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An experimental analysis on the evolution of the transient tip penetration in reacting Diesel sprays

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ABSTRACT

Schlieren imaging has helped deeply characterize the behavior of Diesel spray when injected into an oxygen-free ambient. However, when considering the transient penetration of the reacting spray after autoignition, i.e. the Diesel flame, few studies have been found in literature. Differences among optical setups as well as among experimental conditions have not allowed clear conclusions to be drawn on this issue. Furthermore, soot radiation may have a strong effect on the image quality, which cannot be neglected.

The present paper reports an investigation on the transient evolution of Diesel flame based upon schlieren imaging. Experimental conditions have spanned values of injection pressure, ambient temperature and density for typical Diesel engine conditions. An optimized optical setup has been used, which makes it possible to obtain results without soot interference. Based on observations for a long injection event (4 ms Energizing Time), the analysis has resorted to extensive comparison of inert and reacting sprays parameters, which have made it possible to define different phases after autoignition.

Shortly after autoignition, axial and radial expansion of the spray have been observed in terms of tip penetration and radial cone angle. After that, during a stabilization phase, the reacting spray penetrates at a similar rate as the inert one. Later, the reacting spray undergoes an acceleration period, where it penetrates at a faster rate than the inert one. Finally, the flame enters a quasi-steady penetration phase, where the ratio of reacting and inert penetration stabilizes at a nearly constant value. The duration of the reacting spray penetration stages shows modifications when varying engine parameters such as air temperature, air density, injection pressure, and nozzle diameter. However, the proportionality between reacting and inert penetration has been observed to depend mainly on temperature, in agreement with observed reductions in entrainment when shifting from inert to reacting conditions.

1. Introduction

Throughout the years, transient injection and combustion phenomena within direct injection Diesel engines have been widely studied to optimize engine combustion and emissions. Part of this research effort has been performed by means of optical techniques, which has produced a deep understanding of fundamental processes that have been summarized in conceptual models, such as the ones by Dec [1] or more recently by Musculus et al. [2].

Such investigations have confirmed the fundamental role of fuel–air mixing process over the combustion process. The usual approach for the research community to undertake spray mixing studies has been by de-coupling it from the combustion process by using singular test rigs that reproduce engine thermodynamic conditions in an oxygen-free atmosphere [3–6]. Such non-reacting studies have been focused on the detailed description of quantitative spray parameters, such as vapor spray tip penetration, liquid length, or local equivalence ratio. Classical examples are those by Naber and Siebers [7], which have provided non-reacting penetration data in a wide range of gas densities (from 3.3 kg/m^3 to 58.6 kg/m^3) and air temperature values (from 600 to 1400 K). More recent works [8] confirm that current knowledge of spray flow evolution under inert conditions is quite deep.

On the other hand, there is also a wealth of information of spray processes under reactive conditions, but most of it is devoted to particular phenomena such as autoignition [9], Lift-Off Length [10,11] or soot formation within the diffusion flame [12–16]. Compared to the detailed knowledge of inert spray flow, much less information is available in the literature on the evolution of the spray flow during the ignition and subsequent flame development. This lack of knowledge has even led to some phenomenological models to use a description of the penetration process under inert conditions even after the start of combustion [17].

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A first study reported by Kobayashi et al. [18], where the reacting spray tip penetration was investigated in a rapid compression machine by means of the schlieren technique under thermodynamic conditions characteristic of low engine load (17.2 kg/m^3 density and 627 K temperature), showed for a long injection event (3.8 ms duration) a similar evolution of the spray tip penetration previous to the autoignition process (2 ms) when compared to the non-reacting spray. Soon after the autoignition, they found a slight increase on the spray tip penetration that progressively decreased during the injection event to even penetrate slower than the non-reacting case near the End Of Injection (EOI). Siebers [19] extended the data based in [7] and showed that the reacting spray behavior compared to the inert one depends on ambient density. Penetration was found to be similar to the non-reacting case for the lowest density values due to a long ignition delay, which was similar to observations by Kobayashi [18]. However, as density increased (i.e. shorter ignition delay), the spray penetration began to deviate from the non-reacting case, with a faster progression that could be observed until the EOI.

Pickett and Hoogterp [20] investigated reactive spray penetration with schlieren imaging under moderate EGR conditions (15%O_2; 22.8 kg/m^3 ambient density and 900 K ambient temperature) for a 1.5 ms injection event. Similar trends were observed during the autoignition and later penetration phases as reported by Siebers in [19]. Additionally, they observed a strong radial expansion at the time when tip penetration detaches from the non-reacting case, which also was coincident in time with the sudden increase of the soot luminosity recorded with a photodiode. Close to the EOI, they found that the tip penetration was similar to the penetration of the non-reacting case.

