A comparative study on the effect of simulated EGR environment on spray characteristics under engine-like conditions

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Abstract
Increasing concern over air quality and security of energy supply poses challenges to engine research and manufacturing. Despite improvements in conventional engine design, many alternatives are winning their place in order to further reduce engine-out emissions. Sophisticated operating modes, such as homogeneous charge compression ignition (HCCI) and Partially premixed Charge Compression Ignition (PCCI), often coupled with exhaust gas recirculation and/or aftertreatment are employed for regulating nitric oxide (NO_x) and soot emission levels. However, a totally homogeneous mixture is unachievable in practical engines. Inherent inhomogeneities in fuel concentration and temperature may significantly affect the ignition and combustion processes, hence various control strategies attract research interest. The present work demonstrates the potential of emission reduction in Diesel engines operating under high boost conditions through a combination of multi-injection strategies and high EGR schemes.

Introduction

Stringent vehicular exhaust emission norms, along with increased demand for high performance and comfort levels, challenge engine manufacturers to develop novel engine concepts towards milder operating conditions. These challenges are exacerbated by the global dependence on fossil fuels, which are projected to further increase their share in combustion technologies at exponential rates, at least for the foreseeable future [1]. Given the increasing number of Diesel engines road applications, both in passenger cars and particularly in trucks, where they dominate, their performance optimization is vital [2]. Hence, powerful incentives rise for researching new ways of improving efficiency, as well as exploring new engine concepts as well as alternative fuels.

Modern diesel engines exploit technologies such as common-rail systems, complex fuel injection control strategies, exhaust gas recirculation (EGR) and exhaust gas after-treatment schemes [3], to meet the increasingly stringent emission limitations while maintaining high thermal efficiency and specific power output. Relatively new concepts, such as Homogeneous or Partially-Premixed Charge Compression Ignition (HCCI or PCCI) based on low temperature combustion modes, can allow for better control of ignition timing, affecting the overall combustion and hence favouring engine conditions that inherently produce significantly lower soot and NO_x emissions [4-7].

HCCI operation suffers from the limited range of operating conditions where the autoignition process can be controlled. For example, HCCI operation at low loads is difficult to achieve because of inability to autoignite very lean mixtures, while, at high loads, HCCI can lead to high pressure rise rate causing very high noise and possible damage of the engine. PCCI combustion constitutes an attractive alternative to HCCI (and conventional combustion), 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) are present combined with increased noise levels. As a result, there has been continued research effort placed, which has led to great progress in overcoming the above inherent limitations of PCCI operation [8]. The main focus of current research throughout the world is on theoretical, numerical and experimental studies describing the fundamental governing phenomena of PCCI combustion, investigating a variety of fuel types and, more importantly, developing advanced combustion phasing control strategies linked with different levels of boost in order to extend the operation range with low emission, high efficiency and reasonable noise levels [*e.g.* 9-11].

In PCCI mode, fuel and air are partially mixed prior to combustion and auto-ignition as a result of the temperature increase in the compression stroke is delayed due to dilution with Exhaust gases and control of the injection timing. This operation mode resembles both spark (due to premixing) and compression ignition (due to auto-ignition) engine characteristics. As a result, for diesel-like fuels, one may observe a two-stage heat release, also associated with low temperature kinetic reactions, whereas the time delay between the two stages may be attributed to the negative temperature coefficient (NTC) regime developed between them [12]. However, there is no in-cycle control on combustion phasing and issues related to knock may become a problem.

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The latter makes the control of PCCI engines more difficult. Delayed autoignition is governed by chemical kinetics, thus controlling the combustion phasing requires tuning the auto-ignition kinetics through mixture preparation and dilution with Exhaust Gases (EGR), which is affected by the charge composition (hence, equivalence ratio) and -mainly- the temperature and pressure histories of the reactants during the compression process. Understanding and control of the above process is crucial for successful operation of practical Diesel engines [13-14].

EGR strategies are already implemented on conventional diesel engines aiming to reduce combustion temperature and NO_x emissions by diluting the inlet charge and increasing its heat capacity. The introduction of EGR also constitutes a promising method for controlling PCCI engines over a wide range of speeds and loads; however, PCCI operation requires much higher levels of EGR than currently used in conventional Diesels. In conventional diesel combustion, where the in-cylinder temperature can be as high as 2700 K, resulting respectively in increased NO_x emissions, high EGR reduces NO_x but increases soot. However, this is not the case for very high levels of EGR, which lead to low temperature combustion regimes, which can reduce NOx and soot at the same time.

