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A study on the interaction between local flow and flame structure for mixing-controlled Diesel sprays

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ABSTRACT

A detailed study on the spray local flow and flame structure has been performed by means of PIV and laser-sheet LIF techniques under Diesel spray conditions. Operating conditions were based on Engine Combustion Network recommendations. A consistent comparison of inert and reacting axial velocity fields has produced quantitative information on the effect of heat release on the local flow. Local axial velocity has been shown to increase 50–60% compared to the inert case, while the combustion-induced radial expansion of the spray has been quantified in terms of a 0.9–2.1 mm radius increase. As a result, the drop in entrainment rate has been quantified around 25% compared to the inert case. Streamline analysis also hints at a reduced entrainment under reacting conditions. A 1D spray model under reacting condition has been used, which confirms the modifications obtained in the main flow metrics when moving from inert to reacting conditions. When comparing the flow evolution with the flame structure, little effect of chemical activity on the spray flow upstream the lift-off length has been evidenced, in spite of the presence of formaldehyde in such regions. Only downstream of the lift-off length, as defined by OH LIF, has a strong change in flow pattern been observed as a result of combustion-induced heat release.

1. Introduction

Driven by the need to comply with engine-out emission regulations, last two decades have seen a huge development of the fundamental knowledge related to Diesel spray combustion. Initial efforts were mainly based upon experimental investigations, which enabled the synthesis of conceptual models [1–3] that contained a description of physical and chemical processes taking place during the different stages of the spray evolution. The development of computational models capable of predicting such fundamental processes has been a second major achievement in this scientific field, which can lead to an improved engine design [4]. In the meantime, the synergy between modelling and experiments is leading to an improved understanding of such complex phenomena, as recent activities within the Engine Combustion Network (ECN) demonstrate [5].

Most of the efforts within this field have been devoted to the understanding of the mixing process between fuel and air, which governs Diesel combustion process. Experimental investigations have delivered spray tip penetration [6,7], mixture fraction [7] and local velocity measurements [8,9], which have led to the general conclusion that the mixing process of a Diesel spray is rather similar to that of a gas jet at similar mass momentum and fuel/air density ratio conditions [10]. On the other hand, knowledge on the interaction between mixing process and flame development is a more open topic, where some questions are still unresolved. As an example, lift-off length has been within the scope of many analyses, which have been very often based upon the experimental quantification of this characteristic length [11–13]. The mechanism governing lift-off stabilisation is still not fully explained, with different hypotheses still under discussion, e.g. the stabilisation location at equilibrium between the local flow and combustion velocity or the recirculation of burnt gases at the flame base, among others [14,15]. This characteristic length is also a point of interaction between the mixing field and flame development, with important consequences on soot production as correlations between equivalence ratio at the lift-off length and soot measurements within the flame have shown [12].

Keeping the previous framework in mind, some still unknown issues on the evolution of Diesel sprays can be identified, which mainly have to do with the spray flow development. The latter topic has been deeply analysed in terms of spray tip penetration and, to a much lower extent, with local velocity measurements [8,9,16]. However, except for the classical work by Kobayashi et al. [17] using shadowgraph visualisation and a more recent one by

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Table 1
Investigated operating conditions. 'a' stands for ambient conditions. XO_2 is the mole fraction of oxygen in the ambient.

Condition	*Ta* [K]	rhoa [kg/m^3]	XO_2 [%]	Pinj [bar]	InjDuration [µs]
SA	900	22.8	15/0	1500	1500 (PIV) /5000 (LIF)
T2	780	22.8	15/0	1500	5000
EX	780	14.8	15/0	1500	5000

Rhim and Farrell [16] using PIV, most of such studies have been usually carried out under inert spray conditions. Furthermore, only the latter authors report a detailed comparison between inert and reacting conditions. More systematic approaches have been found recently on the evolution of the spray flow after heat release onset. Evidences have been mainly based on high speed schlieren imaging, which has shown that the evolution of the spray tip penetration departs from the inert one due to heat release [17–21]. The magnitude of the change depends on the operating conditions, ranging from no effect on heat release [20] to a clear acceleration of reacting versus inert penetration [19,21]. Furthermore, an increase in spray width due to heat release has also been quantified [22]. Although most of such phenomena happen during the main injection period, flow effects have also been deeply investigated in the after-end-of-injection phase [9,23,24], due to their implications on late combustion and unburnt hydrocarbon formation.