Finally, preceding work by Desantes et al. [21] made use of a 1D spray model developed in [22] to identify some of the processes occurring during the spray autoignition and subsequent flow penetration. Model predictions were compared to experimental measurements from an optical engine run at a 29 kg/m^3 density and 780 K temperature for injection duration of 1.3 ms. Despite the experimental test matrix is somewhat limited and optical window size did not allow to fully visualize the stabilized flame, the spray width is observed to increase after autoignition, and momentum flux along the spray changes abruptly compared to the inert case, where radially integrated momentum flux is conserved along the spray. The flow reacts in the direction of increasing local velocities, and therefore penetration rate, up to a point where momentum flux is re-balanced, and the flame penetrates as a zero-delay one.

From the above findings, spray tip penetration after autoignition seems to increase over the inert case at a rate somewhat depending on the test conditions. Different experimental results show that sometimes there is a clearly faster penetration, while in other cases differences between inert and reacting spray tip evolution are within the experimental uncertainty. Given the fact that different schlieren optical arrangements were used in previous investigations [18–21], a question can be raised as to how strong the influence of the setup on the results can be or, if this behavior is mainly dependent on the operating conditions.

The present paper tries to contribute to the understanding of the transient effects induced by combustion on the spray penetration and the flow evolution. In agreement with preceding works and also with literature reports, schlieren imaging of the reactive spray evolution will be performed. Careful considerations presented in [23] have been accounted for when setting up the system optics to enable reliable schlieren measurements. Tests have been performed in a Constant-Pressure Flow (CPF) vessel with a much larger visualization system than in [21]. A wide set of conditions has also been investigated to try to evaluate the validity of previous conclusions. Finally, analysis has considered not only spray penetration, but also increase in radial width, and Lift-Off Length measurements. The reported free spray results, with maximum tip penetration in the range of 100 mm, are not intended to be extrapolated to a real engine, where wall distance to the nozzle is typically below 50 mm. However, processes governing tip penetration within the reported experiments should be similar to those within an engine spray. Accordingly, the purpose of the paper is the gaining of fundamental knowledge to understand such phenomena.

The manuscript is structured as follows: Right after this introduction, the experimental facility, optical configuration and processing routines are described. Then, the different operating conditions spanned in this investigation are presented. Analysis of results has been divided into four different subsections. Starting from a general description, the transient evolution of the reacting spray is defined as well as the parameters used for further parametric analysis. After that, considerations for reacting spray 1D modeling in terms of reacting spray angle significance are detailed. Next, a statistical evaluation of Lift-Off Length (LOL) measurements from schlieren images is performed enabling interpretation of the reacting penetration behavior through evaluation of the fuel–air mixtures upstream the LOL. Lastly, the influence of some of the most relevant operating variables (namely injection pressure, air temperature, air density and nozzle diameter) on the global description of the transient flame evolution is evaluated. The conclusions section summarizes the most important finding of this paper.

2. Experimental apparatus

Experiments have been conducted in an optically accessible Constant Pressure Flow vessel (CPF). Gas within this facility can be pressurized and heated up to 15 MPa and 1000 K, respectively. The facility can be operated in either open or closed loop. In the former case, dry fresh atmospheric air is supplied by a volumetric compressor. In closed loop operation, N_2/O_2 mixtures at controlled composition are re-circulated along the circuit, reproducing non-reacting ($[O_2] = 0\%$) or EGR conditions.

The gas velocity across the chamber has been estimated to be minor compared to the spray velocities even at far distances from the spray tip, with approximate values of 0.2 m/s and 0.4 m/s. As a consequence, a quasi-quiescent environment is obtained, and the shot-to-shot spray dispersion is reduced when compared to optical engines and rapid compression machines. Since high temperatures are continuously sensed on the injector tip, a water coolant circuit has been drilled in the injector port in order to maintain a user-selected constant and safe temperature on the injector body. An independent electronic system permits to establish the injection frequency during the experiments, being 0.5 Hz for this investigation.

Four orthogonally drilled ports provide access to the combustion chamber. The first of these accesses is occupied by the injector port and the cooling system for the injector body. The other three accesses are equipped with round quartz windows (128 mm in diameter) in a T-shaped path providing both perpendicular access and frontal view for spray analysis of single-hole nozzles and multiple-hole nozzles, respectively.

3. Schlieren imaging

Based upon the spatial variation of the refractive index of target liquids or gases[24], schlieren is a common technique to evaluate the vapor phase fuel evolution in hot ambient gases such as in test rigs for Diesel combustion investigation. The same arrangement as in previous works [23,25] has been used, namely a “focused single pass” schlieren setup, as sketched in Fig. 1. This optical