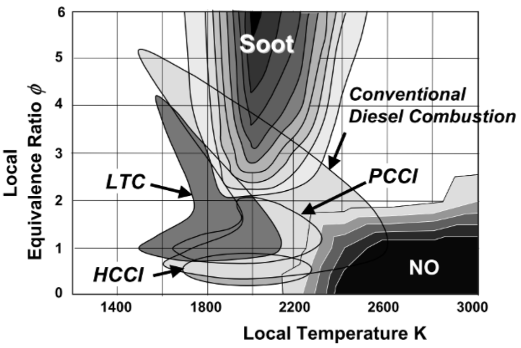

Figure 1 LTC and PCCI concept on φ – T map [18]

A previous parametric study performed on a EURO-V diesel engine at Imperial has revealed the potential of breaking the established NO_x/soot trade-off by introducing higher proportions of EGR at higher boost pressures (up to 4 bar abs). An external unit was utilised to deliver variable boost pressure, in order to maintain all parameters constant apart from boost pressure. Improvements in specific fuel consumption and emissions with moderate levels of boosting at low loads were also obtained [15].

The present work is motivated from the latter campaign and acknowledges operating conditions that achieve the desired emission levels. It attempts to visualise the spray behaviour and autoignition characteristics by means of high speed photography and Laser Induced Incandescence [16] in a single cylinder Ricardo Hydra optical engine installed at Imperial College. Here, additional measurements are performed in the latter apparatus with respect to various EGR levels as previously reported. EGR has been simulated as pure CO_2 stream in order to accurately control and determine its effect on engine behaviour. The experimental campaign has been supported by numerical simulation taking into account detailed chemical kinetics for fuel chemistry. The above results may be elucidated via the understanding of the spray behaviour under similar conditions.

Background – Infrastructure – Concept

It is well established through advanced in-cylinder measurements realised over the past years, a lifted, partially premixed, turbulent diffusion flame, which is created in diesel engines, hosts a number of locally fuel-rich pockets. These are in turn mainly responsible for soot formation. On the other hand, although higher combustion temperatures enhance the burnout of soot, they also reduce air flow entrainment and increase soot formation rates, as well as NO_x formation [17]. The examined concept involves multi-injection strategies which 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 (Fig.1). Soot exhaust emissions are in turn reduced by lowering the local equivalence ratio and re-oxidation of formed soot [18].

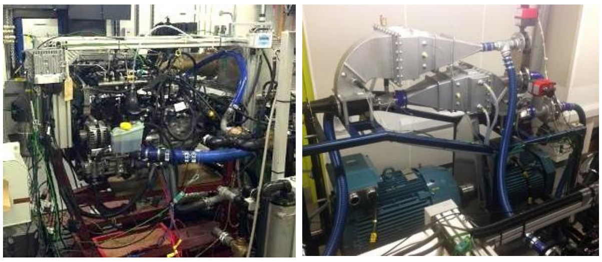

Figure 2 Ford Puma engine and electrical boost unit

Previous work on a 4-cylinder, 2.2 L, 114 kW, EURO-V, Puma diesel engine with common rail (Siemens PRC 2.5 and Continental K10-14), 8 hole injectors (350 Flow 153 CA) revealed extremely low levels of both smoke and NO_x, breaking also the trade-off between emissions and fuel consumption, under heavy EGR conditions.

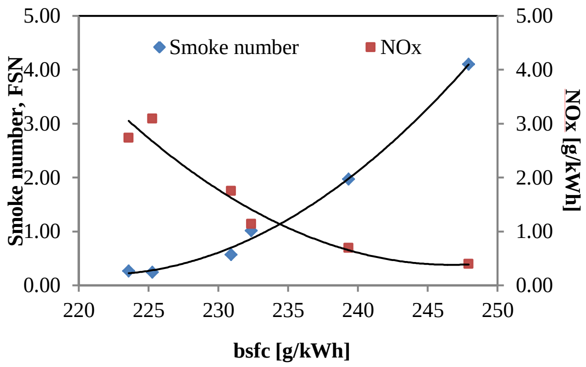

Figure 3 NOx and smoke levels (%) measured

This parametric study was only feasible with the development and incorporation of an electrical boost unit by the team of Imperial College London (Fig.2). The parametric study [15] concerned EGR comprised of 10% high pressure stream and additional 20 to (even) 60% low pressure streams. Indicatively, smoke levels dropped below 1 FSN (filter smoke number or mg/m³) and NO_x levels below 1 g/kWh for conditions corresponding to 1750 RPM, 75 Nm, 6.8 bar BMEP, whereas, fuel conversion efficiency was kept constant, at ca. 45% (Fig.3).

