Experimental characterization of fuel droplet temperature in a spray jet flame

A.Verdier*[1], B.Renou[1], A.Vandel[1], S.Saengkaew[1], G.Cabot[1], G.Gréhan[1], M. Boukhalfa[1]
[1] UMR6614 CNRS-CORIA, 8 Avenue de l'Université 76810 St-Etienne du Rouvray, France

Abstract

This study is dedicated to the understanding of the complex phenomena involved in droplet combustion, such as two-phase flows and heat transfer. Planar laser-induced fluorescence imaging of OH system was used to estimate the structure of the flame. In addition, to provide new information about a new combustion configuration (a spray jet flame at atmospheric pressure and temperature) the physical properties of fuel droplet (temperature and size distribution) was obtained by Global Rainbow Technique (GRT). The results reveal that the topology of co-flow was very important in two-phase combustion. A double flame structure is observed, appearing as two diverging flame fronts originating at the stabilization point. The recirculation zone with swirl entrains droplets and hot chemically active combustion species from the downstream region of the flame and so change considerably the structure of the flame. With these studies, we have extended the classical method of GRT to a different flame configuration in order to understand the interaction between the flame front location and the mean temperature of droplet.

Introduction

Liquid fuels are the primary energy source in a wide range of applications including industrial and residential furnaces, internal combustion engines, and propulsion systems. Pollutant emission reduction is currently one of the major constraints for the design of the next generation combustion chamber. It implies fuel consumption reduction and combustion efficiency increase. To comply with these aims requires an understanding and modeling of the various physical phenomena interacting in the combustion chamber, where liquid fuel is injected. During the evaporation process, the size and temperature of the droplets change so it is necessary to capture the mass and heat transfer between the two phases (liquid and gas). Sprays pose significant challenges to applying non-intrusive optical diagnostic techniques in combustion systems due to complicating factors such as attenuation, scattering of the probe beam, and interference from the droplets. Characteristics such as droplet temperature, droplet size and velocity distribution can play an important role in determining the dominant flame structures. These structures are responsible, ultimately, for determining combustion efficiency and pollutant emissions. Previous studies dedicated to two-phase combustion have considered many configurations such as dilute laminar spray diffusion flames in a co-flow configuration [1] or counter-flow diffusion spray flames. Various combustion regimes have also been studied, partially pre-vaporized sprays [2], partially premixed spray jets, swirling flames [3],[4] etc. Nevertheless, a substantial lack of information regarding the evolution of properties of droplet in a spray jet flame persists. The objectives of this work are mainly to study the structure of spray jet flame and determine the fuel droplets properties. In this context, two diagnostics optics was performed, in the interest to hand correlations of the interactions between the flame brush and the properties of droplet. First, the flame structure was obtained by planar laser-induced fluorescence imaging of OH and then the fuel properties, especially the temperature and size distributions of droplet in spray, was obtained by global rainbow technique.

Experimental setup

1) Apparatus

The burner consists of a fuel injector and a system of co-flow (figure 1). Due to the geometry of the burner, the flame shape is symmetric.

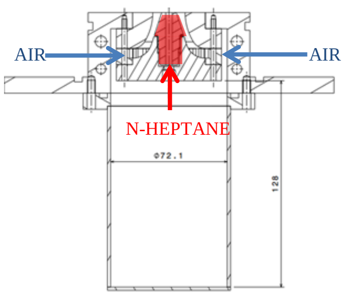

Figure 1 : Combustion Chamber. Blue: laminar coflow (air). Red: fuel injector.

The injection system is composed by an air swirler or no-swirler and a fuel injector located at the center of the burner. Radial swirler is composed of 18 channels (as the no-swirler) but inclined by 45° in order to vary the topology of the co-flow at constant mean flow rate.

*Corresponding author: antoine.verdier@coria.fr

A bed of glass beads and grid were used to attenuate residual turbulent perturbations in the aim to obtain a laminar co-flow of air in the configuration without swirl system.

