High Speed PIV Analysis of the Combustion Regimes During Autoignition of Homogeneous Fuel - Air Mixtures in a RCM

Strozzi, C. [1], Delicourt, A.[2], Bellenoue, M. [2], Sotton, J.[2],
[1] Institut Pprime, CNRS, Université de Poitiers, ISAE-ENSMA
[2] Institut Pprime, CNRS, ISAE-ENSMA, Université de Poitiers
F-86962 Futuroscope Chasseneuil, France

1 Introduction

Autoignition phenomenon is involved in many propulsion systems like compression ignition (CI) engines, but also other modes of operation of automotive engines. For example, Homogeneous Charge Compression Ignition (HCCI), Partially Premixed Compression Ignition (PPCI) or even Spark Assisted Compression Ignition (SACI) are under consideration to optimize both thermal efficiency and pollutant emissions [1]. Increasingly drastic environmental constraints are also imposed to aeronautic engines manufacturers. In order to increase thermal efficiencies of aeronautic turbomachines, it is possible to take advantage of the Humphrey cycle. In this respect, Constant Volume Combustion (CVC) based on premixed or partially premixed combustion was investigated in several studies, see for instance [2,3]. In particular, in the approach of Labarrere et al. [2], end-gas autoignition should rather be avoided, whereas autoignition is the core of the so-called shockless explosion combustion concept [3]. In the both cases, a good knowledge of autoignition behavior of aeronautic fuels is required. Iso-octane and n-decane were chosen by the authors as single-components fuels representative of both the automotive and aeronautic applications evoked above. Furthermore, consideration of the both fuels may be of interest as they exhibit opposite sensitivities to autoignition. As a first step, measurements of ignition delays of premixed iso-octane/O_2/N_2/Ar mixtures are reported for different temperatures in the present abstract.
The second and main issue of the present work is to propose a diagnostic method devoted to the experimental analysis of the combustion regimes related to autoignition with these fuels. In practical devices, reactive mixtures are never perfectly homogeneous and different combustion regimes can be observed depending on the local gradients of reactivity [4,5,6]. For instance, either deflagration or autoignition fronts were reported in a RCM during compression ignition of a fully premixed methane-air mixture [4]. In a previous study, a simultaneous chemiluminescence and 355 nm PLIF diagnostic was proposed to analyze the different combustion regimes in the same device [1]. However, the analysis was limited to apparent velocities of reactive fronts. In the present work, these phenomena are investigated by high speed PIV with prospect to measure propagation velocities relative to the unburned mixture.

2 Experimental device

Experiments are performed with a RCM facility developed in Poitiers. Conditions at TDC (Top Dead Center) are varied by changing both volumetric compression ratio and the diluent gas composition. Two different versions of the RCM are employed in the following: the first one features a square cross section piston with rounded corners. The top of the chamber is fitted with four sapphire perpendicular windows, providing optical accesses orthogonal to the cylinder axis. The field of view corresponds to the full dead volume. The second configuration features a piston with a disc shaped cross section, without any optical access. A flat piston is employed in the both cases with the same compression stroke value of 420 mm.

Gaseous mixtures are prepared following the partial pressure method, where initial pressure is measured with an MKS Baratron 220DA pressure transducer with one millibar accuracy. Iso-octane/O_2/Ar/N_2 mixtures are prepared at ambient temperature in a separate bottle. During compression experiments, pressure evolution is followed by a Kistler 6125CU20 piezoelectric sensor coupled to a 5018A amplifier. More details about the RCM and the sensors can be found in [4].