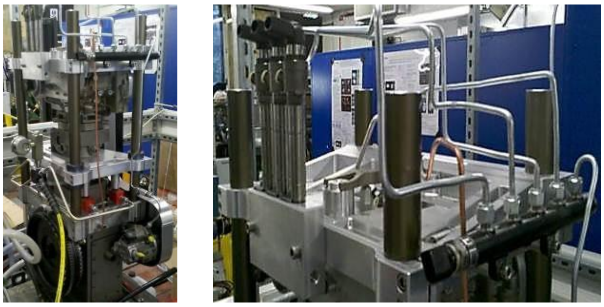

Figure 4 Ricardo Hydra single cylinder optical engine sharing the same cylinder head geometry as the metal Ford engine

In addition, the experimental campaign for mapping and characterizing the engine operation in terms of emissions and performance, was expanded in a single cylinder, optical engine. Optical diagnostics have been applied widely to reveal in-cylinder combustion processes. The single cylinder Ricardo Hydra optical diesel engine at Imperial College used for this work, shared the same injection system as the previously described Puma engine (Fig.4).

The engine head was a standard Ford Puma 2.0L Euro V diesel engine which had been modified to fit onto single cylinder with the head of other cylinders removed. The engine has been also recently modified to incorporate hydraulic systems for effortless assembly and to provide access to the combustion chamber. The work focused on parameterizing the effect of the injection pressure and timing on spray and flame characteristics with high speed imaging and Laser Induce Incandescence measurements [16].

The concept of the present work is structured and organized so as to further foster prior knowledge and exploit obtained experience. The campaign focuses on the following directions; the expansion of previous work towards the incorporation of simulated EGR under chosen injection profiles with optical diagnostics. The extension of previous work towards even more realistic injection profiles simulating multiple rather than split injection strategies. This would include lower amounts of pilot injection compared to the ones used in [16]. The combination and evaluation of optical measurements at Ricardo Hydra and engine-out NO_x/smoke emission measurements from the I4 engine under the exact same injection scheme/pressure/amount/duration, will be proved vital in order to visualize and provide an insight on the governing phenomena of the considered flames.

Finally, the work is supported by numerical calculations based on a code first developed by Mastorakos simulating HCCI, multi-zone engine combustion. During the recent years the code has been modified, *e.g.* with the addition of an EGR subroutine, to realistically capture combustion events. The model incorporates a literature detailed chemical kinetic mechanism with 550 species and 2450 reactions [19].

Results and discussion

In the present section, the combustion behavior of a double and a triple injection strategy, captured by means of high speed imaging is presented. The analysis is performed through flame luminosity, CH and C_2 chemiluminescence and by monitoring and analyzing in-cylinder pressure and respective heat release rates. Figure 5 shows the evolution of the in-cylinder process for Case A as described in Table 1. The La Vision HighSpeedStar with the DaVis acquisition software has been used. The respective in-cylinder pressure along with the heat release rate and the injector signal are also shown below (Fig.6).

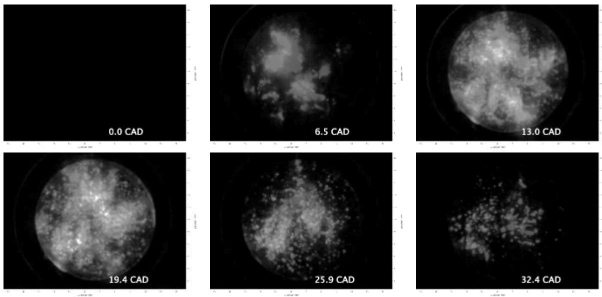

Figure 5 High speed flame luminosity measurements for Case A, *i.e.* triple injection strategy employed.