Air was regulated via a Bronkhorst mass flow controller. Liquid fuel (N-heptane) was stored in a tank, pressurized by a pump and liquid flow rate was regulated by an electronic mass flow controller (Coriolis). The fuel injector is a Delavan hollow cone with an nominal flow rate of 0.35 US/(gal.h with a 80° angle**.**

2) Optical diagnostics

In order to estimate the local flow properties, planar laser induced fluorescence (PLIF) and global rainbow technique (GRT) are used to obtain the location of the reaction zones and the mean temperature of fuel droplet respectively. This section describes the measurement techniques for the apparatus and setup presented in Figure 2.

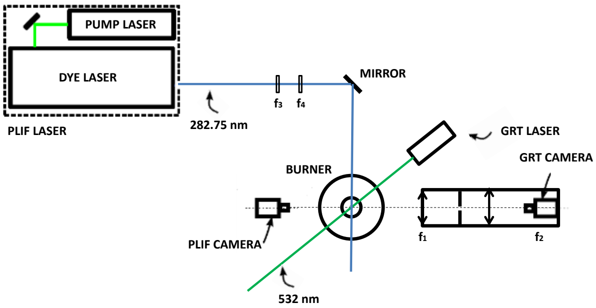

Figure 2 : Schematic representation of the dual measurement technique.

An OH-PLIF system operating at a repetition rate of 5Hz was used to study flame dynamics and to record the hydroxyl radical (OH) in the flame. A Nd-YAG-laser operating at 532nm was used to pump a tunable dye laser (TDL90) supplied with Rhodamine 590 dye. The resultant output pulse energy was 30 mJ/shot in the probe volume. The excitation wavelength was tuned to the Q1(5) ro-vibronic transition of the $A^2\sum{}^+(v'=0) \leftarrow X^2\prod(v"=1)$ band (λ =282.75nm). We made daily adjustments to the excitation wavelength using a laminar premixed CH4/air flame. The resultant laser beam was expanded through a set of fused silica lenses to form a laser sheet. The collection system consisted of an ICCD camera positioned 90° to the laser sheet captures the OH fluorescence at 5Hz on a 1024 × 1024 pixel array (Princeton Instruments PI-MAX 4). The intensifier gate was set to 500 ns, and background noise arising from elastic scattering of the particles used for GRT was reduced with a high-pass colored optical filter (Schott WG295). We adopted a broadband collection strategy from 308 to 330 nm with a bandpass colored filter (Schott UG11). Spatial correction and normalization of the laser sheet profile was taken into account and corrected by filling the combustion chamber with a homogeneous mixture of acetone vapor and air.

To better understand the interaction of the fuel droplets with the flame front, we focused on the measurements of the droplets temperature. The global rainbow technique (GRT), which was introduced by Van Beeck et al.[5], has a large potential of application in actual sprays. It is one of the non-intrusive techniques that can be used to measure average droplets temperature and droplets size distribution. This technique can be applied to any droplet that is sufficiently transparent. If we consider one single droplet (classical rainbow configuration), the main rainbow is generated by the interference between the first internally reflected light and the externally reflected light; it produces a peak of high intensity that is easily identified. The angular location of the rainbow is very sensitive to the droplet refractive index. This means that the location of the rainbow is sensitive to the temperature as well. On top of that the rainbow location is also sensitive to the droplet shape if one single droplet is studied. If we consider several droplets together (GRT configuration), the collective rainbow is created by the summation of a large number of individual rainbows scattered by all the droplets. The analysis of this global rainbow signal gives access simultaneously to both the average droplet temperature and the size distribution. The position of the collective rainbow is especially dependent on the value of the refractive index of the droplets whilst the shape of the global rainbow distribution depends both on the mean diameter and the size distribution. The sensitivity to the particle shape is strongly reduced in that case.

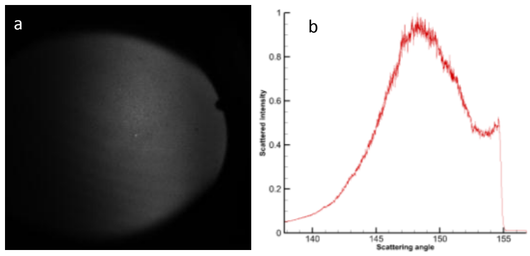

Figure 3 : Experimental global rainbow technique. Image of the rainbow signal (a). (b) Evolution of the intensity as a function of the scattering angle.

