A SIMULTANEOUS SCHLIEREN AND TOMOGRAPHY DIAGNOSTIC FOR THE STUDY OF PREMIXED TURBULENT EXPANDING FLAMES

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Introduction

Recent developments reveal the high performances of downsized spark ignition engine as usable energy source as well as in reduction of pollutant emissions. Since expanding turbulent premixed flames occur in Spark-Ignition (SI) engines, this flame configuration is of great interest in combustion research. Specific conditions for premixed flames (high pressure, high temperature) are still studied and required nowadays an accurate knowledge of their propagation in both laminar and turbulent regime to improve the efficiency of SI engines. Moreover, new conditions of dilution are explored; especially exhaust gas recirculation (EGR) dilution like in compression ignition engine. The effect of these particular conditions of temperature, pressure, fuels and dilution on the laminar burning velocity and on the Markstein length in laminar regime have been previously studied by many authors [1–4] and highlighted a strong impact of the stretch on the flame propagation. Initially presented in the work of Karlovitz et al. [5] and Markstein [6], flame stretch can be easily linked to the flame speed in laminar conditions [7–10]. However, while the link is clear for a laminar flame, the acceleration mechanism of turbulent expanding flames is more complex, since the flame front is affected both by a mean global stretch rate due to the growth rate of the flame, and by local stretch rates related to the flame front wrinkling. Many recent studies [11–15] focused on the impact of various conditions and fuels on the flame response to stretch but investigation is still needed. This work presents experimental turbulent flame speed measurements in a constant-volume combustion chamber using simultaneous tomography and 2-plans Schlieren visualizations. Premixed expanding flames, propagating in homogeneous and isotropic turbulence are investigated. Isooctane was chosen as the fuel due to its use as a surrogate gasoline in engine research and because its response to stretch changes dramatically from lean to rich conditions. The objective of this work is twofold. First, by using simultaneously Tomography and a 2 plans Schlieren diagnostic, the coefficient proposed by Bradley et al. [12] to obtain the turbulent burning speed from Schlieren images is discussed. Secondly, the effect of the following parameters on the flame speed as a function of stretch in turbulent regime are investigated: turbulent intensity, pressure, Markstein length.

Experimental Set-up

a. Combustion vessel

Experiments were conducted in a spherical stainless steel vessel with an inner diameter of 200 mm used for both laminar and turbulent premixed flame propagation investigations. Details about the preparation of the reactive mixture are available in [4]. The initial gases were set to an initial temperature of 423 K with a maximum deviation of 2K. Initial pressure of 1 and 5 bar inside the vessel were studied (maximum deviation of about 1% of the targeted pressure). The gaseous isooctane/air mixture is ignited by a spark produced between two tungsten electrodes 0.5 mm diameter. The vessel is equipped with four quartz windows providing optical access for the use of laser diagnostics. Turbulence is generated by six identical four-blade fans (diameter: 40 mm) located close to the inner wall of the chamber and positioned in a regular octahedral configuration. The fans direct the flow towards the center of the vessel and they run continuously during flame propagation. The speed of each fan can be accurately adjusted from 1000 to 15 000 rpm and is maintained within ±0.1% of the target speed. The turbulent flow was fully characterized in previous work [16], using various diagnostics (LDV, standard and Time-Resolved PIV), in non-reactive conditions. It was particularly shown that the fans generated homogeneous and isotropic turbulence in a central area of 40 mm in diameter. In [16], the turbulence intensity was found to be proportional to the fan speed and the integral length scale L_T independent of the fan speed ($L_T = 3.4\,mm$ [16]).

b. Optical set-up and post-processing

In this study, two high speed imaging were done. The first one consists in a double view Schlieren measurement through the four optical accesses (see Fig. 1). Each Schlieren pathway is made by using a LED, an aperture of 1 mm in order to obtain a point source and two convex metallic mirror (864 mm focal length). At the focus point of the second mirror a 0.5 mm dot is placed and two lenses (200 mm and 160 mm) allow to focus the images directly on the chip of the CMOS camera. With this arrangement, the both views can be recorded with one high speed camera with the full resolution (1024x800 pixels²) and with a magnification ratio of 0.1 mm/pixel. Because one of the goal of this study is to compare the wrinkle radius from the Schlieren images (3D integration along the optical pathway) and from

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tomographic images, a second optical set-up was installed. A high speed Nd-Yag laser enables to make a laser sheet passing between both electrodes and with a tilt angle of 4° to prevent any interaction with the Schlieren arrangement. A second high speed camera mounted with a 200 mm Nikon macro-lens allow to record quasi-simultaneously (with a delay of 5 µs) the Mie scattering images with silicon oil droplets.