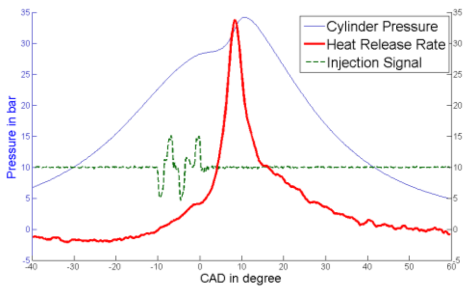

Figure 6 In-cylinder pressure, calculated heat release rate and injector signal for Case A.

The experimental results reveal that the combustion event initializes at approximately 5CAD, while CA50 is achieved at 9.8CAD. An extremely thorough parametric study on similar conditions may be found in [16].

Following the latter case, a triple injection strategy has been employed and further analyzed. Apparently, although the in-cylinder pressure does not change effectively, the heat release characteristics are changed. This is clearly captured in the series of images presented in Fig. 7. Note that both figures 5 and 7 are normalized to the same level, hence their difference in intensity, scales to the level of flame luminosity.

Table 1 Conditions tested

Case	A	B
Engine speed (rpm)	1200	1200
Intake air temperature (^oC)	60	60
IMEP (bar)	1.79	1.79
Injection pressure (MPa)	25	25
Pilot injection(s) (^oCA)	-10.6	-10.6/-8.1
Pilot injection(s) (mg/cycle)	1.68	1.68/1.59
Main injection (^oCA)	-5.6	-5.6
Main injection (mg/cycle)	6.59	5

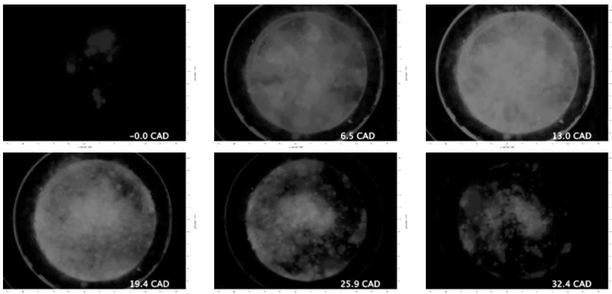

Figure 7 High speed flame luminosity measurements for Case B, *i.e.* triple injection strategy employed.

A striking difference is that combustion initiates earlier in Case B, although further analysis reveals that CA50 is achieved approximately at the same timing, ca. 9.5CAD. However, the apparent heat release rate does not reach the same levels as in Case A, as shown in Fig.8. This behavior may be attributed to the apparently more homogeneous flame shape that is captured in Case B.

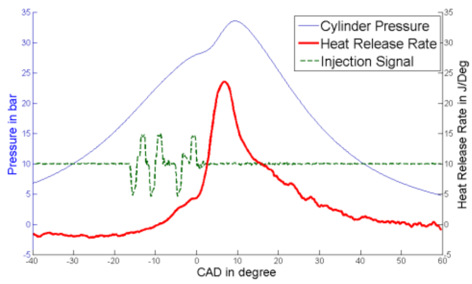

Figure 8 In-cylinder pressure, calculated heat release rate and injector signal for Case B.

Combustion proceeds through a multitude of elementary reaction steps, which involve chemically reactive radicals**.** These intermediates play a dominant role in controlling the network of chemical processes and these species are predominantly involved in fuel consumption and oxidation and are thus of eminent influence on ignition, heat release, flame propagation and flame quenching, as well as pollutant formation reactions [20].

The use of C_2 species depicts the flame zone characteristics capturing in more detail the main combustion event as shown in Fig. 9 between 7 and 13CA. For instance, the swirling flow is evidently exhibited. Note that for this case the swirl ratio was calculated approximately 3.5. The results reveal similar trends as previously recorded (Figs. 5 & 7) promoting the understanding of the effect of the second pilot injection. Moreover, this behavior was further captured by means of CH chemiluminescence.