Velocity measurements are performed in the RCM with the square piston configuration. Ignition of lean isooctane-air mixtures at $\Phi = 0.5$ is under study. A Mesa PIV continuum dual cavity diode pumped Nd:YAG laser is employed to this purpose, see Fig. 1. It is run at 10 kHz per cavity with a total power of 120 W at 532 nm. The 400 µm thick laser sheet illuminates a vertical plane including the cylinder axis. Mie scattering images are recorded at 20 kHz by a Photron SA-Z fast camera fitted with a 100 mm objective. The field of view corresponds to the dead volume, e.g. about 50x30 mm. It is monitored with 888x532 pixel². The fluid flow is seeded as follows: the chamber is initially placed under vacuum, and solid particles of ZrO_2 are deposited in the feeding pipe. Particles diameter is lower than 5 µm (1 µm on average). The reactive mixture is then admitted. Most particles are still suspended when the compression experiment is started 1 min later. Fluid velocity is also measured in the burned gases as the fusion temperature of ZrO_2 is 2988 K. A band-pass filter centered at 532 nm is eventually used (CVI ref. F10-532-2.00) as discussed below.

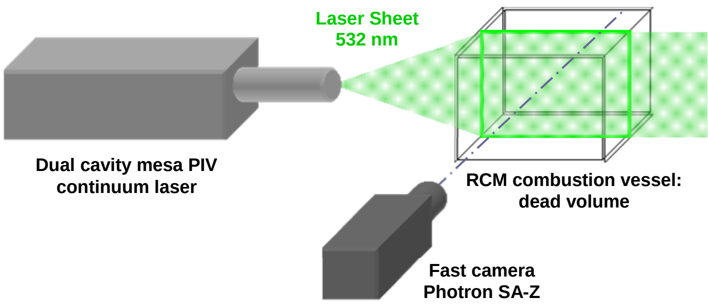

Figure 1. High frequency PIV setup for the RCM.

3 Ignition delay measurements

Ignition delays measured for a stoichiometric mixture of iso-octane/O_2/N_2/Ar with a molar fraction of 21% O_2 are reported in Fig. 2 with blue symbols. Target pressure at TDC is 20 bar. Volumetric compression ratio varies between 8 and 15, Ar/(Ar+N_2) molar ratio varies between 16 and 42 %. The disc shaped cross section piston was employed for the measurements and the ignition delays are defined as the duration between the end of compression and the maximum rate of pressure rise. Temperature is obtained from the adiabatic core temperature hypothesis [4]. It is worth noticing these conditions were investigated by several research teams in the framework of the RCM Workshop [7] and the corresponding results are reported with black symbols. A good agreement is obtained in the range of investigated temperatures which tends to validate the use of the RCM for such reactive mixtures. Additional measurements are planned at higher temperature or lower equivalence ratio.

A lean iso-octane – air mixture is considered for PIV experiments, see Tab. 1. It is chosen for the sake of the comparison to a previous study in similar conditions [1]. The optical configuration with the square section cylinder is employed. Average values of ignition delay of 20.2 and 73.5 ms were reported respectively for P_{TDC} = 26.9 and 19.6 bar in [1]. A fairly good agreement is obtained with the present study, see Tab. 1. It was checked the same ignition delays are obtained with and without ZrO_2 particles. Corresponding pressure traces are reported in Fig. 3. Two-stage ignition occurs: the cool flame is followed by hot ignition, see [1] for more details.

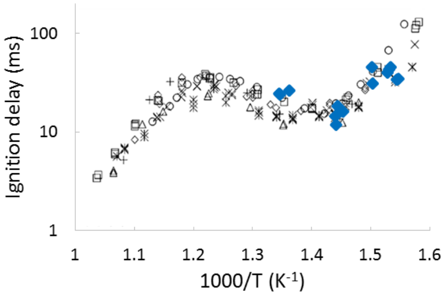

Figure 2. Ignition delays of iso-octane - air mixtures at Φ = 1 and P_{TDC} = 20 bar as a function of temperature. Blue symbols: present measurements with disc shaped cross section cylinder. Black symbols: other groups [7].

