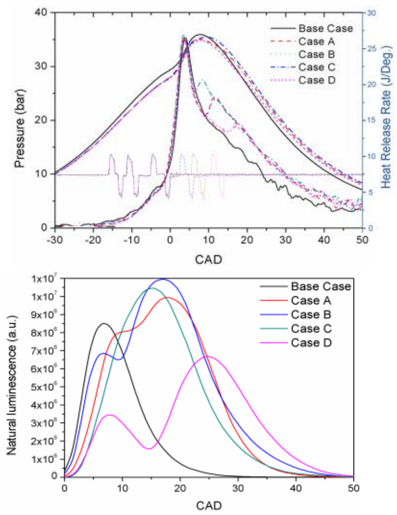

Figure 2. In-cylinder pressure and accumulated heat release rate profiles (top) and integrated natural luminescence signal for all cases considered (bottom)

Apparently, although the in-cylinder pressure does not change effectively, the heat release characteristics do. As indicated more clearly by comparing the accumulated heat release rate profiles, Cases A and B reveal a notable resemblance in HRRs indicating that the amount of injected fuel does not hold and important role as the injection timing is close to the main event.The analysis of in-cylinder pressure trace reveals that the combustion event initializes at approximately 5 CAD, while CA50 is achieved at ca. 11 CAD. For the base case, *i.e*. no post-injection, the combustion event is completed at 22 CAD, whereas for Case A, this happens at approx. 26 CAD where CA90 is achieved. For the rest of the cases, the combustion event is further delayed by ca. 3 CAD, since the fuel amount during the post injection is increased, as indicated by CA10-CA90 observations. However, high speed flame natural luminosity reveals that these observations are only representative for the base case. In other words, when late injection is employed high speed imaging reveals that combustion continues further on. Integrated flame luminosity signal, shown in Fig.2, reveals that for post-injection timings closer to TDC, *i.e*. Cases A-C the combustion main event overlaps with the secondary one due to late injection, whereas for delayed injection, *i.e.* Case D the flame evolution is characterized by two discrete events. Moreover, it could be anticipated that Case D would eventually be characterized by higher end-soot emissions, since the recorded luminosity mainly originates from soot. This could imply lower oxidation rates given that all pressure and HRR profiles are identical after 20 CAD.

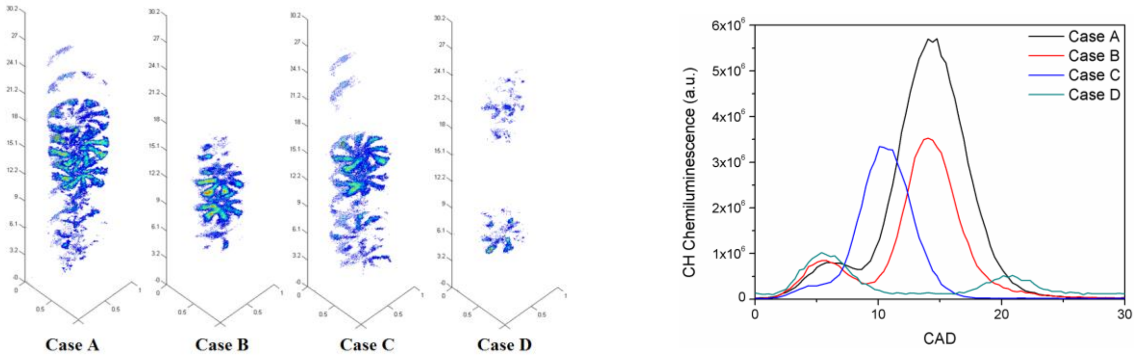

Figure 3. Combustion evolution captured by CH-species chemiluminescence for all studied cases

A multitude of chemically reactive radicals hold a dominant role in controlling ignition, fuel oxidation, heat release, flame propagation and pollutant formation. In particular, CH species may function as a heat release marker and C_2 species are of eminent influence on depicting premixed, fuel rich flame zone characteristics, as described in previously. Figures 3 and 4 present CH and C_2 POD images respectively, for Cases A-D. Measurements of the latter species chemiluminescence provides an insight on the effect of the late injection on mixture reactivity and overlapping with the main combustion event, respectively, and are also discussed against natural flame luminosity observations. Note that the signal intensity of C_2 and CH luminosity varies significantly. Integrated signal as a function of CAD are also shown for each case.