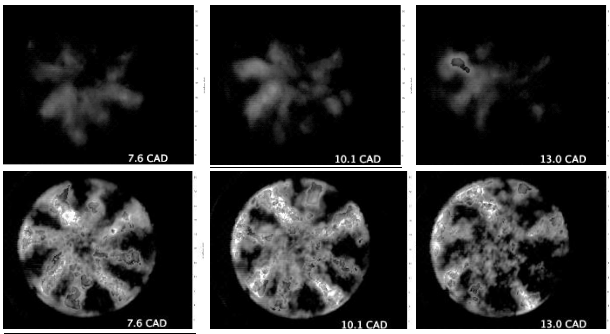

Figure 9 Comparison between Cases A (top) and B (bottom) via C_2 chemiluminescence imaging

Figure 10 shows the comparison of CH (upper) and C2 (lower) chemiluminescence signal for Case B, after Proper Orthogonal Decomposition (POD) post-processing [21] via an in-house developed code. The previously discussed trends regarding the flame development are satisfactory described. In addition, Fig. 10 reveals a remarkable resemblance with the governing pattern of CH imaging (upper raw) with the major underlying pattern of the C_2 data, especially during the main combustion event. However note that the signal intensity apparently varies significantly between C2 and CH images. These findings will be further elaborated and enriched in the poster with measurements with both CO_2 as well other diluents addition.

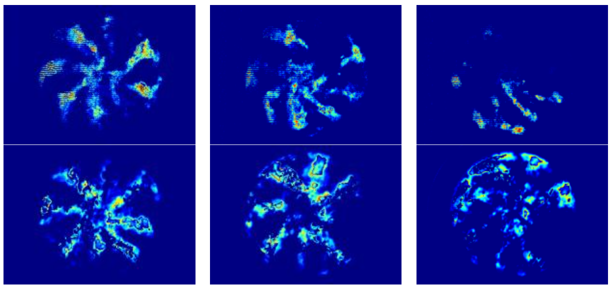

Figure 10 Comparison between CH (upper) and C2 (lower) chemiluminescence signal for Case B for 7.6, 10.1 and 13 CAD subsequently

Finally, the results were simulated with the code described previously. Figure 11 presents the comparison between experimental data and numerical predictions for the conditions similar to Case A as described in Table 1, with the difference being that both the pilot and the main injections were 6 mg. The code incorporated a three zone model with zone sizes 0.5, 0.25 and 0.25 respectively with injection progressing at -15 and -14 CAD, taking place solely at the first two zones [16].

The simulation is able to reproduce major trends and timing, indicating however that further work is required both in terms of kinetic mechanism schemes and zone definition. Nevertheless, as it stands, it provides a base for quick analysis and parameterization of the effect of e.g. engine conditions and injection strategies.

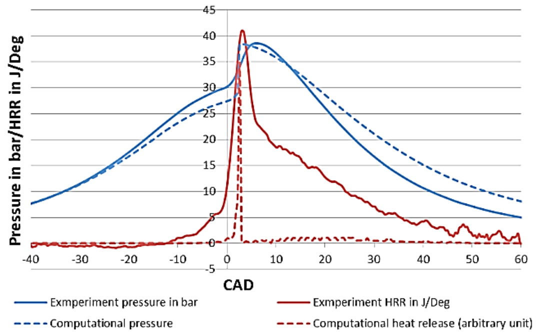

Figure 11 Pressure and heat release experimental data comparison with numerical predictions of a three zone combustion model.

Conclusions – future work

The incorporation of a combination of a high and low pressure EGR stream has sparked the interest of further study, since its effect on both NO_x and soot exhaust levels was found to be paramount. An optical engine sharing the same engine head as the metal one, where the emission measurements were obtained, was utilized in order to visualize the latter trends.

The present paper presents the influence of a multi injection strategy as this is analyzed by 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. Selected experimental cases were additionally simulated by an in-house developed code. The full poster will incorporate results addressing the effect of CO_2 constituent species to the latter flames using both traditional and optical diagnostic techniques, as described earlier.

Results will be verified under engine-like condition utilizing the chemical preheating technique in a combustion research unit (CRU). This suggests that the initial mixture reaches high temperature and pressure through the deflagration of hydrocarbon- hydrogen mixture selected in order to resemble the desired thermo-physical and thermo-chemical properties such as the density and specific heat capacity and heat conductivity. The fuel vapour 'petals' concentration may be visualised by methyl-naphthalene tracer planar laser induced fluorescence (PLIF), showing the spatial distribution of fuel vapor as a function of time (μs) after injection. Indicative results from similar experiments performed in a high pressure, high temperature Constant Volume Combustion Chamber may also be included in the final version of the poster presentation.

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