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Experimental study of the stabilization mechanism of a lifted Diesel-type flame using combined optical diagnostics and laser-induced plasma ignition

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ABSTRACT

The understanding of the stabilization process of Diesel spray flames is a key challenge because of its effect on pollutant emissions. In particular, the close relationship between lift-off length and soot production is now well established. However, different stabilization mechanisms have been proposed and are still under debate. The objective of this paper is to provide an experimental contribution to the investigation of these governing mechanisms. Combustion of a Diesel spray issued from a single-hole nozzle (90 µm orifice, ECN spray A injector) was studied in a constant-volume precombustion vessel using a combination of optical diagnostic techniques. Simultaneous high frame rate (6kfps) schlieren, 355 LIF (excitation at 355 nm and maximum collection at 430 nm) and high-temperature chemiluminescence (collection from 400 nm to 490 nm) or OH* chemiluminescence (collection at 310 nm and frame rate at 60kfps) are respectively used to follow the evolution of the gaseous jet envelope, formaldehyde location and lift-off position. Additional experiments are performed where the ignition of the mixture is forced at a location upstream of the natural lift off position by laser-induced plasma ignition (at 1064 nm). The evolution of the lift-off position until its return to the natural steady-state position is then studied for different ambient temperatures (800 K to 850 K), densities (11 kg/m3 to 14.8 kg/m3) and rail pressures (100 MPa to 150 MPa) using the same set of optical diagnostics. The analysis of the evolution of the lift off position without laser ignition reveals two main types of behaviors: sudden jumps in the upstream direction and more progressive displacement towards the downstream direction. While the former is attributed to auto-ignition events, the latter is studied through the forced laser ignition results. It is found that the location of formaldehyde greatly impacts the return velocity of the lift-off position: if laser ignition occurs upstream of the zone where formaldehyde is naturally present, the lift-off position convects rapidly until it reaches the region where formaldehyde is present and then returns more slowly towards its natural position, suggesting that cool-flame products greatly assist lift-off stabilization. The average return velocity in this second stage depends on the operating conditions.

1. Introduction

During the past 20 years, numerous works have allowed a better representation of combustion in direct injection Diesel engines. Especially, a conceptual model, describing the different stages of Diesel combustion has been proposed by Dec [1] and further detailed [2–4]. It describes the Diesel flame as a two-phase turbulent lifted diffusion flame with a partially premixed area upstream the base of the flame. The distance between the nozzle orifice and the flame; called the lift-off length (LOL), has been shown to play a major role in the soot formation processes [5–9]. The mechanisms explaining the stabilization of the LOL are therefore of first order in understanding and controlling soot formation in the Diesel flame, and as such, have been largely studied [9–19]. More generally, knowledge can also be gained through analogies with the stabilization processes observed in other types of lifted flames, like gaseous lifted atmospheric flames.

The stabilization mechanisms involved in this type of flames have been studied for years [20–40]. In most cases, methane has been chosen as fuel. Resulting from these studies, three main theories have been proposed to explain the flame stabilization, and are illustrated in [24]: premixed flame propagation at the flame base

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[25–32], flamelet quenching driven by a critical scalar dissipation rate [33,41] and stabilization due to large-scale turbulent structure [34,35].

Flame stabilization by premixed flame at the flame base approach is based on the fact that oxidizer and fuel are premixed in the lift-off area. The flame is stabilized where the mean flow velocity is equal to the turbulent flame speed. In this theory, flame stabilization occurs at the contour of the mean stoichiometric mixture [25,26]. More recently, triple flame has been proposed as one of the most convincing approaches [27–31]. A triple flame is able to stabilize even if the mean flow velocity is larger than the flame speed because the flame front is systemically located in an area where the instantaneous flow velocity has the same order of magnitude as the laminar flame speed. The triple flame is able to move to follow the stoichiometric line where the laminar flame speed is maximum [36].

The second approach, flamelet quenching, is based on small-scale turbulent structures. The lift-off occurs where the scalar dissipation rate goes under a critical value. This approach has been discussed for instance by Everest et al. [37]. They found that the local value of the scalar dissipation rate exceeds the predicted value by a factor of sixty. Schefer et al. [38] found that the value of the scalar dissipation rate was considerably below the critical value in the lift-off area. Moreover, flamelet quenching can only explain the lack of flame. Thus, it is doubtful that this theory can fully explain the stabilization mechanisms of a turbulent lifted-flame.

Thirdly, Broadwell et al. [34] have proposed a theory based on large-scale turbulent structures which carried hot combustion products to the edge of the jet. These turbulent structures can lead to upstream ignition. Otherwise, when the re-entrained products are mixed too rapidly with the unburnt jet fluid it leads to extinction. Therefore, the large-eddy structures may cause ignitions (pockets of hot burned products are transported upstream and ignite fuel/air mixture) and extinctions, as argued by Miake-Lye et al. [39], leading to flame stabilization.