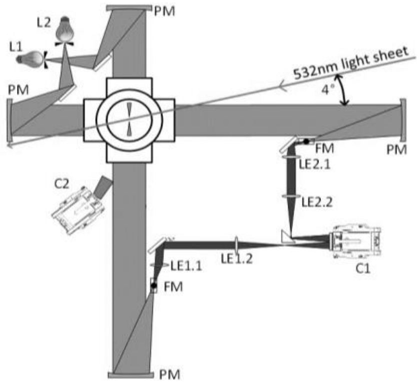

Figure 1 – Experimental setup. L1 and L2 : LED, PM : parabolic mirror, C1 Phantom v1610 camera, C2 Phantom v1210 camera, FM Dot point, LE Lenses

The Schlieren and tomographic images were post-processed to obtain the contour of the flame. As in [9], mean flame radii R_a were derived as those of a circle of equal area to the flame area inside the contour of the flame : $R_{a,S} = \sqrt{A_S/\pi}$ and $R_{a,T} = \sqrt{A_T/\pi}$, where the subscript indicates values determined from Schlieren or tomographic images respectively. A third radius $R_{a,V}$ was defined based on the flame volume estimated from the two Schlieren views $R_{V,S} = \sqrt[3]{3V_S/4\pi}$. The flame volume was determined by integrating the surface of the ellipses as function of the vertical direction. These ellipses were fitted through four points defined as the four contour intersections of both Schlieren views. The turbulent propagation speed was simply derived from the measurement of the flame radius R_a against time (t): $V_T = dR_a/dt$. Because a propagating flame surface undergoes curvature and flow field aerodynamics (strain) effects leading to flame surface modifications, the total stretch needs to be taken into account. Considering the contribution of the macroscopic geometry of the flame, the associate stretch $\kappa_{c,R}$ is defined similarly as for the stretch of a laminar expansion flame:

$$\kappa_{c,R} = \frac{2}{R_a}\frac{dR_a}{dt} \qquad (1)$$

For laminar flame, according to non-linear the relation linking the propagation speed and the stretch, the unstretched propagation speed V_b^0 can be determined as follows [10]:

$$\left(V_b/V_b^0\right)^2 . \ln\left(V_b/V_b^0\right)^2 = -2L_b/V_b^0 \qquad (2)$$

where V_b is the flame speed estimate as equal to dR_a/dt, L_b is the burned gas Markstein length. In the case of turbulent flame propagation, the non-linear relation could not be applied but the turbulent flame speed V_T can still be plotted as a function of the mean curvature stretch $\kappa_{c,R}$.

Nonetheless, according to Bradley et al. [12], the progress variable defined as a mean contour of Mie scattering images could not be compared to the progress variable corresponding to the contour estimated from Schlieren images, due to the 3D optical integration. Then, Bradley et al. proposed to correct the radius by a constant factor C:$R_a = C.R_{a,S}$. The determination of this constant is discussed in this study.

Conclusions

In this study, a new optical diagnostic using simultaneously Mie-scattering tomography and 2-views Schlieren was set in order to discuss the coefficient proposed by Bradley et al. [12] to obtain the turbulent flame speed from Schlieren images. First, the diagnostic enables to select flames that globally keep a spherical shape during the propagation and are not shifted from the centre of the vessel. Second, using the 2-views Schlieren diagnostics, a flame volume has been reconstructed in order to confirm that the use of the radius of only one view enables to describe the flame propagation. Then by comparing both Schlieren and Mie radii, the coefficient used to correct the flame speed obtained from Schlieren images has been estimated. Values were between 0.65 and 0.8 and clearly showed a decrease when increasing the turbulent intensity instead of the value of 0.9 whatever the conditions given by Bradley et al. This is an important result that needs to be considered when measuring the turbulent flame speed with the Schlieren technique. In the second part of the study, the effect of the turbulent intensity, the pressure, and the Markstein lengths on the flame speed evolution as a function of stretch has been evaluated. After a flame radius of 5 mm, chosen to avoid ignition effect, the flame speed increases as the flame stretch decreases. For the lean mixture, increasing the turbulent intensity leads to higher flame speed as already shown in many works. However for the stoichiometric diluted mixture, the flame speed seems to be not affected by the turbulent intensity. More investigation regarding dilution effect will be done in further work to explain this behaviour. When increasing the pressure, the flame speed as a function of stretch is increased due to lower flame thickness and Kolmogorov length scales that provoke higher wrinkling regardless of the Markstein length. However different behaviour are observed between positive and negative L_b. Indeed increasing the turbulent intensity causes a steeper increase of the flame speed for the rich mixture (L_b<0) than for the lean mixture (L_b>0).

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