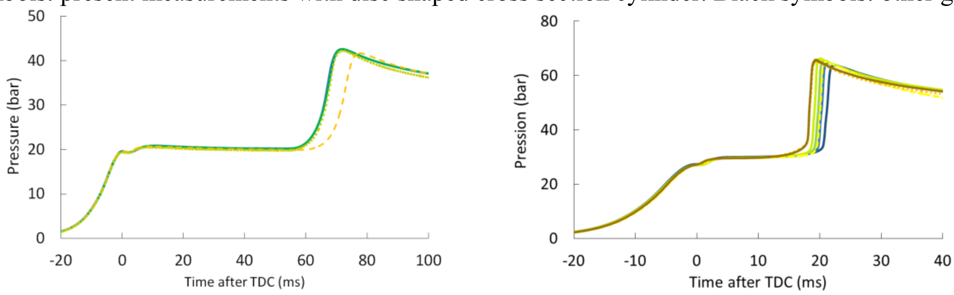

Figure 3, Pressure traces: iso-octane – air autoignition for long (left) and short (right) ignition delays described in Tab. 1. Experiments with ZrO_2 particles are reported in dashed lines.

Table 1. Experimental conditions for the lean iso-octane - air mixture. Optical configuration (square piston). Average values and maximum deviations.

Φ	P_{TDC} (bar)	T_{TDC} (K)	Ignition delay (ms)
0.5	20.0 ± 0.09	725.8 ± 3.1	*long:* 69.1 ± 3.8
0.5	27.68 ± 0.15	727.2 ± 3.2	*short:* 19.7 ± 1.6 ms

4 PIV analysis of combustion regimes

Several conditions were tested to optimize the optical setup for the PIV analysis of reactive processes in the RCM. Autoignition of homogeneous and lean iso-octane – air mixtures is performed with two different pressure values, reported in Tab. 1. They correspond to short and long ignition delay values documented in [1], and thus to different temperature distributions at the onset of hot ignition. In the first case, autoignition is quickly followed by a transition to deflagration which mainly drives the heat release process. In the second case, spontaneous ignition fronts are observed. This results in a higher rate of pressure rise, see [1,4] and Fig. 3.

Reaction zones can be detected from chemiluminescence emissions. Their intensity is weak for the lean mixture, especially for deflagrations - long ignition delays -: the both contributions of chemiluminescence and Mie scattering emissions are recorded with a single camera without any filter. Autoignition fronts feature a higher level of chemiluminescence emission. PIV investigations without any filter are still possible, but not in the whole visualization zone. Therefore a 532 nm band pass filter is employed in that case. Location of the reaction zone is still determined from the recorded images, despite chemiluminescence signal is strongly attenuated by the filter. The occurrence of hot ignition is also detected with a second method: at the onset of the related heat release, there is a large difference of density between unburned mixture and burned gases. This results in different seeding density, which is used to detect the reactive front in the presence of deflagrations. In conclusion, Mie scattering and/or chemiluminescence images are used to detect the reaction front location, whereas velocity fields characterize both the internal aerodynamics and the way it is affected by reactive processes.

4.1 Long ignition delays: deflagration driven process

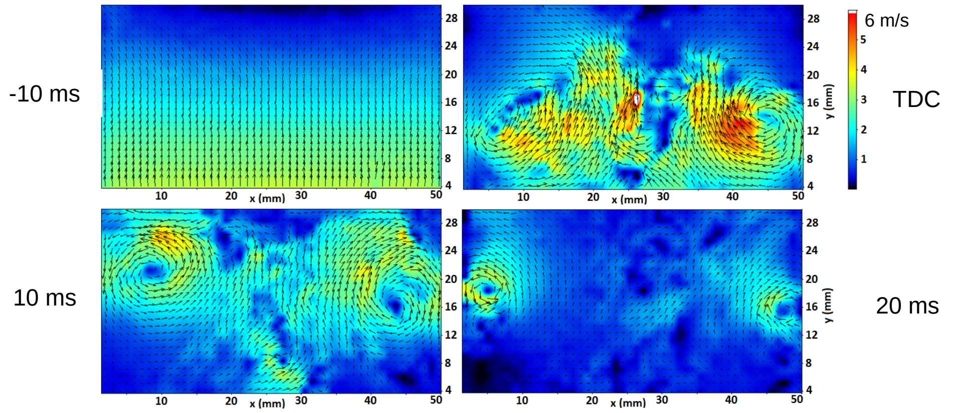

Figure 4. Velocity fields for iso-octane – air mixtures, long ignition delays, before hot ignition. See. Tab 1 and Fig. 5