Several other works have proposed hybrid stabilization mechanisms coupling the different theories mentioned previously. Burgess and Lawn [40] proposed a stabilization governed by turbulent premixed flame where the flame propagates around the periphery of the large eddies. More recently, Lawn [23] argued that large structures of rich mixture coming from the jet can move downstream and auto-ignite due to hot regions. This ignited kernel propagates downstream with a triple flame shape leaving a ribbon of diffusion flame behind it which is drifted by the large scale.

Under Diesel conditions, the lift-off stabilization mechanisms may be different because of high-temperature, high-pressure conditions and Diesel-type fuels and two-phase flow processes. Chemical mechanisms show that Diesel fuels generally exhibits two stages of ignition chemistry [42–44]. The first stage consists of a low-temperature heat release (LTHR, often called cool flame), whereas the second stage is characterized by a high-temperature heat release (HTHR) [2]. Formaldehyde (HCHO), for the 1st stage, and OH, for the 2nd stage, are abundant and measureable species often used as markers of these stages of heat release [2,5,45]. Chemistry-turbulence interactions have been studied in order to better understand stabilization mechanisms of the flame base, and especially discriminate between the roles of the two main candidates to explain the Diesel flame stabilization: flame propagation at the flame base and auto-ignition.

Siebers and Higgins [7] and Siebers et al. [6] used an experimental correlation based on flame propagation [32] to estimate a time average LOL for Diesel flames. Comparison with experimental measurements of average LOL shows a very good agreement, suggesting that flame propagation could be the underlying stabilization mechanism. However, this time average prediction of the LOL does not take into account the nature of the fuel and it has been shown [10–13] that the LOL varied with different fuels. This lack of prediction highlights the fact that some physical phenomena have not been taken into account.

More recently, Venugopal and Abraham [46], based on Reynolds Averaged Navier–Stokes (RANS) have proposed a study of the flame stabilization under diesel conditions. In this work [46], lift-off is modeled to result from flame extinction in the near-field of the jet. The authors have carried test conditions variations in order to propose a power law estimating a time average LOL under diesel conditions. This power law has been compared to the experimental correlation [6,7]. It appears that the coefficients are in quite good agreement. However, the authors argue that it would be inappropriate to conclude that the flame extinction alone can fully explain the flame stabilization. Like highlighted for non-autoignitive conditions, flame extinction can only explain the absence of flame. Thus, other mechanisms like auto ignitions need to be taken into account to explain the flame stabilization.

Many studies have proposed auto-ignition as one of the main stabilization mechanisms [5,9,14–16]. It is clearly established that auto-ignition plays a leading role in the flame stabilization: detached auto-ignition sites upstream of the reaction zone have been observed [5,14] affecting the LOL. Pickett et al. [5] have analyzed the cool flame to investigate the auto-ignition and thus the flame stabilization through the LOL. Cool flames have been found to have a strong effect on the auto-ignition delay because it is the first stage before the high-temperature combustion. The authors [5] have argued that the location of cool flame has some bearings on the lift-off stabilization.

More recently, keeping the idea of flame propagation and auto-ignition, Krisman et al. [17,18,47,48] have proposed a stabilization mechanism including both edge-flames and auto-ignition, using dimethyl ether (DME) as fuel [17,18,47] and n-heptane [48]. As a first step based on a laminar two dimensional Direct Numerical Simulation (2D-DNS) [17]. Then this study has been enriched by a 3D-DNS of a turbulent lifted DME slot jet flame proposed by Minamoto and Chen [19] which confirms the existence of triple flames under the Diesel condition. They also have investigated the impact of the cool flame on laminar premixed flame. They found that the laminar flame speed is increased by a factor 1.3 to 1.8 compared to non-autoignitive conditions. Recent study [49] of 1D premixed flame of DME under autoignitive conditions confirms an increase of the laminar flame speed compared to theoretical flame speed given by a power law. For example, according to Krisman et al. [49], the laminar flame speed computed with Cantera [50] at 1000 K is double the flame speed predicted by a power law [51]. However, it is still unclear how this rise of premixed flame velocity can impact the flame stabilization under turbulent condition.

Finally, another approach [9] is to consider that flame stabilization is due to a combination of premixed flames and large-scale turbulent structures which carry hot combustion products to the edge of the jet [34] leading to auto-ignition. This theory is built on an experimental study performing high-speed high-temperature chemiluminescence visualizations with a forced laser ignition upstream of the flame base.

To summarize, auto-ignitions have been the predominant physical phenomenon to explain the flame stabilization under Diesel condition [9–15]. However, more and more recent numerical studies have shown the presence of partially premixed flame under autoignitive conditions [16–19,52]. A review of fundamental studies relevant to flame stabilization in diesel jets proposed by Venugopal and Abraham [53] concluded that the flame stabilization can be explained by multiple theories listed above. However, mixing theories which have contradictory hypothesis demonstrates that the flame stabilization mechanisms are still not well understood. Based on the theories developed these past 50 years under gaseous lifted atmospheric flames, premixed flames under Diesel condition