Figure 3 displays experimental global rainbow images for n-heptane droplets and the associated intensity profiles were processed by an algorithm based on Nussenzveig's theory.

Saengkaew et al. demonstrated the reliability and the accuracy of the global rainbow technique [6]. It was shown that a measurement of the refractive index of the liquid performed with a precision of 10^4 leads to a temperature accuracy of 0.2 K.

However the temperature obtained from GRT measurements is weighted by the size of the droplets following a $d^{7/3}$ law (i.e. the larger the diameter of the droplets, the most important their contribution to the temperature).

The experimental set-up consisted of an emitting and a collecting system that were interdependent. The light source was a continuous laser (λ= 532 nm).

A first lens collected the light scattered by the particles (f_1 = 150 mm, d_1 = 80 mm). The image of the measurement volume was created on a 3 mm in diameter diaphragm (measurement volume typically equal to $1mm^3$). A second lens (f_2 = 200 mm, d_2 = 100 mm) created the image of the focal plane of the first lens on a screen. The signal was recorded by a CCD camera (LaVision Imager ProX 4M camera 2048*2048 pix^2) with a 85 mm lens. The relationship between the scattering angle and its location on the CCD captor was determined by calibration. This relationship was then used to extract from the images the intensity information as a function of the absolute scattering angle. The exposure time was set to the maximum value possible during the experiments (either 400ms, depending on the signal).

3) Experimental conditions

Two configurations are investigated (table 1) in order to study the structure of spray jet flame and then the interaction between properties of droplets and the flame front. N-heptane and air mass flow ($M_{n\text{-heptane}}$ and M_{Air} respectively) are controlled by mass flow meters. Moreover, to compare different test, the temperature of n-heptane is kept constant and equal to 23°C by a fuel preheater.

Configurations *$M_{n\text{-heptane}}$: 0.28*	*M_{air} (g/s)*
SW18	6.00
N_SW18	3.00

Table 1 : Experimental conditions

For these configurations (SW18 and N_SW18); it is necessary to obtain information about temperature in the spray. So the measurements are presented in a Cartesian coordinate system. The origin of the Cartesian coordinate system is the center of the burner. Each results are represented in non-dimensional coordinates (x/D and y/D), where D is the output diameter of swirler hole (D=11mm); x is the axial position of burner and y the height.

Typical Mie scattering recordings of fuel droplets are reported in Figure 4, for different air injection configurations.

In a spray jet flame, the topology of co-flow is extremely important in the structure of spray and so directly in the structure of flame.

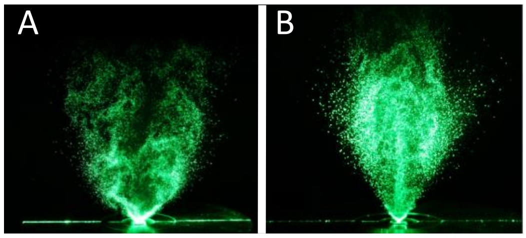

Figure 4 : Fuel droplet Mie scattering A: Configuration with an Air/swirl in the system of co-flow of air B: Configuration without swirl

Indeed, with a swirl, the air flow is set into rotation and changes greatly the trajectory and velocity of droplet in the spray. Different parts of the flow can be clearly identified in the literature. First, zone of negative axial velocity can be observed at the center of the burner. It is called Inner Recirculation Zone (IRZ), and generated when swirl number exceeds critical value of 0.6. For high swirl number, the pressure gradient at the center of the flow is large enough to introduce a recirculation towards the injector. Two additional zones can be observed on the literature. First, the swirler jet corresponds to the main branch exiting from the swirler with high velocity and high velocity fluctuation. Second, the shear layer is the high velocity gradient zone, between IRZ and swirler jet. This different part of the flow impact the stabilization and the structure of the spray jet flame

Results and discussions

Before to show the importance of droplet temperature during the combustion, it is necessary to understand the structure of this flame.