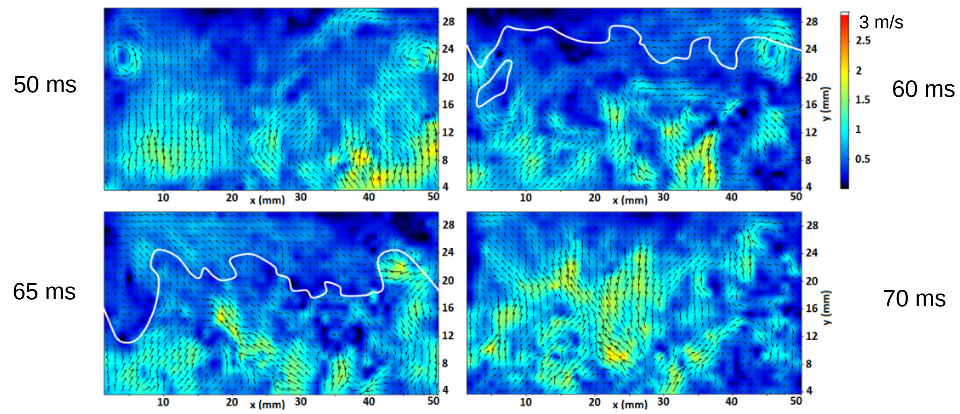

Figure 5. Velocity fields for iso-octane – air mixtures with long ignition delays during hot ignition. See. Tab. 1 and also Fig. 4. Deflagration contours obtained from differences in the seeding density are reported in white lines.

Figure 4 displays the velocity fields measured in the reactive mixture before hot ignition. The lean mixture is compressed at P_{TDC} = 19.8 bar and T_{TDC} = 728.5 K, leading to long ignition delay values. Velocity fields are computed using a commercial software with multi-pass processing. Windows sizes of 32x32 and then 24x24 pixels are used with a 25 % overlap on the final pass. A duration dt = 100 µs separates two consecutive Mie scattering images.

The typical aerodynamics of flat piston RCM is observed in Fig. 4 [4,8]: a one dimensional flow is observed at the end of compression. It is followed by higher velocity zones corresponding to the corner vortices. After the piston stops, the vortices move in the middle of the chamber near the lateral walls. Their velocities progressively decrease and they are almost dissipated 50 ms after TDC. Qualitatively speaking, internal aerodynamics is close to that observed with an inert mixture in similar conditions [8]. The cool flame occurs between TDC and 10 ms and this first stage of ignition does not seem to affect the flow significantly. This will be confirmed in a future study.

Figure 5 reports the velocity fields measured during hot ignition for the same experiment. Please note the velocity scale has changed in comparison to Fig. 4. White lines correspond to the flame position determined from the difference of seeding density. In agreement with a previous work [1], the thermodynamical conditions at TDC lead to deflagrations. The motion of the contours reported in Fig. 5 corresponds to an average apparent velocity of about 1 m/s. Furthermore, the expansion ratio of the lean mixture at TDC is low ρ_u/ρ_b~2.6. These two values are consistent with the weak effect of combustion on the fluid flow. At 60 and 65 ms after TDC, velocity fields do not seem to be affected by combustion in the burned gases, but the flame is wrinkled by the both corner vortices. The latter phenomenon was observed in a greater extent for SACI combustion [1]. Here, lower velocities are measured at these late instants in comparison to the SACI case. The burning velocity remains of the same magnitude order as the residual flow velocities at 60 ms. In order to conclude more firmly, a post-processing will be applied in a near future to estimate the velocity variation through the flame. A different flow pattern is reported at t = 70 ms, e.g. close to the end of the combustion process. Despite corner vortices are dissipated in the measurement plane, the effect of hot ignition remains moderate with velocities lower than 2 m/s.