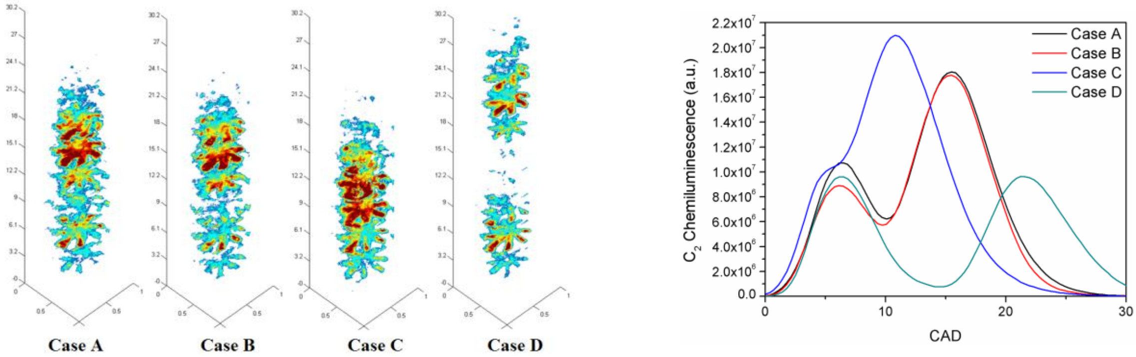

Figure 4 Combustion evolution captured by C_2-species chemiluminescence for all studied cases

In the context of engine operation, an interesting feature is that the increased injected fuel at the same timing (*i.e*. Case A and B) enhances the reaction zone and potentially leads to faster fuel conversion although exhibits slightly less intensity, as both C_2 and CH data suggest. Such an observation could be particularly useful in assessing late injection strategies and it is rather difficult to obtain through pressure trace analysis or natural luminosity imaging. This behavior could also indicate that the last injected fuel amount in Case B was more efficient in terms of enriching fuel-lean areas in the partially premixed zone and in turn lead to a more prompt reaction completion. This is even more pronounced in Case C, where, naturally, the fuel post-injection scheme closer to the TDC, and therefore closer to the main event, increases flame luminosity, as well as mixture reactivity and premixed zones as noted through the total recorded signal of CH and C_2 respectively. This demonstrates that the reaction zone intensity, especially as captured by CH imaging, is enhanced nearly after the TDC and fuel is consumed faster. The latter behavior is also captured by high speed imaging, whereas pressure trace analysis fails to provide such indications. Finally, the late injection *i.e*. Case D, points towards the formation of a district rather than a continuous phenomenon, characterized though be a more mild flame front. Results imply that this flame evolution is also responsible for the peculiar heat release profile, which in turn partially explains why CA90 is achieved practically at the same position. Overall, optical measurements are in agreement with indications based on pressure trace analysis, providing however adequately more insight of the late injection interaction with the main flame.

4 Conclusions – Future work

The combination of pre- and post-injection events is experimentally investigated in a single-cylinder optical engine. The work focuses on the influence of post-injection and results are discussed and analyzed via in-cylinder pressure and heat release measurements. The different combustion modes are also visualized by means of high speed imaging and CH and C_2 chemiluminescence. High speed flame visualization reveal that fuel increase close to the main combustion event does not significantly affect the flame structure and evolution, although might hold an important role on engine-out emissions. The flame intensity is strongly affected when late injection coincides with the main event whereas a late post-injection leads to a virtually secondary flame front formation. Future work includes the application of laser-based diagnostics and measurements on a metal engine sharing the same geometry and injector so as to accurately describe and identify soot formation tendency under the studied conditions.

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