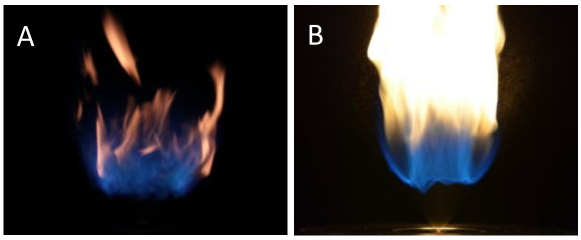

Figure 5: Image of spray jet flame without swirl (B) and with swirl (A)

In a spray jet flame, three regions can be distinguished: a jet liquid breakup region with no apparent presence of reaction, a bluish reaction zone and a sooty yellow zone far downstream as shown in figure 5 (A).

With the condition of mass flow, the combustion regime provides a distinct flame behavior and the structure of this flame is called double flame structure (figure 6).

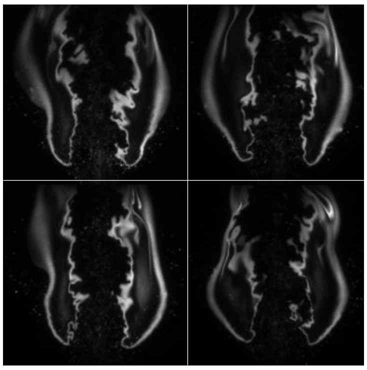

Figure 6: Single-shot OH-PLIF images for hollow cone pressure-swirl nozzle with 6.00 g/s co-flow.

The double reaction zone witnessed consists of two diverging flame fronts on each side of the spray center-line that join together at the flame base, or leading edge. The double reaction zone is also observable due to the bright blue luminescence present at the flame base (figure 5). The inner reaction zone is wrinkled and shows characteristics of partially premixed combustion due to turbulent mixing at downstream locations. This structure of flame is due to the small droplets resulting from the liquid jet breakup because there are responsive to the turbulence gas field near the inner reaction zone. The inner and the outer combustion structures near the leading edge have not the same relative thickness of the OH signal. The outer zone reaction is less wrinkled, more stable, and thicker than turbulent inner zone reaction. The OH images in figure 6 indicate a reduction of the droplet in the region between the inner and outer flame front as a consequence of the rapid evaporation of droplets caused by the appreciable heat-release from the oxidation process. Sometimes, isolated pockets of droplets burn near the shear layer, so in the inner zone combustion. This independent reaction zone is present when the local density of droplet and the amount of oxidizer around them is necessary to initiate combustion. Furthermore, there is occasionally, local extinction zone in the inner reaction zone more precisely near the base of the flame (figure 7 C and D). This instability may be interpreted by an insufficient momentum transfer to entrain the required air for sustaining an inner reaction zone. This configuration illustrates the complexity of spray jet flame and especially the importance of two-phase turbulent mixing near the shear layer.

In order to investigate a configuration that is more directly related to real application for instance as in aeronautic combustor, it is necessary to change the topology of air flow. Indeed, in these applications the air flow is set into rotation by a swirl.

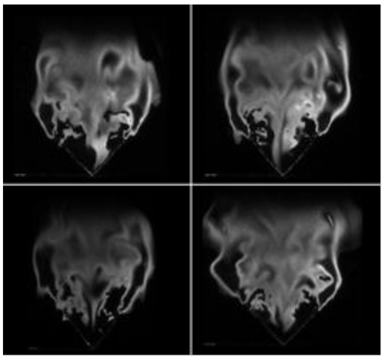

Figure 7: Single-shot OH-PLIF images for hollow cone pressure-swirl nozzle with 3.00 g/s co-flow with swirl.

Figure 7 presents different single shot OH-PLIF image for investigated the influence of swirl in the structure of flame. As shown in this figure, the structure of swirl-stabilized spray jet flame is similarly near the edges of the spray. Indeed, we find the double reaction zone with two diverging flame fronts. Nevertheless, the inner and the outer combustion structures near the leading edge have not the same relative profile of the OH signal than without swirl. The inner reaction zone is less wrinkled than the configuration without swirl.