The immediate question is therefore how the reacting flowfield interacts with the flame structure. A first example has already been discussed above, namely the flame lift-off stabilisation, although many other are possible, which make up the natural framework for the present contribution. The work reported here has two general objectives. On the one hand, a detailed description of the changes in local flow evolution when shifting from inert to reacting conditions will be carried out by means of PIV measurements. The second major point of analysis will be the interaction between the local flow and the flame structure, for which the PIV results will be compared to those obtained by means of LIF techniques. In both cases, the analysis will be based upon ECN collaborative results [5], which have made it possible to build a detailed database of Diesel spray behaviour under inert and reacting conditions, for both local flow evolution and flame metrics. Only the availability of such detailed information will help answer such fundamental questions.

2. Methodology

2.1. Experimental conditions

Experiments have been conducted at IFPEN constant-volume pre-burn vessel, which simulates thermodynamic conditions near top-dead-centre in a compression-ignition engine [25]. The interior of the optical chamber is a cube, 1.4 L in volume, with windows in the cube faces for laser and imaging access. Within the vessel, high ambient temperatures are achieved through the combustion of a flammable gas mixture. The injection is triggered when the desired chamber temperature is reached during the cool-down of the combustion products. Initial pressure and composition (before the combustion event) are selected to obtain the desired temperature, density, and oxygen concentration at the start of injection (see [25] for more details on the vessel operation). Three experimental conditions have been considered in the present study, which are described in Table 1. The first one corresponds to the nominal ECN Spray A (SA) condition, while the other two imply a modification in ambient temperature (T2) and temperature and density (EX) compared to SA. Experimental data have been obtained in three different campaigns:

Table 2
Combustion indicators for the investigated conditions. ID stands for Ignition Delay, OH*LOL for chemiluminiscence-derived lift-off length, $\phi_{cl\ LOL}$ for on-axis equivalence ratio at the lift-off length position and d_{eq} for equivalent diameter (see the definition of this characteristic length within the text).

Condition	ID [µs]	OH*LOL [mm]	$\phi_{cl,LOL}$	d_{eq} [mm]
SA	0.41	17.1	6.90	0.481
T2	0.77	24.6	2.824	0.481
EX	1.19	39.5	2.404	0.597

- A first PIV campaign, producing Spray A (inert/reacting) PIV data (2nd ECN Workshop).
- A second PIV campaign, producing T2 and EX PIV data (3rd ECN Workshop).
- A LIF/OH* campaign, producing SA, T2 and EX LIF data (3rd ECN Workshop).

PIV for SA condition (inert and reacting) and T2 (inert) have been published in [9,26], respectively, although a detailed analysis of entrainment under reacting conditions has not been performed before. LIF/OH* results for SA have been published in [27], and the remaining conditions are analysed here for the first time.

A single-hole Bosch injector (reference units #210678 and 201-02) from the Engine Combustion Network has been used. Fuel pressure is controlled with a pneumatic pump, and the fuel is provided through a common rail, following ECN recommendations [5]. The fuel is n-dodecane, which has a density of 703 kg/m^3 at the experimental conditions. The fuel pressure is set at 1500 bar, for which the steady-state average mass flux through the injector is 2.25 g/s and the corresponding momentum flux is 1.22 N. The nozzle has a 88.6 µm orifice diameter. Injection duration has been long for all experiments (∼5000 µs) to enable the analysis of the steady flow and flame structure, except for the PIV measurements under SA condition, for which the ECN standard 1500 µs injection duration has been used.

Based upon the previous operating conditions, some combustion metrics have been obtained that can help identify the general combustion evolution, namely ignition delay (ID), OH* derived lift-off length (OH*LOL) and an estimation of the equivalence ratio on the spray centreline at the LOL ($\phi_{cl,LOL}$) by means of the 1D spray model referenced below. Such quantitative parameters are included in Table 2, together with the equivalent diameter $d_{eq} = d_0\sqrt{\frac{\rho_f}{\rho_a}}$ according to the classic definition in the literature [28,29], which will be later used to normalise analysis under different entrainment conditions.

2.2. Experimental tools

2.2.1. PIV measurements

A schematic of the optical setup for PIV measurements is shown in Fig. 1 (left). The ambient into which injection occurs is seeded with zirconium oxide particles with a diameter below 5 µm, density 5700 kg/m^3. The estimated Stokes number is below 0.2 in the measurement region. Illumination is provided by a double-pulsed two-cavity 527 nm YLF laser. Each laser cavity is operated at