4.2 Short ignition delays: autoignition driven process

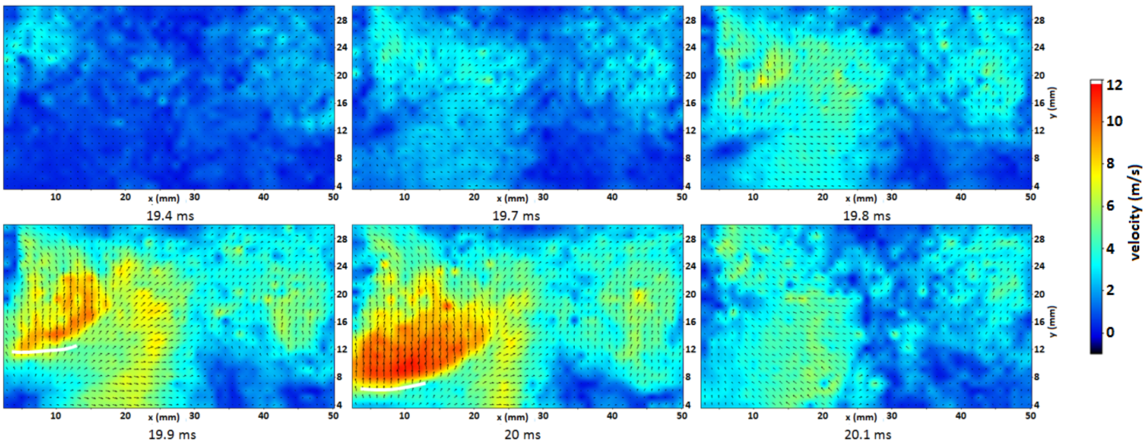

Figure 6. Velocity fields measured for short ignition delays, see. Tab 1. White lines represent the lower part of the reactive front contours obtained from chemiluminescence for the first frame of the couples of Mie scattering images.

Ignition delay is shortened at higher pressure level P_{TDC} = 27.68 bar, see Tab. 1. Fast propagation of autoignition fronts occur, as reported in [1]. A shorter time interval dt = 20 µs separates couples of Mie scattering images. A 532 nm band pass filter is added to the collection system. In Fig. 6, white lines depict the contours of chemiluminescence detected in the left part of the chamber at t = 19.9 and 20 ms. The chemiluminescence method is chosen to monitor the front location as the seeding density is weakly affected by heat release at the end of the combustion process.

The measured velocity field is drastically affected by heat release during hot ignition: after 19.7 ms, the fluid significantly accelerates as it passes through the reaction front. Velocities in the burned gases reach up to 10 m/s behind the front at t = 20 ms. Furthermore, Fig. 6 shows the front propagation starts in a low velocity zone below the corner vortices. This zone is hotter than the corner vortex and features low thermal gradients [8], which is at the origin of the fast auto-ignition front. Similar conclusions were drawn in [4]. From a more quantitative point of view, the autoignition front propagates vertically at about S_a = 40 m/s in the frame of reference of the laboratory. This value is higher than 25 m/s reported in [1]. Furthermore, low velocities of about 4 m/s are measured in the unburned mixture. Indeed, combustion products occupy a large part of the dead volume at these instants and the unburned mixture is getting confined near the piston. This is the reason why propagation velocity relative to the unburned mixture S_{spu} = 36 m/s is close to the apparent velocity S_a at this late stage of the combustion process.

5 Conclusion

Autoignition of lean iso-octane - air mixtures is characterized by high speed PIV in a RCM. The flow field is drastically affected by propagating auto-ignition fronts, which is not the case in the presence of deflagrations. Autoignition fronts propagate with an apparent velocity S_a close to S_{spu}, the propagation velocity relative to the unburned mixture. Future works will focus on similar fronts propagating at the onset of hot ignition, like those reported in [1,9]. Larger differences between S_a and S_{spu} may be obtained in that case. Decane – air mixtures will be considered as well: different results are expected at identical ignition delays values as S_{spu} depends on the temperature sensitivity of ignition delay [4].

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