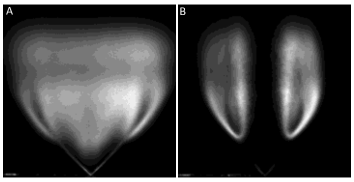

Figure 8: Average images of OH PLIF for two configurations : (A): With swirl and (B) : without swirl

It is important to note, that the stabilization of this spray jet flame is lifted as shown in figure 8 (B). This point of stabilization correspond a zone where the gas composition is close to stoichiometry and the local gas velocity is suitable to the mechanism of stabilization.
Lift-off height is defined here as the distance from the atomizer orifice exit plane, y/D=O, to the lowest position of the bluish reaction zone. Above the lift-off location, two flame-fronts develop from the flame base, one on the co-flow side and another inside the spray. In the average image of OH PLIF (figure 8), the structure of the flame depends on the topology of the co-flow. Indeed, with the swirl configuration, the burnt gases are entrained by IRZ and impact the fuel properties droplets. Moreover the IRZ generate an increase of the angle of atomization. With the OH PLIF image, the fuel properties will be change according the position in the spray.

In two configurations (with and without swirl), the properties of fuel droplet (velocity, temperature and size distributions, may be illustrated and interpreted by schematic schemes (figure 9).

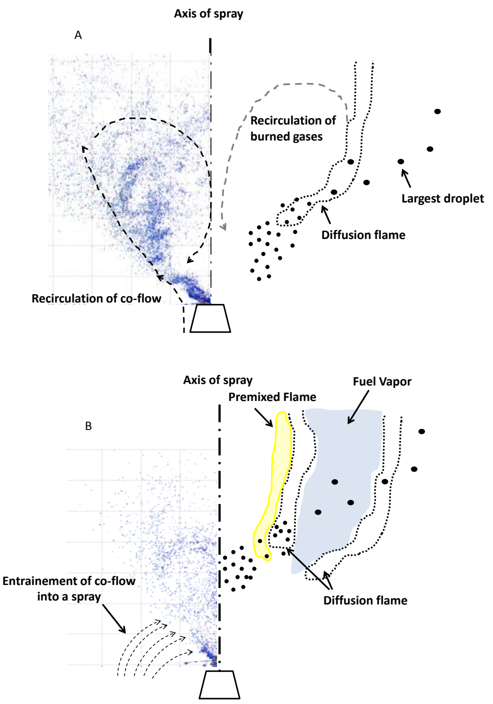

Figure 9: Schematic double flame structure with swirl (A) and without swirl (B)

The small droplets are manly located in the center of spray because they follow the entrainment of air co-flow into the spray. However, the largest droplets are ejected towards the double flame gap; this implies that all the drops are not evaporated during the combustion (figure 9 B). In this condition, while some large droplets cross the reactive zones and small droplet remain in the center of spray, the difference between the velocities enhance the droplet evaporation and produce fuel vapor [7].The fuel vapor produced within the double-flame gap makes possible an outer flame with the oxidant co-flow. However, the inner reaction zone is possible where a mixture of droplets and air is present. Nevertheless, with the swirl, the small droplets, which are mainly located in the N_SW18 configuration near the center of spray, are entrained by the IRZ towards the edge of the spray. The recirculated drops increase the angle of atomization.

In order to estimate the effect of flame brush on fuel droplets temperature, the results was investigated on two heights (y/d= 1.8 and y/d=3.2) in spray and are presented as a function of the adimensional number x/d as shown in figure 10.

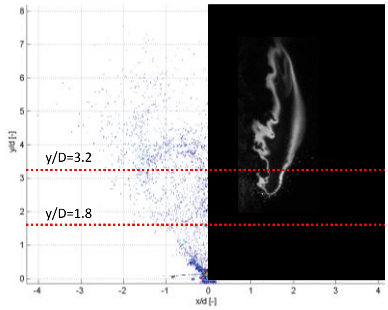

Figure 10: Cartesian coordinate system to measure temperature of droplets by GRT

Moreover, to understand the impact of flame front in the fuel droplet temperature, each test was compared with the configuration in non-reactive case.

Both profiles are similar in the evolution of temperature. Indeed, in x/d = 0 so in the center of spray, the average temperature of droplets is maximum (in non-reactive cases). However, it is important to note that the temperature in the center is superior to the fuel temperature injection (≈+5°C). The first hypothesis is that, the multi-diffusion impact the GRT technique. This point is always defined as work in progress. On the other and, the diminution of fuel droplet temperature with an increase of x/d may be interpreted as a significant cooling of droplet near the periphery of spray. This cooling may be attributed to the fact that the drops (near the edges of spray) have lower velocity and correspond to portions of the recirculated drops [8]. Their residence time is greater which enhance the evaporation.

For a height of y/d=1.8, droplets are always under the flame front so there is no significant elevation temperature of droplet between the reactive and non-reactive configuration. Nevertheless, near the stabilization point of the spray jet flame, the radiation of the double structure flame increases slightly the droplet’s temperature. For a height of y/d=3.2, the droplet temperature decreases slowly far from the flame front as for the previous height but this is followed by a sudden rise in temperature as the droplets arrive in the vicinity of the flame brush. The highest temperature extracted from the GRT image was close to 64°C.

This temperature was obtained for a position near of the inner reaction zone, which droplets was sometimes located in the burnt gases. As the droplets moved closer to the inner reactive zone, due to turbulent mixing, the heat released by the combustion could have contributed to the heating of the fuel droplets.

Between the inner and the outer reaction zone the temperature of droplet should reach the boiling temperature of n-heptane during the evaporation processes, but with the actual position of burner it is not possible to take measure after x/D=1.6.

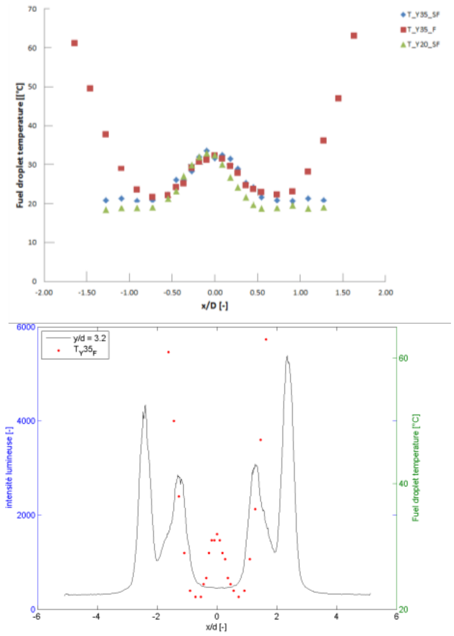

Figure 11: Evolution of fuel droplet temperature

Conclusion:

In a spray jet flame, specific information as the properties of fuel droplets in spray is necessary to understand the structure of two-phase flame and validate appropriate model including heat transfer. The spray jet flame studied in this experimental investigation serves to both provide fundamental insight into the structure of flame in different configuration (with and without swirl) and to provide information about the evolution of droplet's temperature in the spray. The objective was to describe the features of double flame structure in a conventional co-flow and in a swirl co-flow while noting the interaction between the flame front and the fuel droplet temperature. OH PLIF visualization was utilized to visualize combustion structures while the evolution of mean fuel droplet temperature was determined through the global rainbow technique. The experimental results show that the topology of the co-flow has a significant impact in the structure of the flame. An inner and outer flame front (double flame structure) is observed in conventional air co-flow with the instantaneous OH PLIF images (figure 6). The small droplets are manly located in the center of spray because they follow the entrainment of air co-flow into the spray. Due to turbulent mixing at downstream locations, the inner reaction zone presents the characteristics of partially premixed combustion. The recirculation of burned gases in the swirl configuration increases the angle of atomization and change the structure of the flame. The small droplets are entrained by the IRZ towards the edge of the spray. In both configurations, the interaction between the flame front and the fuel droplet temperature is important and generates an evolution of fuel droplet temperature as shown in figure 11. The droplet temperature decreases slowly far from the flame front as for the previous height but this is followed by a sudden rise in temperature as the droplets arrive in the vicinity of the flame brush due to the high temperature of flame.

Acknowledgements:

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